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

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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 where 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 h/cf x 10^{-6}. Four of the buildings (Duplex, 8-Plex, 12-Plex and 138 Unit) had pre-treatment ECTs greater than 50 h/cf x 10^{-6} (or µh/cf) and the two others (11 Story and 4 Story) were below 25 µh/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 buildings[1] 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 µh/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 µg/cf (7.8 to 40.2 µg/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 µg/cf (0.0 to 0.57 µg/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 $\mu g/m^3$). 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 $\mu g/m^3$). 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 $PM_{2.5}$ 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 constitutes 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 <u>total air leakage</u> 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.