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Commercial Building Ventilation Rates and Particle Concentrations

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ABSTRACT

Ventilation rates have been measured in 38 commercial buildings representing a variety of use types, sizes, ages, and mechanical system configurations. A single tracer (SF_6) test was conducted once in 36 buildings over a two- to four-hour period based on mechanical system operation for a prior two-week period. Two buildings were tested twice under different environmental conditions. Whole-building ventilation rates ranged from 0.3 air changes per hour (ach) to 4.2 ach for the 40 building measurements, with an average value of 1.5 ach. Minimum ventilation rates were estimated in 13 of the 38 buildings. These values reveal that four of the 13 buildings have minimum ventilation rates that are less than the ASHRAE ventilation standard of 10 L/s · occupant for smoking occupancies. Several pollutants were monitored in the buildings for 10-day periods during working hours. The pollutant group that most frequently approached or exceeded recognized guidelines was respirable suspended particles; the elevated concentrations were usually associated with nearby tobacco smoking.

INTRODUCTION

In the relatively short period of time since the issue of air quality inside non-industrial structures has become a concern, most exposure studies have focused on the indoor residential environment (Hawthorne et al. 1986; Sexton et al. 1986; Spengler et al. 1985; Turk et al. 1988). Yet for employed men and women, 23% to 32% of their time is spent in nonresidential indoor locations (NAS 1981), including places of business, restaurants, and places of employment. The same percentage may also be appropriate for school-age children. Although the atmosphere in the industrial workplace may be monitored and regulated, that of commercial and institutional buildings (offices and educational facilities) generally is not.

In 1981 the Pacific Northwest Power Planning and Conservation Act authorized a public utility to undertake cost-effective conservation programs to help meet electric load obligations. These measures may include recommendations for reductions in infiltration and the mechanical ventilation rates in commercial and institutional buildings. Since little is known about existing ventilation rates and pollutant concentrations in commercial buildings, this study was undertaken to provide information about indoor environmental conditions in commercial and institutional buildings in the Pacific Northwest. Specific study objectives were to characterize a variety of indoor pollutant concentrations and ventilation rates in 38 buildings, which were selected to represent existing stock and not necessarily xhibit symptoms of poor indoor air quality.

STUDY DESIGN

Study Sample

Thirty-eight buildings were selected for participation in this study to represent a typical sample of the ages, uses, sizes, and ventilation characteristics of Pacific Northwest buildings. None were selected because of previous indications of air quality problems or complaints. Two of the buildings were monitored a second time under different seasonal conditions for a total of 40 building measurements.

The sample was divided equally between two distinct climatic zones: the moderate Pacific Northwest coastal region that includes Portland and Salem, OR, and the more extreme climate of the continentally influenced inland region that includes Spokane and Cheney, WA. Winter measurements were made in fourteen Portland-Salem buildings and in seven Spokane-Cheney buildings. Six Portland-Salem buildings and four Spokane buildings were monitored during spring conditions, while the remaining nine buildings were measured during the summer in Spokane.

Buildings ranged in size from 860 to 34,300 m²; their ages from 0.5 to 90 years; occupancy from 34 to 2500 persons; and HVAC systems from 0 (natural ventilation) to 32 air handlers. During the project 1.7 million occupant-hours of monitoring were accrued. Table 1 summarizes the building characteristics.

Pollutants Monitored

Airborne formaldehyde, water vapor, radon, nitrogen dioxide, respirable suspended particles (RSP), polycyclic

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TABLE 1
BUILDING INFORMATION

BLDG #	CITY	OWNERSHIP	DESCRIPTION	AGE YRS	SMOKING POLICY	OCCUPANCY	HEIGHT STORIES	AREA M2	HVAC SYSTEMS	SUBSTRUCTURE
1	PORTLAND	P	SU SCHOOL	21	R	318	1	2127	32	S
2	PORTLAND	P	SU SCHOOL	21	R	421	1	1403	17	S
3	PORTLAND	P	SU OFFICE	30	O	35	UG	1747	1	A
4	PORTLAND	P	SU LIBRARY	0.5	R	35	2	2490	4	FB
5	PORTLAND	P	RU OFFICE	16	R	34	2	864	5	FB
6	PORTLAND	P	U OFFICE	1	O	1250	16	34,281	3	FB-UP
7	PORTLAND	P	U OFFICE	90	O	250	3	7711	NV + 1	FB
8	SALEM	P	U MULTI	20	O	150	2	4877	2	FB
9	SALEM	P	U OFFICE	3	O	669	5	17,094	2	FB-UP
10	SALEM	P	U OFFICE	40	O	1286	5	15,794	2	FB-ST
11	SALEM	P	U OFFICE	9	R	400	4	10,963	4	FB-UP
12	SALEM	P	U LIBRARY	40	O	80	4	7565	2	FB
13	SALEM	P	U OFFICE	30	O	175	2	6689	3	UB
14	SALEM	P	U OFFICE	40	O	136	2.5	3112	2	FB
15	SALEM	P	U OFFICE	22	O	750	4	17,187	2	FB
16	SPOKANE	P	SU SCHOOL	3	R	700	2	4379	4	S
17	SPOKANE	P	SU SCHOOL	25	R	550	1	7085	6	C
18	SPOKANE	P	U OFFICE	34	O	84	3	2101	NV	UB
19	SPOKANE	P	U OFFICE	15	O	65	4	1782	NV	S-UP
20	SPOKANE	P	U SCHOOL	3	R	835	3	9476	4	FB
21	SPOKANE	P	U MULTI	8	O	150	4	4274	2	UP
22	SPOKANE	P	U OFFICE	62	O	450	8	14,028	1	FB
23	SPOKANE	P	SU LIBRARY	8	R	25	1	1139	2	S-BR
24	SPOKANE	P	SU OFFICE	8	O	50	1	1445	1	S
25	SPOKANE	P	SU OFFICE	12	O	80	2	1546	2	FB
26	SPOKANE	P	U OFFICE	18	O	550	12	20,987	7	FB
27	SPOKANE	P	U OFFICE	4	O	110	5	3604	2	FB
28	SPOKANE	P	U MULTI	15	O	92	5	5127	1	FB
29	SPOKANE	P	SU SCHOOL	15	R	678	3	6968	2	FB
30	SECOND TEST OF BUILDING 17					659				
31	SPOKANE	P	SU MULTI	10	R	250	1	3567	10	S
32	CHENEY	P	SU OFFICE	72	R	300	4	7246	2	UB-ST
33	CHENEY	P	SU MULTI	5	O	600	3	4955	4	S
34	SPOKANE	PR	U OFFICE	9	O	1200	15	19,202	1	FB
35	SPOKANE	PR	U OFFICE	75	O	1200	15	16,635	11	FB-UB
36	SECOND TEST OF BUILDING 11									
37	PORTLAND	P	U OFFICE	35	O	930	8	14,746	15	FB-UP
38	PORTLAND	P	U OFFICE	34	O	1100	10	15,355	23	FB
39	PORTLAND	PR	U OFFICE	8	O	1500	5	15,017	11	FB-UP
40	PORTLAND	PR	U OFFICE	8	O	2500	18	18,214	9	FB-UP

LETTER CODES:

A - ALL BELOW GRADE
BR - BERMED
C - CRAWLSPACE
FB - FINISHED BASEMENT
MULTI - MULTI-PURPOSE
NV - NATURALLY VENTILATED
O - OPEN SMOKING
P - PUBLIC
PR - PRIVATE
R - SMOKING RESTRICTED TO CERTAIN AREAS
RU - RURAL
S - SLAB ON GRADE
ST - SERVICE TUNNEL
SU - SUBURBAN
U - URBAN
UB - UNFINISHED BASEMENT
UG - UNDERGROUND
UP - UNDERGROUND PARKING

aromatic hydrocarbons, carbon dioxide, and carbon monoxide were measured in each building when occupied. This discussion is restricted to measurements of RSP. With only a few exceptions, concentrations of the other pollutants were found to be low.

Measurement Protocol

Each building was monitored for approximately 10 working days over a two-week period. The minimum aggregate sampling time of 75 hours during occupied hours was chosen to give adequate detection sensitivity for the formaldehyde passive sampler. At Building 3, which was occupied 24 hours per day, sampling was continuous for approximately eight consecutive days. One to 10 inside sampling locations were chosen (based on the size of the building)—with an average of approximately four sites per building—to include a distribution of various ventilation conditions, floor heights, structural configurations, occupant activities, and proximity to observed pollutant sources. Smoking sites were defined arbitrarily as areas where at least one person smoked tobacco products within a 10-m radius of the sample location. No record was kept of the amount of smoking that occurred at a smoking site. In buildings with a restrictive smoking policy, an RSP sampling system was placed in the major smoking area, usually a cafeteria or designated lounge space. It is important to note that because of limitations on available instrumentation, sample site locations were not randomly selected. Therefore, results presented are not true spatial averages but rather averages of all variously grouped samplers. In the two repeat building tests, the sampling sites were, where possible, exactly the same for both tests. Outdoor air sampling sites typically were located near the outdoor air inlet of the mechanical ventilation systems. For those buildings that were in close proximity to other buildings being monitored at the same time, a single outdoor sample was collected for the group of buildings.

Respirable suspended particles were collected on an in-line, one-micron, 37-mm-diameter polytetrafluoroethylene filter after passing through a 10-mm nylon cyclone with a size-segregating cut point of 3 microns. Sample air through the system was maintained at 28 cm^3/s independent of filter particle loading up to 12,500 Pa pressure drop. Air flow through the filters continued during occupied hours and was stopped when the building was vacated. If more than one filter was exposed at a site, the combined weight of particles on all filters was used to determine the average RSP concentration for that site.

Ventilation measurements were made using a tracer gas decay technique with SF_6 as the tracer gas. The protocol is similar to the procedures described in ASTM E741-83 (ASTM 1983) and used by Persily and Grot (1985) and others for measuring total ventilation rates in buildings. A gas chromatograph (GC) with an electron capture detector (ECD) was placed at a central location in the building. Small-diameter (1.6mm ID) polyethylene tubing was run from three to nine locations that, when practical, coincided with pollutant sampling sites. Building air was then drawn by a pump through the sample tubes to the GC/ECD, where a valve under microprocessor control sequentially selected sample tubes at one-minute intervals. Sample line purge times were 2 minutes or less; cycle times to repeat a measurement from a particular line were 6 minutes. Because the elapsed sampling cycle time restricted the maximum number of sampling locations to nine, it was not possible to monitor all ventilation systems in some buildings. Supply and return air tracer concentrations were sampled in 14 buildings to determine the fraction of outside air supplied by the system.

To seed SF_6 into the building, the outside air dampers were closed while the air-handling system continued to recirculate interior air. A known amount of SF_6 was slowly metered into each of the mixed air chamber(s) and distributed throughout the building by the supply fan to achieve a building target concentration of approximately 1000 ppb. The ventilation systems continued to operate at 100% recirculation for 30 to 90 minutes after tracer injection to mix the tracer throughout the building. In buildings with little or no mechanical ventilation, windows were closed while the pure SF_6 was manually distributed through the interior space using syringes and sample bags.

The initial mixing of the SF_6 was assumed to be adequate (for starting the decay) when concentrations at the sampling sites in the building were within 10% of one another. Unfortunately, in buildings with more than two mechanical ventilation systems, the SF_6 injection system was inadequate to easily achieve and maintain uniform mixing. Even with outside air dampers closed, unequal amounts of outside air enter the building and cause poor initial mixing, making a determination of local ventilation rates impossible. Within the limitations of time and injection difficulties, when the mixing was judged to be adequate or as complete as possible, the outside air dampers were opened to a position that was typical of conditions during the pollutant monitoring period (during the monitoring period technicians had recorded the outside air damper positions twice daily).

As the outside air diluted the SF_6 in the building, the GC/ECD analyzed samples containing constantly declining concentrations and recorded these data on a strip chart. A log-linear, least-squares regression line was computed for the time series data at each location. Assuming the following relationship,

$$I = (I/t) \ln (C_o / C(t)), \qquad (1)$$

where:

I = ventilation air exchange rate (h^{-1}),
t = time (h),
C_o = initial concentration (chromatograph peak height – mm), and
$C(t)$ = concentration at time t (chromatograph peak height – mm),

air exchange rates were determined as the slope of the best fit line. Other researchers, including Grimsrud et al. (1980), Shaw (1984), and Blomqvist and Sandberg (1985), have estimated a ~10% to 20% measurement error for the SF_6 decay (dilution) technique. Sources of error include a lack of thorough mixing within and between zones and instrument imprecision. In this study, the difficulty of achieving good mixing in some buildings and variations in the ventilation rate during the decay test (caused by dampers changing positions in response to various HVAC system sensors) were the main factors contributing to errors in the ventilation rate measurement.

MEASUREMENT RESULTS

Ventilation Rates

Table 2 presents measurement results for all the buildings. The whole-building average ventilation rates (column 7) are usually a simple arithmetic mean of the calculated ventilation decay rates at all monitoring locations. In buildings where the tracer concentration was monitored in the return air plenum, the return air decay rate was averaged with the average for those measurement locations within the zone common to that return air system. This procedure weights the return decay rates more heavily (up to 50% of the total average) than the individual location measurements. The standard error is the standard deviation of the mean of the individual ventilation rates in a building and indicates the differences in those individual rates. Buildings 30 and 36 in the table are the winter remeasurements of Buildings 17 and 11, respectively.

The arithmetic mean for all 40 air exchange measurements is 1.5 ach while the median is 1.3 ach. Building values ranged from 0.3 to 4.1 ach. A comparison of measured whole-building L/s · occupant values with those present in the ASHRAE ventilation standard 62-1981 (ASHRAE 1981) showed that five buildings where smoking is allowed (10, 18, 24, 27, and 33) are at or below the recommendation for ventilation when smoking is present (10 L/s · occupant). On the other hand, most buildings have values that are considerably above the values recommended in Standard 62-1981. Whole-building occupant

TABLE 2
BUILDING VENTILATION RATE COMPARISON

BUILDING NO.	SEAS.[7]	HVAC[9] SYSTEMS	VOLUME[1] (m^3)	OCCUPANCY[2]	VENTILATION DATA L/s/Occ	ACH SF_6[3]	STD. ERROR[8]	# OF LOC.
1	W	32	6500	318	4.5	0.8	0.15	3
2	W	17	4500	421	6.5	2.2	0.69	3
3	W	1	4500	35	45	1.3	0.07	3
4	W	4	5800	35	27	0.6	0.02	5
5	W	5	4100	34	56	1.7	0.17	4
6	W	3	140,000	1250	27	0.8	0.03	6
7	W	NV + 1	25,000	250	25	0.9	0.10	5
8	W	2	16,000	150	32	1.1	0.05	6
9	W	2	73,000	669	23	0.7	0.01	6
10	W	2	48,000	1286	9.1	0.9	0.03	8
11	W	4	41,000	400	42	3.6	0.38	8
12	W	2	20,000	80	19	0.3[6]	0.03	7
13	G	3	17,000	175	40	1.5	0.04	6
14	G	2	10,000	136	84	4.1	0.35	5
15	G	2	55,000	750	35	1.7	0.10	8
16	G	4	12,000	700	9.9	2.0	0.28	6
17	G	6	26,000	550	31	2.2[6]	0.35	6
18	G	NV	3200	84	6.0	0.6	0.04	5
19	G	NV	6100	65	23	0.9	0.06	5
20	S	4	22,000	835	13	1.8	0.18	8
21	S	2	12,000	150	38	1.8[6]	0.09	8
22	S	1	43,000	450	66	2.5[6]	0.12	7
23	S	2	47,000	25	54	1.0[6]	0.02	6
24	S	1	4600	50	9.9	0.4[6]	0.01	6
25	S	2	4100	80	25	1.8[6]	0.13	7
26	S	7	80,000	550	61	1.5[6]	0.15	9
27	S	2	15,000	110	11	0.3[6]	0.02	8
28	S	1	21,000	92	37	0.6[6]	0.002	8
29	W	2	23,000	678	29	3.0[6]	0.14	8
30[4]	W	6	26,000	659	14	1.3[6]	0.09	7
31	W	10	11,000	250	23	1.9	0.24	8
32	W	2	22,000	300	13	0.6[6]	0.05	8
33	W	4	15,000	600	11	1.6[6]	0.15	9
34	W	1	76,000	1200	26	1.5[6]	0.03	9
35	W	11	53,000	1200	17	1.4	0.18	9
36[5]	W	4	41,000	400	12	1.1[6]	0.01	9
37	W	15	52,000	930	36	2.4[6]	0.12	9
38	G	23	60,000	1100	28	1.9	0.22	9
39	G	11	63,000	1500	31	2.7	0.15	8
40	G	9	80,000	2500	21	2.4[6]	0.22	9
				Arithmetic Mean (AM)	28 (18)	1.5 (0.9)		

[1]Volume - all space within building shell
[2]Occupancy - reported number of persons in building during normal occupied hours
[3]ACH(SF_6) - based on single SF_6 tracer decay measurement
[4]Repeat measurement of Building 17
[5]Repeat measurement of Building 11
[6]Building average ventilation rate includes decay rate measured in return air. Does not include that measured in supply air.
[7]Season Code: G = Spring, S = Summer, W = Winter
[8]Standard error of ventilation rates from each location in a building
[9]Number of air handler systems, NV = naturally ventilated

ventilation rates must be used carefully since calculation of the rate includes building volumes not usually having high occupancy such as storage areas, hallways, and mechanical rooms. The occupant ventilation rate may actually be lower in local, more densely occupied areas. For example, the whole-building outside air ventilation rate per occupant in a school, Building 1, was calculated at 4.5 L/s · occupant. However, a *local* ventilation measurement made in a classroom with 31 occupants was 1.6 L/s · occupant, below the recommended level of 2.4 L/s · occupant.

Ventilation rates are classified by building type in Figure 1. Except for naturally ventilated buildings (0.8 ach) and libraries (0.6 ach), the results for each classification are reasonably consistent. The error bars define the range of decay rates observed for each building; building averages are shown as open or closed symbols within the range. The curly brackets give the average of each building type; the standard error or standard deviation of the mean is given by the width of the bracket. The points along the left vertical axis give the average values of the measurements taken in the various seasons of the year. The uniformity of results for the other classifications is surprising, as is the magnitude of the ventilation values displayed. While 75% of our measurements were below 2.0 ach and within the range of the data of other investigators (Persily and Grot 1985),

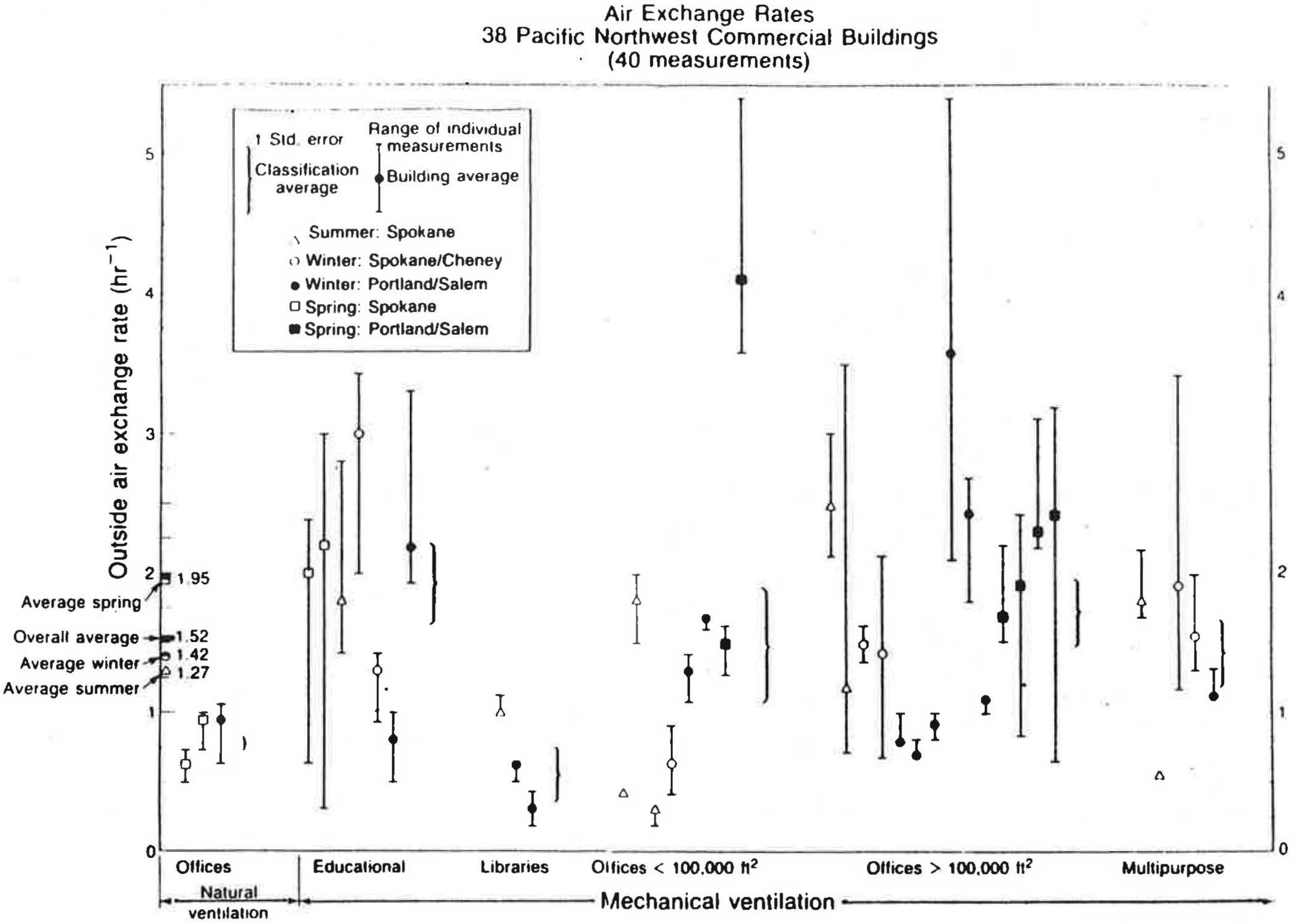

Figure 1 **Ventilation rates classified by building type. Buildings with natural ventilation are grouped at the left portion of the figure. The vertical line for each building defines the range of values observed for particular buildings with the building average shown. The curly brackets give the average of each building type; the standard error or standard deviation of the mena is given by the width of the bracket. The points along the left vertical axis give the average values of the measurements taken in the various seasons of the year.**

relatively high ventilation rates occurred in 10 buildings.

Two of the three naturally ventilated buildings were monitored in the spring when the forces driving infiltration are at a minimum, thereby resulting in a lower ventilation rate influenced by the seasons. All three library buildings were investigated during the summer or winter and can be compared against the mean of 1.5 ach for 15 other mechanically ventilated buildings also monitored during the summer and winter (cf. Table 2).

Average ventilation per occupant for the seven measurements in schools (15.6 L/s · occupant) was lower than in the other buildings (31.6 L/s · occupant), except for the naturally ventilated buildings (17.9 L/s · occupant). This is due to the high occupant density in schools (8.5 m²/occupant) and despite the higher-than-average ventilation rate of 1.9 ach (see Table 3). Only the naturally ventilated buildings had similar occupant ventilation, but it was probably a result of the low ventilation rate for that classification (0.8 ach). Seasonal comparisons in Figure 1 show that there is a suggestive, but weak, statistical difference between spring ventilation rates (2.0 ach) and those of winter (1.4 ach) and summer (1.3 ach). During spring and fall, economizer controls permit greater amounts of outdoor air at temperatures between 13°C and 21°C to enter the building to minimize use of the mechanical air-chilling equipment.

Figure 2 is an example of the tracer decay curves generated for each building. The units on the ordinate, peak height, are maximum heights of the SF_6 chromatographic peaks (mm) and a surrogate for tracer concen-

TABLE 3
Ventilation Rates and Occupant Density for Various Building Classifications

	Number Building Measurements	VENTILATION Mean SF_6 ACH (H^{-1})	Mean L/s · occupant	OCCUPANT DENSITY Mean/S.D.(m²/occ)
Educational	7	1.9	15.6	8.5/3.6
Libraries	3	0.6	33.5	70.4/24.5
Offices <9300m²	8	1.5	35.4	30.2/9.9
Offices >9300m²	14	1.8	30.7	20.2/9.3
Multi-Use	5	1.4	28.3	27.9/18.5
Naturally Ventilated	3	0.8	17.9	27.8/2.9

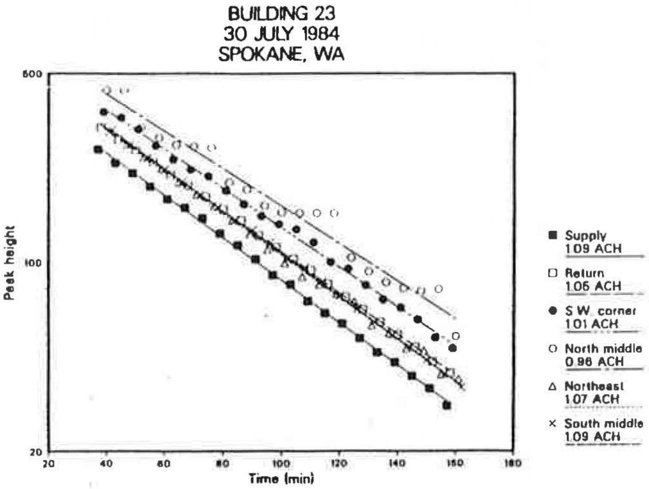

Figure 2 An example of the tracer decay curves generated for determining ventilation reates in the 40 building measurements. The gas shromatographic peak height (mm) is a surrogate for tracer gas concentration. In this building, modulation by a local VAV box causes rapid and dramatic changes in ventilation rates at "north middle."

trations. This figure also shows the effect of modulation in a local variable-air-volume (VAV) box on local ventilation. Sample location "north middle" was a small conference room isolated from any ventilation other than that supplied through the VAV and modulated by a room air temperature controller. The "tread" sections of low ventilation rates are calculated to be less than 0.1 ach, while the "riser" sections of high ventilation rates are approximately 0.7 ach. The periods of low ventilation imply that if they were of long enough duration and a non-occupant-related pollutant source existed, then a potential air quality problem could develop. Fortunately, the duration of the low-ventilation episode is only about 20 minutes and the two-hour average ventilation rate is 1.0 ach, ordinarily considered adequate.

From tracer concentrations measured in a subset of 14 buildings at the main supply and return ducts of the primary air-handling systems estimates could be made of total circulation and recirculation rates. The ratio of outside air to supply air provided by the ventilation system, F, was computed at minimum condition when dampers were closed during mixing and at the operating conditions observed during the decay measurements using Equation 2:

$$F = (C_R - C_s) / C_R \tag{2}$$

where:

C_R = tracer concentration in return duct, and
C_S = tracer concentration in supply duct.

Typically, an average value of F was calculated using three values of C_R and C_S for the minimum fraction and approximately 10 pairs of values for the fraction during operating conditions.

The estimated minimum ventilation rate, I_{min}, is simply the ratio of the minimum outside air fraction to the outside air fraction at operating conditions multiplied by the measured ventilation rate at operating conditions:

$$I_{min} = F_{min} I / F \tag{3}$$

where:

I_{min} = minimum outside air ventilation rate (ach),
F_{min} = minimum fraction of outside air (from Equation 2),
I = outside air ventilation rate (from tracer decays), and
F = fraction of outside air when ventilation rate is I.

Estimated ventilation rates for minimum damper conditions are only approximate since the actual pressure distribution developed by the HVAC system during those conditions may affect the flow of air in the building.

The estimated total circulation, T, was computed from

$$T = I / F \tag{4}$$

and the estimated recirculation, R, from

$$R = T - I. \tag{5}$$

All of these calculated values are summarized in Table 4.

TABLE 4
OTHER VENTILATION PARAMETERS

Building No.	Outside Air: Operating Conditions % Outside Air	ACH	Outside Air: Minimum Conditions % Outside Air	Est. ACH	Est.L/s/Occ	Total Circulation Estimated ACH	Recirculation Estimated ACH
17	45	2.2	6	0.3	4.2	4.9	2.7
20	45	1.8	24	1.0	7.5	4.0	2.2
21	86	1.8	8	0.2	4.2	2.1	0.3
22	41	2.5	4	0.2	5.3	6.1	3.6
23	20	1.0	5	0.3	16	5.2	4.2
24	19	0.4	19	0.4	9.9	2.1	1.7
26	34	1.5	4	0.2	8.1	4.4	2.9
28	13	0.6	13	0.6	37	4.5	3.9
29	61	3.0	13	0.6	5.7	4.9	1.9
30	30	1.3	7	0.3	3.3	4.3	3.0
32	53	0.6	40	0.5	11	1.2	0.6
33	40	1.6	—	—	—	4.0	2.4
34	37	1.5	22	0.9	16	3.9	2.4
38	35	1.9	2	0.1	1.5	5.4	3.5
Arithmetic mean	40	1.6	13	0.4	10	4.1	2.5
ASD	19	0.7	11	0.3	9	1.4	1.2

Ventilation rates in this subgroup of 14 buildings appear to represent the ventilation rates measured in the entire sample of 40 buildings reasonably well. The subsample had a mean ventilation rate of 1.6 ach and an arithmetic standard deviation of 0.74 ach compared with 1.5 ach and 0.87 for the entire sample. One-half of this group of 14 had a minimum outside air percentage of less than 10%, a commonly accepted figure for minimum outside air (Persily and Grot 1985). Four of the buildings—20, 24, 32, and 34—had significant amounts of outside air (19% to 40%) entering the system despite closed dampers. This outside air was entering the system through poorly fitting dampers or, as in the case of Building 20, which had a high-pressure air handler, the negative pressure created upstream of the supply fan caused the outside air dampers to open slightly against the linkages and actuators. Outside air dampers did not seal tightly in Building 24, and Building 34 had a measurable gap of 3 to 6 mm between its damper blades. Although the designated outside air dampers in Building 32 were closed, a large, uncontrolled amount of air was pulled into the basement fan room through a 5 km network of underground service tunnels.

Comparing the estimated minimum whole-building ventilation rate per person from Table 4 with the rates in revised ASHRAE 62, buildings 17, 21, 22, 29, 30, and 38 drop below the recommended 7.0 L/s · occupant minimum ventilation rate for any building when their outside air dampers close. These buildings were not operating at minimum levels during the monitoring period, but were probably ventilated at approximately minimum rates during hot summer days.

Total supply flow rate is an indicator of the amount of air movement within a building and may have an important effect on occupant comfort. The mean estimated total circulation rate for these 14 buildings was 4.1 ach with a relatively small standard deviation of 1.4 ach. Fifty percent of these buildings had total circulation rates between 4.0 and 5.0 ach. This rather tight clustering reflects the common load assumptions used in their designs. The most obvious exception is Building 32, which has a total rate of 1.2 ach. It is the oldest building in this group (72 years) with the original, low-capacity air handler still in operation.

Recirculation rates are important in buildings that have some form of conditioning or cleaning of the air as it passes through the main air handlers. Temperature and humidity control and particle filtration are common examples of air quality management that can occur without the introduction of outside air. Therefore, the more often building air is recirculated through these devices, the better opportunity there is for control of indoor humidity and particle concentrations. However, improper system maintenance and operation can negate the intended benefits.

Two buildings were measured twice and showed ventilation rate variations of 2.2 to 1.3 ach (Buildings 17 and 30) and 3.6 to 1.1 ach (Buildings 11 and 36). In Building 17/30, the initial measurement was made during the spring while the follow-up measurement was made in the winter after building air leakage retrofits were completed. Although the outside air ventilation rate changed in this building, the minimum ventilation determined in the initial and follow-up tests was the same.

Particle Concentrations

Table 5 provides a detailed breakdown of the values of the outdoor, nonsmoking, smoking, and whole-building particle concentration measurements. The ratios of concentrations between the sampling areas are also shown. Figure 3 is a histogram of average building RSP concentrations, while Figure 4 is a histogram of the 178 individual site RSP concentrations. Both distributions are approximately lognormal.

Within the sample of 40 building tests, the range of building mean RSP values ranged from 5μg/m³ (Building 13) to 86 μg/m³ (Building 10), with an arithmetic mean of 30 μg/m³ and a geometric mean of 24 μg/m³. Building averages for smoking areas ranged from below detection (Building 28) to 308 μg/m³ at Building 38. This latter value was based on only one smoking site in that building. For

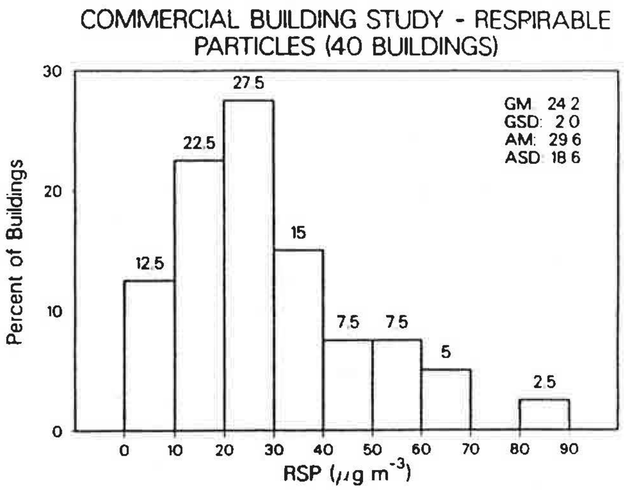

Figure 3 Histogram of building average respirable suspended particle (RSP) concentrations from the 40 building measurement. The geometric mean (GM) is 24.2 g/m3; the geometric standard deviation (GSD) is 2.0; the arithemetic mean (AM) is 29.6 g/m3; and the arithmetic standard deviation (ASD) is 18.6 g/m3.

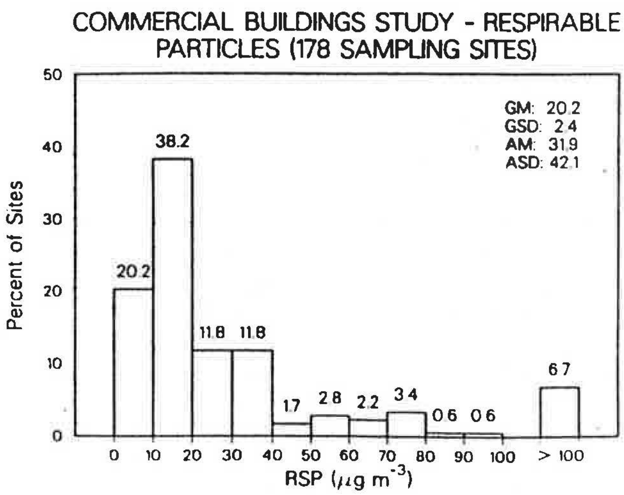

Figure 4 Histogram of respirable suspended particle concentrations from 178 individual sampling sites in the 40 building measurements.

TABLE 5
SMOKING, NON-SMOKING, AND OUTDOOR RSP CONCENTRATIONS AND RATIOS

BUILDING NO.	OUTDOOR (μgm^{-3})	INDOOR (μgm^{-3}) ARITHMETIC MEAN (RANGE) NON-SMOKING	SMOKING③	MEAN④	RATIOS INDOOR NON-SMOKING÷ OUTDOOR	INDOOR SMOKING÷ OUTDOOR	INDOOR MEAN÷ OUTDOOR
1	ND	25(19-36)	ND	25(19-36)	NA	NA	NA
2	ND	19(18-21)	ND	19(18-21)	NA	NA	NA
3	ND	ND	20(16-25)	20(16-25)	NA	NA	NA
4	8	7(6-8)	ND	7(6-8)	0.9	NA	0.9
5	BD	13(13)	14(14)	13(13-14)	NA	NA	NA
6	35	12(11-13)	35(23-59)	28(11-59)	0.3	1.0	0.8
7	35	38(32-44)	39(39)	38(32-44)	1.1	1.1	1.1
8	8	7(7-8)	ND	7(7-8)	0.9	NA	0.9
9	8	11(11)	16(13-20)	15(11-20)	1.3	2.0	1.9
10	9	63(53-74)	95(67-127)	86(53-127)	7.0	11.0	9.6
11	8	23(9-49)	209(209)	63(9-209)	2.9	26.1	7.9
12	ND	10(10)	63(63)	36(10-63)	NA	NA	NA
13	10	5(5-6)	ND	5(5-6)	0.5	NA	0.5
14	6	ND	30(26-34)	30(26-34)	NA	5.0	5.0
15	BD	11(7-14)	12(12)	11(7-14)	NA	NA	NA
16	10	9(8-11)	73(73)	31(8-73)	0.9	7.3	3.1
17	7	11(10-13)	105(105)	40(10-105)	1.6	15.0	6.1
18	7	ND	19(19)	19(19)	NA	2.7	2.7
19	7	ND	20(11-29)	20(11-29)	NA	2.9	2.9
20	18	11(10-11)	ND	11(10-11)	0.6	NA	0.6
21	17	11(9-12)	ND	11(9-12)	0.7	NA	0.7
22	20	18(18)	57(22-165)	50(18-165)	0.9	2.9	2.5
23	11	9(BD-20)	ND	9(BD-20)	0.8	NA	0.8
24	11	44(10-77)	24(24)	37(10-77)	4.0	2.2	3.4
25	68	35(32-38)	109(109)	60(32-109)	0.5	1.6	0.9
26	32	45(20-70)	82(55-123)	67(20-123)	1.4	2.6	2.1
27	52	36(33-38)	61(33-89)	48(33-89)	0.7	1.2	0.9
28	65	36(29-43)	BD	24(BD-43)	0.6	NA	0.4
29	29	10(8-12)	144(144)	32(8-144)	0.3	5.0	1.1
30②	33	24(20-30)	113(113)	37(20-113)	0.7	3.4	1.1
31	13	12(8-18)	268(268)	64(8-268)	0.9	20.6	4.9
32	ND	13(10-17)	36(21-52)	21(10-52)	NA	NA	NA
33	ND	ND	29(12-74)	29(12-74)	NA	NA	NA
34	16	13(10-16)	54(13-117)	28(10-117)	0.8	3.4	1.8
35	18	20(6-35)	50(50)	23(6-50)	1.1	2.8	1.3
36①	20	14(9-18)	72(17-127)	28(9-127)	0.7	3.6	1.4
37	19	21(12-32)	27(11-62)	25(11-62)	1.1	1.4	1.3
38	14	7(BD-9)	308(308)	46(BD-308)	0.5	22.0	3.3
39	11	8(8-9)	13(11-14)	11(8-14)	0.7	1.3	1.0
40	11	10(8-12)	26(11-40)	15(8-40)	0.9	2.4	1.4
AM	19	19	70	30	1.2	6.0	2.3
ASD	16	14	73	19	1.3	7.2	2.2
GM	14	15	44	24	0.9	3.6	1.7
GSD	2.2	1.9	2.7	2.0	2.0	2.6	2.3

①REPEAT TEST OF BUILDING #11
②REPEAT TEST OF BUILDING #17
③SMOKING WITHIN 10 m RADIUS OF SITE
④ARITHMETIC AVERAGE OF ALL SITES IN BUILDING

NA = NOT APPLICABLE
ND = NO DATA COLLECTED
BD = BELOW DETECTION LIMIT

nonsmoking areas, the building averages ranged from 5 $\mu g/m^3$ (Building 13) to 63 $\mu g/m^3$ (Building 10). Individual site measurements in nonsmoking areas ranged from below detection (Buildings 23 and 38) to 77 $\mu g/m^3$ (Building 24); and from below detection (Building 28) to the 308 $\mu g/m^3$ site mentioned above for smoking areas. Figure 5 shows the cumulative frequency of RSP values in the entire sample of 178 indoor sites. The geometric mean of the 178 sites is 20.2 $\mu g/m^3$ with a geometric standard deviation of 2.4. The linearity of the data in this figure demonstrates a close association with the lognormal distribution found to describe many atmospheric pollutant distributions. Using the best fit line applied to the data in Figure 5, it is estimated that in a similar sample approximately 15% of the sites chosen would exceed the 50 $\mu g/m^3$ standard for annual exposure set by the EPA for PM_{10}, i.e., particles less than 10 μm in diameter. If only the smoking sites are considered, the fraction above 50 $\mu g/m^3$ increases to 34%.

Smoking as a Particle Source

Clearly, when tobacco smoking is present, nearby RSP concentrations are elevated significantly. On the other hand, nonsmoking area average concentrations are lower than outdoor levels at 20 of the 29 buildings, even though the outdoor and nonsmoking average RSP concentrations

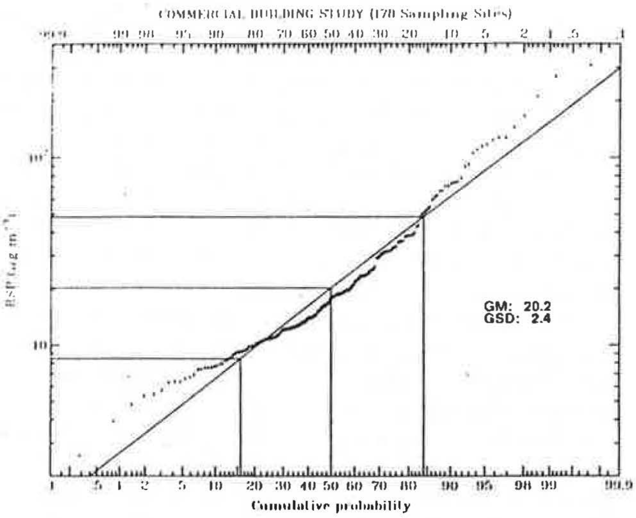

Figure 5 Cumulative probability plot of all 178 indoor sampling locations for RSP. The lognormal distribution of these data suggests that 15% of the sites in a similar sample of buildings would have concentrations greater than the 50 g/m3 concentration limit for PM10.

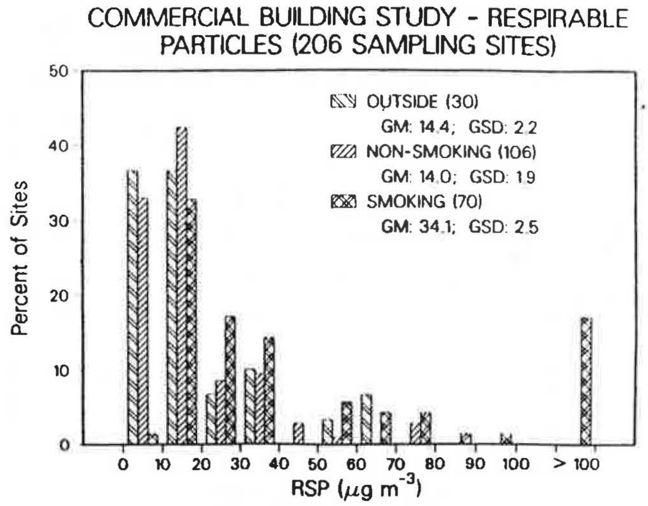

Figure 6 Measurement results at individual sites separated into smoking, non-smoking, and outside locations. Nearby tobacco smoking clearly elevates indoor levels. Although non-smoking and outside mean concentrations are approximately equal, non-smoking levels are lower than outside at 20 of 29 buildings.

for all buildings are similar. Figure 6 shows the comparison of all smoking, nonsmoking, and outdoor sites. For smoking sites the geometric mean was 34.1 $\mu g/m^3$ with a geometric standard deviation of 2.5. This is more than twice the outdoor (14.4 $\mu g/m^3$) and the non-smoking (14.0 $\mu g/m^3$) values.(1)

Not surprisingly, when indoor average nonsmoking RSP concentrations are correlated against outdoor air concentrations, the fit is poor ($R^2 = 0.19$), as seen in Figure 7. The unexplained variation in this comparison is due to recirculation from various indoor sources (predominantly tobacco smoking) and removal and dilution processes.

RSP takes on considerable significance as a health risk through its association with tobacco smoking, where almost all particulate emissions are smaller than 3 μm. Tobacco smoke aerosols released in the sidestream (non-inhaled smoke) and from exhaled puffs (which, taken together, are called environmental tobacco smoke or ETS) contain a wide range of toxic and carcinogenic substances. Smoking as a hazard to the smoker has been clearly documented for years by health authorities, hence the warnings on tobacco products. The increasing voluntary and involuntary regulation of smoking in public places is a result of an awareness of the dangers of ETS to non-smoking persons in the vicinity of smokers. Each cigarette smoked may release 15 mg of respirable particulate matter to the environment (Offerman et al. 1984a). Some of the carcinogenic material in ETS occurs in the form of polycyclic aromatic hydrocarbons (PAH), which was collected on the filters along with RSP and is reported elsewhere (Turk et al. 1987).

Smoking is a cause of nearby elevated RSP concentrations. However, its influence upon the RSP burden of an entire ventilation zone or building is not clearly marked. A building with a very high RSP burden in a smoking area may have a low concentration in the remainder of the building due to a number of removal and dilution processes. The localization of high RSP concentrations to

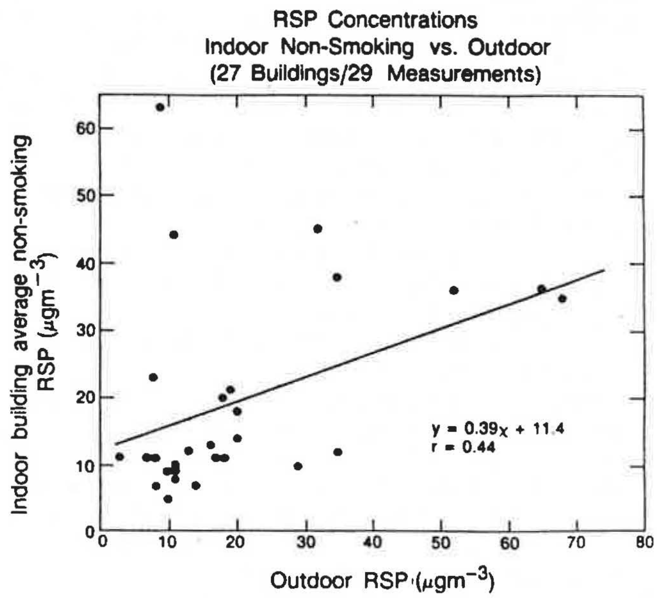

Figure 7 Comparison of indoor non-smoking RSP concentrations to outdoor concentrations. Other factors such as indoor sources (tobacco smoking) and processes of dilution and removal account for the weak dependence of non-smoking area concentrations on outdoor levels.

(1) Note that two sites were not identified as either smoking or nonsmoking and are not included here. Also note that on four occasions, outdoor RSP measurements from a building were also used at a nearby building that had no outdoor measurement (Building 6 at 7, 18 at 19, 23 at 24, and 39 at 40) for computations on Table 5. Thus, the total number of outdoor sites in Figure 6 is reduced to 30. Outdoor RSP values ranged from below detection limits at Buildings 5 and 15 to a maximum of 68 $\mu g/m^3$ at Building 25.

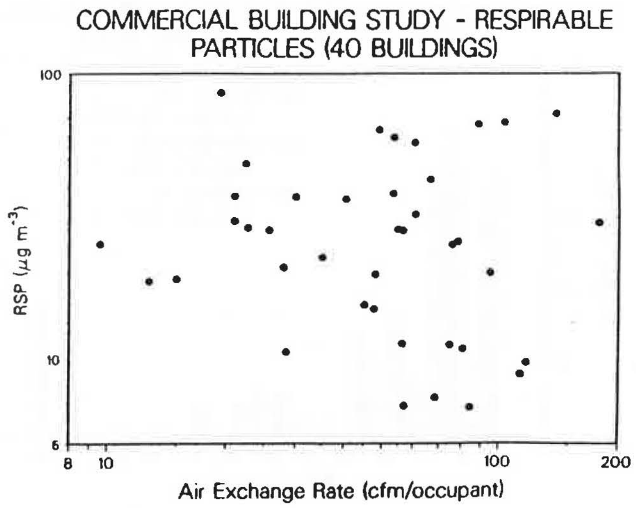

Figure 8 **Plot of building average indoor RSP concentrations vs. while building outdoor air ventilation rates. The lack of correlation indicates that other factors, including RSP source strength, high outdoor concentrations, building volumes, and other removal processes, are important.**

smoking areas in buildings is seen in summary data (Table 5) and in a discussion of a few individual buildings, which follows.

In Building 38, smoking was confined to approximately one-third of the floor space of a cafeteria that is served by three small air-handling units supplying only outside air. This smoking area had a concentration of 308 μg/m^3, while the highest found at any nonsmoking site was 9 μg/m^3. The outside air registered 14 μg/m^3. We suspect that the RSP load of the cafeteria was isolated from the remainder of the building by the separate ventilation systems in the cafeteria itself.

Building 34, with only one large HVAC system (plus the usual bathroom exhausts), had a mean smoking area concentration of 54 μg/m^3 (13 to 117 μg/m^3) compared with a nonsmoking area mean of 13 μg/m^3 (10 to 16 μg/m^3). The outdoor measurement, taken at the air intake for the HVAC system, was 16 μg/m^3. Ventilation rates throughout this large, 15-story building were close to its average of 1.5 ach (1.4 to 1.6 ach) and no special exhaust ventilation was provided in a smoking area with the highest RSP concentration of 117 μg/m^3. Even with the excess RSP due to smoking, the concentrations in nonsmoking areas remained low, possibly due to dilution of particle concentrations by the large building volume (76,000 m^3).

In other buildings (for example, Building 31), designated smoking areas have separate exhaust-only ventilation systems to increase the local ventilation and remove the pollutant before it can enter the remainder of the structure. The one smoking area monitored in Building 31 had an RSP level of 268 μg/m^3, whereas the nonsmoking sites averaged 12 μg/m^3 (8 to 18 μg/m^3), which was approximately equal to the outdoor concentration of 13 μg/m^3. It appears that the exhaust system was partly responsible for the low nonsmoking site levels in this relatively small (11,000 m^3) building.

Sensitivity Studies

Current ventilation standards specify minimum levels of ventilation with outdoor air to maintain good indoor air quality, including the control of indoor particle concentrations. In Figure 8, building average RSP concentrations are plotted against whole-building outdoor air ventilation rates. No correlation of low RSP levels with high ventilation rates (or vice versa) is observed. Explanations for the lack of correlation include higher concentrations outdoors than indoors at some buildings, the variability between buildings in indoor RSP source strength and building volume, and the variability in the efficiency of other removal processes (including filtering).

In most mechanical ventilation systems, the mixture of outside air and return air passes through some type of particle filtering that often includes coarse panel filters occasionally followed by a more efficient bag filter. During our investigations, the condition of the filters varied considerably, from clean to virtually occluded. The condition and efficiency of these filters may be important in controlling the RSP load in buildings where outdoor air is already contaminated and smoking is allowed. Air from smoking areas is not always exhausted directly to the outdoors. It is returned with air from the rest of the building to the main air-handling system, which partially dilutes it with outside air and then distributes it throughout the building, including nonsmoking areas. Some smoke particles are filtered or removed by other mechanisms (e.g., physical deposition, chemical transformation, coagulation), while many of the gas-phase contaminants are unaffected. It is likely that these removal processes, along with dilution by the large building volumes, account for the comparatively low RSP concentrations in nonsmoking areas even when smoking is allowed in certain areas of the building and the outdoor air is contaminated.

In order to examine this process more carefully, we chose to model the RSP concentration using the steady-state mass balance equation for calculating indoor pollutant concentrations:

$$C_\infty = \frac{C_0 IP + S/V}{I + K}. \tag{6}$$

The numerator in Equation 6 represents the pollutant source terms; the denominator, the removal processes. The individual terms are:

K = all removal mechanisms, other than dilution by outside air. Specifically for air handlers with intentional filtration:

$$K = k + \eta R, \text{ where:} \tag{7}$$

η = filter removal efficiency (dimensionless) for particles <3 μm aerodynamic diameter,
R = air recirculation rate (h^{-1}),
k = removal processes including physical deposition and chemical transformation (h^{-1}),
I = outdoor air ventilation rate (h^{-1}),
P = penetration factor for particles entering from outdoors. This is commonly assumed to be unity for infiltrating air in residences. In this analysis, all outside air is assumed to enter through the mechanical system filters. Thus,

$$P = 1 - \eta. \tag{8}$$

S = Total of all indoor particle-generation source strengths.

$$S = s_1 + s_2\text{, where:} \tag{9}$$

s_1 = source strength of tobacco smoke (ηg h^{-1}), and

s_2 = source strength of other particle sources including photocopier and background dust, lint, and microorganisms (ηg h^{-1}).

V = volume of the space (m^3),

C_o = outdoor concentration (ηgm^{-3}), and

C_∞ = steady-state indoor concentration (ηgm^{-3}).

Collecting the terms in expressions 6-9 gives Equation 10, which we examine parametrically.

$$C_\infty = \frac{IC_o(1-\eta) + (s_1 + s_2)/V}{I + k + \eta R} \tag{10}$$

Values for the physical, mechanical, and operational characteristics of one of the buildings studied in this project, Building 34, were chosen to evaluate the sensitivity of the steady-state indoor concentration, C_∞, on filter efficiency and number of smokers. The results are summarized in Figure 9.

The values used in Equation 10 for the sensitivity analysis and their sources are:

C_o = 16 μgm^{-3} (measured in this study)
Occupancy = 1200 (building manager's report)
I = 1.5 h^{-1} (measured in this study by SF_6 tracer decay)
R = 2.4 h^{-1} (calculated from observed return-supply SF_6 concentrations)
V = 76,400 m^3 (building plans)
k = 0.15 h^{-1} (Leader et al. 1984)
η = varied 0.1 to 1.0 (Rivers 1982)
s_1 = (2.0 cigarettes/smoker-h) × (15 × 10^3 μg/cigarette) × (fraction of occupants who smoke) × (occupancy)

[fraction of occupants smoking varied 0.0 to 0.9] (Offerman et al. 1984a)

s_2 = ((1.5 μgm^{-3}h^{-1}) × V) (Offerman et al. 1984a)

A reasonable solution giving the average measured RSP concentration in nonsmoking areas (13 μg/m^3) has a filter efficiency of 86% with 10% of the occupants smoking. A 10% smoking rate in offices has been referred to by other researchers (Leaderer et al. 1984). However, other solutions involving fewer numbers of smokers and a lower (and more realistic) filter efficiency will yield the same concentration. If smoking area concentrations are included in the average, then a smoking rate of 10% and a filter efficiency of 28% will produce the observed arithmetic average concentration of 28 μg/m^3.

Filtering has an important impact on RSP concentrations. Yet its effect is overwhelmed by the increased source strength of additional smokers. For example, approximately doubling the smoking rate from 35% to 75% would require increasing the filtering efficiency by a factor of five, from 20% to 100%, to maintain the same average RSP concentration of 28 μg/m^3. A calculation of the effectiveness of increasing the total recirculation rate by 0.5 ach (21%) is shown by curve f_2(b) of Figure 9. Concentrations should be reduced since the air is now passing through the filters more frequently. This is the case, but reductions are small, ranging from 2% to 11% as the filter efficiency improves. By comparison, a 0.5 ach increase (33%) in the outside air ventilation rate (shown by curve f_2(a)) results in larger reductions, ranging from 11% to 19% as filter efficiency is reduced. It is also important to notice that the outdoor RSP concentrations (16 μg/m^3) are substantially lower than most of the calculated indoor concentrations in this example, whereas outdoor concentrations were actually higher than indoor nonsmoking concentrations at 69% of the buildings in this study. If a higher outdoor concentration is assumed, then indoor concentrations will also be higher, except for instances of filter efficiencies near 100%.

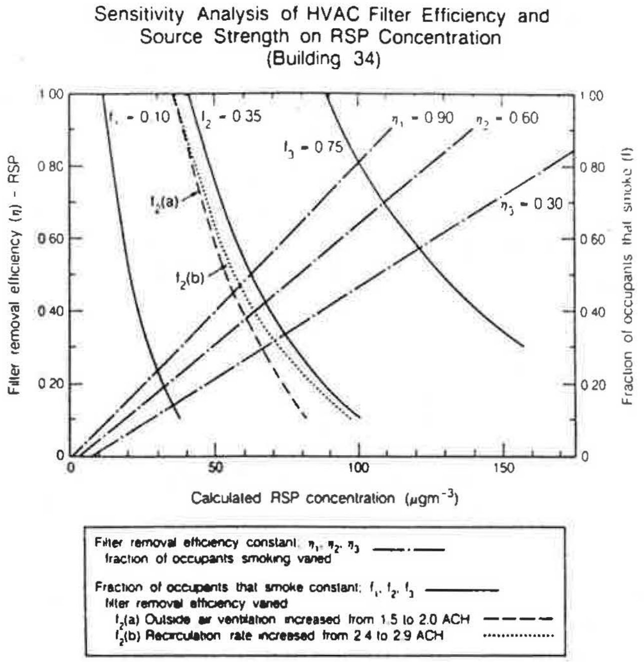

Figure 9 **Sensitivity analysis of HVAC filter efficiency, source strength, and RSP concentration using data from Building #34. The fraction of occupants that smoked (f) has the largest impact on indoor RSP concentrations.**

Additional study is necessary to refine and validate such calculations. In particular, the other natural removal processes in smoking areas may be more important than assumed. Aggregation followed by deposition on surfaces, electrostatic precipitation, filtering by occupant inhalation, and other unidentified effects could be effective mechanisms for removing smoke particles from the air before they circulate into the remainder of the building. These processes could help explain the observation that RSP concentrations remain high only in localized smoking areas.

DISCUSSION AND SUMMARY

Respirable suspended particles (RSP) was the pollutant class monitored in this study that most often exceeded conservatively recognized concentration guidelines. Most of these occurrences were related to nearby tobacco smoking. Building mean RSP ranged up to 86 μg/m^3, with one smoking site reaching 308 μg/m^3. We estimate that 34% of smoking sites in a similar sample would have concentrations exceeding the 50 μg/m^3 annual average concentration for suspended particles whose diameters are smaller than 10 μm (a larger subset of suspended particles than RSP). Local areas of smoking do not always cause a substantial increase of RSP levels in other nonsmoking areas of the ventilation zone or building. The RSP concentrations at these nonsmoking areas were generally lower and not closely correlated to outdoor concentrations. However, a model sensitivity analysis suggests that the amount of tobacco smoking is the single most important variable in determining a building's average RSP concentration, while HVAC filtering efficiency is of secondary importance.

The one-time ventilation measurements from all buildings average 1.5 ach and ranged from a low of 0.3 to 4.1 ach. Buildings with low ventilation rates were not usually associated with elevated concentrations of pollutants measured, although local ventilation may fall below ASHRAE recommendations of 2.5 L/s · occupant in nonsmoking areas and 10 L/s · occupant in smoking areas. The ability to measure local ventilation is essential to providing ventilation that balances energy use and air quality needs.

In 13 of the buildings, minimum ventilation rates were estimated. In 6 of the 13 buildings the minimum ventilation rate was less than 7 L/s · occupant, a value recommended by ASHRAE in its revised ventilation standard as the minimum ventilation rate allowed in any building. In spite of the low estimated minimum rates, the six buildings were operating at an average ventilation rate nine times higher than this during the course of these measurements.

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