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Filter Efficiency vs Particle Size and Velocity

by

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ABSTRACT

Several commercial filter media were evaluated for efficiency as a function of particle size and velocity. Particle size and velocity producing minimum efficiency are different for each media and are well below single fiber theoretical predictions. Experimental efficiencies were generally higher than theoretical total mat efficiencies.

I. INTRODUCTION

Many investigators have predicted an optimum aerosol size for minimum efficiency through fibrous filters.[1-3] These predictions are generally based on theoretical single fiber filtration mechanisms of diffusion, interception, and impaction, usually ignoring electrostatic charge and gravitational effects. Theoretical calculations predict an aerosol size of 0.1- to 0.4-μm for minimum efficiency, and have been verified by some experimental investigators,[4, 5, 6, 7] while others have reported that efficiency continually decreases as particle size decreases.[2, 8, 9] A size for minimum efficiency is important since air cleaning systems are designed to effectively remove particulates of this size. In the United States, 0.3-μm DOP has been selected as the standard test aerosol for testing respirator and high efficiency particulate aerosol (HEPA) filters.[10]

Theory predicts a minimum efficiency for a specific velocity and filter media,[2, 4, 11] however, there is considerable discrepancy in the exact velocity for each filter. Because of these discrepancies, we initiated an experimental program to determine efficiency as a function of particle size and velocity for several commercial filters. Experimental data were compared with total mat theoretical efficiencies for these filters.

II. THEORY

Theoretical filter efficiency predictions are generally based on single fiber filtering mechanisms of diffusion, interception, and impaction, with charge and gravitational effects usually ignored. Single fiber theoretical filtration equations for diffusion and impaction show relatively sharp efficiency cutoffs, while efficiency due to interception remains constant throughout the entire velocity range. Figure 1 shows single fiber theoretical efficiency due to impaction and diffusion with 0.312-μm polystyrene latex aerosol at a filtration velocity of 40 ft/min.[12, 13] Efficiency due to interception was calculated and found to be negligible. Above 10 ft/min, capture of aerosol particles is due to impaction. Below 10 ft/min, diffusion becomes the predominant filtering mechanism. Figure 1 illustrates the sharp cut-off between the two mechanisms. Since this sharp cut-off is not consistent with experimental results, equations developed by C. N. Davies were used to predict theoretical mat efficiency of the various filter media tested.[14] His basic equation for filtration of a homogeneous aerosol by a uniform filter is:

$$\eta = \eta_o e^{-\lambda h}$$

where η is the concentration of particles passing through the filter and η_o the concentration of particles incident on the filter. Filter pad thickness

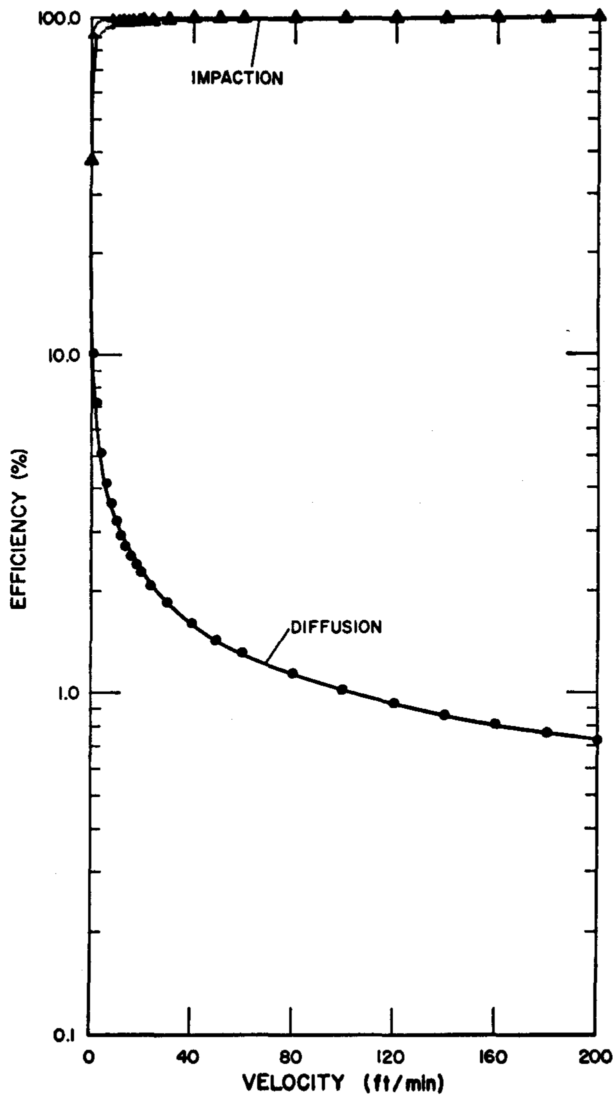

Fig. 1. Single fiber theoretical efficiency vs filtration.

is represented by h, and λ is the index of filtration efficiency determined by,

$$\lambda = \frac{c}{1 - c} \cdot \frac{2}{\pi R} \left(\frac{X}{R} + \frac{v}{\pi V} \right);$$

where c is the filter packing density, π is the filter pressure drop, R is the effective filter fiber radius, and $\frac{X}{R}$ is an interception parameter defined by Davies in terms of air viscosity, particle size, packing density, air velocity, and impaction and diffusion parameters.

Using a LASL computer program, these equations were solved and shown valid only for particle sizes below 6-μm. Other total mat equations were not used because they did not include packing density parameters.[15]

III. EXPERIMENTAL PROCEDURES

Figure 2 shows a schematic of the test apparatus. The aerosol was generated with 3 Penisol nebulizers (2) and impacted on a disk (3) to break up agglomerates. It then passed through a drying chamber (4) and tritium deionizer (5)[16] consisting of two sheets of tritiated foil having 4 curies of tritium adsorbed in a titanium layer. Tritium creates charge equilibriun on aerosols by secondary ionization in air and assists in preventing agglomeration. Aerosol charge was measured with a parallel plate capacitor for 0.312-μm and smaller particles. The deionizer reduced the charge on the 0.312-μm aerosol by 90% and on the 0.176-μm aerosol greater than 98%. The method used made it impractical to attempt to measure charge on larger particles because of their lower electric mobility.

Dilution air (6) then entered the system and the aerosol passed through a second drying chamber (7) to a coupling box (8) with a HEPA filter. The coupling box permitted an air balance between the aerosol inlet and filter sampling systems. The aerosol then traversed a sampling tube (11) with a mixing disk (10) and filter holder (13). Both upstream (12) and downstream (15) samples were analyzed with a LASL-designed forward light scat-

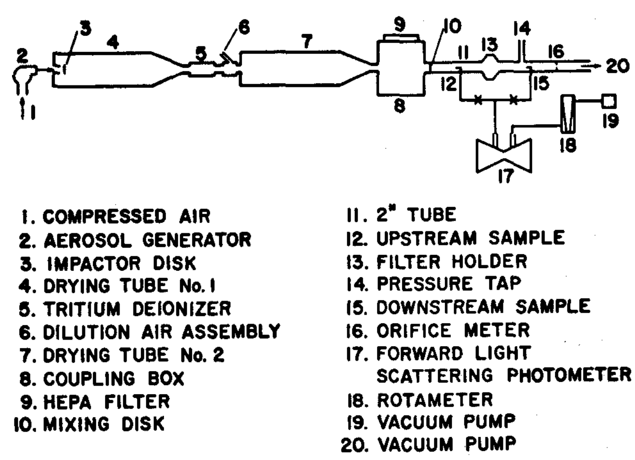

Fig. 2. Schematic of filter test system.

tering photometer (17).[17] This instrument is provided with a 0.01% scale and allows efficiencies of 99.9995% to be measured under high aerosol concentration conditions; however, upstream aerosol concentrations were low and instrument capabilities were reduced to 99.995% efficiency.

IV. RESULTS AND DISCUSSION

Figure 3 shows experimental efficiency data for Whatman 41 filter media. Each curve represents data for 16 different velocities, and maximum deviation from each curve was less than ± 2%. Optium particle size for minimum efficiency is well defined at low velocities. Efficiency decreases as particle size decreases down to 0.264-μm at which point efficiency increases with decreasing particle size (.234- and 0.176-μm) at lower velocities. Differences in efficiency using 0.176- and 0.264-μm aerosols are as high as 20% below 40 ft/min. and the size for minimum efficiency is between 0.234- and 0.312-μm. Data for Whatman 41 had to be taken immediately after the aerosol was introduced because of rapid filter loading with 0.312- to 0.79-μm aerosols. With particles smaller or larger, loading was not as pronounced. This may be due to an interfiber distance allowing particles between 0.312- and 0.79-μm to penetrate deep into the fiber mat and plug the whole filter, rather than an initial surface plugging phenomenon.

Efficiency decreased as the filter was loaded with larger particle sizes at higher velocities. At 20 ft/min, filter efficiency decreased with loading and was significantly decreased with particle sizes below 0.5-μm. At 100 and 150 ft/min, efficiency decreased as the filter was loaded with particles above 0.5-μm. Decreased efficiency with time may be due to fibers being coated with latex particles, thereby reducing available holding forces between particles and fibers. Holding forces between particles may be smaller than those existing between particles and fibers. Decreased efficiency with loading may be associated with a multiple billard-ball effect where entering particles dislodge previously captured particles. Billings has described an effect where particles attach themselves in large chains on fibers.[18] As these chains become sufficiently large, portions break off, resulting in an indicated decreased filter efficiency after loading. This phenomenon has also been observed with long term loading tests performed at this laboratory.[19] Due to low aerosol concentration (approximately 10^9 particles/min) we could not relate loading to an increase in media weight.

Figure 4 illustrates Davies' theoretical total mat filter efficiency vs particle size and velocity for Whatman 41.[14] Larger particles produce higher efficiencies at low velocities. Minimum efficiency occurs with smaller particle sizes as velocity is increased, and is below 0.2-μm in all cases. Figure 5 shows minimum theoretical efficiency vs velocity for Whatman 41. Each data point represents an aerosol size well below 0.3-μm. An important portion of this curve is that below 20 ft/min. which is the range common to respirator filters under normal work loads. Minimum efficiency var-

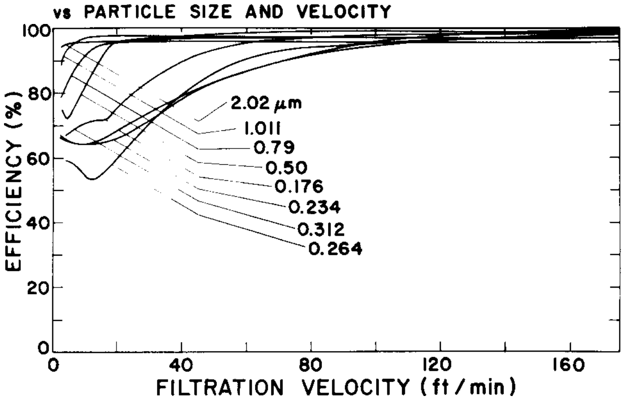

Fig. 3. Whatman 41 filter efficiency vs particle size and velocity.

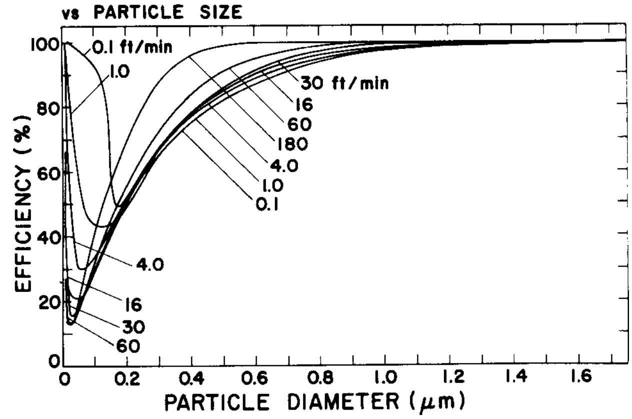

Fig. 4. Whatman 41 theoretical filter efficiency vs particle size.

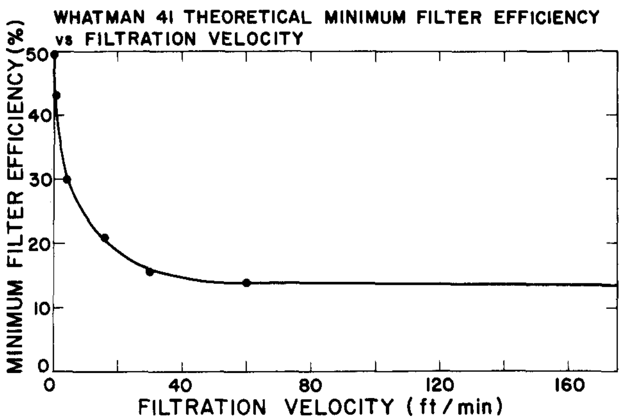

Fig. 5. Whatman 41 theoretical minimum filter efficiency vs filtration velocity.

ies rapidly with velocity, which is important in respirator filter efficiencies due to sinusodial velocity profiles associated with air flow through these filters. Most respirator filters are checked in AEC laboratories at steady velocities with liquid 0.3-μm dioctyl phthalate (DOP) aerosols but 0.3-μm is not the size aerosol that gives maximum penetration through all filters. There are also differences in filter efficiencies between liquid and solid aerosols.[20] Figures 6, 7, and 8 compares theoretical and experimental efficiencies vs particle size for Whatman 41 at velocities of 4, 12, and 140 ft/min. Experimental efficiencies are usually higher than theoretical calculations. Velocity trends shown by these three figures are consistent for velocities up to 180 ft/min. Differences may be attributed to slight agglomeration and charge associated with the experimental aerosol.

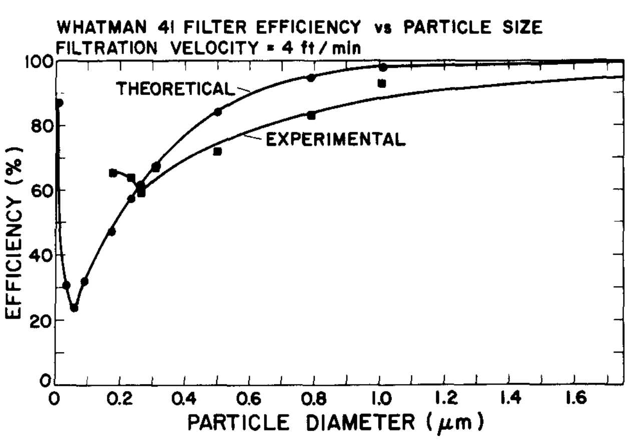

Fig. 6. Whatman 41 filter efficiency vs particle size (filtration velocity = 4 ft/min.)

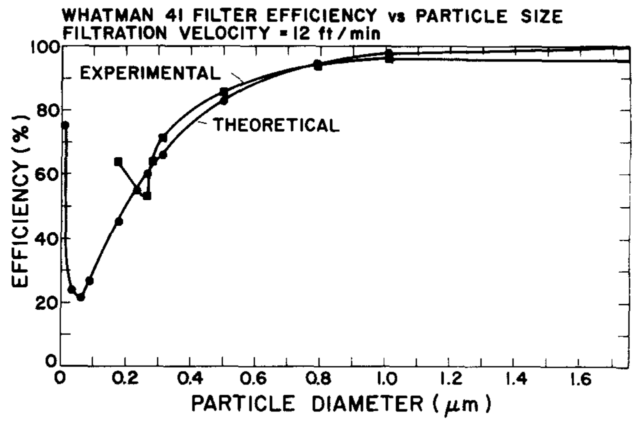

Fig. 7. Whatman 41 filter efficiency vs particle size (filtration velocity = 12 ft/min.)

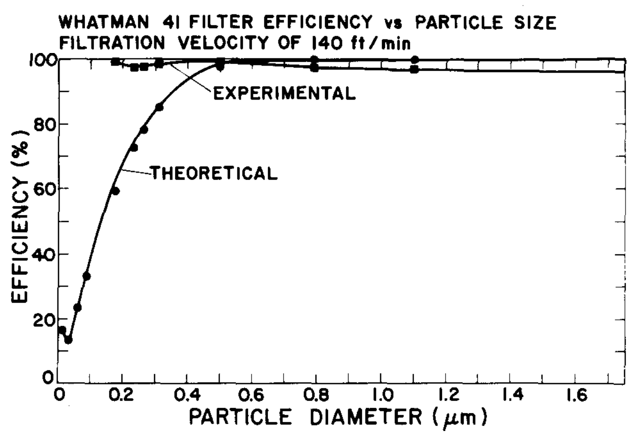

Fig. 8. Whatman 41 filter efficiency vs particle size (filtration velocity = 140 ft/min.)

Figure 9 shows filter efficiency as a function of velocity and particle size for IPC 1478 media. This medium is a loosely woven fiber mat usually used for high velocity sampling. Although velocities reported in this paper are lower than normally used, there is a definite separation for efficiency vs particle size. Each curve in Figure 9 represents test data for 16 velocities and deviation of each data point from its curve was less than ± 2%. At velocities above 15 ft/min, efficiency decreases as particle size decreases down to 0.176-μm. Below 15 ft/min, minimum efficiency occurs with a particle size of approximately 0.5-μm. Efficiency reverses because of diffusion at about 10 ft/min.

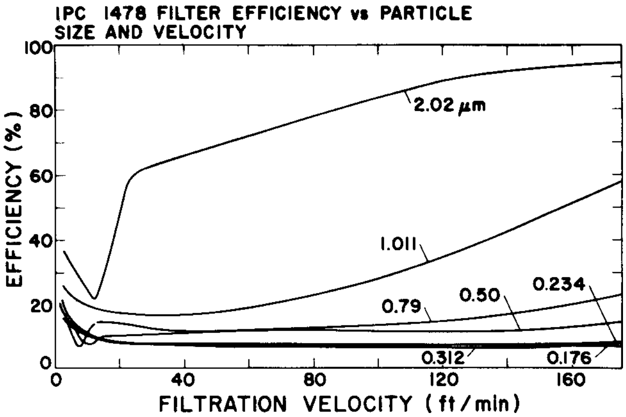

Fig. 9. IPC 1478 filter efficiency vs particle size and velocity.

Figure 10 shows IPC 1478 theoretical efficiency vs particle size at velocities ranging from 0.1 to 180 ft/min.[14] Above 0.2-μm, impaction mechanisms result in higher efficiency with increasing velocity. Below 0.2-μm, efficiencies are higher at lower velocities due to diffusion mechanisms. Theoretical aerosol size for minimum total mat efficiency is approximately 0.03-μm, an order of magnitude smaller than single fiber theory predicts. Figures 11, 12, and 13 show comparisons of experimental and theoretical efficiencies vs particle size at velocities of 4, 12, and 140 ft/min. respectively. Theoretical values are generally lower than experimental values which may be due to some agglomeration and charge associated with experimental aerosols. Agglomeration and charge are not accounted for in theoretical calculations. Experimental impaction mechanisms are more pronounced than theory predicts which may again be explained by agglomeration of polystyrene latex aerosols. IPC 1478 filter loading was not significant with any of the aerosol sizes used.

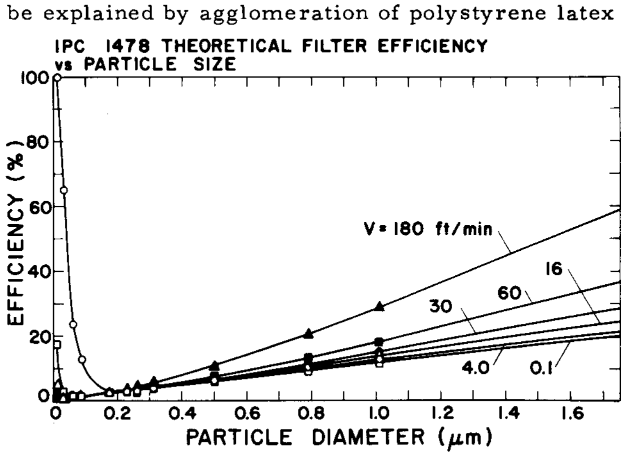

Fig. 10. IPC 1478 theoretical filter efficiency vs particle size.

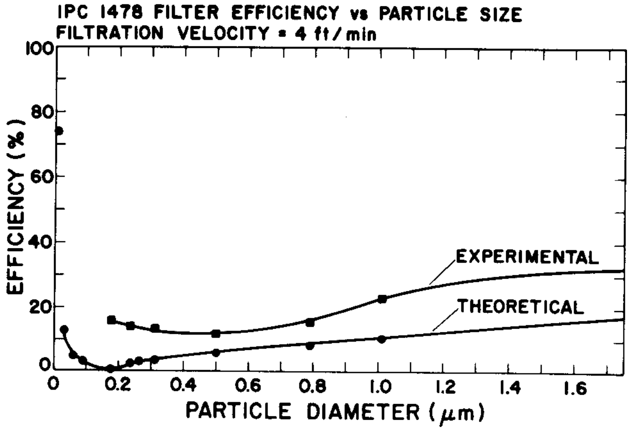

Fig. 11. IPC 1478 filter efficiency vs particle size (filtration velocity = 4 ft/min.)

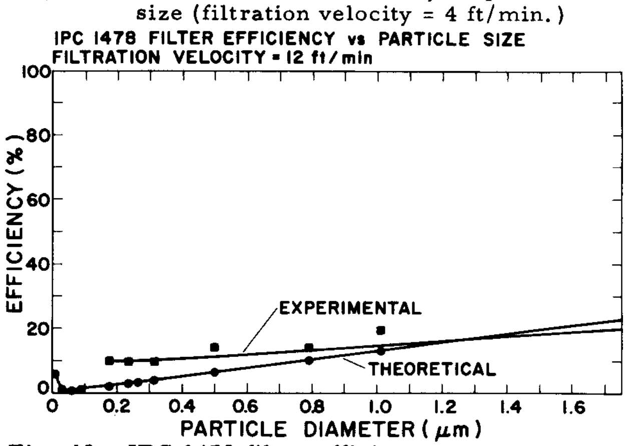

Fig. 12. IPC 1478 filter efficiency vs particle size (filtration velocity = 12 ft/min.)

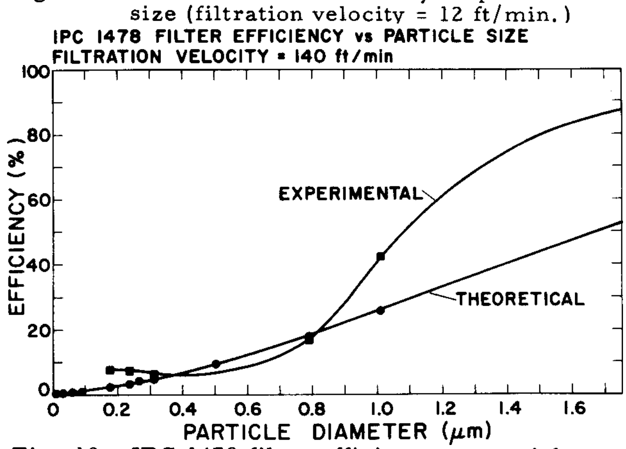

Fig. 13. IPC 1478 filter efficiency vs particle size (filtration velocity = 140 ft/min.)

Both HV 70 and CM 114 filter media have fiber sizes ranging from 0.5- to 35-μm. It was not possible to calculate total-mat theoretical efficiency of these media because Davies' equations are based on homogeneous fiber sizes.

Discrepancies in measuring filter efficiency among various laboratories may be atttributed to poor quality control in manufacturing of the filter media. Some investigators did not look at filter efficiencies with small enough particle sizes to see diffusion parameters becoming effective[4, 2] and others lacked methods of reducing and measuring aerosol charge.[5, 8] We were unable to generate latex aerosols below 0.176-μm because of excessive agglomeration.

V. SUMMARY

Whatman 41 filter media exhibits minimum experimental efficiency with a particle size between 0.234- and 0.312-μm. Theoretical total mat efficiency indicates that particles below 0.2-μm produce minimum efficiency; however, this is a function of velocity. Minimum efficiency occurs at smaller particle sizes as velocity is increased. With all polystyrene latex aerosols tested, pressure drop increased as the filter became loaded. Filter efficiency increased as the filter became loaded at low velocities (20 ft/min); however, at higher velocities (above 100 ft/min), efficiency initially increased and then decreased with continued loading.

Efficiency of IPC 1478 filter media decreases as particle size decreases down to 0.176-μm for velocities above 15 ft/min. Below 15 ft/min, minimum efficiency occurs with a particle size of approximately 0.5-μm. Theoretical total-mat filter efficiency occurs with 0.03-μm particles, an order of magnitude smaller than single fiber theory predicts; however, this is dependent upon velocity.

Results of this study indicate that a re-evaluation of filter testing should be reconsidered since 0.3-μm aerosol does not yield minimum efficiency. Particle size producing minimum efficiency can change significantly at different velocities. It would be desirable to establish a specific set of testing procedures for each type of filter.

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