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Assessment of Non-Smokers' Exposure to Environmental Tobacco Smoke Using Personal-Exposure and Fixed-Location Monitoring

Key Words
Environmental tobacco smoke
Fixed-location monitoring
Personal monitoring
HVAC assessment

Abstract
Fixed-location monitoring has been extensively employed to assess exposure to environmental tobacco smoke (ETS) in offices and other public buildings. In contrast, personal monitoring methods have seldom been used to assess non-smokers' exposure. Simultaneous personal exposure monitoring and fixed-location measurements were conducted in two office buildings in Richmond, Va., USA, to compare the two sampling methods. The results from the personal and fixed-location monitoring showed general agreement in the measured exposure to particle-phase and vapour-phase ETS constituents. The overall results indicate that fixed-location monitoring provides a close approximation of an individual's exposure to ETS, as determined through personal monitoring. A secondary objective of the research was to assess the effectiveness of dilution ventilation for the control of ETS in the workplace. Overall, the results demonstrate that with ventilation in accordance with current ASHRAE Standards, dilution can be an effective means of controlling ETS-related constituents to low concentrations.

Introduction

Environmental tobacco smoke (ETS) is a dilute yet dynamic and complex chemical mixture in air consisting of both vapour-phase and particle-phase compounds [1–4]. Due to the dynamic and unpredictable nature of the two phases, an accurate assessment of ETS exposure may be best characterised by simultaneous monitoring of selective particle-phase and vapour-phase tracers [3]. Non-smokers' exposure to ETS may be determined either through fixed-location monitoring in which instrumentation for sampling is placed at a single location in the indoor environment, or by personal monitoring, in which sampling equipment is attached to individual subjects, and the sampling media are within a subject's breathing zone [5].

Fixed-location monitoring has been widely used to assess ETS exposure in offices and other public buildings, with instrumentation typically housed in briefcases or other enclosures to facilitate unobtrusive data collection. The extensive research data from fixed-location monitoring has been reviewed by Guerin et al. [6]. In contrast,

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relatively few studies have used personal monitoring methods to assess non-smokers' exposure to ETS, particularly in office buildings [5]. Field research has not previously been conducted to directly compare ETS data obtained using the two approaches.

In the research reported here, simultaneous personal exposure monitoring and fixed-location measurements were conducted in two office buildings to compare the two sampling methods and to evaluate the magnitude of differences in ETS exposure data determined through personal and fixed-location monitoring. A secondary objective was to assess the impact of dilution ventilation on ETS exposure through assessment of HVAC system performance concurrently with the ETS-related sampling, thereby assessing the applicability of dilution ventilation as a regulatory option for the control of ETS in the workplace. The research was conducted in Richmond, Va., USA in April 1994.

Methods

Data were gathered over three interrelated phases of the research project: (1) personal-exposure monitoring of ETS-related constituents; (2) fixed-location monitoring, and (3) assessment of the performance of the HVAC systems. The two study buildings were adjacent within a large multi-building facility in Richmond, Va., USA. Smoking was permitted without restriction in both buildings. The two study buildings are identified here as 'building 1' and 'building 2'.

Personal-Exposure Monitoring

In each study building, non-smoking subjects were selected to participate in the personal exposure assessment, using a randomised sampling procedure. Thirteen subjects in building 1 and 12 subjects in building 2 participated over a 2-day period on April 13th and 14th, 1994.

Sampling and Analysis of ETS and Other Indoor Air Quality Parameters. Six phase-selective tracers of ETS exposure were simultaneously determined in the personal monitoring. The measured tracers of particle-phase ETS exposure included total respirable suspended particles (RSP), ultraviolet particulate matter (UVPM), fluorescent particulate matter (FPM) and solanesol. Vapour-phase tracers of ETS exposure included nicotine and 3-ethenylpyridine (3-EP). In addition, total volatile organic compound (TVOC) concentrations were determined as a general indicator of the presence of chemical constituents primarily associated with sources other than ETS in the study buildings. ETS has been shown to be a minor source of TVOC levels in office buildings [7].

Sampling apparatus was attached to each subject for one working day. Subjects were required to wear a standard laboratory coat which housed the sampling equipment, consisting of two air pumps, tubing and sample collection media. The collection media were attached to the lapels of the coats within the occupants' breathing zones.

RSP were determined gravimetrically, in accordance with the American Society for Testing and Materials (ASTM) Standard D4532-92 [8]. Samples were collected by drawing a measured volume of air at a flow rate of 1.9 litre/min through a cyclone assembly with a cut-off point of 3.5 μm, followed by a tared 37-mm diameter, 1.0-μm pore size Fluoropore filter. RSP concentrations were determined from the difference between pre- and post-sampling weights. For an 8-hour sampling period, the limit of detection was 12.5 $\mu g/m^3$ of air.

To provide a more accurate estimate of ETS-related RSP levels, the filter samples from the gravimetric determinations were chemically analysed by the UVPM and FPM methods developed for the estimation of ETS contributions to RSP concentrations [9]. For the UVPM analyses, the filters used in the gravimetric RSP determinations were extracted with methanol and a sample aliquot injected into a columnless high-performance liquid chromatograph (HPLC) equipped with an ultraviolet detector (325 nm). 2,2′,4,4′-tetrahydroxybenzophenone was used as the surrogate standard for quantification. For an 8-hour sampling period, the limit of detection was 2.4 $\mu g/m^3$.

Determinations of FPM were conducted simultaneously with the UVPM determinations on the same filter sample extract by connecting a fluorescence detector (300 nm excitation; 420 nm emission) in series with the ultraviolet detector on the HPLC. Scopoletin was used as the surrogate standard for FPM quantification. For an 8-hour sampling period, the limit of detection for the FPM method was 0.4 $\mu g/m^3$.

Solanesol is a high-molecular-weight alcohol associated specifically with particulate-phase ETS. Solanesol concentrations were determined by analysis of the methanolic extracts used in the UVPM and FPM determinations, with a liquid chromatographic technique developed by Ogden and Maiolo [10]. A sample aliquot of each filter sample extract was injected into an HPLC equipped with an ultraviolet detector (205 nm) and a deuterium lamp. For the 8-hour sampling periods the limit of detection for the method was 0.06 $\mu g/m^3$.

Nicotine concentrations were determined in accordance with ASTM Standard D5075-90 [11]. Samples were collected by drawing air through XAD-4 (a styrene-divinylbenzene copolymer) sorbent tubes at a flow rate of 1 litre/min.

Collected samples were desorbed with ethyl acetate containing 0.01% triethylamine and a sample aliquot was injected into a gas chromatograph equipped with a nitrogen-phosphorus detector. Quinoline was used as the internal standard for quantification. For an 8-hour sampling period, the limit of detection for the method was 0.1 $\mu g/m^3$.

While nicotine has been widely used as a vapour-phase tracer in field research, its appropriateness has been questioned due to unpredictable decay kinetics [3, 12]. Consequently, researchers have investigated the applicability of another vapour-phase constituent, 3-EP, as a suitable tracer [13, 14].

3-EP concentrations were determined using a modified analysis from the ASTM Standard D5075-90 Method for Nicotine in Air [13, 14]. A sample aliquot of the XAD-4 extract from the nicotine analysis was additionally analysed for 3-EP. The chromatographic analysis for 3-EP requires modification of the set-up of the gas chromatograph from the nicotine analysis, including increased temperature span and hold times. Given an 8-hour sampling period, the limit of detection for the analytical method was 0.1 $\mu g/m^3$.

TVOC samples were collected using passive monitors according to ASTM Standard D4597-92 [15]. The activated charcoal sorbent in each passive monitor was extracted with carbon disulphide (CS_2) and a sample aliquot injected into a capillary gas chromatograph equipped with a flame ionisation detector, in accordance with ASTM

Standard D3687-89 [16]. For each sample, TVOC concentrations were determined as the sum total of all chromatogram peak areas and presented as toluene equivalents. The limit of analytical detection for the TVOC method for an 8-hour sampling period was 1.3 μg/m^3.

Salivary Cotinine. At the completion of the personal monitoring period, each subject was requested to provide a specimen of saliva for determination of cotinine levels. The purpose of the cotinine determination was to verify the non-smoking status of the subject, not to assess ETS exposure. Previous research has shown significant differences in salivary cotinine levels between smokers and non-smokers. A 'cut-off' point between current smokers and non-smokers has been suggested as ranging between 20 and 100 ng/ml [17–19].

The saliva samples were analysed for cotinine concentrations by a rapid gas-liquid chromatographic technique developed for the sensitive determination of cotinine in saliva without interference or contamination [20]. One millilitre of saliva was treated with sodium hydroxide and dichloromethane, mixed using a vortex mixer, centrifuged, evaporated to near-dryness and then mixed on a vortex mixer again with acetone. A sample aliquot of the acetone extract was injected into a liquid chromatograph equipped with a nitrogen-phosphorus detector. Pheniramine maleate was used as an internal standard. The detection limit of the method was 1.0 ng/ml.

Subject Activity Log. Each subject who had a personal monitor was also required to maintain an activity log for the duration of the sampling period. The activity log divided the workday into 30-min intervals. For each 30-min segment, the subjects indicated their location in the building, described their work activities, and recorded the number of cigarettes which they were aware of being smoked within their proximity (i.e. within 20 ft). Research has suggested that self-reported exposure using occupant logs provides an accurate method of estimating cigarette consumption [21]. From this information, the reported number of cigarettes per hour were computed to provide a standardised index of self-reported exposure to ETS in the workplace.

Fixed-Location Monitoring

Sampling and Analysis of ETS and Other Indoor Air Quality Parameters. In both study buildings, the same tracers of ETS exposure were monitored at four fixed locations and at the outside air intakes over a 4-day period, including the 2 days of personal-exposure monitoring. Data were gathered at two sites per building on each day. Therefore, replicate data sets were collected at each fixed location over the 4-day period. At each indoor site, a customised briefcase containing air pumps and the sample collection media was installed to gather samples at a height to simulate the occupants' breathing zone. The samplers were installed at the beginning of the workday and remained in place for approximately 8 h. The sampling and analytical procedures used for the RSP, UVPM, FPM, solanesol, nicotine and 3-EP determinations were identical to those used for the personal exposure monitoring. Only the sampling method for TVOC differed, using an active sampling protocol in the briefcase, compared to the passive sampling used in the personal monitoring. The active sampling method followed ASTM Standard D3686-89 [22].

Assessment of HVAC System Performance

The HVAC assessment included determination of (a) total ventilation air flows; (b) the volumes of ventilation air supplied to each fixed-location monitoring site, and (c) continuous monitoring of carbon dioxide (CO_2). The primary objective of the assessment was to determine performance of the HVAC systems as compared to North American ventilation standards developed by the American Society of Heating, Ventilation and Air Conditioning Engineers (ASHRAE) and approved by the American National Standards Institute (ANSI). The ASHRAE/ANSI ventilation standard 62-1989 [23] prescribes outdoor air ventilation rates intended to provide acceptable air quality, given a 'moderate' amount of smoking. For the purpose of dilution ventilation, ASHRAE has assumed 'moderate' smoking to be that of a population that includes 27% smokers, smoking at a rate of 1.25 cigarettes/h [24].

Total Building HVAC Assessment. The HVAC assessment included the collection of both descriptive and quantitative information. The design and operational configurations of the HVAC systems were determined from (a) review of mechanical engineering plans; (b) inspection of HVAC system components, and (c) airflow measurements at the main air-handling units (AHUs). Airflow measurements were taken using a standardised duct traverse method with an electronic micromanometer, fitted with a pitot tube attachment. The instrument has an accuracy of ± 5 cubic feet per minute (cfm).

Fixed-Monitoring Location HVAC Assessment. At each fixed-monitoring location, the total volume of air being supplied to the site was determined by airflow measurements taken at the ceiling diffusers, using an electronic micromanometer equipped with a pitot tube, and an electronic balometer. All measurement methods used in the HVAC assessments conformed with Associated Air Balance Council (AABC) procedures [25]. The airflow measurements taken at the diffuser determined the volume of total air (outside and return) supplied to the fixed monitoring site. The volume of outside air supplied from the diffuser was then calculated, based on the proportion of outside air determined from the measurements taken at the main AHU.

To assess the performance of the HVAC systems with respect to ASHRAE/ANSI Standard 62-1989, the volume of outside air delivered to the building must be (a) divided by the occupant population to determine outside air ventilation rate per occupant, and (b) corrected for ventilation effectiveness.

For engineering analysis of design and performance of HVAC systems, the most appropriate estimate of the building population to calculate outside air ventilation rates is the design occupancy, rather than the observed population, which may vary over a work day. The design occupancy is a standardised criterion used in the design process for HVAC systems, described in Table Two of ASHRAE/ANSI Standard 62-1989 as the 'estimated maximum occupancy'.

The outside air ventilation rates recommended in ASHRAE/ANSI Standard 62-1989 assume well-mixed conditions (i.e. 100% ventilation effectiveness). At present, no standardised method is available to objectively determine ventilation effectiveness. Therefore, to compare the results from both the total-building and fixed-location HVAC assessments with the ventilation requirements described in ASHRAE/ANSI Standard 62-1989, a ventilation effectiveness factor was subjectively estimated through direct observation using smoke pencils and the judgement of the engineers who conducted the HVAC assessment, based on their extensive field experience.

Carbon Dioxide Monitoring. Continuous CO_2 monitors/dataloggers were installed at each fixed-location monitoring site and at the outside air intakes. CO_2 was determined with a non-dispersive infrared (NDIR) analyser, with a measurement range of 0–5,000 ppm and an accuracy of ± 50 ppm.

Table 1. Personal monitoring results, building 1, Richmond, Va.

Date	Subject	Particulate fraction, µg/m³				Gaseous fraction, µg/m³			Saliva cotinine ng/ml	Smoking frequency cig./h
		total RSP	UVPM	FPM	solanesol	nicotine	3-EP	TVOC		
April 13th	E-1	25.1	27.7	5.8	0.14	4.4	1.5	12.4	1.3	1.4
	E-2	28.8	27.5	5.9	0.20	2.7	1.0	6.0	<1.0	0.2
	E-3	15.9	6.4	1.8	0.07	1.7	0.7	12.5	<1.0	3.2
	E-4	28.2	26.0	5.9	0.13	1.4	0.9	<1.3	1.3	1.9
	E-5	47.9	12.9	4.5	0.16	0.6	0.8	12.8	5.6	1.6
	E-6	<12.5	<2.4	1.0	<0.06	0.3	0.5	5.3	3.6	0.0
April 14th	E-7	18.8	8.8	2.5	0.07	4.4	1.2	21.6	<1.0	0.3
	E-8	13.3	12.2	3.0	0.10	1.1	0.7	26.2	3.6	2.2
	E-9	33.5	25.7	12.2	0.49	4.7	1.0	18.2	missing	5.0
	E-10	14.2	9.3	2.6	<0.06	1.3	0.8	11.6	32.9	0.3
	E-11	28.6	32.6	7.4	0.26	1.6	0.7	14.5	79.6	0.5
	E-12	17.3	11.0	3.1	0.10	2.0	0.9	502.6	<1.0	0.5
	E-13	22.8	17.7	4.3	0.11	0.4	1.2	15.8	2.9	0.9
Summary statistics										
April 13th	mean	26.4	17.1	4.1	0.13	1.8	0.9	8.4	2.3	1.4
	median	26.7	19.4	5.1	0.14	1.5	0.8	9.2	1.3	1.5
April 14th	mean	21.2	16.8	5.0	0.17	2.2	0.9	87.2	20.2	1.4
	median	18.8	12.2	3.1	0.10	1.6	0.9	18.2	3.3	0.5
Combined	mean	23.6	16.9	4.6	0.15	2.0	0.9	50.3	11.2	1.4
	median	22.8	12.9	4.3	0.11	1.6	0.9	12.8	2.1	0.9

Results

Building One

Personal-Exposure Monitoring of ETS-Related Constituents

Table 1 presents the results from the personal exposure monitoring conducted in building 1. The upper portion of the table shows individual data sets for each of the 13 subjects who had a personal monitor. The lower part of the table presents descriptive statistics (mean and median) for each day of monitoring separately and for both days combined. In order to calculate the mean values, if a data point for a subject or fixed location was reported as less than the detection limit (e.g. RSP concentration was less than 12.5 µg/m³), the detection limit (i.e. 12.5 µg/m³) was used as the representative value for the calculation of the mean. Therefore, the means may provide a slight overestimation of the true mean in those cases where one or more individual data points were reported as less than the detection limit. Subsequently, the median value is presented as an alternative descriptive statistic.

RSP concentrations for the 13 non-smoking subjects ranged from <12.5 to 47.9 µg/m³, with a mean concentration of 23.6 µg/m³ (median 22.8 µg/m³). Mean RSP levels were slightly higher on April 13th (26.4 µg/m³) compared to the second day of measurement (21.2 µg/m³).

The UVPM analysis showed concentrations ranging between <2.4 and 32.6 µg/m³ (mean 16.9 µg/m³; median 12.9 µg/m³). Analysis of the ratios between RSP and UVPM concentrations suggests that, on average, between 60 and 75% of the determined RSP mass was associated with combustion-related processes, including ETS.

FPM concentrations ranged from 1.0 to 12.2 µg/m³ (mean 4.6 µg/m³, median 4.3 µg/m³). The ratio between RSP and FPM estimated that typically between 20 and 50% of the RSP mass was associated with ETS and other combustion-related processes.

Comparison of the FPM and UVPM results shows substantially lower FPM concentrations, a finding consistent with Ogden et al. [26] who showed that UVPM overestimated ETS-related particulates by up to 30% in an experimental chamber and that FPM provided a more accurate estimate of ETS-related particulate matter.

Mean solanesol concentrations were 0.13 μg/m^3 on April 13th and 0.17 μg/m^3 on April 14th, with a range of concentrations from <0.06 to 0.49 μg/m^3. The weight ratios for solanesol:RSP ranged from 0.33 to 1.46%, with a mean weight ratio of 0.61%. These results are similar to those reported in 'real world' work environments, where a less than 1% weight ratio for solanesol:RSP was reported [27]. The solanesol concentrations suggest that 35–55% of the RSP mass may be attributable to ETS, an estimate similar to that determined from the FPM analysis.

Nicotine concentrations ranged from 0.3 to 4.7 μg/m^3 (mean 2.0 μg/m^3, median 1.6 μg/m^3). 3-EP concentrations ranged from 0.5 to 1.5 μg/m^3, with a mean concentration of 0.9 μg/m^3.

TVOC concentrations for 12 of the 13 subjects who had personal monitors, ranged from <1.3 to 26.2 μg/m^3. However, a concentration of 502.6 μg/m^3 was recorded for 1 subject. As the tracers of particle-phase and vapour-phase ETS exposure for the subject were not elevated above those determined for the others, the elevated TVOC concentration does not appear to be related to ETS exposure. Chromatographic analysis of the TVOC samples identified low-molecular-weight compounds in the C3–C8 range, including toluene and xylene, and higher-molecular-weight compounds in the C9–C11 range. These higher-molecular-weight compounds were qualitatively identified as common indoor VOCs such as terpenes, *d*-limonene and α-pinene, which are typically found in inks, adhesives, air fresheners, and cleaning products.

The salivary cotinine analysis showed cotinine levels of between <1.0 and 5.6 ng/ml for all except 3 of the subjects: 2 subjects showed levels of 32.9 and 79.6 ng/ml, respectively; and one sample was spoiled in transit to the laboratory. Previous research has shown that salivary cotinine levels of less than 6 ng/ml are typical of non-smokers and has also suggested a 'cut-off' point between current smokers and non-smokers as ranging between 20 and 100 ng/ml [17–19]. The higher cotinine concentrations for the two subjects, while elevated above the others, were both within this range. Review of the measured particle-phase and vapour-phase tracers for the two subjects did not show substantial differences in exposure compared to the other subjects. Consequently, the 2 subjects were assumed not to have smoked at work. A possible explanation for the higher cotinine concentrations for the 2 subjects may be dietary intake of nicotine-containing foods, such as leafy vegetables, potatoes and tomatoes. The impact of dietary nicotine on cotinine levels has been demonstrated by several investigators [28, 29].

Smoking Conditions

An estimate of the prevalence and frequency of smoking can be determined from (a) the subject activity logs and (b) the original selection procedures for the subjects. The mean reported smoking frequency was 1.4 cigarettes/h, with a range from 0 to 5 cigarettes/h. From the original survey to identify subjects, the proportion of non-smokers in building 1 was estimated at 22%. The estimated smoking rate of 1.4 cigarettes/h and smoking frequency of 22% is slightly higher than the 1992 US national average smoking rate in office workplaces of 1.21 cigarettes/h and 20.2% smokers reported in the National Health Interview Survey [30].

Fixed-Location Monitoring

The results from the fixed-location monitoring at the four indoor sites and an outdoor site are presented in table 2. The upper portion of the table shows the daily results from each site. The lower part of the table presents summary statistics for each of the monitoring locations and all four indoor locations combined.

RSP concentrations varied substantially between the four fixed-monitoring locations, ranging from <12.5 to 67.4 μg/m^3, with a combined mean concentration for all indoor sites of 29.2 μg/m^3. Outdoor concentrations ranged from 19.4 to 25.6 μg/m^3 (mean 22.5 μg/m^3). UVPM concentrations also varied widely between the four monitoring locations, ranging from <2.4 to 27.3 μg/m^3 (mean 11.5 μg/m^3, median 6.9 μg/m^3). The RSP:UVPM ratio estimates that between 20 and 60% of the RSP mass may be associated with combustion processes, including ETS.

FPM levels ranged from 1.0 to 7.3 μg/m^3 (mean 3.5 μg/m^3, median 2.4 μg/m^3). The RSP:FPM ratios estimate that the source of between 10 and 25% of the RSP mass was ETS and other combustion processes. Similar to the findings from the personal monitoring, FPM concentrations at the fixed-monitoring locations were consistently lower than the corresponding UVPM levels.

Solanesol concentrations ranged from <0.06 to 0.26 μg/m^3 (mean 0.14 μg/m^3, median 0.09 μg/m^3). The weight ratios for solanesol:RSP ranged from 0.2 to 0.7%. The solanesol concentrations estimate that approximately 15–30% of the RSP may be attributed to ETS, similar to the estimate for the FPM analysis. As might be expected, no UVPM, FPM or solanesol concentrations were detected in any of the outdoor RSP samples.

Nicotine concentrations were generally similar at all of the fixed monitoring locations over the measurement period. The mean nicotine level for all sites combined was

Table 2. Fixed-location monitoring results, building 1, Richmond, Va.

Date	Site	Particulate fraction, μg/m³				Gaseous fraction, μg/m³		
		total RSP	UVPM	FPM	solanesol	nicotine	3-EP	TVOC
April 12th	A	29.2	21.4	7.3	0.25	2.0	0.7	62.1
	B	67.4	20.2	5.1	0.21	4.4	1.3	277.5
	out	22.6	<2.4	<0.4	<0.06	NM	NM	3.0
April 13th	C	<12.5	<2.4	1.0	<0.06	3.7	0.9	128.6
	D	22.3	6.6	1.9	0.08	2.1	0.8	287.8
	out	25.6	<2.4	<0.4	<0.06	NM	NM	5.6
April 14th	A	19.7	7.1	2.1	0.07	2.4	0.7	96.0
	B	26.8	27.3	6.4	0.26	1.9	0.9	256.9
	out	22.2	<2.4	<0.4	<0.06	NM	NM	7.4
April 15th	C	14.9	4.8	2.7	0.09	2.4	0.7	411.7
	D	40.4	<2.4	1.4	<0.06	2.6	0.7	138.9
	out	19.4	<2.4	<0.4	<0.06	NM	NM	10.2
Summary statistics								
Means	A	24.5	14.3	4.7	0.16	2.2	0.7	79.1
	B	47.1	23.8	5.7	0.24	3.2	1.1	267.2
	C	7.5	2.4	1.8	0.05	3.1	0.8	270.2
	D	31.4	3.3	1.6	0.04	2.4	0.7	213.4
Combined sites	mean	29.2	11.5	3.5	0.14	2.7	0.8	207.4
	median	22.3	6.9	2.4	0.09	2.3	0.8	192.8
Outdoor	mean	22.5	<2.4	<0.4	<0.06	NM	NM	6.6
	median	22.4	<2.4	<0.4	<0.06	NM	NM	6.5

NM = Not measured.

2.7 μg/m³, with a measured range of 1.9 to 4.4 μg/m³. 3-EP concentrations were also similar at all four fixed-location monitoring sites, ranging from 0.7 to 1.3 μg/m³ (mean 0.8 μg/m³, median 0.8 μg/m³).

TVOC concentrations varied substantially between the four fixed-monitoring locations, ranging from 62.1 to 411.7 μg/m³ (mean 207.4 μg/m³). Indoor TVOC concentrations were an order of magnitude higher than corresponding outdoor levels, which ranged from 3.0 to 10.2 μg/m³. Gas chromatographic analysis identified similar compounds in most samples, including toluene, xylene, *d*-limonene and α-pinene. Typical sources of these TVOCs include cleaning products, inks, adhesives and other common office products.

Comparison of Personal Exposure and Fixed-Location Data

Comparison of the results from the personal monitoring and fixed-location monitoring throughout building 1 shows generally similar mean and median values for both the particle-phase and vapour-phase tracers of ETS exposure. Mean concentrations determined from the personal and fixed-location monitoring were statistically compared using a non-parametric Wilcoxon test [31]. Statistical analysis showed no significant differences between the mean concentrations for each of the six ETS-related tracers ($p < 0.05$).

Mean TVOC concentrations were significantly different for the personal and fixed-location monitoring, with TVOC levels at the fixed-location monitoring higher than those obtained in the personal monitoring. The cause of this discrepancy may relate to the use of different sampling procedures. For the personal monitoring, a passive sampling method was employed, whereas active sampling was used in the fixed-location monitoring. Different collection efficiencies between the sampling methods may be responsible for the varying measured concentrations.

Table 3. HVAC performance assessment, building 1, Richmond, Va.

Total building

Total air cfm	Return air cfm	Outside air cfm	Outside air %	Estimated maximum occupancy based on 7/1,000 ft^2	Outside air ventilation (cfm/occupant) based on 60% ventilation effectiveness
19,834	15,364	4,470	29.1	150	17.9

Fixed-monitoring locations

Site	Total air cfm	Outside air cfm	Outside air (%)	Observed population	Outside air ventilation (cfm/occupant) based on 60% ventilation effectiveness
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

Overall, the statistical similarity in measured ETS-related concentrations in building 1 indicate that fixed-location monitoring (which has been predominantly used to measure ETS-related constituents in office buildings and other workplaces) appears to provide a close approximation to non-smoking occupants' exposure to ETS, as determined through personal monitoring.

HVAC System Performance Assessment

Building 1 is a two-storey structure designed and constructed in 1967/68, with a gross floor area of 21,400 ft^2. Windows throughout the building do not open. Smoking is permitted without restriction in the workplace. Both floors of building 1 are served by a single HVAC system; a constant-volume dual-duct system, with single-stage filtration using synthetic-fibre bag filters at the main AHU (filtration efficiency 30–40%).

Table 3 presents the results of the HVAC system performance assessment of 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–D. From the total building assessment, a total volume of ventilation air of 19,834 cfm was supplied to building 1, of which 4,470 cfm was outside air, representing 29.1% of the total supply air.

To assess the performance of the HVAC system with respect to ASHRAE/ANSI Standard 62-1989, the total volume of outside air delivered to the building was (a) divided by the occupant population to determine outside air ventilation rate per occupant, and (b) corrected for ventilation effectiveness. For building 1, the design occupancy based on ASHRAE/ANSI Standard 62-1989 criteria is 150 persons (21,400 ft^2 approximately 7 persons/1,000 ft^2). Observations and smoke pencil testing indicated duct leakage and supply air stratification in the occupied space. As a consequence, ventilation effectiveness was assessed at 60%.

Given these estimates, the outside air ventilation rate for building 1 was 17.9 cfm/person. This result shows that the HVAC systems were operating nominally in accordance with the ventilation requirements from ASHRAE/ANSI Standard 62-1989, which recommends a minimum outside air ventilation rate for office space of 20 cfm/occupant.

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

CO_2 concentrations were similar at all four indoor monitoring locations, consistently ranging between 500 and 600 ppm during occupied hours. Outdoor CO_2 levels were between 350 and 400 ppm. The minimum outside air ventilation rate requirements recommended in Standard 62-1989 are based on the control of indoor CO_2 concentrations to less than 1,000 ppm. The results of the CO_2

Table 4. Personal monitoring results, building 2, Richmond, Va.

Date	Subject	Particulate fraction, μg/m³				Gaseous fraction, μg/m³			Saliva cotinine ng/ml	Smoking frequency cig./h
		total RSP	UVPM	FPM	solanesol	nicotine	3-EP	TVOC		
April 13th	F-1	40.0	26.2	14.5	0.30	1.7	1.3	67.6	1.4	3.2
	F-2	32.3	33.6	15.9	0.53	2.2	0.9	18.8	1.1	0.7
	F-3	23.6	21.6	6.7	0.27	2.3	1.1	23.0	<1.0	1.2
	F-4	36.0	36.2	7.9	0.15	1.5	0.6	352.3	4.5	0.1
	F-5	28.7	23.6	22.6	0.52	1.6	1.1	13.0	<1.0	0.0
	F-6	16.6	11.1	27.5	0.28	1.1	0.8	21.0	<1.0	0.7
	F-7	33.7	24.2	8.2	0.17	2.2	0.9	38.7	<1.0	1.0
April 14th	F-8	49.6	44.2	25.3	0.51	1.8	1.1	61.0	1.1	1.8
	F-9	30.2	12.9	12.1	0.58	1.6	1.0	48.9	2.0	2.2
	F-10	48.9	21.6	16.1	0.31	2.3	0.9	27.2	<1.0	3.2
	F-11	45.6	18.7	14.4	0.44	1.6	1.1	46.0	1.4	2.4
	F-12	35.3	11.3	9.8	0.42	1.9	0.9	105.3	1.3	0.9
Summary statistics										
April 13th	mean	30.1	25.2	14.8	0.32	1.8	1.0	76.3	1.6	1.0
	median	32.3	24.2	14.5	0.28	1.7	0.9	23.0	<1.0	0.7
April 14th	mean	41.9	21.7	15.5	0.45	1.9	1.0	57.7	1.4	2.1
	median	45.6	18.7	14.4	0.44	1.8	1.0	48.9	1.3	2.2
Combined	mean	35.0	23.7	15.1	0.37	1.8	1.0	68.6	1.5	1.5
	median	35.3	21.6	14.5	0.42	1.7	1.0	46.0	1.1	1.2

monitoring support the conclusions from the HVAC assessment that the volumes of outside air supplied to building 1 were generally in accordance with ASHRAE/ANSI Standard 62-1989.

Building Two

Personal-Exposure Monitoring of ETS-Related Constituents

Table 4 presents the results from the personal exposure monitoring in building 2. RSP concentrations for the 12 non-smoking subjects ranged from 16.6 to 49.6 μg/m³ over the 2 days of personal monitoring, with an overall mean concentration of 35 μg/m³ and median of 35.3 μg/m³.

UVPM concentrations ranged from 11.1 to 44.2 μg/m³ (mean 23.7 μg/m³, median 21.6 μg/m³). Analysis of the ratio between UVPM and RSP estimated that, on average, the source of between 50 and 80% of the RSP is ETS and other combustion-related processes.

FPM concentrations were lower than corresponding UVPM levels, ranging from 6.7 to 27.5 μg/m³ (mean 15.1 μg/m³, median 14.5 μg/m³). The FPM:RSP ratio estimated that the source of between 15 and 50% of the total RSP was ETS and other combustion processes. This finding is again consistent with the experimental research of Ogden and Maiolo [10], who concluded that FPM provides a more accurate estimate of ETS-related particles than UVPM, which may overestimate ETS particles by up to 30%.

Solanesol concentrations ranged between 0.15 and 0.58 μg/m³ (mean 0.37 μg/m³, median 0.42 μg/m³). The weight ratios for solanesol:RSP ranged from 0.42 to 1.9%, which is consistent with solanesol data gathered in both 'real world' work environments [24] and chamber experiments [23]. The solanesol results estimate that, on average, approximately 25 to 60% of the RSP were ETS-related particles, similar to the estimate provided by the FPM analysis.

Nicotine concentrations for the 12 non-smoking subjects were consistent over the 2 days of monitoring, ranging from 1.1 to 2.3 μg/m³ (mean 1.8 μg/m³, median 1.7 μg/m³). 3-EP concentrations ranged from 0.6 to 1.3 μg/m³ (mean and median 1.0 μg/m³).

Table 5. Fixed-location monitoring results, building 2, Richmond, Va.

Date	Site	Particulate fraction, μg/m³				Gaseous fraction, μg/m³		
		total RSP	UVPM	FPM	solanesol	nicotine	3-EP	TVOC
April 12th	A	<12.5	<2.4	<0.4	<0.06	2.1	0.8	454.3
	B	30.5	9.8	11.4	0.37	2.3	1.2	99.1
	out	22.3	<2.4	<0.4	<0.06	NM	NM	31.7
April 13th	C	28.7	13.2	12.8	0.24	1.6	1.0	327.0
	D	16.8	<2.4	<0.4	<0.06	1.5	1.0	82.4
	out	20.1	<2.4	<0.4	<0.06	NM	NM	17.0
April 14th	A	<12.5	<2.4	<0.4	<0.06	1.8	0.7	218.7
	B	13.1	<2.4	<0.4	<0.06	2.4	1.1	113.7
	out	14.4	<2.4	<0.4	<0.06	NM	NM	5.6
April 15th	C	23.2	<2.4	<0.4	<0.06	1.8	1.1	358.1
	D	34.7	<2.4	<0.4	<0.06	0.7	1.0	<1.3
	out	20.7	<2.4	<0.4	<0.06	NM	NM	4.0
Summary statistics								
Means	A	<12.5	<2.4	<0.4	<0.06	2.0	0.8	336.5
	B	21.8	4.9	5.7	0.19	2.4	1.1	106.4
	C	26.0	6.6	6.4	0.12	1.7	1.0	342.6
	D	25.8	<2.4	<0.4	<0.06	1.1	1.0	41.2
Combined sites	mean	18.4	2.9	3.0	0.08	1.8	1.0	206.7
	median	20.0	<2.4	<0.4	<0.06	1.8	1.0	166.2
Outdoor	mean	19.4	<2.4	<0.4	<0.06	NM	NM	14.6
	median	20.4	<2.4	<0.4	<0.06	NM	NM	11.3

NM = Not measured.

Personal exposures to TVOCs were consistent for 10 of the 12 subjects, ranging from 13.0 to 67.6 μg/m³. Higher TVOC concentrations were determined for 2 subjects: measured levels were 352.3 and 105.3 μg/m³. Gas chromatographic analysis identified higher-molecular-weight compounds in all samples, particularly terpenes. A primary source of terpenes is paint. During the personal monitoring periods, renovations including painting were taking place in the basement.

Cotinine levels determined from saliva samples provided by the 12 subjects who had personal exposure monitoring were consistently low, ranging from <1.0 to 4.5 ng/ml. As research has suggested a 'cut-off' point for salivary cotinine to classify non-smokers and smokers of between 20 and 100 ng/ml, the results verify the non-smoking status of all subjects.

Smoking Conditions

The mean smoking frequency estimated from the subject activity logs was 1.5 cigarettes/h, with a range from 0 to 3.2 cigarettes/h over the 2 days of monitoring. From the selection procedures for the subjects who had personal monitoring, the proportion of non-smokers in building 2 was estimated as 22%. Smoking conditions were marginally higher than 'typical' US office workplaces [30].

Fixed Location Monitoring

Table 5 presents the results from the fixed location monitoring in building 2. Total RSP concentrations at the four monitoring locations ranged from <12.5 to 34.7 μg/m³ (mean 18.4 μg/m³, median 20 μg/m³). Outdoor RSP levels ranged from 14.4 to 22.3 μg/m³ (mean 19.4 μg/m³).

The results from the analyses to estimate the proportion of ETS-related particulate matter from the total RSP were inconsistent with the findings from the personal exposure monitoring in both study buildings and the fixed monitoring in building 1. For 6 of the 8 data sets, UVPM, FPM and solanesol concentrations were less than the detection limits for the respective analytical methods. The reason for this apparent anomaly is uncertain. While inherent variability has been observed by the researchers who originally developed the analytical procedures [9, 10], the UVPM, FPM and solanesol results from the fixed-location monitoring in building 2 are anomalous, given that (a) smoking was taking place in the study areas; (b) ETS constituents were clearly quantified in the vapour phase, and (c) particle-phase tracers were quantified in the personal monitoring.

Nicotine concentrations at the four fixed-monitoring locations ranged from 0.7 to 2.4 μg/m³, with a combined mean and median for all sites of 1.8 μg/m³. 3-EP concentrations were also consistent at all four monitoring locations ranging from 0.7 to 1.2 μg/m³ (mean and median 1.0 μg/m³).

TVOC concentrations varied widely between the fixed-monitoring locations, ranging from <1.3 to 454.3 μg/m³ (mean 206.7 μg/m³, median 166.2 μg/m³). Indoor TVOC levels were nearly an order of magnitude higher than outdoor levels, which ranged from 4.0 to 31.7 μg/m³. Chromatographic analysis identified similar compounds in most samples, with a presence of compounds common in paints such as toluene and terpenes.

Comparison of Personal Exposure and Fixed-Location Data

Comparison of the results from the personal monitoring and fixed-location monitoring in building 2 indicates less consistency than the results in building 1, especially in the measurement of the particle-phase tracers of ETS exposure.

Statistical analysis using the Wilcoxon test to compare the mean concentrations determined from the personal and fixed-location monitoring showed statistically significant differences between mean RSP, UVPM, FPM and solanesol concentrations ($p < 0.05$). The significant differences were due to the anomalous cluster of non-detectable concentrations determined in the fixed-location monitoring.

Mean concentrations of the two vapour-phase tracers (nicotine and 3-EP) from the personal and fixed-location monitoring were not significantly different, indicating that the two sampling methods provide a close approximation of occupant exposure to vapour-phase ETS.

Similar to building 1, the differences in mean TVOC concentrations using the active and passive sampling methods were statistically significant, due to differential sampling efficiencies.

HVAC System Performance Assessment

Building 2 is a three-level structure, including two storeys above grade and one storey below grade. Building 2 was designed and constructed in 1988/1989, with a gross floor area of 63,000 ft². Windows throughout the building do not open and smoking is permitted without restriction. Building 2 is served by two variable air volume (VAV) systems with similar design configurations. The main air handling equipment is housed in a basement mechanical room. One VAV system (AHU 1) serves the basement and first floor. The second VAV system (AHU 2) serves the second floor. Both systems are equipped with two stages of filtration. The first stage consists of low-efficiency synthetic-fibre bag filters (20–30%). The second stage is an electrostatic precipitator system to charge and collect particulate matter passing through the first stage.

Table 6 presents the results from the HVAC performance assessments. The upper part of the table shows the airflows delivered by AHU 1 and AHU 2. For AHU 1, the total air supply (outside air plus return air) over that period 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%. Subsequently, the volumes of outside air supplied by AHU 1 to the basement and first floors varied between 5,932 and 10,274 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% was estimated. Given this estimate of ventilation effectiveness and a design occupancy for the two floors served by AHU 1 of 231 people, outside air ventilation rates were similar on both days of measurement, ranging from 21.0 to 35.6 cfm/occupant on April 13th and from 20.6 to 35.7 cfm/occupant on April 14th. Overall, the performance assessment indicates that AHU 1 was operating to provide ventilation rates in accordance with ASHRAE/ANSI Standard 62-1989.

The total air supply distributed by AHU 2 to the second floor over the 2-day period ranged from 12,482 to 16,037 cfm, with the total volumes of outside air ranging from 1,416 to 5,830 cfm. Higher volumes of outside air were measured on April 13th compared to April 14th.

With a design occupancy of 147 and an estimated ventilation effectiveness of 80%, the calculated outside air ventilation rates supplied by AHU 2 varied from 11.1 cfm/occupant to 31.7 cfm/occupant.

Table 6. HVAC performance assessment, building 2, Richmond, Va.

Total building

Date	Time	Total air cfm	Return air cfm	Outside air cfm	Outside air %	Estimated maximum occupancy based on 7/1,000 ft^2	Outside air ventilation cfm/occupant based on 80% ventilation effectiveness
AHU 1: basement and first floor							
April 13th	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 14th	8:30 AM	27,539	20,832	6,707	24.3	231	23.2
	10:10 PM	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 13th	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 14th	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 %	Observed population	Outside air ventilation cfm/occupant based on 80% ventilation effectiveness
A	April 13th	9:00 AM	240	89.1	37.1	3	23.8
	April 14th	9:00 AM	240	58.3	24.3	3	15.5
B	April 13th	9:00 AM	336	108.2	32.2	3	28.8
	April 14th	9:00 AM	330	50.8	15.4	3	13.5
C	April 13th	9:00 AM	220	70.8	32.2	1	56.6
	April 14th	9:00 AM	305	47.0	15.4	1	37.6
D	April 13th	9:00 AM	365	117.5	32.2	3	31.4
	April 14th	9:00 AM	345	53.2	15.4	3	14.2

The results indicate that AHU 2 was providing outside air ventilation rates in accordance with ASHRAE/ANSI Standard 62-1989 for much of the operating day on April 13th, but at ventilation rates below the outside air requirement for office space of 20 cfm/occupant described in ASHRAE/ANSI Standard 62-1989 on April 14th. The differences in the measured outdoor air intake rates on the second floor between April 13th and 14th were due to differences in pressure drops across the outside air intake path. As the total air volume in a VAV system varies with the cooling load, the static pressure in the mixed air plenum varies. Such variation is not unique to the study building, but has been observed in other buildings equipped with VAV systems [32].

The results of the local ventilation performance assessments at the four fixed monitoring locations in building 2 varied over the two days of monitoring. On April 13th, outside air ventilation rates at all four locations were at or above the 20 cfm/occupant criterion described in ASHRAE/ANSI Standard 62-1989, ranging from 23.8 to

56.6 cfm/occupant. On April 14th, outside air ventilation rates were below the 20 cfm/person criterion at three of the four fixed-monitoring sites. Overall, the results from the local ventilation assessments concur with the total building assessment. The VAV systems serving building 2 were providing outside air to the occupied space in accordance with, or marginally below, the outside air requirements described in ASHRAE/ANSI Standard 62-1989.

Measured CO_2 concentrations varied between the different days of monitoring, as a function of variable ventilation rates. CO_2 concentrations were slightly lower during the working day on April 13th (600–700 ppm) than on April 14th (700–850 ppm). The higher CO_2 concentrations on April 14th correspond with lower outside air ventilation rates determined by the HVAC performance measurements. Despite the daily variations in CO_2 concentrations, the results concur with the airflow measurements that the volumes of outside air supplied to building 2 are generally in accordance with ASHRAE/ANSI Standard 62-1989.

Discussion

Comparison of Personal and Fixed-Location Monitoring Methods to Assess ETS Exposure

The findings from this research provide new information about the comparability of data gathered through personal monitoring and fixed-site measurements. Research on non-smokers' exposure to ETS in office workplaces has rarely been conducted by personal monitoring. ETS exposure has predominantly been assessed through fixed-location monitoring, due to the non-obtrusive methods creating minimal disruptions to normal workplace activities. However, the question may be posed as to whether fixed monitoring data are representative of an individual non-smoker's exposure to ETS. Comparison of the personal and fixed location data in the study buildings provides some insight into this question.

The results from building 1 show statistical agreement in the measured exposure to particle-phase and vapour-phase constituents of ETS in the personal and fixed-location monitoring. For building 2, the results of the vapour-phase analyses (nicotine and 3-EP) also showed similar concentrations determined in both the personal and fixed-location monitoring. However, the particle-phase indicators were significantly different, due to the 'cluster' of non-detected levels from the fixed-monitoring locations.

Despite this anomaly, the overall results from the two study buildings indicate that fixed-location monitoring provides a close approximation to an individual's exposure to ETS, as determined through personal monitoring. This finding suggests that the 'real world' data obtained by past researchers, primarily through fixed-location monitoring, is appropriate for estimating occupant exposure to ETS.

Comparison of the Study Findings with Other 'Real World' Data

The data from the two buildings in Richmond add to the growing archive of objective data from the measurement of ETS-related constituents in office buildings. The most widely measured indicators of ETS exposure from the literature have been total RSP and nicotine [6]. Comparison shows that the measured RSP and nicotine concentrations of the vapour-phase and particle-phase indicators of ETS exposure from both the personal and fixed-location monitoring are generally consistent with the levels reported in the research literature.

From fixed-location monitoring in mechanically ventilated office environments in which smoking is permitted, research has shown RSP levels typically to range from 20 to 80 $\mu g/m^3$ [6, 7, 33, 34]. Nicotine concentrations typically have ranged between 1 and 6 $\mu g/m^3$ [6, 7, 35].

Personal exposure monitoring studies to assess ETS exposure in office environments are less common. Coultas et al. [36] reported a mean RSP concentration of 56.7 $\mu g/m^3$ and a mean nicotine level of 4.8 $\mu g/m^3$, for 5 subjects in office buildings in New Mexico. Muramatsu et al. [37] reported nicotine levels ranging from 5 to 19 $\mu g/m^3$ in Japanese office buildings. While the measured concentrations in these studies are higher than those determined in the Richmond study buildings, no information was provided regarding either (a) ventilation conditions or (b) smoking prevalence.

Some researchers have suggested a consistent ratio between measured RSP and nicotine concentrations, and have applied this consistent ratio to predict nicotine from reported RSP concentrations [38]. The results from the study presented here question the conclusion of a consistent ratio between nicotine and RSP levels. Within the overall data set, RSP:nicotine ratios varied from approximately 4:1 to 75:1. The inconsistency of RSP:nicotine ratios has also been reported in a survey of the research literature by Guerin et al. [6], who observed variable ratios from 4:1 to 100:1.

The present study also provides valuable information about tracers of ETS exposure other than total RSP and nicotine. To date, limited 'real world' data have been reported in the research literature for (a) the three methods to estimate the contribution of ETS to the total RSP mass (UVPM, FPM and solanesol), or (b) the use of 3-EP as a tracer for exposure to vapour-phase constituents of ETS.

The UVPM, FPM and solanesol analyses show a high degree of variability associated with the analytical methods. In general, the highest estimates of the proportions of total RSP associated with ETS were obtained from the UVPM analysis. Lower (and less variable) estimates were obtained from the FPM and solanesol analyses. In general, the results are consistent with the conclusions from experimental chamber research that UVPM concentrations tend to be higher than FPM levels, and that both FPM and solanesol may provide a better estimate of ETS-related particulates than UVPM [26].

The measurable levels of 3-EP in the study buildings suggest that it may provide an alternative tracer to nicotine under field conditions. Questions have been raised regarding the appropriateness of nicotine as a tracer for exposure to vapour-phase constituents as it displays non-typical and unpredictable decay kinetics [3, 12]. 3-EP has more predictable decay kinetics and may be more typical of other vapour-phase constituents. The results show that while 3-EP was less abundant than nicotine, it was clearly quantifiable under 'real world' conditions.

Regulatory Implications of the Research

The research also provides an important case study of non-smokers' exposure to ETS in an office environment supplied with outside air ventilation rates in accordance with current ventilation standards, with the results providing information on the effectiveness of dilution ventilation as a regulatory option to control ETS in the workplace.

The HVAC performance assessments determined that the HVAC systems serving both buildings were providing outside air to the occupied space at ventilation rates nominally in accordance with the ASHRAE/ANSI ventilation standard 62-1989. Smoking conditions in both study buildings were slightly greater than 'average' conditions in US office workplaces [30]. However, they are representative of 'moderate' amounts of smoking, assumed for the ventilation rates described in ASHRAE/ANSI Standard 62-1989.

Given HVAC system performance in accordance with ASHRAE/ANSI Standard 62-1989 and a 'moderate' amount of smoking, the concentrations of the various tracers of ETS exposure measured in the two study buildings demonstrate that ETS-related constituent levels may be effectively controlled to low concentrations through general dilution ventilation. This finding suggests that dilution ventilation can provide an appropriate option to accommodate smoking in the workplace, a view contrary to currently proposed regulations for US workplaces. The US Occupational Safety and Health Administration (OSHA) has proposed sweeping indoor air quality regulations which reject the traditional engineering practice of dilution ventilation for the control of ETS and other indoor sources [39]. In the rationale for the proposed OSHA regulations, no research data are cited to justify the rejection of dilution ventilation. The results of the research presented here demonstrate that dilution ventilation can provide an effective means of controlling non-smokers' exposure to ETS and providing acceptable indoor air quality.

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