Aerosol Science & Technology

ISSN: 0278-6826 (Print) 1521-7388 (Online) Journal homepage: http://www.tandfonline.com/loi/uast20

Particle Concentrations and Sizes with Normal and High Efficiency Air Filtration in a Sealed Air-Conditioned Office Building

William J. Fisk , David Faulkner , Doug Sullivan & Mark J. Mendell

To cite this article: William J. Fisk , David Faulkner , Doug Sullivan & Mark J. Mendell (2000) Particle Concentrations and Sizes with Normal and High Efficiency Air Filtration in a Sealed Air-Conditioned Office Building, Aerosol Science & Technology, 32:6, 527-544, DOI: 10.1080/027868200303452

To link to this article: https://doi.org/10.1080/027868200303452

Published online: 30 Nov 2010.

Aerosol Science and Technology 32:527–544, 2000

Published by Taylor and Francis
0278-6826/00/$12.00 + .00

Particle Concentrations and Sizes with Normal and High Efficiency Air Filtration in a Sealed Air-Conditioned Office Building

William J. Fisk, David Faulkner, Doug Sullivan, and Mark J. Mendell
INDOOR ENVIRONMENT DEPARTMENT, MS 90-3058, LAWRENCE BERKELEY NATIONAL LABORATORY, BERKELEY, CA (W.J.F., D.F., D.S.), AND NATIONAL INSTITUTE FOR OCCUPATIONAL SAFETY AND HEALTH, CINCINNATI, OH (M.J.M.)

ABSTRACT. During parts of 7 consecutive weeks, indoor and outdoor particle number concentrations and particle sizes were measured versus time in a large sealed air-conditioned office building without tobacco smoking. Building ventilation rates were also measured. During some periods, the normal filters in the building's air handling systems were replaced with high efficiency filters. A mass balance model was used to help interpret the study data. For all particle sizes, indoor number concentrations varied considerably between weeks and within a single work day. Even with the normal air filters, which have a low efficiency for submicron-size particles, indoor number concentrations of submicron particles were a factor of 3–6 smaller than outdoor particle number concentrations. For the range of particle sizes measured (> 0.3 μm), the indoor particle mass concentration was considerably less than outdoor particle mass concentration. The high efficiency filters dramatically reduced the indoor–outdoor particle concentration ratio for submicron particles (i.e., the decrease was 70% to 95%, depending on particle size). For larger particles, the decreases in indoor concentrations were substantially smaller. Comparisons of model predictions with measured data provide evidence of a large rate of removal of submicron indoor particles by some process other than ventilation or air filtration and also provide evidence of significant indoor generation or resuspension of particles larger than 1 μm.

INTRODUCTION

There is strong evidence that increased morbidity and mortality are associated with larger exposures to small particles (EPA 1996a). This evidence is primarily from epidemiological studies that have found increased rates of death and hospital admissions to be associated with higher outdoor particle concentrations (EPA 1996a). Although these epidemiological studies have focused on outdoor particles, most people's exposures to particles occur primarily indoors, because most people are indoors 90% of the time. Inside buildings, people are exposed both to indoor-generated particles and to particles that enter the building

along with outside air. Indoor and outdoor particles may differ substantially with respect to concentration, size distribution, and chemical composition (EPA 1996b). Indoor sources of particles include smoking, cooking, office equipment, people (e.g., droplet nuclei from coughs and sneezes), pets, microorganisms (e.g., that release spores), aerosol sprays, abrasion of surfaces, and resuspension from surfaces (Owen et al. 1992b; Thatcher and Layton 1995).

Many large commercial buildings lack the strong indoor particle sources, such as tobacco smoking and cooking, that are common in residences. Without strong indoor particle sources, indoor particle concentrations will often be lower than outdoor concentrations as a consequence of several particle removal processes, including intentional particle removal by filtration systems and particle deposition on indoor surfaces. For example, in field studies of 38 commercial buildings by Turk et al. (1989), about 70% of the measured indoor respirable particle mass concentrations[1] measured at nonsmoking sites were lower than the outdoor concentrations.

The published literature provides very limited detailed information on the time variation of particle concentrations and size distributions in large commercial buildings relative to the outdoor particle concentrations and size distributions. Additionally, the effectiveness of high efficiency filters in reducing indoor particle concentrations has not been well documented. The purpose of this paper is to present and discuss such data obtained during a study of the influence of high efficiency filtration on the severity of office workers' acute health symptoms (Fisk et al. 1998; Mendell et al. 1999).

[1] Mass of particles smaller that 2.5 μm in diameter per unit volume of air.

RESEARCH METHODS

Building and Air Handing Unit Descriptions

Particle concentrations as a function of time were measured on the second and fourth floors of a large office building with mechanical ventilation, air-conditioning, and sealed windows. The building was located in St Louis, MO. The floor area and average occupancy were 4130 m^2 (44500 ft^2) and 165 persons on the second floor and 4840 m^2 (52100 ft^2) and 280 persons on the fourth floor. The exterior walls of the building were steel and glass. The building had a large enclosed thermally-conditioned atrium at its core, separated from the office spaces primarily by glass. Except for the bathrooms and elevator lobbies, the floors were fully carpeted. The floors were almost entirely open plan, with fabric-covered partitions surrounding offices for individuals or groups of workers. The furnishings included chairs, desks, file cabinets, and normal office equipment including many desktop computers. Smoking was prohibited within the building.

Each floor of the building had an independent set of four identical air handling units (AHUs). Air was not mechanically recirculated between floors. On each floor, two mechanical rooms located at opposite corners each contained two AHUs. For each AHU, a supply fan drew outside air through louvers and dampers in the exterior walls. The outside air mixed with recirculated indoor air drawn from the mechanical room, and the mixture passed through a bank of eight air filters, each with nominal cross-sectional dimensions of 0.6 m by 0.6 m (24 inch by 24 inch). The filtered air passed through the supply fan, through coils used for cooling, and then into the supply air duct system located in the ceiling plenum above the occupied space. The ventilation systems used variable-air volume

(VAV) controls in the supply air distribution system to modulate the rate of air supply to different sections of the building as needed to maintain the desired indoor temperature. Thus, the total rate of air supplied to the spaces by the building ventilation systems varied with changes in thermal loads. No air filters were present in the VAV control units used during the summer cooling season. The supply air was delivered to the space through diffusers installed in the suspended ceiling that separated the occupied space from the ceiling plenum. Return air was drawn through grilles in the suspended ceiling and flowed through the ceiling plenum to the mechanical rooms. Air exited the floors to the outside through bathroom exhaust fans and, upon demand, through a relief fan located in each mechanical room. The rated maximum supply air flow from the set of four AHUs that serve each floor (Persily et al. 1994) was 18.4 $m^3\ s^{-1}$ (39,000 cfm). With the floor areas provided above and the ceiling height (including the plenums) of 3.5 m (11.5 ft), the maximum rates of supply airflow normalized by the indoor volumes were 4.6 h^{-1} on Floor 2 and 3.9 h^{-1} on Floor 4.

Each AHU had an automatic control system, called an economizer, that increased the rate of outside air drawn into the unit, above a minimum value, when the outside air temperature was below approximately room temperature. (The purpose of economizers is to save energy.) However, during the study period pertinent to this paper, the outside air temperatures were high and outside air dampers were always in the minimum open position during building occupancy, except during a 0.5 h period at one air handler. The time periods with the outside-air dampers in the minimum open position were detected using sensors on the actuators that control outside air damper movement.

Particle Measurements

Airborne particle concentrations were monitored at one outdoor location, adjacent to a fourth floor outside air intake, and two locations within the occupied space of each floor at a height of approximately 1.8 m. The two indoor measurements per floor were at central locations within each half of the floor. Particle concentrations were generally monitored only between 04:00 and 20:00 on Thursdays and between 07:00 and 15:30 on Fridays during nine consecutive weeks starting on July 18, 1996. This paper is based only on data from the first seven weeks, because particle data during weeks eight and nine may have been affected by surface cleaning experiments within the building. There are a few periods of missing data due to errors in programming of the instruments or errors in downloading of data.

Laser-based optical particle counters (Model 237B, Met One, Grants Pass, OR) were used to measure particle number concentration in 6 size ranges, or "bins," of particle diameter[2] (0.3–0.5 μm, 0.5–0.7 μm, 0.7–1.0 μm, 1.0–2.0 μm, 2.0–5.0 μm, > 5.0 μm). The sample flow rates of the instruments, nominally 2.5 L min^{-1}, were monitored each week and were very stable. All reported concentrations reflect the most recent measured sample flow rates. During the measurement periods, the particle counters sampled air continuously. Each indoor particle measurement was based on 2 or 3 min of concurrent sampling and counting. Outdoor measurements were based on 1 min of sampling and counting. The resulting data were recorded in the instrument's memory every 1–3 min[3].

[2] For the largest size bin, particle counts were often only a few per counting period; therefore, this paper uses > 2 μm as the largest particle size range.

[3] Due to data storage limitations, on Thursdays no particle concentration data for outdoors were collected between 06:00 and 09:00 and 12:30 and 3:00.

The particle counter used to measure outdoor air particle concentrations was located indoors and sampled through a ~1.5 m length of plastic tubing that extended to outdoors near a set of outside air inlet louvers at a location with low air velocities. The sample tube was provided by the manufacturer for this application and was installed without sharp bends.

The particle counters were factory calibrated before and after the study. Additionally, all particle counters were intercompared two times by performing measurements at nearly the same location in an undisturbed room. The particle counter used for measurements in outside air retained the 1.5 m length of sampling tube during the instrument intercomparisons. Because we are primarily interested in particle concentration ratios, all measured data have been corrected based on the instrument comparisons, using one of the particle counters as a "reference." The largest corrections made were 6%, 10%, 18%, 15%, and 10% for the smallest to largest particle size bins, respectively. The particle counters have a 50% counting efficiency for 0.3 μm particles, thus the measured number concentrations in the smallest size bin (0.3–0.5 μm) are smaller than the actual concentrations by a factor < 2.

Optical particle counters will undercount particles when concentrations are high due to a tendency for multiple particles passing through the laser beam to be counted as a single particle. For the Met One counters, this undercounting due to coincidence loss, based on information from the manufacturer, is $< 10\%$ at a total particle count of 140 particles per cm^3. During weeks 1–5 of this study, all measured concentrations were < 140 particles per cm^3. During weeks 6 and 7, outdoor concentrations were approximately 200 and 160 particles per cm^3. The estimated undercounting at these higher concentrations was estimated to be $< 11\%$ at 160 particles per cm^3 and $< 14\%$ at 200 particles per cm^3 based on manufacturer's specifications and an equation for coincidence loss (Hinds 1982, p. 344).

The responses of the Met One counters were not compared in a formal set of experiments to the response of a more sophisticated instrument. The uncertainties in absolute values of particle counts made with this type of instrument is considerably larger than the uncertainties in ratios of particle counts.

Ventilation Rate Measurements

Many additional indoor environmental parameters were measured during this study, but only the ventilation rate measurements are clearly pertinent to this paper. The new tracer gas procedure used to measure equivalent steady outside air ventilation rates (ESVRs) is described in detail elsewhere (Faulkner et al. 1998). For the measurements, an indoor pollutant source was simulated with approximately 100 passive sources of a perfluorocarbon tracer gas spaced uniformly per unit floor area. The sources continuously released tracer at a known rate. During the workday periods (7:00 to 17:00) of Thursdays and Fridays, air samples from five to six locations per floor (at a height of ~1.5 m) were collected in gas storage bags. The concentrations of tracer gas in the bag samples were subsequently determined using a calibrated gas chromatograph with electron capture detector. The ESVRs were calculated from a mass balance equation based on the tracer concentrations in the sample storage bags and on the indoor tracer emission rates. The ESVRs are the steady rates of outside air supply that, with thorough mixing of the indoor air, would yield the measured tracer gas concentrations. With the sample inte-

gration periods of this study, the measured values of ESVR are averages for the workday periods of Thursday and Friday.

Air Filtration

During weeks three and five, air filters with an unusually high particle removal efficiency for submicron particles were installed in the AHUs on Floor 4. During weeks four and six, the high efficiency filters were removed from Floor 4 and installed on Floor 2. At all other times, the building's normal air filters were utilized. At the start of the study, all air filters were new.

The normal filters have an initial ASHRAE dust spot filter efficiency rating (ASHRAE 1992a) of 22% and a rating of 27% after extended use. No data were available on the efficiency versus particle size for these specific filters, although filters with a similar ASHRAE rating typically have efficiencies of approximately 3%, 15%, 40%, and 80% for particles with aerodynamic diameters of 0.3 μm, 0.85 μm, 1.5 μm, and 3 μm, respectively (ASHRAE 1992b). Based on manufacturer's data, the high efficiency filters used in this study have a minimum efficiency of 95% for particles with a diameter of 0.3 μm. From filter theory, the efficiency of these filters should be higher than 95% for particles either smaller or larger than 0.3 μm. While the normal filters have no gaskets or seals to limit the bypass of air around them, the high efficiency filters have flexible rubber seals. The published airflow resistance (i.e., pressure drop) of the normal and high efficiency filters was nearly identical for the rates of airflow in the AHUs. Switching between the normal and high efficiency filters caused no discernible change in the supply airflow rate based on multipoint measurements of supply airstream velocity.

Particle Concentration Modeling

To aid in interpreting the experimental data, a steady state mass balance equation for a well-mixed space was employed for particles in each size range:

$$S + (Q_o - Q_{\inf})(1 - E)C_o + Q_{\inf} P C_o = Q_o C + \lambda_{dep} V C + Q_r E C, \quad (1)$$

where the left side of the equation contains the particle source terms and the right side contains particle removal terms. The symbols are defined as follows: S is the indoor particle generation rate; Q_0 is the total rate of outside air entry based on the tracer gas measurements; $Q_{\inf}$ is the estimated rate of air infiltration flow through the building envelope (this air is not filtered); E is the filter efficiency for the particle size under consideration; C_o is the outdoor particle concentration; P is the penetration factor for infiltrating particles; C is the indoor particle concentration; λ_{dep} is a particle deposition coefficient that accounts for particle removal by deposition on indoor surfaces; V is the indoor air volume; and Q_r is the rate at which recirculated indoor air passes through the filters.

The rate of recirculation through the filter

$$Q_r = Q_s - (Q_o - Q_{\inf}), \quad (2)$$

where Q_s is the sum of the supply airflow rates of the AHUs serving the floor.

Solving Equation (1) for C yields

$$C = \frac{S + (Q_0 - Q_{\inf})(1 - E)C_0 + Q_{\inf} P C_0}{Q_0 + \lambda_{dep} V + Q_r E}. \quad (3)$$

Three of the parameters within these equations can be only roughly estimated based on prior research. Considering the sealed construction of the building envelope and the mechanical ventilation, $Q_{\inf}$ is likely to be small relative to Q_o. During periods

without operation of the building AHUs, a prior study (Persily et al. 1991) measured infiltration rates (i.e., products of Q_{inf} and V) of approximately 0.2 h^{-1} in this building. Generally, infiltration rates will be smaller during AHU operation because building pressurization is the design intent; therefore, we assumed an infiltration rate of 0.1 h^{-1} as a model input.

Data on typical values of particle penetration (P) and particle deposition coefficient (λ_{dep}) are very limited. For particles in the 0.3 to 0.5 μm size range, and possibly for the next larger range (0.5–0.7 μm), P may be very close to unity (Ozkaynak et al. 1996; Lewis 1995; Thatcher and Layton 1995). Table 1 provides some of the reported values of λ_{dep} as a function of particle size. The base case values are based on a compilation of data from several references. Relative to these base case values, Lewis (1995) reported a factor of three to four higher deposition coefficients for submicron particles under quiescent conditions and even higher deposition coefficients for all particle sizes under turbulent conditions. From the inconsistencies in reported values, it is evident that values of λ_{dep} are either poorly characterized or highly variable depending on building conditions. All of these deposition coefficients have been determined from experiments in spaces much smaller than a large commercial building, ranging from a 4.4 m^3 chamber (Lewis 1995) to a 550 m^3 house (Thatcher and Layton 1995).

The deposition coefficient is usually characterized (Nazaroff et al. 1993) as the product of a mass transfer coefficient called a deposition velocity and the ratio of indoor surface area to volume (S/V). S/V may change with building size and furnishings. We have not adjusted the reported deposition coefficients to account for the possibility that S/V in the large furnished office building may differ from the S/V of the building or chamber employed to measure the deposition coefficient. S/V is difficult to determine in a large furnished building; however, we suspect that high values of S/V in furnished buildings may cause deposition coefficients for these buildings to exceed the values typically reported in the literature.

Values for the indoor particle generation rate (S) as a function of particle size in large commercial office buildings are not known and may vary considerably among buildings. For the smallest particles, some information can be gained by assuming that S is negligible relative to the rate of particle entry from outdoors.

RESULTS

Ventilation Rates and Their Relationship to Particle Concentrations

Within each floor, the measured values of ESVR were relatively constant, ranging from 1.8 to 2.1 $m^3\ s^{-1}$ on Floor 2 and from 3.2 to 3.5 $m^3\ s^{-1}$ on Floor 4. Based on reviews of plots and regression coefficients,

TABLE 1. Estimates of the particle deposition coefficient (h^{-1}).

	Particle Size						
Reference	0.2 μm	0.4 μm	0.6 μm	0.85 μm	1.5 μm	3.0 μm	5.0 μm
Sextro (1996)[a] (Base Case Values)	0.03	0.06	0.09	0.15	0.35	0.80	1.7
Lewis (1995) (Quiescent Conditions)	—	0.26	0.26	0.31	0.43	0.72	1.1
Lewis (1995) (Turbulent Conditions)	—	2.2	1.4	1.7	2.0	3.1	3.6

[a] Compilation of values from Offermann et al. (1985), Xu et al. (1994), Thatcher and Layton (1995).

there were no significant correlations between particle concentrations and ventilation rates within floors, presumably because of the small range in ventilation rates. However, the substantially higher particle concentrations on Floor 4 during periods of normal filtration may be a consequence (see Equation (3)) of the higher ventilation rates on Floor 4.

Particle Concentrations and Size Distributions

Based on data from week 5, Figure 1 provides an example of the time-averaged particle number concentrations for the workday periods (07:00 to 17:00 of Thursday and 07:00 to 15:30 of Friday) in each particle size range for outdoor air, Floor 2 with normal air filters, and Floor 4 with high efficiency air filters. Three observations based on this figure follow. First, the particle number concentration is dominated by the smallest particles. For the three smallest particle size bins, the particle number concentrations decrease by roughly an order of magnitude as the particle size bin increases one step[4]. Second, it is clear that indoor particle number concentrations are substantially lower than outdoor particle number concentrations, at least for particles smaller than 2 μm. Even with the normal air filters, indoor concentrations of submicron size particles are lower than outdoor number concentrations by approximately a factor of 3–6. Third, number concentrations of submicron particles are much lower on the floor with high efficiency filtration. In fact, during this particular week the number concentration of 0.3–0.5 μm particles was a factor of 26 lower on the floor with high efficiency filters.

[4]The exception is the decrease in particle number concentration by approximately one half order of magnitude with high efficiency filtration as the particle size range increases from 0.5–0.7 μm to 0.7–1.0 μm.

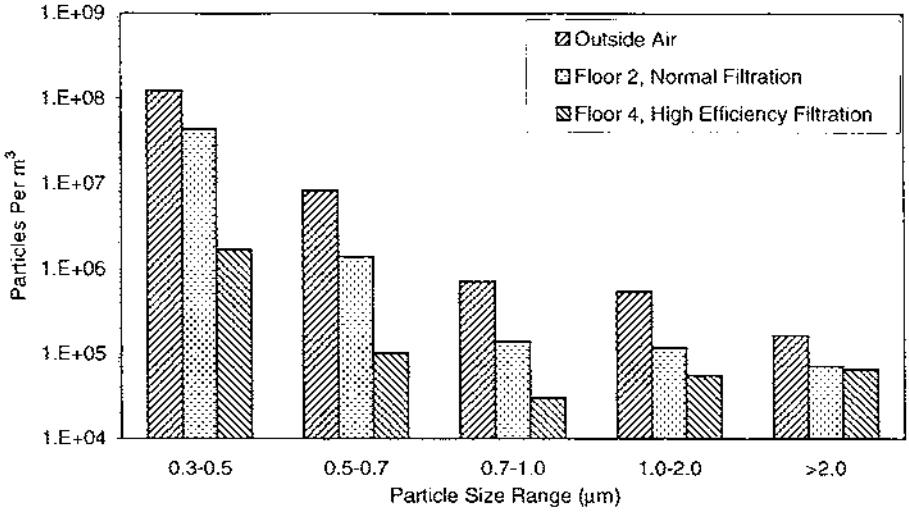

FIGURE 1. Average particle number concentration versus particle size during workday periods of Thursday and Friday of week 5.

Also based on data from week 5, Figure 2 provides an estimate[5] of the particle mass in each size bin, assuming a particle density[6] of 2 g cm^{-3} for all particles (Nazaroff 1989). Measurements for a broader range of particle sizes would be necessary to fully define the size distribution for particle mass. On the floor with normal filtration, for the particle sizes measured, the smallest and largest size bins contained 41% and 45% of the particle mass, respectively. The distribution of particle mass with size is different when the high efficiency filters are used because these filters, as discussed subsequently, reduce concentrations of submi-

[5]The mass concentrations in this figure were estimated from a predicted particle size distribution with particle size bins much smaller than the size bins of the optical particle counters. The process involves creating piecewise curve fits to the measured data for particle number concentration per measurement bin width; using the curve fit equations to estimate concentrations in 41 particle size ranges; correcting for the discrepancy (resulting from imperfect curve fits) between the measured and total-predicted particle numbers in each measurement size bin; and computing the mass concentrations in each of the 41 size bins. A much more simple calculation based on the midpoint of each of the optical particle counter size bins and 3.5 μm for the largest bin (negligible particles were counted in a > 5 μm bin) resulted in 12% to 38% higher total mass concentrations and a 65% higher mass concentration for outdoor particles larger than 2 μm.

[6]Based on particle mass concentrations measurements and simultaneous measurements with an optical particle counter. The relationship between indoor and outdoor particle mass concentrations should be accurately illustrated as long as indoor and outdoor particles of the same size have a similar density.

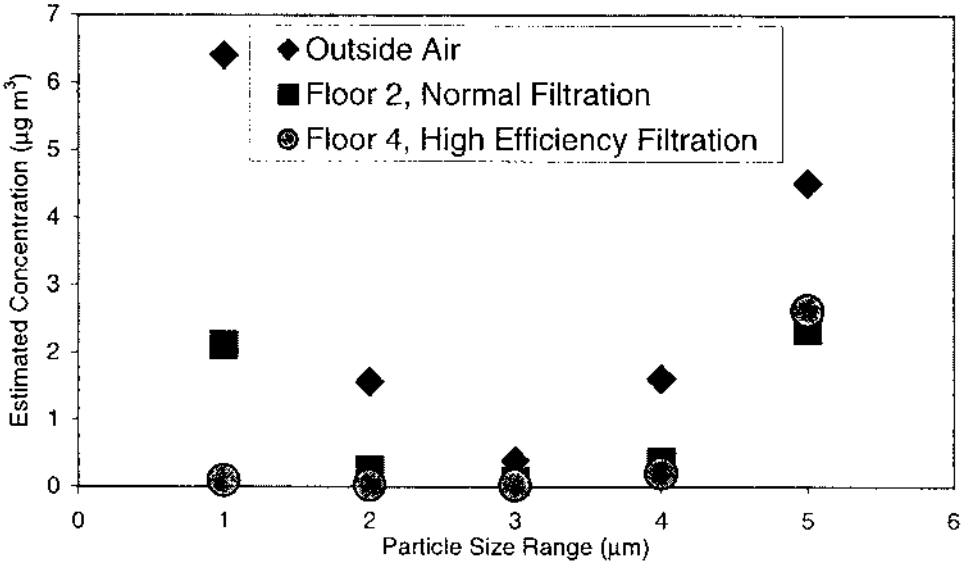

FIGURE 2. Estimated particle mass concentration in each size bin during workday periods of Thursday and Friday of week 5. Total estimated mass concentrations are 15 $\mu g\ m^3$ in outside air, 5.2 $\mu g\ m^3$ on Floor 2, and 2.9 $\mu g\ m^3$ on Floor 4.

cron particles by a large factor. On the floor with high efficiency filtration, particles larger than 1.0 μm accounted for 89% of the particle mass.

Temporal Variation in Particle Concentrations

For 0.3–0.5 μm particles, Figure 3 illustrates the average particle number concentrations for the workday periods of Thursday and Friday as a function of study week. Large week-to-week variations in concentrations are evident. There is a difference of approximately a factor of six between the highest and lowest concentrations. The figure also illustrates that indoor particle concentrations approximately track the outdoor concentrations, at least when normal filters are installed in the AHUs.

For all particle sizes, number concentrations often varied substantially within a single workday, as illustrated in Figure 4 for the smallest particles during a period of normal filtration. Additionally, at numerous times there were spikes in indoor particle concentrations at specific locations that were more common for the larger particles, usually without a corresponding spike in the outdoor particle concentrations. Short duration localized releases or resuspensions of particles indoors are one potential explanation for the observed spikes.

Ratios of Indoor-to-Outdoor Particle Concentration With Normal Filtration

Table 2 provides the average measured ratios of indoor particle number concentrations to outdoor concentrations (I/O ratios) for the Thursday and Friday workday periods of four weeks with normal efficiency filtration on each floor. Even with normal efficiency filters installed, the I/O ratios are only 0.15 to 0.55, thus it is clear

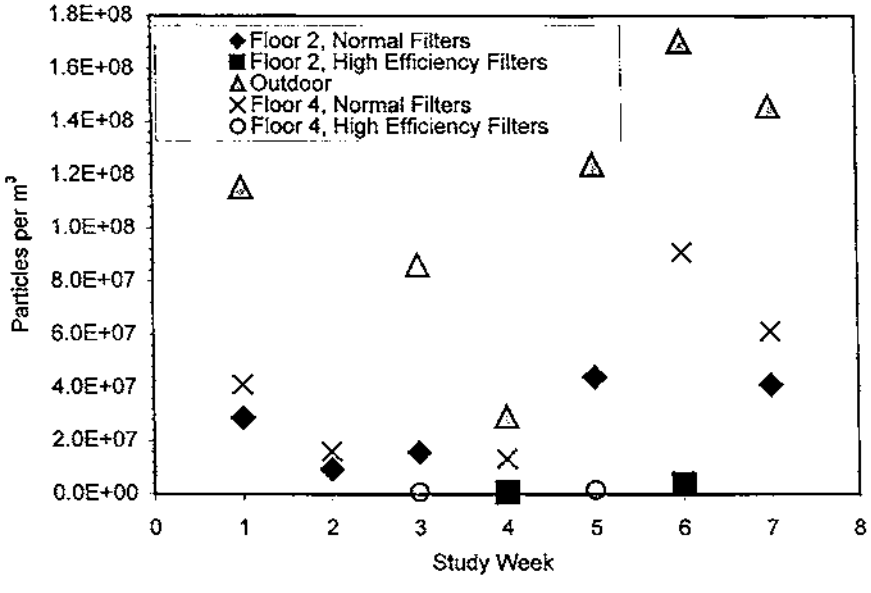

FIGURE 3. Number concentration of 0.3 to 0.5 μm particles during workday periods of Thursday and Friday for the seven study weeks.

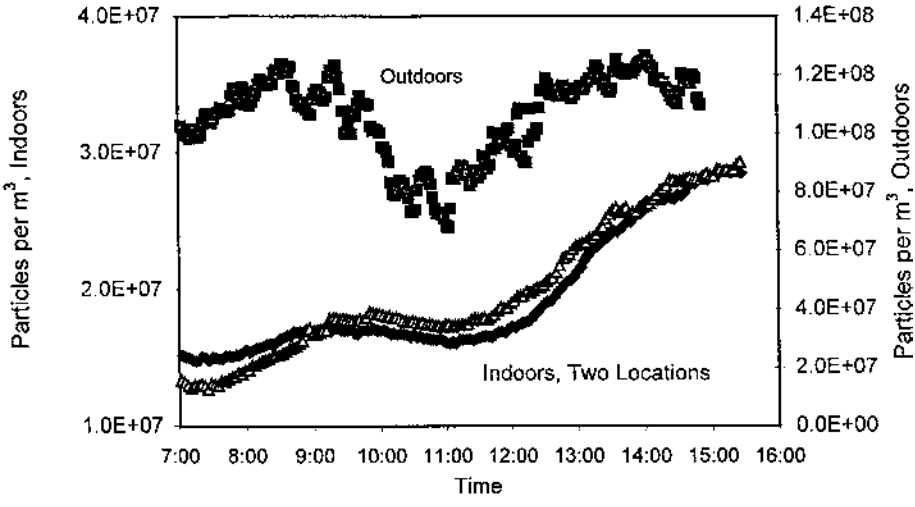

FIGURE 4. Number concentration of 0.3 μm to 0.5 mm particles at the two second floor measurement locations and in outdoor air on August 2, 1996.

that outdoor particle measurements are a poor direct measure of indoor particle exposures in this building. The highest measured I/O ratios are for the largest particles (> 2.0 μm).

Table 2 also provides predictions (based on Equation (3)) of the I/O ratios, for the three sets of particle deposition rates described previously. For these predictions, we used the average measured value of effective steady ventilation rate and the previously-described estimates of filter efficiency. We assumed that the supply airflow rates in the air handlers were two-

TABLE 2. Measured and predicted ratios of I / O particle number concentration

Floor	Particle Size Range (μm)	Estimated Filter Efficiency	Base Case Particle Deposition Coefficient (h^{-1})	Lewis Quiescent Particle Deposition Coefficient (h^{-1})	Lewis Turbulent Particle Deposition Coefficient (h^{-1})	Average Measured Ratio of I / O Particle Number Concentration (C_{in}/C_{out})	Predicted C_{in}/C_{out} With Base Case Deposition Coefficient	Predicted C_{in}/C_{out} With Lewis Quiescent Deposition Coefficient	Predicted C_{in}/C_{out} With Lewis Turbulent Deposition Coefficient
2	0.3–0.5	0.03	0.06	0.26	2.2	0.27	0.75	0.57	0.17
2	0.5–0.7	0.1	0.09	0.26	1.4	0.15	0.52	0.43	0.20
2	0.7–1.0	0.15	0.15	0.31	1.7	0.18	0.41	0.35	0.16
2	1.0–2.0	0.4	0.35	0.43	2.0	0.23	0.17	0.16	0.09
2	> 2.0	0.8	0.80	0.72	3.1	0.52	0.05	0.05	0.03
4	0.3–0.5	0.03	0.06	0.26	2.2	0.44	0.83	0.67	0.23
4	0.5–0.7	0.1	0.09	0.26	1.4	0.26	0.65	0.56	0.28
4	0.7–1.0	0.15	0.15	0.31	1.7	0.28	0.53	0.47	0.23
4	1.0–2.0	0.4	0.35	0.43	2.0	0.38	0.25	0.24	0.13
4	> 2.0	0.8	0.80	0.72	3.1	0.55	0.07	0.07	0.04

thirds of the maximum capacity, that the product of air infiltration flow rate and indoor volume (hereinafter called the infiltration rate) was 0.1 h^{-1} (as explained previously), and that the penetration factor was unity. Finally, the predictions assume negligible indoor particle generation, which is most likely to be a reasonable assumption for the smallest particles.

For the submicron-size particles and the base case or Lewis quiescent deposition rates, the predicted I/O ratios exceed the measured ratios by a factor of 2–3. Accounting for indoor particle generation would increase the discrepancy. Doubling the assumed air infiltration rate or decreasing the particle penetration factor to 0.5 reduces this discrepancy insignificantly. Doubling the filter efficiency, which is probably unrealistic, still leaves large discrepancies, often near a factor of 2. Therefore, the low measured I/O ratios for submicron size particles suggest that particle deposition coefficients are underestimated or suggest that there is some other large unexplained particle removal process for submicron particles. For example, as illustrated in Table 2, the discrepancy between the predicted and measured I/O ratios is substantially diminished if the much higher Lewis turbulent deposition coefficients are used in the model.

For particles larger than 1 μm in size, the measured I/O ratios exceed the predicted ratios, regardless of the choice of particle deposition rates. For the largest particles, the discrepancy is about a factor of 10. Reasonable changes in the model inputs for filter efficiency, infiltration rate, and particle deposition rate will not resolve these discrepancies. A substantial rate of indoor particle generation or resuspension, for particles larger than 1 μm, seems to be the most likely explanation for this discrepancy. Occasional periods with indoor concentrations of particles larger than 1 μm exceeding outdoor concentrations provided additional evidence of indoor generation of these larger particles.

The relationship of the indoor particle mass concentration to that outdoors is of interest because epidemiological studies have generally investigated associations of health effects with outdoor particle mass concentrations, while actual particle exposures occur predominantly indoors. Using the method described previously to estimate particle mass concentrations, Figures 5 and 6 plot I/O particle mass ratios versus study week for floors 2 and 4, respectively. It is clear that indoor particle mass concentrations track outdoor concentrations, although quite imperfectly. Considering only particles smaller than 2 μm, the I/O mass ratios ranged by approximately a factor of 1.7, from 0.19 to 0.28 on floor 2 and from 0.25 to 0.46 on floor 4. During this period, the corresponding outdoor particle mass concentrations varied over a range of 6. The I/O mass ratios for all particles larger than 0.3 μm, i.e., with particles larger than 2.0 μm included, are more variable with time.

Influence of High Efficiency Filtration on Indoor Particle Concentrations

Because the time-varying outdoor particle concentrations have a strong influence on indoor particle concentrations, the benefits of high efficiency filtration cannot be accurately quantified based on the time-average indoor particle concentrations for each filtration mode. Instead, simultaneous indoor and outdoor measurements were used to calculate I/O particle concentration ratios for each week and floor of the building. Dividing the I/O ratios from periods of high efficiency filtration by the I/O ratios from periods of normal filtration yields a more accurate estimate of the influence of high efficiency filtration on indoor particle concentrations. The results of these calcu-

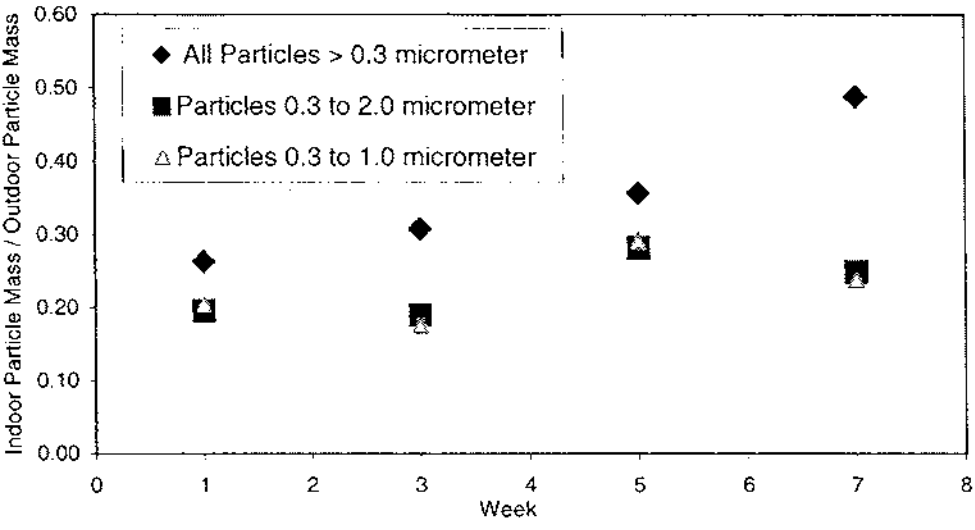

FIGURE 5. Indoor–outdoor ratios of particle mass concentrations with normal filtration versus week for Floor 2.

lations are provided in Figure 7, based on data from throughout the study. This figure illustrates that high efficiency filtration was associated with very large reductions in the indoor particle concentrations for the smallest particles. As particle size increased, the benefits of the high efficiency filtration decreased, presumably because the particle removal efficiency of the normal air filters increases with particle size. Averaging the results from both floors yields the following percent reduction in indoor particle number concentrations: 94% for 0.3–0.5 μm particles; 84% for 0.5–0.7 μm

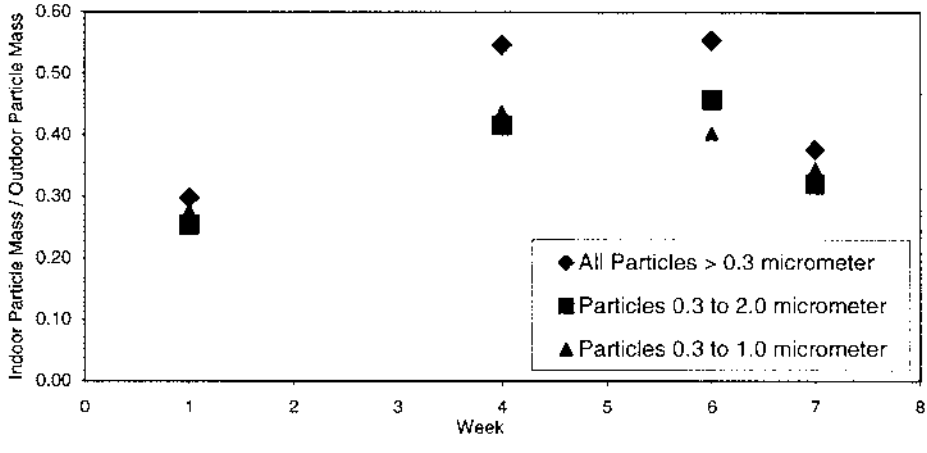

FIGURE 6. Indoor–outdoor ratios of particle mass concentrations with normal filtration versus week for Floor 4.

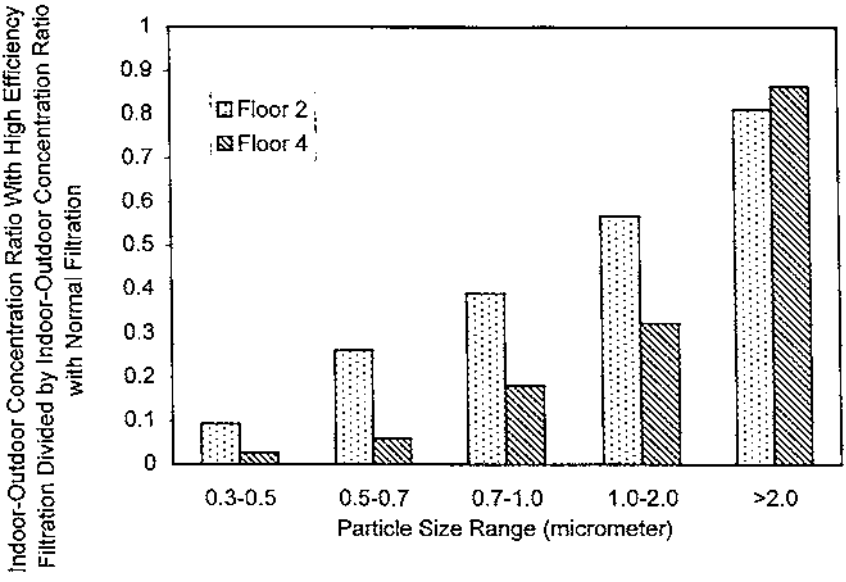

FIGURE 7. Influence of high efficiency filtration on indoor–outdoor particle concentration ratios.

particles; 72% for 0.7–1.0 μm particles; 55% for 1.0–2.0 μm particles; and 16% for > 2.0 μm particles.

Figure 7 illustrates that the high efficiency filters were effective in reducing concentration of small particles on both floors; however, the filters were less effective on Floor 2 than on Floor 4. Part of the explanation for this is that the I/O ratio with normal filtration is higher on Floor 4 than on Floor 2, presumably because of the higher ventilation rate on Floor 4. Additional potential explanations for these findings include a higher rate of infiltration of unfiltered air into Floor 2 or a higher rate of air leakage around the high efficiency filters on Floor 2.

When the modeled and measured effects of high efficiency filtration were compared, it became immediately apparent that the air infiltration rate has a very strong influence on indoor particle concentrations when the filters are nearly 100% efficient. With 95% efficient filters, the rate of particle entry from outdoors due to infiltration will often be considerably larger than the rate of particle entry via the outside air that passes through the filters.

DISCUSSION

The indoor particle number concentration was dominated by the smallest particles. This finding has been observed in many prior studies of indoor and outdoor air. With normal filtration, most of the indoor particle mass was from the smallest and largest particles.

Even with the normal air filters, which have a low efficiency for submicron size particles, indoor number concentrations of submicron particles were a factor of 3–6 smaller than outdoor particle number concentrations. Additionally, for the range of particle sizes measured, the indoor particle mass concentration was considerably less than outdoor particle mass concentration. Other published comparisons of indoor and outdoor particle concentrations in large commercial buildings without smoking are

limited. The field studies of commercial buildings by Turk et al. (1989) included indoor and outdoor data from seven buildings with restricted smoking. In five of these buildings, indoor respirable particle mass (RSP) concentrations were less than outdoor RSP concentrations (I/O ratios were 0.3–0.9, but typically close to 0.9). Also, at ~70% of the indoor measurement sites distant from smoking, RSP concentrations were less than outdoor RSP concentrations. Similarly, Brightman et al. (1996) reported that indoor particle mass concentrations for particles smaller than 10 μm (PM_{10}) were less than outdoor PM_{10} concentrations within 11 of 16 commercial buildings. Jamriska and Morawska (1996) found that the indoor number concentration of 17 to 700 nm particles in an office building were about 40% less than outdoor concentrations. Thus our finding that indoor particle concentrations were smaller than outdoor concentrations is typical of previous findings from large commercial buildings without smoking.

For all particle sizes, indoor number concentrations varied considerably between weeks and within a single work day. For submicron size particles, indoor number concentrations roughly tracked outdoor concentrations. For particles smaller than 2 μm, the indoor mass concentration roughly tracked the outdoor mass concentration. Other studies have also reported large temporal variations in particle concentrations within commercial buildings (Jamriska and Morawska 1996; Miyazaki and Narasaki 1996; Weschler and Schields 1988; Turner et al. 1996). These findings suggest that short-term particle concentration measurements, which are very common, have a limited utility for assessment of time average indoor particle exposures.

The high efficiency filters dramatically reduced the I/O particle number concentration ratio for submicron particles (i.e., the decrease was ~70% to 95%, depending on particle size). For particles between 1 and 2 μm in size, the reduction was ~50%. For larger particles, the reduction in concentration was only ~20%. Our model predictions based on Equations (1)–(3) indicated that low air infiltration rates (obtained from pressurizing the building or by providing an air tight envelope) are necessary to benefit fully from high efficiency filtration. We identified few papers with similar measured data from commercial buildings. Krzyzanowski and Reagor (1990) measured I/O particle number concentration ratios in a telecommunications equipment building with 85% and 20% ASHRAE dust spot efficiency[7] filters. The higher efficiency filters reduced the I/O ratio by ~50% for particles larger than 0.5 μm and by ~40% for particles larger than 1.0 μm. Several papers have provided predictions of the benefits of high efficiency filtration. Herlin (1997) used a model to predict that changing from 30% to 85% efficient[8] filters in a telecommunications office would reduce the I/O ratio for RSP by 11% to 86% depending on the degree of building pressurization. Owen et al. (1992a) also used a model to predict that switching from normal to high efficiency filters in a building with smokers would reduce the indoor particle mass concentration by ~70%. Also based on modeling, Turk et al. (1989) found that high efficiency filters would substantially decrease RSP concentrations, but that concentrations would remain high if a substantial fraction of the workers smoked.

Generally, respirable size particles are thought to be the most likely to cause adverse health effects (EPA 1996a, 1996b);

[7] The dust spot efficiency is the filter efficiency determined using the ASHRAE Standard 52.1 (ASHRAE 1992a).

[8] Efficiency was defined as the fraction of fine particle (< 2.5 μm) mass removed by the filters.

thus the findings in this and other papers suggest that the use of high efficiency filters in building AHUs may be beneficial for health. However, using high efficiency filters in place of normal filters would not be expected to decrease health effects associated with indoor particles larger than approximately 2 μm in size because normal filters are relatively efficient for these large particles. Many of the intact bioaerosols may be larger than 2 μm.

The comparison of predicted and measured I/O particle concentration ratios suggest that the base case (and commonly used) particle deposition coefficients for submicron size particles are substantially underestimated relative to the actual deposition coefficients in this building. Thus, our findings provide some support for higher particle deposition coefficients, such as those measured under turbulent conditions by Lewis (1995). Another possibility is that the deposition coefficients in this large office building are higher than coefficients most commonly reported because this furnished office building has a much larger value of S/V than the chambers or buildings used to measure deposition coefficients. Alternately, our model-measurement discrepancies may suggest that there is some other large unexplained indoor particle removal process for submicron particles. Losses of particles from indoor air when the air flows through ducts are being investigated. Based on the predictions of Wallin (1993), these losses are very small for submicron size particles. However, model predictions by Sippola (1998) indicate large (e.g., 50%) depositional losses of submicron particles when air flows through duct systems with rough interior surfaces, such as internal fiberglass insulation and sections of flexible duct.

Differences between the indoor and outdoor air temperature and humidity could influence the measured I/O particle concentration ratio and, consequently, increase or decrease discrepancies between the modeled and measured I/O ratios. In this air-conditioned building, both temperature and relative humidity were, on average, lower indoors. Three phenomena related to temperature or humidity are considered. First, when outdoor air is cooled, e.g., when drawn into an air-conditioned building, ammonium nitrate particles may be formed via a gas-to-particle conversion involving ammonia and gaseous nitric acid (Stelson and Seinfeld 1982); however, no published verification of this form of particle formation indoors was identified. If this process of particle formation was incorporated in the model, the discrepancy between the modeled and measured I/O particle concentration ratio would increase. Second, the reduction in indoor relative humidity due to air conditioning could lead to a decrease in particle size—presumably causing the size of some indoor particles to decrease to a point where they are not detected by the optical particle counters. The influence of humidity on particle size depends on the particle composition and the size of some particles is unaffected by humidity (Dua and Hopke 1996). Some particles increase in size at high humidity; however, their size is nearly independent of relative humidity when the humidity is below approximately 75% to 80% (Hinds 1982). During the study, indoor relative humidities were typically between 40% and 60%. Outdoor humidity was not measured; however, based on hourly weather data for a typical meteorological year we expect the outdoor humidity to exceed 75% RH (and 80% RH) during 23% (and 17%) of the workday period (07:00 to 16:00) between July 18 and August 6. Although this phenomenon could help to explain the discrepancy between measured and predicted I/O particle concentration, the expected magnitude of the effect is modest. During ~ 80% of the study

period, the outdoor humidity was below ~75% and indoor particles should not diminish significantly in size because of the lower indoor humidity.

The third phenomenon relates to the approach for measuring outdoor particle concentrations. The particle counter was located in a room with a normal indoor temperature, while the sample stream was drawn into the optical particle counter from outdoors through a 1.5 m long tube, with about 50% of this tube located indoors. The relative humidity of the air in the sample tube could increase due to cooling of the sample stream caused by heat transfer through the tube wall. This increase in relative humidity could increase the size of the particles entering the optical particle counter—causing more of the smallest outdoor particles to be detected—and increase the measured outdoor particle concentration. We cannot entirely rule out this phenomenon as an explanation of the discrepancy; however, for two reasons the anticipated effect is small. First, the heat released by pumps and electronics in optical particle counters tends to heat the sample as it passes through the instrument (Biswas et al. 1984), counteracting the hypothesized cooling that occurs in the short sample line. Second, in the set of weather data for St. Louis, when the outdoor humidity is high the outdoor air temperature tends to be near to the indoor temperature, limiting or eliminating any cooling of the sample stream. For example, the average outdoor temperature during workday periods with an outdoor relative humidity exceeding 75% is estimated (from the typical weather data) to equal 23°C, corresponding to a typical indoor temperature. In summary, after considering these three phenomena, it seems unlikely that differences between the indoor and outdoor air temperature and humidity are a primary cause of the observed discrepancy between measured and modeled indoor particle concentrations.

The comparison of predicted and measured I/O particle concentration ratios also provide evidence of a significant rate of indoor generation or resuspension of particles larger than 1 μm. Previous studies have reported similar findings (Thatcher and Layton 1995; Turk et al. 1998; Ozkaynak et al. 1996).

CONCLUSIONS

The most important conclusions from this study are as follows:

Indoor concentrations of respirable size particles in large sealed mechanically ventilated buildings without tobacco smoking can be substantially lower than outdoor concentrations.

Indoor particle concentrations in large sealed mechanically ventilated buildings vary considerably with time.

Replacement of normal air filters with high efficiency can dramatically reduce indoor number concentrations of submicron size particles (e.g., by 90%).

This study provides evidence of a large rate of removal of submicron indoor particles by some process other than ventilation or air filtration. Thus, actual particle deposition coefficients in this building for submicron size particles may exceed base case (and commonly used) particle deposition coefficients by a large factor.

This work was supported by the Assistant Secretary of Energy Efficiency and Renewable Energy, Office of Building Technology, State, and Community Programs, Office of Building Systems of the U.S. Department of Energy (DOE) under contract No. DE-AC03-76SF00098, by the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention, and by the Office of Research and Development, U.S. Environmental Protection Agency. Any opinions expressed in this paper are those of the authors and do not necessarily reflect those of the sponsors nor is any official endorsement to be implied.

We acknowledge and thank the following individuals: Robert Raber for technical assistance and advice regarding the selection of a high efficiency filter methodology; Sharon Wentz for extensive logistical assistance within the study building; Dan Frank, John Aubuchon, and Ron Wisniewski for providing information on and access to the study building ventilation systems; and Richard Sextro for providing published data on particle deposition coefficients. We also thank Tracy Thatcher and Richard Sextro for helpful review comments on a draft of this document.

References

ASHRAE (1992a). *Methods of Testing Air Cleaning Devices Used in General Ventilation for Removing Particulate Matter*, ASHRAE Standard 52.1, American Society for Heating, Refrigerating, and Air Conditioning Engineers, Atlanta, GA.

ASHRAE (1992b). *1992 ASHRAE Handbook*: *HVAC Systems and Equipment*, American Society for Heating, Refrigerating, and Air Conditioning Engineers, Atlanta, GA.

Biswas, P., Jones, C. L., and Flagan, R. C. (1984). Distortion of Size Distributions by Particle Sampling Instruments. In *Aerosols*: *Science, Technology and Industrial Applications of Airborne Particles*, edited by B. Y. H. Liu, D. Y. H. Pui, and H. J. Fissan. Elsevier Science Publishing Co., Inc., New York, pp. 191–194.

Brightman, H.S., Womble, S. E., Ronca, E. L., and Girman, J. R. (1996). Baseline Information on Indoor Air Quality in Large Buildings (BASE'95), *Proceedings of Indoor Air'96*, *The 7th International Conference on Indoor Air Quality and Climate*, Vol. 3:1033–1042, Seec Ishibashi, Inc., Japan.

Dua, S. K., and Hopke, P. K. (1996). Hygroscopicity on Indoor Aerosols and its Influence on the Deposition of Inhaled Radon Decay Products, *Environment International* 22 (SUPPL. 1):S941–S947.

EPA (1996a). *Air Quality Criteria for Particulate Matter*, Volume III, U.S. Environmental Protection Agency, EPA/600/AP-95/001c.

EPA (1996b). *Air Quality Criteria for Particulate Matter*, Volume I, U.S. Environmental Protection Agency, EPA/600/AP-95/001a.

Faulkner, D., Fisk, W. J., Sullivan, D. P., and Thomas, J. M. Jr. (1998). *Characterizing Building Ventilation with the Pollutant Concentration Index*: *Results from Field Studies*. Proceedings of IAQ '98, pp. 27–35, ASHRHE, Atlanta, Georgia.

Fisk, W. J., Faulkner, D., Sullivan, D., Dong, M., Dabrowski, C., Thomas, J. M. Jr., Mendell, M. J., Hines, C. J., Ruder, A., and Boeinger, M. (1998). *The Healthy Building Intervention Study*: *Objectives, Methods, and Results of Selected Environmental Measurements*, LBNL-41546, Lawrence Berkeley National Laboratory, Berkeley, CA.

Herlin, M. K. (1997). The Pressurized Telecommunications Central Office: IAQ and Energy Consumption, *Proceedings of Healthy Buildings/IAQ'97*, Vol. 2, pp. 329–334, Healthy Buildings/IAQ '97, Washington, D.C.

Hinds, W. C. (1982). *Aerosol Technology*: *Properties, Behavior, and Measurement of Airborne Particles*, Wiley Interscience, New York.

Jamriska, M., and Morawska, L. (1996). The Effect of Ventilation and Filtration on Reduction of Indoor Air Exposure to Submicrom Pollutant Particles—Case Study, *Proceedings of Indoor Air'96*, *The 7th International Conference on Indoor Air Quality and Climate*, Vol. 2:753–758, Seec Ishibashi, Inc., Japan.

Krzyzanowski, M. E., and Reagor, B. T. (1990). The Effect of Ventilation Parameters and Compartmentalization on Airborne Particle Counts in Electronic Equipment Offices, *Proceedings of Indoor Air'90*, *The 5th International Conference on Indoor Air Quality and Climate*, Vol. 2, pp. 409–414, International Conference on Indoor Air Quality and Climate, Ottawa.

Lewis, S. (1995). Solid Particle Penetration into Enclosures, *Journal of Hazardous Materials* 43:195–216.

Mendell, M. J., Fisk, Dong, M. X., W. J., Petersen, M., Hines, C. J., Faulkner, D., Deddens, J. A., Ruder, A. M., Sullvan, D., and Boeniger, M. F. (1999). Enhanced Particle Filtration in a Non-problem Office Environment: Preliminary Results from a Double Blind Crossover Intervention Study. *American Journal of Industrial Medicine* 1:55–57.

Miyazaki, T., and Narasaki, M. (1996). Characteristics of Particulate Matter, Metals and Water Soluble Ions in an Air-Conditioning System, *Proceedings of Indoor Air'96*, *The 7th International Conference on Indoor Air Quality and Climate*, Vol. 2:393–398, Seec Ishibashi, Inc., Japan.

Nazaroff, T., and Naraski, M. (1989). Mathematical Modeling and Control of Pollutant Dynamics in Indoor Air. Ph.D. Thesis, California Institute of Technology.

Nazaroff, W. W., Gadgil, A. J., and Weschler, C. J. (1993). Critique of the Use of Deposition Velocity in Modeling Indoor Air Quality. In *American Society of Testing and Materials Standard Technical Publication 1205*, ASTM, Philadelphia, PA.

Offermann, F. J., Sextro, R. G., Fisk, W. J., Grimsrud, D. T., Nazaroff, W. W., Nero, A. V., Revzan, K. L., and Yater, J. (1985). Control of Respirable Particles in Indoor Air with Portable Air Cleaners, *Atmospheric Environment* 19:1761–1771.

Owen, M. K., Ensor, D. S., Lawless, P. A., Hanley, J. T., and Sparks, L. E. (1992a). Relating Air Cleaner Efficiency to Indoor Air Quality, *Proceedings of IAQ'92*, pp. 397–402, ASHRAE, Atlanta, GA.

Owen, M. K., Ensor, D. S., and Sparks, L. E. (1992b). Airborne Particle Sizes and Sources Found in Indoor Air, *Atmospheric Environment* 26A(12):2149–2162.

Ozkaynak, H., Xue, J., Spengler, J., Wallace, L., Pellizzari, E., and Jenkins, P. (1996). Personal Exposure to Airborne Particles and Metals: Results from the Particle Team Study, *Journal of Exposure Analysis and Environmental Epidemiology* 6(1):57–78.

Persily, A. K., Dols, W. S., and Nabinger, S. J. (1994). Air Change Effectiveness Measured in Two Modern Office Buildings, *Indoor Air* 4:40–55.

Persily, A. K., Dols, W. S., Nabinger, S. J., and Kirchner S. (1991). *Preliminary Results of the Environmental Evaluation of the Federal Records Center in Overland Missouri*, NISTIR 4634, National Institute of Standards and Technology, Gaithersburg, MD.

Sextro, R. G. (1998). *Personal Communication*, Indoor Environment Department, Lawrence Berkeley National Laboratory, Berkeley, CA.

Sippola, M. (1998). *Personal Communication*, Department of Environmental Engineering, University of California, Berkeley, CA.

Stelson, A. W., and Seinfeld, J. H. (1982). Relative Humidity and Temperature Dependence of the Ammonium Nitrate Dissociation Constant, Atmospheric Environment 16(5): 983–992.

Thatcher, T. L., and Layton, D. W. (1995). Deposition, Resuspension, and Penetration of Particles within a Residence, *Atmospheric Environment* 29:1487–1497.

Turk, B. H., Grimsrud, D. T., Brown, J. T., Geisling-Sobatka, K. L., Harrison, J., and Prill, R. J. (1989). Commercial Building Ventilation Rates and Particle Concentrations, ASHRAE Transactions 95(1):422–433.

Turk, B. H., Powell, G., Casey, M., Fisher, E., Ligman, B., Marquez, A., Harrison, J., Hopper, R., Brennan, T., and Shaughnessy, R. (1998). Impact of Ventilation Modifications on Indoor Air Quality Characteristics at an Elementary School. Proceedings of Healthy Buildings/IAQ'97, 1:155–160, IAQ '97, Washington, DC.

Turner, W. A., McKnight, F., and Bearg, D. (1996). PM-10, PM-2.5, and Laser Optics Particle Sampling: How the Building Operator can Benefit from this Type of Information, *Proceedings of IAQ'96*, pp. 210–218, ASHRAE, Atlanta, GA.

Wallin, O. (1993). Calculation of Particle Deposition in Ventilating Duct Systems, *Proceedings of Indoor Air'93*, Vol. 6, pp. 355–360, Indoor Air'93, Helsinki, Norway.

Weschler, C. J., and Shields, H. C. (1988). The Influence of HVAC Operation on the Concentrations of Indoor Airborne Particles, *Proceedings of IAQ'88*, pp. 166–181, ASHRAE, Atlanta, GA.

Xu, M., Nematollahi, M., Sextro, R. G., Gadgil, A. J., and Nazaroff, W. W. (1994). Deposition of Tobacco Smoke Particles in a Low Ventilation Room, *Aerosol Science and Technology* 20:194–206.

Received October 26, 1998; accepted November 1, 1999.