
**Reduction of Environmental Tobacco Smoke Transfer
in Minnesota Multifamily Buildings
Using Air Sealing and Ventilation Treatments**

November 2004



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SUMMARY

Objectives

This study was completed as part of a research project focused on environmental tobacco smoke (ETS) in apartment buildings. Minnesota renters, who comprise 25.4% of Minnesota households and who disproportionately include minorities, low income households, and young adults, have no guarantee of a smoke-free place to live. As a result, they are sometimes exposed to environmental tobacco smoke (ETS) entering their apartments from other apartments, from hallways or other common areas of their building, or from balconies, patios or grounds outside the building -- a phenomenon that we refer to here as “ETS transfer” or “secondhand smoke transfer.” The two goals of this project are to build a sound base of knowledge that will facilitate the designation of smoke-free apartment buildings and the treatment of smoking permitted buildings to minimize ETS transfer.

This report summarizes the results from field studies to evaluate the effectiveness of air sealing and ventilation treatments to reduce ETS transfer. The primary questions addressed in this project are:

- What are typical contaminant dispersion and air flow 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 air flow 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 air flow and contaminant transfer between units be reduced by air sealing, and at what cost?
- How much can air flow 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, this project does not provide complete answers to these questions. However, the results substantially improve our practical ability to reduce inter-unit air flows and hence the transfer of ETS in multifamily buildings in Minnesota.

Methodology

Building Treatments

Three approaches were used to reduce the ETS concentration in the nonsmoker’s units:

1. Ventilation systems in the smoker’s unit were installed or upgraded to help dilute the ETS that was released in those units.

2. The transfer of ETS from the smoker's units to the nonsmoker's 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 nonsmoker's unit were installed or upgraded to help dilute the ETS that was transferred to those units.

All three approaches were applied to the test buildings. Leaks between units were expected to include obvious (i.e. gaps around hydronic heating pipes and plumbing penetrations) and hidden leaks (cracks between the floor and the wall that were hidden behind baseboards and gaps in the floor or ceiling around pipes located in mechanical chases). Specific leakage sites were identified using visual inspections and adaptations of other building diagnostic methods typically used for single family houses. The goal for the ventilation systems was to achieve a continuous exhaust flow of not less than 25 cubic feet per minute (cfm) in each unit and not more than a 5 cfm 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.

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. Inter-unit air leakage, air flows, and contaminant transfer were studied before and after air sealing and ventilation improvements were applied to selected units in the buildings.

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 is determined by pressurizing the guarded (test) zone while a second fan is used to pressurize the adjacent zones to the same level as the guarded zone. All air leakage values are reported as the flow required to produce a pressure difference of 50 pascals, which is commonly referred to as the cfm50.

A passive multiple perfluorocarbon tracer (PFT) gas method was used to provide information on one week average outdoor air ventilation rates to each unit, inter-unit air flow 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 air flow 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 inter-unit air flow rates. Samplers were placed in any remaining test units to track the movement of the tracer gas sources. In the first year of the study the one week monitoring was conducted before and after both the air sealing and

ventilation treatments were completed. In the second year of the study the measurements were also conducted between the air sealing and ventilation work so that the effect of the two treatments could be evaluated separately.

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 simply the average concentration measured in the monitored unit of the PFT gas released in the test unit divided by the average source rate for that PFT gas. The ECT can be used to compute the concentration of a contaminant in the monitored unit for a known 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 all three approaches to reducing the ETS concentration in the nonsmoking units:

1. Continuous ventilation to dilute ETS in the smoker's unit.
2. Air sealing and balancing ventilation to reduce ETS transfer from the smoker's to nonsmoker's unit.
3. Continuous ventilation to dilute ETS in the nonsmoker's unit.

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 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.

Nicotine and fine particulate measurements were conducted in a sample of the units to provide a direct measurement of the transfer of ETS between units. Nicotine is commonly used as a marker for ETS because there are accurate methods for measuring the levels typically produced by smoking in indoor areas and ETS is typically the dominant or only significant source of nicotine in indoor air. Nicotine was monitored using passive samplers. Fine particulate measurements were included because the concentrations produced by smoking are measurable and a health concern. Fine particulate (PM_{2.5}) concentrations were measured using a constant flow rate sample pump to draw air through a particulate monitor that consisted of a single-stage impactor with an after-filter. It was expected that the sorption of nicotine and filtering of fine particulates between apartment units would differ from that of the PFT gases. One of the project goals was to collect preliminary information on nicotine sorption and fine particulate filtration as those ETS constituents are transferred between apartment units.

Tenant Surveys

For the second year of the study the participating residents were asked to complete two questionnaires. The pre-treatment questionnaire focused on the resident's concern with tobacco smoke or odor transfer into their unit, how the transfer occurred, the seasonality of the problem, and the location of the smokers in the building. The post-treatment questionnaire included questions regarding the change in the frequency/strength of tobacco smoke/odor transfer, whether changes were due to the treatments, their level of satisfaction with the work, and willingness to pay for the work.

Test Buildings

The tests were conducted on six multifamily buildings which were representative of those most commonly found in Minnesota. The results from renter surveys showed an increase in reported problems with building age, but no significant correlation of problems with number of stories or number of units. Census data and renter survey results were used to identify key characteristics for the six test buildings. In addition to the number of units, the buildings were screened for age, number of stories, heating system type, and presence of bathroom/kitchen exhaust fans. Finally, in order to allow a better comparison between tracer gas and particulate/nicotine measurements it was best to have smokers in a single unit in the building or in a unit that was isolated from other units with smokers.

It was decided that for the first year of the study the three buildings would be selected from the smaller size ranges (2 to 4, 5 to 9 and 10 to 19 unit buildings). The duplex, 8-plex, and 12-plex buildings met all of the selection criteria. They were all built on or before 1970, had two or three stories, central hydronic heating, recirculating hood kitchen fans, and were of frame construction. The duplex and 12-plex units had intermittently operated bathroom ceiling exhaust fans and the 8-plex 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 inter-unit air leakage of existing, occupied units. As a result, one of the buildings was selected to be typical of large public housing buildings. Since those buildings are renovated more frequently, there is more opportunity for greater access to allow more extensive air sealing. An 11 story condominium built in 1982 with concrete floors was selected to be representative of large public housing. The other two buildings were selected to be representative of newer construction. Air sealing at the time of construction is expected to be more effective and less expensive than air sealing of existing buildings, so developing information relevant to current construction was important. One of the two remaining buildings is a 138 unit, three story walkup apartment building built in 1999. The second is a 38 unit, four story condominium built in 2001. Both buildings have individual forced air heating in the units

Results and Discussion

Existing Conditions

Tracer gas measurements confirmed that air flow 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. The units on the higher floors of the buildings had a greater fraction of air from other units or inter-unit air flow. When the results from all six buildings were combined, the average fraction of inter-unit 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 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. As a result, units on lower floors tend to get 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 inter-unit air flow 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 inter-unit air flow. However, even two of the seven monitored units in the three-story apartment building built in 1999 had inter-unit air flows that were greater than 20% of the total air flow into the units.

Air leakage tests indicated that the median total air leakage for the individual units ranged from 454 to 2,368 cfm₅₀ and the median value for all units was 861 cfm₅₀. Not only was there a considerable difference in leakage between buildings, but for four of the buildings there was 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. In addition, the air leakage for each individual unit can only be determined by measuring the air leakage. The guarded zone tests showed that the median air leakage to adjacent apartments was 155 cfm₅₀ and that the fraction of air leakage to adjacent units was 27% of the total leakage. As might be expected from the air flow results, the newer buildings generally had a lower fraction of inter-unit 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 inter-unit 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.

After Building Treatments

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 air-tight 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 4 Story building. A relatively new aerosol sealing process was used to achieve an 86% average reduction in duct leakage.

After the air sealing work was completed on all the buildings, the median total air leakage was reduced to 722 cfm50 with a typical reduction of 139 cfm50 per unit and a relative reduction of 18%. 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 while only one of the units in the 138 Unit building had a reduction greater than 100 cfm50. There were significant differences in the reduction in inter-unit 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 inter-unit leakage was less than 210 cfm50 for all of the units and five of the units in the 138 Unit building had leakages less than 100 cfm50. It is encouraging that the inter-unit leakage of the 12-Plex units was typically reduced by 54% and that there were moderate (15%) inter-unit 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 eliminated.

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 inter-unit 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 often are connected to an intermediate area between units such as a floor cavity or mechanical chase. The restriction in the air flow between units can be a combination of the restriction due to the leaks from the 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.

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 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 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. Before treatments only 23% of the units meet ASHRAE 62-2001

minimum ventilation requirement and 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 inter-unit air flow. After both air sealing and ventilation treatments were complete, three of the six buildings had reductions in the median fraction of inter-unit 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%. Not surprisingly, the largest reduction occurred for the Duplex which had the highest pre-existing fraction of inter-unit air flow. 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.

The effective contaminant transfer (ECT) was found to provide the best method for evaluating the effect of the air sealing and ventilation treatments on ETS transfer. The average ECT for all of the units was $45.6 \text{ h/cf} \times 10^{-6}$. Four of the buildings (Duplex, 8-Plex, 12-Plex and 138 Unit) had pre-treatment ECTs greater than $50 \text{ h/cf} \times 10^{-6}$ (or $\mu\text{h/cf}$) and the two others (11 Story and 4 Story) were below $25 \mu\text{h/cf}$. The four buildings with the highest ECTs generally had the highest fraction of inter-unit air flow. 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 buildings¹ is significantly higher than the relative change in the measured inter-unit 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.

The post-treatment reduction in ECT for the test units in all six buildings averaged $18.6 \mu\text{h/cf}$ or 41% of the pre-treatment value. Overall, 71% of the units had a reduction in ECT and 58% of the units had a reduction greater than 50%. 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 inter-unit air flow 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 air flow is most likely through air leaks in the building structure and not via common areas.

ETS Measurements

For the three units where there was heavy smoking, the nicotine levels ranged from 0.22 to $1.14 \mu\text{g/cf}$ (7.8 to $40.2 \mu\text{g/m}^3$). The nicotine concentrations in the nonsmoker's units were very low. The median values for the different monitoring periods ranged from 0.0 to $0.016 \mu\text{g/cf}$ (0.0 to $0.57 \mu\text{g/m}^3$). A comparison of the concentrations in the smoker's and nonsmoker's units indicates that most nonsmokers in an apartment building will be exposed to nicotine

¹ Inter-unit air leakage was not available for the 4 Story building.

concentrations that are less than 1% of that in the smoker's unit. The low nicotine levels in the nonsmoker's units and changes in the patterns of smoking did not allow the nicotine measurements to be used to evaluate the effectiveness of the air sealing and ventilation treatments. The nicotine measurements were used to compare the rate of transfer of nicotine and PFT between units. The results indicate that the PFT transfer rate ranges from 2 to 10 times greater than the nicotine transfer rate, with a median value of about 6.

There were numerous problems with the particulate measurements that limited the use of those results. The concentration of PM_{2.5} in the smoker's units ranged from 2.0 to 7.1 µg/cf (71 to 250 µg/m³). The median concentration of PM_{2.5} in the nonsmoker's units ranged from 0.13 to 0.20 µg/cf (4.8 to 7.0 µg/m³). A comparison of the fine particulate concentrations in the smoker's and nonsmoker's units indicates that most nonsmokers in an apartment building will be exposed to PM_{2.5} concentrations that are less than 10% of that in the smoker's unit. The high and variable background levels of PM_{2.5} did not allow the measurements to be used to evaluate the effectiveness of the treatments. However, the measurements were used to indicate that at least 75% of the particulates are filtered as they are transferred between units. This rate is about twice as high as the 37% and 43% filtration rate of PM_{1.0} particles moving through the exterior envelope of a house reported by CMHC (2003b). Further measurements in a building with a higher transfer rate and low background level of PM_{2.5} would be necessary to better quantify the filtration of PM_{2.5} particles as they move between units in a multifamily building.

Tenant Surveys

Before any work was performed, 48% of the residents indicated that they had tobacco smoke entry into their unit at least some time during the previous year and 10% said that the entry occurred often or most of the time. A total of 91% of the residents said the frequency of tobacco smoke entry was reduced after the air sealing and ventilation work was completed and 55% said it entered much less often. Over 80% of the residents felt that the tobacco smoke odors were much or somewhat weaker than before the treatments and no residents felt that tobacco smoke odors were more frequent or stronger. Overall, the questionnaire results indicate that the residents were very pleased with the improvement in the smoke transfer problem, but only half attributed the improvement to the treatments and about 10% would be willing to pay an amount close to the value of the work.

Implications

This study was able to identify a number of useful recommendations for future studies of ETS transfer in multifamily buildings and methods to reduce the transfer of ETS:

- Nicotine and particulate measurements in multifamily buildings are useful for determining the typical or maximum concentration of those constituents when the concentration in the smoker's apartment is known. They are also helpful in understanding the nicotine absorption and particulate filtering that occurs when ETS is transferred between units. The uncertainties with nicotine absorption, particulate filtering, intermittent smoking from multiple locations, and variable indoor particulate sources do not allow measurements of nicotine or particulate concentrations to be

used to reliably evaluate the effectiveness of building treatments on ETS transfer in multifamily buildings.

- The PFT method provides a simple and accurate method for evaluating the movement of nonsorbing contaminants in buildings. PFTs can be used to simultaneously evaluate the movement of up to seven contaminants over long time periods.
- There is a significant concern regarding ETS transfer in multifamily buildings. Almost half of renters surveyed reported experiencing it in their current apartments and almost two-thirds had experienced it in some apartment they had lived in. Ten percent of renters say ETS comes into their apartments from elsewhere often or most of the time.
- 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. Continuous ventilation that is balanced between units provides a significant benefit and should typically cost of \$300 to \$500 per unit.
- There needs to be more focus on air sealing at the time of construction or major remodeling. Many air leakage paths can not be sealed after construction is complete or when the unit is occupied. Effective continuous ventilation is also less expensive to install at the time of construction.
- It is probably best to use the total air leakage of each unit for any new construction or existing building performance standard. Both the interior and exterior air leakages of each unit are important in multifamily buildings. The total leakage includes both interior and exterior leakage and the total leakage test is much easier to implement than the guarded zone technique. In addition, the pressure between units during the leakage test can be used as an indicator of the leakage between units.

BACKGROUND

Environmental tobacco smoke (ETS) is a significant indoor air quality concern in US residences. Exposure to ETS has been linked to an increased risk of many adverse health outcomes, including lung cancer, asthma onset and exacerbation, and acute respiratory illness (National Cancer Institute, 1999). ETS is comprised of a complex dynamic of over 4,000 gas and condensed phase compounds. Some of these are regulated by the US federal government as hazardous air pollutants (US Environmental Protection Agency, 2003). A recent study by Nazaroff and Singer (2004) modeled the exposure of a typical nonsmoker who lives with smokers in a single family residence to 16 hazardous air pollutants (HAPs) that exist in sidestream cigarette smoke. They found potential concern for noncancer health effects from chronic exposures to four of the HAPs and substantial lifetime cancer risks (~2 to 500 per million) for five known or probable human carcinogens.

The actual exposure of a nonsmoker in a single family house depends on numerous factors including: number of cigarettes smoked, location of the smoker and nonsmoker, size of the house, degree of isolation between the smoker/nonsmoker by closed doors and walls, air infiltration rate/pattern, ventilation system operation, operation of air filters, and mixing of house air due to forced air or ventilation system fans. For example, a study by Miller-Leiden and Nazaroff (1996) used a multi-zone indoor air model to determine that the ETS concentration in a downstairs area was about 75% lower than that for an upstairs area with a smoker and that operation of a portable air filter in the smoker's room reduced concentrations by 15 to 30%. In another study of 69 smoking and nonsmoking homes in Manchester England (Gee et al. 2002), samples of numerous ETS markers showed that levels are significantly higher in the living room than the children's bedroom. While such studies of ETS exposure in single family residences are extremely important, they largely ignore exposure for a significant portion of the population – renters in multifamily buildings.

The 2000 Census¹ reported that renters accounted for 25.4% of all Minnesota households and rental households disproportionately include minorities, low income individuals, and young adults – populations of significant concern for smoking cessation. Most renters have no guarantee of a smoke-free place to live and about half report ETS entry into their units from other apartments, common areas of the building, or from outside the building (CEE 2001a). The goal of this project is to build a sound base of knowledge that will facilitate two types of actions to reduce renters' exposure to ETS in their homes:

- designation of smoke-free apartment buildings, and
- treatment of smoking-permitted buildings to minimize transfer of ETS among units.

¹ Based on information from the Minnesota State Demographer's internet site at <http://front.mnplan.state.mn.us/demography/Cen2000profiles/cen00profhouse.html>

The project includes four interrelated applied research activities:

1. **Qualitative interviews of multifamily building owners and managers.** These interviews provide an understanding of the barriers and information needs owners face in addressing smoke-free buildings and ETS transfer between units.
2. **A survey of a stratified random sample of Minnesota renters.** This survey quantifies the extent and severity of perceived problems with ETS transfer among renters, both overall and within population groups of key concern to the Minnesota Partnership for Action Against Tobacco (low income households, young adults, and minorities¹). It provides solid information on the marketability of smoke-free rental housing and the importance of ETS-free units to renters, both overall and by market segment. It also provides data on the distribution of reported problems with ETS transfer by building type and location within buildings.
3. **Legal research.** Technical legal research summarizes the status of the law with regard to designation of smoke-free buildings and taking or failing to take actions to minimize ETS transfer in smoking-permitted buildings. It examines federal and state legislation, regulations, case law, and secondary sources in the areas of landlord-tenant law, civil rights law, negligence/tort law, and nuisance and environmental rights law. The research provides the information necessary to develop a model smoke-free lease clause, and to identify changes to statutes, ordinances and regulations that would facilitate smoke-free rental housing and reductions in ETS transfer in smoking-permitted housing.
4. **Buildings research.** This research quantifies contaminant dispersal and air movement among units in a sample of multifamily buildings in Minnesota, using passive perfluorocarbon tracer gas techniques, multiple fan depressurization and air flow modeling, supplemented by measurements of fine particulate mass and nicotine. The work focuses on those building types found in Task 2 to have the greatest problems. After testing to diagnose the causes of unwanted air transfer, air leaks in the building structure are sealed and the ventilation system(s) are upgraded. The tests are repeated to determine the effect of the air sealing and ventilation improvements. Successful treatments are identified and associated costs quantified.

The results from the first three tasks have been published in previous reports (CEE 2001a, CEE 2001b, CEE 2002). Some of the key findings of the tenant survey task related to perceived problems with ETS in multifamily buildings transfer are:

- Twenty-nine percent of rental households have one or more smokers. Twenty-three percent of rental households said they allow smoking in their apartments, 18% “sometimes” allow it, and 59% do not allow it.
- Forty-eight percent of rental households in multifamily buildings in Minnesota report that, at times, tobacco smoke odors get into their current apartment from somewhere else in or around the building. Three percent say that this occurs “most of the time” and 7% say that it occurs “often.”
- Respondents who said that tobacco smoke odor at times gets into their current apartment from somewhere else were asked how much this odor bothers them. Five percent of

¹ Particular minorities of concern to MPAAT are Black, African-American, or African; Hispanic or Chicano; American Indian or Native-American; and Southeast Asian (Cambodian, Hmong, Vietnamese, Laotian, or Thai).

those who are experiencing ETS transfer (2% of all renters) said it bothers them so much that they are thinking of moving. Thirty-two percent of those who are experiencing it (15% of all renters) said it bothers them “a lot,” and 42% of those who are experiencing it (20% of all renters) said it bothers them “a little.”

- Among those who experience ETS transfer in their current apartments, 43% said that the most common way the tobacco smoke gets into their apartment is from the hallway, 23% said the most common route is through their windows, 9% said the most common route is through air leaks from other apartments and 6% said the most common route is through bathroom or kitchen fans. Secondhand smoke transfer is reported to occur roughly equally in all four seasons.

Thus, the tenant survey results indicate that about half of the renters notice smoke transfer into their units and that 17% of all renters say it bothers them a lot or so much that they are considering moving.

This report summarizes the results of the fourth research activity: buildings research. The purpose of this task is to measure typical ETS transfer and air movement among units in a sample of multifamily buildings in Minnesota, to treat the buildings to reduce air movement, and to measure the reduction in ETS transfer and air movement due to the treatments.

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” air flow. 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, Heller and Sherman 1995, Feustel and Diamond 1996).

Over the past 20 years, a small number of researchers have used multi-tracer gas techniques to measure air flows 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 air flows 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 air flow into units came from other units. Individual units in those buildings receiving as much as 35% of their total air flow from other units, in spite of the fact that all three buildings had poured 1½ inch gypcrete-on-plywood floors. Harrje et al. (1988) used constant concentration and perfluorocarbon tracer (PFT) techniques to determine that an average of 22% of the air flow into the 4th 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 air flow 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 inter-unit leaks. He used the air leakage results with a multi-zone air flow 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 inter-unit 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.

Many multifamily buildings in Minnesota have little or no mechanical ventilation. The most common type of 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 inter-unit air flows. Exhaust-only systems can cause pressure differentials between units that increase inter-unit air flow. 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, Heller and Sherman 1995, Herrlin 1999). That typically results in a shift of additional air flow from the adjoining units to the unit with the exhaust fan operating. 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. Only 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 inter-unit flow than operating fans individually and recommended continuous operation of these fans.

Only two of the published studies of inter-unit leakage and air flows (Modera et al. 1986 and Diamond et al. 1986) are directly relevant to early 1900s low-rise construction in Minnesota. None of the studies are directly relevant to the 1960s through 1980s low-rise buildings that make up much of the Minnesota multifamily housing stock, since new low-rise construction in Sweden and in the Pacific Northwest is substantially tighter than 60s to 80s vintage buildings in Minnesota. Nor are the publications directly relevant to the 2 to 4 unit wood-frame construction common in smaller Minnesota rental buildings. Few published reports of multifamily buildings have studied the effect of air sealing or ventilation improvements on inter-unit air flows. CMHC (1996) used a calibrated, multi-zone air flow model of a 12-story condominium in Ontario to conclude that compartmentalization strategies can provide more uniform ventilation rates and reduced air flow between units. However, no actual treatments were applied or measurements made to confirm these conclusions.

It is also important to note that there have been few or no ETS measurements in multifamily buildings to evaluate the transfer of ETS between units in multifamily buildings. All of the studies mentioned above have either used tracer gases to evaluate inter-unit air movement or pressurization tests to measure air leakage paths. Measurements of nicotine, fine particulates, and tracer gases were used in this study to evaluate ETS transfer. While tracer gas measurements may be valid to model the transfer of some ETS constituents, it is likely that the movement of ETS between units through often tortuous leakage paths will not produce a single “transfer coefficient” that can be applied to all ETS constituents.

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 non-sorbing tracer gas, but the sorption of lower volatility HAPs (e.g. cresols, naphthalene, and polycyclic aromatic hydrocarbons) and the ETS tracer nicotine is significant and must be considered when monitoring or modeling those compounds (Singer, Hodgson and Nazaroff 2003, Singer et al. 2002). 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. When lower volatile ETS markers are used to evaluate ETS concentrations, they will tend to underestimate the exposure of more volatile and particulate constituents. For example, nicotine measurements have been shown to underestimate by a factor of 2 to 8 the ETS particulate transport from a smoker’s room to a child’s bedroom (Apte et al 2002). Adding to the complexity is the fact that the rate of nicotine sorption appears to be affected by relative humidity, concentration in air, type of surface, and ventilation (Piade’, D’Andre’s, and Sanders 1999, Singer et al. 2002). It has been suggested that nicotine sorption may be controlled by two time constants with one describing an irreversible process and another that reaches saturation within hours (Piade’, D’Andre’s, and Sanders 1999). Finally, in situations where smoking has stopped or the spread of ETS has decreased, the long-term re-emission of lower volatile compounds such as nicotine can cause those markers to over-predict the exposure of more volatile ETS constituents.

The indoor concentration of particulates in residences and the generation of particulates from smoking are also an important health concern and have been studied by numerous groups. A review of indoor air particle studies by Wallace (1996) reported some of the following findings:

- The most important indoor source of coarse and fine particles was smoking. It was estimated that the increase in $PM_{2.5}$ due to smokers was 0.7 to 1.3 $\mu\text{g}/\text{cf}$ or 25 to 45 $\mu\text{g}/\text{m}^3$. The contribution of a single cigarette was estimated to range from 0.028 to 0.057 $\mu\text{g}/\text{cf}$ or 1 to 2 $\mu\text{g}/\text{m}^3$ averaged over a 24 hour period. A single cigarette appears to generate about 14 mg of $PM_{2.5}$.
- Cooking was the second most important indoor source. The estimated contribution from cooking ranged from 0.28 to 0.57 $\mu\text{g}/\text{cf}$ or 10 to 20 $\mu\text{g}/\text{m}^3$. Cooking was estimated to emit 4 mg/min of $PM_{2.5}$.
- Unknown sources were found to account for about 25% of the indoor $PM_{2.5}$ concentration. The “personal cloud” that occurs from walking over carpets or cleaning carpets (CMHC 2003a) may be one of the unknown sources. Particulate levels were found to rise with greater occupant activity.
- Many studies reported $PM_{2.5}$ concentrations for nonsmoking houses:

- ✓ Neas et al (1994) – 470 children in Six-City study: 0.5 $\mu\text{g}/\text{cf}$ or 17.3 $\mu\text{g}/\text{m}^3$ with 25/75 percentile values of about 0.3 to 0.6 $\mu\text{g}/\text{cf}$ or 11 and 21 $\mu\text{g}/\text{m}^3$.
- ✓ Spengler et al. (1985) – Kingston-Harriman portion of Six-City study: 73 participants with average indoor concentration of 0.8 $\mu\text{g}/\text{cf}$ or 28 $\mu\text{g}/\text{m}^3$.
- ✓ Leaderer and Hammond (1991) – 7-day indoor air samples for homes in NY State: Suffolk (n=30) – 0.49 $\mu\text{g}/\text{cf}$ or 17.3 $\mu\text{g}/\text{m}^3$ and Onondaga (n=45) – 0.4 $\mu\text{g}/\text{cf}$ or 14.1 $\mu\text{g}/\text{m}^3$.
- Most studies showed poor correlation of personal exposure to outdoor particle concentration. However, repeated measurements for the same individual provided a better correlation to outdoor concentrations.
- The “penetration coefficient” or transfer of outdoor particulates to the indoors was estimated to be 1.0 – or no filtering of particulates as air infiltrates through the building envelope.

This indicates that fine particle concentrations due to smoking in multifamily buildings should be measurable in the smoker’s unit. It is not clear whether the contribution of particles from a smokers unit will have a measurable effect on the concentrations in adjoining apartments. Depending on the rate of air and particulate transfer, the contribution of smoking related particulates may be similar in magnitude to the typical variations in particulate sources due to cooking and other occupant activities.

It is also interesting that Wallace (1996) concluded that the building envelope did not filter particles from incoming air. A recent study by CMHC (2003b) of how the house exterior envelope and ventilation systems filter particles from outdoor air entering the house found that the house envelope filtered 43% of $\text{PM}_{1.0}$ and 37% of PM_{10} particles from the infiltrating air. It is likely that much of this filtration was caused by air movement through the house exterior insulation. It is not clear whether the same filtering effect would occur for the movement of air through unit to unit leaks where the air would not normally encounter insulation.

Clearly much remains to be learned about the transfer of ETS between units in multifamily buildings and effective techniques to reduce the level of transfer. The primary research questions addressed in this task are:

- What are typical contaminant dispersion and air flow 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 air flow and contaminant transfer between units differ by building type or by differences in construction detail between buildings? How does this differ by presence and type of mechanical ventilation system?
- How much can air flow and contaminant transfer between units be reduced by air sealing, and at what cost?
- How much can air flow 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, this project does not provide complete answers to these questions. However, the results substantially improve our practical ability to reduce inter-unit air flows and hence the transfer of ETS in multifamily buildings in Minnesota.

METHODOLOGY

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. Inter-unit air leakage, air flows, and contaminant transfer were studied before and after air sealing and ventilation improvements were applied to selected units in the buildings.

Building Selection

The tests were conducted on six multifamily buildings which were reported to have the greatest ETS problems and were representative of those most commonly found in Minnesota. Three buildings were studied in the first year of the project and an additional three buildings in the second year. Because of the need to secure owner participation, the sample was a convenience sample. Because of the cost of the treatments, the sample was not of a size to be statistically representative of any building type. However, the nature of multifamily building construction is such that there is a reasonable amount of similarity within buildings of a given type. The criteria necessary to identify the most common building types were determined from census data and survey results.

The results from the renter surveys conducted in Task 2 were used to identify those types of Minnesota rental properties with the greatest ETS transfer problems. The trends showed an increase in reported problems with building age, but no significant correlation of problems with number of stories or number of units. The owner surveys conducted in Task 1 did not yield any consistent trends in building characteristics and observed ETS transfer problems. As a result, the six buildings were selected to be representative of those most commonly found in Minnesota – with an emphasis on older buildings.

The 1990 Census reported that 22% of Minnesota tenants lived in 2 to 4 unit apartment buildings, 10% in 5 to 9 unit buildings, 19% in 10 to 19 unit buildings, 22% in 20 to 49 unit buildings, and 21% in 50 or more unit buildings. It was decided that for the first year of the study the three buildings would be selected from the smaller size ranges (2 to 4, 5 to 9 and 10 to 19 unit buildings) and that larger buildings would be studied in the second year. In addition to the number of units, the buildings were screened for age, number of stories, heating system type, and presence of bathroom/kitchen exhaust fans. The building's age was included because it was felt that many construction characteristics (i.e. type of cladding, exterior wall construction, and interior wall construction) would trend with age. It was expected that the number of stories would affect the typical number of adjoining units and the magnitude of the winter stack effect. Central heating systems were expected to have a greater number of mechanical chases and the presence of exhaust fans would effect occupant controlled ventilation and the type of ventilation upgrades possible.

Responses from the tenant surveys were used to generate Figures 1 – 4 pertaining to those four characteristics. The information was then used to develop the selection criteria for the three buildings listed in Table 1.

Figure 1. Tenant survey: building age

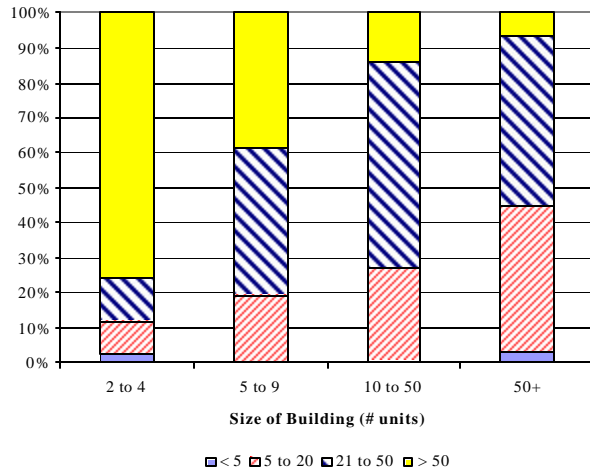


Figure 2. Tenant survey: number of stories

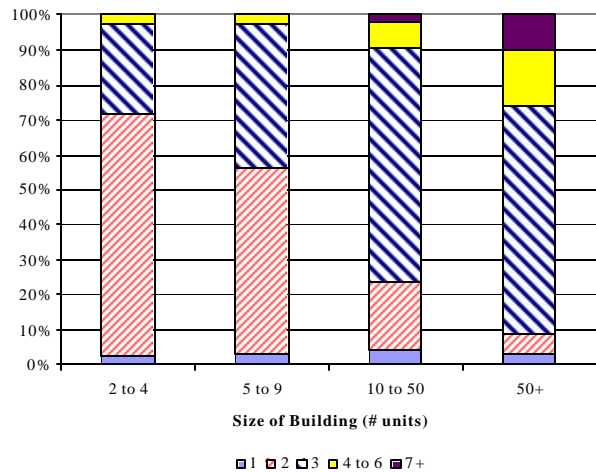


Figure 3. Tenant survey: individual heating system type (yes – individual, no – central)

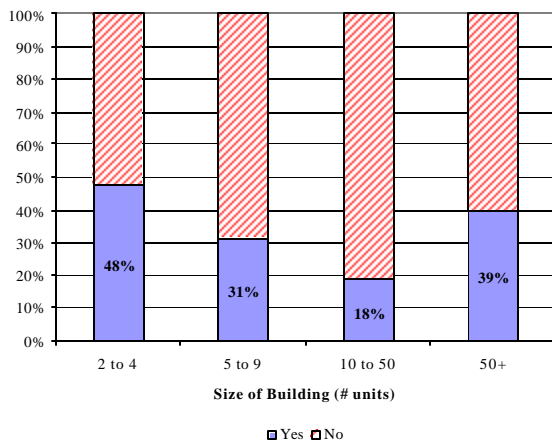


Figure 4. Tenant survey: bath or kitchen fans present

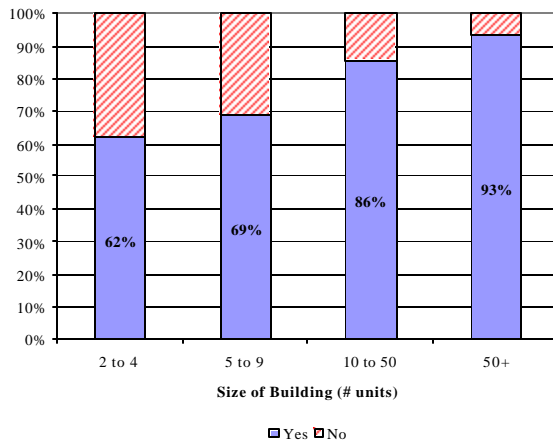


Table 1. Screening criteria for three buildings in first year of study

#	# Units	Age (yrs)	# Storys	Heating System	Bath Fans
1	2 – 4	50+	2 – 3	Central or Indiv.	Probably
2	5 – 9	21+	2 – 3	Central	Probably
3	10 - 19	21 - 50	3	Central	Yes

Based on the researchers' experience with Minnesota apartment buildings, it was desired to have one of the buildings with central exhaust ventilation in the bathrooms and another with individual bathroom fans. Also, the owner survey indicated that 95% of the buildings were wood framed and that Class C (older, well-maintained buildings in stable areas and limited

amenities) buildings are most typical. In addition to identifying buildings with the proper characteristics, the relatively intrusive testing and treatments required that the owners and tenants needed to be cooperative¹. The numerous trips for measurements and treatments to each building also required that the buildings be located near the project staff in the twin cities metropolitan area. Buildings with an existing “smoke transfer” complaint were expected to have the most cooperative tenants and owners, since the treatments included in the study were expected to help solve their problem. Finally, it was best to have smokers in a single unit in the building or isolated from other units in the buildings with smokers to allow a better comparison between tracer gas and particulate/nicotine measurements.

Some of the selection criteria were the same for the second year of the study:

- located in the twin cities metropolitan area
- smokers in a limited number of units
- high level of owner or manager interest/cooperation

Most of the remaining selection criteria for building characteristics were changed 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 inter-unit air leakage of existing, occupied units. As a result, one of the buildings was to be typical of large, public housing and the other two were to be newer buildings.

Large public housing buildings are renovated more frequently, which provides a potential opportunity for greater access to allow more extensive air sealing. The objective for that building was to identify a high rise with a masonry exterior, concrete floors, and central hydronic heating. For the remaining test buildings, the objective was to identify two buildings built after 1990. This would provide information that could be applied to newer buildings and those currently in construction. Air sealing at the time of construction is expected to be more effective and less expensive than air sealing of existing buildings, so developing information relevant to current construction was important. The goal was for one of the newer buildings to be a large low-rise building (more than 25 units, and most likely 100 or more) and for the remaining building to be a 8 to 16 unit low rise building. The 8 to 16 unit building would be easier to test and treat a high fraction of the units than a larger building, but 8 to 16 unit buildings are not common in new construction. If necessary, the third building would have more than 16 units.

Multiple methods were used to recruit building owners to participate in the project:

- 23 owners indicated during Task 1 interviews that they might be interested in providing a building
- two tenants who had contacted ANSR with problems with ETS transfer
- project staff presentations and round table discussions with the Multi Housing Association’s Small Investors’ Group
- owners or building managers that had participated in CEE energy or facility assessment programs

¹ Tenants were offered a \$50 to \$150 incentive for their participation in the project.

Owners were called to provide them information about the project, determine their level of interest, and obtain a list of their buildings that may fit our selection criteria. Project staff then conducted “drive-by” inspections of qualified buildings to confirm owner information and on-site visits were conducted for those buildings that met the criteria. After buildings were identified that met all the criteria, project staff met with the building owners/managers and tenants to describe the project and obtain their consent. The tenants and owner/managers received written information about the project. The building owners were asked to sign a contract agreement and the tenants a consent form (the latter approved by our independent review board). An acceptable test and work schedule was then negotiated with the owners and tenants.

Air-Sealing and Ventilation Treatments

Building treatments included sealing air leaks between units and modifying the ventilation to continuously operating systems that produced approximately the same flow rate in each unit. Leaks between units were expected to include both obvious and hidden leaks. The former included, for example, leaks around plumbing and hydronic heating pipes or around electrical outlets. The latter type included cracks between the floor and the wall that were hidden behind baseboards and gaps in the floor or ceiling around pipes located in mechanical chases. Specific leakage sites were identified using visual inspections and adaptations of other building diagnostic methods typically used for single family houses. A chemical smoke pencil was used to release small amounts of smoke near suspected air leakage sites while the calibrated fan or blower door was used to depressurize or pressurize the unit. In some cases, the blower door was used to pressurize or depressurize an adjoining unit while chemical smoke was used to investigate leaks in the test unit. An infrared (IR) camera was sometimes used to identify the location or size of hidden air leaks. An IR camera is able to display small differences in surface temperatures that may be due to incoming cold or warm air. When investigating air leaks to the outside for energy conservation purposes, the camera is first used to identify naturally occurring cold or warm spots caused by outside air infiltrating into the unit or from thermal deficiencies (i.e. insulation voids). The blower door is then used to depressurize the unit and the IR camera is used to search for new cold or warm spots caused by air entry. This approach was modified to help identify inter-unit leakage. First, an outside window was opened in an adjoining unit to lower the air temperature of that unit. Then the blower door was used to depressurize the test unit and the IR camera was used to search for cold spots or leaks between the units.

Permanent materials commonly used to air seal single family homes (e.g. high-quality caulks, expanding foam, and recessed light air sealing kits) were used to accessible seal air leaks. In limited cases, accessible floor/ceiling leaks around pipes in mechanical chases were sealed using standard fireproofing methods. In another case expanding foam was injected into the cavity of a plumbing wall to stop the flow of air up the cavity. Details of these treatments are discussed in the Results section and Appendices.

Ventilation systems were modified or installed as required to achieve a continuous exhaust flow of not less than 25 cfm in each unit and not more than a 5 cfm 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. Some individual bathroom ceiling fans were replaced with quiet models that were rated for continuous operation. The wiring was

modified to operate the fan continuously and the existing ductwork was cleared of obstructions as feasible. In other cases a centrifugal fan was installed in the exhaust fan ductwork and operated continuously induce a flow through the existing ceiling fan. For buildings with central exhaust systems the speed of the roof mounted fans was adjusted as necessary, manual dampers were fixed open, ductwork obstructions or air leaks were repaired, and constant flow regulators were installed to assure an acceptable level of ventilation that could not be obstructed by the tenants.

The Minnesota codes also include requirements for kitchens and bathrooms. In addition to living spaces, ASHRAE Standard 62-2001 specifies outdoor air requirements for three other types of residential facility spaces: kitchens, baths/toilets, and garages. For kitchens the ventilation requirement is 100 cubic feet per minute (cfm) of intermittent exhaust ventilation, 25cfm of continuous exhaust ventilation, or an operable window. For bathrooms the ventilation requirement is 50cfm of intermittent exhaust ventilation, 20cfm of continuous exhaust ventilation, or an operable window. Section 1203.3 of the 1997 Uniform Building Code also includes a requirement for bathroom ventilation. This Section requires that bathrooms be supplied with natural ventilation or, if natural ventilation is not provided, a mechanical system with an exhaust air flow rate of no less than five air changes per hour. All modified systems were designed and installed to meet these code requirements.

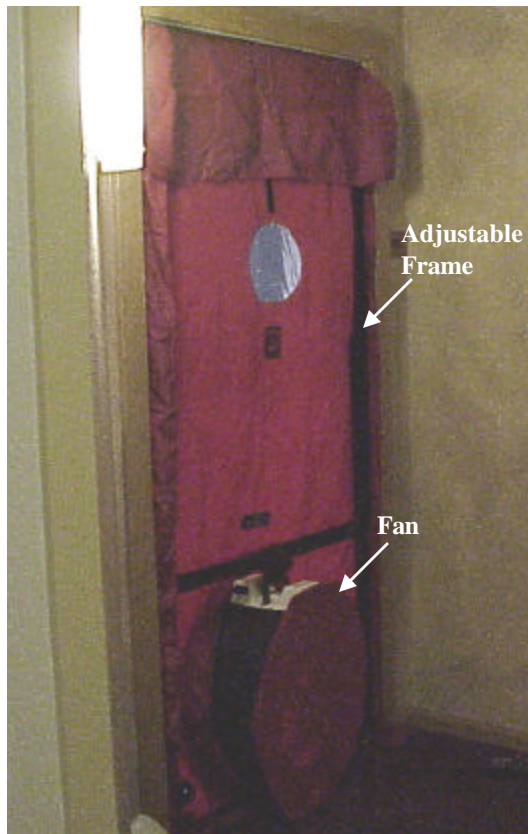
Air Leakage Measurements

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. For this method a variable-speed fan was mounted in an adjustable panel that could be temporarily fitted into a doorway (Figure 5). The fan was used to pressurize or depressurize the interior space by a measured amount (ΔP , Pascal or Pa). Pressure taps on a precisely calibrated nozzle were used to measure air flows (Q , cubic feet per minute or cfm). Measuring the pressure differential across the boundary of the space and the fan air flow for a range of pressurization or depressurization levels allows the permeability characteristics of the boundary to be determined, in the form of an empirical power-law equation with a flow coefficient (C) and exponent (n).

$$Q = C \cdot \Delta P^n \tag{1}$$

All air leakage values are reported as the flow required to produce a pressure difference of 50 Pa (Q^{50}) – which is commonly referred to as the cfm₅₀.

Figure 5. Fan assembly installed in a hall doorway



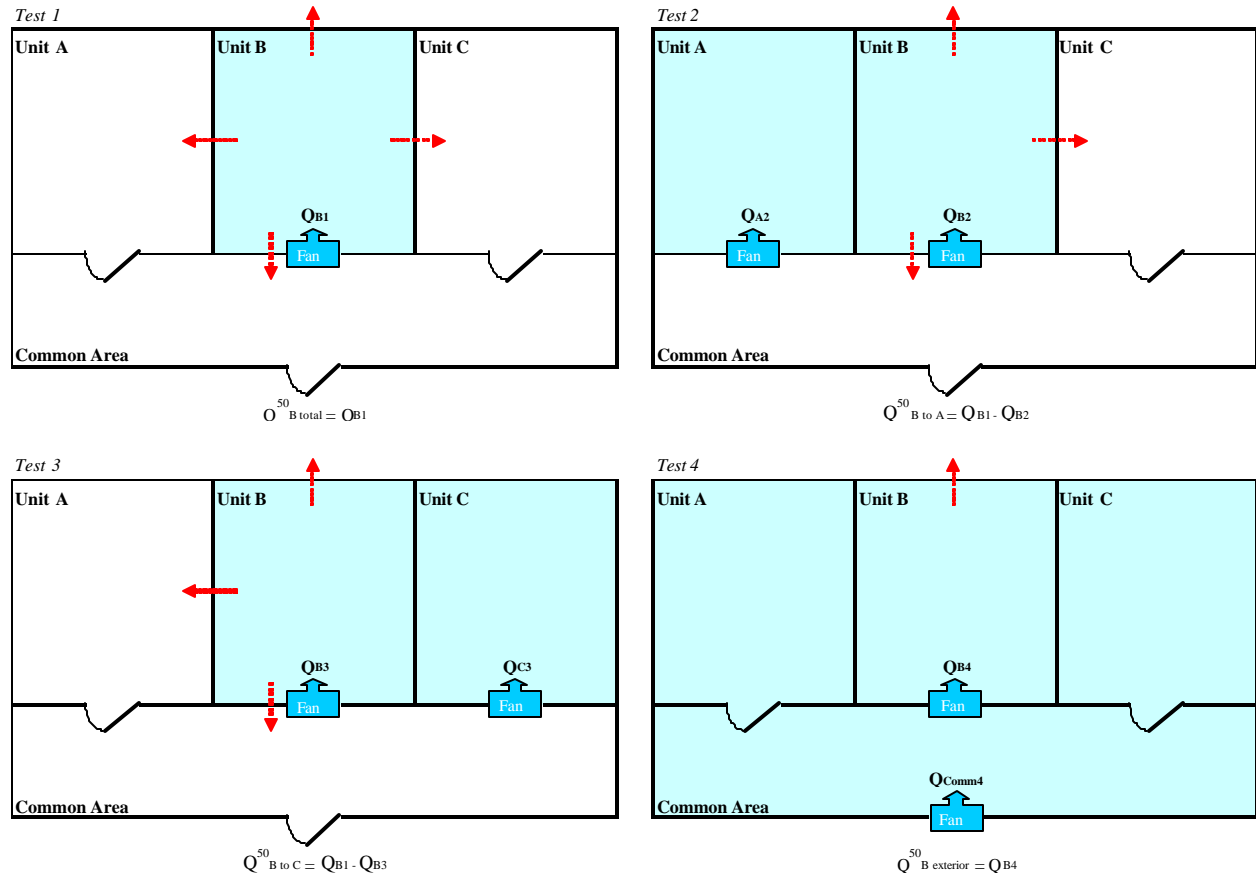
Note – unit/hall leakage due to door undercut is eliminated with this assembly

A typical single fan air leakage or blower door test is used to measure the leakage of the exterior envelope of a building that can be treated as a single open volume. A fan is placed in one of the exterior doors and all interior doors are left open so that the pressure of the entire building with respect to the outside is approximately the same. For the guarded-zone technique, the permeability of the internal walls, floors or ceilings between adjacent units is determined by pressurizing the guarded (test) zone, with the adjacent zones either pressurized to the same level as the guarded zone or kept at outdoor pressure. The permeability of internal surfaces can be determined from air flow measurements taken with various fan configurations and relative pressurizations (Feustel 1989, Bohac et al. 1987, Furbringer et al 1988, Modera et al. 1986, Levin 1988).

A typical sequence of tests for one unit in an apartment building with three units and a common area is shown in Figure 6. Test 1 was used to determine the unit's total air leakage. For test 2 a second fan was installed in the hall doorway of unit A and the two fans were adjusted so that the pressure difference between the units was equal to zero. The difference in the Q^{50} for the first two tests yields the air leakage between unit B and A. The four tests provide a measure of the unit's total leakage, leakage to each adjoining unit, and leakage to the exterior. In addition, the leakage to the adjoining units and exterior can be subtracted from the total to obtain the leakage

to the common area. This sequence was repeated for each unit in the building that was included in the study. Only units that were directly above or to the side of each “test” unit were included. Units diagonal to or across the hall from the test unit were not included in the process. For the larger buildings in the second year of the study it was not possible to depressurize the entire common area or hallway. As a result, it was not possible to measure the leakage to the exterior or common area for those units.

Figure 6. Guarded-zone test sequence for 3 unit apartment building



Shaded sections indicate areas that are pressurized to the same level.

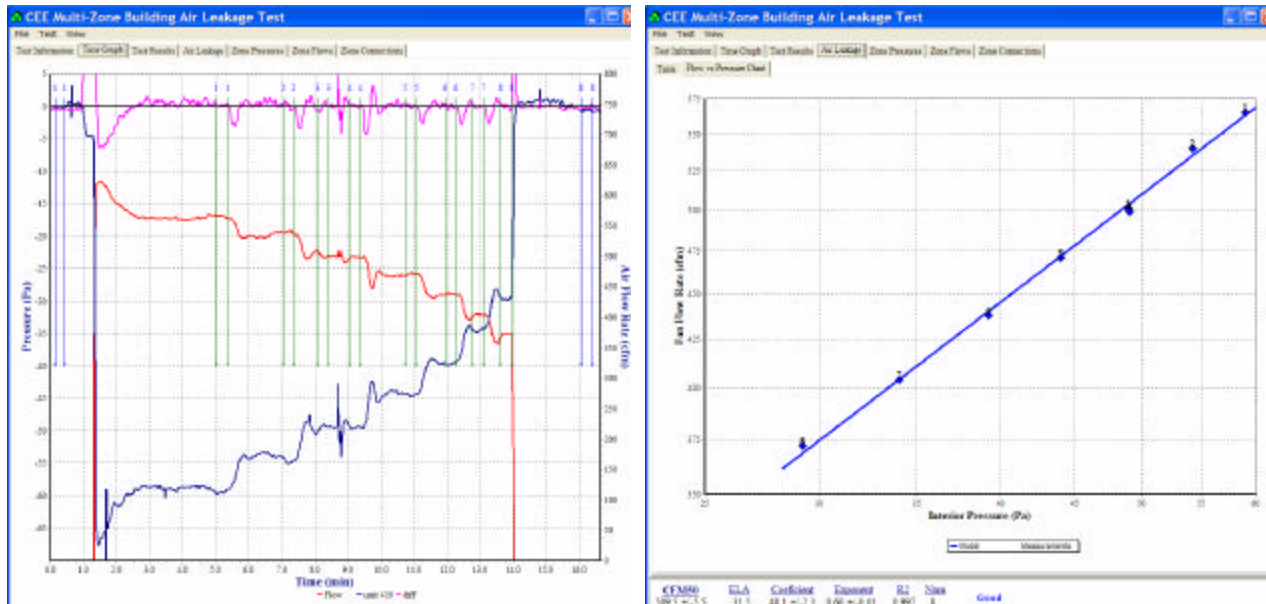
It is important to note that the calculations for the guarded zone technique assume that there is a single leakage path between the units and that the relationship between flow and pressure for those leakage paths can be described by equation (1). In multifamily buildings the leakage from one unit to another often travels through relatively large mechanical chases or open floor joists and those areas can be open to multiple units or the outside. Shao et al. (1992) determined that the guarded zone technique will not properly quantify air leakage paths that travel through “branched connections” or intermediate zones. It appears that the guarded zone technique can significantly underestimate inter-unit leakages (as much as 30 to 50%) when most of the leakage between two units is through large cavities that also have leaks to the outside or common area. Further work is required to better estimate errors due to intermediate zones, but those errors are

expected to be typically less than 25% of the measured value. Other studies have evaluated the errors that are due to wind fluctuations and non-zero pressures between the units when two fans are operating (Furbringer and Roulet 1991 and Herrlin and Modera 1988). The time averaging of pressure/flow measurements and automated fan speed controls used for this study helps significantly reduce those errors.

While there are published standards for a conducting single-fan test, there is no accepted standard available for conducting multiple fan air leakage tests. The single-fan Canadian General Standards Board Standard 149.10-M86 (1986) specifies the procedures for a multi-point air leakage test of a detached building that has no interior partitions. The total leakage of each unit was measured in accordance with Standard 149.10 and applicable procedures were used for the guarded-zone measurements. Typically, 12 to 16 second average measurements of the unit to exterior pressure difference and fan flow rate were recorded for six to eight pressure differences ranging from 30 to 65 Pa. When a two-fan test was conducted, values were only recorded when the average pressure difference between the two units being pressurized was within 0.2 Pa of zero.

The one second pressure and flow measurements for a typical depressurization test are displayed in Figure 7. The red line represents the fan flow rate, the blue is the unit pressure with respect to outside, and the fuchsia is the pressure difference between the units. The green vertical lines designate the eight measurement periods and the two sets of blue lines designate the “baseline” measurements when the fan was turned off. The average of the two baseline measurements are used to adjust each of the “fan-on” measurements for unit/outside pressure differences due to wind and staff effects. The regression technique specified by the Standard was used to compute the flow coefficient, flow exponent and Q^{50} and associated uncertainties for each configuration. Figure 7 also displays the log-log regression plot for the eight recorded measurements. A Taylor’s series approach to error propagation (Beckwith et al, 1981) was used to calculate the uncertainty of the unit to unit air leakages.

Figure 7. One-second pressure/flow measurements and regression analysis for a typical test



The tests were conducted using two types of variable speed, calibrated fans. The larger has a capacity from approximately 100 to 5,700 cfm and the capacity of the smaller fan is approximately 70 to 1,350 cfm. The larger fan was custom calibrated by the manufacturer¹ before each of the two test years and the smaller fan was calibrated before the second year of tests. Flow measurements made without the custom calibration had an accuracy of 3% of the flow rate and the accuracy was from 1 to 1.5% with the custom calibration. Pressure measurements were performed using an eight channel, digital micromanometer that was calibrated annually in accordance with manufacturer guidelines and has a specified accuracy of the greater of 0.1 Pa or 0.5% of the measurement. The pressure channels were auto-zeroed every one to two minutes to minimize zero drift errors.

Before the advent of microprocessor controlled, digital micromanometers, accurate guarded-zone tests using two fans were difficult and time consuming. Variations in wind speed and direction causes pressure fluctuations that sometimes requires changes to the fan speed in both test areas. Also, changes to the speed of one fan typically require a proportional change in the speed of the second fan. Customized air leakage test software was developed by project staff to help automate the process and improve the accuracy of its measurements. The customized software automatically adjusted the fan speed to achieve the pre-set unit/out pressure for each of the six to eight measurements of the test unit. A second, identical program was run simultaneously to automatically adjust the speed of the second fan to produce a zero pressure difference between the two units. Average values were recorded when the pressure in the test unit was stable and the pressure difference between the units was within 0.2 Pa of zero. The baseline pressure (zero fan flow and fan housing blocked) was measured before and after the six to eight measurements. The program also allowed the user to remove any “invalid” measurements from the analysis.

¹ Energy Conservatory, Minneapolis, MN.

The summary results and one-second measurements were stored in a text file and the same program can be used to display the results at a later time.

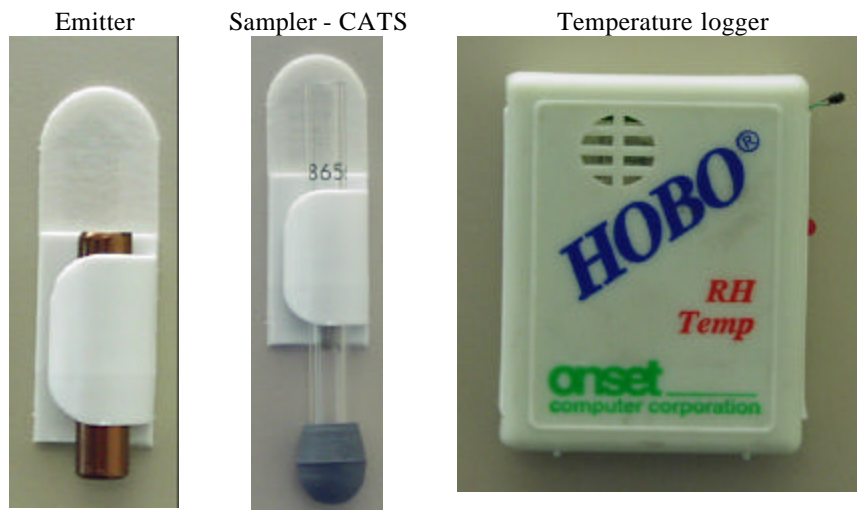
Tracer Gas Air Flow Measurements

A passive tracer gas method was used to provide information on one week average outdoor air ventilation rates to each unit, inter-unit air flow rates, and ETS transport between units in the building. The measurements were made using the multiple perfluorocarbon tracer (PFT) gas system developed by Brookhaven National Laboratory (Dietz et al. 1985a, b, Dietz 1988, AIVC 1991). That was the least intrusive and least expensive of the techniques available to measure air flows in multi-zone buildings. Side-by-side tests have shown reasonable agreement with the much more intrusive and costly constant concentration and constant injection techniques (Harrje et al. 1988, 1990). The PFT system uses small passive emitters and samplers placed in the apartment units under study to evaluate air flows. Sampling periods can be as short as a few hours or as long as several months. A one week sampling period was used for this project to help average out day to day occupancy effects and help assure comparable driving forces (indoor-outdoor temperature differences and wind) for pre- and post-treatment periods.

The PFTs used by Brookhaven National Laboratory are in the generic class of perfluoroalkylcycloalkanes (Dietz and D'Ottavio, 1982). They are fully fluorinated, contain only carbon and fluorine, and have no unsaturated bonds. As such, they are extremely stable, chemically and physically, and are biologically very inert. PFTs can be inhaled or ingested with no concern. They have an appreciable vapor pressure, so they do not adsorb readily to surfaces. Finally, they have low, stable atmospheric background concentrations due to few, if any, global sources.

The passive PFT emitter, or source, consisted of a 1 ¼" long x ¼" diameter aluminum shell with a silicon rubber plug in one end, containing a small (0.024 in³ or 0.4 mL) volume of PFT. Figure 8 displays an emitter installed in one of the plastic clips that were used to hold the emitters in place. The permeation tube emitted a tracer gas at a rate from 18 to 122 in³/h x 10⁻⁶ (300 to 2,000 nL/h). The rate varied by type of PFT and ambient temperature (approximately 2% increase per °F). The temperature of each emitter was monitored continuously during the sampling periods using a miniature (1 ¾" x 2 ¼" x ¾") battery-powered single-channel temperature logger. The capillary adsorption tube samplers (CATS), 3" long and ¼" diameter, collected the tracers by passive adsorption onto a pre-conditioned, charcoal-like adsorbant. The rate of adsorption of the PFTs was proportional to their concentration in the surrounding air. The cap on one end of the CATS was removed at the start of each sampling period. At the end of the period the cap was put back in place and the CATS returned to be analyzed using a gas chromatograph. The average concentration of the PFTs was calculated from the amount of tracer collected, the sample rate, and exposure time. Blanks and duplicates were included for quality control. The system had the capability to release and analyze up to seven different PFTs. The uncertainty of the source rate for two emitters in each zone was assumed to be ±10% and the PFT concentration measurement error was assumed to be about ±5% for concentrations above the limit detection limit. For units that had two or more CATS, the standard deviation of the concentration measurements was used as for the concentration uncertainty. In general, the variation in concentration within the unit due to incomplete mixing causes a greater error than the errors in the sampling and analysis equipment.

Figure 8. PFT system components



Each apartment was treated as a single, well mixed zone. Two emitters were placed in each “tagged” apartment to provide a more uniform tracer concentration, average out variations in individual emitter source rates, and produce measurable gas concentrations. Two CATS were used in each tagged unit to provide a better determination of the average concentration in the zone and to indicate the uniformity of the concentration. In some buildings there were units that could not be tagged, but the occupants agreed to allow their unit to be monitored. For those units one CATS was used to monitor the PFT concentrations. The emitters and CATS were placed so that the tracer gas would be released close to the incoming air streams and allowed to mix with the apartment air before being collected by the CATS or exiting the apartment. The emitters were typically placed on an interior wall near an exterior wall or wall adjacent to the common area. No mixing fans were used in the apartments. Care was taken so that the emitters were not placed in an area with large temperature swings (i.e. near a heating supply register or hydronic baseboard unit) that would significantly affect the source rate or where the emitted tracer gas would be immediately pulled out of the apartment (i.e. near a window or hallway door). The CATS were placed on an inside wall as far from the emitters as possible. The emitters and CATS were never placed in a bedroom, since closing the bedroom door could somewhat isolate them from the rest of the apartment. It is important to note that these measurements were being conducted in occupied units for one week time periods. The locations had to be selected to be somewhat unobtrusive to the occupants. Without mixing fans, the tracer gas concentrations within the apartment units were not always uniform. In addition, the occupants were asked to keep their windows and exterior doors closed during each monitoring period. During the second year of the study the occupants were also asked to record the number of cigarettes smoked each day, the number of hours they had any windows open, and the number of minutes that they ran any of their exhaust fans.

The measured tracer concentrations and known emission rates were used to solve a system of steady-state equations consisting of N^2 mass balance equations and $2N+1$ flow balance

equations, where N is the number of zones. This provided an estimate of the air flow rates between each of the zones and the outdoor air ventilation rate into each zone. The uncertainty of the air flows were computed using techniques reported in the literature (D'Ottavio et al. 1988).

The measured outdoor air ventilation rate was compared to code requirements or standards for ventilation in residential buildings to determine if the unit ventilation rates were acceptable. New multifamily buildings built in Minnesota are required to comply with American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) Standard 62-1989 (the previous version of 62-2001). For residential facility living areas, ASHRAE 62-2001 requires a minimum outdoor air flow rate of 0.35 air changes per hour (ach), but not less than 15 cfm per person (see ASHRAE 62-2001 Table 2.3). The Standard also notes that “ventilation is normally satisfied by infiltration and natural ventilation.” As a result, ASHRAE 62-2001 does not require mechanical ventilation for living spaces in multifamily buildings and very few systems are installed in Minnesota multifamily buildings. However, the minimum outdoor air flow rate of 0.35 ach or 15 cfm per person is an appropriate level for evaluating adequate ventilation.

It is important to note that the passive tracer air flow calculation technique used by the PFT analysis systematically under predicts the actual flow of outdoor air into a zone (Sherman 1989c) and ventilation rates computed by this technique are sometimes referred to as the “effective ventilation” rate. The under prediction occurs because the tracer gas concentration in a zone for a constant tracer gas source is not linearly related to the air flow rate. The degree of under prediction depends on the variation in the air flow rate. An analysis of the modeled seasonal infiltration rate of single family buildings suggests an under prediction from 15 to 35% (Sherman 1989c). 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.

In order for all the outside air and inter-unit air flow rates to be computed properly, there must be a different type of PFT emitter in every zone involved in the air flow interactions. Tagging every unit and the common area is possible for small (e.g., 2 to 6 unit) multifamily buildings, but not larger multifamily buildings. Analysis of air flows in larger buildings requires simplifying assumptions regarding how the zones interact and thoughtful placement of the sources. An approximate “rule of thumb” is that when there are zones that are not tagged with a PFT source, the computed flow of outdoor air into a unit will include the flow of any outdoor air that travels through an “untagged” zone before it enters the unit. 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 inter-unit air flow rates. Samplers were placed in any remaining test units to track the movement of the tracer gas sources.

ETS Measurements

Nicotine and fine particulate measurements were conducted in a sample of the units to provide a direct measurement of the transfer of ETS between units. In addition, an analysis of the PFT concentrations resulting from normalized source rates was used to model the transfer of non-sorbing ETS constituents. Given the inherent difficulties with variations in the background

concentrations of ETS particulates, the sorption/re-emission of nicotine, and the small number of units to be tested, this work was considered to be exploratory. It was hoped that the results would provide some valuable insights to guide future research in this area.

Nicotine Measurements

Nicotine is commonly used as a marker for ETS because there are accurate methods for measuring the levels typically produced by smoking in indoor areas and ETS is typically the dominant or only significant source of nicotine in indoor air. As noted previously, the sorption of nicotine to indoor surfaces and along air leakage paths will reduce the level of nicotine in air that moves from a smoker's unit to a nonsmoker's unit. The level of sorption is greater for nicotine than the more volatile compounds of ETS. So until there is information available on the sorption characteristics of ETS transported through building air leakage paths, an evaluation of contaminant transfer that is based on nicotine measurements can only apply to nicotine.

One week average nicotine concentrations were measured with passive diffusion monitors¹. The monitors rely on a known rate of passive diffusion into a treated filter medium housed in a 1 1/2" diameter plastic container (Figure 9). The monitor can be worn as personal monitor or left in place for ambient measurements (Hammond and Leaderer 1987). The exposed samplers were returned to the measurement laboratory where the quantity of nicotine was subsequently extracted and measured by gas chromatography. The samplers were used in all buildings that had at least one smoker. They were installed at the same location and were exposed over the same time period as the PFT samplers. Two nicotine samplers were installed in all units where a smoker lived and in units immediately to the side or above/below the smoker's unit. A single sampler was placed in the remaining test units. Blanks and duplicates were included for quality control. The limit of detection for the one week sample periods was approximately 0.002 µg/cf or 0.07 µg/m³ with an uncertainty of ±10% for concentrations greater than 0.004 µg/cf or 0.15 µg/m³ and an uncertainty of ±50% for concentrations below 0.004 µg/cf or 0.15 µg/m³ (Apte et al 2002).

Figure 9. Passive nicotine monitor



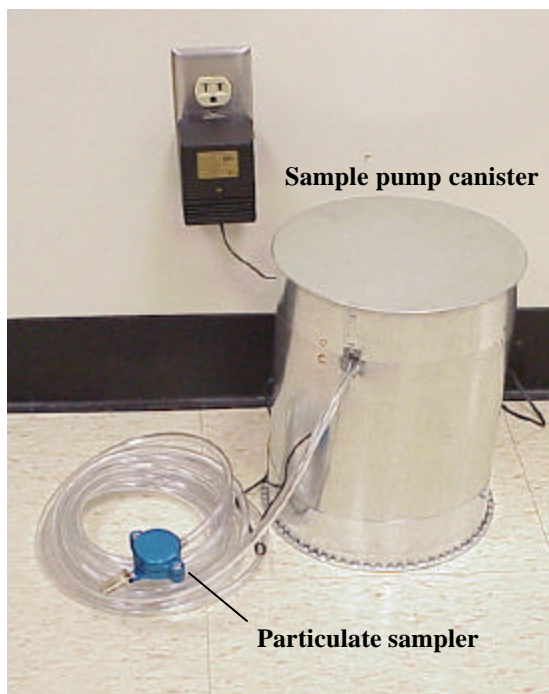
¹ Samplers and analysis provided by the University of California, Berkeley School of Public Health.

Particulate Measurements

Fine particulate measurements were included because the concentrations produced by smoking are measurable and a health concern. It was expected that fine particle concentrations due to smoking in multifamily buildings would be measurable in the smoker's unit. It was not clear whether the contribution of particles from a smokers unit will have a measurable effect on the concentrations in adjoining apartments.

One week average fine particulate concentrations were measured using a constant flow rate sample pump to draw air through a particulate monitor that consisted of a single-stage impactor with an after-filter¹ (Figure 10). The operation of the sampler is based on the inertial separation of airborne particles using a conventional impactor (Marple and Liu 1974). The sample pump had a nominal flow rate of 0.07 cfm or 2 L/m and the impactor had a cut point of 2.5 μm ($\text{PM}_{2.5}$). Pre-conditioned after-filters were analyzed gravimetrically before and after the sample period to determine the mass of sampled particles. The sample pump air flow rate was measured in-place at the start and end of the sample period using a NIST traceable bubble flow meter. The sample pump was placed in an acoustically treated canister to reduce to noise generation to a level acceptable to occupants.

Figure 10. Particulate monitor



Laboratory conditioned blanks, blanks located in the apartment units, and duplicate monitors were included for quality control. For each sample period the change in weight of the filter from

¹ Model 200 Personal Environmental Monitor, MSP Corp., Minneapolis, MN.

the blank monitor located in the apartment was used to adjust of net weight of the remaining filters. An analysis of seven sets of lab and apartment blanks indicated that that the precision error due to the measurement and transportation process was 0.0074 µg/cf or 0.26 µg/m³. For the five set of duplicates which had a concentration representative of a typical non-smoker, the median difference in the mass concentration was 0.014 µg/cf or 0.49 µg/m³ or 12% of the measured value. There are a number of factors that could affect the precision of the sampling process including: air flow measurement and particulate capture efficiency. In both cases the precision is most likely to be proportional to the measured value. Using that assumption, the precision of the sampling process is estimated to be about 10% of the measured value.

The monitors were used in all buildings that had at least one smoker. They were installed at the same location and were exposed over the same time period as the PFT samplers. One monitor was installed in all units where a smoker lived and in units immediately to the side or above/below the smoker's unit. If additional monitors were available, they were placed in units immediately above or below the other monitored units. The particulate monitors were placed near one of the PFT and nicotine samplers. Six monitors and pumps were available in the first year of the study and a total of ten monitors and nine pumps were available in the second year of the study¹. There was no overlap in the monitoring periods for the buildings, so the entire set of monitors could be used in each building.

Tracer Gas Measurements

An analysis of the PFT concentrations resulting from the known source rates of the different PFTs was used to model the transfer or dilution of non-sorbing ETS constituents. As discussed previously, more volatile ETS constituents (for which there are also significant health concerns) have low levels of sorption and should be accurately modeled by non-sorbing tracer gases – such as PFTs (Singer, Hodgson and Nazaroff 2003, Singer et al. 2002). Thus, the PFT measurements can be used to model the time averaged transport of the more volatile compounds in ETS when it is assumed that the compounds are being released at a constant rate. Since PFT releases are controlled and can be isolated to individuals units, this method provides a powerful metric of contaminant transport from many units (up to seven simultaneously) to all surrounding units that were monitored.

A new term “effective contaminant transfer” (ECT) is 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 ($C_{M,T}$):

$$ECT(M)_T = C_{M,T} / S_T \quad (2)$$

The units of ECT are time per volume or typically h/cf, h/m³. Lower values of ECT indicate less contaminant transfer or reduced exposure in the monitored unit. The ECT is particularly useful for this study because it incorporates all three factors that affect the level of the contaminant at the monitored location or unit where the exposure is taking place:

¹ The blank monitor was not connected to a pump.

1. The dilution of the contaminant that occurs in the unit for which the contaminant is released,
2. The rate at which the contaminant (or air) transfers from the test unit with the source to the monitored location,
3. The dilution of the contaminant in the monitored location.

The first and third factors are determined by the ventilation rate, or total air flow, of the apartment unit. Increased ventilation in the units will cause a decrease in the ECT. The second factor is determined by the rate of air flow from the test unit to the monitored location. Reducing the size of the air leakage paths by air sealing and correcting exhaust flow imbalances between the units will decrease the inter-unit air flow and the contaminant transfer or ECT.

The Effective Contaminant Transfer values can be used with Exposure-Relevant Emission Factors (EREF) and the rate of cigarette smoking (N_{cig}/t) to compute an estimated concentration in the unit of interest. For example, if it is assumed that 20 cigarettes are smoked over a 24 hour period in unit 101, the EREF for acrolein is 610 $\mu\text{g}/\text{cig}$ (Singer, Hodgson and Nazaroff 2003) and the $ECT(201)_{101}$ for unit 201 for gases released in unit 101 is $0.08 \times 10^{-3} \text{ h}/\text{cf}$ ($0.083 \text{ h}/\text{cf}$ is the inverse of 200 cfm^1), the average concentration of acrolein in unit 201 is estimated to be:

$$\begin{aligned}
 C_{101,acrolein} &= EREF(acrolein) (N_{cig}/t) ECT(201)_{101} & (3) \\
 &= (610 \mu\text{g}/\text{cig}) (10\text{cig}/24 \text{ hr}) (0.08 \times 10^{-3} \text{ h}/\text{cf}) \\
 &= 0.02 \mu\text{g}/\text{cf} \text{ or } 0.72 \mu\text{g}/\text{m}^3
 \end{aligned}$$

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 $ECT(M)_i$ for a source released in the i th unit that is transferred to unit M.

$$C_M = \sum_{i=1}^n S_i \cdot ECT(M)_i \quad (4)$$

In addition, the ECT's for a unit can be summed to evaluate the relative magnitude of total air and contaminant transfer into that unit. It can be used to calculate the exposure in a unit for a contaminant that is released uniformly in other units in the building. It also provides a general indication of how much the occupants of a single unit are being exposed to sources from other units in the building.

For this study there was a focus on reducing the exposure of ETS from a known smoker's unit and to reduce the level of any contaminants or odors from other units in the building. Consequently, two different types of analysis will be used to evaluate the magnitude of contaminant transfer in the buildings and the effectiveness of the air sealing and ventilation treatments:

¹ For a single -zone building, the ECT is simply the inverse of the effective ventilation rate.

1. Tabulate and compare the sum of the ECTs for individual, monitored units for transfer from all of the other units where a PFT gas was released. This evaluates the overall transfer of contaminants being released in the building.
2. Tabulate and compare the ECT from the smoker's unit to the other monitored units in the building. If smoking occurred in two or more units, the unit with the most smoking was chosen for the analysis. This evaluates contaminant transfer from a single, known source.

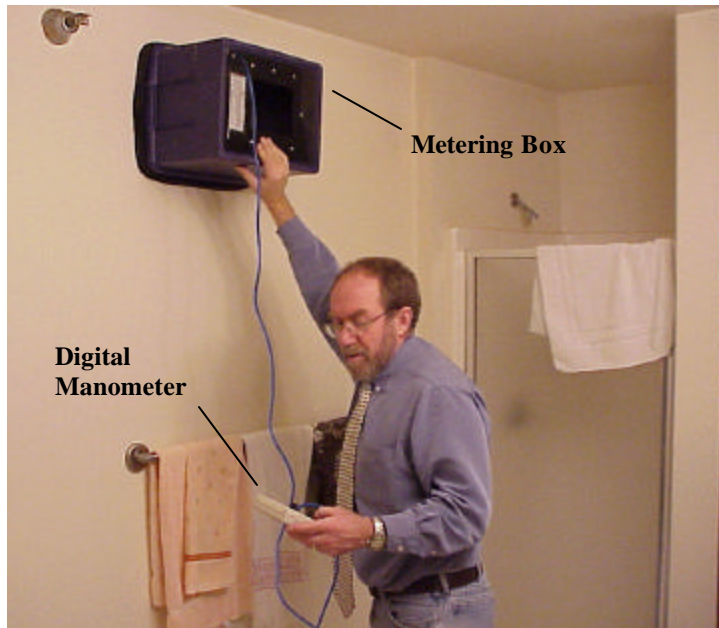
The ratio of PFT concentration measurements can also be used to compute the ETS concentration in a nonsmoker's unit from the concentration of ETS in the smoker's unit. This provides a measure of two of the three factors involved with determining the concentration at the monitored location for a known source rate: (1) the rate of contaminant transfer from the unit where the contaminant is being released to the monitored location and (2) the dilution of the contaminant in the monitored location. However, it does not consider the dilution that occurs in the unit where the contaminant is being released.

It is important to note that the ECT's generated using PFT measurements are only valid for nonsorbing contaminants. The sorption and filtration rate of a contaminant would also need to be considered when calculating the actual concentration of a specific contaminant. A comparison of the measured nicotine and particulate concentrations in nonsmoker units to the concentrations calculated using the nicotine and particulate concentrations in the smoker's unit multiplied by the PFT concentration ratio is used to evaluate the absorption of nicotine and filtration of particulates during the transfer process.

Ventilation System Measurements

The supply and exhaust flow rates of the corridor ventilation systems were measured using back-pressure compensated flow hood measurements (Gladstone and Bevirt 1997, AABC no date). An Exhaust Fan Flow Metering Box with a calibrated, adjustable orifice was used to measure the air flow rate of an exhaust fan (Figure 11). The size of the Metering Box is approximately 13" x 16" x 8". During the measurement procedure, the Meter Box is placed directly over the grille of an operating exhaust fan. The Metering Box is pushed up against the wall or ceiling so that the flexible gasket on the end of the Metering Box creates an air tight seal around the grille. The pressure difference across the orifice is used to compute the air flow rate through the exhaust fan. The pressure drop is typically less than a 2 to 6 Pa, so the flow restriction due to the flow measurement box reduces the fan air flow rate by less than a few percent. The measurement accuracy is typically 10% of the flow rate. Most commercially available flow hoods are designed for measuring higher air flow rates and do not provide accurate measurement of typical ceiling exhaust fans.

Figure 11. Exhaust fan flow meter



Resident Surveys

During the first year of the study the project staff received numerous comments from residents regarding the effect of the air sealing work and ventilation improvements, but there was no systematic method for recording those comments. It was felt that the tenant feedback provided valuable insights as to the perceived pathway of the ETS or odor transport and the effect of the treatments. While measured reductions in ETS transfer was an important research objective, in order for future owners or occupants with an ETS transfer problem to pay for treatment work there must be an occupant perception that treatments help address the problem.

For the second year of the study the participating residents were asked to complete two questionnaires. One before any work was done to the building and another at least one week after all of the treatments (air sealing and ventilation) had been completed. The pre and post two page questionnaires are included in Appendix A. All of the questions required quantitative responses and many also allowed for comments or an explanation of the response. The pre-treatment questionnaire focused on the resident's concern with tobacco smoke or odor transfer into their unit, how the transfer occurred, the seasonality of the problem, and the location of the smokers in the building. The post-treatment questionnaire included questions regarding the change in the frequency/strength of tobacco smoke/odor transfer, whether changes were due to the treatments, their level of satisfaction with the work, and willingness to pay for the work.

RESULTS

Test Buildings

The key characteristics of the six selected buildings are displayed in Table 2 along with information on the number of units treated and units where residents smoked. Exterior photographs and floor plans for the buildings are displayed in Figures 12 to 17. The Duplex, 8-Plex, and 12-Plex buildings selected for the first year of the study conformed to all of the selection criteria displayed in Table 1 of the Methodology section. They are all centrally heated, over 20 years old, have two to three stories, and have bathroom exhaust fans. All of the units in the Duplex and 8-Plex were tested and treated. Cost and test equipment limitations allowed for only six of the twelve units in the 12-Plex to be tested and treated. 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. The 11 Story building was typical of large, public housing and the 138 Unit and 4 Story were newer buildings. For these larger buildings only a cluster of the units could be tested and treated. Seven or eight units were treated and up to 14 of the units were tested. More detailed building descriptions are included in Appendices B – G along with detailed results from the field tests.

Table 2. Characteristics of the six selected buildings

Characteristic	First Year Buildings			Second Year Buildings		
	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
Units w/smoker H-heavy L-light	None	#3 - H #4 - L	#6 - L	123- H	410 – H 414 - L	404 - L
# Stories	2	2	3	3	11	4
Const. Year	mid-1930	1970	1964	1999	1982	2001
Type	Apartment	Condo	Apartment	Apartment	Condo.	Condo/Comm.*
Exter. Cladding	Stucco	Brick	Stucco/Brick	Stucco/Brick	Brick	Stucco
Floor Const.	2x10 frame	2x10 frame	2x10 frame	Poured conc.	Poured conc.	Open truss
Floor area (sf)						
Unit type 1	Upper: 1140	1 bdrm: 704	All: 780	F: 1072	#10: 768	1 bdrm: 882
Unit type 2	Lower: 1140	2 bdrm: 918		G: 1140	#12: 1029	1 bdrm: 1000
Unit type 3				G1: 1236	#14: 1131	1 bdrm: 1028
Unit type 4				J: 1271		2 bdrm: 1445
Unit type 5				J mod: 946		2 bdrm: 1509
Unit type 6				Guest: 325		
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 .

Figure 12. Building Duplex exterior photo and 1st/2nd floor plans



Figure 13. Building 8-Plex exterior photo and first floor plan



Figure 14. Building 12-Plex exterior photo and second floor plan.

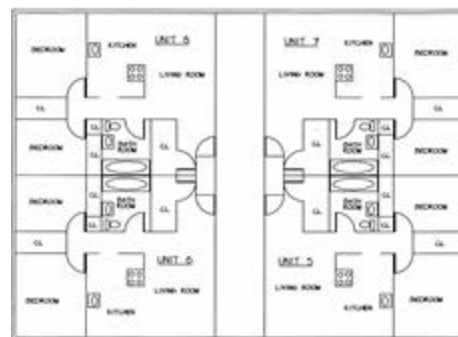


Figure 15. Building 138 Unit exterior photo and first floor plan

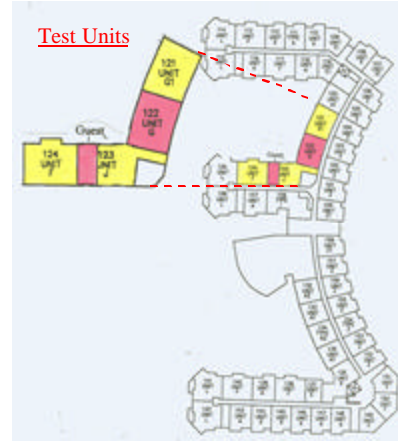


Figure 16. Building 11 Story exterior photo and first floor plan

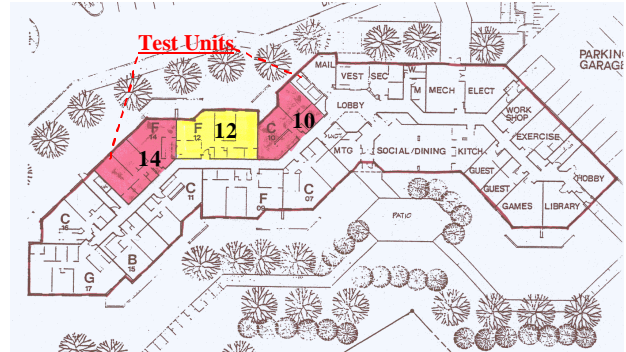
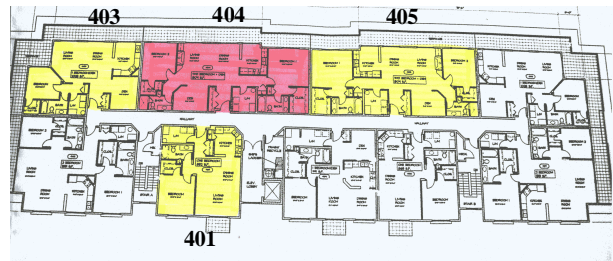


Figure 17. Building 4 Story exterior photo and 4th floor plan



Air-Sealing and Ventilation Treatments

Air Sealing

Infrared camera scans were used extensively in the first few buildings along with the release of chemical smoke near suspected leakage sites while the unit was pressurized or depressurized. Experience from the first few buildings helped determine a pattern of common leakage areas that included: baseboard/floor, plumbing pipe penetrations, exhaust fan housing connection to walls, sprinkler pipe penetrations, and hydronic heat pipe penetrations between units (see Figure 18). These areas were sealed using appropriate caulks and expanding foam. As crews and project staff became more experienced, the use of chemical smoke was more commonly restricted to determining the magnitude of suspected air leaks. Newer buildings often had leaky recessed lights that were treated with air-tight inserts. 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 is a huge open area between units. That can be a source of air and contaminant transfer if the plumbing access is not properly sealed. In one building the peg board that was originally used for the plumbing access panel was replaced with a solid board.

Figure 18. Typical apartment leakage sites and standard air sealing treatments



Smoke movement into gap behind baseboard (138 Unit building)



Foam treatment for large gap. Smaller gaps treated with clear acrylic caulk.



Moderate-sized wall gaps around bathroom/kitchen plumbing (138 Unit building)



Foam used to seal around the gaps



Significant wall gaps around bathroom exhaust fan housing (4 Story building)



Gaps sealed with caulk and metal tape



Large gap in wall between units for hydronic heating pipe (11 Story building)



Foam used to seal gap around pipe



Open gap around sprinkler pipe (4 Story building)



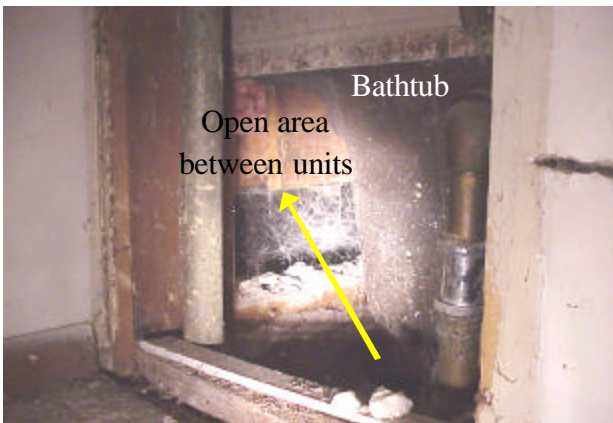
Caulk used to seal around pipe



Large leak in and around recessed light fixture (4 Story building)



Insert used to create air-tight seal



Common wall between units at bathtub is often completely open so that a person could stick their hand from one unit into the other.



Sometimes there are gaps between the wall and plumbing access panel. Or even worse - the panel is made from peg board to enhance transfer between units..

Less typical air sealing approaches were also completed for individual buildings. An open plumbing chase in the 12-Plex building was sealed by multiple foam injections into the cavity (see Figure 19). The 11 Story building with concrete floors had mechanical chases with huge floor/ceiling gaps around metal ductwork and piping. In general, the chases were not accessible. In the one chase that was accessible the gap was filled with mineral wool and sealed with a listed fire barrier.

Figure 19. Less typical apartment leakage sites and air sealing treatments



Foam injected at top of open plumbing cavity to create continuous plug to stop air movement up cavity (12-Plex building)



Wall patched and ready for final coat of paint



Looking down at large gaps around metal duct and pipes in a mechanical chase (11 Story building)



Mineral wool applied into large gaps



Seal with listed fire barrier

A summary of the cost and description of the air sealing treatments for each building is included in Table 3. More detailed descriptions and photographs of the air sealing work are included in Appendices B – G. For the three buildings in the first year of the project the initial goal was to spend about 4 hours per unit on air sealing so that the cost was kept to a level that may be more acceptable to building owners. For the 8-Plex and 12-Plex buildings the labor averaged 4 to 6 hours per unit with an average per unit cost of \$317 and \$431 respectively. Diagnostics indicated that the numerous, diffuse leaks in the Duplex building would require additional air sealing effort to achieve any success. The air sealing crew spent 24 hours per unit for a total cost of \$1,662 per unit.

Table 3. Cost and description of air sealing treatments

Building	Labor (hr/unit)	Material (\$/unit)	Total ¹ (\$/unit)	
Duplex	24	\$102	\$1,662	
Total air leakage test indicated that the units were very leaky. Some large and many diffuse openings from basement to both units due to balloon framing, vertical radiator pipes, and subfloor gaps. Caulked baseboards in units and sealed leaks from basement. Was not possible to seal all diffuse leaks from basement to units. Complete air barrier would require spray foam of entire basement ceiling.				
8-Plex	4.5	\$24	\$317	
Air leakage appeared to be concentrated to a few significant areas: the space under the bathtub, closet baseboards, kitchen plumbing penetrations, and hydronic radiator pipe penetrations. Limited access did not allow all leakage sites to be treated.				
12-Plex	5.3	\$85	\$431	
Infrared scan showed significant air movement up/down bathroom plumbing wall chase. There did not appear to be much air flow across the hall. The 2"x6" plumbing wall chase was sealed using multiple foam injections into the wall (see Figure 19). Accessible bathroom and kitchen plumbing pipes were also sealed.				
138 Unit	10.3	\$49	\$715	
A visual inspection indicated a fairly high level of construction details for this newer building. The IR and visual inspection found few hidden air leaks. Accessible plumbing and sprinkler pipes were sealed. Carpet was pulled back to seal baseboard/wall joints with clear acrylic caulk. Medicine cabinets were removed to seal plumbing chase leaks with foam. Ductwork seam leaks were sealed with caulk to reduce leakage to soffit areas.				
11 Story	7.6	\$25	\$499	
Work was limited to sealing sprinkler pipe, plumbing penetrations, and hydronic baseboard pipe penetrations. There were vertical mechanical chases that had large openings around the pipes and ductwork. Most chases were not accessible. The pipes and ducts in the chase adjacent to unit 410 were sealed using approved fire proofing techniques.				
4 Story	7.1	\$87	\$551	
Air leakage tests indicated that the units in this new building were relatively leaky. All ductwork was located in the 24" truss ceiling volume. Duct leakage measurements indicated that the ductwork was very leaky. Leakage between truss area and other adjoining apartments could not be determined. Aeroseal duct sealing method was able to achieve an average 86% reduction in duct leakage. There was additional work in units 301 and 401 due to the odor transfer complaint from unit 401. Baseboards were sealed in the kitchen area of both units. Large openings in the pocket door could not be addressed.				

1- for \$63 - \$65/hr labor rate

For the second year of the study it was decided that additional air sealing time would be spent in an effort to achieve greater inter-unit leakage reductions than what was achieved in the first year. The guideline for the amount of air sealing time was doubled to about eight hours per unit. The actual amount of time spent per unit varied from 7.1 hours for the 4 Story building to 10.3 hours for the 138 Unit building. Most of the leakage sites for these buildings were similar to those of the three older buildings treated in the first year of the study and similar air sealing techniques were applied to those areas. The 11 Story building with concrete floors had larger, vertical mechanical chases that had not been seen in previous buildings. The air sealing applied to one of the accessible chases is displayed in Figure 19.

The newer 138 Unit and 4 Story buildings had a couple of features that required new air sealing approaches. Some units had numerous recessed lights that were treated with air-tight inserts. These buildings also had individual forced air heating systems with ductwork that leaked air into the ceiling soffits or the truss volumes where they were located. It was expected that those cavities would be connected to adjoining units or the common area. For the 138 Unit building, all interior sections of the ductwork that were accessible were sealed with caulk. The duct leakage was measured to be greater for the systems in the 4 Story building and was expected to be a more significant source of air transfer between units. A relatively new aerosol sealing process¹ was used to perform duct sealing. For this process all of the supply and return registers are plugged and a patented system is used to inject a fog of aerosolized sealant particles into the pressurized ductwork (see Figure 20). The particles are directed towards and deposited at the leaks. As shown in Table 4, the equivalent leakage area of the ducts before they were sealed ranged from 37 to 61 square inches. The leakage was reduced by an average of 86% to yield duct leakages that ranged from 1 to 8 square inches. The duct sealing work cost \$1,250 per unit and that cost is not included in Table 3. The cost was higher than typical, because the nearest trained contractor at that time was more than 300 miles from the twin cities.

Figure 20. Duct sealing aerosol injection system



¹ This proprietary technique is available from Carrier AeroSeal LLC, Corporation,

Table 4. Results of duct sealing at 4 Story building

Unit	Leakage (cfm @25Pa)		Equivalent Leakage Area (sq in)		
	Pre	Post	Pre	Post	Reduction
301	260	7	49	1	97%
302	217	49	41	8	77%
305	197	41	37	8	79%
401	250	28	46	5	89%
403	197	41	37	8	79%
404	319	19	61	4	94%
405	204	30	39	6	85%
Min	197	7	37	1	77%
Median	217	30	41	6	85%
Average	235	31	44	6	86%
Max	319	49	61	8	97%

Ventilation

The ventilation systems were intended to augment natural air infiltration into the units and assure a moderate level of ventilation in warmer weather. Existing systems were modified or new ones installed as required to achieve a continuous exhaust flow from each unit. The goal was to achieve no more than 5 cfm difference in the flow rate of adjoining units and a minimum flow of 25 cfm from every unit. However, the target flow for each building varied depending on the size of the units, typical occupancy, and limitations of working with the existing systems. Table 5 lists the cost and measured flow rates achieved by each system. The cost of the ventilation system work varied from \$167 per unit for upgrades to the existing central exhaust system of the 8-Plex building to \$1,425 for an exterior wall mounted fan in one of the units of the 4 Story building. A cost from \$300 to \$500 should be expected for most typical installations.

Table 5. Cost, description, and flow rates of ventilation system treatments

Building	Cost/unit ¹	Ventilation System Work	Measured Flow Rate (cfm)		
			Min	Median	Max
Duplex	\$693	New central multi-point exhaust	26	28	28
8-Plex	\$167	Constant air regulators in existing central exhaust for bathrooms	23	26	28
12-Plex	\$359	Replace bathroom ceiling exhaust fans	35	37	42
138 Unit	\$438	New central multi-point exhaust from existing bathroom ceiling exhaust fans	20	23	28
11 Story	\$300 ²	Constant air regulators/duct sealing of existing central exhaust for bathrooms	18	20	22
4 Story	\$1,425	Wall mounted hi/low exhaust fan for 1 unit that was the source of the cooking odors		25	

1- for \$90/hr labor rate

2 – estimate based on expected cost for treating next set of fans using experienced gained from project work

New two or three point central exhaust systems were installed in the Duplex and 138 Unit buildings. The systems consisted of a two or three port manifold installed immediately before an in-line fan located in the attic (see Figure 21). The fan outlet was ducted to a termination located on the roof. Constant air regulators (CARs – see Figure 22) were installed in the duct from each unit to help automate the flow balancing process. The CARs have a flexible diaphragm that expands and contracts to produce a nearly constant air flow rate over a range of duct pressures. For the Duplex new ducts were installed from the manifold to fixed louver registers in the two units and a third duct was connected to the plumbing chase to help exhaust a sewer gas leak from that area. The system achieved the flow rate goals. A flow of 26 cfm was obtained from the lower unit and 28 cfm from the upper unit.

Figure 21. In-line exhaust fan and sound baffle/manifold located in the attic

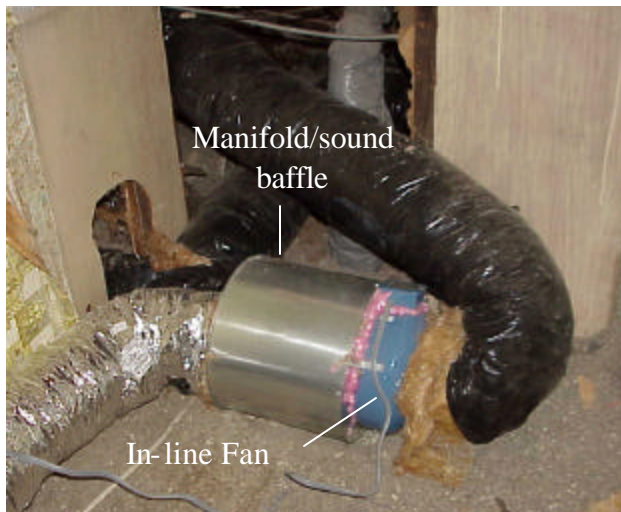


Figure 22. Constant air regulator installed at manifold inlets



For the 138 Unit building it was not feasible to run new ducts to the first and second floor units so the ducts from the existing bathroom exhaust fans were connected to the manifolds. With this arrangement air was continuously drawn through the existing bathroom exhaust fans. If the occupants turned on their exhaust fan, the flow through the fan would increase slightly. The exhaust flow rates ranged from 20 to 26 cfm in the nonsmoker's units, which was close to the goal of 25 cfm and met the goal of no more than 5 cfm difference between units. It was determined that the additional noise level from a bigger fan was not worth the extra flow that would have been produced. The restriction in the duct from the smoker's unit was repaired and the CAR was left off to produce a slightly higher flow of 28 cfm. This was intended to provide better ventilation and help assure that any imbalance in the exhaust flow rates would tend to draw air from the nonsmoker's units into the smokers unit. The cost per unit for those systems was \$693 for the Duplex with new ductwork and \$438 for the 138 Unit building where the existing ductwork was used.

For the 12-Plex building the existing bathroom ceiling exhaust fans were replaced by quiet ceiling exhaust fans that are rated for continuous operation (Panasonic model FV-05). The existing ductwork was not modified and the switches were wired to operate the fans continuously. The fans are rated to produce a flow rate of 50 cfm against a static pressure of 0.1" water and 31 cfm against 0.25" water. The measured flows using the existing 3" diameter ducts ranged from 35 to 42 cfm with a median value of 37 cfm. It was felt that the somewhat higher flow would be a benefit to some of the units where there were more than three occupants. The fans cost \$359 per unit to install using a contractor who was familiar with installing fans of this type for a sound insulation program.

The existing central exhaust systems in the 8-Plex and 11 Story buildings were modified to achieve acceptable and more consistent flow from each unit. For the 8-Plex building all that was required was to clean out the debris from the ducts, install a CAR in each duct at the inlet register, and remove the adjustable louvers. This approach only cost \$167 and the maintenance staff was trained on the process for other units in the complex. Before the work was performed the exhaust flows in the eight units ranged from 9 to 53 cfm with an average of 31 cfm. After the work the average dropped to 26 cfm and the flow rates only varied from 23 to 28 cfm. The change in flows was particularly helpful in this building. Before the work the smoker's unit had the lowest flow and there was as much as a 44 cfm difference between the flow from the smoker's unit and one of the adjoining nonsmoker units. This tended to draw air (and ETS) from the smoker's unit to the nonsmoker's unit. A more even distribution of exhaust flow rates eliminated that effect. It is also possible to install a higher flow CAR or eliminate the CAR so that there is a higher exhaust flow for the smoker's unit. That can help reverse thermal stack or wind driven flow from a smoker's unit to adjoining units. The drawback to that approach is that maintenance staff have to remember to re-balance exhaust flows when a smoker moves out of a unit.

The central exhaust system in the 11 Story building required more extensive work. Before the project started the building manager had conducted "tissue paper" tests¹ and determined that most of the units on the lower four floors of the building had little or no flow into the bathroom exhaust registers. In fact, in some weather conditions air came out of the registers. It was expected that all of the units served by an exhaust fan would need to be treated in order for any of the units to have acceptable flow. So all of the units in the "12" stack (e.g. units with numbers ending in 12) and the "14" stack were treated. The first attempt to improve the situation was to install 30 cfm CARs in each of the registers. This helped reduce the flow from the units on the highest two or three floors, but there was only a marginal improvement in the flow in units below the 8th floor. When the CARs were installed, project staff noticed that where the horizontal duct and riser from each unit entered the vertical shaft² most of the area of the vertical shaft was blocked. The restriction was worse where the vertical shaft and duct risers ran through the concrete floors because the cutouts in the floors were smaller than the vertical shaft. The next step was to cut out the bottom of each elbow to reduce the restriction and to seal the top portion of the shaft that extends above the roof. This improved the situation so that in the minimum flow

¹ A tissue was placed up against the register and a value from 0 (tissue falls away) to 3 (tissue strongly held against register) was assigned.

² Fire code requires that each duct that enters the vertical shaft have a 90 degree elbow with an extension pointing upwards. Alternatively, a fire damper can be installed in the duct.

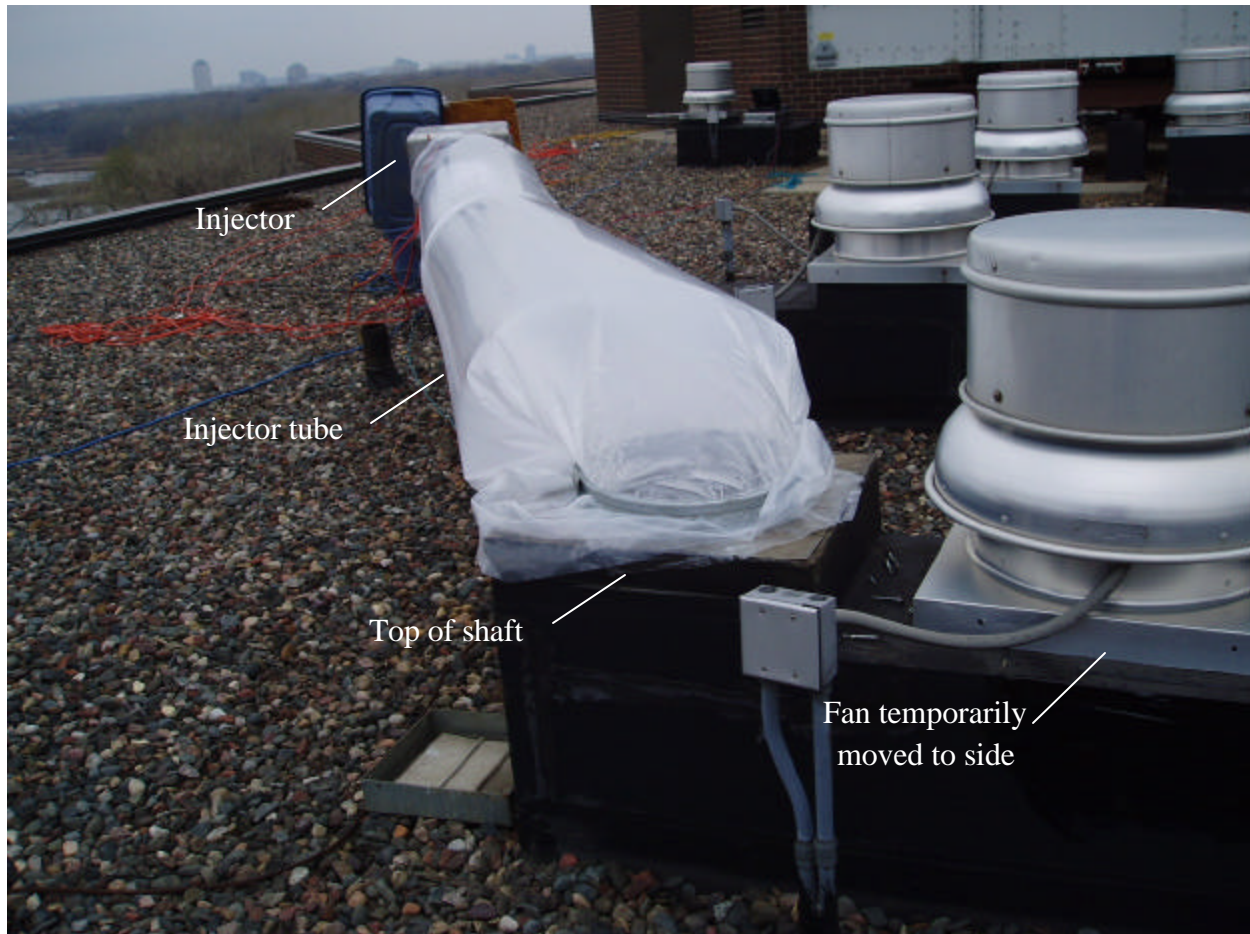
at the bottom of the 12 stack of units was 9 cfm and the minimum flow for the 14 stack was 15 cfm.

The flow through each roof mounted fan was measured after the second step was completed. The total flow through the fan was 580 cfm and the flow coming in through the registers was only 203 cfm. This indicated that about 65% of the flow through the fan was coming in through leaks in the ductwork and not directly from the units. Since the vertical, gypsum board shaft was not accessible; the Aero seal duct sealing technique was applied to the central shafts, 3” horizontal risers were added to the exhaust ducts for the top three floors, and the cutouts in the duct elbows for the lower eight floors were repaired¹. For the Aero seal process a plug was installed in the inlet registers for all of the units in the stack served by the fan, the fan was removed, and the system was installed to the shaft on top of the roof (see Figure 23). This was the first commercial application of the Aero seal method for a high rise exhaust duct. The duct sealing reduced the air leakage to 34% for the 14 stack and 23% for the 12 stack. Further sealing may have been obtained by a higher capacity injection system that is currently under development². After the duct sealing and further flow balancing was complete, the exhaust flows for the two stacks varied from 17 to 22 cfm except for a low flow of 14 cfm on the 10th floor of the 12 stack. The median flow for the 12 stack was 18 cfm and 20 cfm for the 14 stack. It was determined that the flows were acceptable for the low occupancy of the units and no further work was performed. The fan speeds would have been increased if there were further complaints.

¹ The duct elbow cutouts were no longer necessary with the reduction in flow that occurred when the leakage was reduced.

² An early version of the modified system was used to seal two additional shafts. The system was able to reduce the duct leakage to less than 15% of the fan flow rate and completed the work in less time than required for the first two shafts.

Figure 23. Duct sealing aerosol injection system connected to central shaft



Only one exhaust fan was installed in the 4 Story building. It was felt that enough ventilation would be provided by a combination of infiltration through the rather leaky exterior walls and some supply ventilation would be drawn in through the combustion air duct¹ when the furnace ran for heating or cooling. In addition, each of the units had only one or two occupants. A through-wall exhaust fan was installed in unit 301 to help the occupants exhaust some of the cooking odors. The fan was configured to run continuously at a flow rate of 25 cfm and a switch was installed so that the occupant can turn the fan to high speed (flow rate of 75 cfm) when desired. The installation was rather expensive (\$1,425), due to the difficulty in running the electrical wires and ductwork.

Air Leakage Measurements

The objective of the air sealing work was to reduce the air leakage paths between units. Any reduction in exterior leakage was an unintended by-product of that work. Guarded zone air

¹ The combustion air duct was connected to the return ductwork, so extra air is drawn in through the duct when the furnace fans operated.

leakage measurements were conducted to measure the effect of the air leakage work. For the first year of the study the guarded zone method was used to directly measure the total and exterior leakage of each unit. The difference between those two measurements provided an estimate of the sum of leakage to the adjoining units and common area¹. For the second year of the study more extensive tests were conducted that also provided estimates of leakage to individual adjoining units. When interpreting the results, it is important to note that for the 8-Plex and 12-Plex the values for leakage to adjoining units also included leakage to the common areas.

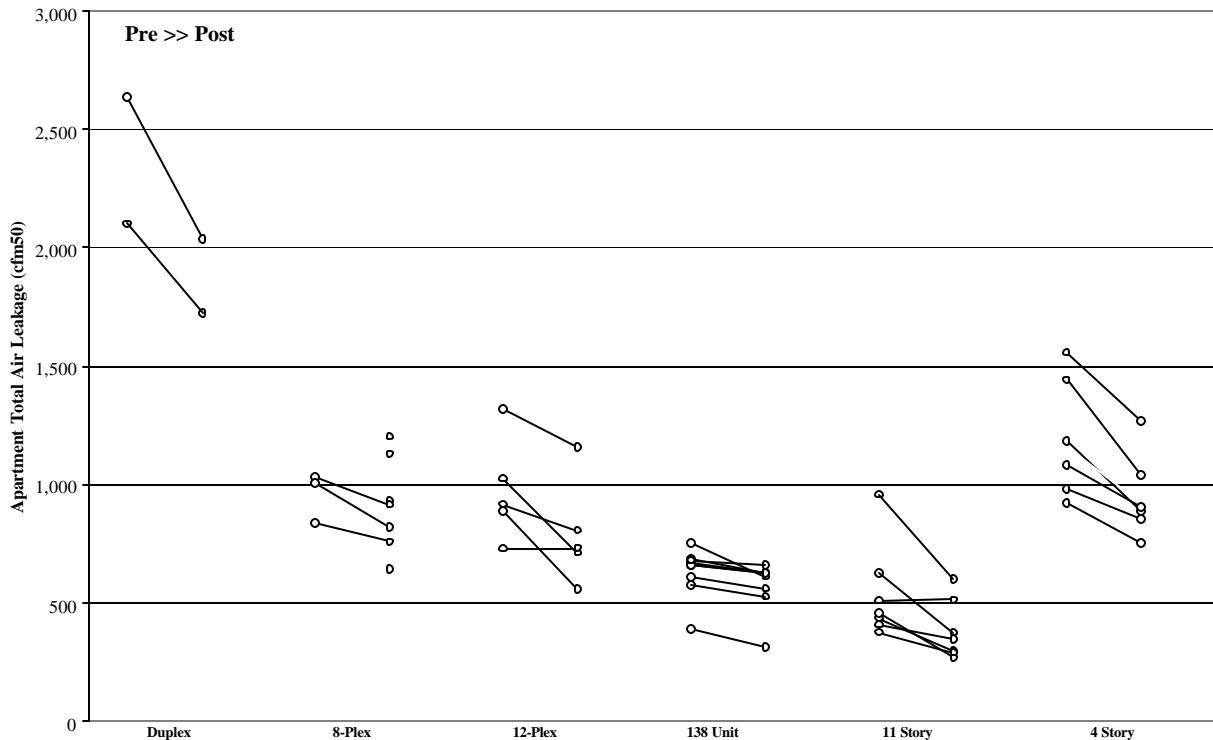
Before any work was done, the total air leakage in the buildings varied from 376 cfm50 in one unit in the 11 Story building to 2,636 cfm50 in the lower unit of the Duplex and the median value was 861 cfm50. Table 6 provides information on the pre/post total air leakage by building and Figure 24 provides a graphic representation of the total air leakage for each test unit in the buildings. More detailed results are available for all of the buildings in Appendices B – G. The results show that the units in the 11 Story building had the lowest total leakage and that the duplex was more than twice as leaky as the next leakiest building. Except for the Duplex and 8-Plex, there was almost a two to one variation in the leakiest to tightest unit in each building. That indicates that for most buildings there is a significant variation in leakage and that one or two measurements are not enough to characterize the leakage of all the units in a building.

Table 6. Summary of pre/post change in total unit air leakage

Building	Pre-Treatment (cfm50)			Post-Treatment (cfm50)			Leakage Change (cfm50)			Leakage Change (%)		
	Min	Median	Max	Min	Median	Max	Min	Median	Max	Min	Median	Max
Duplex	2,101	2,368	2,636	1,723	1,879	2,036	-600	-489	-379	-23%	-20%	-18%
8 Plex	837	1,008	1,031	757	818	916	-190	-115	-79	-19%	-11%	-9%
12 Plex	731	917	1,318	559	732	1,160	-326	-157	1	-37%	-12%	0%
138 Unit	390	665	754	314	618	660	-141	-45	-20	-20%	-8%	-3%
11 Story	376	454	958	267	348	600	-359	-137	1	-41%	-32%	0%
4 Story	921	1,156	1,559	750	905	1,270	-402	-235	-125	-28%	-19%	-13%
All Buildings	376	861	2,368	267	722	1,879	-489	-139	1	-41%	-18%	0%

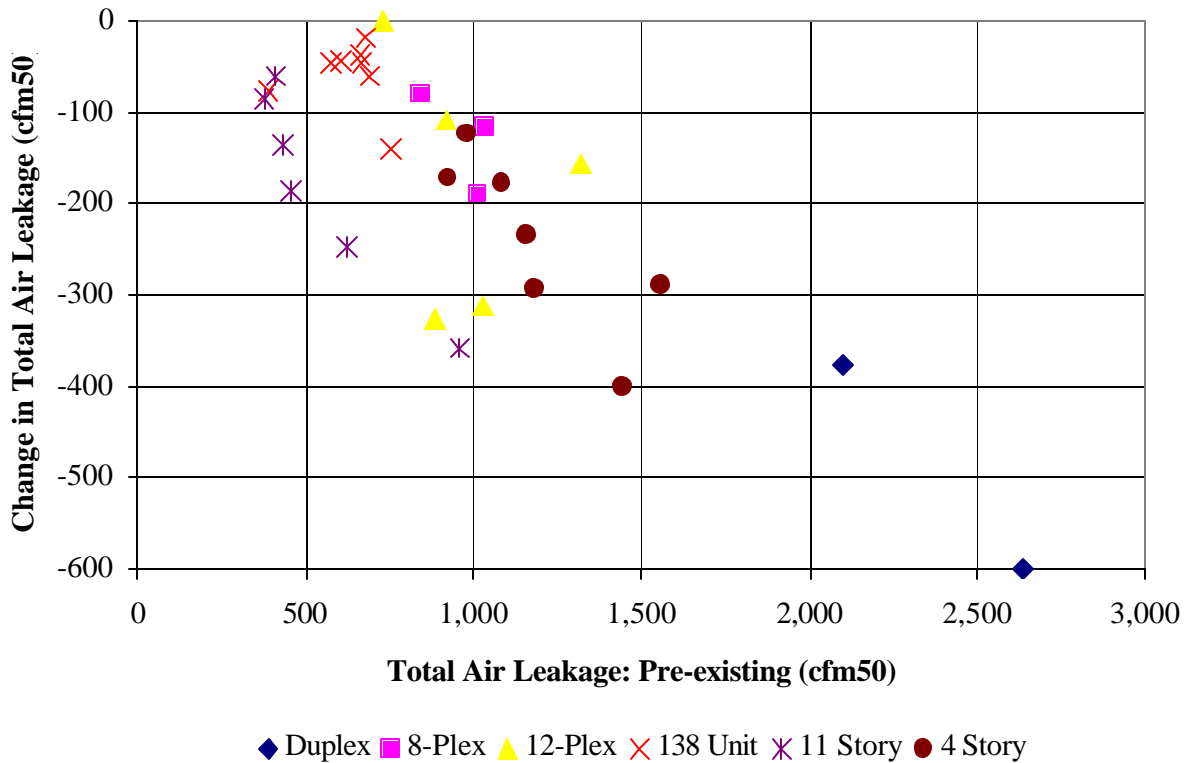
¹ Both guarded zone and advanced single fan (e.g. zone pressure diagnostics or ZPD) methods were used for the three buildings in the first year of the study. It was expected that the guarded zone method would provide a direct measure of the total and exterior unit air leakages and that the ZPD results would provide more details on the leakage between units. A comparison of guarded zone and ZPD results showed fairly good agreement in the exterior leakage and inter-unit leakage. Unfortunately, the ZPD estimates of air leakage from the units to the common area appeared to be unrealistically large and the source of this discrepancy was not been determined. The ZPD measurements are included in the Appendices and only the guarded zone results are included in the main body of this report.

Figure 24. Pre/post change in total unit air leakage for individual units



Overall, after work was completed the median total air leakage was reduced to 722 cfm50 with a typical reduction of 139 cfm50 per unit and a relative reduction of 18%. 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 (Figure 25). The lowest median reduction for a building was 45 cfm50 for the new 138 Unit building which had the second lowest pre-existing air leakage. The greatest reductions were obtained for the 24 hours of air sealing per unit that was spent on the Duplex. The next largest reduction was for the 4 Story building where both air sealing and duct sealing was performed. However, 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 air leakages, yet four of the eight units in the 11 Story building had reductions greater than 125 cfm50 while only one of the units in the 138 Unit building had a reduction greater than 100 cfm50.

Figure 25. Pre/post change versus pre-existing total air leakage for individual units



As discussed previously, the primary air sealing objective was to reduce the air leakage between units. Table 7 presents the pre/post inter-unit air leakages for each of the six buildings and Table 8 presents the ratio of the inter-unit leakage divided by the total leakage¹. The tables also include the pre/post change and the percent change in inter-unit leakage. Figure 26 displays the pre/post inter-unit leakage for individual units. The inter-unit leakages for individual units varied from 5 cfm50 for one of the units in the 138 Unit building to 654 cfm50 for one of the units in the 8-Plex and the median value for all the units was 155 cfm50. The three older buildings studied in the first year of the project had the highest inter-unit leakages. However, the values for the 8-Plex and 12-Plex included leakage to the common area. Those two buildings also had the highest relative inter-unit leakage, with over half of the total leakage being to other units and the common area. For all of the units the median ratio of the inter-unit leakage divided by the total leakage was 27%. As with the total leakage, there were typically large differences in the range of inter-unit leakage for each building.

¹ For the 4 Story building there were some unoccupied units between test units and the building owner would not provide access to those units. Consequently, few measurements of inter-unit leakage are available for the 4 Story building.

Table 7. Summary of pre/post change in inter-unit air leakage

Building	Pre-Treatment (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 ¹	492	504	654	419	454	501	-153	-74	-50	-23%	-15%	-10%
12 Plex ¹	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%

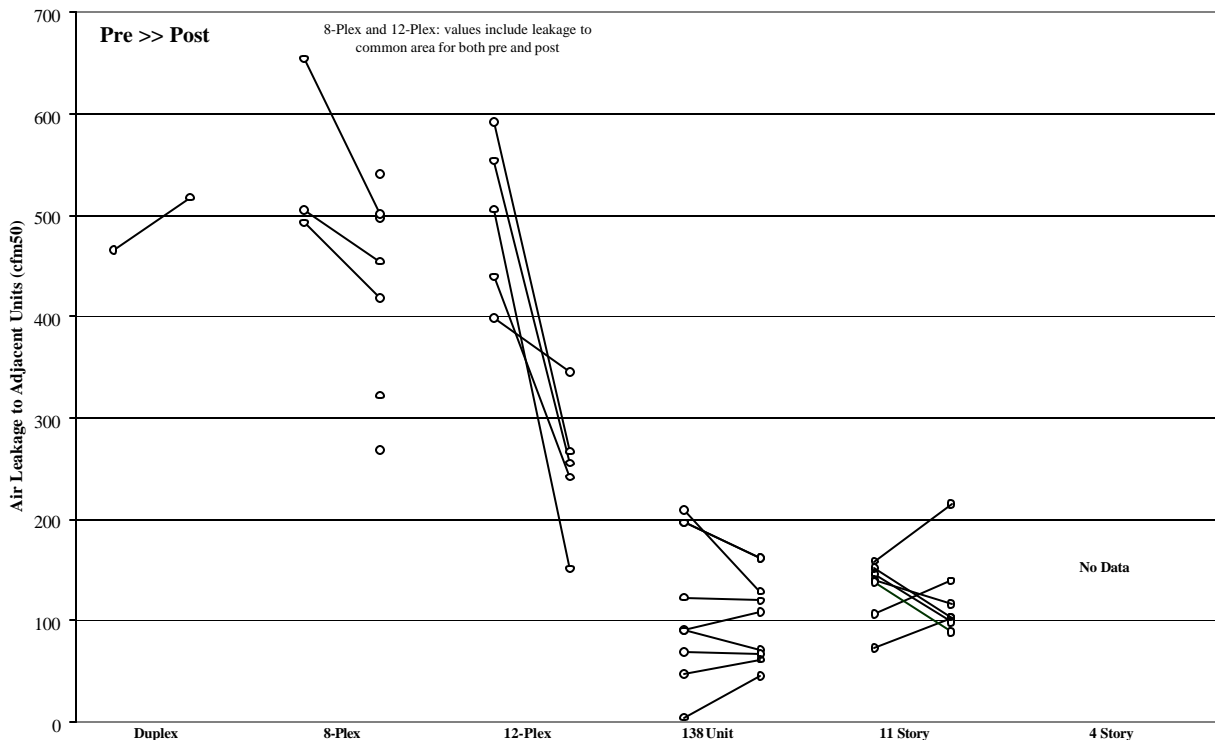
1 - leakage to adjacent units includes leakage to common area

Table 8. Summary of pre/post change in inter-unit/total air leakage

Building	Pre-Treatment (%)			Post-Treatment (%)			Change			Percent Change		
	Min	Median	Max	Min	Median	Max	Min	Median	Max	Min	Median	Max
Duplex		20%			28%			8%			40%	
8 Plex ¹	49%	59%	65%	50%	55%	61%	-4%	-4%	1%	-6%	-6%	1%
12 Plex ¹	33%	57%	60%	Not Enough Data								
138 Unit	1%	16%	31%	7%	18%	26%	-11%	2%	6%	-34%	13%	880%
11 Story	17%	26%	39%	17%	34%	44%	-10%	13%	19%	-36%	41%	116%
4 Story	Not Enough Data											
All Buildings	1%	27%	65%	7%	32%	61%	-11%	1%	19%	-53%	1%	880%

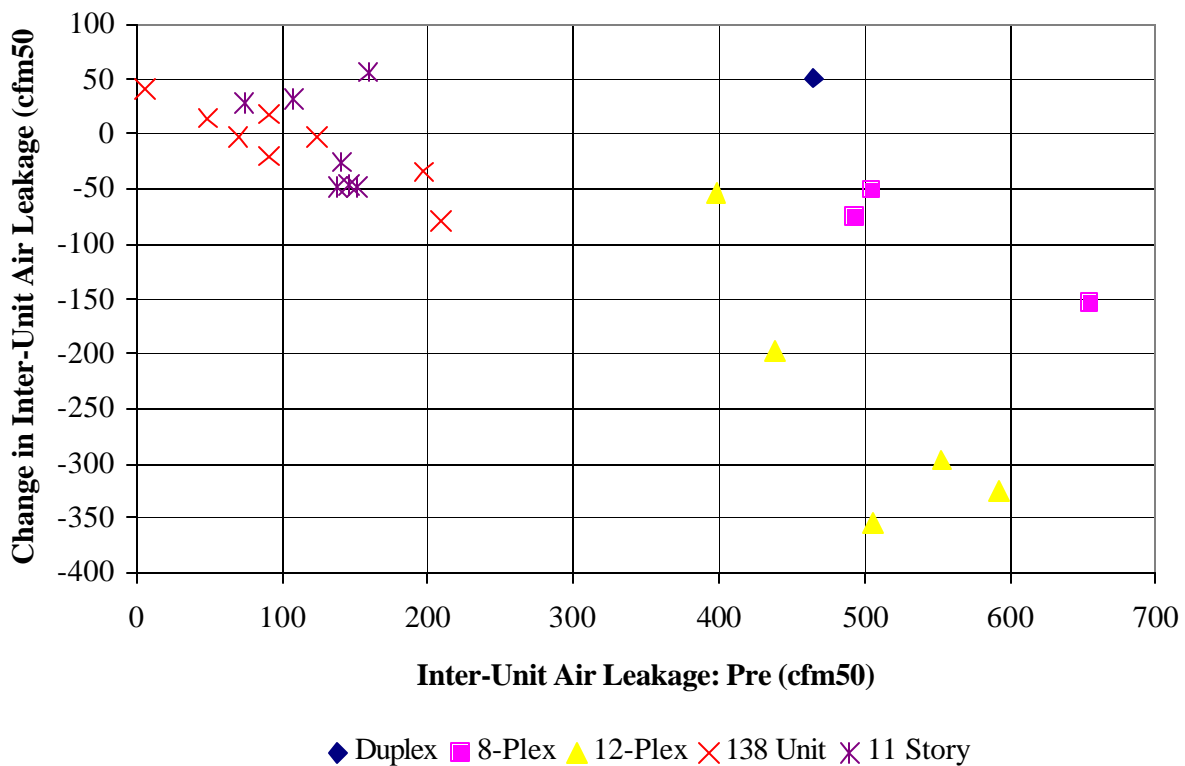
1 - leakage to adjacent units includes leakage to common area

Figure 26. Pre/post change in inter-unit air leakage for individual units



As shown in Figure 27, there were significant differences in the reduction in inter-unit leakage between buildings. The Duplex, 138 Unit, and 11 Story buildings all had median reductions of 25 cfm50 or less. In fact, almost all of the pre/post changes in inter-unit leakage for individual units in those three buildings were within two standard errors of zero. This indicates that the guarded zone method was not able to measure a significant pre/post different in the inter-unit air leakage. This result is not surprising for the 138 Unit and 11 Story buildings, since the pre-existing inter-unit leakages were all less than 210 cfm50 and five of the units in the 138 Unit building had leakages less than 100 cfm50.

Figure 27. Pre/post change versus pre-existing inter-unit air leakage for individual units



More detailed guarded zone tests for the Duplex showed that almost all of the reductions in the total unit leakages were due to reductions in leakage from the units to the common area (e.g. basement and back staircase) and there was no significant change in the exterior leakage or leakage directly between units. There were significant changes in the inter-unit leakages for the 8-Plex and 12-Plex. The median change in inter-unit leakage for those buildings was 74 and 298 cfm50 respectively and it appears for almost every unit the change in leakage was entirely due to a reduction in the inter-unit leakage.

It was not surprising that the air leakage results for the Duplex showed that the 20% average reduction in the total unit leakage was all due to reductions in leakage to the basement. Over a third of the air sealing efforts were spent in the basement sealing leaks in the subfloor of the lower unit and leaks into cavities that traveled up to the upper unit. It was hoped that this would reduce the flow of musty basement air into the units and help reduce the stack driving forces that caused much of the air entering the upper unit to come from the basement and lower unit.

It was unfortunate that it was not possible to have access to the unoccupied units in the 4 Story building to help determine how much of the 20% average leakage reduction was to the adjoining units. It is likely that much of the reduction in total leakage was due to reduced duct leakage to the ceiling truss space. Measurements made during the air leakage tests indicated that the truss space for many of the units had approximately the same leakage area to the unit as to adjoining spaces and the outside. Since most of the leakage was in the supply ducts, when the furnace fan operated any leakage would cause air to flow out of the leaks into the truss area. That pressurized the truss space causing some of the leaking air to re-enter the unit and about half of it to flow into the adjoining units or outside.

The small reductions in total (8%) and inter-unit (4%) leakage for the 138 Unit building is not surprising considering that the median pre-existing inter-unit leakage was only 90 cfm50 or 15% of the total leakage. It is encouraging that the inter-unit leakage of the 12-Plex units was typically reduced by 54% and that there were moderate (15%) inter-unit leakage reductions for the 8-Plex. One explanation for the success of the air sealing at the 12-Plex was that the pre-existing leakage was large and that a single, direct, large leakage path (e.g. the plumbing chase) was identified and treated.

In all of the buildings there were many leakage paths that were identified, but not treated. There were often objects that could not be readily moved (water beds, large book cases, cases with hundreds of CDs, furniture with breakable items on top) that did not allow baseboard sections to be sealed. There were also kitchen built-ins and other cabinets that would have had to have been removed in order to be sealed completely. In addition, there were many plumbing chases, mechanical chases, and floor/ceiling cavities that were not accessible without cutting access through finished materials. Finally, the leaks in the tops of interior partition walls were not accessible. All of these leaks would be much easier, or at least feasible, to seal during the time of construction or major remodeling. For buildings where that is not possible, some of the leaks would be more accessible during a change in occupancy.

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 inter-unit 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 often are connected to an intermediate area between units such as a floor cavity or mechanical chase. The restriction in the air flow between units can be a combination of the restriction due to the leaks from the 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. Experienced air sealing technicians will often note that they did not

see any change in the measured air leakage until they started sealing the last gaps in an area. This type of situation proposes a particular problem for air sealing multifamily units where access issues may only allow a portion of an area (such as a section of baseboard) to be treated. Again, it is easiest to seal leaks at the time of construction before all the barriers to access are put in place.

The guarded zone testing method can also cause some leaks to be measured as part of the total leakage test, but not as leakage to adjacent units. Some mechanical chases are open to multiple units in a vertical stack of a multi-story building. When the guarded zone technique is applied to individual, adjacent units the leakage into chases that are connected to multiple units may be greatly underestimated as a leakage to an adjacent unit even though the leak allows air to transfer between units. This may partially explain why only a reduction of 25 cfm50 inter-unit leakage was measured for the 11 Story building when the reduction in the total leakage was 137 cfm50. The error would not have been as great for the 8-Plex and 12-Plex, since all of the units were pressurized at the same time as the test unit. Given the difficulty and some of the inherent errors in the guarded zone test method, air sealing practitioners and agencies that need to set air tightness guidelines for multifamily units should consider using the total leakage test and results.

Figure 28 provides a different technique for displaying the pre/post inter-unit and total air leakage for the individual units. Except for the 4-Plex chart, the blue bars represent the inter-unit leakage and the red diagonal bars represent the leakage to the exterior or sum of exterior and common space. A quick view of the pre/post drop in the top of the bars confirms that the total leakage was reduced for almost all of the units. An examination of the height of the blue bars relative to the height of the top of the bars provides a graphical representation of the relative size of the inter-unit to the total. This confirms that the inter-unit leakage is relatively small for the 11 Story and 138 Unit buildings, but that it is significant for the 8-Plex and 12-Plex buildings and that there were noticeable pre/post reductions for inter-unit leakage for those two buildings.

Detailed results from the guarded zone and ZPD measurements for leakage to individual units are included in Appendices B – G. A sample of the more detailed guarded zone inter-unit leakage measurements for the 11 Story building is displayed in Figure 29. This graphic makes it easier to determine that the total unit leakages of the units in the 12 stack are consistently lower than those of the 10 stack that are adjacent to the elevator shaft. In addition, the vertical leakage between units in the 10 stack appears to be significantly greater than the vertical leakage for the other stacks. That could be due to a leakier mechanical chase adjacent to the 10 stack. Also, the horizontal leakages are of similar magnitude to the vertical leakages.

Figure 28. Pre/post air leakage of individual test units (cfm50)

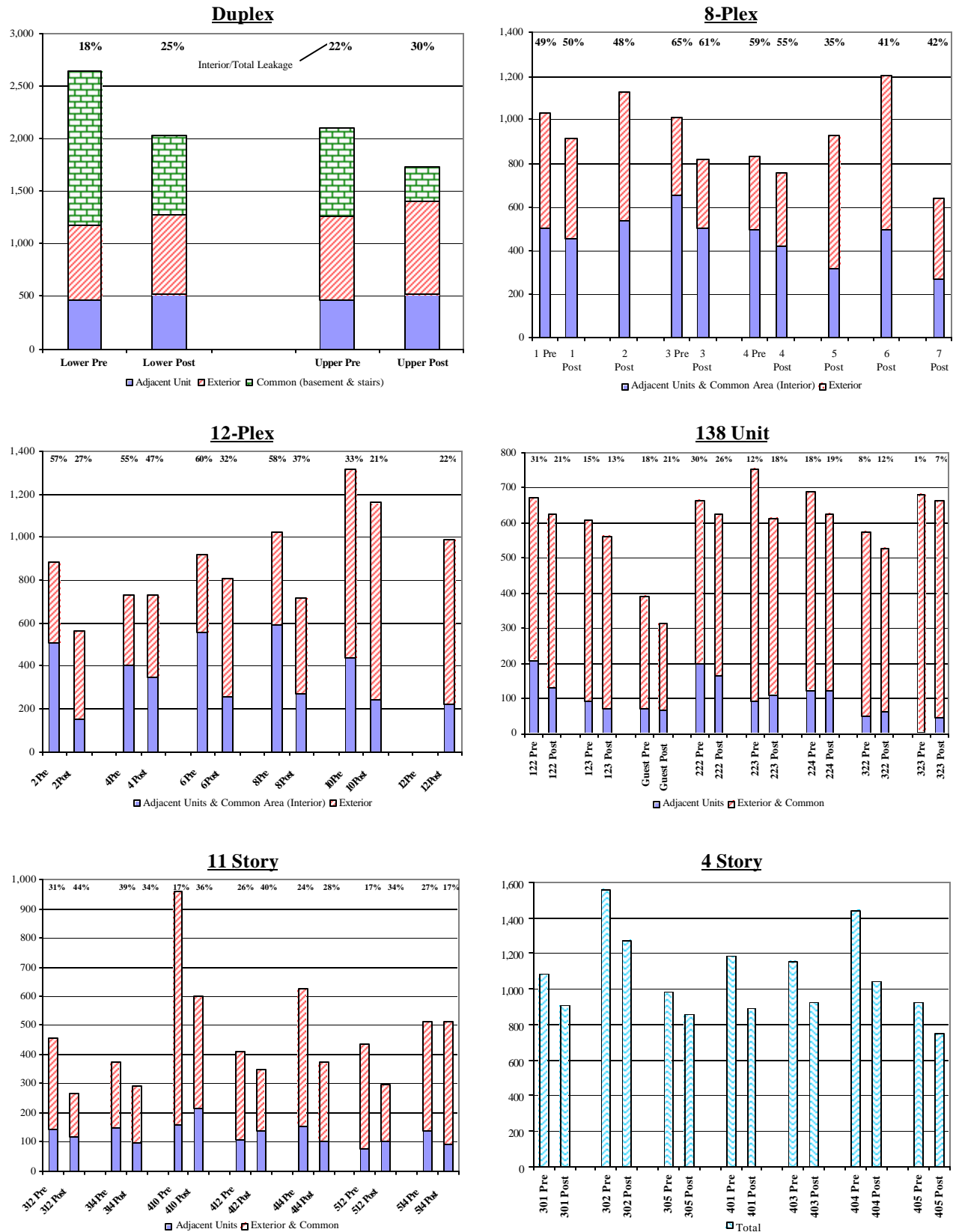


Figure 29. Total and inter-unit air leakage for the 11 Story building: pre-treatment

	712		
	<u>616</u>		
	33	↕	
	612		
	<u>517</u>		
	20	↕	
514	512	510	
<u>511</u>	↔ 24	<u>435</u>	↔ 10
			<u>592</u>
45	↕	20	↕
414	412	410	
<u>624</u>	↔ 44	<u>409</u>	↔ 2
			<u>958</u>
19	↕	42	↕
314	312	310	
<u>376</u>	↔ 54	<u>454</u>	↔ 24
			<u>594</u>
	21	↕	
	212		
	<u>416</u>		

Elevator

- 111 - treated units
- 111 - unit w/smoker, treated
- 111 - units monitored, but not treated
- #### - total leakage (cfm50)
- ## - leakage between units

Tracer Gas Air Flow Measurements

The PFT method was used to provide information on one week average of outdoor air infiltration rates to each unit, inter-unit air flow rates, and ETS transport between units in the building. Each unit was treated as a single, well-mixed zone. Except for the Duplex, the availability of only seven different PFTs limited monitoring to a subset of the units in each building and the common

area was not included as a zone. For this situation, an approximate “rule of thumb” is that when there are zones that are not tagged with a PFT source, the computed flow of outdoor air into a unit will include the flow of any outdoor air that travels through an “untagged” zone before it enters the unit. For the buildings studied the flow between units is often very small, so the fraction of inter-unit flow that is designated as infiltration should be relatively small. It should be noted that for this report the term air infiltration is used to describe the movement of outdoor air into a building through leaks in the building exterior and open windows or doors.

For the first year of the study the PFT monitoring was conducted before any work was done and after both the air sealing and ventilation treatments were complete. In the second year of the study monitoring was also performed between the completion of the air sealing and start of the ventilation work. However, only one exhaust fan was installed in the 4 Story building, so only pre/post air sealing monitoring was conducted for that building. During the second year of the study the residents were also asked to complete a daily log that included the number of cigarettes smoked and the number of hours a window was left open. Table 9 displays information on the start date, average outside temperature, resident smoking, and window opening periods for each of the monitoring periods. In order to minimize weather effects, the pre/post monitoring periods for a building were scheduled so that the outdoor temperature would be similar for the periods. This was generally successful. For four of the buildings the monitoring periods had average outdoor temperatures within 5°F of each other. For the 138 Unit building the outdoor temperature for the final monitoring period was about 15°F less than that for the other two periods and for the 11 Story building the first monitoring period was about 25°F less than the other two periods. In general, air infiltration and stack effect driven inter-unit air flows are expected to increase with lower outdoor temperatures. However, for those two buildings the residents also had fewer hours of open windows during the colder weather which may have helped offset the greater stack effect for some of the units.

Table 9. Monitoring period outside temperature, cigarette use, and window openings

Unit	Period	Start Date	Tout (F)	Smoking				Open Windows		Total (hrs)
				Unit	# Cigs	Unit	# Cigs	(unit: hours)		
Duplex	Pre	12/7/2001	32	None				Not Monitored		
Duplex	Post	3/26/2002	37	None				Not Monitored		
8-Plex	Pre	1/4/2002	30					Not Monitored		
8-Plex	Post	2/19/2002	29					Not Monitored		
12-Plex	Pre	1/16/2002	22					Not Monitored		
12-Plex	Post	3/4/2002	20					Not Monitored		
138 Unit	Pre	12/3/2002	21	123	252			122: 56, 124: 1.5, 223: 2.75, 321: 2.0		62
138 Unit	Air Seal	1/7/2003	20	123	215			122: 64, 123: 3.0, 124: 10, 223: 5.0, 224: 0.5		82
138 Unit	Ventilation	2/4/2003	6	123	170			223: 2.0		3
11 Story	Pre	2/25/2003	19	410	129	414	19	310: 5.0, 412: 2.5, 414: 4.0, 510: 1.0, 612: 0.25, 712: 1.83		15
11 Story	Air Seal	3/18/2003	45	410	123	414	22	212: 15.0, 310: 82.5, 314: 43.0, 410: 18.5, 414: 10.5, 512: 5.0, 514: 53.0, 712: 36.0		277
11 Story	Ventilation	4/21/2003	45	410	95	414	0	212: 60, 310: 102, 314: 8.410: 5.5, 510: 10, 514: 34, 612: 8, 712: 51		290
4 Story	Pre	3/27/2003	40	404	1			305: 3, 401: 0.75, 404: 0.5		4
4 Story	Air Seal	4/10/2003	44	404	1			403: 1.5, 404: 2.8, 305: 27		31

A summary by building of the air infiltration and total flow into each unit is displayed in Tables 10 and 11 and the air infiltration and total flows for individual units is displayed in Figures 30

and 31. The pre-treatment median infiltration rate varied from a low of 26 for the 138 Unit building to a high of 45 for the 4 Story building. There was a general, but not perfect trend of higher infiltration rates for buildings with higher air leakage. It is interesting that for the three buildings in the second year for which pre/post air sealing information is available there is little or no change in the median infiltration or total flow for the buildings. Thus, for those three buildings the air sealing appeared to have no measurable effect on air infiltration. On the other hand, the five units that had ventilation treatments had significant increases in the median infiltration rate after the ventilation was installed. The relative change in the median infiltration rate was also significant – ranging from 54 to 112%. The largest increase of 43 cfm occurred for the 12-Plex where the highest flow rate exhaust fans (35 to 42 cfm) were installed. The next largest increase of 29 cfm occurred for the 11 Story building where the continuous exhaust ventilation was increased from close to zero to about 20 cfm. Some of the individual unit changes in infiltration rate also correlate well with the ventilation changes. For example, for unit 8 in the 8-Plex the exhaust flow rate was decreased by 28 cfm and the infiltration rate dropped by 32 cfm. However, in the same building the exhaust flow rate for unit 1 decreased by 1 cfm and the infiltration rate increased 39 cfm. It is likely (and the year 2 resident logs confirm) that the amount of time and size of the area that residents opened windows was responsible for some of the unanticipated variations in the infiltration rates of the individual units.

Table 10. Summary of pre/post change in individual unit infiltration rate

Building	Pre-Treatment (cfm)			After Sealing (cfm)			After Ventilation (cfm)			Pre to Post Change (cfm)			Pre to Post Change (%)		
	Min	Median	Max	Min	Median	Max	Min	Median	Max	Min	Median	Max	Min	Median	Max
Duplex	12	28	43				35	43	50	7	15	22	17%	54%	182%
8-Plex	19	38	58				26	50	79	-32	26	39	-56%	95%	147%
12-Plex	23	38	75				57	73	157	24	43	82	65%	112%	181%
138 Unit	15	26	47	17	26	55	31	41	53	-5	16	23	-11%	75%	129%
11 Story	18	28	79	16	28	86	45	69	124	18	29	92	35%	94%	286%
4 Story	26	45	61	22	48	88				-14	-4	59	-22%	-11%	199%

Table 11. Summary of pre/post change in individual unit total air flow rate

Building	Pre-Treatment (cfm)			After Sealing (cfm)			After Ventilation (cfm)			Pre to Post Change (cfm)			Pre to Post Change (%)		
	Min	Median	Max	Min	Median	Max	Min	Median	Max	Min	Median	Max	Min	Median	Max
Duplex	35	40	46				53	58	62	16	17	18	36%	42%	52%
8-Plex	19	41	77				44	55	81	-32	28	44	-42%	101%	162%
12-Plex	28	38	92				64	82	189	30	49	97	79%	99%	192%
138 Unit	20	31	48	21	27	55	36	42	54	-5	16	22	-11%	71%	98%
11 Story	21	29	83	17	28	89	47	70	124	18	29	92	29%	88%	278%
4 Story	29	49	62	24	49	89				-13	-6	60	-21%	-12%	200%

Figure 30. Pre/post change in air infiltration for individual units

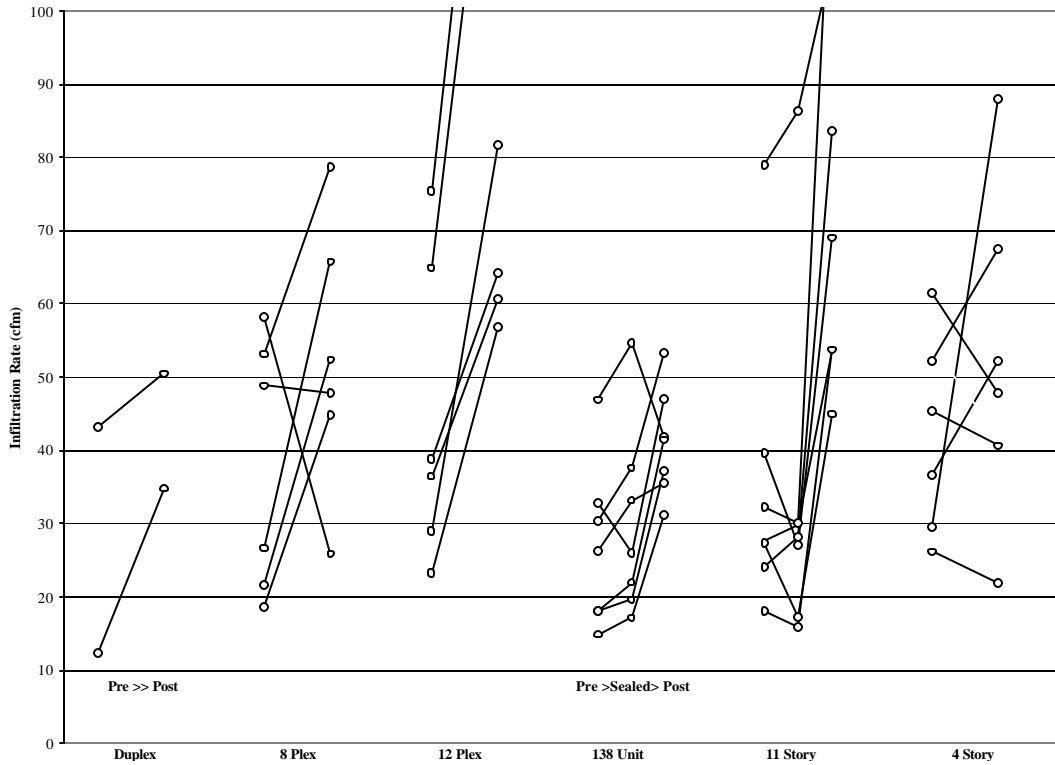
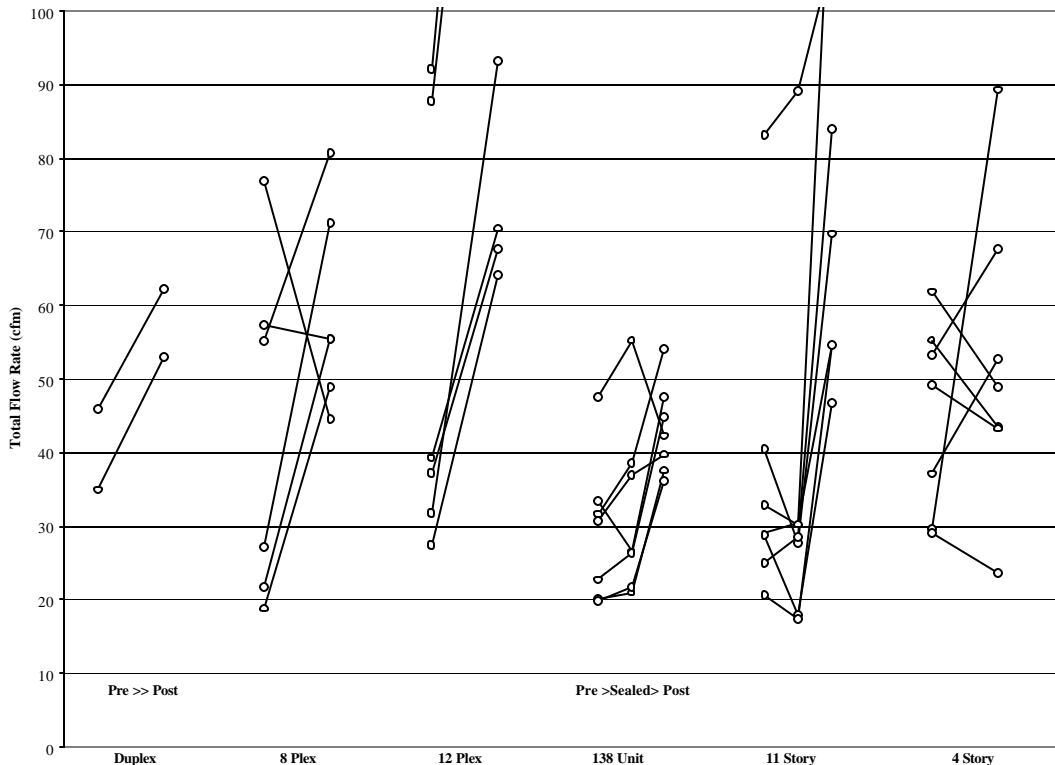


Figure 31. Pre/post change in total air flow into individual units



The measured air infiltration rates were also compared to ASHRAE Standard 62-2001 requirements for outdoor air to determine if the unit ventilation rates were considered to be acceptable. Table 12 displays a summary of that analysis. Before any work was done to the buildings a high fraction of the units did not meet ASHRAE 62 requirements. The 8-Plex had the highest compliance with 50% of the units having acceptable ventilation. After the continuous ventilation systems were installed the level of compliance increased substantially. Three of the buildings (8-Plex, 12-Plex, and 11 Story) had all or all but one of their units in compliance. The lower compliance for the 138 Unit building indicates that it may have been better to install higher capacity CARs to increase the exhaust flow rates for those systems. In addition, only about a third of the units in the 4 Story building complied with the ventilation requirements. However, all except one of the units had an infiltration rate over 40 cfm which should be acceptable for the current low occupancy rates of those units. Finally, while neither of the units in the duplex complied with the requirement the infiltration rates were significantly improved from the pre period. The infiltration rate of the lower unit increased to 50 cfm and the rate of the upper unit increased by almost a factor of three from 12 cfm to 35 cfm.

Table 12. Percentage of units that meet or exceed ASHRAE 62 outdoor air requirements

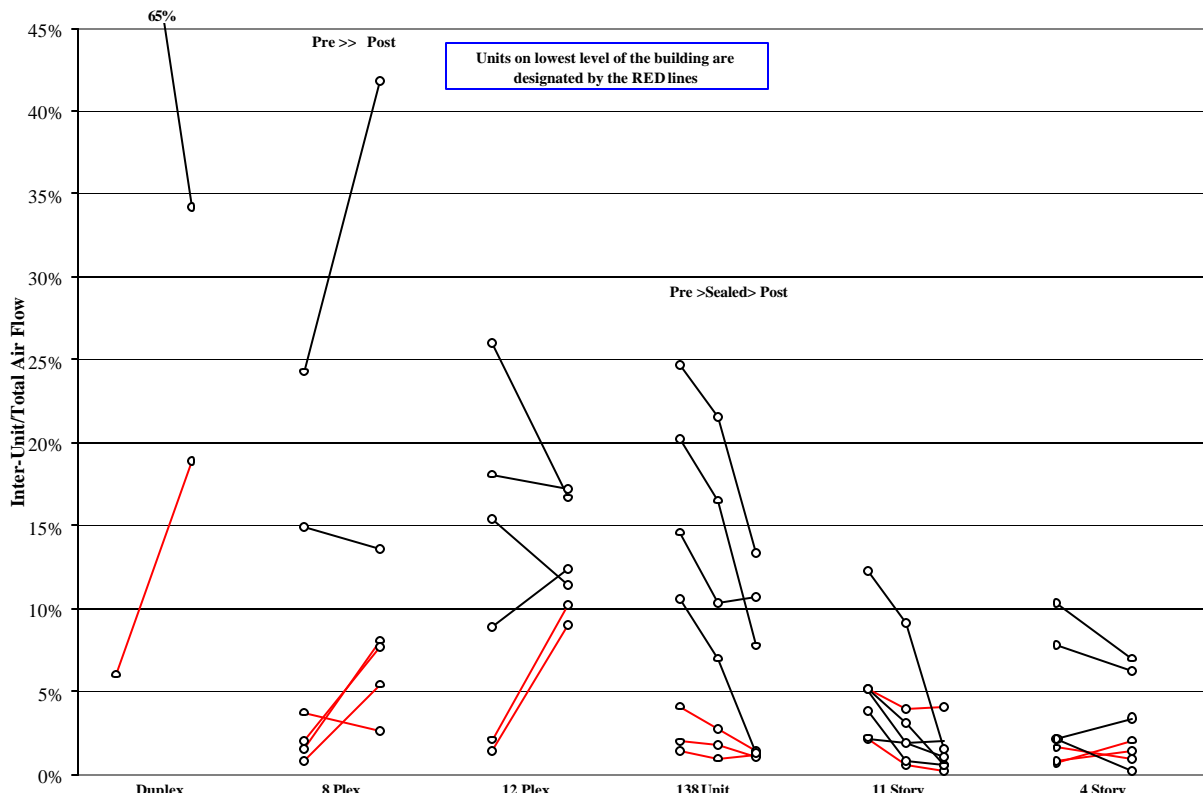
Building	Pre-Treat	After Seal.	After Vent.	Pre/Post Change
Duplex	0%		0%	0%
8-Plex	50%		83%	33%
12-Plex	33%		100%	67%
138 Unit	14%	14%	29%	14%
11 Story	14%	14%	86%	71%
4 Story	14%	29%		14%
All Units	23%	19%	60%	37%

While one goal of the treatments was to improve the ventilation systems to provide acceptable levels of ventilation, the other goal was to air seal the units to reduce the transfer of air and ETS between units. The transfer of air between units was evaluated by comparing the fraction of air that entered a unit from other units to the total amount of air entering the unit. A summary of that ratio for the pre/post monitoring periods is displayed in Table 13 for the six buildings and the values for individual units is displayed in Figure 32. The Duplex had the highest median fraction of inter-unit air flow (35%). For the 8-Plex, 11 Story, and 4 Story buildings the pre-existing fraction was already at or below 5%. In Figure 31 the units on the lowest level in each building are designated by red lines. As mentioned previously, the units on the lowest level have the smallest measured fraction of air entering from other units. It is important to note that for the 11 Story and 4 Story buildings and units below those tested are not tagged with a PFT gas, so air flow from those units is indicated as infiltration air.

Table 13. Summary of pre/post change in air flow from adjacent units divided by total flow into a unit

Building	Pre-Treatment (%)			After Sealing (cfm)			After Ventilation (%)			Change		
	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%	5%	42%	-30%	-1%	18%

Figure 32. Pre/post change in air flow from adjacent units divided by total flow into a unit

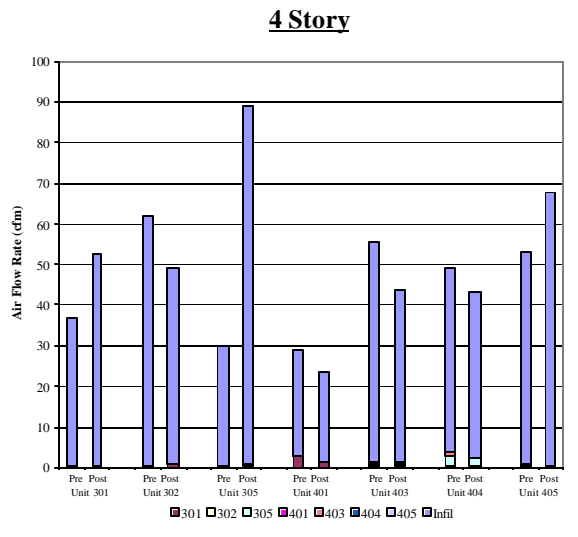
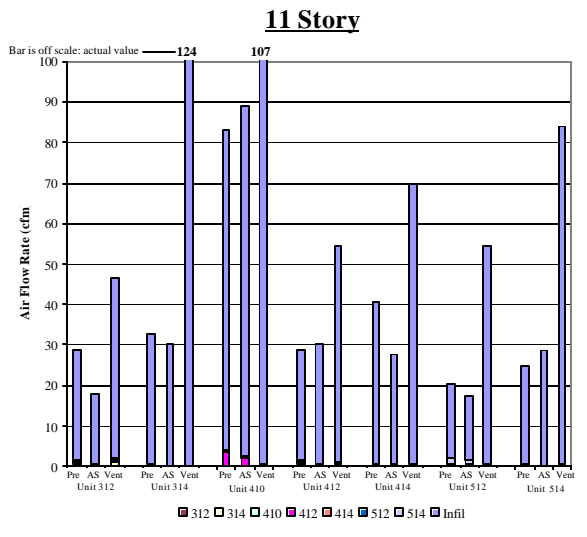
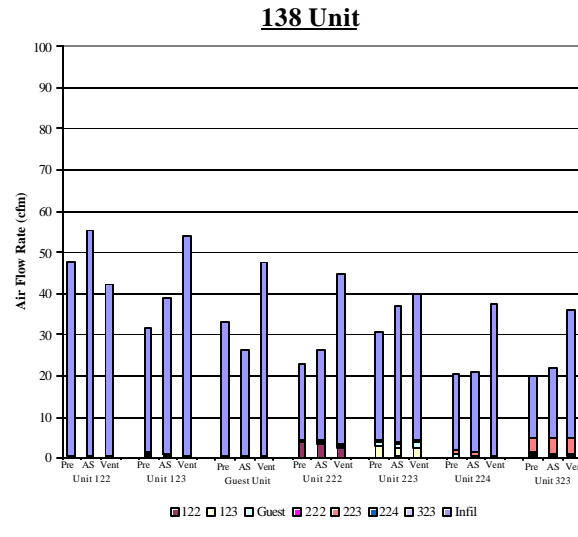
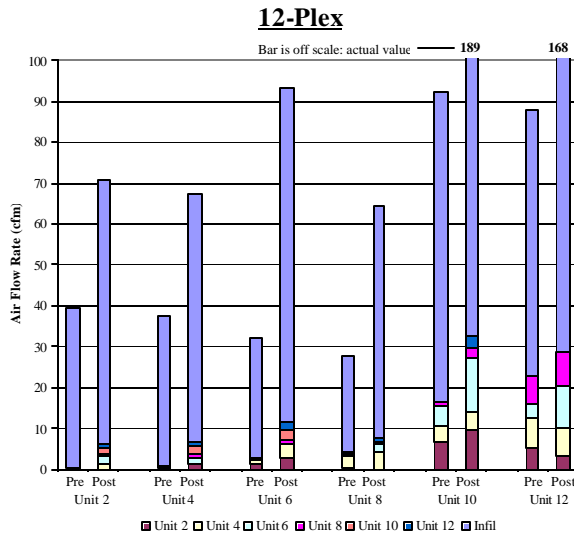
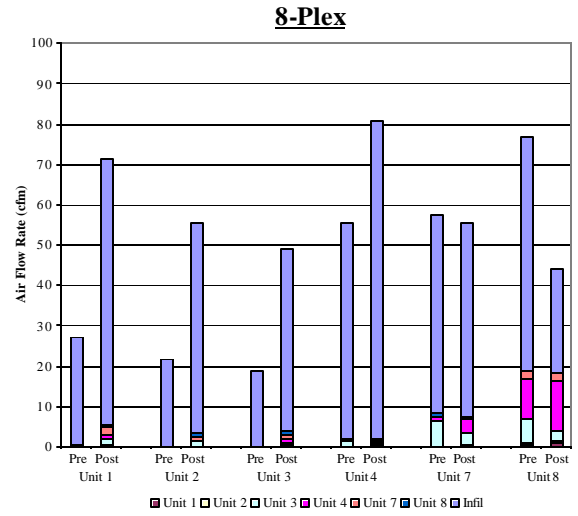
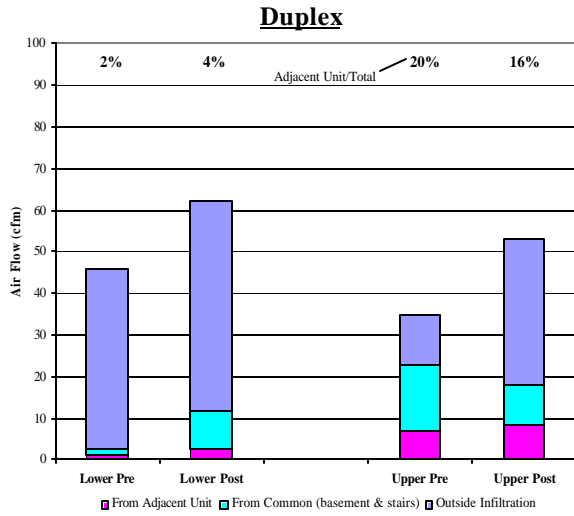


There were some interesting changes in the fraction of inter-unit flow when the treatments were applied to the buildings. For the three buildings in the second year of the study that were monitored after the air sealing was complete, the fraction of inter-unit flow decreased for all of the units in the 138 Unit and 11 Story buildings and over half of the units in the 4 Story building. Overall, 86% of the units had a reduction in the inter-unit flow fraction. However, the magnitude of the median reduction was only 2%. So the air sealing appeared to result in a consistent, but small, reduction in the fraction of inter-unit air flow.

After both air sealing and ventilation treatments were complete three of the six buildings had reductions in the median fraction of inter-unit flow rate of 3% or greater. While that may not seem very significant, the relative change was large. The fraction for the 11 Story building decreased from 5% to 1% and that for 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 inter-unit air flow. 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. As discussed previously, the continuous exhaust ventilation helps counteract the stack effect driven flow in the buildings.

The charts in Figure 33 provide a visual representation of the source and magnitude of the air flows into the units of each of the buildings. The blue bars represent the air infiltration into the unit and the bars with other colors represent the flows from other units. The top of the stacked bars represent the total flow into a unit. The maximum range for each of the charts has been set to 100 cfm so that it is easier to compare the flow magnitudes of different buildings. The pre/post increase in the top of the bars confirms that almost all units had an increase in the total incoming flow rate. For most of the buildings there is not a clear trend in total flow with the floor of the building. For the 138 Unit building there appears to be a slight trend for higher infiltration and total flow for the units on the lower floors. The most consistent trend is that the units on the lowest level have little or no flow from other units during the pre-monitoring period. As expected, the stack effect causes the units on the higher level to receive a portion of their air from the lower levels. In general, most of the air from the lower levels comes from the unit directly below. It is also interesting to note that for the post-treatment period many of the units on the lower level had flow from units above or to the side. Unfortunately, the installation of continuous exhaust fans in the lower units causes the pressure dynamics to change so that it is more likely for air to be drawn from adjacent units.

Figure 33. Pre/post air flow of individual test units (cfm)



ETS Measurements

Nicotine Measurements

Nicotine was monitored to provide a direct measure of the transfer between units of one of the components of ETS. Passive samplers were used for all the buildings where there was a smoker in at least one of the test units. The nicotine measurements were conducted at the same time as the PFT measurements. In the first year of the study the samplers were limited to the units directly adjacent to the smoker's unit and in the second year they were included in all the units where there was a PFT sampler.

A summary of the nicotine measurements for the five monitored buildings is displayed in Table 14 and results for individual units are displayed in Figure 34. There was almost no smoking in the 4 Story building (the resident in unit 404 reported smoking one cigarette per week) and fairly low levels of smoking in the 12-Plex. The 8-Plex, 138 Unit, and 11 Story buildings had at least one unit where there was a significant level of smoking. At the 8-Plex the pre/post nicotine measurements for unit 3 were 0.74 and 1.14 $\mu\text{g}/\text{cf}$ (26.3 and 40.2 $\mu\text{g}/\text{m}^3$) and there was a much lower level of smoking in unit 4. The smoking in the 138 Unit building was isolated to unit 123 (measured values of 0.78, 0.53, and 0.42 $\mu\text{g}/\text{cf}$) and there were two units in the 11 Story building with smokers (410 and 414). The concentrations obtained in the heavier smokers units are consistent with what would be expected from the measured ventilation rate and cigarette source rate¹.

The nicotine concentrations in the nonsmoker's units are very low. The median values for the different monitoring periods range from 0.0 to 0.016 $\mu\text{g}/\text{cf}$ (0.0 to 0.57 $\mu\text{g}/\text{m}^3$). In fact, only 30% of the measurements were greater than the limit of detect ability (LOD) of 0.002 $\mu\text{g}/\text{cf}$ (0.07 $\mu\text{g}/\text{m}^3$) and only 21% were greater than the level at which the measurements are reported to have an uncertainty of $\pm 10\%$ (0.004 $\mu\text{g}/\text{cf}$). One use of the building summary data is to divide the nicotine concentrations in the nonsmoker's units to that of the unit with the heaviest smoker. That "dilution ratio" helps determine the typical exposure of nonsmokers in an apartment complex to nicotine from a smoker's unit. For the eight monitoring periods in the three buildings with a heavy smoker there was only one period for which the concentration of nicotine in the nonsmoker's units was greater than 1% and the median ratio for the eight periods was 0.3%. This indicates that most nonsmokers in an apartment building will be exposed to nicotine concentrations that are less than 1% of that in the smoker's unit.

It is possible to conduct a more systematic analysis for each of the nicotine measurements in the individual units. A comparison of the nicotine concentration in the nonsmoker units before and

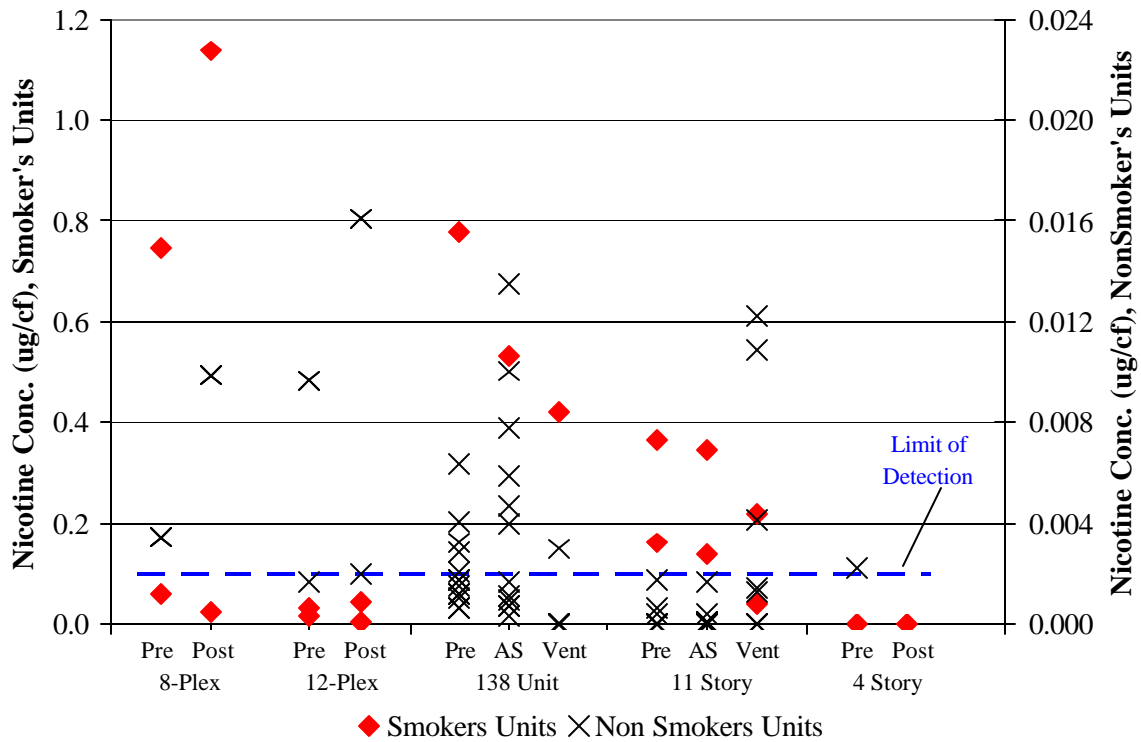
¹ For example, for the pre-treatment period the occupants of unit 123 in the 138 Unit building reporting smoking 36 cigarettes per day and the measured ventilation rate was about 45 cfm or 0.35 air changes per hour (ach). Singer et al. (2003) reported an emission factor of 820 $\mu\text{g}/\text{cig}$ for a furnished test chamber with a ventilation rate of 0.3 ach. For the specified conditions the calculated nicotine concentration is 0.45 $\mu\text{g}/\text{cf}$, which is about 60% of the measured value. That level of agreement is reasonable considering the variation in nicotine emission rate with different surfaces and air change rates. There is also likely to be considerable variations in ETS concentration in the room where smoking is taking place.

after a treatment can be used to evaluate the level of transfer of the nicotine into the nonsmoker's unit and the dilution that occurs in the unit. However, this analysis required the nicotine source rate to be the same before and after the treatment. In order to control for changes in the nicotine source, the post-treatment period concentrations were multiplied by the ratio of the pre/post period concentrations of nicotine in the dominant smokers unit. This analysis was applied to all units for which the pre/post nicotine concentrations were greater than two times the LOD. Unfortunately, there was only one unit that met these criteria and for that unit the concentration increased by 75%. However, the analysis assumes that the smoker's unit is the only source of nicotine in the building (including the unit being analyzed). For the low nicotine transfer measured in this study smoking only one or two cigarettes over the one week sample period can greatly affect the outcome. This severely limits the use of nicotine to evaluate the transfer of ETS from one specific unit to another.

Table 14. Summary of nicotine measurements for smoker and nonsmoker units

Building	Period	(ug/cf)						(ug/m ³)					
		Smoker 1	Smoker 2	Min	Median	Average	Max	Smoker 1	Smoker 2	Min	Median	Average	Max
8-Plex	Pre	0.744	0.061	0.003	0.003	0.003	0.003	26.30	2.15	0.12	0.12	0.12	0.12
8-Plex	Post	1.138	0.025	0.010	0.010	0.010	0.010	40.22	0.89	0.35	0.35	0.35	0.35
12-Plex	Pre	0.030	0.015	0.002	0.010	0.007	0.010	1.05	0.52	0.06	0.34	0.25	0.34
12-Plex	Post	0.042	0.003	0.002	0.016	0.011	0.016	1.50	0.11	0.07	0.57	0.40	0.57
138 Unit	Pre	0.778		0.001	0.002	0.002	0.006	27.49	0.00	0.02	0.06	0.08	0.23
138 Unit	After Seal	0.534		0.000	0.002	0.004	0.013	18.88	0.00	0.00	0.06	0.14	0.48
138 Unit	Ventilation	0.418		0.000	0.000	0.000	0.003	14.77	0.00	0.00	0.00	0.01	0.11
11 Story	Pre	0.365	0.160	0.000	0.000	0.000	0.002	12.89	5.64	0.00	0.00	0.01	0.06
11 Story	After Seal	0.345	0.136	0.000	0.000	0.000	0.002	12.20	4.79	0.00	0.00	0.01	0.06
11 Story	Ventilation	0.221	0.040	0.000	0.003	0.009	0.033	7.82	1.41	0.00	0.10	0.32	1.16
4 Story	Pre	0.000		0.000	0.001	0.002	0.006	0.00	0.00	0.00	0.05	0.07	0.21
4 Story	Post	0.001		0.000	0.000	0.001	0.002	0.03	0.00	0.00	0.02	0.02	0.08

Figure 34. Nicotine measurements for all monitored units



The nicotine measurements can also be used to compare the rate of transfer of nicotine and PFT between units. If nicotine transferred at the same rate as the PFT gases, the ratio of the nicotine concentration in a nonsmoker's unit divided by the nicotine concentration in the smoker's unit would be the same as the concentration ratio for the PFT gas released in the smoker's unit. It is expected that the absorption of nicotine during the transfer process will result in a lower ratio for nicotine than PFT. The PFT and nicotine concentration ratios for the 138 Unit and 8-Plex buildings are displayed in Figures 35 and 36 respectively. As expected, the PFT ratio is almost always considerably greater than the nicotine ratio. The higher ratios for unit 4 in the 8-Plex is due to the intermittent smoking in that unit. It is likely that some of the atypically high nicotine ratios for the 138 Unit building were also due to intermittent smoking or possibly a visitor.

Figure 35. PFT and nicotine concentrations divided by concentration in smoker's unit: 138 Unit

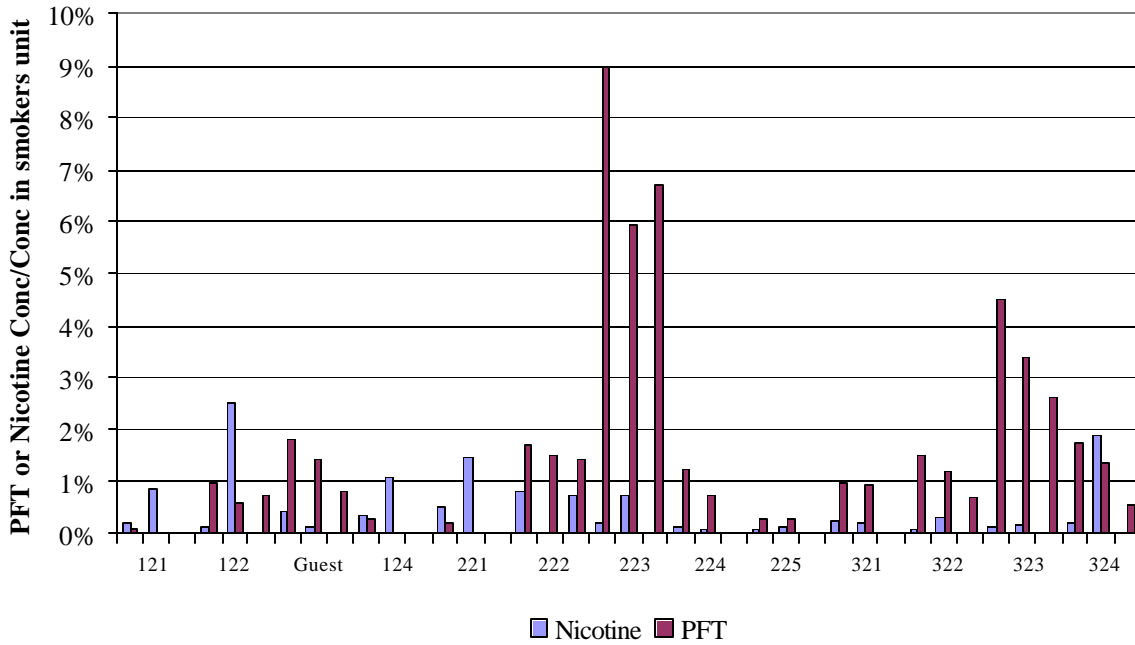
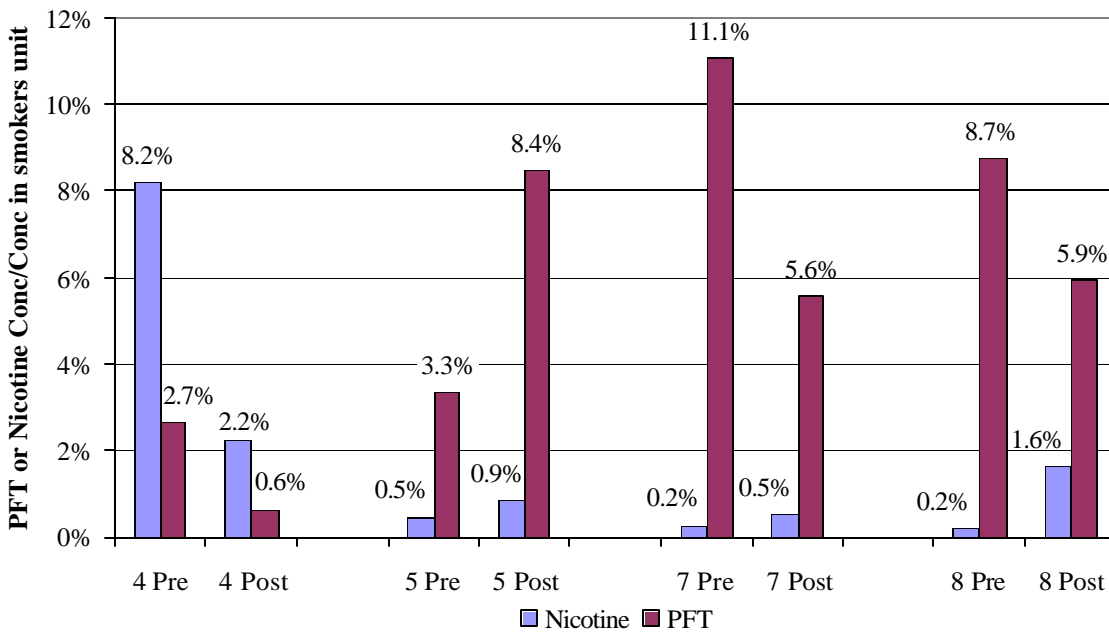


Figure 36. PFT and nicotine concentrations divided by concentration in smoker's unit: 8-Plex



Another way to evaluate the difference between PFT and nicotine transfer is to use the PFT concentration ratio with the nicotine concentration in the smoker's unit to calculate the level of nicotine concentration that would occur in the nonsmoker's unit if nicotine transferred at the same rate as PFT gases. That approach was used to generate the measured and calculated

nicotine concentrations for the 8-Plex and the 138 Unit building that are shown in Figures 37 and 38 respectively. Again, the nicotine concentrations predicted from the measured transfer of PFT gases is consistently greater than the actual measurements. The charts indicate that the rate of PFT transfer was from 2 to 40 times greater than that of nicotine. To compare the two transfer rates more systematically, the measured and calculated nicotine concentrations were compared for all of the nicotine measurements greater than 0.004 $\mu\text{g}/\text{cf}$. A compilation of the 16 measurements is shown in Table 15. The column “Calc/Meas” is an estimate of the PFT transfer rate divided by the nicotine transfer rate. If the values less than 1.0 are ignored (likely due to intermittent smoking), the PFT transfer rate ranges from 2 to 10 times greater than the nicotine transfer rate, with a median value of about 6. This is very similar to the result reported by Apte et al (2002) that the rate of particle transfer from the living room to a child’s bedroom was 2 to 8 times greater than the rate for nicotine. However, some of the results where the nicotine concentration was below the LOD indicate that the nicotine transfer rate could be much more than 10 times lower than that of PFT gases. It is likely that the materials present in the air leakage path and the frequency that the air contacts surfaces greatly affects the nicotine absorption as air transfers from one unit to another. It should be expected that there will be large variations in the nicotine transfer rate for different buildings and units within those buildings.

Figure 37. Measured and PFT calculation of nicotine concentration for 8-Plex nonsmoking units

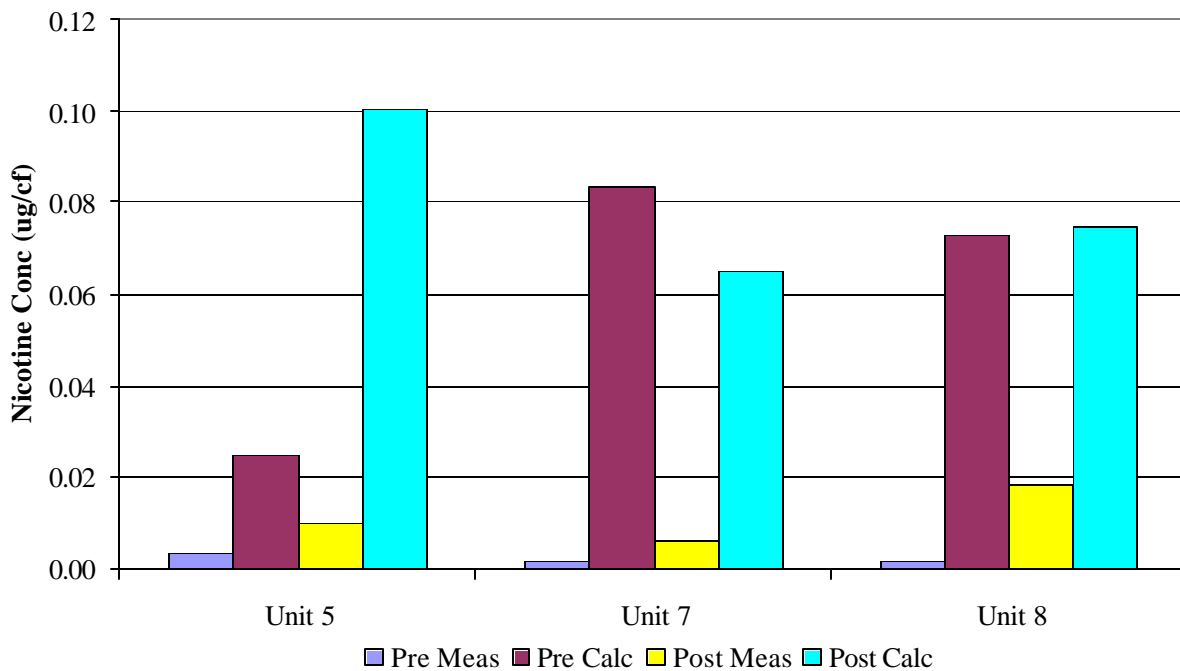


Figure 38. Measured and PFT calculation of nicotine concentration for 138 Unit nonsmoking units

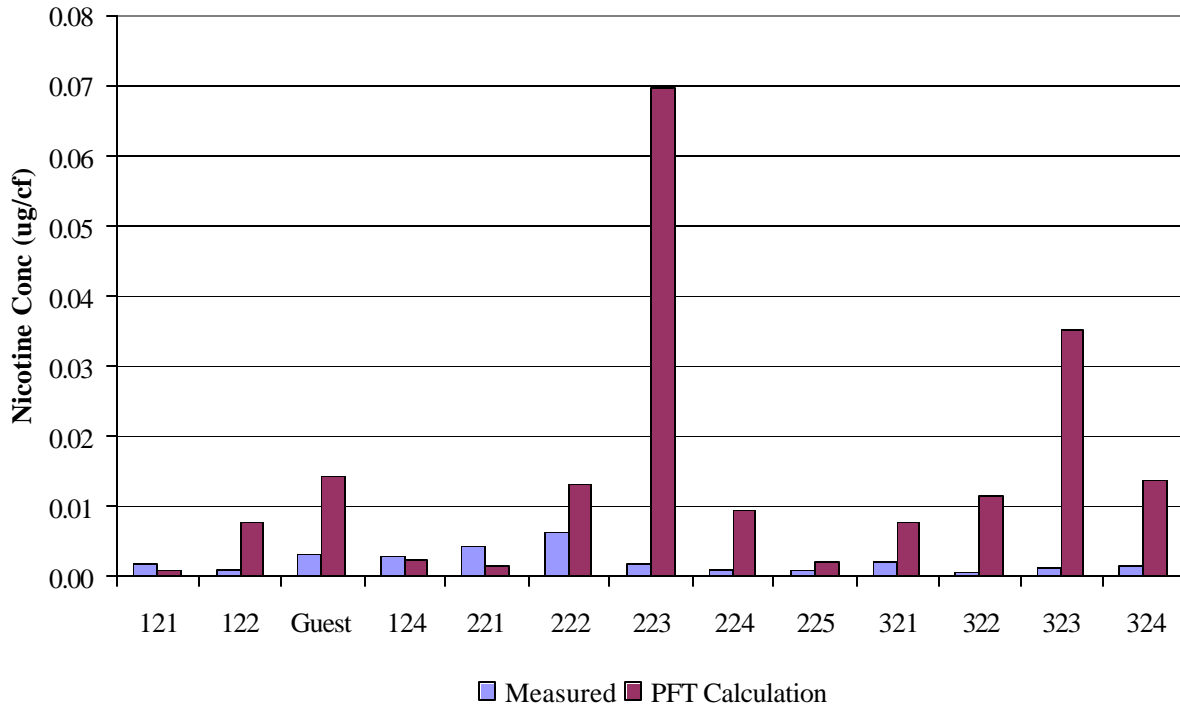


Table 15. Comparison of nicotine and PFT transfer between units

Building	Period	Unit	Meas	Calc	Calc/Meas
8-Plex	Post	5	0.010	0.096	9.7
8-Plex	Post	7	0.010	0.063	6.4
8-Plex	Post	8	0.010	0.063	6.4
138 Unit	Pre	221	0.004	0.002	0.4
138 Unit	Pre	222	0.006	0.013	2.1
138 Unit	After Seal	121	0.005	0.000	0.0
138 Unit	After Seal	122	0.013	0.003	0.2
138 Unit	After Seal	124	0.006	0.000	0.0
138 Unit	After Seal	221	0.008	0.000	0.0
138 Unit	After Seal	223	0.004	0.032	7.9
138 Unit	After Seal	324	0.010	0.007	0.7
11 Story	Ventilation	312	0.012	0.000	0.0
11 Story	Ventilation	510	0.033	0.006	0.2
11 Story	Ventilation	512	0.029	0.000	0.0
11 Story	Ventilation	612	0.011	0.000	0.0
11 Story	Ventilation	712	0.004	0.000	0.1

Particulate Measurements

Fine particulates ($PM_{2.5}$) were monitored to provide a direct measure of the transfer between units of one of the components of ETS. Passive samplers were used for all the buildings where there was a smoker in at least one of the test units. One week average fine particulate concentrations were measured using a constant flow rate sample pump to draw air through a particulate monitor that consisted of a single-stage impactor with an after-filter. In the first year of the study the samplers were limited to the units directly adjacent to the smoker's unit and in the second year they were included in all the units where there was a PFT sampler. The measurements were only conducted in buildings where there was at least one unit with a smoker, so no measurements were conducted in the Duplex.

There were numerous problems with the particulate measurements. In the first year the reported concentrations from the 8-Plex and 12-Plex varied by more than two orders of magnitude and many were not within the range of concentration levels reported by previous studies. Project staff had follow-up discussions with the commercial laboratory that prepared and analyzed the samples, but the source of the errors in the measurement process could not be determined. A laboratory at the University of Minnesota (UM) was used to prepare and analyze the samplers for the second year of the study. Before any field tests were conducted, a series of duplicate field measurements were conducted to confirm the UM laboratory produced repeatable results that were within the expected concentration range. Even with those quality control measures in place, the filters from the first set of measurements from the 138 Unit building were contaminated with oil from the impact ring. None of the measurements from that monitoring period were useable. Also, the sample pumps were powered from an AC adapter and there were instances when the sample pumps did not restart after a power interruption. Finally, drywall was being repaired (including finishing sanding) during the monitoring periods in some of the test units of the 11 Story building. The particulate concentrations from those units were unusually high. Those large sources of drywall dust eliminated the ability to focus on ETS as the single largest source of fine particulates in the building.

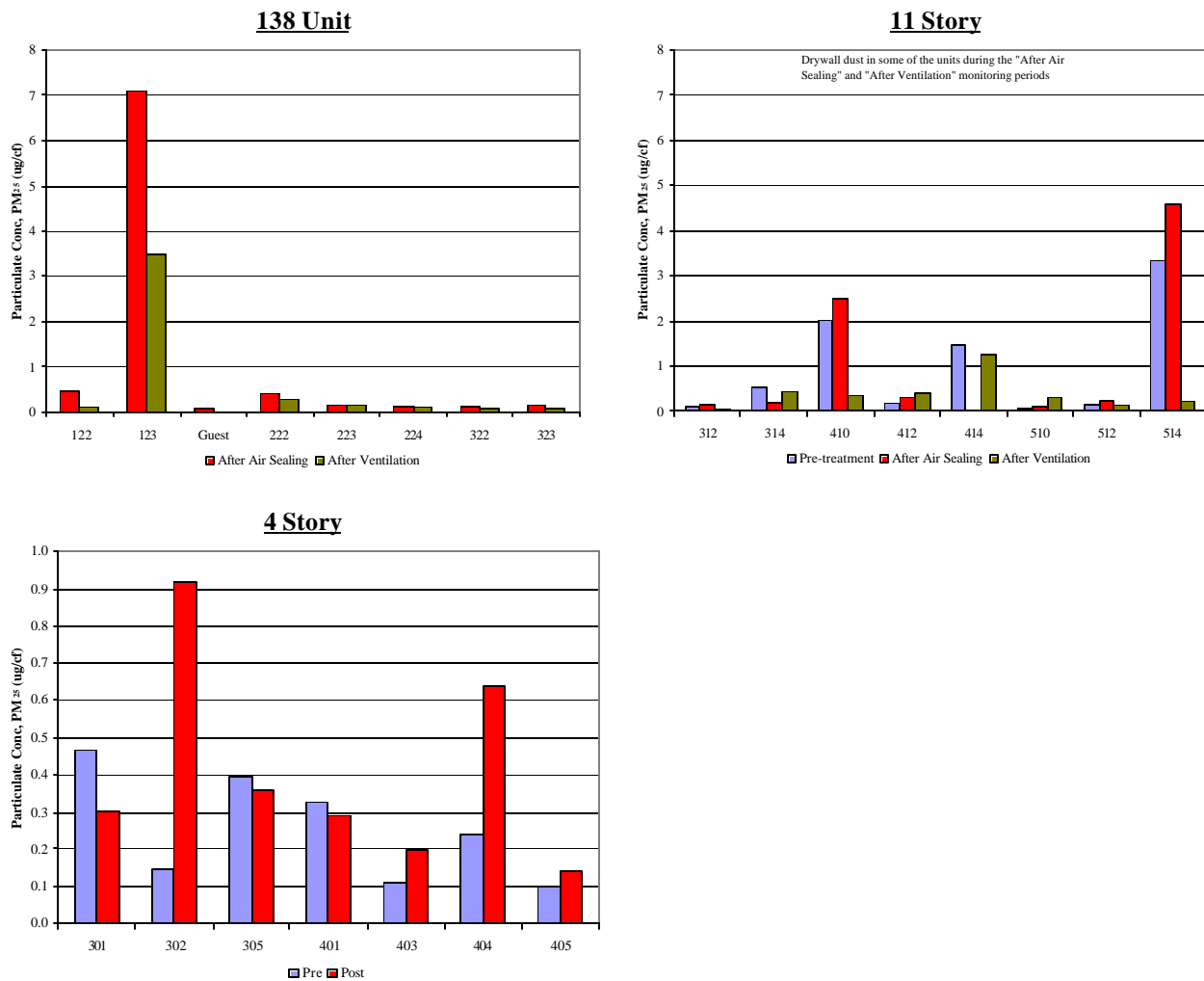
A summary of the particulate measurements for the three monitored buildings with valid data is displayed in Table 16 and results for the individual units for the are displayed in Figure 39. As was previously indicated by the nicotine results, there was almost no smoking in the 4 Story building (the resident in unit 404 reported smoking one cigarette per week). Because there is not a single, strong source of ETS fine particulates in the 4 Story building, the results can not be used to evaluate the effect of the treatments on ETS transfer. However, the results provide useful information on the typical variation of particulate concentrations in multifamily buildings. For the pre-treatment period the concentrations of $PM_{2.5}$ for all seven units ranged from 0.10 to 0.47 $\mu\text{g}/\text{cf}$ (3.6 to 16.5 $\mu\text{g}/\text{m}^3$) and had a median value of 0.24 $\mu\text{g}/\text{cf}$ (8.5 $\mu\text{g}/\text{m}^3$). For the post-treatment period the concentrations of $PM_{2.5}$ ranged from 0.14 to 0.92 $\mu\text{g}/\text{cf}$ (5.0 to 32.5 $\mu\text{g}/\text{m}^3$) and had a median value of 0.30 $\mu\text{g}/\text{cf}$ (10.5 $\mu\text{g}/\text{m}^3$). So it is reasonable to expect a variation of 0.2 to 0.6 or more in the concentration of $PM_{2.5}$ due to outdoor and indoor sources other than ETS.

Table 16. Summary of particulate measurements for smoker and nonsmoker units

Building	Period	Smoker 1	Smoker 2	Min	Median	Average	Max	Smoker 1	Smoker 2	Min	Median	Average	Max
138 Unit	Pre	Oil Contamination											
138 Unit	After Seal	7.081	NA	0.106	0.154	0.174	0.418	250.21	NA	3.75	5.44	6.16	14.79
138 Unit	Ventilation	3.483	NA	0.097	0.134	0.150	0.283	123.09	NA	3.44	4.75	5.30	10.02
11 Story	Pre	2.008	1.476	0.090	0.160	0.220	0.542	70.94	52.16	3.18	5.67	7.79	19.16
11 Story	After Seal	2.491	*	0.122	0.197	0.202	0.295	88.02	*	4.31	6.97	7.12	10.42
11 Story	Ventilation	0.333	1.277	0.050	0.269	0.260	0.417	11.75	45.14	1.75	9.52	9.19	14.72
4 Story	Pre	0.242	NA	0.102	0.238	0.259	0.468	8.54	NA	3.59	8.40	9.16	16.55
4 Story	Post	0.641	NA	0.142	0.298	0.369	0.919	22.63	NA	5.02	10.53	13.03	32.47

* - pump failure

Figure 39. Pre/post particulate measurements of individual test units



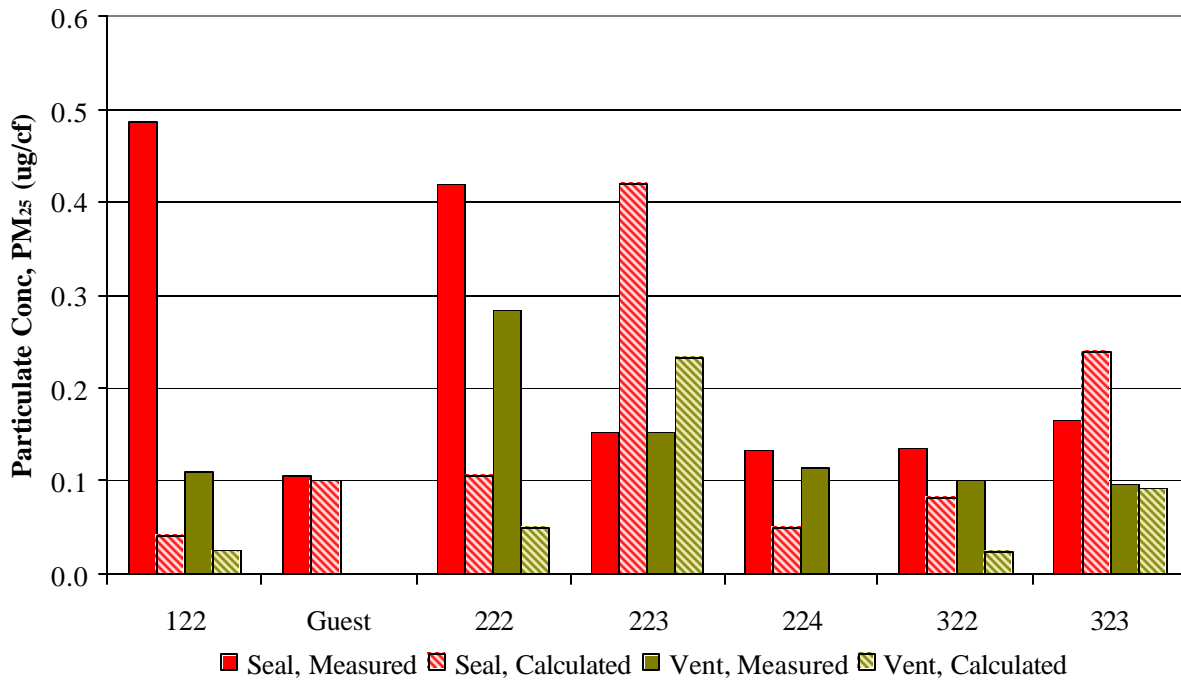
The concentration of PM_{2.5} in the smoker's unit (123) of the 138 Unit building was 7.08 µg/cf (250 µg/m³) during the pre-treatment period and 3.48 µg/cf (123 µg/m³) during the post-treatment period. The concentration of PM_{2.5} in the smoker's units of the 11 Story building ranged from 0.33 to 2.49 µg/cf (12 to 88 µg/m³). The concentrations in the 11 Story building are about twice the range of typical values reported by Wallace (1996) and the concentrations in unit 123 of the 138 Unit building were three to six times what was expected. However, if the emission rate of

14 mg/cig is used (Wallace 1996) along with the rate of cigarettes smoked in unit 123 (36/day) and the ventilation rate of 45 cfm, the concentration of $PM_{2.5}$ is expected to be 7.8 $\mu\text{g}/\text{cf}$. That is only 10% greater than the measured value. Thus, it appears that the concentrations measured in the smoker's units were reasonable. The median concentration of $PM_{2.5}$ in the nonsmoker's units ranged from 0.13 to 0.27 $\mu\text{g}/\text{cf}$ (4.8 to 9.5 $\mu\text{g}/\text{m}^3$) and that range narrows even further to 0.13 to 0.20 $\mu\text{g}/\text{cf}$ (4.8 to 7.0 $\mu\text{g}/\text{m}^3$) if the value from the 138 Unit building (where there were drywall repairs) is removed. Those values are somewhat lower than the medians for the 4 Story building and are lower than the median values of 0.5 to 0.8 $\mu\text{g}/\text{cf}$ reported by Wallace (1996).

One use of the building summary data is to divide the $PM_{2.5}$ concentrations in the nonsmoker's units to that of the unit with the heaviest smoker. That "dilution ratio" helps determine the typical exposure of nonsmokers in an apartment complex to particulates from a smoker's unit. For the four monitoring periods in the two buildings with a heavy smoker the ratio varied from 2.2 to 8.0% and the median value was 5.9%. This indicates that most nonsmokers in an apartment building will be exposed to $PM_{2.5}$ concentrations that are less than 10% of that in the smoker's unit. Given that the concentrations of $PM_{2.5}$ in the nonsmokers' units of the buildings with a heavy smoker were generally lower than those for the 4 Story building that did not have a heavy smoker, it is likely that even in an apartment building with a heavy smoker ETS is not the most significant source of $PM_{2.5}$ in the units of nonsmokers.

The $PM_{2.5}$ measurements can also be used to compare the rate of transfer of $PM_{2.5}$ and PFT between units. If $PM_{2.5}$ transferred at the same rate as the PFT gases and there were no other sources of $PM_{2.5}$ within or outside the building, the concentration of $PM_{2.5}$ in a nonsmokers unit would be equal to the concentration of $PM_{2.5}$ smoker's unit multiplied by the concentration of PFT in the nonsmoker's unit divided by the concentration of PFT in the smoker's unit. That approach was used to develop the measured and calculated values of $PM_{2.5}$ for the 138 Unit building that are displayed in Figure 40. In the two units with the highest rate of PFT transfer from unit 123(223 and 323), the calculated $PM_{2.5}$ concentration is greater than the measured value. In fact, for the "Seal" or after air sealing period the measured value for unit 223 is only 37% that of the calculated value. Given that the measured value for unit 223 is similar in magnitude to the concentration of the other units, it appears that at least 75% of the $PM_{2.5}$ from the smoker's unit is filtered as the air and particulates move from the smoker's unit to 223. It is likely that the filtration rate is even greater than 75%. This is about twice as high as the 37% and 43% filtration rate of $PM_{1.0}$ particles moving through the exterior envelope of a house reported by CMHC (2003b). Further measurements in a building with a higher transfer rate and low background level of $PM_{2.5}$ would be necessary to better quantify the filtration of $PM_{2.5}$ particles as they move between units in a multifamily building.

Figure 40. Measured and PFT calculation of particulate concentration for 138 Unit nonsmoking units



Tracer Gas Measurements

An analysis of the PFT concentrations resulting from the known source rates of the different PFTs was used to model the transfer or dilution of non-sorbing ETS constituents. The PFT measurements conducted for the air flow calculations were used to model the time averaged transport of the more volatile compounds in ETS. Since PFT releases are controlled and can be isolated to individuals units, this provides a powerful metric of contaminant transport from many units (up to seven simultaneously) to all surrounding units that were monitored. It is important to note that the results are obtained for a constant source and that there is no absorption or filtration of the gases during the transport process.

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 simply the average source rate for the PFT gas released in a test unit divided by the average PFT concentration measured in the monitored unit of the gas released in the test unit. Two different sets of analysis were used for this report. First, the sum of the ECTs for individual, monitored units for transfer from all of the other units where a PFT gas was released were tabulated and compared. Second, the ECT from the smoker's unit to the other monitored units in the building were tabulated and compared. The first analysis provides an overall evaluation of the contaminant transport of all the treated units and the second focuses on the transport from only the smoker's unit. This analysis was conducted for all monitoring periods for all six buildings. In the first year of the study six different PFTs were available and there were seven

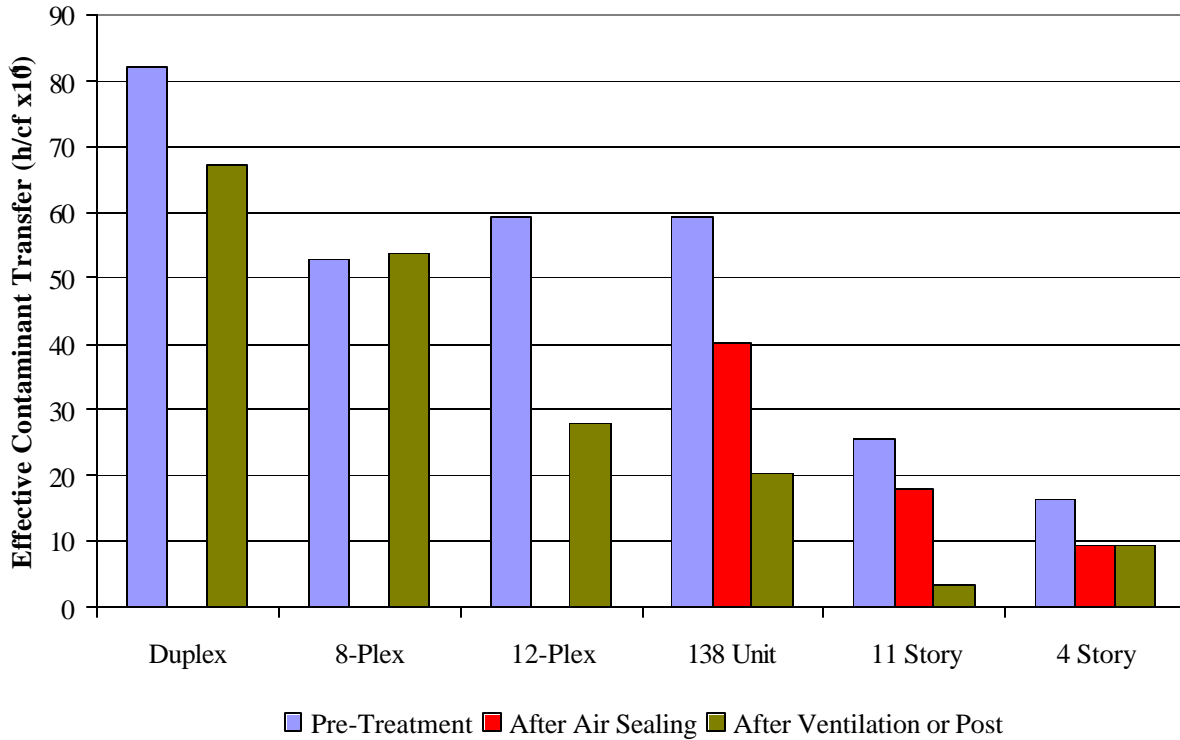
for the second year of the study. As a result, the analysis was conducted for up to six units per building in the first year of the study and seven units in the second year.

The building average sums of the ECTs for monitored units are displayed in Table 17 and Figure 41. The average ECT for all of the units was $45.6 \text{ h/cf} \times 10^{-6}$. Four of the buildings (Duplex, 8-Plex, 12-Plex and 138 Unit) had pre-treatment ECTs greater than $50 \text{ h/cf} \times 10^{-6}$ (or $\mu\text{h/cf}$) and the two others (11 Story and 4 Story) were below $25 \mu\text{h/cf}$. The four buildings with the highest ECTs generally had the highest fraction of inter-unit air flow (Table 13). The one exception was the 8-Plex which had a median fraction of inter-unit flow of only 3%. However, the inter-unit air flow measurements for the 8-Plex were conducted for all four first floor units, but only two from the second floor. All four second floor units were included in the ECT analysis. The inter-unit flow fractions for the two second floor units (15% and 24%) were much higher than those for the first floor (average of 2%). If the inter-unit air flow was measured for all four second floor units, it is likely that the median fraction would have been from 10% to 15%. That range is consistent with the other four buildings with high pre-treatment ECTs.

Table 17. Pre/post building average ECT ($\text{h/cf} \times 10^{-6}$) for all monitored units

Building	Pre	Seal	Vent/Post	After Air Sealing			After Ventilation or Post		
				(h/cf)	%	% Red	(h/cf)	%	% 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 Units	45.6	22.6	27.1	-23.1	-51%	81%	-18.6	-41%	71%

Figure 41. Pre/post building average ECT for all monitored units



For the three buildings in the second year of the study the ECTs were calculated after the air sealing work was completed. The ECT reduction ranged from 7.0 to 19.2 $\mu\text{h}/\text{cf}$ and the relative reduction ranged from 29% for the 11 Story building to 43% for the 4 Story building. Overall, 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 buildings¹ is significantly higher than the relative change in the measured inter-unit air leakages (4% and 17% reductions, Table 7). This is somewhat surprising considering that the units in the two buildings had a median reduction in total leakage of 8% and 32% respectively. A reduction in the exterior leakage would tend to reduce infiltration and increase the ECT. 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.

The post-treatment reduction in ECT for the test units in all six buildings averaged 18.6 $\mu\text{h}/\text{cf}$ or 41% of the pre-treatment value. Overall, 71% of the units had a reduction in ECT and 58% of the units had a reduction greater than 50% (Figure 42). For the units that had an increase in ECT, the increase was less than 15 $\mu\text{h}/\text{cf}$ for over half of those units (Figure 43). The pre/post ECTs for the individual units are displayed in Figure 44. The charts show that the increases in ECT generally occurred for units on the lower levels which already had low ECTs. As was discussed previously, 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

¹ Inter-unit air leakage was not available for the 4 Story building.

units there was a small increase in inter-unit air flow. A histogram of the pre and post ECTs for individual units is displayed in Figure 45. The percentage of units with ECTs less than 10 $\mu\text{h}/\text{cf}$ increased from 32% to 45% and the percentage that had ECTs greater than 50 $\mu\text{h}/\text{cf}$ decreased from 32% to 16%.

Figure 42. Frequency histogram of the pre/post relative change in ECT for all monitored units

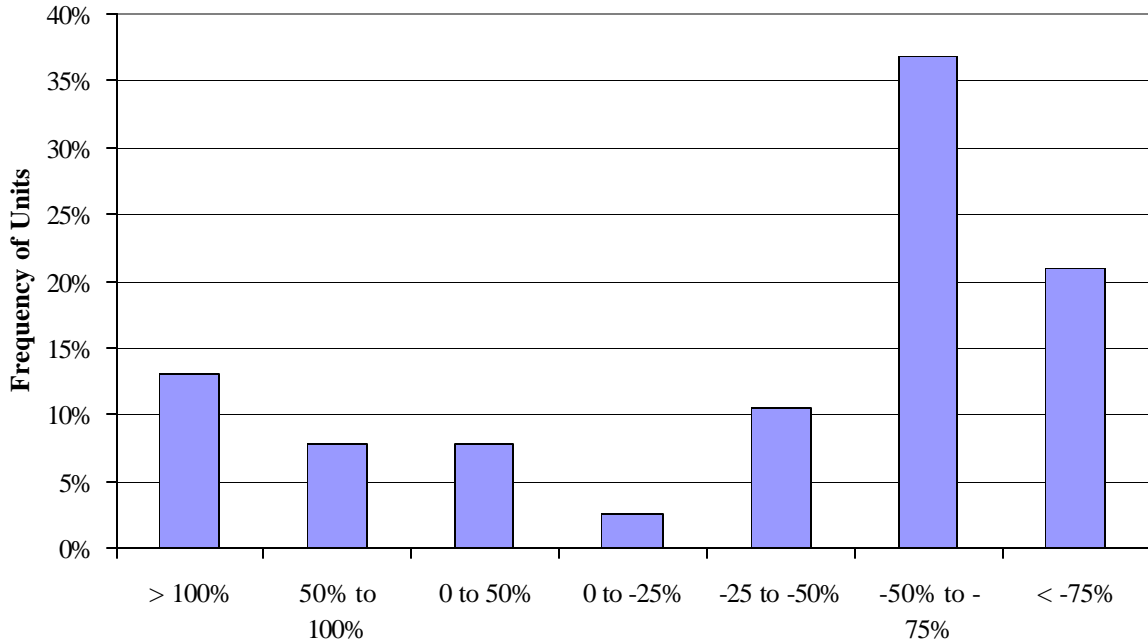


Figure 43. Frequency histogram of the pre/post change in ECT for all monitored units

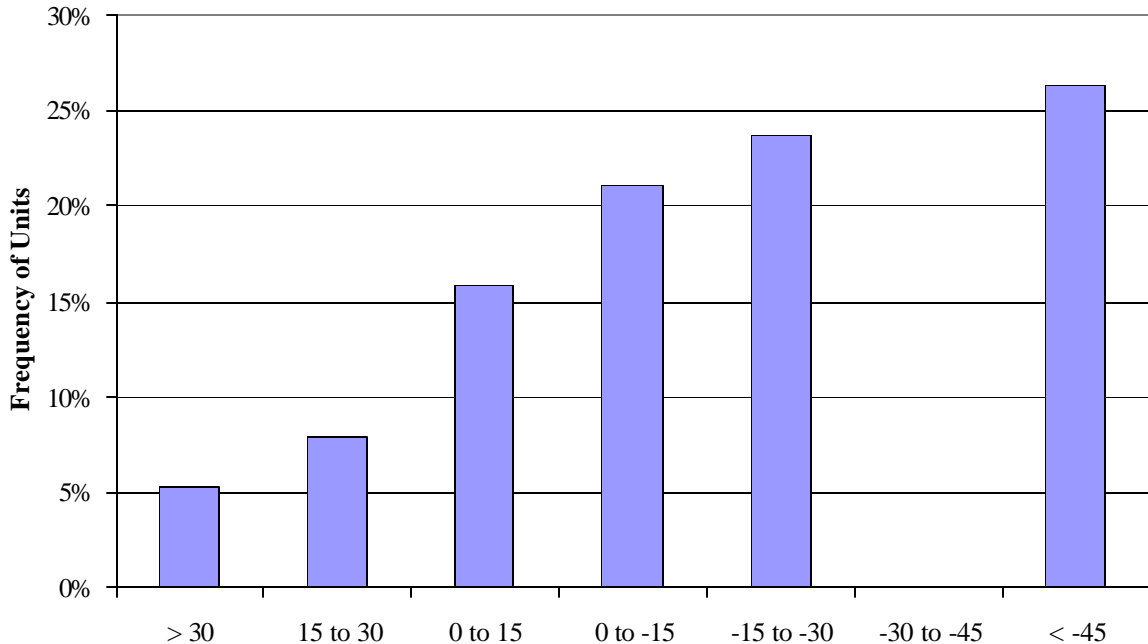
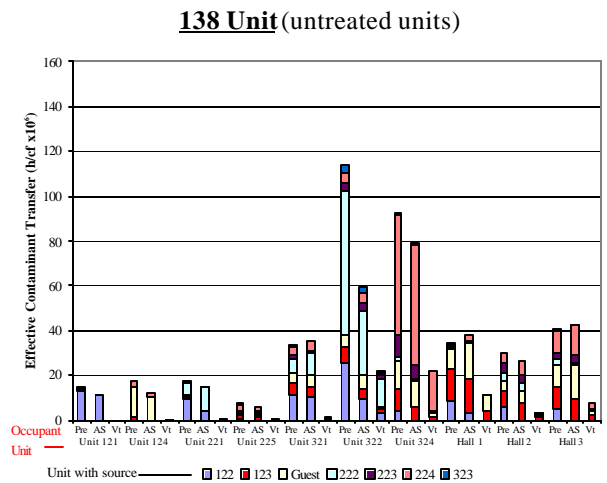
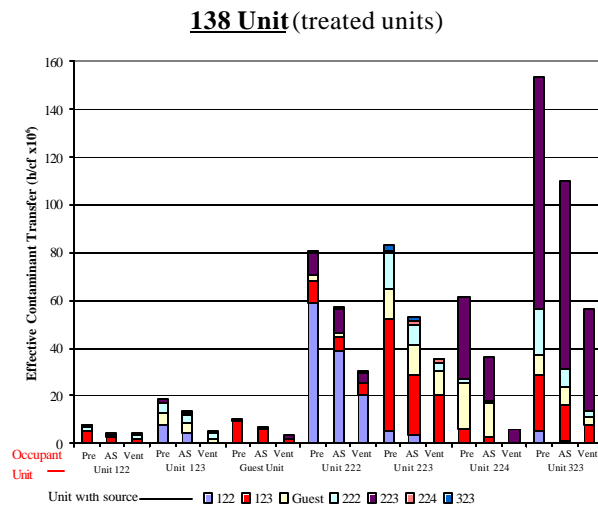
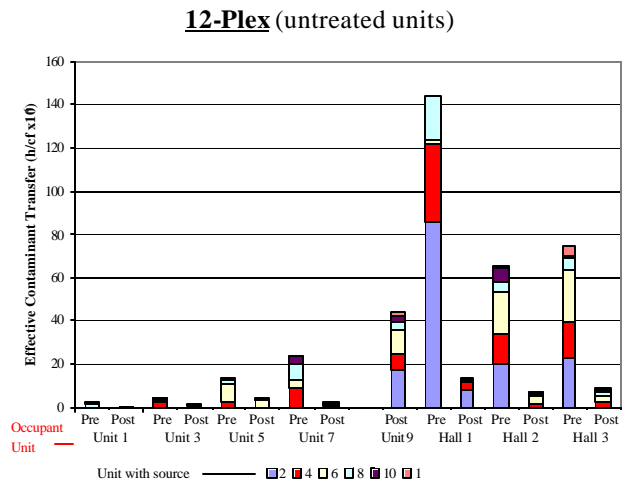
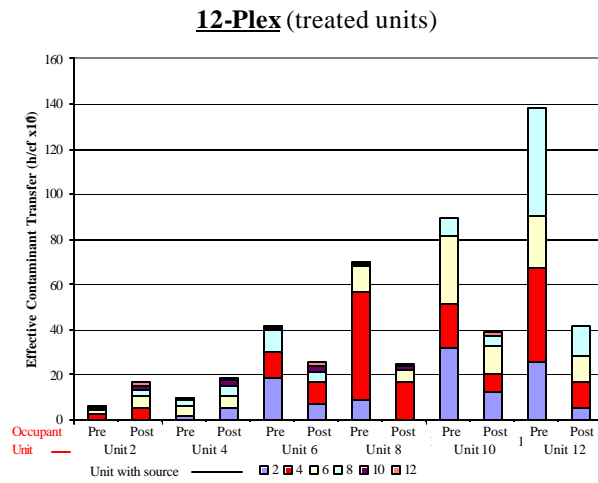
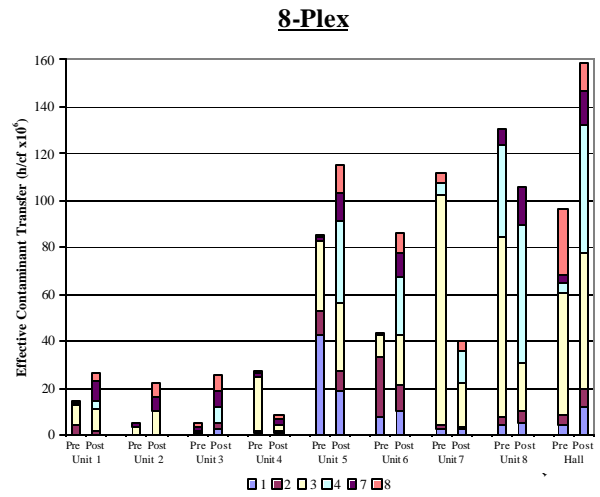
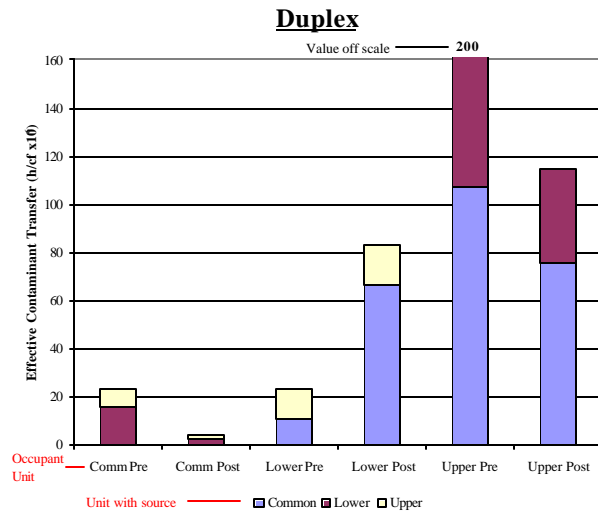
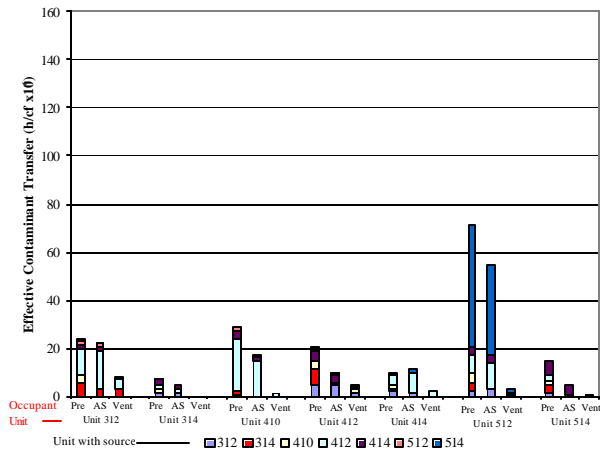


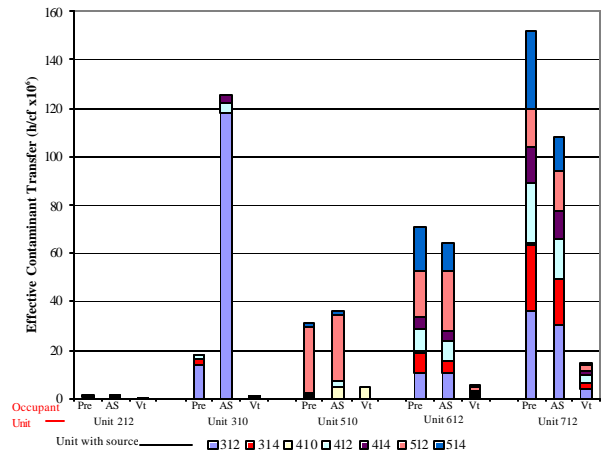
Figure 44. Pre/post Effective Contaminant Transfer of individual units



11 Story (treated units)



11 Story (untreated units)



4 Story

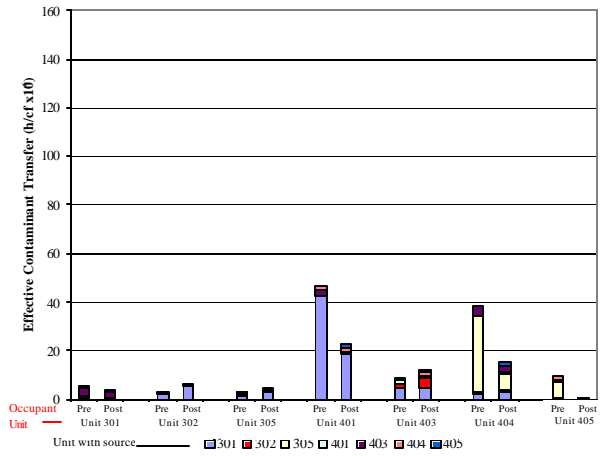
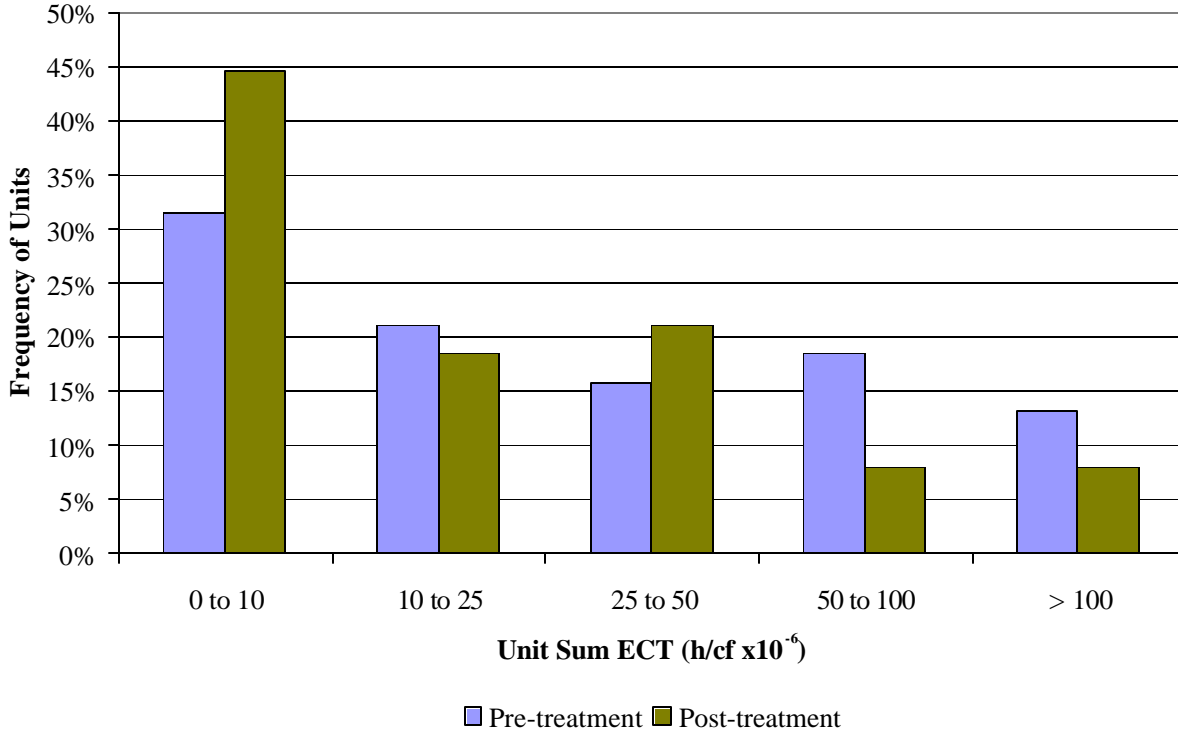


Figure 45. Frequency histogram of the pre and post ECT for monitored units



The 8-Plex was the only building that did not have a measurable change in the average ECT. It is likely that the main reason for the lack of improvement is that there was already continuous exhaust ventilation in the building and the average exhaust flow from the units was not changed. The balancing of the exhaust flows between units caused the ECT to increase in some of the units and decrease in others. For example, the increased exhaust flow in units 2 and 3 resulted in a significant increase in the PFT measured infiltration rates for those units. However, there was also an increase in the flow from other units and the net effect of those two changes was an increase in ECT of about 19 μ h/cf for the two units.

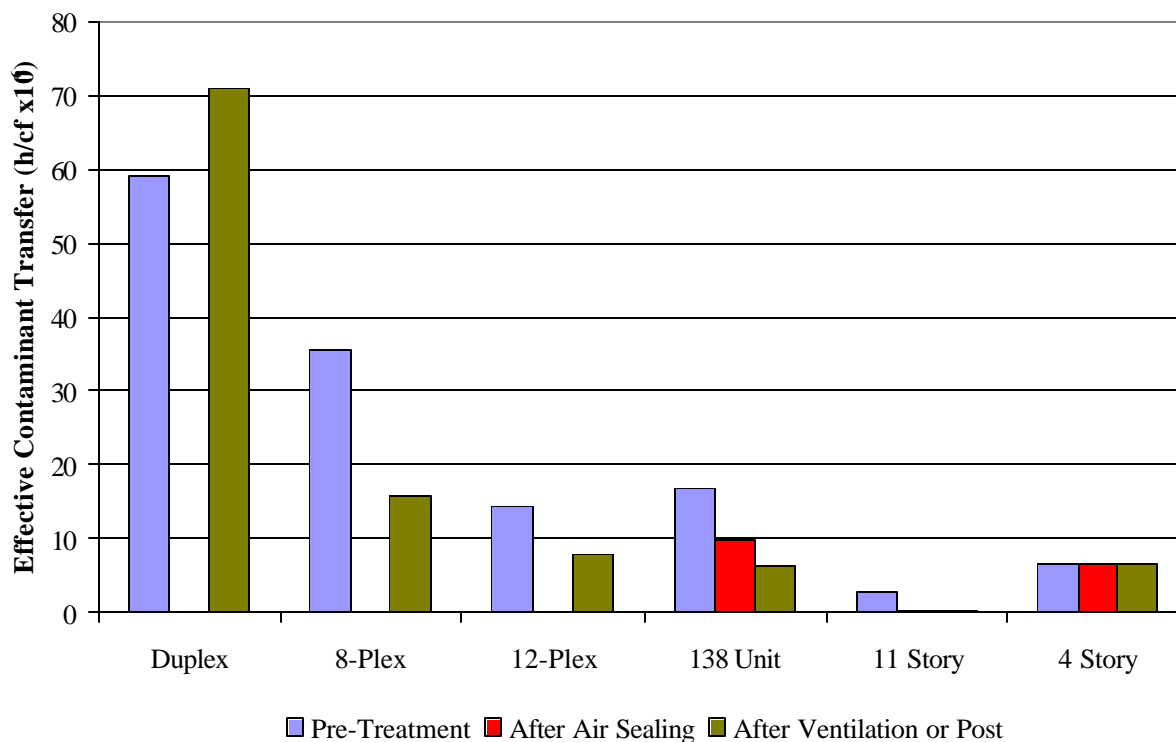
While there was not a significant change in the building average ECT for the 8-Plex, the ECT for the source in the smoker’s unit (#3) decreased by 37% (Table 18 and Figure 46). So the treatments had a significant result on the ECT that was of greatest concern. Overall, the relative reduction in ECT from the smoker’s unit for the six buildings (38%) was similar to that for all the sources in the buildings (41%). Also, 72% of the units had a reduction in the ECT from the smoker’s unit.

Table 18. Pre/post building average ECT (h/cf x 10⁻⁶) for the smoker's unit

Building	Pre	Seal	Vent/Post	After Air Sealing			After Ventilation or Post		
				(h/cf)	%	% Red	(h/cf)	%	% Red
Duplex	59.2		70.9				11.7	14%	50%
8-Plex	35.6		15.8				-19.8	-37%	57%
12-Plex	14.2		7.9				-6.3	-45%	60%
138 Unit	16.9	9.8	6.3	-7.1	-42%	100%	-10.5	-62%	100%
11 Story	2.7	0.2	0.3	-2.5	-92%	100%	-2.5	-90%	100%
4 Story	6.6	6.5	6.5	0.0	0%	50%	0.0	0%	50%
All Units	18.6	5.5	11.6	-13.1	-70%	83%	-7.0	-38%	72%

Note – for the Duplex the basement/staircase was designated as the “smoker’s unit”, since that was considered to be a likely source of moisture and odor complaints.

Figure 46. Pre/post building average ECT for the smoker's unit



There are interesting trends in the ECT’s for individual units (Figure 44). The values are generally lower for the units on the lower floors. Also, the ECTs from lower units to the floor above are almost always greatest for the unit that is directly above. This indicates that the air flow is most likely through air leaks in the building structure and not via common areas.

Resident Surveys

The pre-treatment questionnaire focused on the resident's concern with tobacco smoke or odor transfer into their unit, how the transfer occurred, the seasonality of the problem, and the location of the smokers in the building. The post-treatment questionnaire included questions regarding the change in the frequency/strength of tobacco smoke/odor transfer, whether changes were due to the treatments, their level of satisfaction with the work, and willingness to pay for the work. In an effort to encourage residents to complete the questionnaire and to help compensate them for their time, residents received an incentive of \$20 when they completed a questionnaire before any work was done to the building and another \$20 for completing a post-treatment questionnaire. There was a 94% response rate to the pre-treatment questionnaire and a 91% response to the post-treatment questionnaire. All three non-respondents to the post-treatment questionnaire lived in the 4 Story building.

Figure 47 presents a summary of the results for some of the questions included in the pre-treatment questionnaire and a detailed tabulation of the responses are available in Appendix A. The frequency of reported smoke entry is nearly identical to that from the large-scale tenant survey completed in a previous task (CEE 2001b). Forty-eight percent of the residents indicate that they had tobacco smoke entry into their unit at least some time in the previous year and 10% said that the entry occurred often or most of the time. Seventeen percent of the residents said that the smoke entry bothered them "a lot". There was no consistent pattern in where the residents thought smoke was entering their apartment. A nearly equal fraction from 9 to 12% thought that the smoke was entering through open windows, the hallway, the bath or kitchen fan, leaks from other apartments or other ways. There was some seasonality in reported smoke entry, with lower frequency of reported problems in the spring and winter. The responses differed slightly between the three buildings, with a somewhat higher smoke odor frequency and level of bother for the 138 Unit and 11 Story buildings. The responses for the questions regarding cooking odors were similar to those for tobacco smoke, except that there was a higher level of bother for cooking odors in the 4 Story building.

Figure 47. Pre-treatment resident survey results regarding tobacco odors.

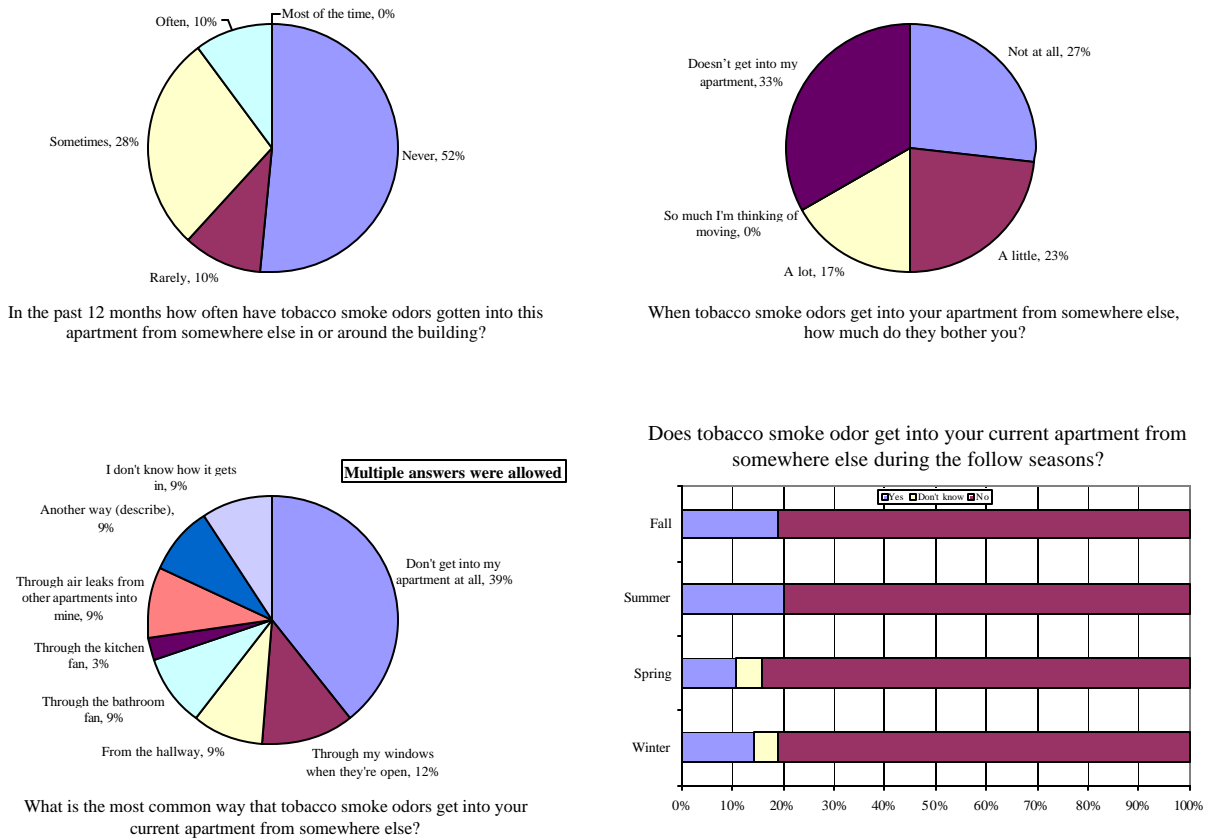
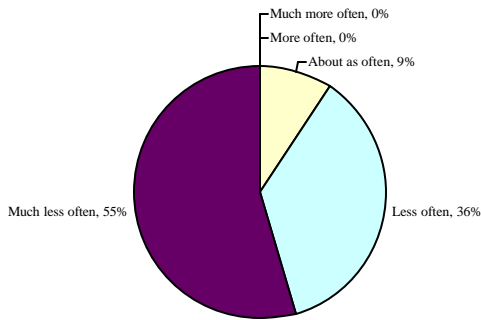


Figure 48 includes a summary of the responses to some of the questions included in the post-treatment questionnaire. A total of 91% of the residents said the frequency of tobacco smoke entry was reduced and 55% said it entered much less often. Over 80% of the residents felt that the tobacco smoke odors were much or somewhat weaker than before the treatments and no residents felt that tobacco smoke odors were more frequent or stronger. The same two questions were asked regarding cooking odors and the responses were nearly identical. The fraction of residents that said they were very satisfied with the amount of odor transfer increased from 40% before the treatments to almost 80% after the treatments. Also, after the treatments no residents indicated that they were very or somewhat dissatisfied with smoke odor transfer. There were no significant differences in the frequency of the responses by building.

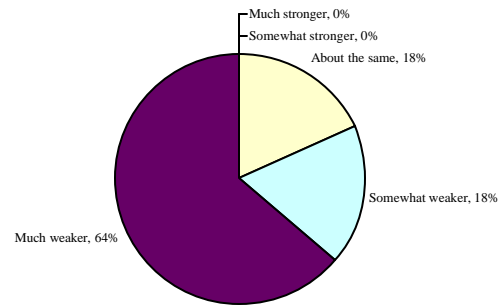
It is interesting that only half of the residents felt the improvement in the odor transfer problem was due to the treatments, while 20% said the improvement was due to other factors and 30% did not know what caused the change. Most of the respondents that said that the improvements were due to other factors or did not know the cause lived in the 11 Story building where “unseen” modifications were made to the ventilation system. Forty-seven percent of the residents said that they would be willing to pay \$100 or more for the improvements, but only 11% said that they would pay and amount that approached the actual cost of \$500 or more. The condominium

owners (buildings 138 Unit and 11 Story) were only slightly more inclined (54%) to pay \$100 or more for the work. However, the residents in the 11 Story building are retired and many live on fixed incomes. Overall, the questionnaire results indicate that the residents were very pleased with the improvement in the smoke transfer problem, but only half attributed the improvement to the treatments and about 10% would be willing to pay an amount close to the value of the work.

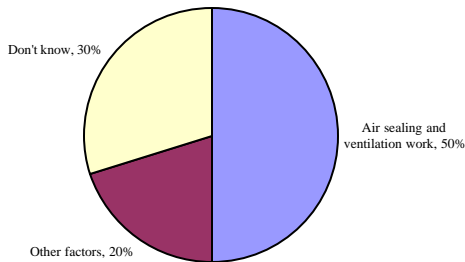
Figure 48. Post-treatment resident survey results regarding tobacco odors



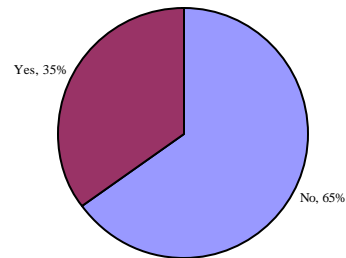
Since the work was completed, have tobacco smoke odors gotten into your apartment from somewhere else [response] than they did before the work was done?



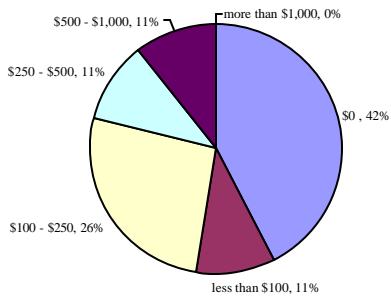
Since the work was completed, have tobacco smoke odors that have gotten into your apartment from somewhere else been [response] than they were before the work was done?



If you reported any changes in the frequency or strength of tobacco smoke odors, do you feel that these changes were due to the air sealing and ventilation work or to other factors?

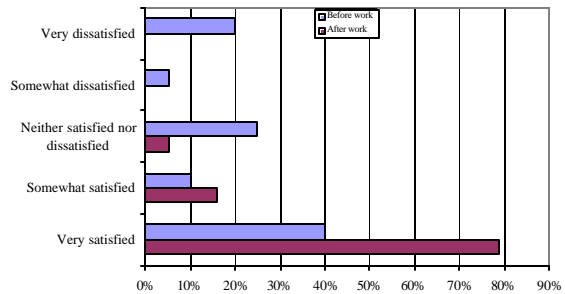


Have the air sealing and ventilation work had any other effects that you have noticed?



Based on the benefits you perceived, how much would you have been willing to pay for the air sealing and ventilation work completed in your apartment?

How satisfied were/are you with the amount of odor transfer into your apartment?



Results are reported for only those residents that lived in a unit that had air sealing and/or ventilation treatments. More detailed information, including the results from residents in units that were not treated and a breakdown of the responses by building, are included in Appendix A.

DISCUSSION

Tracer gas measurements confirmed that air flow 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. The units on the higher floors of the buildings had a greater fraction of air from other units or inter-unit air flow. When the results from all six buildings were combined, the average fraction of inter-unit 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 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. As a result, units on lower floors tend to get 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 inter-unit air flow 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 inter-unit air flow. However, even two of the seven monitored units in the three-story apartment building built in 1999 had inter-unit air flows that were greater than 20% of the total air flow into the units.

Air leakage tests indicated that the median total air leakage for the individual units ranged from 454 to 2,368 cfm₅₀ and the median value for all units was 861 cfm₅₀. Not only was there a considerable difference in leakage between buildings, but for four of the buildings there was a factor of two difference between the tightest and leakiest units in the same building. This indicates that for most multifamily buildings the air leakage for individual units can not be accurately predicted from measurements on a sample of units. The guarded zone tests showed that the median air leakage to adjacent apartments was 155 cfm₅₀ and that the fraction of air leakage to adjacent units was 27% of the total leakage. As might be expected from the air flow results, the newer buildings generally had a lower fraction of inter-unit 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 inter-unit 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.

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 air-tight 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 4 Story building. A relatively new aerosol sealing process was used to achieve an 86% average reduction in duct leakage.

After the air sealing work was completed on all the buildings, the median total air leakage was reduced to 722 cfm50 with a typical reduction of 139 cfm50 per unit and a relative reduction of 18%. 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 while only one of the units in the 138 Unit building had a reduction greater than 100 cfm50. There were significant differences in the reduction in inter-unit 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 inter-unit leakage was less than 210 cfm50 for all of the units and five of the units in the 138 Unit building had leakages less than 100 cfm50. It is encouraging that the inter-unit leakage of the 12-Plex units was typically reduced by 54% and that there were moderate (15%) inter-unit 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 eliminated.

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 inter-unit 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 often are connected to an intermediate area between units such as a floor cavity or mechanical chase. The restriction in the air flow between units can be a combination of the restriction due to the leaks from the 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.

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 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 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. Before treatments only 23% of the units meet ASHRAE 62-2001 minimum ventilation requirement and 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 inter-unit air flow. After both air sealing and ventilation treatments were complete, three of the six buildings had reductions in the median fraction of inter-unit flow rate of 3% or greater. The fraction for the 11 Story building decreased from 5% to 1% and that for 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 inter-unit air flow. 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.

For the three units where there was heavy smoking, the nicotine levels ranged from 0.22 to 1.14 $\mu\text{g}/\text{cf}$ (7.8 to 40.2 $\mu\text{g}/\text{m}^3$). The nicotine concentrations in the nonsmoker's units were very low. The median values for the different monitoring periods ranged from 0.0 to 0.016 $\mu\text{g}/\text{cf}$ (0.0 to 0.57 $\mu\text{g}/\text{m}^3$). A comparison of the concentrations in the smoker's and nonsmoker's units indicates that most nonsmokers in an apartment building will be exposed to nicotine concentrations that are less than 1% of that in the smoker's unit. The low nicotine levels in the nonsmoker's units and changes in the patterns of smoking did not allow the nicotine measurements to be used to evaluate the effectiveness of the air sealing and ventilation treatments. The nicotine measurements were used to compare the rate of transfer of nicotine and PFT between units. The results indicate that the PFT transfer rate ranges from 2 to 10 times greater than the nicotine transfer rate, with a median value of about 6.

There were numerous problems with the particulate measurements that limited the use of those results. The concentration of $\text{PM}_{2.5}$ in the smoker's units ranged from 2.0 to 7.1 $\mu\text{g}/\text{cf}$ (71 to 250 $\mu\text{g}/\text{m}^3$). The median concentration of $\text{PM}_{2.5}$ in the nonsmoker's units ranged from 0.13 to 0.20 $\mu\text{g}/\text{cf}$ (4.8 to 7.0 $\mu\text{g}/\text{m}^3$). A comparison of the fine particulate concentrations in the smoker's and nonsmoker's units indicates that most nonsmokers in an apartment building will be exposed to $\text{PM}_{2.5}$ concentrations that are less than 10% of that in the smoker's unit. The high and variable background levels of $\text{PM}_{2.5}$ did not allow the measurements to be used to evaluate the effectiveness of the treatments. However, the measurements were used to indicate that at least 75% of the particulates are filtered as they are transferred between units. This rate is about twice as high as the 37% and 43% filtration rate of $\text{PM}_{1.0}$ particles moving through the exterior envelope of a house reported by CMHC (2003b). Further measurements in a building with a higher transfer rate and low background level of $\text{PM}_{2.5}$ would be necessary to better quantify the filtration of $\text{PM}_{2.5}$ particles as they move between units in a multifamily building.

The effective contaminant transfer (ECT) was found to provide the best method for evaluating the effect of the air sealing and ventilation treatments on ETS transfer. The average ECT for all of the units was $45.6 \text{ h/cf} \times 10^{-6}$. Four of the buildings (Duplex, 8-Plex, 12-Plex and 138 Unit) had pre-treatment ECTs greater than $50 \text{ h/cf} \times 10^{-6}$ (or $\mu\text{h/cf}$) and the two others (11 Story and 4 Story) were below $25 \mu\text{h/cf}$. The four buildings with the highest ECTs generally had the highest fraction of inter-unit air flow. 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 buildings¹ is significantly higher than the relative change in the measured inter-unit 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.

The post-treatment reduction in ECT for the test units in all six buildings averaged $18.6 \mu\text{h/cf}$ or 41% of the pre-treatment value. Overall, 71% of the units had a reduction in ECT and 58% of the units had a reduction greater than 50%. 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 inter-unit air flow 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 air flow is most likely through air leaks in the building structure and not via common areas.

Before any work was performed, 48% of the residents indicated that they had tobacco smoke entry into their unit at least some time during the previous year and 10% said that the entry occurred often or most of the time. A total of 91% of the residents said the frequency of tobacco smoke entry was reduced after the air sealing and ventilation work was completed and 55% said it entered much less often. Over 80% of the residents felt that the tobacco smoke odors were much or somewhat weaker than before the treatments and no residents felt that tobacco smoke odors were more frequent or stronger. Overall, the questionnaire results indicate that the residents were very pleased with the improvement in the smoke transfer problem, but only half attributed the improvement to the treatments and about 10% would be willing to pay an amount close to the value of the work.

This study was able to identify a number of useful recommendations for future studies of ETS transfer in multifamily buildings and methods to reduce the transfer of ETS:

- Nicotine and particulate measurements in multifamily buildings are useful for determining the typical or maximum concentration of those constituents when the concentration in the smoker's apartment is known. They are also helpful in understanding the nicotine absorption and particulate filtering that occurs when ETS is transferred between units. The uncertainties with nicotine absorption, particulate filtering, intermittent smoking from multiple locations, and variable indoor particulate sources do not allow measurements of nicotine or particulate concentrations to be

¹ Inter-unit air leakage was not available for the 4 Story building.

used to reliably evaluate the effectiveness of building treatments on ETS transfer in multifamily buildings.

- The PFT method provides a simple and accurate method for evaluating the movement of nonsorbing contaminants in buildings. PFTs can be used to simultaneously evaluate the movement of up to seven contaminants over long time periods.
- There is a significant concern regarding ETS transfer in multifamily buildings. Almost half of renters surveyed reported experiencing it in their current apartments and almost two-thirds had experienced it in some apartment they had lived in. Ten percent of renters say ETS comes into their apartments from elsewhere often or most of the time.
- 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. Continuous ventilation that is balanced between units provides a significant benefit and should typically cost of \$300 to \$500 per unit.
- There needs to be more focus on air sealing at the time of construction or major remodeling. Many air leakage paths can not be sealed after construction is complete or when the unit is occupied. Effective continuous ventilation is also less expensive to install at the time of construction.
- It is probably best to use the total air leakage of each unit for any new construction or existing building performance standard. Both the interior and exterior air leakages of each unit are important in multifamily buildings. The total leakage includes both interior and exterior leakage and the total leakage test is much easier to implement than the guarded zone technique. In addition, the pressure between units during the leakage test can be used as an indicator of the leakage between units.

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