Indoor Air 2011; 21: 36–44
www.blackwellpublishing.com/ina
Printed in Singapore. All rights reserved

INDOOR AIR
doi:10.1111/j.1600-0668.2010.00680.x

Secondhand smoke transfer and reductions by air sealing and ventilation in multiunit buildings: PFT and nicotine verification

Abstract Surveys suggest that transfer of secondhand smoke (SHS) between units in multiunit residential buildings is common, but measured data are rare. This study was undertaken to quantify bulk air transfer between units and document transfer of SHS species before and after treatments that sealed boundaries between units and provided a minimum amount of continuous exhaust ventilation of each unit. Six buildings in Minnesota were studied. Treatments were performed in clusters of up to eight units in each building, including zero to two units occupied by smokers. Bulk air transfer was quantified through passive perfluorocarbon tracer (PFT) gas tests. SHS transfer was evaluated using passive nicotine sampling. The median fraction of air entering a unit that came from other units tagged with PFTs ranged from 0.021 in a new condominium building to 0.353 in a 1930s duplex, with an overall median of 0.041. Treatments provided a median decrease of 29% in the fraction of transferred air and reduced PFT concentrations by about 40%, because of increased ventilation of both source and target apartments. Nicotine was transferred at only one-sixth the rate of PFTs. Involuntary exposure to SHS can be reduced but not eliminated by modifying existing, occupied multiunit buildings.

D. L. Bohac[1], M. J. Hewett[1], S. K. Hammond[2], D. T. Grimsrud[3]

[1]Center for Energy and Environment, Minneapolis, MN, USA, [2]School of Public Health, University of California, Berkeley, CA, USA, [3]Grimsrud & Associates, Minneapolis, MN, USA

Key words: Secondhand smoke; Air sealing; Ventilation; Nicotine; PFT tracers; Multifamily housing.

D. L. Bohac
Center for Energy and Environment
212 3rd Avenue North, #560
Minneapolis, MN 55401-1459
USA
Tel.: 612-802-1697
Fax: 612-335-5888
e-mail: dbohac@mncee.org
The work was performed by the Center for Energy and Environment.

Received for review 15 February 2010. Accepted for publication 2 July 2010.

Practical Implications

Recent studies of secondhand smoke exposure in multiunit housing indicate transmission of SHS constituents from smokers' units to those occupied by nonsmokers. A straightforward solution for this problem is to eliminate air leakage transfer between these units. This study describes a 2-year investigation of air sealing and ventilation improvements in six multiunit buildings located in a heating-dominated climate region of the US. The results quantify the reduction in interunit transfer of air between smokers' and nonsmokers' units. While it is possible to reduce the transfer when done with care, it is extremely difficult to eliminate these flows unless the buildings are vacated and extensively rebuilt. Eliminating air leakage between smokers' and nonsmokers' units is not a practical means of solving SHS transmission in an existing building.

Introduction

Secondhand smoke (SHS) is a significant indoor air quality concern in US residences (HHS, 2006). Exposure to SHS has been linked to an increased risk of many adverse health outcomes, including lung cancer, onset and exacerbation of asthma, and acute respiratory illness (NCI, 1999). Both particulate and gas-phase constituents are implicated. Many carcinogens in SHS, including polycyclic aromatic hydrocarbons (PAH) and tobacco-specific N-nitrosamines, are concentrated in the particle phase (Hecht and Hoffmann, 1988; Hoffmann and Wynder, 1986). Exposure to filtered (gas-phase) SHS has also been shown to increase tumour rates in mice at the same rate as exposure to unfiltered SHS (Witschi et al., 1997).

A study by Nazaroff and Singer modelled the exposure of a typical nonsmoker who lives with smokers in a single-family residence to 16 hazardous air pollutants (HAPs) in sidestream cigarette smoke (Nazaroff and Singer, 2004). They found potential concern for noncancer health effects from chronic exposures to four of these and substantial lifetime cancer risks (approximately 2–500 per million) for five known or probable human carcinogens. Several studies in single-family homes have found a decrease in concentration as SHS moves from the source to adjoining rooms in the same residence, especially for nicotine (Apte et al., 2002; Lofroth, 1993). Little work has been published on the exposure to SHS of occupants in multiunit buildings where smoking is allowed. Kraev et al. report tobacco smoke contamination in 49 units in low-income housing in Massachusetts (Kraev et al., 2009). For the 33 nonsmokers' units, the average nicotine concentration was 0.21 $\mu g/m^3$ and the median was 0.06 $\mu g/m^3$. The authors suggest that the transfer of SHS-contaminated air from smokers' to nonsmokers' units could be addressed through changes in building design and operation. Ghaemghami et al. investigated complaints of SHS intrusion in three apartments in Boston using short-term, real-time measurements of ultra fine particles, respirable particles, and particle-borne PAHs (Ghaemghami et al., 2006). They observed high concentrations of particles near suspected routes of SHS intrusion.

The goal of this study is to strengthen the body of knowledge available to support adoption of smoke-free multihousing policies by quantifying non-smoking renters' exposure to SHS that migrates into their apartments from elsewhere in or around the building. Large numbers of non-smoking renters currently experience such SHS incursions, against which they have no recourse under the Minnesota Clean Indoor Air Act nor under similar legislation in most other states. In a survey of a random sample of 405 renters in multiunit buildings in Minnesota, 48% reported that, at times, tobacco smoke odours entered their current apartment from elsewhere in or around the building (3% most of the time, 7% often, 20% sometimes and 18% rarely) (Hewett et al., 2007). Thirty-seven per cent of those experiencing SHS transfer said it bothered them a lot or so much that they were thinking of moving. Households with children and households below the federal (HHS) poverty level reported significantly more frequent SHS transfer. Among owners and managers interviewed, 27% identified tobacco smoke odour as the most common source of objectionable air drifting into apartments from elsewhere in or around the building, second only to the number that identified food odours (45%). Most did not view SHS transfer as a significant factor in tenants' decisions to rent or to move. Yet 46% of renters said they would be extremely or very interested in living in a smoke-free building (63% of renters in households with no smokers and 8% of households with one or more smokers).

This article describes a systematic study of SHS transfer within multiunit buildings in Minnesota, using measurements of nicotine from smokers' units and perfluorocarbon tracers (PFTs) released by the researchers. The study also examined the effectiveness of air sealing and ventilation improvements in reducing or eliminating SHS transfer. Leakage area measurements from this study have been reported previously (Bohac et al., 2007). This article reports the nicotine and bulk air transfer measurements before and after leakage reduction and examines the effectiveness of this strategy to limit exposure for nonsmokers.

Methods

Measurements

The transfer of SHS between apartment units was characterized using two primary approaches: guarded-zone pressurization tests and passive PFT methods (Bohac et al., 2007). Those approaches were supplemented by measurements of nicotine concentrations. In the first year of the study, interunit air leakage [guarded-zone tests], airflow [PFTs], and contaminant transfer [nicotine] measurements were conducted before any air sealing or ventilation treatments and after all treatments were completed. In the second year, the airflow and contaminant transfer measurements were also conducted between the air sealing work and the ventilation work so that the effect of the two treatments could be evaluated separately. For both years, the measurements were conducted during the heating season when windows were more likely to be closed.

A passive multiple PFT gas method developed by Brookhaven National Laboratory was used to provide information on 1-week average outdoor airflow rates to each unit, interunit airflow rates, and estimated SHS transport between units in the building (Dietz et al., 1986). A different type of PFT source was placed in each 'tagged' apartment and passive samplers were used to measure the average concentration of each PFT in the 'target' apartments. The measured tracer concentrations and known constant emission rates were used to solve a system of steady-state mass and flow balance equations and thereby estimate the airflow rates between each of the units and the outdoor airflow rate into each unit. This method assumes that the emission rates are constant and that each unit can be treated as a single zone with a uniform PFT concentration.

When there were more units than types of tracer gases (seven), a different type of source was placed in the smoker's unit and each surrounding unit. The additional tracer sources were placed in a unit one floor up or down from the smoker's unit to better track the expected stack effect that occurs in Minnesota's winter climate. Samplers were placed in each of these and any remaining test units to track the movement of the tracer gases. In this situation, air entering from another unit that did not have a PFT emitter would have been modelled as 'outdoor' air. This resulted in an underestimation of interunit flow rates for units that were on the outer edge of the cluster of tagged apartments.

PFT permeation-limited sources were prepared at the Tracer Technology Center at Brookhaven National

Laboratory and shipped with capillary adsorption tube samplers (CATS) to the CEE staff. Temperature data loggers were installed in each unit in conjunction with the tracer sources to monitor local temperatures, which affect the emission rates of the sources. Two sources and two CATS were typically installed in each apartment. The sum of the emission rates and the average of the CATS concentrations were used in the airflow rate calculations. After monitoring for 1 week, the samplers were capped and shipped back to BNL for analysis. Uncertainties in flow rates (including uncertainties in source emission rates and analysis of adsorbed PFTs) varied between 10% and 15% in the results received from BNL.

It is important to note that the passive tracer airflow calculation technique used in the PFT analysis systematically under-predicts the actual flow of outdoor air into the zone (Sherman, 1989). Ventilation rates computed by this technique are sometimes referred to as 'effective' ventilation rates. Fortunately, the PFT method provides an appropriate ventilation rate to couple a constant pollutant source rate with the resulting concentration in the zone. Thus, the PFT method is well suited to the objectives of this study.

The PFT method was also used to model SHS transfer between units. Recent studies have shown that more volatile SHS constituents (e.g. acetaldehyde, acrolein, acrylonitrile, benzene, 1,3-butadiene, and formaldehyde) have low levels of sorption and can be modelled by a nonsorbing tracer gas (Singer et al., 2002, 2003). These studies also show that the sorption of lower volatility HAPs (e.g. cresols, naphthalene, and polycyclic aromatic hydrocarbons) and nicotine is significant and must be considered when monitoring or modelling those constituents. Lower volatility SHS markers tend to underestimate the exposure to more volatile and particulate constituents (Apte et al., 2002; Lofroth, 1993). For example, nicotine measurements have been shown to underestimate by a factor of 2–8 the SHS particle transport from a smoker's room to a child's bedroom in single-family homes (Apte et al., 2002). As all of the constituents identified by Nazaroff and Singer as being of 'particular concern as contributors to health risk from chronic, residential SHS exposure' were more volatile components of SHS, tracer gas measurements likely provide good exposure estimates for some of the more hazardous SHS constituents but likely overestimate levels of less volatile constituents, unless their sorption characteristics are considered (Nazaroff and Singer, 2004).

Nicotine measurements were conducted in a sample of the units to provide a direct measurement of the transfer of SHS constituents. Nicotine is often used as a marker for SHS because there are accurate methods for measuring the levels produced by smoking in indoor areas, and SHS is typically the only significant source of nicotine in indoor air. The passive monitors used to monitor nicotine rely on a known rate of passive diffusion into a treated filter medium housed in a 38 – mm-diameter plastic container. The exposed samplers were returned to the measurement laboratory where the nicotine was subsequently extracted and measured by gas chromatography (Hammond and Leaderer, 1987). Two nicotine samplers were installed in all units, where a smoker lived and in units immediately beside or above/below the smoker's unit. A single sampler was placed in the remaining test units. The nicotine samplers were exposed over the same period and placed in the same locations as the PFT samplers. The limit of detection for the 1-week sample periods for the passive nicotine sampler was approximately 0.07 μg/m^3 with an uncertainty of ±10% for concentrations greater than 0.15 μg/m^3 and an uncertainty of ±50% for concentrations below 0.15 μg/m^3 (Apte et al., 2002).

Building treatments

Two treatments were used to reduce SHS concentrations in nonsmokers' units:

- Sealing leakage paths between units reduced the transfer of SHS from the smokers' units to the nonsmokers' units.
- Ventilation was improved.
- Ventilation systems in the smoker's unit were installed or upgraded to help dilute the SHS generated in those units.
- Ventilation systems in the nonsmokers' units were installed or upgraded to help dilute the SHS transferred to those units.
- Ventilation flows were balanced so that the ventilation system did not cause air to be drawn from one unit to another.

Single-family exterior envelope air leakage diagnostics and sealing methods were adapted to address interunit leakage. Air leaks were identified by a combination of visual inspections, infrared camera inspections, and the release of chemical smoke near suspected leakage sites while units were pressurized or depressurized with a blower door. Between 4 and 5 h were spent sealing each unit in the 8-Plex and 12-Plex. Sealing time was increased to 7–10 hours per unit for the three buildings in the second year of the study. Twenty-four hours per unit were spent treating the more extensive leaks in the Duplex. During the second year of the study, duct leakage to a ceiling truss area was identified as a likely source of air transfer between units in the 4-storey building. An aerosol sealing process was used to achieve an 86% average reduction in duct leakage (Conant et al., 2004). For all buildings combined, the median reduction in total unit air leakage was 18%.

The design guideline for the ventilation systems was to achieve a continuous exhaust flow of 42 m^3/h or greater in each unit and an 8 m^3/h or less difference in the flow rate of adjoining units. These systems were intended to augment natural air infiltration into the units and assure a moderate level of ventilation in warmer weather. In some buildings, the ventilation work consisted of new multipoint exhaust systems and in others it entailed replacement of existing bathroom ceiling exhaust fans with quieter fans rated for continuous operation. For the 11-storey building with central exhaust, a combination of duct sealing, removing duct restrictions and installing constant air regulators were required to produce a near uniform exhaust flow rate from the units. Only 23% of the units met ASHRAE 62-2001 ventilation requirements before treatment, while 60% met this standard after ventilation work.

Test buildings

Tests were conducted on a convenience sample of six multiunit buildings representative of those most commonly found in Minnesota. Census data and renter survey results were used to identify key criteria for the six test buildings. Buildings were screened for number of units, age, number of storeys, heating system type, and presence of bathroom/kitchen exhaust fans. To allow a better comparison between tracer gas and nicotine measurements, where possible, tests were conducted in buildings that had smokers in a single unit or in a unit that was separated from other units with smokers by one or more units.

The three buildings tested in the first year had 2–19 units, two or three storeys, central hydronic heat, and recirculating or no kitchen fans. They were also built in 1970 or earlier and were of frame construction (see Table 1). Two of the buildings had intermittently operated bathroom ceiling exhaust fans and one had a central exhaust system.

During the second year of the study, the emphasis shifted to larger buildings and buildings in which air sealing might be more effective. Experience from the first year of the study indicated that it is often difficult to reduce the interunit air leakage of existing, occupied units. Air sealing at the time of construction or renovation is expected to be more effective and less expensive. One of the second-year buildings (designated '11 storey') was selected because it was similar to large public housing buildings which are renovated more frequently than privately owned buildings. The other two buildings were selected to be representative of newer construction. Buildings were occupied during the tests. Occupants kept logs with records of number of cigarettes smoked and times windows were open (the average indoor–outdoor temperature difference during monitoring was 21 ± 7 °C so window opening was not common).

Results

Pretreatment airflow and leakage

Tracer gas measurements confirmed that airflow between units in apartment buildings can be significant. Before treatments, each of the six buildings had at least one unit where the fraction of transferred air (airflow from other tagged units/ total air entering the unit) was greater than 0.1 (Table 2: inter/total > 0.1). The units on the upper floors of the buildings received a greater fraction of their air from other units. For example, in the 12-Plex the fraction of air transferred from other units was 0.012 and 0.022 for the two monitored units on the first floor and 0.182 and 0.260 for the two units on the third floor. For all six buildings combined, the median fraction of inter-unit flow was 0.02 for the units on the lowest floor, 0.05 for those on the middle floors, and 0.16 for those on the upper floors. This trend is because of the thermal stack effect that causes air to enter through leakage paths near the bottom of the building, rise through the building and exit through leakage paths near the top of the building during the heating season. The median fraction of interunit airflow within buildings ranged from 0.021 for the new four storey condominium to 0.353 for the 1930s

Table 1 Characteristics of the six test buildings

	First-year buildings			Second-year buildings		
Characteristic	Duplex	8-Plex	12-Plex	138 Unit	11 Storey	4 Storey
# of units	2	8	12	138	178	38
# tested/treated	2/2	8/8	6/6	8/14	7/12	7/7
# Storeys	2	2	3	3	11	4
Const. year	Mid-1930	1970	1964	1999	1982	2001
Type	Apartment	Condo	Apartment	Apartment	Condo.	Condo/Comm.[a]
Ext. cladding	Stucco	Brick	Stucco/Brick	Stucco/Brick	Brick	Stucco
Floor construction	2 × 10 frame	2 × 10 frame	2 × 10 frame	Poured concrete	Poured concrete	Open truss
Heating system	Central hydronic	Central hydronic	Central hydronic	Forced air furnaces	Central hydronic	Forced air furnaces
Cooling system	Window AC units	Thru-wall AC units	Thru-wall AC units	Individual ducted units	Central hydronic	Individual ducted units
Bath fan(s)	Ceiling on/off	Continuous roof	Ceiling on/off	Ceiling on/off	Continuous roof	Ceiling on/off
Kitchen fan	Recirculating hood	Recirculating hood	Recirculating hood	Recirculating hood	Exhaust hood, continuous	Exhaust hood, on/off
Common area ventilation	None	None	None	Corridor supply/return	Corridor supply/return	Corridor supply/return

[a] First floor has retail space and upper three floors are condominiums.

Table 2 Inter unit and total flows (1-week averages) measured before and after air sealing and ventilation improvements were made in the six buildings. A statistical summary of each category is presented as the final entry in the table

			Pre			Post			Change (Post–Pre)			
	Unit	Floor	Inter unit (m^3/h)	Total (m^3/h)	Inter unit/total	Inter unit (m^3/h)	Total (m^3/h)	Inter unit/total	Inter unit (m^3/h)	Total (m^3/h)	Inter unit/total	Relative reduction (%)
Duplex	Lower	1	4.8	78.0	0.060	20.0	106.0	0.189	15.2	28.0	0.129	214%
	Upper	2	38.4	59.5	0.646	30.8	90.0	0.342	−7.6	30.5	−0.304	−47%
8-plex	1	1	0.8	46.2	0.017	9.3	121.0	0.077	8.5	74.8	0.060	344%
	2	1	0.3	36.9	0.008	5.1	94.1	0.054	4.8	57.2	0.046	575%
	3	1	0.5	32.1	0.016	6.6	82.9	0.080	6.1	50.8	0.064	411%
	4	1	3.6	93.8	0.038	3.6	137.0	0.026	0.0	43.2	−0.011	−29%
	7	2	14.4	97.4	0.148	12.7	94.1	0.135	−1.7	−3.3	−0.013	−9%
	8	2	31.8	131.0	0.243	31.6	75.6	0.418	−0.2	−55.4	0.175	72%
12-plex	2	1	0.8	66.8	0.012	10.9	120.0	0.091	10.1	53.2	0.079	660%
	4	1	1.4	63.4	0.022	11.7	115.0	0.102	10.3	51.6	0.080	362%
	6	2	4.8	54.2	0.089	19.5	158.0	0.123	14.7	103.8	0.034	39%
	8	2	7.1	46.7	0.152	12.4	109.0	0.114	5.3	62.3	−0.038	−25%
	10	3	28.4	156.0	0.182	55.2	322.0	0.172	26.8	166.0	−0.010	−6%
	12	3	38.7	149.0	0.260	47.6	286.0	0.166	8.9	137.0	−0.094	−36%
138-unit	122	1	1.0	80.9	0.012	0.8	71.9	0.011	−0.2	−9.0	−0.001	−10%
	123	1	2.2	53.9	0.041	1.4	91.7	0.015	−0.8	37.8	−0.026	−63%
	Guest	1	1.0	56.7	0.018	0.8	80.7	0.010	−0.2	24.0	−0.008	−44%
	222	2	7.8	38.6	0.202	5.9	76.3	0.077	−1.9	37.7	−0.125	−62%
	223	2	7.6	52.2	0.146	7.1	67.6	0.105	−0.5	15.4	−0.041	−28%
	224	2	3.6	34.2	0.105	0.8	63.9	0.013	−2.8	29.7	−0.093	−88%
	323	3	8.3	33.6	0.247	8.2	61.3	0.134	−0.1	27.7	−0.113	−46%
11-storey	312	3	1.0	63.0	0.016	0.8	89.5	0.009	−0.2	26.5	−0.007	−43%
	314	3	1.2	55.9	0.021	0.3	211.0	0.001	−0.9	155.1	−0.020	−95%
	410	4	7.3	141.0	0.052	1.0	183.0	0.005	−6.3	42.0	−0.047	−90%
	412	4	2.5	49.4	0.051	1.9	91.7	0.021	−0.6	42.3	−0.030	−59%
	414	4	1.5	68.8	0.022	1.2	118.0	0.010	−0.3	49.2	−0.012	−54%
	512	5	4.2	35.0	0.120	1.4	92.8	0.015	−2.8	57.8	−0.105	−88%
	514	5	1.5	42.5	0.035	0.7	143.0	0.005	−0.8	100.5	−0.030	−86%
4-storey	301	3	1.0	63.0	0.016	0.8	89.5	0.009	−0.2	26.5	−0.007	−43%
	302	3	0.7	105.0	0.007	1.7	83.1	0.020	1.0	−21.9	0.013	200%
	305	3	0.3	50.5	0.006	2.0	152.0	0.013	1.7	101.5	0.007	119%
	401	4	5.1	49.4	0.103	2.7	40.1	0.067	−2.4	−9.3	−0.036	−35%
	403	4	2.0	94.0	0.021	2.5	73.9	0.034	0.5	−20.1	0.013	60%
	404	4	6.5	83.6	0.078	4.6	73.6	0.063	−1.9	−10.0	−0.015	−19%
	405	4	1.9	90.6	0.021	0.2	115.0	0.002	−1.7	24.4	−0.019	−90%
	10%		0.7	35.8	0.012	0.8	69.3	0.007	−2.6	−9.7	−0.100	−88%
Summary statistics	25%		1.0	48.1	0.017	1.1	78.5	0.012	–-1.3	24.2	−0.037	−56%
	50%		2.5	59.5	0.041	3.6	92.8	0.054	−0.2	37.8	−0.012	−29%
	75%		7.2	87.1	0.133	11.3	120.5	0.110	5.1	57.5	0.013	66%
	90%		22.8	120.6	0.226	26.5	173.0	0.170	10.2	102.9	0.073	355%
	Average		7.0	70.1	0.092	9.3	113.7	0.078	2.3	43.6	−0.014	53%

up/down duplex. The median fraction for all of the units was 0.041 (see Table 2). The newer buildings tended to have a lower fraction of interunit airflow. However, even in the 138-unit building (built in 1999), two of the seven monitored units had a fraction of transferred air >0.2.

Post-treatment airflow

For three of the six buildings (duplex, 138 unit, and 11 storey), the median reduction of the fraction of interunit flow achieved by the treatments was 0.03 or greater. Overall, the fraction of interunit flow decreased by a median reduction of 29% (see Table 2). In general, the fractions decreased for units on the upper floors and increased slightly for units on the lower floors (Figure 1). This suggests that the air sealing helped reduce interunit airflow because of the thermal stack effect, but providing properly balanced, continuous exhaust ventilation may have increased airflow from other units into the lower level units. One reason this occurred is that the buildings with continuous, roof exhaust ventilation (8-Plex and 11 storey) tended to have lower flow rates to the units on the lower floors. So balancing the exhaust between units reversed an imbalance that had been causing more air to move from lower to upper flow units.

The fraction of interunit flow was reduced for 24 of the 35 monitored units. Six of the units with an increase were on the lowest level of the building (marked by shaded numbers in Table 2). The increase in interunit flow for four of the other five units was less than or

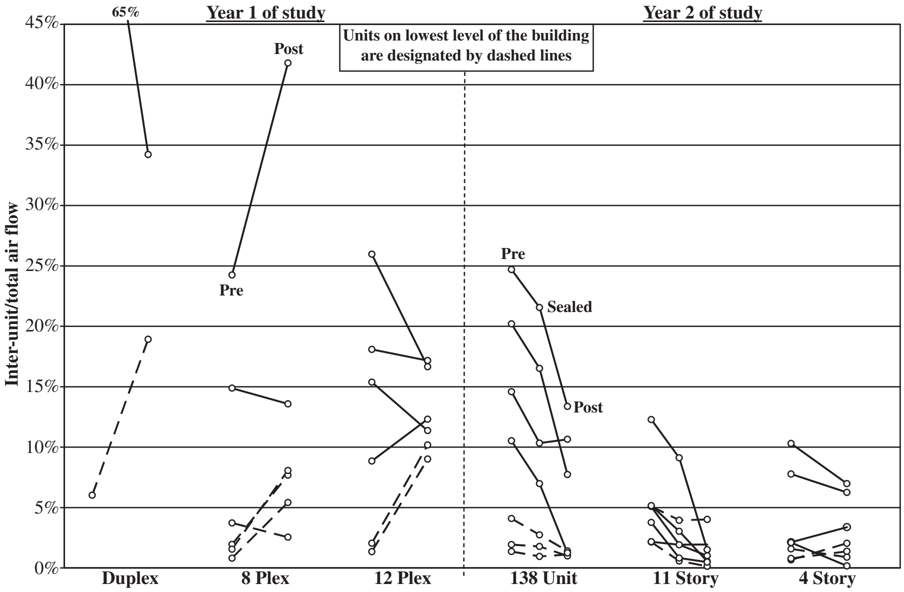

Fig. 1 Airflow from adjacent units as a percentage of total flow into unit. This figure is a summary of measured results from the six buildings collected into a single figure. The data displayed to the left of the vertical dotted line portion shows results from the three buildings treated in the first year of the study; the right-hand portion shows results from the second year. The ratios shown in the figure are 1-week averages. Both the 138 unit and 11-storey show results before, after sealing, and after ventilation improvements in the buildings

equal to 2 m^3/h. Measurements of change in two of the buildings from the second year of the study (138 unit and 11 storey) showed reductions in the interunit fraction for each unit studied. The median relative reduction for these two buildings was 55%. The median total airflow for all units studied increased by 56% (59.5–92.8 m^3/h).

The ratio of the PFT concentration in the nonsmoker's unit to the rate of release of that PFT in the smoker's unit quantifies the effect of restricted air transfer, ventilation in the nonsmoker's unit, and ventilation in the smoker's unit. Thus, it provides an estimate of the SHS levels to which occupants of the nonsmoker's unit are exposed for a given source strength (e.g., smoking rate) in the smoker's unit. This ratio can be evaluated before and after treatment as another measure of treatment impacts. For these six buildings, such an analysis showed that the air sealing and ventilation treatments together reduced the contaminant concentrations in nonsmokers units by a median of 29%. For the two buildings in the second year of the study where air sealing and comprehensive ventilation improvements were evaluated separately, sealing achieved an average reduction of 31% and the combination of sealing and ventilation a reduction of 78%.

SHS measurements

Passive nicotine samplers were deployed for the same period as the PFT system in each building where there was a smoker in at least one of the test units. For the three units in the 8-Plex, 138 unit, and 11-storey buildings where there was heavy smoking, nicotine levels ranged from 7.8 to 40 μg/m^3. Nicotine concentrations in nonsmokers' units were very low, with median values ranging from 0.0 (< LOD) to 0.4 μg/m^3 (see Table 3). As these are 1-week averages and smoking is intermittent, peak values would have been considerably higher.

Comparison of concentrations in the smokers' and nonsmokers' units for the three buildings with heavy smokers indicated that only 13% of nonsmokers' units had nicotine concentrations that were greater than 1% of that in the smoker's unit. Nicotine concentrations were above the LOD for 28% of the nonsmokers' units.

Table 3 Summary of 1-week average nicotine concentration (μg/m^3) for smoker and nonsmoker units

				Nonsmoker's units		
Building	Period	Smoker 1	Smoker 2	Minimum	Median	Maximum
8-Plex	Pre	26.3	2.2	0.1	0.1	0.1
8-Plex	Post	40.2	0.9	0.2	0.4	0.7
12-Plex	Pre	1.1	0.5	0.1	0.2	0.3
12-Plex	Post	1.5	0.1	0.1	0.1	0.6
138 Unit	Pre	27.5	0.0	0.0	0.1	0.2
138 Unit	After Seal	18.9	0.0	0.0	0.1	0.5
138 Unit	Ventilation	14.8	0.0	0.0	0.0	0.1
11 Storey	Pre	12.9	5.6	0.0	0.0	0.1
11 Storey	After Seal	12.2	4.8	0.0	0.0	0.1
11 Storey	Ventilation	7.8	1.4	0.0	0.1	1.2
4 Storey	Pre	0.0	0.0	0.0	0.1	0.2
4 Storey	Post	0.0	0.0	0.0	0.0	0.1

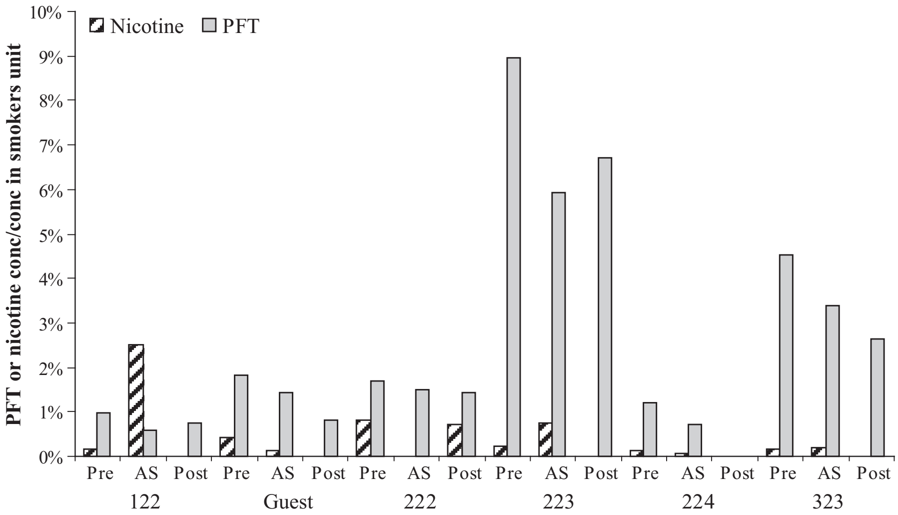

Fig. 2 Perfluorocarbon tracer (PFT) and nicotine concentrations in other units as a percentage of concentration in smoker's unit: 138 unit. The PFT source was placed in apt 123 which was occupied by a heavy smoker. This unit is adjacent to #122, directly below #223 and two floors below #323. The ratios shown are 1-week averages

If nicotine transferred at the same rate as the PFT gases, the ratio of the nicotine concentration in a nonsmoker's unit to the nicotine concentration in the smoker's unit would be the same as the concentration ratio in these two units for the PFT gas released in the smoker's unit. These ratios were analysed for the 8-Plex and 138 unit, where there was one unit with heavy smoking (Figure 2). The nicotine ratios were almost always considerably lower than the PFT ratio, as expected because of the strong sorption of nicotine. Overall, the PFT transfer rate ranges from 2 to 11 times greater than the nicotine transfer rate, with a median value 6 times greater (Table 4).

Table 4 Comparison of nicotine and perfluorocarbon tracer (PFT) transfer for the PFT that was released in the smoker's unit (1-week averages)

			Nicotine				
Building	Unit	Period	Smoker (S) μg/m^3	NonSmk (NS) μg/m^3	Ratio (NS/S) (%)	PFT Ratio (NS/S) (%)	PFT/ nicotine
8-Plex	5	Pre	26.3	0.12	0.46	3.33	7.2
8-Plex	5	Post	40.2	0.35	0.87	8.45	9.7
8-Plex	7	Post	40.2	0.21	0.52	5.57	10.6
8-Plex	8	Post	40.2	0.66	1.64	5.92	3.6
138 Unit	Guest	Pre	27.5	0.11	0.41	1.81	4.4
138 Unit	222	Pre	27.5	0.23	0.82	1.70	2.1
138 Unit	122	AS	18.9	0.48	2.52	0.60	0.2[a]
138 Unit	223	AS	18.9	0.14	0.75	5.94	7.9
138 Unit	222	Post	14.8	0.11	0.72	1.42	2
				Min	0.41	0.60	2
				Median	0.75	3.33	5.8
				Average	0.97	3.86	5.9
				Max	2.52	8.45	10.6

[a] Possibly because of smoking in unit or erroneous nicotine measurement, value not included in summary statistics.

Discussion

Air leakage tests showed that the pre-existing total and interunit leakage was larger for the older buildings tested in the first year and that the units would not meet established standards. The Leadership in Energy and Environmental Design (LEED®) Green Rating System for New Construction and Major Renovations requirement for environmental tobacco smoke (ETS) control of residential buildings where smoking is allowed specifies that the equivalent leakage area of each unit must be less than 0.19 cm^2 per 9.29 m^2 of floor, ceiling, and wall area (LEED-NC, 2009). None of the units in the older buildings tested in the first year of the project met this requirement. However, 88% of the units in the newer 138-unit building and 86% of the units in the 20-year-old 11-storey building met this standard. For these buildings, no special air sealing efforts were made during construction, but it is possible that the fire code sealing requirements led to the tighter units. While a high fraction of these newer units met the LEED® requirement, there were still SHS complaints in each building.

This study explores the practicality of reducing exposure to SHS for nonsmokers in smoking-permitted multiunit dwellings. Ghamghami et al. and Kraev et al. have recently documented transfer of SHS to non-smoking apartments in multifamily buildings in the Boston area (Ghaemghami et al., 2006; Kraev et al., 2009). As the Surgeon's General report states that 'there is no safe level of exposure to SHS and even brief exposure can affect both children and adults' (HHS, 2006), the policy issue of safety for nonsmokers in multiunit housing is an important one. Two potential solutions would be: (A) ban smoking in multifamily buildings and (B) retrofit multifamily buildings to eliminate SHS transfer between units occupied by smokers and nonsmokers.

These choices are reminiscent of the policy issues related to smoking in bars and restaurants. To eliminate exposure to nonsmokers in restaurants, smoking sections were separated from non-smoking sections by (A) locating smoking sections closer to the kitchen so that high volume exhaust fans would remove smoking contaminants through kitchen exhaust hoods, (B) installing fixed walls between smoking and non-smoking sections, and (C) installing separate ventilation systems for the smoking and non-smoking sections. While each strategy helped to reduce, but not eliminate, exposures for nonsmokers, restaurant employees who moved between the sections continued to receive large exposures to SHS. Only after smoking bans were implemented were exposures experienced by non-smoking customers reduced substantially [Ott et al., 1996; Repace, 2004; Waring and Siegel, 2007; Huss et al., 2010].

This study explores the potential to reduce exposure in non-smoking apartments by reducing leakage between units and improving the ventilation in both smokers' and nonsmokers' apartments. If successful, smokers and nonsmokers could occupy units in the same building without risk or annoyance to either group.

This goal, unfortunately, was not demonstrated successfully in this study. Careful implementation of best practice air sealing procedures and ventilation improvements moderately reduced but did not eliminate interunit flow between units containing smokers and nonsmokers. This is demonstrated by the PFT tracer measurements showing nonzero airflow between units containing smokers and nonsmokers. The tracer gas measurements are supported by measurements of nicotine in units housing nonsmokers.

To summarize: a reasonable amount of air sealing work by skilled practitioners, combined with balancing to reduce driving forces, did not substantially reduce the fraction of airflow between units in the multiunit buildings in this study. Increasing ventilation rates (in addition to air sealing and balancing) reduced the expected concentrations in nonsmokers' apartments for a given source strength in smokers' apartments by about 30%.

The study was able to identify useful recommendations to reduce, but not eliminate, the transfer of SHS in multiunit buildings where smoking is permitted:

- More focus should be placed on air sealing and ventilation work at the time of construction or major remodelling. Many air leakage paths cannot practicably be sealed after construction is complete or when the unit is occupied. Continuous ventilation is also less expensive to install at the time of construction.
- Air sealing of existing multiunit buildings should focus on larger, concentrated leaks. The best opportunity is to seal plumbing or other chases. Any air sealing needs to include almost all of the leaks connected to chases or floor/ceiling/wall cavities.
- Continuous ventilation that is balanced between units provides a significant benefit and should typically cost \$300–\$500 per unit for installation. For the two buildings with an existing central exhaust system, there was no additional electric use or ventilation heating/cooling loads as the work only involved balancing and sealing or cleaning the ducts. For the four buildings where continuous exhaust systems were added, the power use ranged from 13 to 50 watts/unit and the additional flow rate ranged from 39 to 65 m^3/h. In a Minnesota climate, this heating load would increase energy costs by approximately \$60/year.
- Although tighter units that met LEED® ETS leakage requirements may provide some reduction in SHS transfer, air sealing and ventilation approaches will not completely eliminate SHS transfer between units.
- The PFT method provides a simple and accurate way to evaluate the movement of nonsorbing contaminants in buildings.
- The ratio of the PFT concentration in a nonsmoker's unit to that in a smoker's unit quantifies the combined effect of restricted air transfer and ventilation in the nonsmoker's unit on contaminant levels.
- Passive nicotine samplers provide an inexpensive method for verifying – but not quantifying – SHS transfer from a smoker's unit in some settings. One week monitoring resulted in measurable levels of nicotine in 28% of the non-smoking units near a smoker's unit. Extending the monitoring period to 2–4 weeks should allow nicotine to be detected for a higher fraction of actual SHS transfer situations. However, the transfer rate of nicotine is typically six times lower than that of nonsorptive gases so when used as a SHS tracer it greatly underestimates transfer of less sorptive components of SHS.

Acknowledgements

This research project was funded in part by ClearWay Minnesota^{SM}. Any public dissemination of information relating to the grant was made possible by Grant Number RC 2000-0015 from ClearWay Minnesota. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of ClearWay Minnesota. The authors thank Dr. Russell Dietz and the staff of the Tracer Technology Center at Brookhaven National Laboratory who analysed the PFT samplers and assisted in the design of the PFT measurements.

References

Apte, M.G., Gundel, L.A., Dod, R.L., Chang, G.M. and Sextro, R.G. (2002) A pilot study of the behavior of gas- and particle-phase SHS tracers in residences. Proceedings of the 9th International Conference on Indoor Air Quality and Climate. Vol. **5**, Monterey, CA, 97–104.

Bohac, D.L., Hewett, M., Fitzgerald, J. and Grimsrud, D. (2007) Measured change in multifamily unit air leakage and air flow due to air sealing and ventilation treatments. Thermal Performance of the Exterior Envelopes of Buildings X. Proceedings of the Tenth International Conference on the Thermal Performance of the Exterior Envelopes of Whole Buildings; Clearwater Beach, FL.

Conant, A., Modera, M.P., Pira, J., Proctor, J. and Gebbie, M. (2004) Comprehensive diagnostic and improvement tools for HVAC-System installations in light commercial buildings, United States Department of Energy National Energy Technology Laboratory DOE Award No. DE-FC26-01NT41256. San Rafael, CA, Proctor Engineering Group, Ltd., 2004.

Dietz, R.N., Goodrich, R.W., Cote, E.A., Wieser, R.F., Gammage, R., Sherman, M., Lagus, P. and Krutson, E. (1986) Detailed description and performance of a passive perfluorocarbon tracer system for building ventilation and air exchange measurements. in: Trechsel, H.R. and Lagus, P.L. (eds) *Measured Air Leakage Performance of Buildings, ASTM STP 904*. Philadelphia, PA, American Society for Testing and Materials, 203–264.

Ghaemghami, J., Dumyahn, T., Shea, J. and Bethune, L. (2006) Tobacco smoke intrusion investigation in Boston: three case studies. Presented that the American Public Health Association 134th Annual Meeting and Exposition, Nov. 4-8, 2006, Boston, MA. Abstract #132631.

Hammond, S.K. and Leaderer, B.P. (1987) A diffusion monitor to measure exposure to passive smoking, *Environ. Sci. Technol.*, **21**, 494–497.

Hecht, S.S. and Hoffmann, D. (1988) Tobacco-specific nitrosamines, an important group of carcinogens in tobacco and tobacco smoke, *Carcinogenesis*, **39**, 875–884.

Hewett, M.J., Sandell, S.D., Anderson, J. and Niebuhr, M. (2007) Secondhand smoke in apartment buildings: Renter and owner or manager perspectives. Nicotine & Tobacco Research V 9, Supplement 1, S39–S47.

HHS (US Department of Health and Human Services) (2006) *The Health Consequences of Involuntary Exposure to Tobacco Smoke: a Report of the Surgeon General.* Atlanta, GA, USA, US Department of Health and Human Services, Centers for Disease Control, Coordinating Center for Health Promotion, National Center for Chronic Disease Prevention and Health Promotion, Office on Smoking and Health.

Hoffmann, D. and Wynder, E.L. (1986) Chemical constituents and bioactivity of tobacco smoke. In: Zaridze, D.G. and Peto, R., (eds) *Tobacco- A Major International Health Hazard.* Lyon, France, IARC Publications;**74**, 145–166.

Huss, A., Kooijman, C., Breuer, M., Böhler, P., Zünd, T., Wenk, S. and Röösli, M. (2010) Fine particulate matter measurements in Swiss restaurants, cafés and bars: what is the effect of spatial separation between smoking and non-smoking areas? *Indoor Air*, **20**, 52–60.

Kraev, T.A., Adamkiewicz, G., Hammond, S.K. and Spengler, J.D. (2009) Indoor concentrations of nicotine in low-income, multi-unit housing: associations with smoking behaviours and housing characteristics, *Tob. Control*. Published Online First: 13 Aug 2009. doi: 10.1136/tc.2009.029728.

LEED-NC (2009) *Green Building Design and Construction*. Washington, DC, US Green Building Council, 415–417.

Lofroth, G. (1993) Environmental tobacco smoke: multicomponent analysis and room-to-room distribution in homes, *Tob. Control*, **2**, 222–225.

Nazaroff, W.W. and Singer, B.C. (2004) Inhalation of hazardous air pollutants from environmental tobacco smoke in US residences. *J. Expo. Anal. Environ. Epidemiol.*,**14** (Supp. 1), S71–S77.

NCI (National Cancer Institute) (1999) Health effects of exposure to environmental tobacco smoke, Report of the California Environmental Protection Agency smoking and tobacco control monograph, Report no. 10. Bethesda, MD, USA, Department of Health and Human Services, National Institutes of Health, National Cancer Institute.

Ott, W., Switzer, P. and Robinson, J. (1996) Particle concentrations inside a tavern before and after prohibition of smoking: evaluating the performance of an indoor air quality model, *J. Air Waste Manag. Assoc.*, **46**, 1120–1134.

Repace, J. (2004) Respirable particles and carcinogens in the air of Delaware hospitality venues before and after a smoking ban, *J. Occup. Environ. Med.*, **46**(9), 887–905.

Sherman, M.H. (1989) Variation-induced bias in passive ventilation measurement, *Build. Environ.*, **24**, 347–354.

Singer, B.C., Hodgson, A.T., Guevarra, K.S., Hawley, E.L. and Nazaroff, W.W. (2002) Gas-phase organics in environmental tobacco smoke. 1. Effects of smoking rate, ventilation, and furnishing level on emission factors, *Environ. Sci. Technol.*, **36**, 846–853.

Singer, B.C., Hodgson, A.T. and Nazaroff, W.W. (2003) Gas-phase organics in environmental tobacco smoke. 2. Exposure-relevant emission factors and indirect exposures from habitual smoking, *Atmos. Environ.*, **37**, 5551–5561.

Waring, M.S. and Siegel, J.A. (2007) An evaluation of the indoor air quality in bars before and after a smoking ban in Austin, Texas, *J. Expo. Sci. Environ. Epidemiol.*, **17**, 260–268.

Witschi, H., Espiritu, I., Maronpot, R.R., Pinkerton, K.E. and Jones, A.D. (1997) The carcinogenic potential of the gas phase of environmental tobacco smoke, *Carcinogenesis*, **18**, 2035–2042.