Measured Change in Multifamily Unit Air Leakage and Airflow Due to Air Sealing and Ventilation Treatments

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ABSTRACT

This paper summarizes the results from field studies to evaluate the effectiveness of air sealing and ventilation treatments to reduce environmental tobacco smoke transfer between units in six Minnesota apartment buildings. Multiple fan air leakage tests were used to quantify the exterior and interunit air leakage. Week-long perfluorocarbon tracer measurements incorporating up to seven different gases were used to estimate infiltration and interapartment airflow rates.

Air leakage tests indicated that, before treatments, the median total leakage of all tested units was 861 cfm50, with the median for individual buildings ranging from 454 to 2368 cfm50. For four of the buildings there was almost a factor of two difference between the tightest and leakiest units in the same building. The median leakage to adjacent units was 155 cfm50 or 27% of the total leakage. The air sealing produced a median reduction in interunit leakage of 54% and 15% for two of the buildings, but it did not have a measurable effect at three of the other buildings.

Tracer gas measurements showed that the fraction of air coming from other units compared to total ventilation varied from 2% for a new four-story condominium to 12% for a three- story 12-plex. The air sealing resulted in a consistent—but small—reduction in interunit airflow, and the installation of the continuous ventilation systems resulted in a nearly three-fold increase in the number of units that met minimum ventilation requirements.

INTRODUCTION

The nature of apartment-building construction is such that leakage paths between units are invariably present and are often quite numerous when no particular effort is made to eliminate them during construction. Air moves through these leakage paths in response to small differences in pressure between the units. The differences in pressure may be due to natural forces or to mechanical ventilation. During the heating season, warmer air inside a building is less dense than outside air. This causes cold outside air to enter through leaks in the lower portion of the building, rise through the inside of the building, and exit through leaks in the upper portion of the building. This is known as “stack effect” airflow. Overpressure on the windward side of a building and underpressure on the leeward side tends to move air within the building from the windward to the leeward side. Tests have shown that in cold climates in the winter, the stack effect dominates over the wind effect (Francisco and Palmiter 1994; Palmiter et al. 1995; Feustel and Diamond 1996).

Over the past 20 years, a small number of researchers have used multitracer gas techniques to measure airflows between units in multifamily buildings, often as a secondary outcome of studies focused on measuring air exchange with the outdoors. Francisco and Palmiter (1994) used a constant injection multi-tracer measurement system to study airflows in three new low-rise apartment buildings in the Pacific Northwest. They found that on a building average basis 13% to 26% of the total airflow into units came from other units. Individual units in those buildings were receiving as much as 35% of their total airflow from other units, despite the fact that all three buildings had poured 1.5 in. gypcrete-on-plywood floors. Harrje et al. (1988) used constant concentration and perfluo-

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rocarbon tracer (PFT) techniques to determine that an average of 22% of the airflow into the fourth-floor apartments in a mid-rise building in New Jersey was coming from elsewhere in the building rather than from outdoors. Feustel and Diamond (1996) used tracer gas techniques to determine that the airflow between two apartments in a steel and concrete high-rise was less than 4% of the total for the unit.

Multiple-fan or guarded-zone techniques have also been used to measure the air leakage between units in multifamily buildings. Modera et al. (1986) used the guarded-zone technique on an early 1900s low-rise masonry apartment building in Minnesota to determine that an average of 52% of the effective leakage area for each apartment was between apartments or interunit leaks. He used the air leakage results with a multizone airflow model to determine that whenever the wind blew perpendicular to the long side of the building the leeward apartments on the upper stories would receive almost no fresh air, regardless of wind speed. Using the same methods, Diamond et al. (1986) found slightly higher levels of interunit leakage for a low-rise apartment building of similar vintage in Chicago. Levin (1988) used the multiple-fan-pressurization technique to determine that 12% to 36% of the total leakage area in three Swedish apartments was leakage between apartment units.

Almost all of the outdoor air entry into Minnesota apartment buildings occurs through air infiltrating through leaks and through open windows. Unlike large commercial buildings, continuous mechanical ventilation is seldom present in apartment buildings. The most common type of ventilation system is exhaust-only, with either individual bathroom exhaust fans that operate intermittently with an ON/OFF switch or bathroom continuous exhaust with a central roof-mounted fan. Some newer buildings have heated supply ventilation into the common spaces. These systems are either designed to have the supply air transfer into units through door undercuts or they have balanced exhaust air returns in the same common area.

While building ventilation systems can increase the flow of outdoor air into units, unbalanced systems can also increase airflows between units. For example, when a kitchen or bathroom exhaust fan is turned on in only one unit, the exhaust flow causes that unit to be depressurized relative to the adjoining units (Feustel and Diamond 1996; Francisco and Palmiter 1994; Palmiter et al. 1995; Herrlin 1999). That typically results in a shift of additional airflow from the adjoining units to the unit with the operating exhaust fan. Supply and exhaust systems, even if balanced so that supply flows are less than exhaust flows, do little to overcome natural stack and wind effects in these buildings and their attendant problems (Herrlin 1999). In addition, it is not uncommon to find that the gaps under some of the doors have been sealed (Feustel and Diamond 1996; CMHC 1997), which will create additional disparities in pressure between units. One published study (Francisco and Palmiter 1994) tested changes in the operating strategies of ventilation systems that might improve performance. This study found that operating all apartment ventilation fans simultaneously produced less interunit flow than operating fans individually and recommended continuous operation of these fans.

OBJECTIVES

This field study was completed as part of a comprehensive research project focused on environmental tobacco smoke (ETS) in apartment buildings. The two goals of this project were to build a sound base of knowledge that would facilitate the designation of smoke-free apartment buildings and the treatment of smoking-permitted buildings to minimize ETS transfer. Results from renter surveys, building owners or managers interviews, and smoke-free apartment legal research have been reported by Hewett et al. (2007). This paper summarizes the results from field studies to evaluate the effectiveness of air sealing and ventilation treatments to reduce heating season ETS transfer between units in six Minnesota apartment buildings.

The primary questions addressed in this project were:

- What are typical contaminant dispersion and airflow rates between apartment units in multifamily buildings in Minnesota? How does the transfer of nicotine and fine particulates compare to the transfer of tracer gases?
- How does airflow and contaminant transfer between units differ by building type or by differences in construction details between buildings? How does this differ by presence and type of mechanical ventilation system?
- How much can airflow and contaminant transfer between units be reduced by air sealing, and at what cost?
- How much can airflow and contaminant transfer between units be reduced by better design, balance, or operation of mechanical ventilation systems, and at what cost?

Since testing and treatment of multifamily buildings is costly, the project did not provide complete answers to these questions. However, the results substantially improved our practical ability to reduce interunit airflows and, hence, the transfer of ETS in multifamily buildings in Minnesota. This paper presents a summary of the most significant findings from the field study. The project final report (CEE 2004) provides a more comprehensive description of the results.

METHODS

Building Treatments

Three approaches were used to reduce the ETS concentration in the nonsmoking units:

1. Ventilation systems in the smoking units were installed or upgraded to help dilute the ETS that was released in those units.

2. The transfer of ETS from the smoking units to the nonsmoking units was reduced by sealing the leakage paths between the units. In addition, the amount of ventilation in all of the units was balanced so that the ventilation system did not cause air to be drawn from one unit to another.
3. Ventilation systems in the nonsmoking unit were installed or upgraded to help dilute the ETS that was transferred to those units.

The design guideline for the ventilation systems was to achieve a continuous exhaust flow of not less than 25 cfm (11.8 L/s) in each unit and not more than a 5 cfm (2.4 L/s) difference in the flow rate of adjoining units. These systems were intended to augment natural air infiltration into the units and ensure a moderate level of ventilation in moderate weather. Air leakage paths were identified using visual inspections and adaptations of other building air sealing diagnostic methods typically used for single-family houses.

Measurements

The transfer of ETS between apartment units was characterized using two primary approaches: multiple fan pressurization tests and passive tracer gas methods. Those approaches were supplemented by measurements of nicotine and fine particulate mass. In the first year of the study, interunit air leakage, airflows, and contaminant transfer tests were conducted before and after both the air sealing and ventilation treatments were completed. In the second year of the study, the airflow and contaminant transfer measurements were also conducted between the air sealing and ventilation work so that the effect of the two treatments could be evaluated separately.

Multiple fan or guarded-zone air leakage tests were used to quantify the size of the building leakage paths and determine the effect of the air-sealing treatments on the magnitude of those leakage paths. A doorway-mounted, variable-speed fan was used to pressurize or depressurize the interior space by a measured amount. For the guarded-zone technique, the permeability of the internal walls, floors, or ceilings between adjacent units was determined by pressurizing the guarded (test) zone while a second fan was used to pressurize the adjacent zones to the same level as the guarded zone (Feustel 1989; Bohac et al. 1987; Furbringer et al. 1988; Modera et al. 1986; Levin 1988). All air leakage values were reported as the flow required to produce a pressure difference of 0.2 in. H_2O (50 Pa), which is commonly referred to as the *cfm50*.

A passive multiple perfluorocarbon tracer (PFT) gas method developed by Brookhaven National Laboratory (Dietz et al. 1985a, 1985b; Dietz 1988; AIVC 1991) was used to provide information on one-week average outdoor air ventilation rates to each unit, interunit airflow rates, and ETS transport between units in the building. A different type of PFT source was placed in each "tagged" apartment unit, and passive samplers were used to measure the average concentration of each PFT released in the building. The measured tracer concentrations and known emission rates were used to solve a system of steady-state mass and flow balance equations to provide an estimate of the airflow rates between each of the units and the outdoor air ventilation rate into each zone. When there were more units than types of tracer gases (seven), the treated units with sources were clustered together around the unit with the smoker. Also, any additional tracer gas source types were installed in a unit one floor up or down from the cluster to better track the expected stack effect or vertically dominated interunit airflow rates. Samplers were placed in any remaining test units to track the movement of the tracer gas sources.

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

A new metric, the effective contaminant transfer (ECT), was used to define the magnitude of the transfer of a contaminant source to the monitored location (e.g., where the exposure is taking place). The ECT is a function of the average source rate for the PFT gas released in a test unit T (S_T) and the average PFT concentration measured in the monitored unit M of the gas released in the test unit ($C_{M,T}$):

$$\mathrm{ECT}(M)_T = C_{M,T} / S_T \tag{1}$$

The ECT can be used to compute the concentration of a contaminant in the monitored unit for a known constant source rate in the test unit. Lower values of ECT indicate greater dilution or less transfer of the contaminant to the monitored unit. The advantage of the ECT for evaluating the effectiveness of the building treatments is that it takes into consideration the effect of changes in ventilation and ETS transfer between units on reducing the ETS concentration in the nonsmoking units.

One of the benefits of the ECT is that it can be used to calculate the concentration of a contaminant in one location for a situation where there are multiple source locations. For example, the concentration of a pollutant in unit M for a pollutant released at multiple other units in the building (1...n) can be easily determined by summing the source rate in each other unit (S_i) multiplied by the $\mathrm{ECT}(M)_i$ for a source released in the ith unit that is transferred to unit M:

$$C_M = \sum_{i=1}^{n} S_i \cdot \mathrm{ECT}(M)_i \tag{2}$$

In addition, the ECTs from several locations can be summed to determine the concentration that would occur in the monitored unit for a contaminant released uniformly in multiple locations in the building. The change in the sum of the ECTs from all the PFTs released in the building was used as an indicator of the relative effectiveness of the air sealing and ventilation treatments.

This method of computing contaminant transfer is only valid for contaminants that have sorption and air transport characteristics similar to the gases used to conduct the measurements—in this case nonsorbing PFTs. Recent studies have shown that more volatile ETS constituents (e.g., acetaldehyde, acrolein, acrylonitrile, benzene, 1,3-butadiene, and formaldehyde) have low levels of sorption and can be modeled by a nonsorbing tracer gas. These studies also show that the sorption of lower volatility hazardous air pollutants (e.g., cresols, naphthalene, and polycyclic aromatic hydrocarbons) and nicotine is significant and must be considered when monitoring or modeling those compounds (Singer et al. 2002, 2003). Since all of the compounds identified by Nazaroff and Singer (2004) as being of "particular concern as contributors to health risk from chronic, residential ETS exposure" were more volatile, tracer gases measurements will likely provide good exposure estimates for some of the more hazardous ETS compounds.

One-week measurements of nicotine and fine particle were conducted in a sample of the units to provide a direct measurement of the transfer of nicotine and particles between units. It was expected that the sorption of nicotine and filtering of fine particulates between apartment units would differ from that of the PFT gases. The results of those measurements and analysis are not included here, but are available in the project final report (CEE 2004).

RESULTS AND DISCUSSION

Test Buildings

The tests were conducted on six multifamily buildings, which were representative of those most commonly found in Minnesota. Census data and renter survey results were used to identify key characteristics for the six test buildings. The buildings were screened for number of units, age, number of stories, heating system type, and presence of bathroom/kitchen exhaust fans. In order to allow a better comparison between tracer gas and particle/nicotine measurements, tests were conducted in buildings that had smokers in a single unit or in a smoking unit that was isolated from other units with smokers.

The key characteristics of the six selected buildings are displayed in Table 1, along with information on the number of units tested and treated. It was decided that for the first year of the study the three buildings would have from 2 to 19 units; be built in or before 1970; have two or three stories, central hydronic heating, and recirculating hood kitchen fans; and be of frame construction. Two of the buildings had intermittently operated bathroom ceiling exhaust fans and one had a central exhaust system.

For the second year of the study there was switch in emphasis to larger buildings and buildings for which air sealing was more likely to be effective. Experience from the first year of the study indicated that it is often difficult to significantly reduce the interunit air leakage of existing, occupied units. One of the buildings (designated "11 Story") was selected to be typical of large public housing buildings, since those buildings are renovated more frequently. The other two buildings were selected to be representative of newer construction. Air sealing at the time of construction or renovation is expected to be more effective and less expensive than air sealing of existing, occupied buildings.

Existing Conditions

Tracer gas measurements confirmed that airflow between units in apartment buildings can be a significant concern. Before any air sealing or ventilation work was performed, every one of the six buildings had at least one unit for which more than 10% of the air entering the unit came from another unit (see Table 2). The units on the higher floors of the buildings had a greater fraction of air from other units or interunit airflow. When the results from all six buildings were combined, the average fraction of interunit flow was 2% for the units on the lowest floor, 7% for the units in the middle floors, and 19% for the units on the upper floors. This trend is due to the thermal stack effect during the heating season. Units on lower floors tend to get almost all of their air from outside and the units on the upper floors get a significant portion of their air from units below them.

The building average fraction of interunit airflow varied from 2% for a new four-story condominium to 12% for a three-story 12-plex. A 1930s up/down duplex had the highest value of 35%, and the median value for all of the units was 5%. These fractions were somewhat lower than the 13% to 26% range reported for three new three-story buildings in the Pacific Northwest (Francisco and Palmiter 1994). There was a general trend that the newer buildings had a lower fraction of interunit airflow. However, even two of the seven monitored units in the three-story apartment building built in 1999 had interunit airflows that were greater than 20% of the total airflow into the units.

As shown in Table 3, air leakage tests indicated that the median total air leakage for the individual units ranged from 454 to 2368 cfm50 (214 to 1118 L/s @ 50 Pa), and the median value for all units was 861 cfm50 (406 L/s @ 50 Pa). Not only was there a considerable difference in leakage between buildings, but for four of the buildings there was almost a factor of two difference between the tightest and leakiest units in the same building. Table 3 also displays the total leakage of individual units by building as indicated by the equivalent air leakage (ELA) for a reference pressure of 0.016 in. H_2O (4 Pa) and discharge coefficient of 1. The ELA provides a more intuitive indication of the level of air leaks in the unit envelope. The Leadership in Energy and Environmental Design (LEED®) Green Rating System for New Construction and Major Renovations requirement for ETS control of residential buildings where smoking is allowed specifies that the ELA of each unit must be less than 1.25 in.^{2} per 100 ft^2 of floor, ceiling, and wall area (LEED-NC 2005). As shown in Table 3, none of the units

Table 1. Building Characteristics

	First Year Buildings			Second Year Buildings		
Characteristic	Duplex	8-plex	12-plex	138-unit	11-story	4-story
# Units	2	8	12	138	178	38
# Tested/treated	2/2	8/8	6/6	8/14	7/12	7/7
# Stories	2	2	3	3	11	4
Const. year	mid-1930	1970	1964	1999	1982	2001
Type	Apartment	Condo.	Apartment	Apartment	Condo.	Condo./comm.*
Ext. cladding	Stucco	Brick	Stucco/brick	Stucco/brick	Brick	Stucco
Floor const.	2 × 10 in. wood frame	2 × 10 in. wood frame	2 × 10 in. wood frame	Poured concrete	Poured concrete	Open truss
Floor area, ft^2 (m^2)						
Unit type 1	Upper: 1140 (106)	1 bedroom: 704 (65)	All: 780 (72)	F: 1072 (100)	#10: 768 (71)	1 bedroom: 882 (82)
Unit type 2	Lower: 1140 (106)	2 bedroom: 918 (85)		G: 1140 (106)	#12: 1029 (96)	1 bedroom: 1000 (93)
Unit type 3				G1: 1236 (115)	#14: 1131 (105)	1 bedroom: 1028 (96)
Unit type 4				J: 1271 (118)		2 bedroom: 1445 (134)
Unit type 5				J mod: 946 (88)		2 bedroom: 1509 (140)
Unit type 6				Guest: 325 (30)		
Heating system	Central hydronic	Central hydronic	Central hydronic	Forced air furnace	Central hydronic	Forced air furnace
Cooling system	Window units	Thru-wall AC	Thru-wall AC	Indiv. ducted	Central hydronic	Indiv. ducted
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 hd. & contin.	Exhaust hood
Common area ventilation	None	None	None	Corridor supply/ return	Corridor supply/ return	Corridor supply/ return

*First floor has retail space and upper three floors are condominiums.

Table 2. Airflow from Adjacent Units Divided by Total Flow into a Unit

	Pretreatment (%)			After Sealing (%)			After Ventilation (%)			Change		
Building	Min.	Median	Max.	Min.	Median	Max.	Min.	Median	Max.	Min.	Median	Max.
Duplex	6%	35%	65%				19%	27%	34%	–30%	–9%	13%
8-plex	1%	3%	24%				3%	8%	42%	–1%	5%	18%
12-plex	1%	12%	26%				9%	12%	17%	–9%	1%	8%
138-unit	1%	11%	25%	1%	7%	22%	1%	1%	13%	–12%	–4%	0%
11-story	2%	5%	12%	1%	2%	9%	0%	1%	4%	–11%	–3%	–1%
4-story	1%	2%	10%	0%	2%	7%				–3%	–1%	1%
All units	1%	5%	65%	0%	3%	22%	0%	8%	42%	–30%	–1%	18%

Table 3. Total Air Leakage of the Individual Units

Building	Ref. Flow Rate (cfm50)			ELA (in.^{2})			NELA (si/100 ft^2)			
	Min	Median	Max	Min	Median	Max	Min	Median	Max	<1.25
Duplex	2101	2368	2636	115	130	145	3.16	3.56	3.97	0%
8-plex	837	1008	1031	46	55	57	1.93	2.04	2.46	0%
12-plex	731	917	1318	40	50	72	1.61	2.02	2.90	0%
138-unit	390	665	754	21	37	40	0.86	1.01	2.06	88%
11-story	376	454	958	21	25	53	0.57	0.76	2.14	86%
4-story	921	1156	1559	51	63	86	1.05	1.85	2.30	14%
All buildings	376	861	2636	21	47	145	0.57	1.66	3.97	22%

Table 4. Summary of Pre-/Post-Change in Inter-Unit Air Leakage

Building	Pretreatment (cfm50)			Post-Treatment (cfm50)			Leakage change (cfm50)			Leakage Change (%)		
	Min	Median	Max	Min	Median	Max	Min	Median	Max	Min	Median	Max
Duplex		466			518			52			11%	
8-plex*	492	504	654	419	454	501	–153	–74	–50	–23%	–15%	–10%
12-plex*	399	506	592	151	256	346	–355	–298	–53	–70%	–54%	–13%
138-unit	5	90	209	46	90	162	–80	–3	41	–38%	–4%	851%
11-story	73	141	159	89	104	215	–49	–25	56	–35%	–17%	40%
4-story	Not enough data											
All buildings	5	155	654	46	156	518	–355	–41	56	–70%	–16%	851%

* Leakage to adjacent units includes leakage to common area.

in the older buildings tested in the first year of the project meet this requirement. However, almost all of the units in the newer 138-unit building and 20-year-old 11-story condominium meet this standard.

The guarded-zone air leakage tests showed that the median air leakage to adjacent apartments was 155 cfm50 (73 L/s @50 Pa) and that the fraction of air leakage to adjacent units was 27% of the total leakage (see Table 4). As might be expected from the airflow results, the newer buildings generally had a lower fraction of interunit leakage than the older buildings. The detailed measurements of leakage to adjacent units also provided interesting information on the pattern of leakage within the buildings. For example, the interunit leakage for the stack of units adjacent to an elevator shaft in the 138-unit building was greater than that for other units in the building, and the horizontal leakage appeared to be of similar magnitude as the vertical leakage.

Change in Air Leakage After Sealing

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. There were many types of leaks common in all the buildings: baseboard/floor gaps, plumbing pipe penetrations, exhaust fan housing connection to walls, sprinkler pipe penetrations, and hydronic heat pipe penetrations between units. These areas were sealed using appropriate caulks and expanding foam. The common wall between the bathrooms of adjoining units was also an area of concern. There was often no drywall on the wall studs on the lower section of the wall area covered by the bathtubs. As a result, there was a huge open area between units that could be a source of air and contaminant transfer if the plumbing access was not properly sealed. Newer buildings often had leaky recessed lights that were treated with airtight inserts. Typically, four to five hours per unit was spent air sealing units in the 8-plex and 12-plex buildings, and that level of effort was increased to seven to ten 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 four-story building. A relatively new aerosol sealing process was used to achieve an 86% average reduction in duct leakage. The project final report (CEE 2004) includes a more thorough description and pictures of the air leakage sites and sealing techniques.

After the air sealing work was completed on all the buildings, the median total air leakage was reduced to 722 cfm50 (341 L/s @ 50 Pa) with a typical reduction of 139 cfm50

(66 L/s @ 50 Pa) per unit and a relative reduction of 18%. Figure 1 displays the pre-/post-interunit and total air leakage for the individual units. Except for the 4-plex chart, the blue shaded bars represent the interunit leakage and the red diagonal bars represent the leakage to the exterior or sum of exterior and common space. There was a significant variation in the pre-/post-change in total air leakage, with the expected trend of greater reductions in leakage for the leakier units. The pre-existing air leakage and level of air sealing efforts alone were not enough to predict the air leakage reduction. A similar amount of air sealing time was devoted to the units in the 138-unit and 11-story buildings, and they had similar pre-existing air leakages, yet four of the eight units in the 11-story building had reductions greater than 125 cfm50 (59 L/s @ 50 Pa), while only one of the units in the 138-unit building had a reduction greater than 100 cfm50 (47 L/s @ 50 Pa). There were significant differences in the reduction in interunit leakage between buildings. The duplex, 138-unit, and 11-story buildings all had median reductions that were within the measurement error of the guarded-zone technique. This result is not surprising for the 138-unit and 11-story buildings, since the pre-existing interunit leakage was less than 210 cfm50 (99 L/s @ 50 Pa) for all of the units, and five of the units in the 138-unit building had leakages less than 100 cfm50 (47 L/s @ 50 Pa). It is encouraging that the interunit leakage of the 12-plex units was typically reduced by 54% and that there were moderate (15%) interunit leakage reductions for the 8-plex. One explanation for the success of the air sealing at the 12-plex was that a concentrated leakage path (e.g., the plumbing chase) was present, identified, and sealed.

It is also possible that in some of these units there were significant leaks that were sealed, but the sealing did not result in a measurable change in the interunit leakage. Air leakage paths are often thought of as discrete and direct leaks between units. In reality, multiple air leaks through a wall, floor, or wall/floor interface are often connected to an intermediate area between units, such as a floor cavity or mechanical chase. The restriction in the airflow between units can be a combination of the restriction due to the leaks from one unit into a plumbing chase and the leaks from the plumbing chase into the next unit or common area. When the leakage between the plumbing chase and the next unit is smaller than the leaks from the unit being treated, it is possible to seal most of the leaks in the unit without having a measurable effect on the resistance of the entire leakage path. In addition, when that wall or floor cavity is connected to other units beyond the adjacent unit, the air leakage reduction measured by the guarded zone test can show up as a reduction in the total leakage with little or no reduction to the adjacent unit.

Change in Airflow After Treatments

The ventilation work included installing new multipoint exhaust systems and replacing existing bathroom ceiling exhaust fans with a quieter model rated for continuous operation. The cost of the improvements ranged from $170 per unit to modifications to the central exhaust system to $450 per unit for the installation of new ceiling exhaust or multipoint exhaust systems. The work on existing central exhaust systems typically included cleaning out the debris from the ducts, installing a constant air regulator at the inlet register of each duct, and removing the adjustable louvers. For the central exhaust system in the 138-unit building, large leaks in the main vertical shaft did not allow the rooftop fan to draw air from the units on the lower floors. The aerosol sealing process was used to reduce the duct leakage from 65% down to 23% to 34%. Through the combination of duct sealing and removing restrictions from the upper section of the exhaust shaft, the system was able to achieve a near-uniform exhaust flow from the units on the upper and lower floors. Based on tracer gas measurements, before treatments only 23% of the units met the *ANSI/ASHRAE Standard 62-2001, Ventilation for Acceptable Indoor Air Quality*, minimum ventilation requirement. That fraction increased to 60% after the ventilation work was completed. Three of the buildings (8-plex, 12-plex, and 11-story) had all or all but one of their units in compliance.

The air sealing appeared to result in a consistent, but small, reduction in the fraction of interunit airflow. The fraction of interunit airflow for individual units is displayed in Figure 2. After both air sealing and ventilation treatments were complete, three of the six buildings had reductions in the median fraction of interunit flow rate of 3% or greater (see Table 2). The fraction for the 11-story building decreased from 5% to 1%, and the 138-unit building decreased from 11% to 1%. Not surprisingly, the largest reduction occurred for the duplex, which had the highest pre-existing fraction of interunit airflow. In general, the fractions decreased for the units in the upper floors of the buildings and increased slightly in the units on the lower floors of the buildings.

Change in Contaminant Transfer After Treatments

The ECT was found to provide the best method for evaluating the combined effect of the air sealing and ventilation treatments on ETS transfer. As shown in Table 5, before treatments the average ECT for all of the units was 45.6 $h/f^3 \times 10^{-6}$ or 45.6 $\mu h/f^3$ (5.80 s/m^3). Four of the buildings (duplex, 8-plex, 12-plex, and 138-unit) had ECTs greater than 50 $\mu h/f^3$ (6.36 s/m^3), and the two others (11-story and 4-story) were below 25 $\mu h/f^3$ (3.18 s/m^3). The four buildings with the highest ECTs generally had the highest fraction of interunit airflow. For the three buildings in the second year of the study, the ECTs were calculated after the air sealing work was completed. The relative reduction ranged from 29% for the 11-story building to 43% for the 4-story building and the ECT was reduced for 81% of the treated units. It is interesting that the relative change in the ECT for the 138-unit and 11-story buildings is significantly higher than the relative change in the measured interunit air leakages (4% and 17%). The measured reductions in ECT indicate that the air sealing in the two buildings was more effective in reducing contaminant transfer than indicated by the guarded zone air leakage measurements.

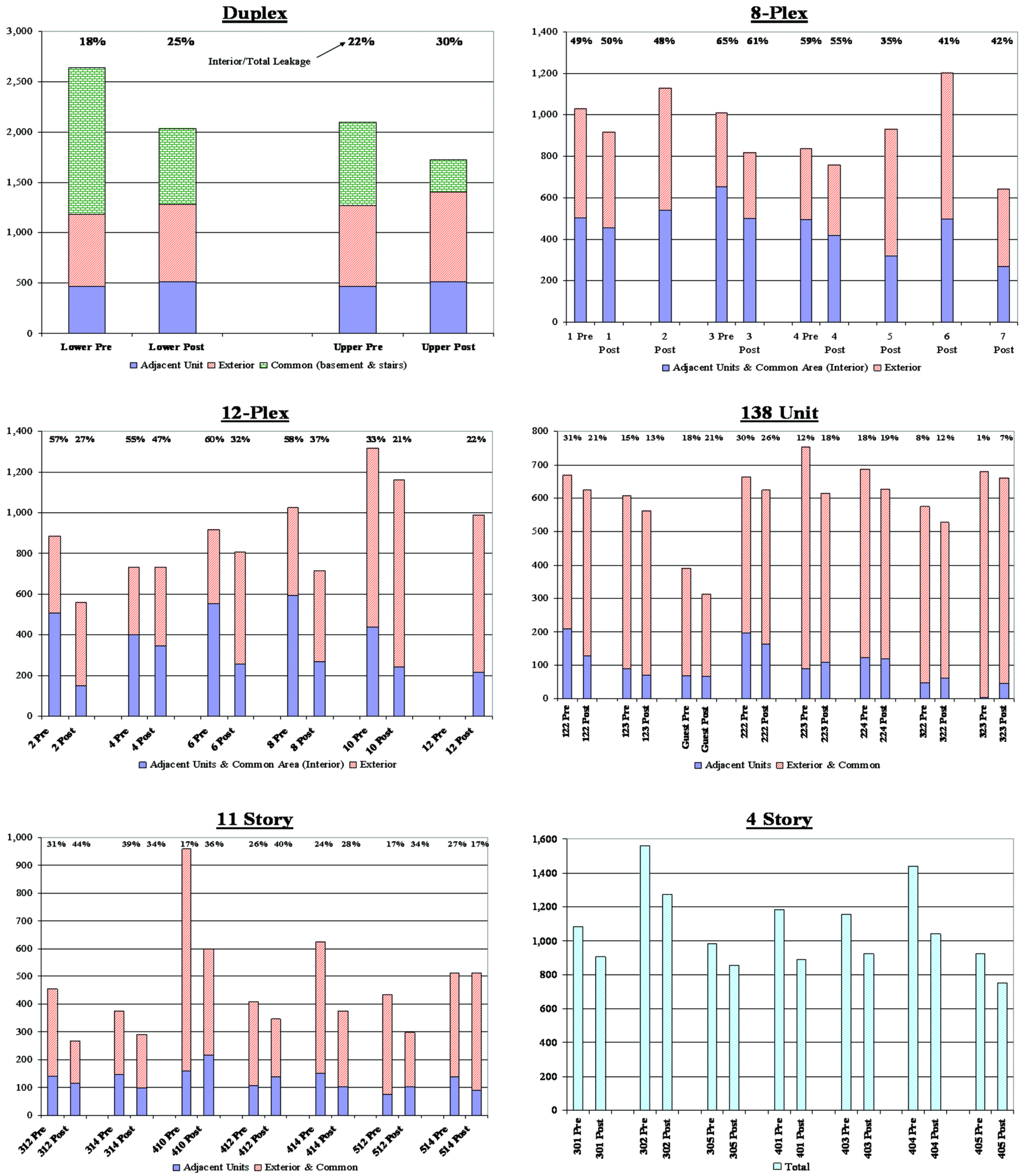

Figure 1 *Pre-/post-air leakage of individual test units (cfm50).*

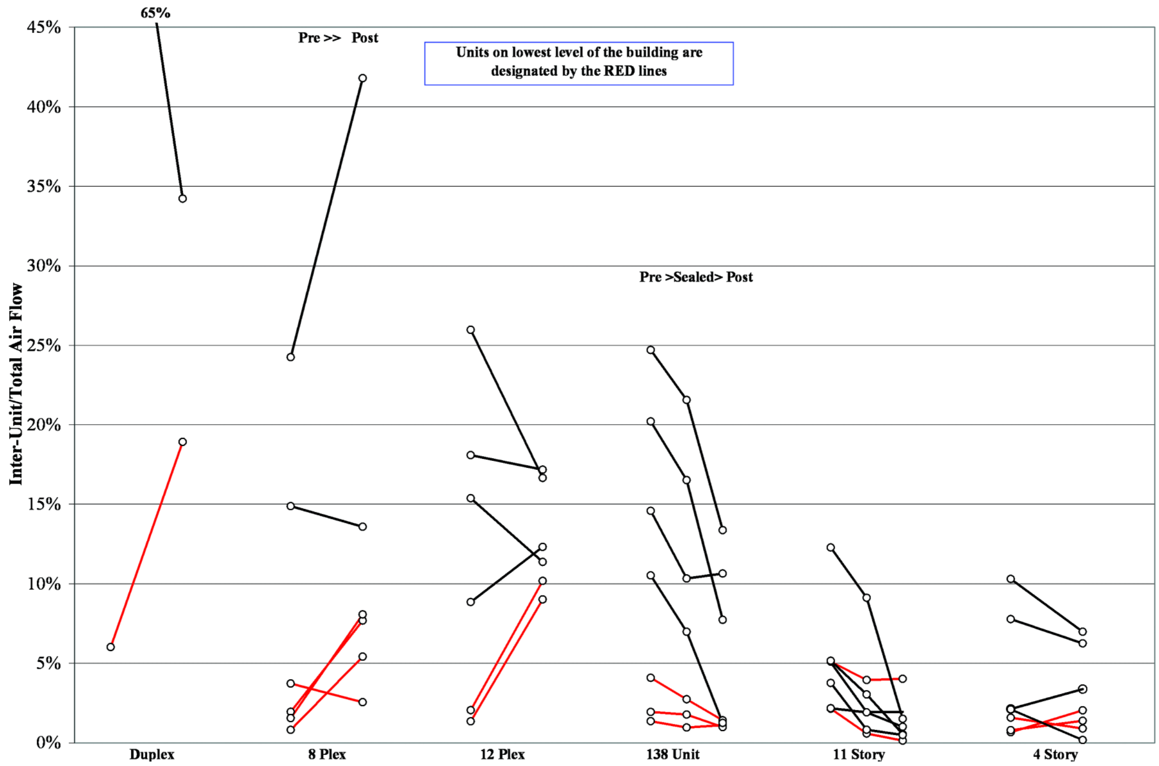

Figure 2 *Pre-/post-change in airflow from adjacent units divided by total flow into a unit.*

Table 5. Pre-/Post-Building Average ECT and Change for All Monitored Units

Building	Pre	Seal	Vent/Post	Change After Air Sealing			Change After Ventilating and Sealing		
				(μh/ft^3)	%	% Red*	(μh/ft^3)	%	% Red*
Duplex	82.2		67.2				–15.0	–18%	67%
8-plex	52.8		53.6				0.8	2%	38%
12-plex	59.3		27.9				–31.4	–53%	67%
138-unit	59.5	40.3	20.3	–19.2	–32%	100%	–39.2	–66%	100%
11-story	25.5	18.0	3.2	–7.5	–29%	86%	–22.3	–87%	100%
4-story	16.4	9.4	9.4	–7.0	–43%	57%	–7.0	–43%	57%
All buildings	45.6	22.6	27.1	–23.1	–51%	81%	–18.6	–41%	71%

* Percent of units with pre-/post-reduction in ECT.

The post-treatment reduction in ECT for the test units in all six buildings averaged 18.6 μh/f^3 (2.36 s/m^3) or 41% of the pretreatment value. Overall, 71% of the units had a reduction in ECT, and 58% of the units had a reduction greater than 50%. Figure 3 displays the pre-/post-ECT for individual units. Increases in ECT generally occurred for units on the lower levels, which already had low ECTs. The installation of continuous ventilation caused the pressure dynamics to change so that it was more likely for air to be drawn from adjacent units. For many of the lower units, this resulted in a small increase in interunit airflow and ECT. An analysis of the results for individual units indicates that the ECTs from lower units to units on the floor above are almost always greatest for the unit that is directly above. This suggests that the airflow is most likely through air leaks in the building structure and not via common areas.

CONCLUSIONS

The field studies provided useful information on both the air leakage and airflow characteristics of the existing buildings and the changes that occur after air sealing and ventilation treatments are applied to the buildings. Before any air sealing

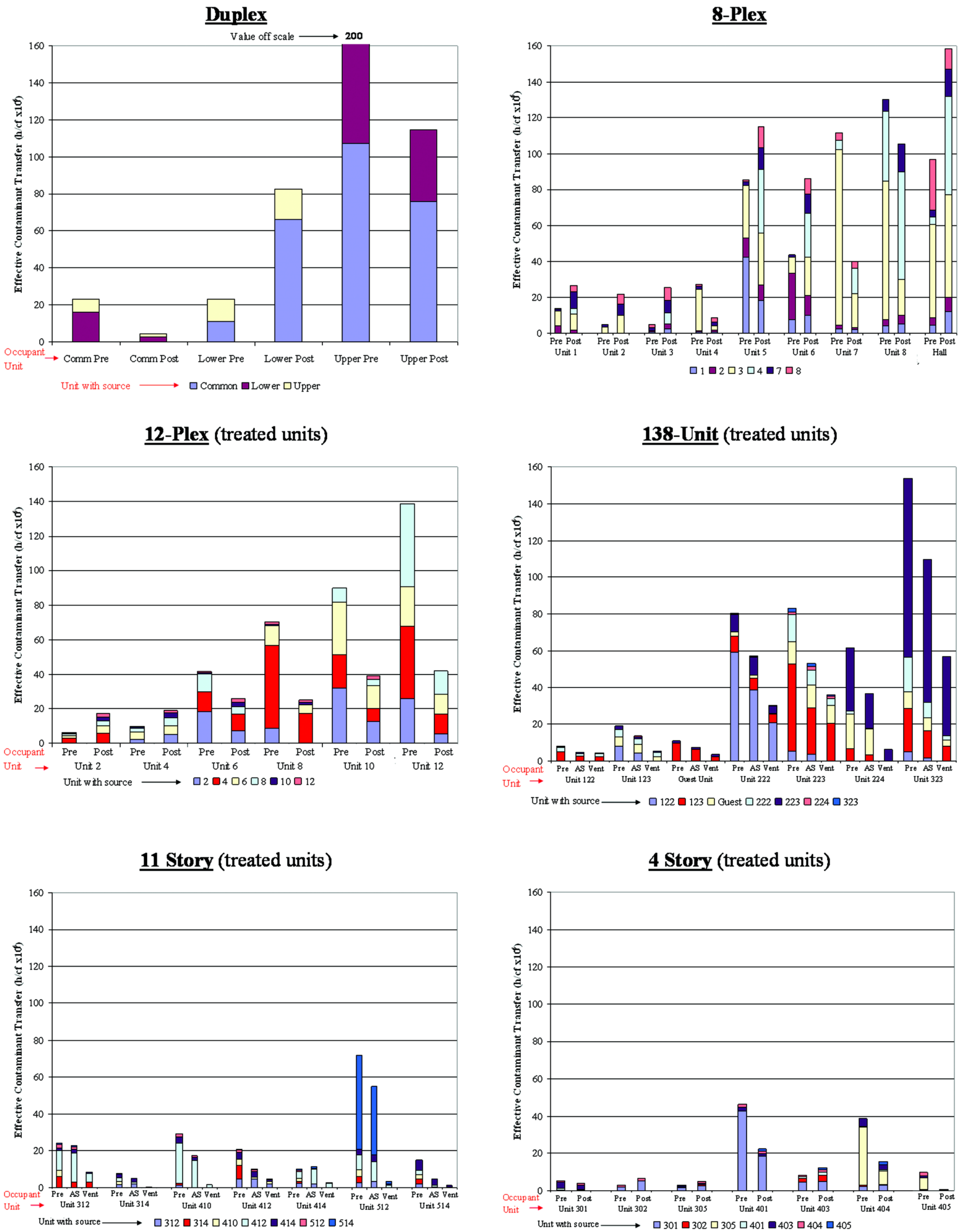

Figure 3 *Pre-/post-effective contaminant transfer of individual units.*

or ventilation work was performed, the median total air leakage for the individual units ranged from 454 to 2368 cfm50 (214 to 1118 L/s @50 Pa). For four of the buildings there was almost a factor of two difference between the tightest and leakiest units in the same building. This indicates that for most multifamily buildings, measurements must be conducted on a significant sample of units in order to accurately determine the average air leakage of all the units, and the air leakage of each unit was known to be measured with much accuracy. None of the units in the older buildings tested in the first year of the project meet the LEED-NC requirement for normalized ELA of 1.25 in.^{2} per 100 ft^2 of envelope area (LEED-NC 2005). Almost all of the units in the newer 138-unit building and 20-year-old 11-story condominium meet this standard. This implies that the LEED's air leakage requirement can be met using standard construction practices and, given that occupants in those buildings have ETS transfer complaints, suggests that the requirement may not be sufficient to adequately mitigate against ETS transfer. Further field studies are required to confirm this assumption.

The median air leakage to adjacent apartments was 155 cfm50 (73 L/s @50 Pa) and the fraction of air leakage to adjacent units was 27% of the total leakage. The newer buildings generally had a lower fraction of interunit leakage than the older buildings. Week-long tracer gas tests showed that every one of the six buildings had at least one unit for which more than 10% of the air entering the unit came from another unit. The units on the higher floors of the buildings had a greater fraction of air from other units or interunit airflow. When the results from all six buildings were combined, the average fraction of interunit flow was 2% for the units on the lowest floor, 7% for the units in the middle floors, and 19% for the units on the upper floors. The median value for all of the units was 5%. There was a general trend that the newer buildings had a lower fraction of interunit airflow.

Typically four to five hours per unit was spent air sealing units in the 8-plex and 12-plex buildings and that level of effort was increased to seven to ten hours per unit for the three buildings in the second year of the study. There was no significant reduction in the interunit leakage for the duplex, 138-unit, and 11-story buildings. This might have been expected for the 138-unit and 11-story buildings, since the pre-existing interunit leakage was less than 210 cfm50 (99 L/s @50 Pa) for all of the units and five of the units in the 138-unit building had leakages less than 100 cfm50 (47 L/s @50 Pa). There were moderate (15%) interunit leakage reductions for the 8-plex and a reduction of 54% for the 12-plex units. For the 12-plex there was a concentrated leakage path (e.g., the plumbing chase) that was present, identified, and sealed. The air sealing appeared to result in a consistent, but small, reduction in the fraction of interunit airflow. It is recommended that air sealing of existing multifamily 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. The difficulty in addressing many leakage paths indicates that air sealing should be much more effective at the time of construction or major remodelling.

The ventilation work included the installation of new multipoint exhaust systems and replacing existing bathroom ceiling exhaust fans with a quieter model rated for continuous operation. The cost of the improvements ranged from $170 per unit for the work on the central exhaust systems to $450 per unit for the installation of new exhaust systems. Tracer gas measurements indicated that before treatments only 23% of the units meet ASHRAE Standard 62-2001 minimum ventilation requirements, and the compliance increased to 60% after the ventilation work was completed. Three of the buildings had all or all but one of their units in compliance. After both air sealing and ventilation treatments were complete, three of the six buildings had reductions in the median fraction of interunit flow rate of 3% or greater. The fraction for the 11-story building decreased from 5% to 1% and the 138-unit building decreased from 11% to 1%. In general, the fractions decreased for the units in the upper floors of the buildings and increased slightly in the units on the lower floors of the buildings.

A new metric, the effective contaminant transfer (ECT), was used to define the magnitude of the transfer of a contaminant source to the monitored location (e.g., where the exposure is taking place). The ECT was found to provide the best method for evaluating the combined effect of the air sealing and ventilation treatments on ETS transfer. Before any work was completed in the buildings, the four buildings with the highest ECTs generally had the highest fraction of interunit airflow. After air sealing was completed, the relative reduction of the ECT ranged from 29% for the 11-story building to 43% for the 4-story building, and the ECT was reduced for 81% of the treated units. This was significantly higher than the relative change in the measured interunit air leakages (4% to 17%), which suggests that the air sealing was more effective in reducing contaminant transfer than indicated by the interunit air leakage measurements.

After the air sealing and ventilation improvements were completed, 71% of the units had a reduction in ECT and 58% of the units had a reduction greater than 50%. The results suggest that the installation of continuous ventilation caused the pressure dynamics to change so that it was more likely for air to be drawn from adjacent units. In addition, it appears that verticle air transfer is most likely through air leaks in the building structure and not via common areas. The significant reduction in contaminant transfer and improvement in the ventilation rates indicates that the installation of continuous, balanced ventilation contributed significantly to the reduction in the ETS in nonsmoking units.

ACKNOWLEDGMENTS

This research project was funded in part by ClearWay Minnesota. Any public dissemination of information relating to the grant was made possible by Grant Number RC 2000 0015 from ClearWay Minnesota. The contents of this paper

are solely the responsibility of the authors and do not necessarily represent the official views of ClearWay Minnesota.

The authors wish to thank Dr. Katherine Hammond and the staff at the Environmental Health Sciences Department at the University of California, Berkeley, who analyzed the nicotine samplers and provided input on the field monitoring procedures. We would also like to thank Dr. Russell Dietz and the staff of the Tracer Technology Center at Brookhaven National Laboratory who analyzed the PFT samplers and assisted in the design of the PFT measurements.

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