Indoor Air 2001; 11: 35–48
http://journals.munksgaard.dk/indoorair
Printed in Denmark. All rights reserved

INDOOR AIR
ISSN 0905-6947

Characterization of Particulate Emissions from Occupant Activities in Offices

MARIANNA LUOMA[1]* AND STUART A. BATTERMAN[2]

Abstract This paper characterizes the relationship between occupant activities and indoor air particulate levels in a non-smoking office building. Occupant activities were recorded on video. Particulate concentrations were monitored by three optical particle counters (OPCs) in five size ranges at three heights. Particulate mass concentrations were measured gravimetrically and bioaerosol concentrations were determined by impaction methods. Occupant activities and number concentrations were determined with 1-min resolution over a 1-week period. Occupant activities such as walking past or visiting the monitoring site explained 24–55% of the variation of 1- to 25-μm diameter particle number concentrations. Statistical models associating particulate concentrations with occupant activities depended on the size fraction and included an autocorrelative term. Occupant activities are estimated to contribute up to 10 μg m^{-3} in particulate concentrations per person. Number concentrations of particles smaller than 1 μm had little correlation with indoor activities other than cigarette smoking and were highly correlated with outdoor levels. The method can be used to characterize emissions from activities if rapid measurements can be made and if activities can be coded from the video record.

Key words Emission sources; Indoor air quality; Occupants; Offices; Optical particle counters; Video.

Practical Implications
This study associated occupant activities, recorded on video, with changes in indoor particle concentrations, monitored by optical particle counters. Occupant activity measures derived from video taping accounted for 24–55% of the variability in particulate concentration in the case study office building. The study demonstrated that occupant-related particulate emissions can be quantified and that particulate levels are elevated in a person's microenvironment. For example, the effect of one person putting on a sweater near a monitoring site was quite dramatic. The method provides a practical way to quantify occupant activities and their impact on IAQ with potential application in residential, commercial and industrial settings.

Received for review 12 September 1997. Accepted for publication 12 March 2000.

Introduction

Occupants and occupant-related activities can cause emissions that increase concentrations of essentially all indoor air pollutants, e.g., CO_2 and volatile organic compounds (VOCs), (Hodgson, 1991; Batterman and Peng, 1995), bacteria and fungi (ACGIH, 1989b; Lehtonen et al., 1993), and particles (Kamens et al., 1991). Occupant-related particulate emissions in office and home environments include fibers, soil, skin cells, hair, bacteria and fungi shed from skin and clothes, smoking, dust entrained or suspended from the floor by walking, and emissions from materials handled (including aerosol products) or machines operated (Kamens et al., 1991; Owen et al., 1992; Thatcher and Layton, 1995). Such emissions may elevate pollutant levels throughout the building and cause dramatic increases in the immediate vicinity or "microenvironment" of an individual (Spengler et al., 1985; Jantunen et al., 1996). Like other pollutant sources, occupant-related emissions require characterization in order to determine concentrations that are normal and perhaps unavoidable and, if necessary, to design control strategies.

Methods to characterize particulate emissions are not well developed, unlike VOC emissions which are readily measurable using mass balance and chamber approaches (ECA, 1991; Colombo et al., 1993; ECA 1995). Chamber tests may be applicable to some materials which release particles due to aging and/or vibration, e.g., ceiling tiles (Nordtest, 1989; Larsen et al., 1996), and some occupant activities, e.g., vacuuming, may be evaluated in very large chambers. Generally, particulate emissions result from both the generation

[1]*VTT Building Technology, PL 1804, FIN-02044 VTT, Finland, Fax: +358 9 455 2408, e-mail: Marianna.Luoma@vtt.fi,* [2]*Environmental and Industrial Health, University of Michigan, Ann Arbor, Michigan, USA, *Author to whom correspondence should be addressed.*

of new particles and the resuspension of previously settled particles, processes that depend on vibration, humidity, temperature, particle accumulation, air velocity, etc. Without reproducing such building-specific conditions, chamber tests may not provide meaningful results. Additionally, many occupant behaviors cannot be easily reproduced in even very large chambers.

This paper examines relationships between particulate concentrations and occupant activities in an office building. Both qualitative and quantitative (statistical) approaches are used to associate activity measures, derived from video monitoring, with particulate concentrations, measured using optical particle counters.

Material and Methods

The simplest approach to characterize an activity is to determine whether it is associated with high pollutant levels, thus, an "observational" method might identify high concentration periods and determine the activities associated with these periods. Alternatively, "interventions" might be staged and concentrations monitored for changes. Either way requires a more or less continuous and representative record of pollutant concentrations and control or understanding of confounding factors, e.g., changes in outdoor pollutant levels.

Statistical methods to characterize emission sources use a regression of pollutant concentrations (the dependent variable) with activity factors (the independent variables), both measured as time series under typical conditions such that

$$C_t = \Sigma_i A_{i,t} S_i + \varepsilon_t \quad (1)$$

where C_t=concentration at time t ($\mu g\ m^{-3}$), $A_{i,t}$=measured activity factor for source i and time t (activity units), S_i=estimated concentration attributable to source i ($\mu g\ m^{-3}$ activity^{-1}), and ε_t=random error or residual ($\mu g\ m^{-3}$). This approach resembles several of the "receptor models" used to apportion sources of ambient air pollutants (Henry et al., 1984; Batterman, 1992), and the technique used by Franke and Wadden (1987) to estimate indoor emissions at a welding shop and a lunchroom. Several assumptions are required. First, a sufficiently long record of pollutant concentrations and activities is required. Second, the activity factors must include all sources that affect concentrations. The omission of a source, including outdoor sources, will cause errors. Third, an activity is expected to cause the same average impact (since S_i is constant), implying that emissions, ventilation and dilution are constant. Fourth, autocorrelation and periodicity (seasonality) of the pollutant should be minimal. Since ventilation systems in most buildings mix (rather than displace) air, autocorrelation between sequential IAQ measurements may be significant, especially for spaces where the air exchange rate × ventilation effectiveness product is small (Luoma and Batterman, 1997) and if sampling rates are high, e.g., one measurement per minute. One approach to handle autocorrelation substitutes an autoregressive model for Equation 1

$$C_t = \Sigma_i A_{i,t} S_i + \rho C_{t-1} + \varepsilon_t \quad (2)$$

where ρ=autocorrelation between successive concentrations, and C_{t-1} is the concentration in the previous period, i.e., the lag 1 concentration. More complex autoregressive models may be used, depending on the statistics of the process.

An additional issue in statistical models is that "background" or outdoor sources may provide large contributions to some indoor pollutants, and it is not feasible to develop activity factors for these sources. Approaches to "remove" the effects of background sources on the regression include subtracting or modeling the effect of outdoor concentrations on indoor levels, using indoor/outdoor (I/O) ratios for the dependent variable, and using time series techniques to "detrend" the data. Given data requirements and the potentially complex dynamics of building exchange processes, the latter approach appears the most promising. The effect of a random or varying mean can be removed using first-order differences, i.e., sequential concentrations are differenced to form a new dependent variable (equivalent to the derivative) for the regression in Equations 1 and 2 (Box and Jenkins, 1970; Bras and Rodriguex-Iturbe, 1985). Random changes in slope may be removed using a second order difference. Unlike the use of I/O ratios or more physically-based techniques, differencing operations do not distinguish between indoor and outdoor sources. However, indoor sources should be identifiable if their emissions cause relatively brief "spikes" or increases in concentration, while the introduction of outdoor air through the HVAC system produces more gradual changes which can be removed by differencing.

Case Study

Observational and statistical approaches are evaluated using a case study which included indoor and outdoor monitoring of air quality parameters and video taping and subsequent coding of occupant activities. The study building is a 3-story office building in Espoo (population 220,000) in southern Finland that is typical of many midsize offices in the Nordic countries. Constructed in 1971 and renovated in 1980, the 4,000 m^2 building has both large open areas and small offices used for administrative

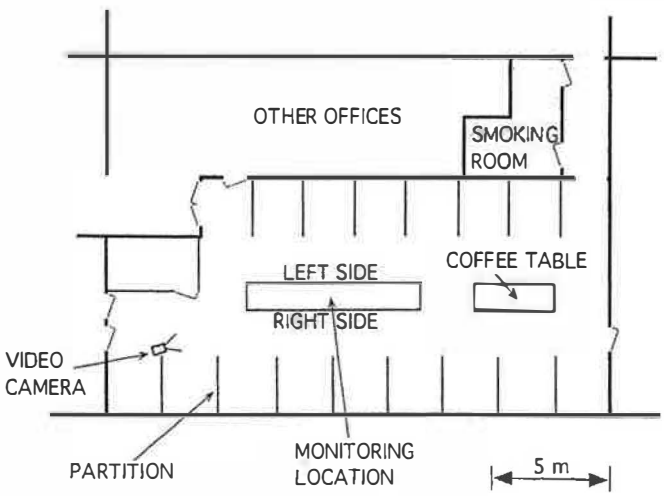

Fig. 1 Plan view of the study room

and clerical work. During the study period (October 21–28, 1996), the building contained ~70 people. The building is generally well maintained and a regular cleaning schedule is followed. Smoking is allowed in one designated room on each floor that is separately exhausted. The building's HVAC system consists of a constant-air-volume air handling unit, ceiling slot diffusers, EU3 filters, cooling and heating coils, a heat recovery unit, and a perimeter hot-water radiative system. Outside air enters via a louvered roof inlet. The system uses 100% outside air during working hours (5:00 to 17:00) and 100% return air otherwise.

One of the larger rooms on the second floor was studied. This 9.6 m×21.6 m×3.1 m room contained 16 workstations in an open floorplan with 1.5-m high partitions (Figure 1). During most of the study period, the room contained 5.9±2.3 people, the indoor temperature was 24.2±0.3°C, and the relative humidity was 33±1% (mean ±standard deviation shown). The room meets the air velocity (<0.18 m/s), ventilation (≥10 L/s, person), CO_2 (<1,500 ppm) and particulate (<60 μgm^{-3}) concentration guidelines for Finnish office buildings, but exceeds the temperature guideline (21°C, Ministry of the Environment, 1987). This occasionally has led to occupant complaints.

Given the HVAC system capacity (~12 $m^3\ s^{-1}$), the building air exchange rate (AER) was ~3.5 h^{-1}. Measurements of supply air in 5 small offices gave AERs=0.6, 0.8, 1.5, 2.2, and 7.6 h^{-1} (Kovanen and Heikkinen, 1994). The AER in the room studied was 1.4 hr^{-1}, based on occupant-generated CO_2 as a tracer gas (Luoma and Batterman, 1997).

During the study week, outdoor temperatures were ~6°C, except Thursday morning when temperatures dropped to 0°C, and Friday afternoon, when temperatures rose to 9°C. Light rains on Monday ended on Tuesday and skies remained overcast through Wednesday, sunny on Thursday, and overcast on Friday. Winds were light (<1.5 m s^{-1}) Monday through Thursday, but increased to 3.5–4.5 m s^{-1} on Friday. Weather observations were collected on a 10 m tower approximately 1 km from the building site.

IAQ Measurements

Pollutants measured at the center of the room at 1.1 m height throughout the study period included particulate mass, particle numbers in five size ranges, CO_2, viable bacteria and viable fungi concentrations. On Monday through Thursday, particle number and bioaerosol concentrations were also measured at 13 other locations in the room, and on Friday at three heights (0.4, 1.1, 1.8 m) at the room's center. Additionally, particulate mass, number, and bioaerosol concentrations were measured outdoors near the roof top air inlet. Most monitoring was conducted from 9:00 to 15:30 during normal business hours in the occupied building. Monday through Thursday data were primarily used to derive correlations of indoor and outdoor pollutants. The statistical analysis of activity factors uses Friday's measurements.

Mass concentrations were determined gravimetrically using open-face filter cassettes, 37-mm diameter, 0.8-μm pore size polycarbonate filters (Millipore, Bedford, MA, USA), a flow rate of 14.2 L min^{-1}, and a 6.5-h sampling period. Filters were equilibrated for >24 h in a constant humidity room prior to weighing to a precision of 1 μg. CO_2 was measured in 1 min averages using NDIR (Binos 100; Leybold Ag., Hanau, Germany). Bioaerosol samples, taken every 30 min on Monday through Thursday, and at 9:15, 12:00 and 14:40 on Friday, were collected using N6-Andersen impactors, 5 min samples, malt extract agar for fungi, and tryptone glucose yeast agar for bacteria. Fungi samples were incubated for 6 days at room temperature (ACGIH, 1989b) and bacteria samples were incubated for 5 days at 30°C. Colony forming units (cfu) were counted.

One-min particle number concentrations were measured using three optical particle counters (OPC, CI-500; Climet Instruments Co., Redlands, CA, USA), each of which counted particles in 6 size channels (greater than 0.3, 0.5, 1, 5, 10, and 25 μm) in a 2.83 L min^{-1} sample flow. Adjacent channels were differenced to obtain particle number concentrations in five size ranges. Although the OPCs had been recently calibrated by the manufacturer, the instruments gave significantly different responses in some channels with test aerosols. For example, concentrations of 0.3- to 0.5-μm diameter particles showed up to 7-fold variation when test aerosol DEHS (di-ethyl hexyl sebacate) was used in laboratory tests. Differences were smaller, but still significant, e.g. up to 2-fold variation, when outside air was used as test aerosol. Field calibrations were made using side-by-side measurements collected each morning in the office. Using linear regression, two of the OPCs were calibrated to match the third or "reference" OPC for 0.3- to 0.5- and 0.5 to 1-μm size ranges. Independent data (2 h of side-by-side measurements collected the following Monday) showed that corrected data had high correlation ($0.89<r<0.96$) to the reference instrument and reasonable relative errors (0.6 to 24.3%) for 0.3- to 0.5- and 0.5- to 1-μm particles. Concentrations of particles exceeding 1 μm diameter were not corrected since the disagreement between the instruments was very high, e.g., relative biases during the validation period for the 1- to 5-, 5- to 10-, and 10- to 25-μm ranges were 340, 75% and 150%, respectively.

Activity Monitoring

Occupant activities were recorded with a video camera (Panasonic NV-S7E, Matsuhita Electric Industrial Co. Ltd., Japan) placed in a corner of the room at ~1.5 m height and ~9 m distant from the monitoring location (Figure 1). The field-of-view encompassed nearly all of the room. Recording was conducted continuously (except to change tapes) from 9:30 to 15:00 from Tuesday through Friday. Clock time was recorded and displayed on the tape. Six types of activities on Friday were coded with one min resolution for two periods, 10:00–12:00 and 12:40–14:40 (the lunch break was excluded, variable names in parentheses below):

- Number of persons walking past the monitoring location on the right (WARI), left (WALE) and far sides (WABE)
- Number of persons visiting the monitoring location (VIRE); and
- Number of persons visiting the drafting board (VIBE) or coffee table (VICO).

"Walks" generally happened quickly and the person rarely stopped. The person may have held papers, folders, etc., may have come towards or away from the camera, and occasionally came in from outdoors or left for out-

doors wearing a coat. "Visits" required that the person stop and spend ~1 min at the indicated location. Visits to the monitoring location were infrequent, either short visits by the researcher to check the equipment, or longer visits by the occupants to study documents. A total of 500 activities were coded in the 4-h study period (~115 walks on the right, 84 walks on the left, 17 walks between the tables), 20 person-min at the reference location in 9 separate visits, and 264 activities by the drafting board or coffee table.

Occupancy was counted in the study room every 30 min on Monday through Thursday, and every 20 min on Friday.

Statistical Analysis

Analyses of the collected data included descriptive statistics, mean tests using one-factor ANOVAs, normality tests using the K-S Lilliefors test, and time series and linear regression models (Excel 5.0 and SPSS 6.0.1). Multiple regressions used number concentrations as the dependent variable. Independent variables included the 6 activity factors (Equation 1), and the activity factors with the autoregression variable (Equation 2). CO_2 concentrations were included as an indicator of occupancy. Because some delay might be expected between activities and the detection of pollutants, activity factors were lagged 0, 1, 2 and 3 min and the CO_2 concentration was lagged 0 and 1 min. Thus, a total of 26 independent variables were available (6 activity factors × 4 lags + CO_2 × 2 lags). Variable selection used the stepwise procedure with $F \leq 0.05$ to enter and $F \geq 0.10$ to exit (Norusis, 1993). Separate regressions were performed for the five particle size ranges and the three heights. The effect of occupant activities was estimated as changes in both number and mass concentrations, as described below.

Estimating Mass Concentrations

Mass concentrations were estimated from number concentrations (counts l^{-1}) by calculating the geometric midpoint diameter $D_{mi} = \sqrt{D_u D_l}$, where D_u and D_l are upper and lower diameter (μm), respectively, of the i_{th} size range (ACGIH 1989a). Then, the mass concentration in the size range C_i (μg m^{-3}) is

$$C_i = N_i \left(\frac{\rho}{1000}\right)\left(\frac{\pi D_{mi}^3}{6}\right) \quad (3)$$

where N_i = measured number concentration for the size range (l^{-1}) and ρ=particle density (g cm^{-3}). The total mass concentration is $C = \sum_{i=1}^{n} C_i$ where n =number of size ranges. The density ρ, which depends on the particle origin, shape and other factors, was determined by minimizing the sum-of-squares between predictions and observations using a non-linear solver (Excel 5.0).

The optical particle instrument had a rated sensitivity of 0.3 μm, thus particles >0.3 μm should have been counted. However, particles <0.3 μm would not be counted and their mass would be omitted. The mass of particles <0.3 μm was estimated by assuming that these particles were in the accumulation mode (particles formed primarily by coagulation of smaller particles), (Willeke and Baron, 1994) using a lognormal size distribution, median diameter D_{50}=0.32 μm, and a geometric standard deviation σ_g=2.16, based on the average urban aerosol (Willeke and Baron, 1994). Then, particle number concentrations in 0.04- to 0.08-, 0.08- to 0.15-, and 0.15- to 0.3-μm size ranges were estimated using the measured 0.3–0.5 μm number concentration. The fraction of particles F_i in the i_{th} size range is estimated as (Willeke and Baron, 1993)

$$F_i = \frac{\ln(D_u) - \ln(D_l)}{(\ln\sigma_g)\sqrt{2\pi}} \exp\left(-\frac{(\ln(D_m) - \ln(D^{50}))^2}{2(\ln\sigma_g)^2}\right) \quad (4)$$

The particulate concentration in the i_{th} size range, N_i (l^{-1}), was estimated as

$$N_i = \frac{F_i}{F_{0.3\text{–}0.5}} N_{0.3\text{–}0.5} \quad (5)$$

where $F_{0.3\text{–}0.5}$=fraction of particles in the 0.3- to 0.5-μm size range, and $N_{0.3\text{- to }0.5}$=number concentration in the 0.3- to 0.5-μm size range (l^{-1}). Finally, Equation 3 was used to estimate mass. A similar extrapolation was made for large particles, assuming a lognormal size distribution with D_{50}=5.7 μm and σ_g=2.21, respectively, taken from the average coarse mode urban aerosol (Willeke and Baron, 1994) and using measured counts of 10- to 25-μm particles.

Given the expected size distribution, the geometric midpoint diameter was not a good approximation for all size ranges. Because the coarse fraction mode was expected to be in the range of 3–10 μm, the 3.5 μm was used for the 1- to 5-μm size range (instead of 2.2 μm), and 12.5 μm (instead of 15.8 μm) for the 10- to 25-μm size range. A sensitivity analysis examined these changes.

Results

IAQ Levels and Trends

Means, standard deviations and extrema of particle number, fungi, bacteria and CO_2 concentrations are listed in Table 1, and mean particle mass concentrations and occupancies are shown in Table 2. Particulate concentration indoors averaged 13±3 μg m^{-3} and 20±11 μg m^{-3} outdoors. These levels, as well as the concentrations of fungi, bacteria and CO_2, were low or normal. Concentrations of all IAQ parameters dropped on Friday from levels observed earlier in the week. Compared to the Monday–Thursday average, particulate mass concentrations dropped by 36% indoors and 52% outdoors, particle number by 24–52% (depending on the size category, with smaller particles showing greater changes), fungi by 23%, and bacteria by 32%. CO_2 dropped by only 8%, but accounting for background levels (~360 ppm), the CO_2 attributable to occupants dropped by 27%. Changes in indoor levels can be explained by lower outdoor concentrations and fewer occupants in the study room. For Monday through Thursday, occupancy averaged 6.9±2.4 and ranged from 1 to 10. On Friday, occupancy averaged 4.9±2.5 in the morning (9:30–12:00), 6.5±0.7 at midday (12:00–13:00), and 6.9±2.3 in the afternoon (13:00–

Table 1 Statistics of indoor concentrations measured at the reference site. 1-min averages

Statistics		Sample Day	Height (m)	Number Concentration (l^{-1})					Fungi[2] (cfu m^{-3})	Bacteria[2] (cfu m^{-3})	CO_2 (ppm)
				0.3–0.5 μm	0.5–1 μm	1–5 μm	5–10 μm	10–25 μm			
Mean	(l^{-1})	Monday–Thursday[1]	1.1	42760	2345	58.8	14.5	3.4	110	233	502
Stdev	(l^{-1})			7669	643	18.8	4.6	1.6	60	83	27
Max	(l^{-1})			63210	4701	145.2	33.6	11.3	276	382	561
Min	(l^{-1})			24683	1154	21.2	3.2	0.4	7	64	430
No. of Observations				1524	1524	1524	1524	1524	50	50	1524
Mean	(l^{-1})	Friday[3]	1.1	24152	1139	39.1	9.9	2.6	114	144	465
Stdev	(l^{-1})			3465	208	7.6	3.1	1.4	30	29	22
Max	(l^{-1})			31811	1763	65.4	20.1	10.2	99	177	535
Min	(l^{-1})			18283	802	23	3.2	0	21	134	413
No. of Observations				238	238	238	238	238	6	6	238
Mean	(l^{-1})	Friday[3]	0.4	24264	1192	104.8	13.9	6.2	61	160	–
Stdev	(l^{-1})			4094	333	23.7	5.8	3.8	29	23	–
Max	(l^{-1})			35898	2431	221.2	44.2	36.7	148	177	–
Min	(l^{-1})			16696	666	55.8	4.2	0.7	57	134	–
No. of Observations				238	238	238	238	238	3	3	–
Mean	(l^{-1})	Friday[3]	1.8	24961	1181	80.3	9	4.8	78	172	–
Stdev	(l^{-1})			3763	299	10.6	2.7	2	21	4	–
Max	(l^{-1})			32683	1966	103.2	16.6	11	99	170	–
Min	(l^{-1})			18180	654	54.4	1.8	0.7	78	120	–
No. of Observations				238	238	238	238	238	3	3	–

[1] Sampling time from 8:30 to 15:30
[2] 5 min samples
[3] Statistics calculated for the sampling period (10:00–12:00 and 12:40–14:40)

Table 2 Daily means of outdoor and indoor mass concentrations and occupancies

		Monday	Tuesday	Wednesday	Thursday	Friday
Conc. outdoors	(μg m^{-3})	17.9	15.1	18.3	39.5	10.9
Con. indoors	(μg m^{-3}	15.7	13.7	11.6	14.2	8.9
Occupancy		6.5	7.6	6.9	6.4	5.9

15:00). Occupancy reached 11 during the afternoon coffee (14:05).

Figure 2 plots number concentrations on Friday. Trends of small particles (<1 μm diameter) were similar each day. Concentrations increased indoors around coffee and lunch times (10:30, 11:30–12:00 and 14:00), possibly due to smoke escaping from the smoking room (location indicated in Figure 1). Concentrations of these small particles decreased significantly in the afternoon (one factor ANOVA, $P<0.01$, $n=360$). There were no significant differences in <1 μm particulate concentrations by height (one factor ANOVA, $P>0.09$, $n=119$). In contrast, outdoor trends differed from day to day. Monday had four periods of high (11:00, 13:00, 14:00, and 15:30) then low concentrations, probably due to particle scavenging by intermittent rainfall. On Tuesday and Wednesday, concentrations were higher in the morning and slowly decreased over the afternoon. On Thursday, three peaks occurred (10:30, 11:30, and 13:30) and concentrations decreased sharply after 13:30, probably due to wind direction shifts.

Trends of large (5–25 μm diameter) particulate concentrations appeared largely random and uncorrelated with known indoor or outdoor sources. Morning and afternoon concentrations did not vary by time of day ($p=0.46$, $n=360$, for 5–10 μm particles; $p=0.23$, $n=360$, for 10–25 μm particles). However, concentrations of coarse particles varied by height ($P<0.01$, $n=238$ for 5–25 μm particles), a possible result of differences in instrument responses (see Appendix 1). Frequent "spikes" of 5–25 μm particles at the lowest (0.4 m) sampling height exceeded levels observed at 1.1 and 1.8 m heights (Figure 2). Number concentrations of 10–25 μm particles often were very low, and 35% were below 3 l^{-1}. Because low counts are associated with high variability, hypothesis testing may not be very meaningful for >10 μm particles.

The intermediate size range (1–5 μm) showed characteristics of both fine and coarse particles. Concentrations differed by height ($P<0.01$, $n=360$) but not by time of day ($P=0.57$, $n=360$). Differences between heights for this size range, as for the larger particles, may result from instrument differences (Appendix 1).

CO_2 levels varied little between 9:00 and 15:00 other

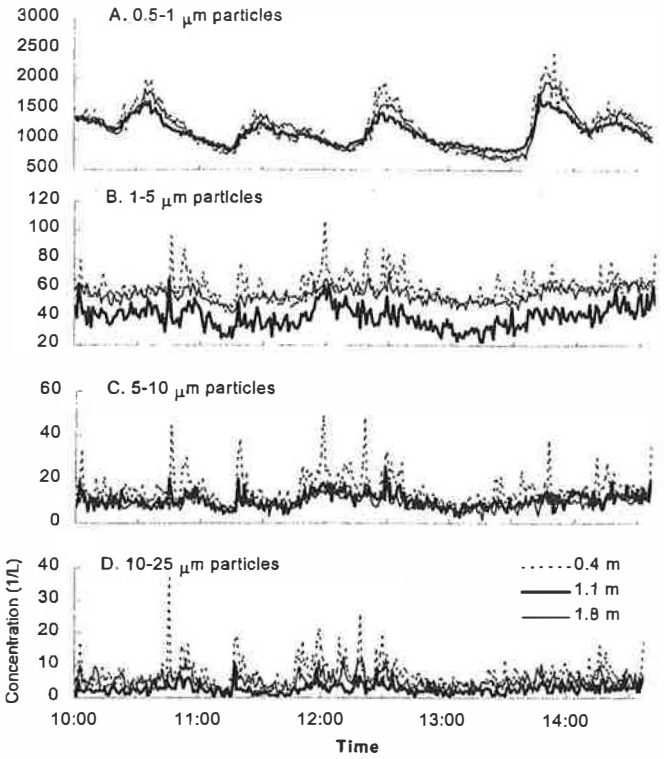

Fig. 2 Indoor air particle number concentrations measured on Friday. 1-min averages are plotted. Study periods are 10:00–12:00 and 12:40–14:40

than a ~60 ppm decrease at 11:30 when some occupants left for lunch. Concentrations of fungi and bacteria did not differ by sampling heights (one-way ANOVAs, P=0.60 and P=0.89, respectively, n=9), or by sampling times (one-way ANOVAs, P=0.12 and P=0.34, respectively, n=9).

Differences in mean concentrations between the central sampling location and 13 other locations around the room simultaneously measured Monday through Thursday were small for airborne fungi (mean relative difference=24%), bacteria (19%), and <1 μm particle numbers (22%).

Correlations between IAQ Parameters

Concentrations of several IAQ parameters were highly correlated (Table 3). Indoors, 0.3- to 0.5- and 0.5- to 1-μm particles had strong correlation (r=0.88); 1- to 5-μm particles had moderate positive correlation with both 0.5–1 μm (r=0.38) and 5- to 10-μm (r=0.84) particles; and 5- to 10- and 10- to 25-μm particles had strong correlation (0.89). Indoor and outdoor concentrations were moderately correlated in the fine fraction (r=0.72 for 0.3- to 0.5-μm particles; r=0.69 for 0.5- to 1-μm particles), not surprising given the low efficiency EU3 filters in this building. Indoor and outdoor concentrations of intermediate and coarse particles (1–25 μm) had near zero correlation, and concentrations of >5 μm particles were not associated with fine (<1 μm) particles. Indoor CO_2 concentrations were positively and significantly (r=0.57) correlated with >1 μm particulate concentrations indoors, but not with bacteria or fungi concentrations. For fungi, the only correlation that differed statistically from zero was with indoor 1–5 μm number concentrations (r=0.28). Bacteria concentrations had positive correlation with number concentrations in all particle size ranges. Air velocity was not significantly correlated to any parameter.

Observational Method

Particle number trends from Tuesday through Friday were examined to identify high concentration periods. A number of periods of 2- to 20-min duration were identified during which indoor levels were elevated, but outdoor levels were typical and unchanging. The same periods were identified when first-order differences were examined which account for trends in outdoor levels.

As indicated by the correlations, 0.3–0.5 and 0.5–1 μm number concentrations changed together. Using the video record, several activities were identified with high concentration periods of these particles: 1) bioaerosol sampling, which took place every 30 min and involved installing and removing agar plates from the impactor; 2) somebody handling papers by the monitoring site; 3) one or several persons leaving the room to smoke and coming back after ~5 min; and 4) a person wearing a coat and standing near the monitoring site. These activities were not consistently associated with increased concentrations. People walking on the left side of the room, possibly coming from the smoking room, also appeared to increase fine particle numbers.

Levels of the larger (1–25 μm) particles generally increased together, as seen by simultaneous "spikes" in Figure 2. Using the video record, several activities were identified with these higher concentration periods: 1) bioaerosol sampling; 2) frequent walks past and between the center tables; 3) opening large boxes (containing office supplies) at the center table; 4) several people working at the center table; and 5) an occupant putting on a sweater very near to the OPCs. It is instructive to examine such events in detail. As an example, Figure 3 shows particle number trends at three heights on Friday morning during the "sweater event". Concentrations remained about average as five occupants walked past the monitoring site (one each at 11:17, 11:18, and three at 11:20). At 11:21, a person within 1.5 m of the OPCs put on his sweater. Subsequently, 1–5 and 5–10 μm particle levels increased for 1 min by a factor of 1.5 and 3, respectively. Increases

Table 3 Correlation coefficients of IAQ parameters using 15-min averages for particle counts, CO_2 and velocity, and 5 min for fungi and bacteria. r=correlation coefficient. n=number of observations

			Particle size					Fungi (cfu/m³)	Bacteria (cfu/m³)	CO_2 (ppm)	Velocity (m/s)
			0.3–0.5 (μm)	0.5–1.0 (μm)	1–5 (μm)	5–10 (μm)	10–25 (μm)				
0.3–0.5	(μm)	r	1.000*	0.884*	0.400*	0.304*	0.259	−0.051	0.345*	0.228	0.146
		n	52	52	52	52	52	50	50	49	49
0.5–1.0	(μm)	r	0.884*	1.000*	0.384*	0.305*	0.255	−0.069	0.304*	0.277	0.099
		n	52	52	52	52	52	50	50	49	49
1–5	(μm)	r	0.400*	0.384*	1.000*	0.842*	0.778*	0.281*	0.292*	0.699*	−0.005
		n	52	52	52	52	52	50	50	49	49
5–10	(μm)	r	0.304*	0.305*	0.842*	1.000*	0.894*	0.078	0.335*	0.515*	−0.061
		n	52	52	52	52	52	50	50	49	49
10–25	(μm)	r	0.259	0.255	0.778*	0.894*	1.000*	0.233	0.336*	0.489*	−0.044
		n	52	52	52	52	52	50	50	49	49
Fungi	(cfu/m³)	r	−0.051	−0.069	0.281*	0.078	0.233	1.000*	−0.103	−0.011	−0.035
		n	50	50	50	50	50	50	49	47	47
Bacteria	(cfu/m³)	r	0.345*	0.304*	0.292*	0.335*	0.336*	−0.103	1.000*	0.246	0.117
		n	50	50	50	50	50	49	50	47	47
CO_2	(ppm)	r	0.228	0.277	0.699*	0.515*	0.489*	−0.011	0.246	1.000*	0.145
		n	49	49	49	49	49	47	47	49	49
Velocity	(m/s)	r	0.146	0.099	−0.005	−0.061	−0.044	−0.035	0.117	0.145	1.000*
		n	49	49	49	49	49	47	47	49	49

* P-value is <0.05

were substantially greater and lasted longer at the 0.4 m height. Concentrations of <1 μm particles showed a slowly increasing trend from 11:18–11:29 but no rapid changes were associated with this event. Additional walks past the monitoring site occurred at 11:22, 11:23, and 11:24. During the last walk the researcher visited the sampling site. A slight increase of >1 μm particles at the 0.4 m height occurred at 11:25. Such situations may lead to short term increases in concentrations of the larger particles. Impacts of individual activities, e.g., walks and visits were not always clear, but the stronger sources could be discerned. Concentration increases were delayed and lasted only a few minutes. In other cases, however, no specific activities could be associated with a high concentration period.

Statistical Analysis

Table 4 lists regression models resulting from the stepwise variable selection procedure for <1 μm particles. These models use number concentrations and differenced number concentrations as dependent variables, activity factors and CO_2 as independent variables, and the 1-min lagged concentration as an autoregressive variable. Four types of models are presented for particle number concentrations in two size ranges measured at three heights. (24 separate models are shown.) The coefficients in the table indicate the change in 1 min concentrations associated with the activity, e.g., a person walking on the left (WALE) increases concentrations of 0.5- to 1-μm particles at the 0.4 m sampling height particles by 85 l^{-1}.

Using only activity factors and CO_2 as independent variables, the regressions explained little of the variance in <1 μm particulate concentrations (R^2 from 0.13 to 0.26). The activity WALE (walks on left side) was selected in all equations, in accordance with observations that fine particles escaped from the smoking room and increased concentrations. Much higher R^2 values (0.83–0.98) were obtained when the autoregressive variable (LAGCONC) was included. These models account for the autocorrelation of indoor concentrations, but not for changes in outdoor air concentrations. The autoregressive models using differenced concentrations (the two right-hand columns of Table 4) may be the most meaningful since they account for outdoor sources (which do not have activity factors) and autocorrelation. These models had a small number of independent variables, and the WALE variable was eliminated. The R^2 values were small (0.08 to 0.25). The CO_2 concentration (related to occupancy) appears only in two equations and is small or negative. Overall, the low R^2 values and the lack of consistent relationships with activity factors indicate that observed indoor activities had little association with fine fraction particulate concentrations. Although the observational analysis discussed previously suggested that some occupant activities occurred during high concentrations of <1 μm particles, the statistical models suggest that these were chance events.

Since indoor and outdoor concentrations of >1 μm particles were largely independent (e.g., near-zero correlations in Table 3), models for the larger particles did not use differenced concentrations as dependent vari-

Table 4 Regression coefficients for the 0.3- to 1-μm particles in the multiple regression equations for the 0.4 m, 1.1 m and 1.8 m height. All variables listed are statistically significant ($P<0.05$). All independent variables are included. n=240

Sampling Height (m)	Independent Variable	Activity Factors Only Dependent Variable Number Conc.		Activity Factors and Autoregression Dependent Variable Number Conc.		Activity Factors Only Dependent Variable Differnce in Conc.		Activity Factors and Autoregression Dependent Variable Difference in Conc.	
		0.3–0.5 μm	0.5–1 μm	0.3–0.5 μm	0.5–1 μm	0.3–0.5 Lm	0.5–1 μm	0.3–0.5 μm	0.5–1 μm
0.4	WALE		84.8	405.4					
	WALELAG1	810.3	67.1						
	WALELAG2	1095.7	104.7						
	WALELAG3	1150.6	75.5						
	VIBELAG1		−150.6						
	VIBELAG2	−2328.7							
	VICO		−54.4						
	VICOLAG3		81.8						
	CO_2LAG1		2.1						
	LAGCONC			0.90	0.91			−0.22	−0.30
	Constant	23433.7	184.6	2167.2	103.8			4.2	−1.2
	R^2	0.134	0.260	0.838	0.831	0.000	0.000	0.047	0.089
1.1	WALE		56.3	−155.7		−168.7		−168.7	
	WALELAG1	822.9	47.6						
	WALELAG2	851.4	53.6						
	WALELAG3	724.4	47.7						
	VIBELAG1				21.3				23.1
	VIBELAG3	−1600.0							
	VICLAG1			−71.7		−75.4		−75.4	
	VICOLAG3	299.3	31.7						
	VIRE			−398.4		−401.8		−401.8	
	VIBELAG1						23.1		
	LAGCONC			0.99	0.98				
	Constant	23199.9	1031.1	479.5	24.8	192.8	−3.8	192.8	−3.8
	R^2	0.143	0.200	0.961	0.946	0.072	0.030	0.072	0.030
1.8	WALE	1045.9	81.3						
	WALELAG1	956.1	72.6						
	WALELAG2	1110.9	84.2						
	WALELAG3	953.9	74.7						
	VIBE			401.4	28.5	405.3	28.8	406.3	28.8
	VIBELAG1	−1911.5	−133.8	−305.1		−302.0		−503.7	
	VIBELAG2							267.7	
	VICOLAG2			−77.9	−4.9	−78.9	−5.0	−52.0	−5.0
	VICOLAG3	611.3	52.3						
	VIRE			−398.8		−400.1		−283.4	
	CO_2	−39.2							
	LAGCONC			1.00	1.00			0.321	
	Constant	40837.0	1026.1	193.3	4.4	124.4	1.7	68.9	1.6
	R^2	0.223	0.261	0.979	0.969	0.143	0.075	0.253	0.075

ables. Also, visits to the drafting table (VIBE) were occasionally found with negative coefficients as were several variables that were lagged 2 or 3 min. Because such results are physically implausible, these variables were eliminated and models were based on stepwise selection from the 11 remaining independent variables. Table 5 summarizes the 18 regression models (2 types, 3 heights, 3 size fractions) for the >1 μm particles.

At the 0.4 m height, selected variables included visits to the monitoring location (VIRE) and walks on the right (WARI), both lagged by 1 min. These walks were in the immediate vicinity of the OPC. Adding the autocorrelative variable slightly decreased the coefficients of these variables. CO_2 was included except for the 5–10 μm size range using the autocorrelative variable. The autocorrelative variable was not statistically significant for 10- to 25-μm particles. The R^2 values for autocorrelation models ranged from 0.24 (10- to 25-μm particles) to 0.43 (1- to 5-μm particles).

At the 1.1 m height, the equations contained five activity factors and the variable VIRE was included in all size ranges. In the autoregressive models, the coefficients decreased slightly (as seen at the 0.4 m height), and the VICO variable disappeared. Occupant activities on either side of the table containing the monitoring equipment apparently affected concentrations

Table 5 Regression coefficients for the 1- to 25-μm particles in the multiple regression equations for the 0.4, 1.1, and 1.8 m heights. All variables are statistically significant ($P<0.05$). 11 independent variables included. n=240

Sampling Height (m)	Independent Vairable	Activity Factors Only			Activity Factors and Autoregression		
		1–5 μm	5–10 μm	10–25 μm	1–5 μm	5–10 μm	10–25 μm
0.4	WARILAG1	6.02	1.49	0.72	5.79	1.56	0.72
	VIRELAG1	29.28	6.06	5.44	22.60	4.55	5.43
	CO_2	0.41	0.05	0.02	0.26		0.02
	LAGCONC				0.37	0.29	
	Constant	−89.09	−9.73	−5.67	−56.02	8.33	−5.67
	R_2	0.320	0.194	0.237	0.432	0.249	0.237
1.1	WABE		1.36	0.73		1.19	0.70
	WALE	2.12	0.59		1.76	0.57	
	WARI	1.30			1.02		
	WARILAG1		0.59	0.39		0.57	0.34
	VICO		0.22				
	VIRE	4.96	2.95	1.77	4.06	2.37	1.65
	CO_2			0.02			0.02
	CO_2LAG1	0.12	0.04		0.06	0.04	
	LAGCONC				0.49	0.27	0.21
	Constant	−17.03	−11.74	−7.63	−8.10	−10.63	−6.32
	R	0.230	0.285	0.309	0.442	0.326	0.349
1.8	WALELAG1	2.30					
	WARILAG1				1.27		
	VICO	0.91					
	VIRELAG1	5.27	2.26	2.42		1.78	1.81
	CO_2	0.24	0.04	0.03	0.10	0.03	
	CO_2LAG1						0.02
	LAGCONC				0.05	0.29	0.35
	Constant	−31.49	−11.51	−8.74	11.73	−8.37	−6.22
	R_2	0.322	0.157	0.185	0.545	0.231	0.288

since variables for walks on right and left sides (WALE and WARI) were included. CO_2 was included in all equations. The highest R^2 (0.44) was obtained for 1- to 5-μm particles. Coefficients of most variables were smaller than seen at the 0.4 m height, possibly a calibration issue (see Appendix 1), although R^2 values were higher, indicating that more variance in particle concentrations was explained by occupant activities.

At the 1.8 m height, explanatory variables for 1- to 25-μm particles reduced mainly to VIRE and CO_2. The 1–5 μm model also included WARI lagged 1 min and, as before, obtained the highest R^2 (0.55).

In summary, concentrations of <1 μm particles could not be consistently associated with the occupant activities monitored. Levels of larger particles were statistically associated with occupant activities (walks and visits) and a general occupancy variable (CO_2). Model results, including the variables selected, depended on both monitoring height and size fraction. These models explained between 24 and 55% of the variance in particulate concentrations.

Particle Density and Concentration Impacts from Occupant Activities

The particle density that best matched observations (using Equations 3–5), 1.45 g cm^{-3}, gave good agreement between calculated and observed mass concentrations (r=0.96, average absolute bias=1.8 μg m^{-3}, n=18). Particle densities are a function of particle size and composition, e.g., 1.1–1.4 g/cm^3 for plant material and pollen, 1.77 for ammonium sulfate, 2.0 for coal fly ash, 2.17 for sodium chloride, and 2.7 for aluminum (Willeke and Baron, 1994). The estimated value is reasonable given this range of densities, thus particle numbers are converted to mass using ρ=1.45 g cm^{-3}.

The particle size distribution, by particle number and estimated mass, for the Friday study period is shown in Table 6. Extrapolated number concentrations for 25- to 35-μm particles on Friday averaged 0.2–0.4 l^{-1}, depending on height, giving mass concentrations of 4–8 μg m^{-3}. Although the number concentrations are extremely low, the large particles add significant mass. However, this extrapolation is not felt to be reliable for several reasons. First, measured number concentrations of 10- to 25-μm particles, on which the extrapolations were based, were extremely low and not felt to be reliable. Second, no upper size can be assigned to particles measured in this channel, so the midpoint diameter cannot be determined. Finally, extrapolations are highly dependent on the distributional assumptions and thus highly uncertain. For these reasons, the following omits the coarse mode extrapolation.

Table 6 Measured number concentrations and estimated mass concentrations for Friday. Increase in particulate concentration caused by one person visiting or walking by the monitoring site. See Table 5 for regression coefficients

Height	Size Range (μm)	Median Size (μm)	Daily Mean		Visit		Walk by	
			Counts (l^{-1})	Mass (μg m^{-3})	Counts (l^{-1})	Mass (μg m^{-3})	Counts (l^{-1})	Mass (μg m^{-3})
0.4	0.04–0.08[2]	0.05	2228	0.00				
	0.08–0.15[2]	0.11	12145	0.01				
	0.15–0.3[2]	0.21	29442	0.21				
	0.3–0.5	0.39	24264	1.07				
	0.5–1	0.71	1192	0.32				
	1–5	3.5	58.60	1.90	22.60	0.74	5.79	0.19
	5–10	7.1	13.90	3.72	4.55	1.22	1.56	0.42
	10–25	12.5	6.20	9.18	5.43	8.05	0.72	1.07
	25–35[2,3]	29.6	0.43	8.44				
	Sum			16.41		10.01		1.67
1.1	0.04–0.08[2]	0.05	2218	0.00				
	0.08–0.15[2]	0.11	12089	0.01				
	0.15–0.3[2]	0.21	29306	0.21				
	0.3–0.5	0.39	24152	1.07				
	0.5–1	0.71	1139	0.31				
	1–5	3.5	39.10	1.27	4.06	0.13	1.02	0.03
	5–10	7.1	9.90	2.66	2.37	0.64	0.57	0.15
	10–25	12.5	2.60	3.86	1.65	2.45	0.34	0.50
	25–35[2,3]	29.6	0.18	3.54				
	Sum			9.38		3.22		0.69
1.8	0.04–0.08[2]	0.05	2292	0.00				
	0.08–0.15[2]	0.11	12493	0.01				
	0.15–0.3[2]	0.21	30288	0.22				
	0.3–0.5	0.39	24961	1.10				
	0.5–1	0.71	1181	0.32				
	1–5	3.5	54.80	1.78			1.27	0.04
	5–10	7.1	9.00	2.42	1.78	0.48		
	10–25	12.5	4.80	7.12	1.81	2.68		
	25–35[2,3]	29.6	0.33	6.54				
	Sum			12.97		3.16		0.04

[1] 1 min average concentration
[2] Extrapolated concentrations for the size range
[3] Omitted from the total sum

The Friday study period was somewhat atypical. On this day, <1 μm particles contributed 1.6 μg m^{-3} and >5 μm particles 6.5 μg m^{-3}, equal to 17 and 70%, respectively, of the total mass (9.4 μg m^{-3}). On Monday-Thursday, <1 μm particles contributed 2.9 μg m^{-3} and >5 μm particles 9.0 μg m^{-3}, or 21 and 65% of the total (13.8 μg m^{-3}). Thus, while indoor levels were low on Friday, the size distribution remained similar and bimodal. The fine fraction mass was small, despite the much larger particle number concentrations.

The impact of occupant activities on particulate mass concentrations can be estimated by combining models across size fractions, ignoring lags, and converting number concentrations to mass. A person putting on a sweater (depicted in Figure 3) increased the (1 min) airborne mass concentration at the 1.1 m height by 16 μg m^{-3} (from 6 to 22 μg m^{-3}). Concentrations near the floor (0.4 m height) were elevated by 10 μg m^{-3} and 1.7 μg m^{-3} by a visit and a walk past, respectively. Increases were smaller in the breathing zone, i.e., 3.2 and 0.7 μg m^{-3} for a visit and a walk, respectively (Table 6). A walk past the right side increased concentrations by 1.7 and 0.7 μg m^{-3} at 0.4 and 1.1 m heights, respectively. It should be noted that the models are linear, i.e., two visits or walks per min would double the impact. Also, the calculations include only 1- to 25-μm particles.

Discussion

This study associated occupant activities, recorded on video, with changes in indoor particle concentrations, monitored by optical particle counters. Consistent and statistically robust estimates of impacts for >1 μm particles were derived for several occupant activities, such as visits and walks past the monitoring site and room occupancy (based on CO_2 concentrations). For example, the model C=22.6 VIRELAG1 + 5.8 WARILAG1 + 0.26 CO_2 + 0.37 LAGCONC – 56 explained 43% of the variance of 1–5 μm particle

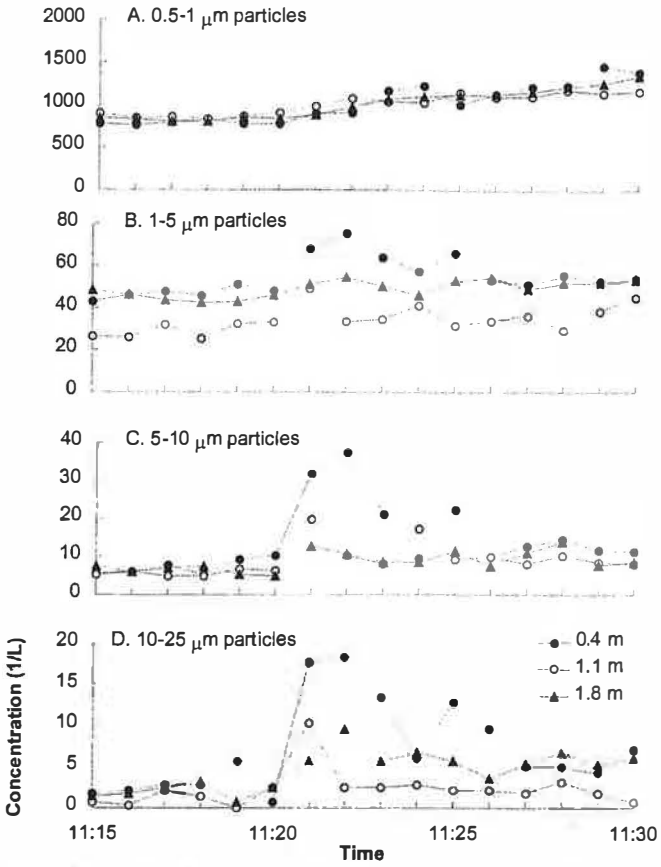

Fig. 3 The effect of an occupant activity on indoor particle number concentrations at three heights. At 11:21 an occupant puts on his sweater

number concentrations at the 0.4 m height. In this model, a visit increases the number concentration by 22.6 l^{-1}, much more than the 5.8 l^{-1} from a person walking past, probably since a visit lasted longer. Based on the estimated particle density, a visit by one person increases concentrations by 3–10 μg m^{-3} and a single walk by 1–2 μg m^{-3}, depending on location. These figures are case study specific, but they demonstrate that occupant-related emissions can be quantified and that particulate levels are elevated in a person's microenvironment.

The initial associations between high levels of <1 μm particles and occupant activities such as persons leaving the smoking room were not confirmed in the statistical analysis. However, the periodicity and timing of concentration peaks suggest entry of cigarette smoke into the office due to some mechanism, e.g., incomplete capture of particles in the smoking room, reingestion of smoke in the building air intake, etc. Mainstream cigarette smoke has a bimodal size distribution with modes at ~0.25 and ~5 μm (Chang et al., 1985); sidestream smoke has a median diameter of ~0.22 μm (Leaderer et al., 1984). No periodicity was observed in the larger size range. The <1 μm diameter particle mass inferred from optical measurements was only 2–3 μg m^{-3} (~20% of airborne total), of which smoking contributed about one-third. This suggests that the smoking room minimized, but did not eliminate, passive smoke exposure.

The increase in particulate concentrations from occupant activities such as visits and walks is at least partly due to particle resuspension from the surfaces. The mass of dust on floors which can be resuspended is quite large and even a small portion resuspended can make a large impact on airborne concentrations (Thatcher and Layton, 1995). In this study, resuspension from the floor is indicated by the higher impacts found at low (0.4 m) heights for the larger (5–25 μm) particles, which are most readily resuspended (Thatcher and Layton, 1995). Impacts might be considerably larger in rooms with carpets, dirty floors, etc. Additional particle sources associated with occupants besides resuspension include particle shedding from people, e.g., dispersal of skin cells, fibers, and other particles. The effect of putting on a sweater near a monitoring site was quite dramatic.

Few studies have examined impacts of occupant activities other than smoking on particulate levels. In residences, Thatcher and Layton (1995) showed that occupants significantly affected the concentration of airborne particles with diameters >5 μm, e.g., walking in and out of a room nearly doubled coarse fraction particulate concentrations. Chao et al. (1996) found that concentrations in hallways increased as number of people increased. Raunemaa et al. (1989) showed that concentration increased with the duration of an activity, consistent with the present results which show that emissions are proportional to duration of the visit (or the number of walks). The impacts estimated here are somewhat lower than those found in these studies.

Video techniques have been previously used in occupational settings to evaluate relationships between exposures and work routines. The Picture Mix Exposure (PIMEX) system uses real-time measurements of chemical and/or physical agents in the breathing zone and video recording to superimpose concentrations on pictures of the workplace and the worker (Rosen and Andersson, 1989; Rosen, 1993). PIMEX applications include using a light-scattering instrument to monitor dust concentrations during stone crushing operations; the brief concentration peaks during some operations were shown to have a minor effect on the total exposure (Andersson and Rosen, 1995). Unlike the IAQ studies here, statistical analysis may not be necessary to identify (and quantify) exposures in in-

dustrial applications where concentrations are high and clearly related to work routines.

Evaluation of Statistical Methods

Somewhat different techniques must be used to estimate indoor emission sources for different particle sizes. Small particles (<1 μm) largely result from combustion processes (Chow, 1995) including tobacco smoking (Owen et al., 1992) and have not been associated with occupancy or occupant activities such as walking or sitting (Thatcher and Layton, 1995). However, Aso et al. (1993) measured short-term (~90 s) upward movement (~0.3 m) of small particles after a futon was beaten. The low-efficiency HVAC filters in the study building led to high correlation between indoor and outdoor concentrations of the small particles, and indoor levels essentially tracked outdoor levels. For particles below a few μm, it is critical to correct for outdoor levels in order to observe effects of occupant activities. The lower outdoor air concentrations on Friday should have increased the ability to associate occupant activities and indoor pollutant levels. The use of differenced concentrations helps to eliminate the effect of slowly varying trends in outdoor aerosols. Still, estimates of particulate emissions would be improved by better filtration of outdoor air. For particles exceeding a few μm diameter, HVAC system filtration is usually effective and indoor emission sources predominate. Thus, differencing operations are not needed. In the non-smoking office studied, >1 μm particles constitute the bulk (8–13 $\mu g\ m^{-3}$) of the aerosol. In offices where smoking occurs, however, concentrations will be much higher and particulate size distributions will be shifted downward, e.g., volume distribution show 0.2–0.3 μm modes (Owen et al., 1990).

In general, a time series of indoor pollutant concentrations will be autocorrelated (Luoma and Batterman, 1997). If neglected, autocorrelation will tend to inflate the estimated impacts of activities. In this study, the autoregressive model portrayed an exponential decay in concentrations after short (1 min) activities. For example, at 1.1 m height, an increase of 3 $\mu g\ m^{-3}$ associated with a visit drops to 0.8 $\mu g\ m^{-3}$ in the second min. This is in general accordance with others who have found that particle concentration decrease with time after the activity, e.g, Thatcher and Layton (1995).

While the parameters of the statistical models are robust, the models explained only 43–55% of the variation of 1- to 5-μm particles, and less (24–35%) for particles exceeding 5 μm. The unexplained fraction may arise from unaccounted activities, variability in emissions, an insufficient number of observations, measurement errors (in part due to low particle counts), and the relatively long sampling period (1 min is long compared to the duration of many activities). Sampling frequencies must be selected with respect to the duration of the elevated concentrations (which depend on the activity and mixing time), the ability to record activities, and the monitoring instrument's performance. Shorter averaging times may clarify results. In an occupational (non-office) setting, Franke and Wadden (1987) noted that great variability in the occupant activities was not accounted for using 10-min observation intervals. Observed concentrations might be better explained by more detailed coding of occupant activities, e.g., noting outdoor clothes and/or shoes, objects carried, etc.

Estimating Mass and Comparing OPCs

Estimating the mass concentration of a certain size range requires the use of a midpoint diameter to represent the size range in the calculation. A small change in the midpoint diameter can significantly change the mass concentration, i.e., 0.1 μm change alters the mass in the 1–5 μm range by 3%. Consequently, the estimated mass concentration is sensitive to the midpoint diameter of the size range. More precise mass estimates might be obtained using OPCs with more size channels, or using other real-time or near real-time particulate monitors.

The disagreement in the counts measured by the three OPCs restricts comparisons among the three instruments. No consistent way was found to correct counts in the 1–25 μm size ranges. Thus, the vertical gradient of particulate concentrations cannot be determined from measurements using the three OPCs sited at different heights in the office building. The difficulties in OPC calibration may not be seen if only one instrument is used. Others have encountered discrepancies in response, resolution and counting efficiency, e.g., Makynen et al. (1982) and ASTM (1992), although these problems do not seem appreciated by many users.

Conclusion

Statistical models incorporating occupant activity measures derived from video taping accounted for 24–55% of the variability in particulate concentrations in the case study office building. Study results indicate that occupant activities such as walks and visits increased concentrations of coarse (5–25 μm) particles by up to 10 $\mu g\ m^{-3}$ per person in the vicinity of the activity. Model parameters were generally consistent. Observations during peak concentrations of fine particles

(<1 μm) suggest that some occupant activities might also increase in fine particle concentrations, but these were not indicated in the statistical models. It is important to account for autocorrelation in the pollutant time series, a variety of activity types and potential confounders, and the model structure will vary depending on the pollutant. Overall, statistical models provide a practical way to quantify IAQ impacts related to occupant activities with potential applications in residential, commercial, and industrial buildings.

Acknowledgements

The authors gratefully acknowledge the financial support from the VTT Building Technology, the Academy of Finland, and the University of Michigan.

Nomenclature

C = total mass concentration (μg m^{-3})
CC_i = mass concentration for the i_{th} size range (μg m^{-3})
D_l = lower diameter for the size range (μm)
D_{mi} = geometric midpoint for the i_{th} size range (μm)
D_u = upper diameter for the size range (μm)
D_{50} = geometric mean for the lognormal distribution (μm)
σ_g = geometric standard deviation for the lognormal distribution (μm)
F_i = fraction of particles in the i_{th} size range
N_i = number concentration for the i_{th} size range (l^{-1})
n = number of size ranges
ρ = density of the particles in the i_{th} size range (g cm^{-3})

References

ACGIH (1989a) *Air sampling instruments for evaluation of atmospheric contaminants*, Cincinnati, OH, American Conference of Governmental Industrial Hygienists.

ACGIH (1989b) *Guidelines for the assessment of bioaerosols in the indoor environment*, Cincinnati, OH, American Conference of Governmental Industrial Hygienists.

Andersson, I.-M. and Rosen, G. (1995) "Detailed work analysis for control of exposure to airborne contaminants in the workplace", *Applied Occupational and Environmental Hygiene*, **10**, 537–544.

Aso, N., Yoshizawa, S. and Tang, H. (1993) "Behavior of particles generated from floor". In: *Proceedings of Indoor Air '93*, Helsinki, Finland, Vol. 4, pp. 43–48.

ASTM (1992) *Standard practice for secondary calibration of airborne particle counter using comparison procedures*, F 649–80, Philadelphia, PA, The American Society for Testing and Materials.

Batterman, S. (1992) "Optimal estimators for ambient air quality levels", *Atmospheric Environment*, **26A**, 113–123.

Batterman, S. and Peng, C. (1995) "TVOC and CO_2 concentrations as indicators in indoor air quality studies", *American Industrial Hygiene Association Journal*, **56**, 55–65.

Box, G.E.P. and Jenkins, G.M. (1970) *Time series analysis. Forecasting and control*, San Francisco, CA, Holden-Day, Inc.

Bras, R.L. and Rodriquez-Iturbe, I. (1985) *Random functions and hydrology*, Reading, MA, Addison-Wesley Publishing Company.

Chang, P-T., Peters, L.K. and Ueno, Y. (1985) "Particle size distribution of mainstream cigarette smoke undergoing dilution", *Aerosol Science and Technology*, **4**, 191–207.

Chao, C.Y.H., Tung, T.C.W. and Chan, T.W.T. (1996) "Wind effect and human movement on airborne particulate concentration at office entrance areas". In: *Proceedings of Indoor Air '96*, Nagoya, Japan, Vol. 2, 423–428.

Chow, J.C. (1995) "Measurement methods to determine compliance with ambient air quality standards for suspended particles", *Journal of Air & Waste Management Association*, **45**, 320–382.

Colombo, A., De Bortoli, M. and Tichenor, B.A. (1993) "International comparison experiment on the determination of VOCs emitted from indoor materials using small test chambers". In: *Proceedings of Indoor Air '93*, Helsinki, Finland, Vol. 2, pp. 573–578.

ECA (1991) *Guideline for the characterization of volatile organic compounds emitted from indoor materials and products using small test chambers*, Report No. 8, EUR 13593 EN, Luxembourg, Office for Official Publications of the European Community.

ECA (1995) *Determination of VOCs emitted from indoor materials and products*, Report No. 16, EUR 16284 EN, Luxembourg, Office for Official Publications of the European Community.

Franke, J.E. and Wadden, R.A. (1987) "Indoor contaminant emission rates characterized by source activity factors", *Environmental Science and Technology*, **21**, 41–45.

Henry, R.C., Lewis, C.W. and Hopke, P.K. (1984) "Review of receptor model fundamentals", *Atmospheric Environment*, **18**, 1507–1515.

Hodgson, A.T., Daisey, J.M. and Grot, R.A. (1991) "Sources and source strengths of volatile organic compounds in a new office building", *Journal of Air & Waste Management Association*, **41**, 1461–1468.

Jantunen, M., Hanninen, O., Saarela, K., Cavallo, D., Katsouyannin, K., Lebret, E., Kuenzli, N., Sram, R. and Zmirou, D. (1996) "Air pollution exposure distributions of adult urban populations in Europe: Design of the EXPOLIS-study". In: *Proceedings of Indoor Air '96*, Nagoya, Japan, Vol. 1, pp. 1125–1129.

Kamens, R., Lee, C., Wiener, R. and Leith, D. (1988) "A study to characterize indoor particles in three non-smoking homes", *Atmospheric Environment*, **25A**, 939–948.

Kovanen, K. and Heikkinen, J. (1994) *European audit project to optimize indoor air quality and energy consumption in office buildings. National report of Finland*, Espoo, Finland, VTT Building Technology.

Larsen, A., Nielsen, P.A. and Wolkoff, P. (1996) "Labeling of emission from building products. First year status". In: *Proceedings of Indoor Air '96*, Nagoya, Japan, Vol. 1, pp. 353–358.

Leaderer, B.P., Cain, S.W., Isseroff, R. and Berglund, L.G. (1984) "Ventilation requirements in buildings – II. Particulate matter and carbon monoxide from cigarette smoking", *Atmospheric Environment*, **18**, 99–106.

Lehtonen, M., Reponen, T. and Nevalainen. A. (1993) "Everyday activities and variation of fungal spore concentrations in indoor air", *International Biodeterioration and Biodegradation*, **31**, 25–39.

Luoma, M. and Batterman, S. (1997) "Short-term temporal variability of IAQ measurements: Effects of autocorrelation and air exchange rates", Manuscript submitted to *American Industrial Hygiene Association Journal*.

Ministry of the Environment. (1987) *Finnish building code. Part D2 Ventilation and indoor environment*, Helsinki, Finland, Ministry of the Environment.

Makynen, J., Hakulinen, J., Kivisto, T. and Lehtimaki, M. (1982) "Optical particle counters: Response, resolution and counting efficiency", *Journal of Aerosol Science*, **13**, 529–535.

Nordtest. (1989) *Ceiling boards, mineral fibres: Emis ion*, NT Build method 347, Espoo, Finland, Nordtest.

Norusis, M.J. (1993). *SPSS for Windows. Base system users guide*, Release 6., Chicago, SPSS Inc.

Owen, M.K., Ensor, D.S. and Sparks, L.E. (1992) "Airborne particle sizes and sources found in indoor air", *Atmospheric Environment*, **12**, 2149–2162.

Raunemaa, T., Kulmala, M., Saari, H., Olin, M. and Kulmala, M.H. (1989) "Indoor air aerosol model: Transport indoors and deposition of fine and coarse particles", *Aerosol Science and Technology*, **11**, 11–25.

Rosen, G. and Andersson, I.-M. (1989) "Video filming and pollution measurement as a teaching aid in reducing exposure to airborne pollutants", *Annals of Occupational Hygiene*, **1**, 137–144.

Rosen, G. (1993) "PIMEX®. Combined use of air sampling instruments and video filming: Experience and results during six years of use", *Applied Occupational and Environmental Hygiene*, **8**, 344–347.

Spengler, J.D., Treitman, R.D., Tosteson, T.D., Mage, D.T. and Soczek, M.L. (1985) "Personal exposures to respirable particulates and implications for air pollution epidemiology", *Environmental Science and Technology*, **19**, 700–707.

Thatcher, T.L. and Layton, D.W. (1995) "Deposition, resuspension, and penetration of particles within a residence", *Atmospheric Environment*, **29**, 1487–1497.

Willeke, K. and Baron, B.A. (1994) *Aerosol measurement. Principles, techniques, and applications*, New York, Van Nostrand Reinhold.