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Performance and cost of particle air filtration technologies

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Performance and Costs of Particle Air Filtration Technologies

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Abstract

This paper predicts the reductions in the indoor mass concentrations of particles attainable from use of filters in building supply airstreams and also from use of stand-alone fan-filter units. Filters with a wide efficiency range are considered. Predicted concentration reductions are provided for indoor-generated particles containing dust mite and cat allergen, for environmental tobacco smoke particles, and for outdoor-air fine mode particles. Additionally, this paper uses a simple model and available data to estimate the energy and total costs of the filtration options. Predicted reductions in cat and dust-mite allergen concentrations range from 20% to 80%. To obtain substantial, e.g., 50%, reductions in indoor concentrations of these allergens, the rate of airflow through the filter must be at least a few indoor volumes per hour. Increasing filter efficiencies above approximately ASHRAE Dust Spot 65% does not significantly reduce predicted indoor concentrations of these allergens. For environmental tobacco smoke particles and outdoor fine mode particles, calculations indicate that relatively large, e.g., 80%, decreases in indoor concentrations are attainable with practical filter efficiencies and flow rates. Increasing the filter efficiency above ASHRAE 85% results in only modest predicted incremental decreases in indoor concentration. Energy costs and total costs can be similar for filtration using filters with a wide range of efficiency ratings. Total estimated filtration costs of approximately $0.70 to $1.80 per person per month are insignificant relative to salaries, rent, or health insurance costs.

Introduction

Filters and other particle air cleaners are used extensively in buildings to remove particles from incoming outdoor air and from recirculated indoor air. Historically, filters were installed to reduce the accumulation of deposited particles on HVAC equipment which diminished air flow rates and impeded heat transfer. Within the last two decades, the potential benefits to health have been increasingly recognized as a primary purpose of filtration. Other potential benefits of filtration include reducing unsightly soiling of indoor surfaces and reducing the deposition and accumulation of organic matter on surfaces such as HVAC ducts where it can become odorous or provide a substrate for microbiological colonization.

In commercial buildings, filters are typically installed in the supply airstreams of forced-air heating, ventilating, and air conditioning (HVAC) systems that provide heated or cooled air to occupied spaces. In U.S. commercial buildings, this supply airstream is usually a mixture of outdoor air and recirculated indoor air, while in many European commercial buildings the supply airstream is often entirely outdoor air. In U.S. residences, filters are commonly installed in the recirculated airstreams of forced-air heating and cooling systems. Stand-alone, e.g., portable, fan-filters units are also relatively common, particularly in residences.

Several classes of health effects are linked to particle exposures that may be reduced via filtration. Allergy and asthma symptoms may be produced in susceptible people upon inhalation of allergenic particles, such as pet allergens, dust mite allergens, pollens from outdoor plants, and fungal spores or fragments from outdoors or indoor sources (Committee on Health Effects of Indoor Allergens 1993, Committee on the Assessment of Asthma and Indoor Air 2000). Infectious diseases such as influenza and some common colds can result from the inhalation of droplet nuclei from people's coughs and sneezes that carry infectious organisms (e.g., Dick et al. 1987; Couch 1981). Some particles of indoor or outdoor origin may contain inflammatory or toxic agents; an example is endotoxin in the cell walls of certain bacteria (Milton 1996). Environmental tobacco smoke (ETS), a mixture of particles and gases, is associated with increases in lung cancer, heart disease, asthma exacerbation, and other health effects (EPA 1992, California EPA 1997). Increased concentrations of particles in outdoor air are associated with increases in hospital admissions, deaths, and other health effects (EPA 1996a); however, most people's exposures to these outdoor particles occur predominately indoors where approximately 90% of the time is spent. Outdoor particles smaller than approximately 2.5 μm in aerodynamic diameter are thought to be more strongly associated with these health effects (EPA 1996a, EPA 1996b). The small particles in outdoor air, less than approximately 1 μm in aerodynamic diameter, are produced substantially from combustion processes and through photochemical reactions (EPA 1996b). In industrial settings, not considered in this paper, there are additional sources of particles and associated health effects.

The sizes of particles associated with adverse health effects vary widely. Many of the particles of microbiologic origin tend to be larger than 1 μm in aerodynamic diameter, with some exceeding 10 μm (Committee on Health Effects of Indoor Allergens 1993, Committee on the Assessment of Asthma and Indoor Air 2000). Most of the particle mass in environmental tobacco smoke is contained within particles with diameters between 0.1 μm and 1.0 μm (Miller and Nazaroff 2001). The usual outdoor particle distribution is considered to be bi-modal or trimodal. The particle mass within the outdoor fine particle mode, as defined by Whitby (1978), is contained between 0.03 and 4.0 μm particles, with approximately 90% of this mass in particles smaller than 1.0 μm.

Despite the widespread use of filtration systems, the influence of different air filtration options on indoor concentrations of particles has not been well documented. Information on the relative costs and energy use of different filtration options is also not readily available. Chamber studies have assessed the rates of particle removal by stand-alone filtration units. A few field studies, primarily within houses, have monitored the influence of filtration on total particle number or mass concentrations, generally without distinguishing between particles from different sources. The Committee on the Assessment of Asthma and Indoor Air (2000) estimated the reduction in various size particles from a range of filtration options. This paper expands upon the Committee's work, integrating over particle size to predict reductions in the indoor concentrations of particles from various sources. Additionally, this paper provides examples of the costs and energy use of different filtration options.

Methods

Reductions in indoor concentrations

A mass-balance model was used to estimate the reductions in the indoor concentrations of different particle types from use of air filtration systems, including filters in HVAC systems and stand-alone filters. The modeling assumes a well-mixed indoor space and integrates over particle size, accounting for the size distributions of source-specific particles and the size-dependent variations in both filter performance and particle deposition losses to surfaces. We have used the percentage reduction in indoor particle mass concentration as the performance metric, with the reference case typically being no filter. Calculations were performed for outdoor fine-mode particles (as defined in Appendix 1) and for three types of indoor-generated particles – those with dust mite allergen, with cat allergen, and from ETS.

The computations for the indoor concentrations of particles of each type are made in discrete size bins (see Appendix 1) and then integrated. The mass balance equation is

$$C_{indoor} = \sum_j \frac{S_j / V + C_{OA,j}[Q_{OA}(1-\varepsilon_{S,j}) + Q_I \; P_j]}{Q_R \varepsilon_{S,j} + Q_{OA} + Q_I + Q_C \varepsilon_{C,j} + \beta_j} \qquad (1)$$

where: j is the bin number; Q_R is the recirculation air flow rate through the supply-air filters; Q_{OA} is the outside air flow rate through the supply-air filters; Q_I is the rate of infiltration of unfiltered air; Q_C is the flow rate through stand-alone filters; ε_S is the particle removal efficiency of the supply air filters; ε_C is the particle removal efficiency of the stand-alone fan-filter unit ; β is the rate of particle depositional loss; S is the indoor particle source strength ; V is the indoor volume; and P is the penetration factor for particles entering via air infiltration. C_{OA} is the outdoor particle concentration which is non-zero only for outdoor fine mode particles. All flow rates, denoted by Q, and the particle deposition loss rate β are normalized by the indoor volume; therefore, these variables have the dimension of the reciprocal of time. In general, a reference indoor concentration ($C_{reference}$) was calculated with the same equation except the filter efficiencies were set to zero. For a few calculations of the benefits of stand-alone fan-filter units, the reference calculation assumed a low-efficiency supply air filter, i.e., $\varepsilon_{S,}$ was greater than zero.

The percentage reduction in indoor concentration was then calculated from the equation

$$\%\text{Reduction} = 1 - \left(C_{indoor} / C_{reference} \right) \qquad (2).$$

As an overall (i.e., single-number) efficiency rating, we have characterized filters according to the ASHRAE Dust Spot Efficiency Rating (ASHRAE 1992), the standard rating used by U.S. industry. To denote the ASHRAE Dust Spot Efficiency, we will use the notation "ASHRAE nn%" where "nn" refers to the Dust Spot Efficiency rating. There is no unique filter efficiency curve, i.e., curve of particle removal efficiency versus particle size, for each Dust Spot Efficiency Rating; hence, we have prformed calculation with example efficiency curves from the data provided by Hanley et al. (1994) and from manufacturers' data. These efficiency curves are provided in Figure 1. To maintain readability, we have not shown curves for the "Pocket" and HEPA filters. The "Pocket" filter is a second filter with an ASHRAE 95% rating. Its efficiency curve is slightly better than the curve provided for ASHRAE 95%, e.g., the Pocket filter has a minimum efficiency of 68%. For the high efficiency particulate air (HEPA) filter which has a rated minimum efficiency of 99.997%, we assume an efficiency of unity for all particles. Data on the efficiency curves of a furnace filter are contradictory. In contrast to the curve within Figure 1, one set of unpublished data indicates that furnace filters have a maximum efficiency between 10% and 20% for 0.9 to 2.5 μm particles and an efficiency less than 10% for both smaller and larger particles. The efficiency curves used in calculations represent the performance of clean (unused) filters. As filters load with particles, their efficiency increases, consequently, our calculated reductions in indoor particle concentrations are conservative. More detailed filter efficiency data are expected in the future as filter manufacturers develop filter performance data using a new ASHRAE rating system for filters (ASHRAE 1999).

We neglected air bypass around filters. Bypass is the leakage of air between adjacent filters and between filters and the framework holding the filter. Insufficient information is available on typical rates of bypass for various types of filters. By neglecting bypass, we overestimate the particle removal efficiencies of the filtration systems.

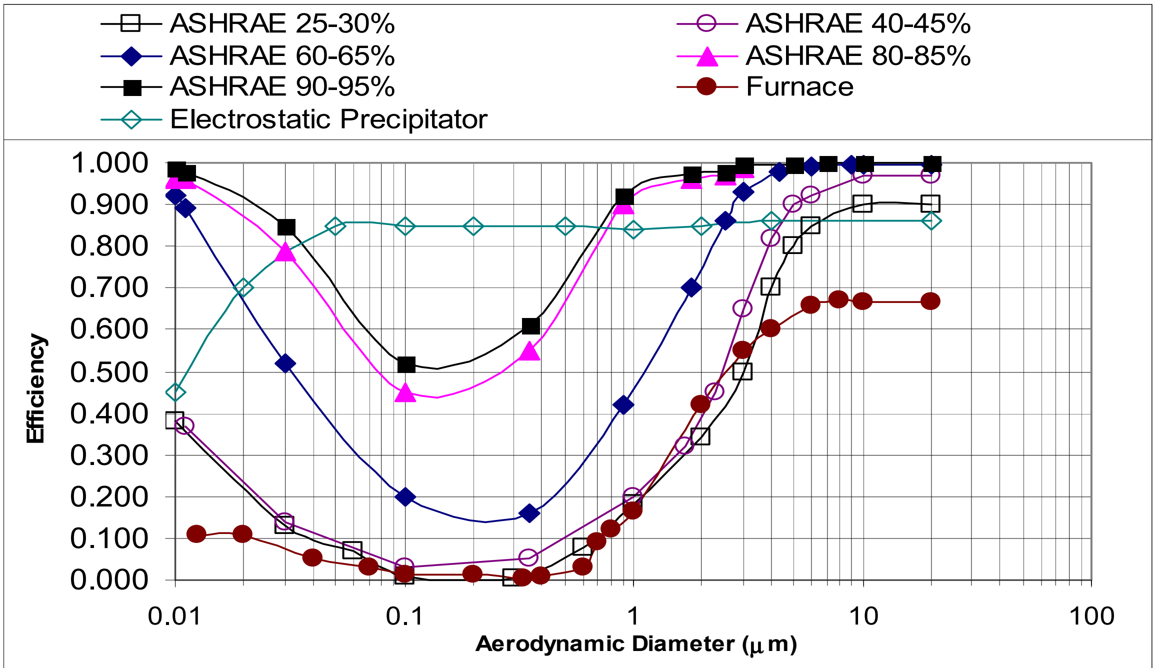

Figure 1. Particle removal efficiencies used in the calculations

The deposition coefficient β is the product of a mass transfer coefficient called the deposition velocity (Nazaroff and Gadgil 1993) and the ratio of indoor surface area to volume (S/V). S/V may change with building size and furnishings. Although the deposition velocity is the more fundamental parameter, it is usually based on measured values of deposition coefficient and estimated values of S/V. For this paper, deposition velocities were based on a combination of measured data from full-size rooms and extrapolations consistent with theoretical predictions. At present, there is considerable uncertainty in the typical values of deposition velocities for buildings; therefore, our calculations have been performed using two sets of deposition velocities. Most calculations are based on the base case deposition velocity curve in Figure 2 which fits the data of Thatcher (Lawrence Berkeley National Laboratory, unpublished) and Xu et al. (1994) with extrapolations consistent with the theoretical predictions of Lai and Nazaroff (2000). A few supplementary calculations were performed with the alternate deposition coefficient curve shown in Figure 2, which fits the data of Abt et al. (2000) and Fogh et al. (1997). Given the uncertainty in deposition velocities, no attempt was made to fit the data statistically – we simply used values from a smooth curve through the available data. The assumed value of S/V was 2.7 based on measurements in a set of offices accounting for the surface area of furnishings, as well as walls, ceiling, and floor.

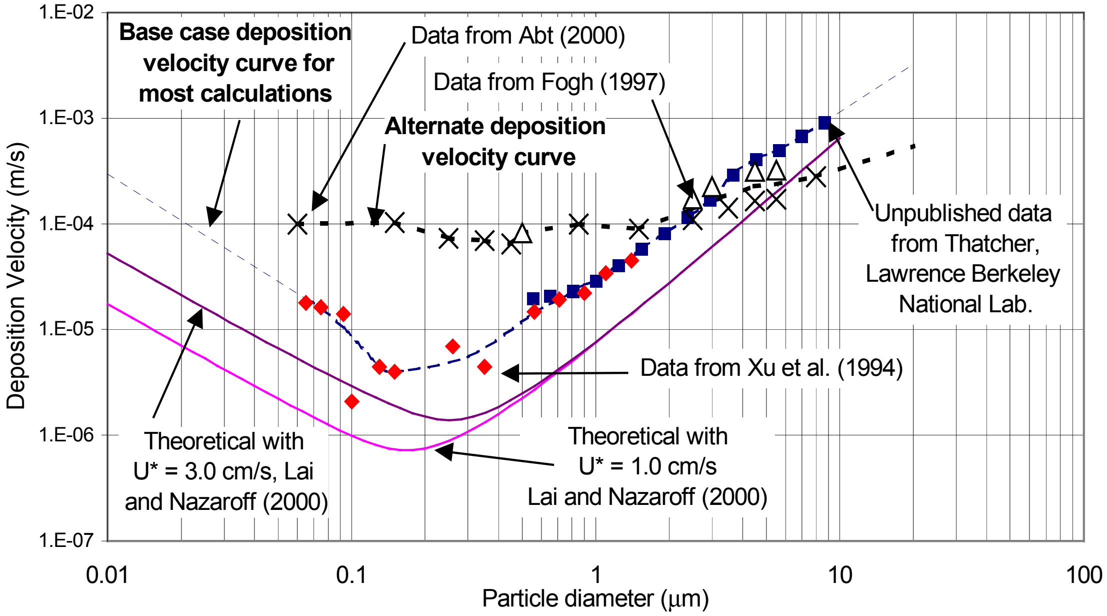

Figure 2. Deposition velocities reported by others and curves (dashed lines) illustrating the deposition velocities used in calculations.

The particle penetration factor P only enters into our calculations for outdoor fine-mode particles, and even then it only affects the rate of particle entry via air infiltration. Data on typical values of particle penetration (P) are quite limited. For outdoor fine mode particles, P may be close to unity (Ozkaynak et al. 1996, Lewis 1995, Thatcher and Layton 1995), although Vette et al (2001) reported lower measured values ranging from approximately 0.5 to 0.8 for 0.01 to 2 µm particles. We have assumed that P equals unity for all outdoor fine mode particles.

In this model, the size distribution for indoor-generated particles should be the size distribution of emitted particles, however, such information was not available for cat and dust mite allergen. For these allergens, we used measured size distributions in indoor air as an approximate surrogate for the size distribution of emitted particles. Appendix 1 presents the size distributions employed and references the sources of the size distribution data.

Other parameter inputs, such as flow rates through filters and outside air ventilation rates, were based on typical design values for building heating, ventilating, and air conditioning systems. For filters in supply airstreams of HVAC systems, we assumed that the rates of outside airflow and recirculation airflow were four and one indoor volumes per hour respectively (denoted by 4 h^{-1} and 1 h^{-1}). Most calculations with supply airstream filters assumed an air infiltration rate of 0.25 h^{-1}. For some calculations, we assumed no infiltration or no recirculation. For calculations involving portable fan-filter units or a portable electrostatic precipitator (ESP), we assumed an infiltration rate of 0.5 h^{-1} typical of a residence, and assumed rates of airflow through the filters of two, five, and 10 h^{-1}.

Costs of Air Filtration

We have estimated the costs of using different types of filters in HVAC supply airstreams. As background for the cost calculation, we note that filters vary a great deal in the degree of pleating (i.e., folding of the filtration media) and in the depth in direction of airflow. Depth may vary from approximately 2 cm to 30 cm. With an increase in depth and pleating, the area of filtration media increases, price usually increases, and the ratio of pressure drop to efficiency usually decreases. To limit pressure drops, more efficient filters tend to have increased pleating and depth. Because of their increased surface area, these larger filters will often have an increased lifetime between replacements.

The total costs of different air filtration options per unit of filtered air flow were estimated considering the costs of periodically replacing the filters (materials plus labor) and the incremental costs of energy used by fans. Since products with a similar particle removal performance can vary in price and airflow resistance (which affects energy costs), our estimates are examples that serve only to illustrate approximate costs and their variability among the filtration options.

The following equation was employed to compute life cycle cost:

$$\text{Cost per unit airflow} = \frac{\text{Filter Cost} + \text{Labor Cost per Filter Installation} + \text{Energy Cost}}{(\text{Filter Lifetime})\ (\text{Air Flow Rate})} \qquad (3)$$

The costs of a variety of filters were provided by venders. We used an electricity cost of $0.10 per kWh.

Limited information was available for estimating the costs of labor for periodic filter replacement (removing old filters and installing new ones). The standard handbook for estimating labor time required for facilities management and repair (RS Means 1999) does not provide different time estimates for filters with different efficiency ratings and allocates only 0.078 labor-hours for filter replacement in air handling systems that would typically have 3 to 8 filters, corresponding to 0.6 to 1.6 minutes of labor per filter. With the total labor cost of $46 per hour (RS Means 1999), including overhead and profit, the cost per filter installation is only $0.5 to $1.2. We have used $1.2 per filter in one set of calculations. However, based on our experience, filter installation labor and costs will often be higher than these estimates. For example, documentation from the U.S. Department of Defense (DOD 1987) estimates 0.07 labor-hours (4.2 minutes) per filter for removal and replacement of cartridge filters, the most common type of filter. In addition, we believe that installation labor and costs will increase with filter efficiency because more efficient air filters are larger and heavier, and sometimes have more complex installation hardware. Consequently, calculations were also performed using the following installation labor cost schedule: $3 (4 min.) per filter for filters with a depth in the direction of airflow ≤ 10.2 cm; $5 (6.5 min.) per filter for filters with a depth of 15.2 cm, and $10 (13 min.) per filter for filters with a depth ≥ 30.5 cm.

The lifetime of filters can be roughly estimated. As filters collect particles their resistance to airflow (i.e., pressure drop) increases. Filter manufacturers usually provide a recommended maximum pressure drop, e.g., 250 Pa, at which replacement of the filter is recommended. The increase in pressure drop across a filter as it loads with deposited particles is determined in a standard test involving a special test dust (ASHRAE 1992). The resulting data yield a “dust holding capacity” at maximum recommended pressure drop and a particle removal efficiency (Arrestance) for this test dust. With this information, the lifetime was estimated via the equation

$$\text{Filter Lifetime} = \frac{\text{Dust Holding Capacity}}{(\text{Arrestance})(\text{Inlet Particle Concentration})(\text{Air Flow Rate})} \qquad (4)$$

When calculations were based on manufacturer’s data, the flow rate assumed for this calculation was the manufacturer’s recommended value. When calculations were based on data provided by Hanley et al. (1994), we used the flow rates in their tests. We assumed that airflow occurred 12 hours per day and six days per week, typical of the periods of operation of many commercial building ventilation systems. For the inlet particle concentration, we used the arithmetic average of the indoor and outdoor daytime PM10 concentration (i.e., mass concentrations of particles smaller than 10 µm aerodynamic diameter) from a survey of 28 U.S. office buildings[1] [13 µg m^{-3} indoors, 31 µg m^{-3} outdoors, 22 µg m^{-3} average]. The filter arrestance was provided by manufacturers.

Sources of error in the calculation of filter lifetime include the following: (1) The test dust mixture used to assess dust holding capacity contains more coarse particles than typical indoor and outdoor air, and the dust holding capacity of filters for real particles and this test dust may differ. (2) The average particle removal efficiency for the mixture of real particles entering filters is likely to be smaller than the Arrestance. (3) The average inlet particle concentration in practice will exceed the PM10 concentration because the PM10 measurement excludes particles larger than 10 µm. The second and third error will tend to counteract one another.

The energy cost was computed from the equation

$$\text{EnergyCost} = (\text{Fan Power})(\text{Fan Operating Time})(\text{Electricity Price}) \qquad (5)$$

with fan power estimated using standard fan laws (ASHRAE 1996)

$$\text{FanPower} = \frac{(\text{Air Flow Rate})(\text{Time Average Pressure Drop Across Filter})}{(6356)(\text{Motor Efficiency})(\text{Fan Efficiency})} \qquad (6)$$

For the time average pressure drop across the filter, we averaged the initial and final pressure drop. Values of 0.9 and 0.75 were used for the motor efficiency and fan efficiency, respectively. These values are representative of the performance of large motors and fans used in large commercial building HVAC systems. Smaller size systems will often have less efficient motors and fans.

Results

Reductions in particle concentrations

Figure 3 shows the predicted reductions in indoor concentrations of pollutants from use of eight filters in supply airstreams, ranging from a residential furnace filter (ASHRAE Dust Spot Rating not available) to a HEPA filter. For cat and dust-mite allergen, which is predominately found in particles with a diameter of several micrometers, the predicted reductions in indoor mass concentrations (mass per unit air volume) range from approximately 20% to 60%. Increasing filter efficiencies above approximately ASHRAE 65% (or 85%) does not reduce indoor concentrations significantly because even moderate efficiency filters work well for the larger diameter particles containing most of the cat and dust-mite allergen. Predictions vary depending on the source of data on particle size distribution.

For environmental tobacco smoke particles, which are almost entirely submicron in size, the predicted indoor concentration reductions from use of low efficiency filters (furnace filter, ASHRAE 30% and 45%) are very small (5% to 12%). Increasing the filter efficiency to ASHRAE 85% yields a predicted concentration reduction of 61%. Further increases in filter efficiency bring modest additional benefits, up to a 75% reduction in concentration with a HEPA filter.

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[1] Data from the first set of 28 buildings in a 100 building survey undertaken by the U.S. EPA was analyzed by M.G. Apte at Lawrence Berkeley National Laboratory (unpublished).

For outdoor fine-mode particles, the predicted benefits of low-efficiency filters, ASHRAE 45% and lower, are again quite small. The predicted reduction in concentrations from a filter with an ASHRAE 85% rating is 80% with base-case assumptions (1 h^{-1} of mechanical outside air ventilation, 0.25 h^{-1} of unfiltered infiltration, and 4 h^{-1} of recirculation). Upgrading to a HEPA filter brings only a modest additional benefit, with a predicted reduction in indoor concentration of 95%. If there is no infiltration, the predicted reductions in indoor concentration are two to six percentage points higher. If the building does not recirculate air, as in many European offices, the concentration reductions are significantly smaller. Also, without recirculation, the benefits of increasing filter efficiency above ASHRAE 85% are more pronounced.

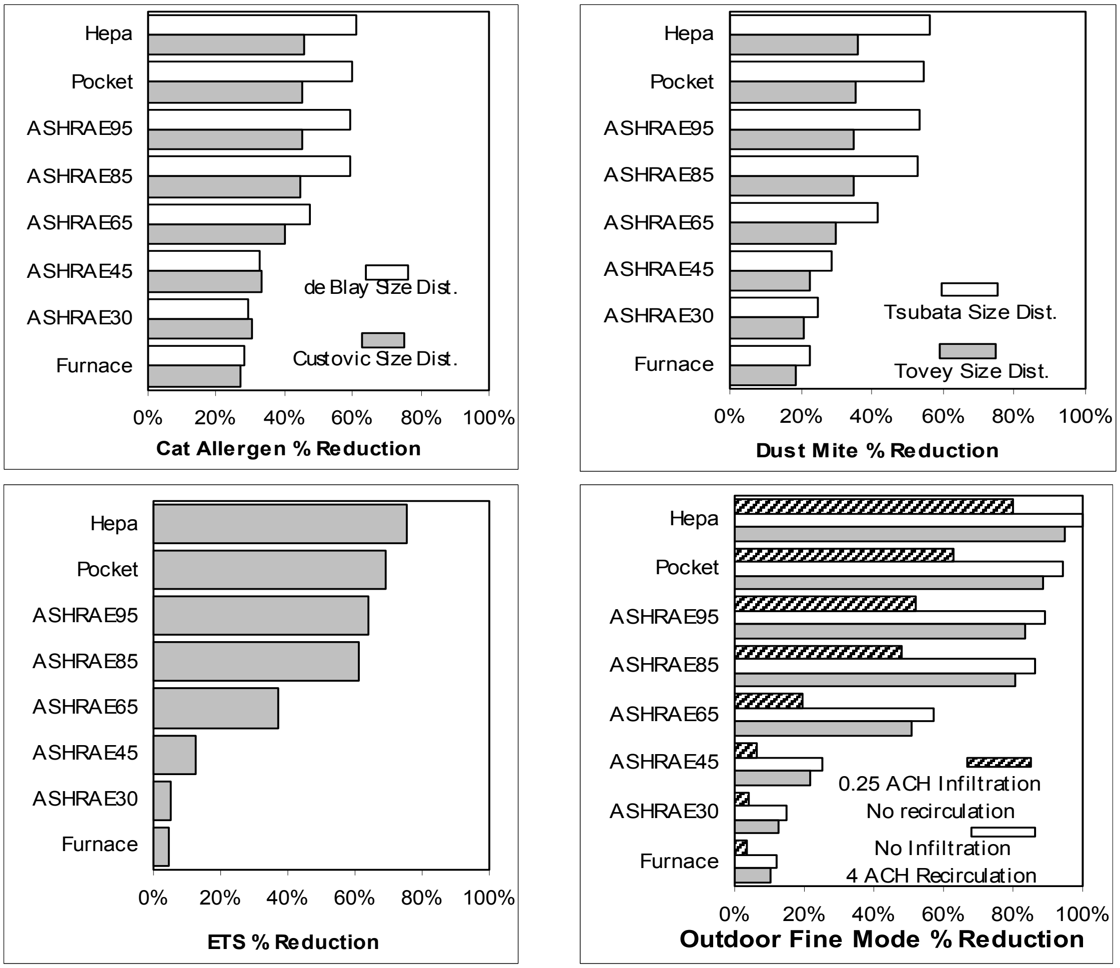

Figure 3. Predicted reductions in particle concentrations with supply airstream filtration. Unless indicated otherwise, the following conditions apply: 1 h^{-1} outside air supply, 4 h^{-1} of recirculation, and 0.25 h^{-1} of unfiltered air infiltration.

Figure 4 illustrates the predicted reductions in indoor airborne cat allergen from the use of four types of fan-filter units as a function of the rate of airflow through the filter. The results presented for the two particle size distributions differ significantly. The reference for the top two charts is the predicted concentration with no filter, while the reference for the bottom two charts is the predicted concentration in a building with a furnace filter with a recirculation rate of 4 h^{-1}. Predicted reductions in cat allergen concentrations range from 35% to 86% if the reference is no filtration and from 26% to 79% if the reference building recirculates air through a furnace filter. Increasing the filter efficiency above ASHRAE 85% results in little incremental reduction in indoor concentration. Increasing the flow rate through the strand-alone fan filter unit decreases the indoor concentrations substantially.

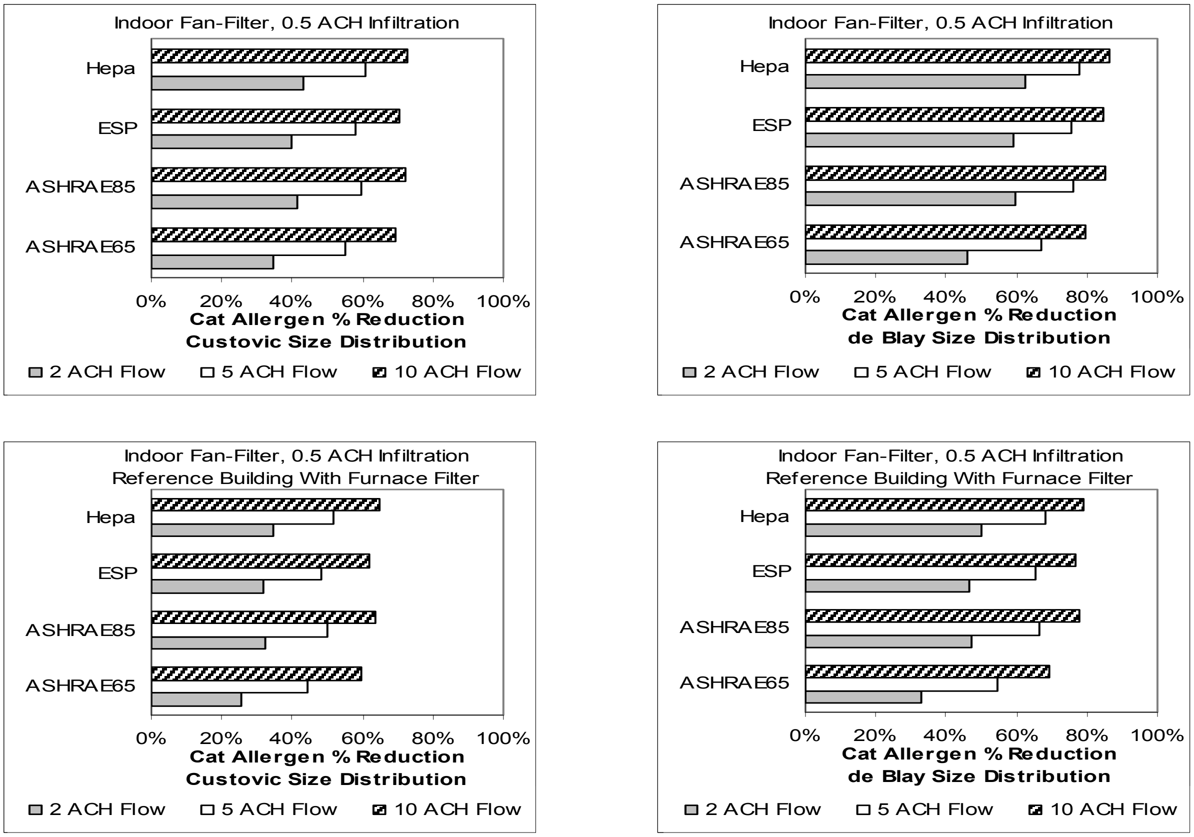

Figure 4. Predicted reductions in airborne cat allergen concentrations with stand-alone fan-filter units.

Figure 5 shows the predicted reductions in concentrations of dust mite allergen, ranging from 30% to 83%, with use of stand-alone fan filter units. If the reference building has a furnace filter (results not shown), the range is 20% to 78%. The benefits of increasing filter efficiency above ASHRAE 65% are small, with almost no benefit to increasing the efficiency above ASHRAE 85%. The predicted benefits of filtration are considerably, e.g., 20 percentage points, larger if one uses the particle size distribution of Tsubata et al. (1996) relative to the distribution of Tovey et al. (1981).

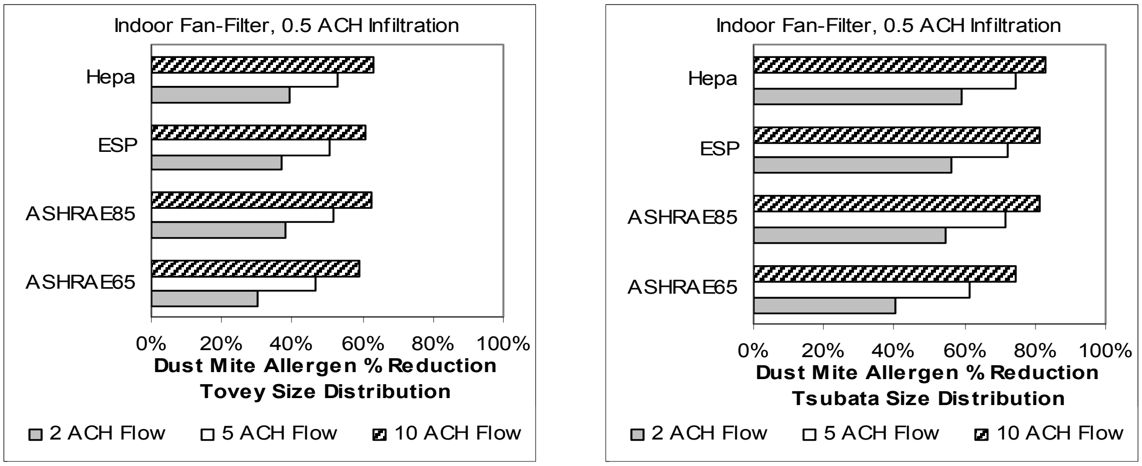

Figure 5. Predicted reductions in airborne dust mite allergen concentrations with stand-alone fan-filter units.

The predicted reductions in ETS and outdoor fine mode particles from use of stand-alone fan-filter units are illustrated in Figure 6, with the reference building having no filtration. Results are almost identical if the reference building has a furnace filter (results not shown). For ETS particles, the predicted decreases in concentration range from 40% to 95%. Increasing filtration flow rates is beneficial. The benefits of increasing filter efficiency above ASHRAE 85% are modest. The predicted reductions in concentrations and associated trends are very similar for outdoor fine-mode particles.

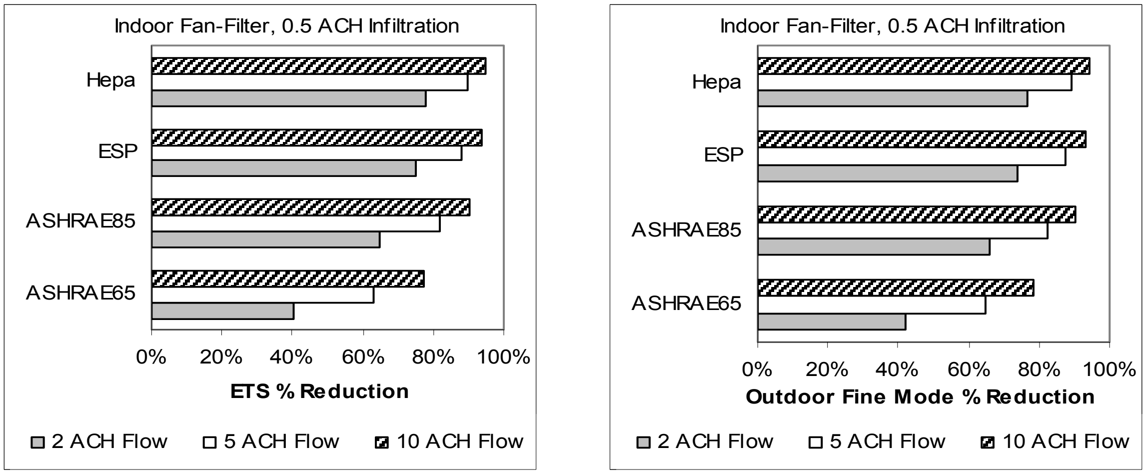

Figure 6. Predicted reductions in ETS and outdoor fine-mode particles with stand-alone fan-filter units.

For brevity, we have not included another set of figures with predicted particle concentrations reductions calculated using the alternate deposition velocity curve shown in Figure 2. The changes from the predicted base-case concentration reductions are complex, e.g., they both increase and decrease, because the two deposition velocity curves cross at a particle diameter of approximately 2 µm. In general, the change in predicted reduction in indoor particle concentration is less than 10 percentage points (i.e., less than 10% on the horizontal scales of the figures). For filters in HVAC supply airstreams (always referencing the lightly-shaded bars in Figure 3), a few examples of changes in the predicted percentage reduction in indoor concentrations follow: (1) reductions in cat allergen increase by 5 to 12 percentage points; (2) reductions in dust mite allergen increase by 8 to 17 percentage points; (3) reductions in ETS concentrations decrease by 1 to 11 percentage points; (4) reductions in indoor concentrations of outdoor fine mode particles increase by 0 to 3 percentage points.

Filtration costs

Figure 7 displays the predicted energy and total costs of using ASHRAE 25% to ASHRAE 95% filters in supply airstreams. Cost are provided per 470 L/s (1000 ft^3/min) of filtered supply air, which would typically serve 5 –7 persons in a U.S.-style office building with air recirculation or 10 to 15 occupants in European buildings without air recirculation. Monthly energy costs range from \$3.26 for a filter with an efficiency rating of 30% to \$5.94 for a filter with an efficiency of 95%. Using the fixed installation cost per filter of \$1.20 from RS Means (1999), total monthly costs range from \$3.80 to \$10.40. With the labor cost schedule, total monthly costs range from \$3.90 to \$11.10. There is a general tendency toward higher energy and total costs with higher efficiency filters; however, the costs of using different filter models of the same efficiency vary widely. Consequently, use of more efficient air filters does not always increase cost. For example, monthly costs per 470 L/s (1000 ft^3/min) of filtered supply air were as high as \$5.60 for a 25% filter efficiency and as low as \$4.20 for a filter with a 60% efficiency.

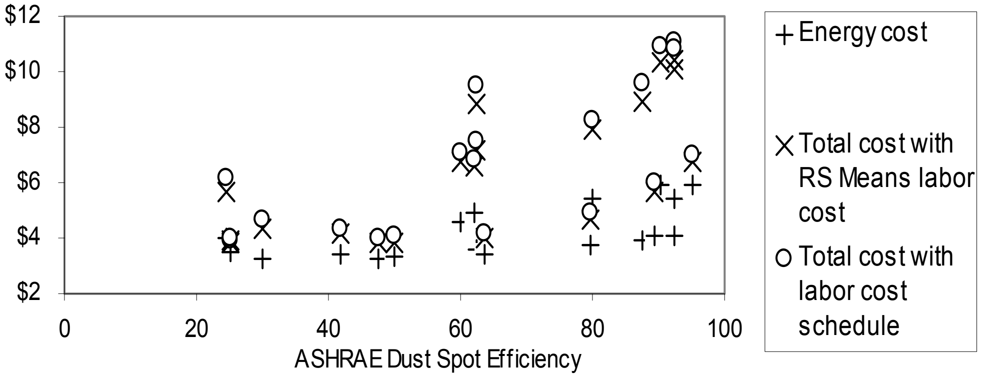

Figure 7. Monthly cost per 470 L/s (1000 ft^3/min) of supply air filtered.

The costs displayed on Figure 7 are based on the manufacturers' rated air flows and recommended final pressure drops for the filters. With the assumed inlet particle concentrations and hours of usage, the predicted filter lifetimes range from two to 27 months. Energy consumption and energy costs will be smaller if the filter is replaced with a smaller final pressure drop; however, the costs of purchasing filters and the labor for filter replacement will increase. Using the data available from one major filter manufacturer, a limited sensitivity analyses explored the trends in total life cycle cost as final pressure drops decreased from the manufacturer's recommended values. In general, total predicted monthly costs increased or decreased only slightly, less than 10%, as the final pressure drop at filter replacement was decreased by up to 100 Pa. In a few cases, total monthly costs decreased by 30%. Consequently, more frequent filter replacement could save energy and sometimes also slightly decrease filtration costs.

Discussion

Filter selection and costs

The allergens that often elicit allergy and asthma symptoms, such as dust mite and cat allergen, are predominately present within particles with a diameter larger than 2 μm. To reduce indoor concentrations of mite and cat allergen, a moderate efficiency filter, a such as one with an ASHRAE 60% rating, is predicted to be nearly as effective as a HEPA filter. To obtain substantial, e.g., 50%, reductions in indoor concentrations of these allergens, the rate of air flow through the filter must be at least a few indoor volumes per hour. To obtain a concentration reduction on the order of 75%, the rate of airflow through the filter must be approximately 10 indoor volumes per hour, which may be impractical except within individual rooms.

Allergens in pollens also elicit allergy symptoms. Pollen grains tend to have large aerodynamic diameters, e.g., > 10 μm (Committee on the Assessment of Asthma and Indoor Air 2000), consequently the comments provided above for dust mite allergens should also apply qualitatively for many pollens. However, recent studies indicate that some plant allergens, such as grass and birch allergen, is present within much smaller particles, including particles smaller than 1 μm (e.g., Rantio-Lehtimaki et al. 1994, Schappi et al. 1997, Speiksma et al. 1990, 1991).

ETS and outdoor fine mode particles are much smaller than dust mite and cat allergen, with nearly all of the particle mass in particles with a diameter below 2 μm, and much of this mass within submicron-size particles. However, even for these small particles, increasing the filter efficiency rating above ASHRAE 85% results in only a modest additional decrease in indoor particle concentrations, usually less than ten percentage points.

Our predictions indicate that relatively large decreases in indoor concentrations of ETS and outdoor fine-mode particles are attainable with practical filtration options. For example, the predicted concentration reductions from an ASHRAE 85% supply air filter in a HVAC system with recirculation are 60% for ETS and 80% for outdoor fine mode particles. Similar magnitude reductions in concentrations are predicted from use of stand-alone fan-filter units with a flow rate of 5 indoor volumes per hour and ASHRAE 65% or 85% rating. However, filters with an efficiency rating of ASHRAE 45% or lower, which are used very often in commercial and residential HVAC systems, are not effective for reducing indoor concentrations of these particles.

Anecdotally, building engineers and operators often report that high efficiency filters in the supply airstreams of HVAC systems have an excessive airflow resistance, consume too much energy, and are prohibitively expensive. However, our analyses do not support such anecdotal reports for filter efficiencies up to ASHRAE 90%. The average of the initial and recommended-final pressure drops does not necessarily increase significantly with a higher efficiency rating (results not shown). For example, the average pressure drop of four ASHRAE 30% filters was about 160 Pa, while three out of six ASHRAE 90% filters had very similar average pressure drops of approximately 185 Pa. The energy costs, which depend on average pressure drop, and total costs can also be similar for filters with a wide range of efficiency ratings. Based on the available data, the more efficient filters generally have a higher cost; however, these costs are small on a per person basis. The total range in monthly costs shown on Figure 7 is approximately \$4 to \$11. . With a supply air flow rate per occupant typical of U.S. office buildings, the corresponding filtration cost range is \$0.70 to \$1.80 per person per month, which is insignificant relative to salaries, rent, or health insurance costs.

At present, the stand-alone fan filter units marketed for residential use are predominately HEPA filters. We did not attempt to survey the cost and power use of these units. However, as an example a very popular HEPA-filter model with a maximum flow rate of 140 L/s (20 volumes per hour in a 30 m^3 bedroom) has an initial cost of ~\$250, a manufacturers rated power consumption of 350W at high fan speed (resulting in \$310 per year of fan energy with continuous operation), and an annual filter replacement cost of ~\$100. Consequently, these units can consume significant energy and be costly to operate. The analyses within this paper indicate that fan-filter units with a lower efficiency rating will be nearly as effective for most indoor pollutants. Compared to a HEPA filter unit, the energy use and costs of lower-efficiency fan-filter units should be considerably smaller.

Limitations of this analyses

In addition to the assumptions stated in the previous methodology section, a few limitations and uncertainties deserve a brief discussion. First, it is not certain that our particle concentration metric -- airborne mass per unit volume -- is the most relevant metric for health. For example, perhaps the airborne cat allergen within particles smaller than 2 μm contributes more to asthma symptoms than an equivalent amount of cat allergen within larger particles. We have used the mass concentration because it is the most common metric, but further research is needed to identify the metrics most relevant for health.

For cat and dust mite allergen, uncertainties regarding typical particle size distribution are another limitation. Our predicted concentration reductions differ by as much as 20 percentage points (but typically by much less), with different size distribution data. Uncertainties about typical values of particle deposition velocities within buildings and about other particle losses, e.g., in duct systems, also lead to substantial uncertainties in the concentration reductions attained with air filtration.

The particle concentration reductions from use of a furnace filter remain particularly uncertain. Predicted indoor particle concentration reductions would have been much smaller if our calculations had used the unpublished furnace filter efficiency curve with a maximum efficiency of 20%.

Finally, our filtration cost calculations were based on the readily available data from three filter suppliers. There is no assurance that these data are representative of the most commonly used filters.

Conclusions

1. Predicted reductions in cat an dust mite allergen concentrations with filtration range from 20% to 80%. To obtain substantial, e.g., 50%, reductions in indoor concentrations of these allergens, the rate of air flow through the filter must be at least a few indoor volumes per hour. Increasing filter efficiencies above approximately ASHRAE 65% does not significantly reduce predicted indoor concentrations of cat and dust mite allergen.

2. Relatively large, e.g., 80%, decreases in indoor concentrations of ETS and outdoor fine-mode particles are attainable with practical filter efficiencies and flow rates. Increasing the filter efficiency above ASHRAE 85% results in only modest predicted incremental decreases in indoor concentrations of these particles. Filters with an efficiency rating of ASHRAE 45% or lower are not effective for reducing indoor concentrations of these particles.

3. Energy costs and total costs can also be similar for filters with a wide range of efficiency ratings. Total filtration costs of approximately $0.70 to $1.80 per person per month are insignificant relative to salaries, rent, or health insurance costs. More frequent filter replacement, than recommended by manufacturers, could save energy and sometimes also slightly decrease filtration costs.

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Appendix 1. Particle size distributions used in the modeling.

Tables A1 – A6 provide the particle size distributions used in the analyses. Calculatons for each size bin used the geometric mean diameter. The results reported by de Blay et al. (1981) and Tovey et al. (1981) did not include full information on the particle size cuts for the cascade impactor used in measurements. This information was obtained from a detailed evaluation of the performance of the impactor by Soole (1971a, 1971b).

Table A1. Cat allergen size distribution from Custovic et al. (1988)

Bin Min. (μm)	Bin Max (μm)	Geo. Mean (μm)	Fraction of Mass
0.43	0.65	0.54	0.02
0.65	1.1	0.875	0.01
1.1	2.1	1.6	0.02
2.1	3.3	2.7	0.04
3.3	4.7	4	0.14
4.7	5.8	5.25	0.12
5.8	9	7.4	0.21
9	20	14.5	0.44

Table A2. Cat allergen size distribution from de Blay et. al. (1998)

Bin Min. (μm)	Bin Max (μm)	Geo. Mean (μm)	Fraction of Mass
0.1	1.5	0.8	0.22
1.5	4	2.75	0.18
4	12	8	0.34
12	20	16	0.26

Table A3. Dust mite allergen size distribution from Tovey et al. (1981)

Bin Min. (μm)	Bin Max (μm)	Geo. Mean (μm)	Fraction of Mass
0.1	1.5	0.8	0.027
1.5	4	2.75	0.018
4	12	8	0.067
12	20	16	0.888

Table A4. Dust mite allergen size distribution from Tsubata et al. (1996)

Dust Mite Allergen	**Tsubata et al. (1996)**		
Bin Min. (μm)	Bin Max (μm)	Geo. Mean (μm)	Fraction of Mass
0.1	0.43	0.265	0.031986
0.43	0.65	0.54	0.031874
0.65	1.1	0.875	0.046628
1.1	2.1	1.6	0.036862
2.1	3.3	2.7	0.052424
3.3	4.7	4	0.05842
4.7	7	5.85	0.08184
7	11	9	0.1758
11	20	15.5	0.4838

Table A5. Outdoor fine mode particle size distribution from Whitby (1978)

Bin Min. (μm)	Bin Max (μm)	Geo. Mean (μm)	Fraction of Mass
0.010	0.016	0.013	0.1%
0.016	0.025	0.020	0.3%
0.025	0.040	0.032	0.7%
0.040	0.063	0.050	1.7%
0.063	0.100	0.079	4.8%
0.100	0.158	0.126	11.3%
0.158	0.251	0.200	19.5%
0.251	0.398	0.316	23.5%
0.398	0.631	0.501	19.8%
0.631	1.000	0.794	11.7%
1.000	1.585	1.259	4.8%
1.585	2.512	1.995	1.4%
2.512	3.981	3.162	0.3%

Table A6. Environmental tobacco smoke size distribution from Miller and Nazaroff (2001)

Bin Min. (μm)	Bin Max (μm)	Geo. Mean (μm)	Fraction of Mass
0.086	0.110	0.098	0.064
0.110	0.140	0.125	0.112
0.140	0.177	0.159	0.170
0.177	0.226	0.201	0.179
0.226	0.287	0.256	0.156
0.287	0.364	0.325	0.115
0.364	0.463	0.413	0.112
0.463	0.588	0.525	0.047
0.588	0.747	0.668	0.011
0.747	0.950	0.849	0.008
0.950	1.207	1.078	0.010
1.207	1.534	1.370	0.008
1.534	1.949	1.741	0.006
1.949	2.477	2.213	0.000
2.477	3.148	2.812	0.001