Dilution Ventilation To Accommodate Smoking: A Case Study

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"Real world" exposure data are presented for buildings that use dilution ventilation to minimize nonsmoker exposure to environmental tobacco smoke

The principal consensus standard on ventilation to control indoor air quality in the United States is ASHRAE Standard 62-1989, *Ventilation for Acceptable Indoor Air Quality*.[1] Table 2 of this standard prescribes outside air ventilation requirements to maintain acceptable air quality in a variety of commercial and institutional facilities. A footnote to this table states that the ventilation rates were "chosen to control carbon dioxide and other contaminants with an adequate margin of safety and to account for health variations among people, varied activity levels, and a moderate amount of smoking."

The research reported here was designed to assess the effectiveness of the dilution ventilation provisions in ASHRAE Standard 62-1989 in controlling environmental tobacco smoke (ETS) in the office workplace. Data were gathered through three interrelated phases:

- Assessment of HVAC system performance.
- Personal exposure monitoring of ETS-related constituents.
- Fixed location monitoring.

The two buildings studied were adjacent within a large multi-building facility in Richmond, Va. Staff working in these two office buildings performed similar job functions, typical of the North American nonindustrial workplace.

System performance assessment

Total building HVAC assessment. The assessment of the HVAC systems included the collection of descriptive and quantitative information. The design and operational configurations of the HVAC system were determined from review of mechanical engineering plans, inspection of HVAC system components, and air flow measurements taken using a standardized duct traverse method with an electronic micromanometer fitted with a pitot tube attachment.

Fixed monitoring location HVAC assessment. The total volume of air supplied to each of four fixed sites in each building was determined by air flow measurements taken at the ceiling diffusers using an electronic micromanometer. The air flow measurements determined the volume of total air (outside and return) supplied to the fixed monitoring site. The volume of outside

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[1]*Superscript numerals indicate references listed at end of article.*

TABLE 1—Building 1 HVAC performance assessment.

Total building

Total air, cfm	Return air, cfm	Outside air, cfm	Outside air, percent	Estimated maximum occupancy (based on 7 per 1000 sq ft)	Outside air ventilation (based on 60 percent ventilation effectiveness), cfm per occupant
19,834	15,364	4470	29.1	150	17.9

Fixed monitoring locations

Site	Total air, cfm	Outside air, cfm	Outside air, percent	Observed population	Outside air ventilation (based on 60 percent ventilation effectiveness), cfm per occupant
A	986	286.9	29.1	9	19.2
B	170	49.5	29.1	1	29.4
C	410	119.3	29.1	3	23.9
D	760	221.2	29.1	7	19.0

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air supplied from the diffuser was then calculated from the proportion of outside air determined from the measurements taken at the main air handling unit (AHU).

To determine the outside air ventilation rate, one must know the ventilation effectiveness. While the term *ventilation effectiveness* has been variously defined by different researchers,[2] it is used here to focus on distribution of ventilation air from the central AHUs and the mixing of ventilation air within the occupied space. No standardized method exists to determine ventilation effectiveness objectively. Therefore, a ventilation effectiveness factor was subjectively estimated through direct observation using smoke pencils and the judgment of the engineers who conducted the HVAC assessment.

In addition to the air flow measurements, continuous monitors for carbon dioxide (CO_2), temperature, and relative humidity were installed at each indoor site and at the outside air intakes.

Personal exposure monitoring. Using a random sampling procedure, we selected 13 nonsmoking subjects in Building 1 and 12 subjects in Building 2 to participate in the personal exposure assessment. The personal exposure monitoring was performed on April 13 and 14, 1994.

ETS consists of both vapor- and particle-phase components.[3,4] Total respirable suspended particles (RSPs) were measured as the tracer of particle-phase ETS exposure, and nicotine was used as an indicator of exposure to vapor-phase ETS. Both have been widely used as indicators of ETS exposure.[5]

RSPs were determined gravimetrically in accordance with ASTM Standard D4532-92, *Standard Test Method for Respirable Dust in Workplace Atmospheres*,[6] and nicotine concentrations were determined in accordance with ASTM Standard D5075-90, *Standard Test Method for Nicotine in Indoor Air*.[7] Sampling apparatus, housed in standard laboratory coats, was attached to each subject for one working day. The sampling equipment consisted of two air pumps, tubing, and sample collection media, which were attached to the lapels of the coats, adjacent to the subjects' breathing zone.

Each subject was required to maintain an activity log for the duration of the sampling period, which divided the work day into 30-min segments. For each segment, the subjects indicated their location in the building, described their work activities, and recorded the number of cigarettes they were aware of being smoked in their proximity—*i.e.*, within 20 ft. From this information, the reported number of cigarettes per hour were computed.

TABLE 2—Results from Building 1 personal exposure and fixed location monitoring.

Date	Statistic	Total RSP, µg/m³	Nicotine, µg/m³	Smoking frequency, cigarettes per hr
Personal				
April 13	Mean	26.4	1.8	1.4
	Median	26.7	1.5	1.5
	Range	<12.5 to 47.9	0.3 to 4.4	0 to 3.2
April 14	Mean	21.2	2.2	1.4
	Median	18.8	1.6	0.5
	Range	13.3 to 33.5	0.4 to 4.7	0.3 to 5.0
Combined	Mean	23.6	2.0	1.4
	Median	22.8	1.6	0.9
	Range	<12.5 to 47.9	0.3 to 4.7	0 to 5.0
Fixed location				
A	Mean	24.5	2.2	
B	Mean	47.1	3.2	
C	Mean	13.7	3.1	
D	Mean	31.4	2.4	
Combined	Mean	29.2	2.7	
	Median	22.3	2.3	
	Range	<12.5 to 67.4	1.9 to 4.4	
Outdoor	Mean	22.5	—	
	Median	22.4	—	

Fixed location monitoring. In both study buildings, the same tracers of ETS exposure were monitored at the four fixed monitoring locations, which were selected to include various workplace configurations, areas of the buildings served by different AHUs, and sites in proximity to one or more of the personal monitoring subjects. At each indoor site, a customized briefcase containing air pumps and the sample collection media was installed at the beginning of the work day and remained there for approximately 8 hr. The sampling and analytical procedures used were identical to those for the personal exposure monitoring.

Results for Building 1

Building 1 is a 30-yr-old, two-story office structure with a gross floor area of 21,000 sq ft. Windows do not open, and smoking is permitted without restriction. Both floors are served by a single HVAC system—a constant-volume, dual-duct system with a series of mixing boxes. The HVAC system includes single-stage filtration with synthetic bag filters at the main AHU with an estimated filtration effectiveness of 40 percent.

Table 1 presents the results of the HVAC system performance assessment for Building 1. The upper part of the table presents the air flows for the total building determined at the main AHU, and the lower portion shows the measured volumes of ventilation air supplied to each fixed location monitoring site, identified as A through D.

A total volume of 19,834 cfm of ventilation air was supplied to Building 1, of which 4470 cfm was outside air, representing 29.1 percent of the total air supply. The air flows were substantially below the design air flow of 30,185 cfm. To assess the performance of the HVAC system with respect to ASHRAE 62-1989, one must first divide the total volume of outside air delivered to the building by the design occupancy to determine the outside air ventilation rate per occupant and then correct for ventilation effectiveness.

Observations and smoke pencil

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testing indicated duct leakage and supply air stratification in the occupied space. Therefore, ventilation effectiveness was assessed at 60 percent. Given this estimate and an estimated design occupancy of 150 persons, the outside air ventilation rate for Building 1 was 17.9 cfm per person. This result shows that the HVAC systems were operating nominally in accordance with the ventilation requirements of ASHRAE 62-1989.

The results of the local ventilation performance assessments at the fixed location monitoring sites in Building 1 show that all four were being supplied with volumes of outside air in accordance with or slightly below ASHRAE 62-1989. Based on design occupancy, the calculated local ventilation rates ranged from 19.2 to 29.4 cfm per occupant.

The continuous monitoring of CO_2, temperature, and relative humidity at the four fixed monitoring sites and at the outdoor air intakes indicated that the HVAC systems serving Building 1 were providing ventilation and thermal comfort conditions in accordance with ASHRAE standards.[8]

Table 2 presents the results from the personal exposure and fixed location monitoring conducted in Building 1. The upper portion of the table shows summary statistics (mean, median, and range) for the personal exposure monitoring for each of the two days of monitoring and both days combined. The lower part of the table summarizes the results from the fixed location monitoring. In calculating the mean values, we reported data points less than the detection limit as the detection limit. Therefore, the mean may provide a slight overestimation of the true mean in those cases where one or more data points were reported as less than the detection limit.

Total RSP concentrations from the personal exposure monitoring of the 13 nonsmoking subjects ranged from <12.5 to 47.9 $\mu g/m^3$ (mean = 23.6 $\mu g/m^3$ and median = 22.8 $\mu g/m^3$). Nicotine concentrations ranged from 0.3 to 4.7 $\mu g/m^3$ (mean = 2.0 $\mu g/m^3$ and median = 1.6 $\mu g/m^3$).

Total RSPs varied substantially among the four fixed monitoring locations, ranging from <12.5 to 67.4 $\mu g/m^3$ (mean = 29.2 $\mu g/m^3$). Nicotine concentrations were similar at all locations with a mean level of 2.7 $\mu g/m^3$ and a range of 1.9 to 4.4 $\mu g/m^3$.

An estimate of the prevalence and frequency of smoking can be determined from the subject activity logs and the original selection procedures for the subjects. From the activity logs, the mean reported smoking frequency was 1.4 cigarettes per hr, ranging from 0 to 5 cigarettes per hr. From the telephone survey of staff, the proportion of smokers in Building 1 was estimated at 22 percent. These figures are slightly higher than the 1992 U.S. national average smoking rate in office workplaces of 1.21 cigarettes per hr and 20.2 percent smokers, reported in the *National Health Interview Survey*.[9]

Results for Building 2

Building 2 is a 15-yr-old, three-level office structure with a gross

TABLE 3—Building 2 HVAC performance assessment.

Total building

Date	Time	Total air, cfm	Return air, cfm	Outside air, cfm	Outside air, percent	Estimated maximum occupancy (based on 7 per 1000 sq ft)	Outside air ventilation (based on 60 percent ventilation effectiveness), cfm per occupant
AHU 1—basement and first floor							
April 13	8:35 AM	27,666	17,392	10,274	37.1	231	35.6
	2:00 PM	24,480	18,416	6,064	24.8	231	21.0
	3:30 PM	25,696	18,720	6,976	27.1	231	24.2
April 14	8:30 AM	27,539	20,832	6,707	24.3	231	23.2
	10:10 AM	25,938	16,896	9,042	34.9	231	31.3
	1:30 PM	26,960	16,672	10,288	38.2	231	35.7
	3:10 PM	25,132	19,200	5,932	23.6	231	20.6
AHU 2—second floor							
April 13	8:35 AM	12,482	8,456	4,026	32.2	147	21.9
	1:00 PM	13,460	7,630	5,830	43.3	147	31.7
	1:35 PM	13,460	10,440	3,016	22.5	147	16.4
April 14	8:30 AM	16,037	13,076	2,461	15.4	147	13.4
	1:05 PM	13,606	11,564	2,042	15.0	147	11.1
	2:30 PM	13,606	12,166	2,634	19.4	147	14.3

Fixed monitoring locations

Site	Date	Time	Total air, cfm	Outside air, cfm	Outside air, percent	Observed population	Outside air ventilation (based on 60 percent ventilation effectiveness), cfm per occupant
A	April 13	9:00 AM	240	89.1	37.1	3	23.8
	April 14	9:00 AM	240	58.3	24.3	3	15.5
B	April 13	9:00 AM	336	108.2	32.2	3	28.8
	April 14	9:00 AM	330	50.8	15.4	3	13.5
C	April 13	9:00 AM	220	70.8	32.2	1	56.6
	April 14	9:00 AM	305	47.0	15.4	1	37.6
D	April 13	9:00 AM	365	117.5	32.2	3	31.4
	April 14	9:00 AM	345	53.2	15.4	3	14.2

floor area of 63,000 sq ft. Windows do not open, and smoking is permitted without restriction.

Building 2 is served by two variable air volume (VAV) systems with similar design configurations. One VAV system (AHU 1) serves the basement and first floor. The second (AHU 2) serves the second floor. Both are equipped with two stages of filtration. The first stage is low-efficiency (20 to 30 percent) bag filters while the second is an electrostatic precipitation system.

Table 3 presents the results from the HVAC performance assessment. The upper part of the table shows the air flows delivered by AHUs 1 and 2. For both, seven sets of replicate measurements were taken over the two-day monitoring period. For each replicate set, the total air, return air, and outside air measurements were all conducted at the same time, and an outside air percentage was calculated for each set.

For AHU 1, the total air supply (outside air plus return air) ranged from 25,132 to 27,666 cfm, with the proportion of outside air as a percentage of the total supply varying from 23.6 to 37.1 percent. The volumes of outside air supplied by AHU 1 to the basement and first floors varied between 5932 and 10,274 cfm. The design maximum total air flow for AHU 1 was 38,550 cfm.

Observation and smoke pencil analysis indicated minimal duct leakage but some stratification of the ventilation air in the occupied space. A ventilation effectiveness factor of 80 percent was estimated. Given this estimate and a design occupancy for the floors served by AHU 1 of 231, outside air ventilation rates were similar on both days of measurement, ranging from 21.0 to 35.6 cfm per occupant on April 13 and from 20.6 to 35.7 cfm per occupant on April 14.

Six sets of replicate measurements were collected for AHU 2 over the same period. The total air supply distributed by AHU 2 ranged from 12,482 to 16,037 cfm, with the total volume of outside air ranging from 1416 to 5830 cfm. Higher volumes of outside air were measured on April 13. Plan analysis showed a design maximum air flow for AHU 2 of 24,615 cfm. with a design occupancy of 146 and estimated ventilation effectiveness of 80 percent, the calculated outside air ventilation rates supplied by AHU 2 varied from 11.1 to 31.7 cfm per occupant.

The results indicate that AHU 2 was providing outside air ventilation rates below the outside air requirement of 20 cfm per occupant for office space on April 14. The differences in the measured outdoor air intake rates between the two dates were caused by pressure drops across the intake path. As the total air volume in a VAV system varies with the cooling load on the building, the static pressure in the mixed air plenum varies. Such variation has been observed in other buildings equipped with VAV systems.[10]

The continuous monitoring of CO_2, temperature, and relative humidity indicated acceptable ventilation and thermal comfort conditions.

Table 4 summarizes the results from the personal exposure and fixed location monitoring in Building 2. The upper portion of the table shows summary data for the personal monitoring, and the lower portion provides summary descriptive statistics for fixed location monitoring.

TABLE 4—Results from Building 2 personal exposure and fixed location monitoring.

Date	Statistic	Total RSP, µg/m³	Nicotine, µg/m³	Smoking frequency, cigarettes per hr
Personal				
April 13	Mean	30.1	1.8	1.0
	Median	32.3	1.7	0.7
	Range	16.6 to 40.0	1.1 to 2.3	0 to 3.2
April 14	Mean	41.9	1.9	2.1
	Median	45.6	1.8	2.2
	Range	30.2 to 49.6	1.6 to 2.3	0.9 to 3.2
Combined	Mean	35.0	1.8	1.5
	Median	35.3	1.7	1.2
	Range	16.6 to 49.6	1.1 to 2.3	0 to 3.2
Fixed location				
A	Mean	<12.5	2.0	
B	Mean	21.8	2.4	
C	Mean	26.0	1.7	
D	Mean	25.8	1.1	
Combined	Mean	21.5	1.8	
	Median	20.0	1.8	
	Range	<12.5 to 34.7	0.7 to 2.3	
Outdoor	Mean	19.4	—	
	Median	20.4	—	

Total RSP concentrations from the personal exposure monitoring of the 12 nonsmoking subjects over the two days ranged from 16.6 to 49.6 µg/m³ (mean = 35 µg/m³ and median = 35.3 µg/m³). Nicotine concentrations for the subjects were consistent over the monitoring period, ranging from 1.1 to 2.3 µg/m³ (mean = 1.8 µg/m³ and median = 1.7 µg/m³).

RSP levels at the four monitoring locations ranged from <12.5 to 34.7 µg/m³ (mean = 21.5 µg/m³ and median = 20 µg/m³). Outdoor RSP levels ranged from 14.4 to 22.3 µg/m³ (mean = 19.4 µg/m³). Nicotine concentrations at the four fixed locations ranged from 0.7 to 2.3 µg/m³ (mean and median = 1.8 µg/m³).

The mean smoking frequency estimated from the subject activity logs was 1.5 cigarettes per hr, with a range from 0 to 3.2 cigarettes per hr over the two days. From the selection procedures for the personal monitoring subjects, the proportion of smokers in Building 2 was estimated at 22 percent.

Conclusions and discussion

The data gathered in the two study buildings provide an important case study of nonsmoker exposure to ETS in an office environment supplied with outside air ventilation rates nominally in accordance with ASHRAE Standard 62-1989, with smoking prevalence rates consistent with "average" smoking conditions in U.S. office workplaces.

Both the total building and fixed location HVAC performance assessments showed that, based on design occupancy loads, the HVAC systems were providing outside air to the occupied space at ventilation rates either in accordance with or slightly below the 20 cfm per occupant recommended in the ASHRAE standard and in conformance with comfort conditions recommended in ASHRAE Standard 55-1992, *Thermal Environmental Conditions for Human Occupancy*. These conclusions were further confirmed by the test results of the continuous monitoring of CO_2, temperature, and relative humidity in the study buildings.

Smoking conditions in both study buildings were representative of moderate amounts of smoking as defined by ASHRAE as 27 percent smokers with a rate of 1.25 cigarettes per hr.[11]

Concentrations of RSPs and nicotine measured at the fixed monitoring locations and during the personal exposure monitoring were similar. RSP concentrations in both buildings are similar to levels measured in other office environments with either no smoking or the presence of a moderate amount of smoking. Research has shown RSP levels to range typically from 20 to 80 $\mu g/m^3$ in mechanically ventilated buildings in which smoking is permitted throughout and from 15 to 50 $\mu g/m^3$ in nonsmoking buildings and nonsmoking areas of mechanically ventilated buildings where smoking is restricted to designated areas.[12-15]

Nicotine concentrations in both buildings were consistent with data reported from other office workplaces in which smoking is permitted without restriction, ranging between 1 and 6 $\mu g/m^3$.[5,13,15]

The low concentrations of the tracers of ETS exposure measured in the study buildings demonstrate that ETS-related constituent levels are effectively controlled through general dilution ventilation, which includes the effects of dilution by both outdoor and recirculated air.

ASHRAE Standard 62-1989 was based on research relating ventilation flow rates to measured concentrations of ETS tracers under laboratory conditions.[16] This research showed that an outdoor air ventilation rate of 20 cfm per occupant controlled tracers of ETS exposure to acceptable levels under conditions of moderate smoking activity. The results from the study buildings provide real-world verification of the experimental basis for ASHRAE Standard 62-1989. **HPAC**

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