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Filtration of Airborne Microorganisms

The critical aspects of filter sizing and a methodology for predicting a filter'.s effectiveness against allergens, bacteria, and viruses

By W.J. Kowalski, PhD, PE,

and ***W.P. Bahnfleth, PhD, PE***

The Pennsylvania State University

W. J. Kowalski*, PhD, PE, is a research associate, and* ***W.P. Bahnfleth****, PhD, PE, is an asssociate professor in the Department of Architectural Engineering at The Pennsylvania State University. Kowalski researches and develops immune-building technologies and designs air-cleaning systems for health-care facilities, while Bahnfleth, a member of HPAC Engineering.s Editorial Advisory Board, teaches and conducts research in the area of building mechanical and energy systems. They can be contacted at* ***drkowalski@psu.edu*** *and* ***wbahnfleth@psu.edu****.*

Filtration, along with dilution ventilation, exhaust, and source control, is one of the primary means of controlling indoor-air quality. High-efficiency filtration protects against the intrusion and spread of airborne pathogens and allergens in indoor environments. The filtration of microorganisms is a topic that requires special focus because of the unique characteristics of both, filters and airborne pathogens in the submicron size range.

This article addresses the critical aspects of filter sizing and provides a methodology for predicting a filter's performance against airborne microorganisms. Results of studies on the filtration of viruses and bacteria are compared with theoretical filter performance. Also, some fieldperformance results are reviewed.

An aircraft-cabin HEPA filter with continuous pleated media to reduce leakage

Aerobiological contaminants

The biological contaminants of indoor air include pollen, animal dander and other allergens, fungal and bacterial spores, bacteria, and viruses.

Pollen. Pollen, which can cause allergic reactions in susceptible individuals, comes seasonally from outdoor air. The size of pollen - about 10 to 100 microns - ensures removal by panel filters or pleated filters in the 20-to-30-percent dust-spot-efficiency range, but not by dust filters.

Animal dander and other allergens. Dander consists of skin cells or organic matter from cats, dogs, mice, dust mites, cockroaches, or other animals. Dander induces allergic reactions in sensitive individuals. Prolonged exposure to allergens may induce allergic reactions even in people who do not have allergies. These particles vary in size from 1 to 100 microns, with a mean size of about 7 to 20 microns. Dust filters alone are insufficient for their control.

Fungal and bacterial spores. Although fungal and bacterial spores normally originate outdoors, they also can be generated indoors when conditions support their growth. Typically ranging in size from about 1 to 20 microns, they can easily penetrate dust filters. High-efficiency filters, with 25-to 90-percent dust-spot efficiency, remove spores at increasing rates. **Figure 1** shows how airborne microbes line up on the performance curve of a 60-to-65-percent filter. Note that dander, shown at both 7 and 20 microns to illustrate its size range, and most spores fall on the 100-percent removal-efficiency line.

Bacteria. Pathogenic (diseasecausing) bacteria typically come from human or animal sources indoors. At about 0.2 to 2 microns in size, they are too small to be intercepted by ordinary dust filters. Filters of 80- to 90-percent dust-spot efficiency are required to remove most airborne bacteria.

Viruses. The smallest microbes, viruses range in size from 0.01 to 0.3 micron. A high-efficiencyparticulate- air (HEPA) filter can remove viruses at high rates, while even a 60-percent filter can remove up to half of some viruses.

Although specific guidelines concerning acceptable indoor concentrations do not exist for most microbes, some have been suggested.1 In general, they imply that to maintain healthy buildings, nonpathogenic bacteria and spores should be kept below the lower of 10 percent of outdoor levels or 100 colony forming units (cfu) per cubic meter, while levels of pathogenic microbes should be kept as close to zero as possible - or at least well below the infectious dose, if it is known.

Simple models of air mixing in multizone building systems normally provide adequate results for selecting appropriate filters.[2] The most sophisticated methods of analysis use computational fluid dynamics to predict air and contaminant movements in rooms.

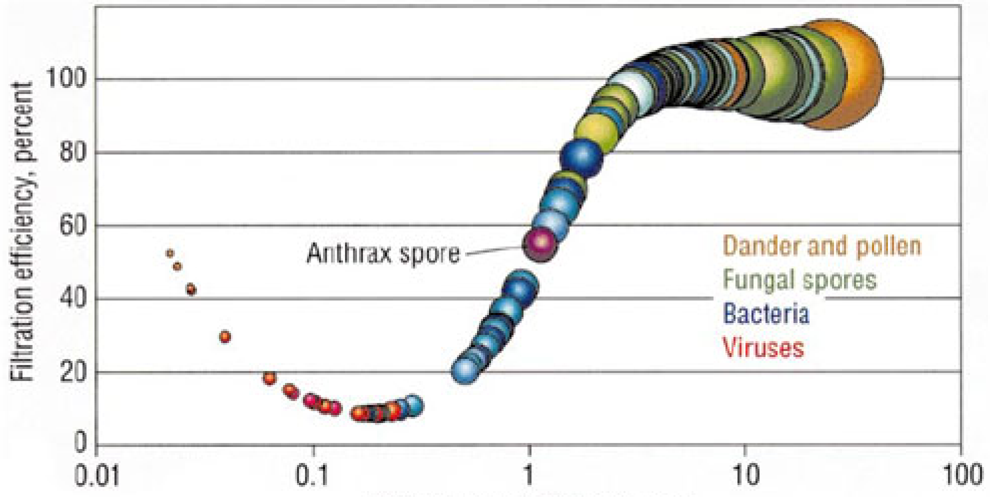

Figure 1 : Airborne microbes overlaid on the performance curve of a 60-to-65-percent-dust-spot-efficiency filter. The circular areas represent the mean diameter of microbes in relative proportion

Filters and filter performance

A filter's effectiveness against airborne microbes primarily depends on the characteristics of the filter, the velocity of the air, the size of the particles, and the type of microbe.

The filters available today meet many specialized needs. The basic types range from the lowestefficiency dust filters, such as rolltype filters used in commercial buildings, to HEPA and ultra-lowpenetration- air (ULPA) filters used in cleanrooms and operating rooms.

This article is concerned with filters in the nominal-dust-spotefficiency range of 25 to 90 percent and HEPA filters, otherwise known as Group III filters.[3] ANSI/ ASHRAE Standard 52.2-1999, Method of Testing General Ventilation Air Cleaning Devices for Removal Efficiency by Particle Size, provides new designations for these filters in terms of their minimum efficiency reporting value. However, these ratings do not necessarily correlate with nominal arrestance and can be assigned only after testing. For simplicity, only the manufacturer's nominal (dust spot) efficiency will be considered here.

Figure 2 shows generic performance curves for Group III filters based on a multi-fiber filter model.[4]

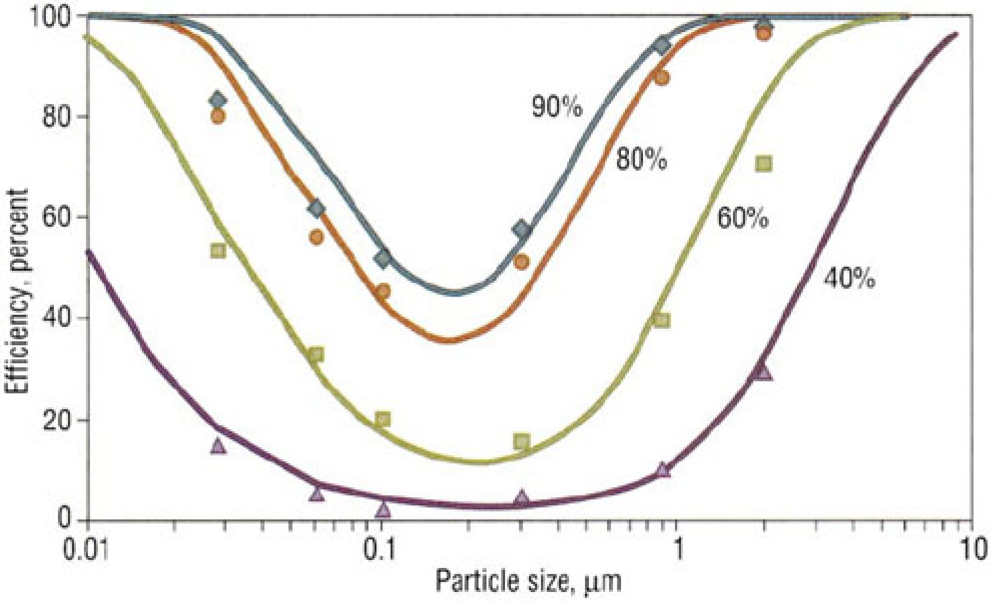

Figure 2 : Performance-curve models for five filters extended into the virus-size range and compared with data from Ensor.[5]

All filters have the following general characteristics:

- Their performance decreases with increased velocity.
- Their performance increases with increased age and filter loading.
- Their pressure drop increases over time as they become loaded.
- Their increased pressure drop may reduce airflow or, if flow is held constant, increase fan energy consumption.

The performance of filters in the field depends, to a large extent, on the efficiency with which contaminants are swept across rooms and into return-air registers. Air mixing can also be an important factor. Studies have shown that the actual efficiency of filters in removing indoor contaminants can be far less than the rated efficiency.[6] Still, substantial reductions in indoor-airparticle counts can be achieved with high-efficiency filters.[7,8]

Health-care facilities normally employ a variety of filters. For instance, the American Society of Heating, Refrigerating and Air- Conditioning Engineers (ASHRAE) recommends a 90-percent filter preceded by a 25-percent filter for general areas of hospitals and a 25-percent filter for administrative ones.[3] For laboratories, ASHRAE recommends an 80-percent filter, while in operating rooms, it recommends a 25-percent, a 90- percent, and a HEPA filter in series. These recommendations are widely adopted in the United States - sometimes even as state law.

Health-care facilities often implement various types of source control through the use of zoning and isolation rooms. Commercial buildings, however, have limited opportunity to apply source control methods because the source usually is the occupants, the outdoor air, or both.

Through dilution ventilation, contaminants are removed in a way that essentially is additive to the effect of filtration. Unfiltered outside air may, however, bring in environmental bacteria and spores. Building airhandling systems typically recirculate most building air, with outside-air rates of 15 to 25 percent.

Some types of facilities use 100- percent-outside-air systems that do not recirculate. Examples include certain health-care facilities, veterinary facilities, and laboratories. Often, the outside-air—and even the exhaust-air—systems of these facilities include HEPA filters.

In some cases, high-efficiency filters could be used in place of HEPA filters to save costs without sacrificing performance or adversely affecting the health of occupants.

Bacteria intercepted by filters eventually die from dehydration or natural causes, while spores may live indefinitely.[9,10] Antimicrobial filters and ultraviolet germicidal irradiation (UVGI) are two weapons in the war against microbial growth on filters.

The practice of HEPA-filtering outside air or exhaust air to the outside may represent overdesign in many cases. Few, if any, environmental microbes have an adverse effect on healthy individuals, and these are removed at high rates by high efficiency filters. Contaminated air exhausted to the outside disperses rapidly to harmless concentrations, after which any microbes rapidly die off from exposure and dehydration. Although the filtration of exhaust addresses concerns about the re-entry of contaminants, the proper design and location of intakes and exhausts is a more appropriate solution.

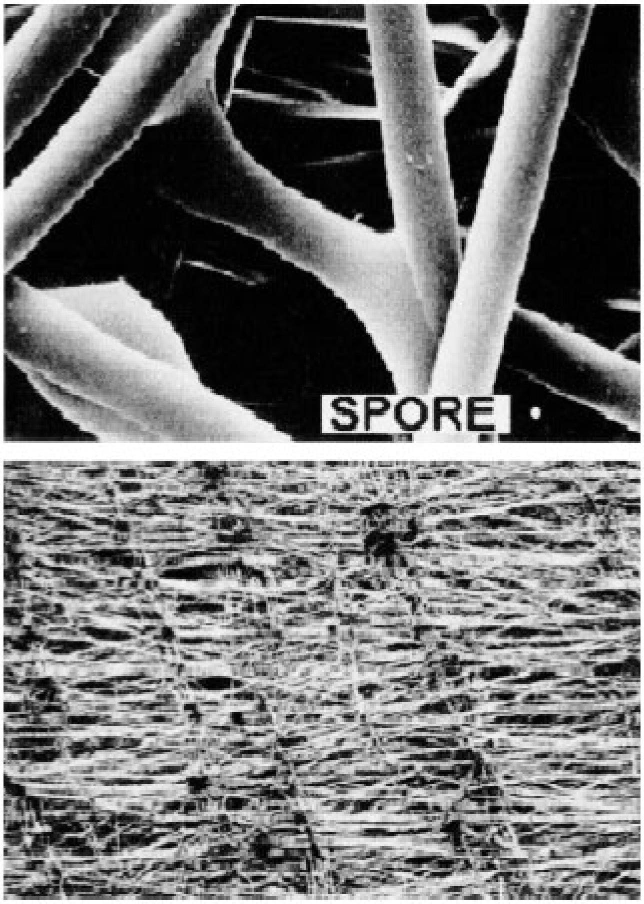

Photo courtesy of W.L. Gore & Associates Inc.

Typical filter media with fiber diameters of approximately 20μm (top) compared with a ePTFE filter media (bottom). Shown for reference is a 2-μm spore.

Most filter media consist of a random array of fibers with diameters in the 1-to-20-micron range. A recent development in filtration technology, expanded polytetrafluoroethylene (ePTFE), consists of a denser relatively ordered arrangement of smaller-diameter polymer fibers.[11] This array allows thinner media to be used while producing higher efficiency, although at the cost of higher pressure drops.

The performance goals of an airdisinfection system lie at the heart of any economic evaluation. To determine how effective filtration can be in comparison - or combination - with dilution ventilation, filter performance must be scrutinized in terms of the targeted airborne microbes.

Modeling microorganisms

Microbes tend to be spherical or ovoid in shape and exist as populations that span a distinct size range. All submicron-sized collections of particles tend to distribute themselves lognormally, with smaller particles outnumbering larger ones. Because the size distribution does not form a normal bell curve, the average of the minimum and maximum diameters is not representative of the mean and may not predict filtration rates accurately.

Figure 3 shows the populationsize distribution of *Legionella pneumophila*, which is lumped at the lower end and compares well with the predicted lognormal curve. The test was performed in water.

Actual size distributions have not been determined for most airborne microbes.

As a result, actual mean diameters cannot be known. Fortunately, the logmean diameter, computed by taking the average of the logarithms of the minimum and maximum diameters, provides an excellent approximation of the mean diameter.[4]

Large differences may exist between the logmean and average diameters of microbes. For example, if the average diameter of Chlamydia pneumoniae (about 0.85 micron) were used in place of the logmean diameter (0.55 micron), the removal rate of a 90-percent filter would be predicted to be 95 percent instead of the actual 80 percent. Even greater discrepancies than this can result when considering non-spherical bacteria.

Non-spherical microbes must have their aspect ratio (the ratio of width to length) accounted for in the model. Spherical microbes such as Rhizopus have an aspect ratio of 1.0, while Stachybotris has one that varies from about 0.3 to 0.5. Equivalent diameters can be established by various techniques to account for the filterability of non-spherical microbes. The authors published a table of mean diameters of more than 100 airborne pathogens that were adjusted to include these factors.[4]

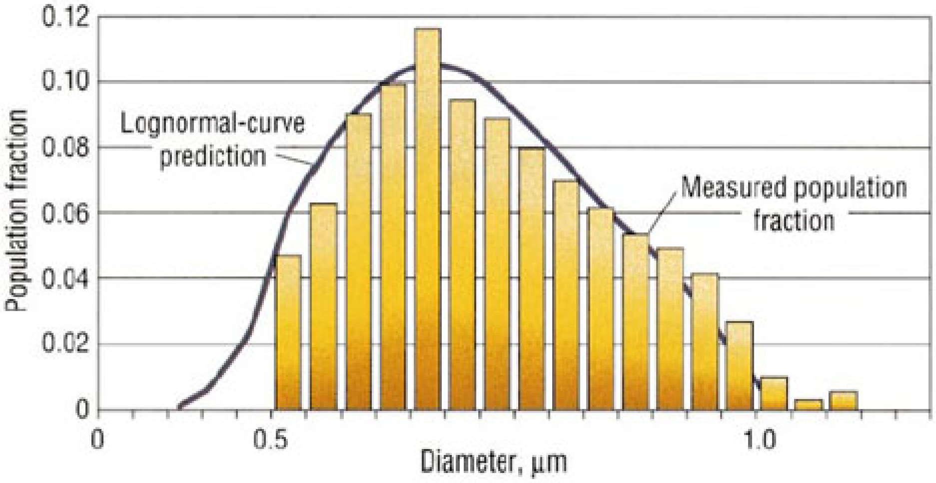

Figure 3 : The measured size distribution of *Legionella pneumophila* compared with the predicted lognormal curve. The data were taken using a Coulter counter, with sizes limited to 0.6 μm and higher

Filter-model results

Mathematical filter models can provide a variety of useful information about a filter's performance against airborne microbes and under various conditions, such as high velocities and recirculation. **Figure 4** shows the results of modeling to determine the most penetrating microbes to a HEPA filter. Curiously, all three microbial groups-viruses, bacteria, and fungal spores - show up in this range, and they include several of the more common nosocomial (hospitalacquired) infections. The number of microbes penetrating a HEPA filter may not be significant because it depends on risk levels and concentrations, but this example illustrates a characteristic of all filters: Certain microbes penetrate more effectively than others.

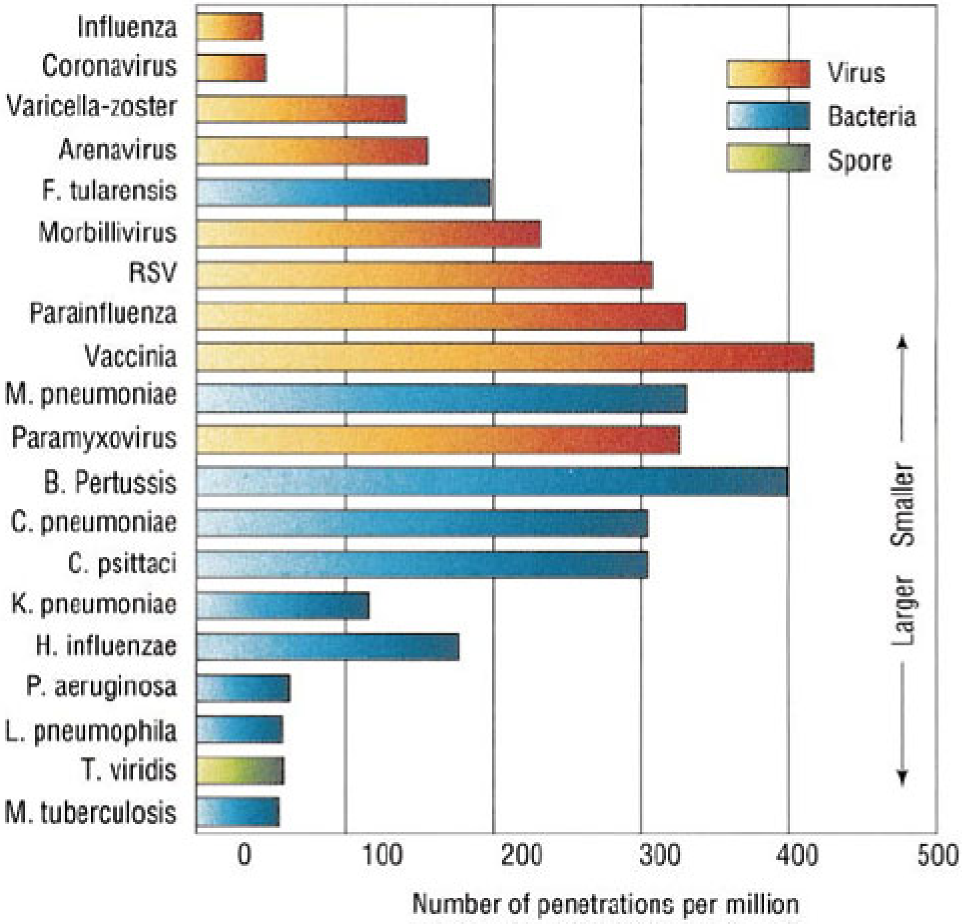

Figure 4 : The most penetrating microorganisms to a HEPA filter

The logmean diameters given in Reference 4 can be used in conjunction with any filterperformance curve to determine a similar array of most-penetrating microbes. However, as noted previously, most catalog performance curves do not extend into the virussize range, although studies have evaluated particular penetration for this range.[5]

Recirculating air through a filter increases the effective filtration rate. Overall filtration efficiency increases with the number of passes through a filter. The efficiency resulting from a large number of passes through an 80- or 90-percent filter can approach that of a single pass through a HEPA filter. **Figures 5a and 5b** illustrate this effect for a recirculation-filter unit in a model room with no outside air, assuming perfect plug flow. Under normal conditions, airflow would be mixed, and these filters would not approach HEPA-filter performance so closely after so few passes. However, the comparison illustrates the potential of recirculation-filter units.

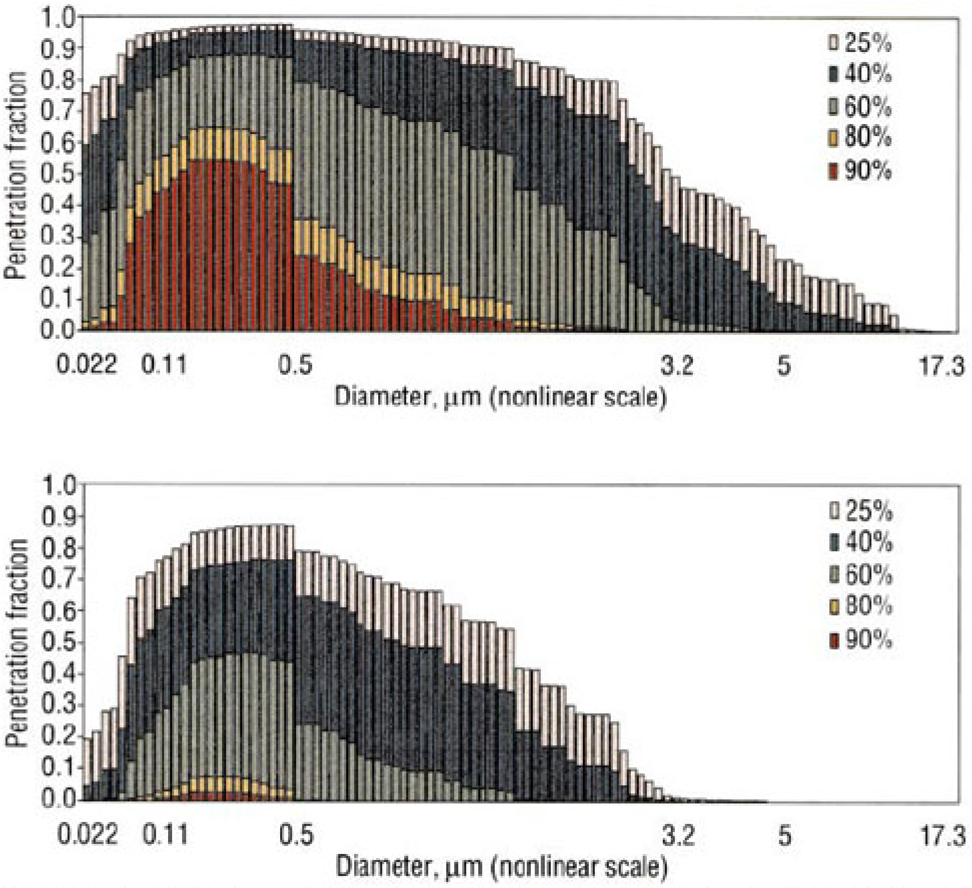

Figure 5A, 5B : A comparison of penetrations by microbes after a single pass (top) and after six passes (bottom) through model filters

Figure 5a shows the number of penetrations expected after a single pass of the entire pathogen database found in Reference 4 through all five filters. The HEPA-filter penetrations, being approximately zero, are not visible on this scale. **Figure 5b** shows the penetrations after six passes through the same filters. Note how closely the 90-percent filter simulates a HEPA filter after six passes.

Figure 6 shows the removal rates of various filters in combination with dilution ventilation in a well-mixed space of a model building with a 100,000-cfm system. The microbes included equal proportions of viruses, bacteria, and fungi, with an initial concentration of 90,000 cfu per cubic meter. This model considered the internal generation of viruses and bacteria, as well as fungal spores entering with outside air. In this model, indoor concentrations reached steady-state conditions within a few hours, and the final building concentrations differed in each case. Real-world conditions would have retarded the rate at which asymptotic concentrations were reached. However, this does not alter the fact that filter choice determines the final level of air quality for all building applications.

This analysis suggests that the HEPA filter may provide little improvement over the use of an 80- or 90- percent filter - which costs considerably less to own and operate - in cases in which the immediate removal of a contaminant is not critical. The analysis applies to single spaces or building volumes only. In multizone systems, consideration would have to be given to the fact that microbes may be recirculated to other areas. Also, a detailed analysis would be required to assess overall system performance.

Facilities, such as hospitals and laboratories, that encounter specific microbial threats require moredetailed performance comparisons.

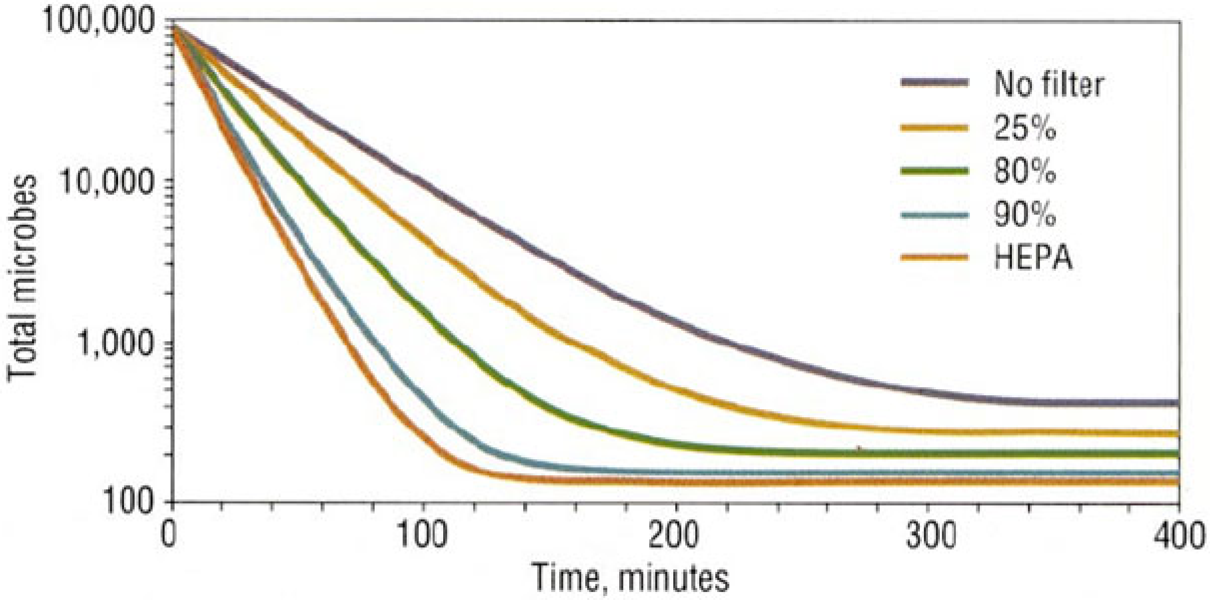

Figure 6 : A comparison of removal rates of various filters located in a supply-air duct in combination with dilution ventilation with 25-percent outside air

Complementary disinfection technologies

Besides source control and dilution ventilation, other technologies may complement filter operation. These include UVGI, photocatalytic oxidation, ionization, and pulsed light. Little data is available to predict the performance of these technologies, except for UVGI, which will serve as an example.

Figure 7 shows the percent of a select group of microbes (from the pathogen database of Reference 4) remaining after passing through a 25- percent filter, an 80-percent filter, and a UVGI system. Notice how the microbes most resistant to the filters tend to be susceptible to UVGI and vice-versa. UVGI has greater success against small microbes, such as viruses, while filters have greater success against large ones, such as spores.[12]

Some of the microbes in the database of Reference 4 could not be used in the example above because most UVGI rate constants for microbes remain unknown. It is reasonable to assume, however, that most viruses will succumb to UVGI exposure and that most spores will be removed by filters. Hence, combination systems offer an ideal solution.

A combined filtration and UVGI system can be "tuned" to target certain microbes. In the above example, tuning the system to remove all microbes completely could be accomplished by decreasing the airflow rate, increasing the ultraviolet power, or changing to a more-efficient filter. Basic techniques of economic optimization could be used to find the best solution.

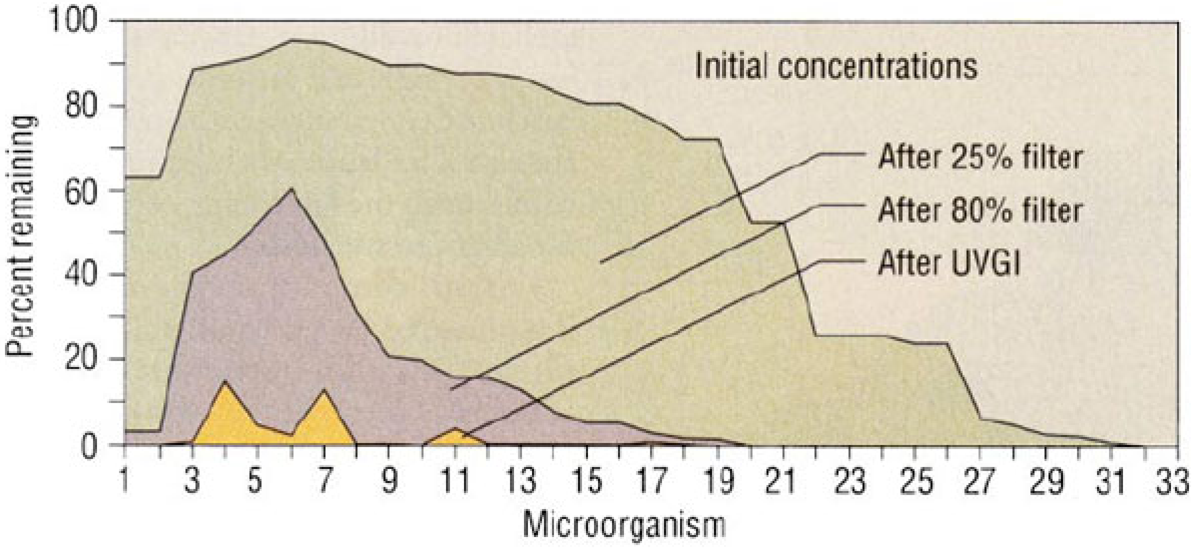

Figure 7 : Microbial populations before and after filters and a UVGI system. Only microbes with known UVGI rate constants are included, ordered in size from smallest (1) to largest (33)

Economics of filtration

Table 1 summarizes the life-cycle costs of 25-, 80-, and 90- percent filters and HEPA filters. **Figure 8** compares these costs for the model building analyzed earlier. The dilution-ventilation system, with 25- percent outside air, forms a baseline that remains constant for all four filters. The bulk of the energy costs comes from the fan energy consumed by the filter pressure losses.

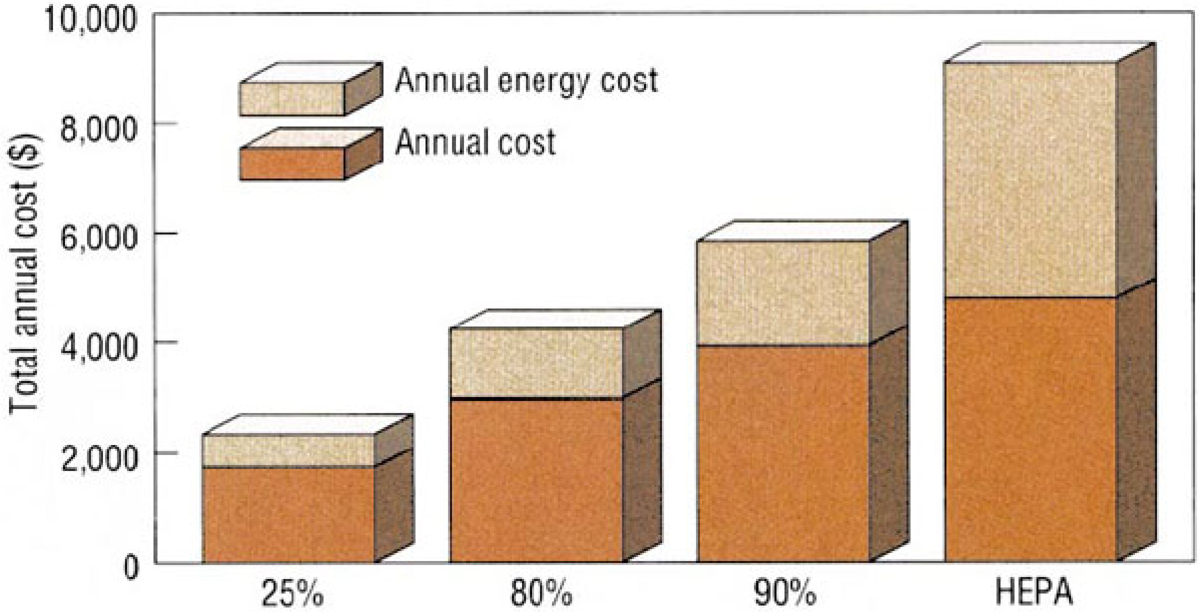

Figure 8 : A comparison of the life-cycle costs of four filters. The 90-percent and HEPA filters include a prefilter

Table 1 : The life-cycle costs of 20-to-25-percent, 80-to-85-percent, 90-to-95-percent, and HEPA filters

Design airflow (cfm)	100,000	100,000	100,000	100,000
Model	20-25%	80-85%	90-95%	HEPA
Length (in.)	24	24	24	24
Width (in.)	24	24	24	24
Depth (in.)	1	6	12	11.5
Face area (sq. ft.)	4	4	4	4
Air velocity (fpm)	350	500	500	250
Media velocity (m per sec)	1.023	0.350	0.97	0.025
Pressure losses at design conditions				
dP average (in. wg)	0.56	0.955	0.975	1.25
Air horsepower	9.817	16.741	17.092	21.913
Fan efficiency (%)	84.0	84.0	84.0	84.0
Motor efficiency (%)	95.0	95.0	95.0	95.0
Combined efficiency (%)	79.8	79.8	79.8	79.8
Add. fan-motor hp	7.83	13.36	13.64	17.49
Total energy cost (kW)	5.84	9.96	13.09	15.96
Operating period (hr)	3,744	3,744	3,744	3,744
Total fan energy (kWh)	21,871	37,298	49,015	59,755
Rate ($ per kWh)	0.08	0.08	0.08	0.08
Annual energy cost ($)	1,750	2,984	3,921	4,780
Replacement cost				
Average filter life (hr)	8,760	8,760	8,760	8,760
Number of filters	72	50	50	100
Filter hours per year	269,568	187,200	187,200	374,400

Replacements per year	31	21	21	43
Cost per filter ($)	13	49	62	75
Annual cost ($)	400	1,047	1,325	3,205
• prefilter cost ($)				800
Maintenance ($)	200	200	200	300
Annual cost ($)	600	1,247	1,925	4,306
Total annual cost ($)	2,350	4,231	5,846	9,086

For this comparison, the outside air is assumed to have a constant concentration of 100 spores per cubic meter. In addition, 2 percent of the 6,000 building occupants are assumed to be producing airborne bacteria and viruses at a rate of 100 microbes per hour. The microbial challenge to the building approximates normal winter conditions and provides an aerobiologically balanced array of test pathogens.

Note that although energy costs increase somewhat linearly from the 25-percent filter to the HEPA filter, annual costs increase almost exponentially. This can be attributed to the 90-percent and HEPA filters both including a 25-percent prefilter and the HEPA filter operating at 250 fpm instead of the 500 fpm of the other filters. This velocity difference necessitates twice as many HEPA filters for the same total airflow.

The model building used in this economic study includes a 100,000- cfm system with a fan-motor efficiency of 85 percent and a motor efficiency of 95 percent. Pressure drops varying from clean to dirty throughout the life of each filter were accounted for, with fans operating continuously. Representative costs from a leading filter manufacturer were used.

The cost efficiency of an airdisinfection system can be determined by dividing the removal rate—in colony-forming units—by the life-cycle cost of the filter. **Figure 9** compares the four filters using the analysis from Figure 6, but with equal generation rates for viruses, bacteria, and spores. The steady-state removal rates of the filters alone, divided by the life-cycle costs from Figure 8, show the HEPA filter to be less costeffective than the other types. Although the extra costs of a HEPA filter may not be justifiable for the removal of a broad array of microbes, they could be, for example, in applications that target only viruses

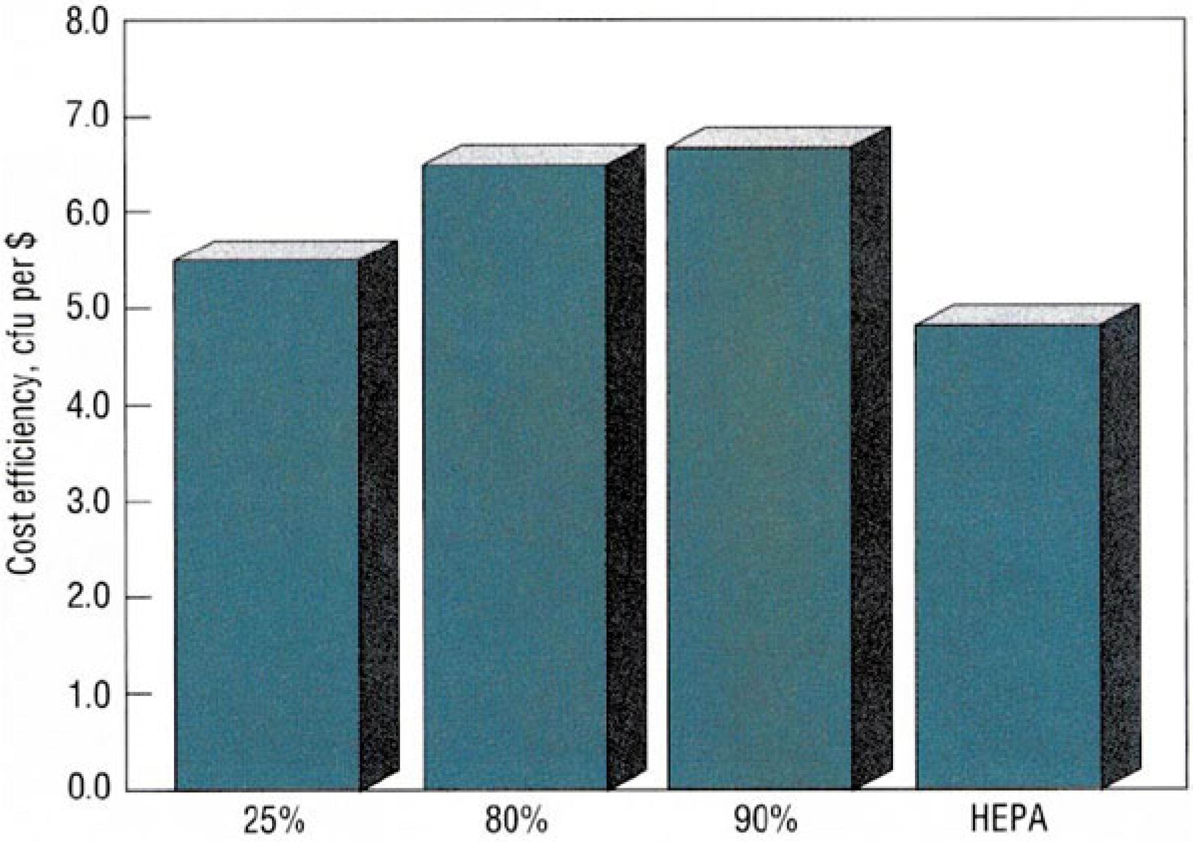

Figure 9 : The cost efficiency of 25-, 80-, and 90-percent filters and HEPA filters

Summary

The use of high-efficiency 80- and 90- percent filters can produce air-quality improvements that approach those with HEPA filters, but at a much lower cost. The use of HEPA filters may be overkill in many applications. Indeed, the use of HEPA filters in air exhaust air seems difficult to justify considering that outside air disperses microbes and sterilizes itself.

Analysis suggests that the use of HEPA filters in outside-air intakes has dubious value because environmental spores can be adequately removed by highefficiency filters. Exceptions include health facilities where immunocompromised patients cannot tolerate any level of ambient bacteria or fungal spores.

Because filters remove a broad range of microbes, their performance resembles that of dilution ventilation. A HEPA-filter system operating at the same outside-airflow rate as a ventilation system will remove approximately equal numbers of airborne contaminants, assuming the outside air is clean.

Poor ventilation can reduce the effectiveness of recirculation filters. Where serious indoor-air-quality problems exist, controlling problems at their source should be the primary focus. Options for controlling source problems include local recirculation filters, providing supply air to the source, and exhausting return air from the source.

The combination of filtration and UVGI offers an efficient means of controlling both, the largest microbes and spores and the smallest bacteria and viruses. Such combinations can be tuned and optimized to match any application.

Microbial populations have size distributions that form lognormal curves. Logmean diameters should be used to determine removal rates. Estimates of filtration rates based on the average diameter of a microbe can produce gross errors.

The authors hope this article enhances the understanding of filtration for the control of indoorair quality and leads more designers to include filtration in their designs as a primary means of controlling airborne disease.

Acknowledgements

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