UCRL-53311
Distribution Category UC-41

UCRL--53311

DE83 008439

Particle Size for Greatest Penetration of HEPA Filters—and Their True Efficiency

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Manuscript date: December 1, 1982

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Abstract

The particle size that most greatly penetrates a filter is a function of filter media construction, aerosol density, and air velocity. In this paper the published results of several experimenters are compared with a modern filtration theory that predicts single-fiber efficiency and the particle size of maximum penetration. For high-efficiency particulate air (HEPA) filters used under design conditions this size is calculated to be 0.21 μm diam. This is in good agreement with the experimental data. The penetration at 0.21 μm is calculated to be seven times greater than at the 0.3 μm used for testing HEPA filters. Several mechanisms by which filters may have a lower efficiency in use than when tested are discussed.

Introduction

High-efficiency particulate air (HEPA) filters used in the nuclear industry are pretested for efficiency using a monodispersed dioctylphthalate (DOP) aerosol of 0.3-μm diam. This testing is based on the assumption that 0.3-μm-diam particles are the most penetrating for HEPA filters. If this is not the size for maximum penetration, then "what is?" and "how much greater is the penetration?" are questions that need to be answered for an accurate evaluation of environmental releases of hazardous materials. To answer these questions I reviewed the literature and summarize it here.

It is very difficult to measure the efficiency of a HEPA filter as a function of particle size. Typically, the aerosol concentration upstream from a HEPA filter is a few times 10^5 greater than that downstream. If the upstream concentration is too high, then filter loading is a problem. If it is too low, then the aerosol downstream cannot be detected with sufficient accuracy. Another approach is to measure the efficiency as a function of particle size on filters that are similar to HEPA filters but are of less efficiency. A theory is then developed that can be used to predict the efficiency function of a HEPA filter.

The first two papers reviewed measured the efficiency function directly on HEPA filters. The remaining papers were reviewed to show that a theory has been developed that adequately predicts the efficiency of a filter and, in particular, the particle size of maximum penetration.

Theory Review

The most modern theories of filtration of fine particles on fibrous filters have been published by Liu and associates at the University of Minnesota[1-4] and by Fuchs and associates at Karpov Institute of Physical Chemistry in Moscow.[5-9] Older theories have been discussed in books[10,11] and several of the experimental papers reviewed. The modern theories show that filtration efficiency is a function of the filter media properties, the aerosol properties, and the properties of air. I have used the theory derived by Liu and associates in this report.

In their paper on this subject, Lee and Liu[2] present the following:

> Stechkina et al.[9] suggested that the predominant filtration mechanisms in the immediate neighborhood of maximum penetration size are diffusion and interception with the inertial impaction mechanism playing only a minor role. Consequently, only these

mechanisms are considered here. In a separate study,[12] the authors obtained the following single fiber efficiency using the boundary layer approach and the Kuwabara viscous flow field:

$$\eta = 2.6\left(\frac{1-\alpha}{K}\right)^{1/3} Pe^{-2/3} + \left(\frac{1-\alpha}{K}\right)\frac{R^2}{1+R}, \qquad (1)$$

where

η = single fiber efficiency
α = fiber volume fraction of filter (solidity),
u = filtration velocity,
D_p = particle diameter,
D_f = fiber diameter,
D = diffusion coefficient of particles,
Pe = Peclet number = uD_f/D,
R = interception parameter = D_p/D_f,
K = Kuwabara's hydrodynamic factor
$= -\frac{1}{2}\ln\alpha - \frac{3}{4} + \alpha - \frac{\alpha^2}{4}$.

The first term on the right hand side of Eq. (1) describes the efficiency due to Brownian diffusion and the second term that due to interception. The single fiber efficiency in Eq. (1) is related to the overall efficiency of the filter mat by

$$E = 1 - \exp\left[\frac{-4\,\eta\alpha L}{\pi D_f(1-\alpha)}\right], \qquad (2)$$

where

E = the overall efficiency of filter,
L = thickness of filter.

In Eq. (2), E increases monotonically with increasing η. Therefore, the particle size that gives the minimum single fiber efficiency also results in the highest penetration through the filter.

Lee and Liu then determined the size of maximum penetration (SOMP) by differentiating Eq. (1) with respect to particle size and setting the derivative to zero. However, they had to make two approximations first, in order to perform the calculus and solve explicitly for $D_{p,min}$ or SOMP. The first approximation involves substituting a function of D_p in place of D. This is good over a limited range. The second approximation is that the term $(1 + R)$ in the denominator of the interception term is equal to 1, or that D_p is much smaller than D_f. They consider that this is a good approximation since SOMP is about 0.3 μm and a "typical fiber size is normally over 5 μm," thus causing an error of less than 0.3/5 or 6%. This is not true for HEPA filters because the fiber diameter is typically 0.7 μm; thus an error of 0.3/0.7 or 43% would occur in the efficiency due to interception. They also assume that inertial impaction is negligible. This is probably true under their experimental conditions but not under every experimental condition. In an earlier paper by Yeh and Liu[3] inertial impaction is discussed and is shown to become important for Stokes numbers greater than ~0.1, depending on the value of R. Explicit analytical equations are not given in the paper, but some parametric curves of value are shown. Stechkina et al.[13] gave an equation for single-fiber efficiency due to inertial impaction. It was:

$$\eta_{St} = \frac{(St)\,I}{(2K)^2}, \qquad (3)$$

where

$$I = (29.6 - 28\,\alpha^{0.62})R^2 - 27.5\,R^{2.8}, \qquad (4)$$

St = Stokes constant.

The equation for I must be incorrect because for values of $R > 1$, the I term is negative, and Yeh and Liu found that for $R < 1$, the method of Stechkina et al. overestimates the efficiency in most cases—the larger the R, the larger the error. Therefore, I did not include a term for inertial impaction.

In order to graphically compare the equations suggested by Lee and Liu with the experiments listed in Table 1, I plotted these equations for the wide variety of parameters found in the literature. I did not make the simplifying assumptions given in Lee and Liu[2] for the diffusion coefficient or that $R \ll 1$. I calculated the diffusion coefficient without simplifying assumptions:

$$D = \frac{kTC}{3\pi\mu D_p}, \qquad (5)$$

where

k = Boltzmann constant,
T = absolute temperature,
μ = gas viscosity,
C = slip correction factor.

For the slip correction factor I used the Knudsen-Weber equation:

$$C = 1 + a\frac{\lambda}{D_p} + b\frac{\lambda}{D_p}\exp\left(-c\frac{D_p}{\lambda}\right), \quad (6)$$

where

λ = mean free path of gas molecules,
a, b, c = 2.492, 0.84, and 0.435 according to Fuchs.[6]

Lee and Liu used approximations for the slip correction factor. For the interception term, I used the equation given by Lee, Eq. (5.26),[1] as the most complete and accurate:

$$\eta_R = \frac{(1+R)}{2K}\left[2\ln(1+R) - 1 + \alpha + \left(\frac{1}{1+R}\right)^2\left(1-\frac{\alpha}{2}\right) - \frac{\alpha}{2}(1+R)^2\right]. \quad (7)$$

The complete equation is now so complex that one cannot find the partial derivative of efficiency with respect to particle size. However, by plotting efficiency vs particle size for various values of D_f, α and u, one can read the SOMP from the plots for any case of interest (Fig. 1). For selected values of α and u, I have also plotted D_f vs

Table 1. Sources of experimental data.

	Filter media				Aerosol		
Author	Composition	Fiber diameter, D_f (μm)	Solidity, α	Thickness, L (mm)	Composition	Diameter, D_p (μm)	Specific gravity, ρ_p
Schuster and Osetek[14]	Fiberglass HEPA[a]	0.7	0.0516	0.60	DOP	0.07-0.29; Hetero[b]	0.986
Gonzales et al.[15]	Fiberglass HEPA[a]	0.7	0.0516	0.60	PuO_2	<0.121- >11.0; Hetero	< 11.46[c]
Thomas and Yoder[16]	Fiberglass FG-50, AAF	1.5	0.005	12	DOP	0.25-11.0; Homo[b]	0.986
Chen[17]	Fiberglass "B" glass	3.0	0.02-0.08	[d]	[e]	0.15-0.72; Homo	[e]
Dyment[18]	Fiberglass Aerosolve 95	0.85	0.00267	12.7	NaCl	0.02-0.7; Hetero	2.165
Ramskill and Anderson[19]	Fiberglass J	2	0.055[f]	0.737	DOP	0.26,0.28,0.30; Homo	0.986
	Viscose F	12	0.193[f]	1.52	H_2SO_4	0.31,0.6,0.8,1.0; Homo	1.836
Anderson et al.[20]	Fiberglass A	1.12	0.20[g]	0.71	DOP	0.26-0.32; Homo	0.986
	Fiberglass AA	0.87	0.20[g]	0.75	DOP	0.26-0.30; Homo	0.986
	Fiberglass AAA	0.62	0.20[g]	0.28	DOP	0.26-0.30; Homo	0.986
	Viscose 1.5 D	12	0.19	0.95	DOP	0.26-0.32; Homo	0.986
	Viscose 3.0 D	17	0.15	0.50	DOP	0.26-0.32; Homo	0.986
Stafford and Ettinger[21]	Cellulose Whatman 41	3.6	0.28	0.25	Polystyrene-latex	0.176-2.02; Homo	1.055
	Cellulose IPC 1478	16	0.19	0.56	Polystyrene-latex	0.176-2.02; Homo	1.055
Rimberg[22]	Cellulose Whatman 41	3.6	0.28	0.25	Polystyrene-latex	0.264-1.099; Homo	1.055
	Cellulose IPC 1478	16	0.19	0.56	Polystyrene-latex	0.264-1.099; Homo	1.055

[a]Author specified a commercial HEPA filter for ducts. I have assumed its properties to be the same as the 1000-cfm HEPA made by American Air Filter Company.

[b]The term Hetero indicates that a heterogeneous aerosol was used—a broad range of particle sizes. Homo indicates that a number of homogeneous particle sizes were used, each aerosol having a narrow size distribution.

[c]The specific gravity of crystalline PuO_2 is 11.46. The bulk density of the aerosol, which is made of agglomerates, is unknown but less than that of a crystal.

[d]Thickness was not given; author gave the single-fiber efficiencies so it was not needed.

[e]Aerosol composition was not given. I have assumed it was spheres of specific gravity = 1.

[f]Solidity was calculated from $\Delta P/u$ data and Davies' relationship.

[g]Authors based solidity of 0.20 on a glass fiber density of 1.25. A Johns-Manville employee states that density of glass fibers is 2.61. This would halve the solidity.

SOMP as determined from the complete equation and by Lee and Liu's Eq. (13) which contained the simplifying assumptions (Fig. 2). They agreed well except at the small fiber diameters. It was shown by Lee[1] that these equations fit their data well; therefore, none of their data will be shown here. In cases where the Stokes number is significant, >0.1, the position of the SOMP may shift to smaller particle sizes. The above equation for η_R gives problems when used at extremes. For $\alpha \geq 0.05$ and $R \geq 5$, the last term in the expression dominates and finally makes η_R negative. $R = 5$ for a particle diameter of 1 μm with a fiber diameter of 0.2 μm. This is past the SOMP for a 0.2-μm fiber.

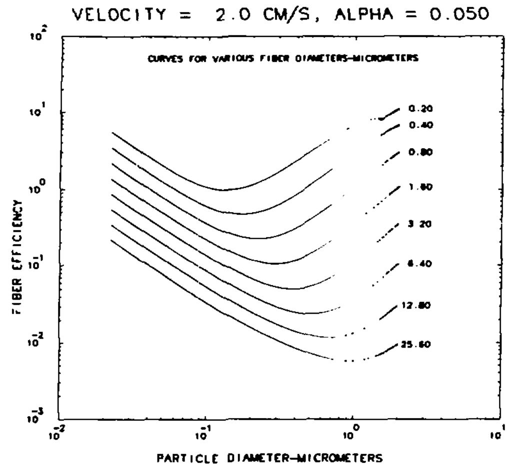


Figure 1. Efficiency vs particle size for various fiber diameters.

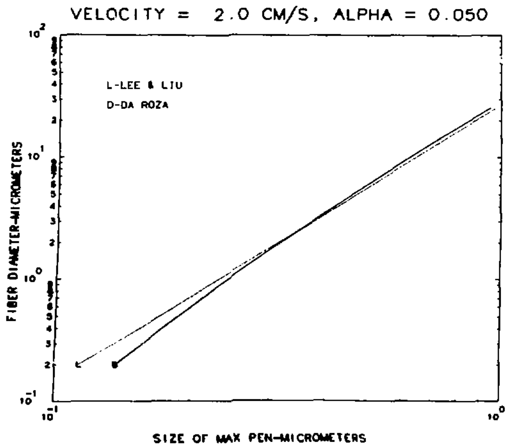


Figure 2. Fiber diameter vs SOMP, from Lee and Liu[2] and from Eq. (7).

Experimental Review

From an extensive literature search, nine reports on the subject were chosen for comparison of their data with the theory (see Table 1). Factors used in making the choices were: similarity to HEPA filter conditions, completeness of information, and apparent accuracy. To compare the theory with the experimental data, the complete theoretical equation was plotted using the appropriate values of fiber diameter, solidity, and velocity. The matching experimental values were also plotted. Each report will now be discussed.

Figure 3 shows the data of Gonzales et al. at Los Alamos for PuO_2 powder through a 25-cfm HEPA filter. They made determinations at both the standard filtration velocity of 25 cfm, which gives an air velocity of 1.9 cm/s in the filter media, and at one-half the standard velocity. The particle size was measured with an Anderson impactor and the aerodynamic equivalent diameter reported as a size interval; thus their data are plotted as a bar graph. They reported the penetration for each size interval as the mean of several runs (from 7 to 14 runs) with different filters. There appears to be a SOMP in the interval between 0.44 and 0.96 μm for the group of higher-efficiency HEPA filters and in the interval 0.22 to 0.44 for the group of lower-efficiency filters at full-flow testing. In half-flow testing, the SOMP is in the larger interval for both groups. The theoretical curve indicates that at full flow the intervals of 0.12 to 0.22 and 0.22 to 0.44 should be about the same and of lower efficiency than any other group. At half flow the 0.22 to 0.44 interval should be of lowest efficiency. It is hard to get a firm number, but the theory predicts a SOMP about one-third as large as measured by Gonzales et al.

This difference can be explained by considering the difference between the two kinds of diameters used. The theory uses a geometric diameter; i.e., the diameter of a sphere of equal volume, whereas Gonzales measured the aerodynamic diameter; i.e., the diameter of a sphere of unit density having the same Stokes number. Using the following equation from Hesketh,[23]

$$D_p^2 \rho_p C = D_{pa}^2 C_a \ , \qquad (8)$$

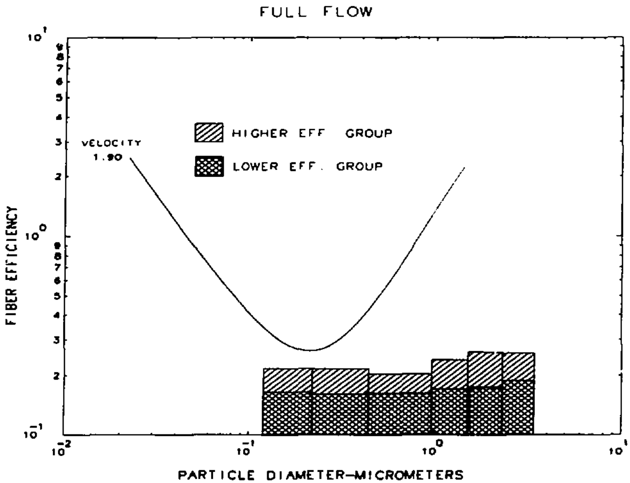
where C and C_a are the appropriate Cunningham slip coefficients, we can determine the density of a particle, ρ_p, that would have a geometric diameter, D_p, of 0.2 μm and an aerodynamic diameter, D_{pa}, of 0.6 μm. It is 6.1 g/cm^3. Likewise, a D_p of 0.2 μm and a D_{pa} of 0.4 μm would require a density of 3.0 g/cm^3. Since the density of a single solid PuO_2 particle is 11.46 g/cm^3, it is reasonable that an aggregate of smaller particles might have a density of 3 to 6 g/cm^3. Thus, the aerodynamic diameters measured by Gonzales should be divided by 2 or 3 to convert them to geometric diameters. This would bring the SOMPs into good agreement. Gonzales used the aerodynamic diameter, as he thought that inertial impaction was the chief mode of particle collection. The Stokes number for a 0.3-μm particle of density 11 g/cm^3 is 0.26. For a density of 1 it is 0.023. The detailed calculations of Yeh and Liu indicate that for the Stokes numbers encountered in this experiment inertial impaction is negligible.

Figure 4 shows the data from Schuster and Osetek for DOP through a 25-cfm HEPA filter. They did not give any filtration parameters, only that their system was a scaled-down version of a typical industrial HEPA filter system with the same flow volume per unit filter surface area. The value of α was obtained from measurements on a disassembled HEPA filter made by American Air Filter Company. A glass density of 2.61 g/cm^2 was used. This was obtained from Johns-Manville Company in Denver, as was the mean surface diameter of 0.7 μm although a filter is made from a broad range of fiber diameters. The points plotted were obtained from a smooth curve drawn through their data. The conversion was made from protection factor, P.F., to single-fiber efficiency using Eq. (2) and Penetration $= 1 - E = 1/\text{P.F.}$

The calculated SOMP agrees well with the experimental data and is 0.21 μm. The calculated magnitude of η is high, but the shape of the curve agrees well. One would expect the experimental data to give a flatter curve since the real HEPA filter is composed of a range of fiber diameters.

Figure 5 shows the data of Thomas and Yoder for a DOP aerosol collected by a loose fiberglass filter mat. The points plotted were obtained from a smooth curve drawn through their data, and are not their actual data points. To better compare the SOMPs, the points were adjusted upward by a factor of two to approximate the location of the calculated curve. Their data clearly show the existence of a SOMP and are in good agreement with the theory.

Figure 6 shows the data of Chen. His values for η_0 were changed to η_α by his equation $\eta_\alpha = \eta_0 (1 + 4.5\,\alpha)$ using an α of 0.05. His η_α is the same as η used in this report. As can be seen by the scatter



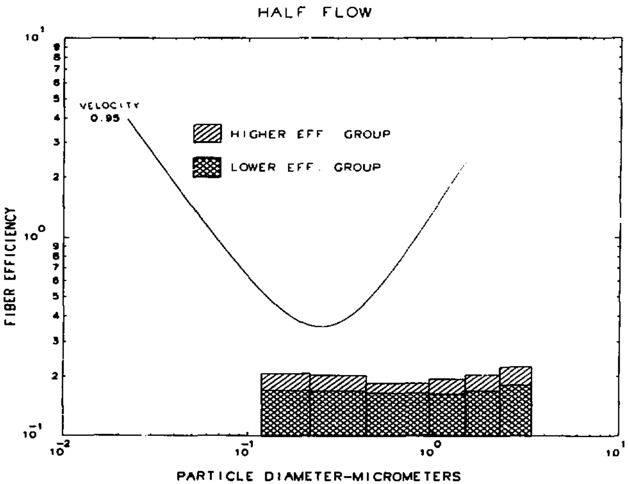


Figure 3. Data from Gonzales et al.[15] for standard filtration velocity and half standard filtration velocity.

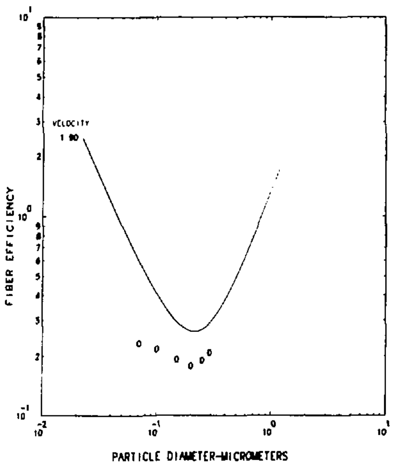


Figure 4. Data from Schuster and Osetek.[14]

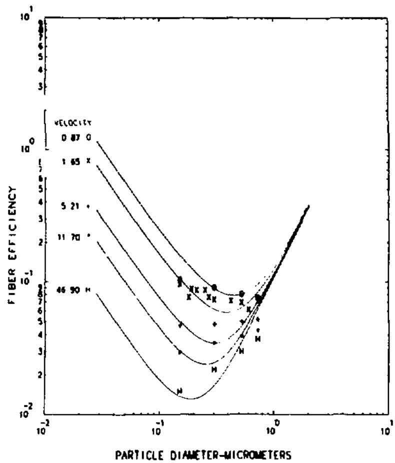


Figure 6. Data from Chen.[17]

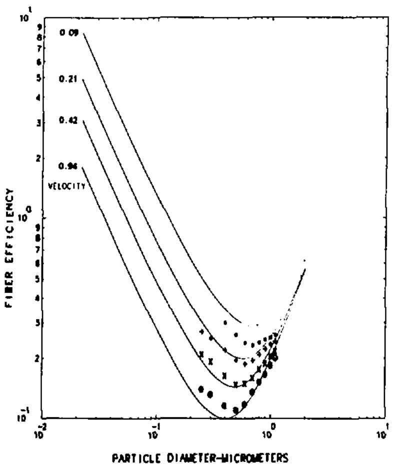


Figure 5. Data from Thomas and Yoder.[16]

in the points, actual data points are plotted, not smoothed values. The agreement between theory and Chen's data is very good in both SOMP and magnitude of the single-fiber efficiency.

Figure 7 shows the data of Dyment. The magnitude of the efficiency agrees but the experimental value of the SOMP is smaller at all three velocities. The reason for this may be due to the nature of the aerosol used. It was sodium chloride, which is a solid cube of density 2.2 g/cm^3. I corrected the reported mean projected diameters by a factor of 1.1 using the calculations of Dyment.[24] The density greater than one would shift the SOMP in the observed direction, but it would be by a negligible amount. In another report,[25] Dyment describes a filtration experiment with the same filter material but a methylene blue aerosol. He measured the particle size distribution and concentration both before and after the filter with a Goetz spectrometer and obtained a SOMP between 0.15 and 0.20 μm at 2.5 cm/s. This is a little closer to the theory.

Figure 8 shows the data of Ramskill and Anderson. They did not give the values of α for their

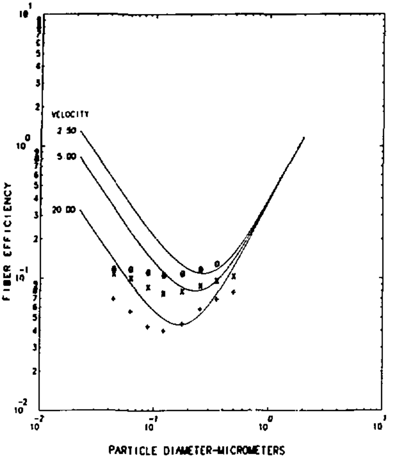


Figure 7. Data from Dyment.[18]

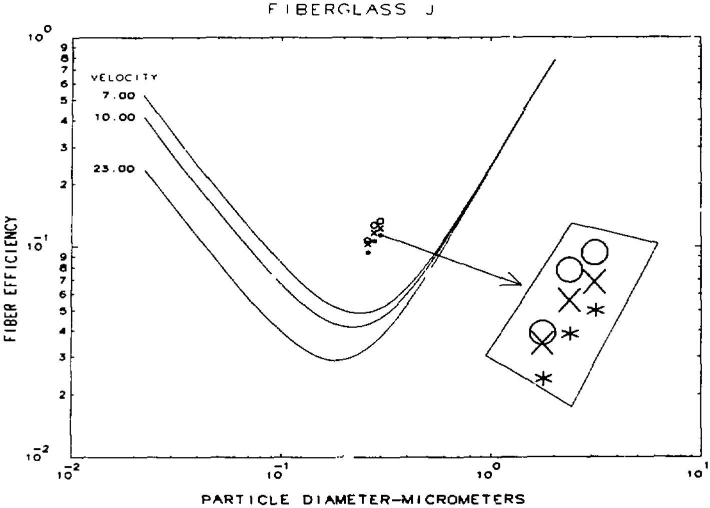
filters, but they did give the pressure drop vs velocity. I used the following semi-empirical equation by Davies[11] (p. 36) to estimate the α for two of their filters:

$$16\alpha^{1.5}(1 + 56\alpha^3) = \frac{\Delta P D_f^2}{4\mu u L}, \quad (9)$$

where μ is the viscosity of air and ΔP is the pressure drop across the filter at an air velocity of u. The theory underestimates the efficiency a little, but clearly shows why they did not find a SOMP. The data taken on H_2SO_4 gives a hint that there is some inertial filtration.

Figure 9 shows the data of Anderson et al. To better compare the experimental data with the theory, the single-fiber efficiency calculated from the experimental data has been multiplied by 10 for the glass fibers. This shows that the slopes of the curves agree fairly well. The absolute magnitude of the fiber efficiency is uncertain since it depends strongly upon the solidity. The solidity was given as 0.20 by Magee et al.[26] They based this on a glass fiber density of 1.25 g/cm^3 and referenced Hall.[27] Hall's textile handbook does not reference the density, but is possibly referring to a bundle of single fibers. The density of glass fibers used in filters was given by a Johns-Manville Company employee as 2.61 g/cm^3. The solidity would then be calculated as 0.094. This would raise the single-fiber efficiency by a factor of 2.4 and lower the theoretical curve only slightly.

Figure 10 shows filtration curves for two paper filters, Whatman 41 and IPC 1478. A phone discussion with the technical consultant at Whatman Paper Division revealed that one cannot give a fiber diameter or even a range of fiber diameters for their paper. It is apparently a mass of branches and splits of all sizes of cellulose. Therefore, I used Eq. (9) to calculate D_f which is now an effective fiber diameter. The α and L were obtained from Lockhart et al.[28] and the ΔP and u from Rimberg.[22] The D_f for IPC 1478 was calculated the same way. Both Stafford and Ettinger's[21] measurements and Rimberg's[22] are in general agreement with the theory for Whatman 41 even though the efficiency was overestimated. Rimberg's data on IPC 1478 agree well on efficiency but show a smaller SOMP than the theory.



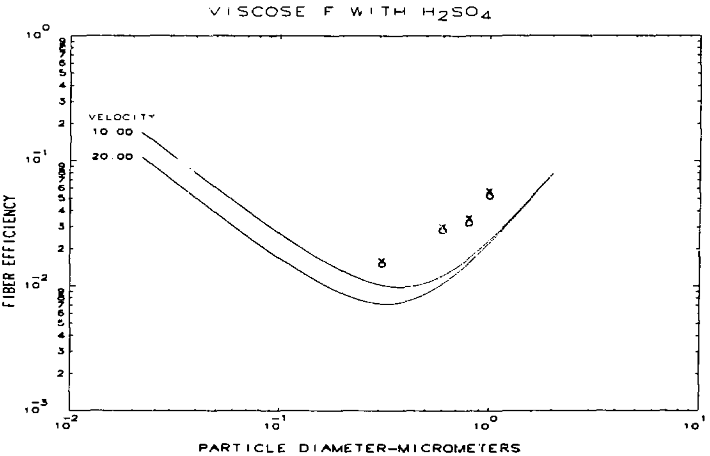


Figure 8. Data from Ramskill and Anderson[19] for Fiberglass J and Viscose F with H_2SO_4.

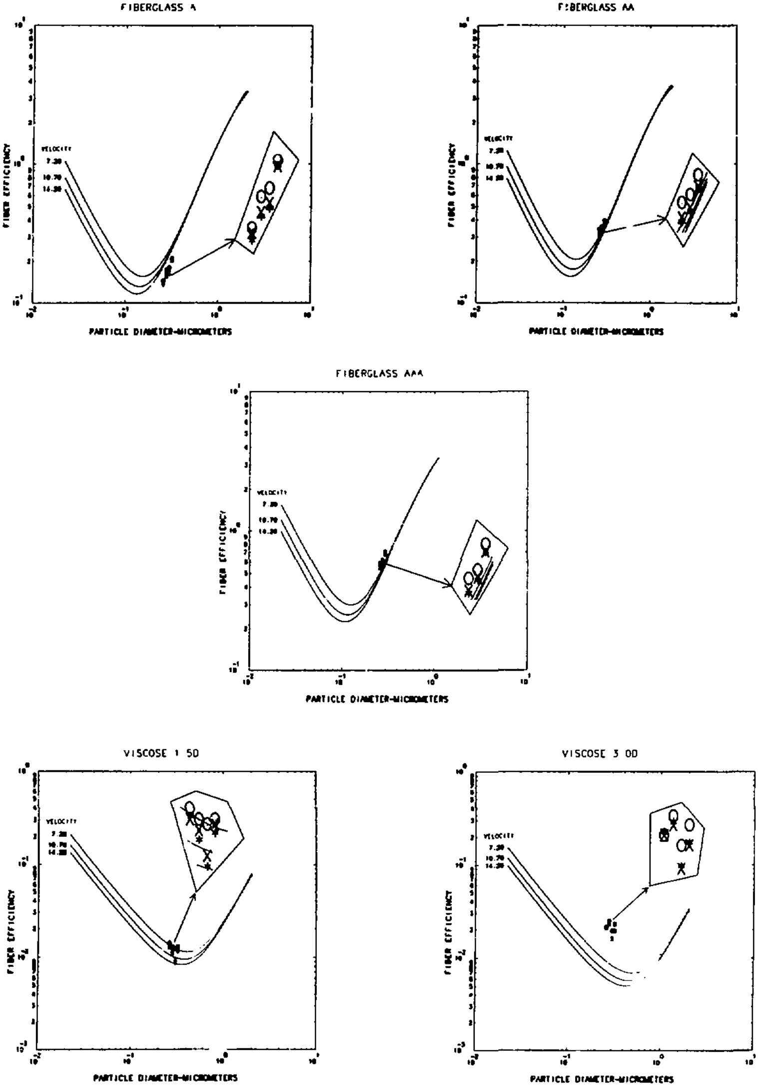


Figure 9. Data from Anderson et al.[20]

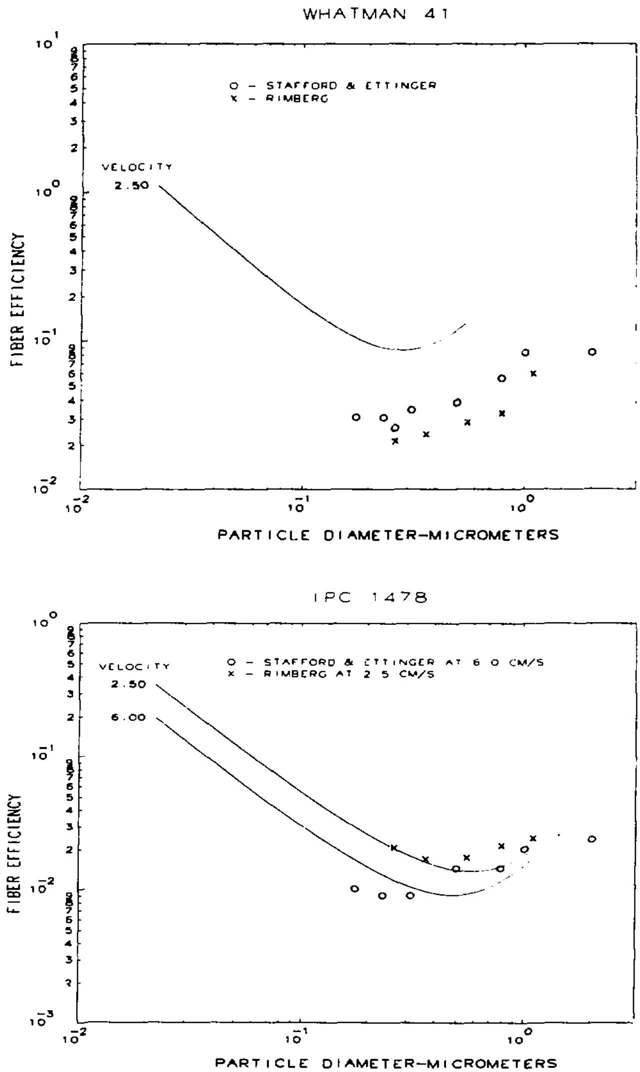


Figure 10. Data from Stafford and Ettinger[21] and Rimberg[22] for Whatman 41 and IPC 1478.

Summary

From a study of the figures and the comparisons in Table 2, it can be seen that the theory is adequately verified. We may now use the theoretical calculations for HEPA filters to get the best value for the SOMP, and an estimate of the penetration at 0.3 μm compared with that at the SOMP. This can be obtained from Figs. 3 and 4. Using Eq. (2), the filter media efficiency can be

Table 2. Comparison with theory.

Author	Filter media	Filtration velocity (cm/s)	Particle Size of Maximum Penetration (µm)	
			Theory	Experiment
Schuster and Osetek[14]	Fiberglass HEPA	1.9	0.21	0.2
Gonzales[15]	Fiberglass HEPA	1.9	0.21	0.44-0.96[a]
				0.22-0.44[b]
		0.95	0.25	0.44-0.96[c]
Thomas and Yoder[16]	Fiberglass FG-50	0.094	0.70	0.70
		0.21	0.58	0.60
		0.42	0.48	0.52
		0.94	0.40	0.50
Chen[17]	Fiberglass "B" Glass	0.87	0.45	Agrees[d]
		1.65	0.39	Agrees
		5.21	0.30	Agrees
		11.7	0.25	Agrees
		46.9	0.19	Agrees
Dyment[18]	Fiberglass Aerosolve 95	2.5	0.27	~0.13
		5.0	0.23	~0.15
		20.0	0.18	~0.11
Ramskill and Anderson[19]	Fiberglass J	7	0.24	Agrees
		10	0.22	Agrees
		23	0.18	Agrees
	Viscose F	7	0.38	Agrees
		10	0.32	Agrees
Anderson et al.[20]	Fiberglass A	7.2	0.16	Agrees
		10.7	0.14	Agrees
		14.2	0.13	Agrees
	Fiberglass AA	7.2	1.5	Agrees
		10.7	1.3	Agrees
		14.2	1.2	Agrees
	Fiberglass AAA	7.2	1.3	Agrees
		10.7	1.2	Agrees
		14.2	1.1	Agrees
	Viscose 1.5 D	7.2	0.42	Agrees
		10.7	0.38	Agrees
		14.2	0.35	Agrees
	Viscose 3.0 D	7.2	0.50	Agrees
		10.7	0.45	Agrees
		14.2	0.43	Agrees
Stafford and Ettinger[21]	Cellulose Whatman 41	2.5	0.28	~0.25
	Cellulose IPC 1478	6.0	0.48	~0.3
Rimberg[22]	Cellulose Whatman 41	2.5	0.28	~0.25
	Cellulose IPC 1478	2.5	0.60	~0.4

[a] Higher-efficiency group of filters.

[b] Lower-efficiency group of filters.

[c] Both groups of filters.

[d] "Agrees" indicates that the data points agree with the slope of the theoretical curve but were not taken at the SOMP.

calculated from the single-fiber efficiency. This is summarized in Table 3 for both full-flow and half-flow rates. The ratio of penetration at the SOMP (0.21 μm) to that at 0.3 μm is 7.1, which compares well with the experimental ratio of 5.5 reported by Schuster and Osetek.

It should be noted that particles smaller than the SOMP may not always be removed with an efficiency greater than that at the SOMP. Mazzini[29] describes an experiment wherein particles of about 0.02-μm diameter acted as nuclei of condensation so that they had a diameter of about 0.2 μm (mostly due to condensed water) when they passed through a HEPA filter. Thus, they were removed at a lower efficiency than expected for 0.02-μm particles.

Various people have expressed concern that the efficiency of a clean filter measured over a short time may not be the same as for a loaded filter over a long period of time. Most experiments show that the efficiency increases as a filter is loaded; however, note the following comment by Rivers of American Air Filter Company made on Ref. 30:

> I certainly agree with the conclusions of your paper. A couple of statements at the beginning from a practical case don't hold entirely. The statement that the efficiency goes up throughout the life of the filter is largely true.
>
> However, in roughing filters, it is widely observed that the point comes where the filter will elute or pass collected dust. I believe Mitchell of Battelle, Columbus, did some studies which indicated this is also true for HEPA filters: that you can get to the state where a certain amount of migration results, and the efficiency then goes down. And when you look at the photograph #4, I think it is pretty obvious why. Little feathers break off and slowly pass through.

Also Schuster and Osetek's[14] data show that when a NaCl aerosol is used, the efficiency increases with loading, but for a DOP aerosol, the efficiency first increases with loading and then decreases to an efficiency poorer than with no loading.

Others are concerned that alpha-emitting isotopes may move through a filter by aggregate recoil transfer. To quote from Ryan and McDowell,[31]

> Aggregate recoil transfer is a phenomenon specific to surfaces of alpha-emitting radioactive material where, due to the kinetic energy made available by alpha decay, clusters of atoms are ejected into the surrounding medium. Such atom clusters, known as aggregate recoil particles,[32] may contain up to 10^6 atoms. Particles of alpha-emitting material, which are collected in normal HEPA filter operation with near 100% efficiency, may be sources of aggregate recoil particles. Aggregate recoil particles produced from a larger collected particle may undergo re-entrainment in the moving air-stream and subsequent redeposition downstream in the filter. If an alpha decay event occurs within this particle again, re-entrainment and redeposition may occur. This process leads to a net transfer of radioactive material in the downstream direction.

The production of aggregates of ^{212}Pb particles and the sizing of their aggregate recoil particles was studied by Vento.[33] The penetration characteristics of the particles through a filter were studied by Ryan et al.[34] Both studies were done at Lowell Technological Institute. After Ryan went to ORNL, he and McDowell performed experiments using several different radioisotopes and methods of source preparation. This work was reported in detail at an ERDA Air Cleaning Conference[35] and a summary was also published.[36] Finally, they studied two sets of four HEPA filters that had been used in series in a plutonium facility.[31] In all of their work, they looked at the amount of material collected on several filters used in series. A general observation on their data would be that successive stages of filtration did not give as large a decontamination factor as expected. They present a model based on aggregate recoil particles which they claim fits the data. However, the variance in the model's rate constants is large. I do not think that their experiments proved the model. However, their data cannot be explained by conventional filtration theories either. McDowell has told me that he has had difficulty repeating some of the experiments, but still believes in the mechanism. I considered the physical possibilities for aggregate recoil and agree that it can exist. Whether it is of sufficient magnitude to produce the results obtained by Ryan and McDowell can only be determined by further careful experimentation.

Table 3. Summary of HEPA filter results.

	Full flow	Half flow
Filtration velocity (cm/s)	1.9	0.95
SOMP (μm)	0.21	0.25
η at SOMP	0.263	0.356
η at 0.3 μm	0.296	0.367
P at SOMP	1.65×10^{-7}	6.59×10^{-10}
P at 0.3 μm	2.32×10^{-8}	3.43×10^{-10}
$P_{SOMP}/P_{0.3}$	7.1	1.9

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