# Multifamily Ventilation Retrofit Strategies

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Kohta Ueno, Joseph Lstiburek, and Daniel Bergey

Abstract:

*In multifamily buildings, central (typically rooftop) ventilation systems often have poor overall performance, overventilating some portions of the building (resulting in excess energy use), while simultaneously underventilating other portions of the building (resulting in diminished indoor air quality). These issues are often tied to multistory stack effects (warm air rising at cold outdoor conditions), and a lack of compartmentalization (airtightness) between floors and between units. These issues are exacerbated by the presence of multistory shafts (e.g., elevator shafts, stairwells, and ventilation shafts). Central corridor supply and makeup air systems combined with rooftop central exhaust systems are particularly problematic. The recommended solution is to isolate the units from one another and from corridors, shafts, elevators, and stairwells by means of greater airtightness.*

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

BUILDING TECHNOLOGIES PROGRAM

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**K. Ueno, J. Lstiburek, and D. Bergey**
*Building Science Corporation*


December 2012

Building America U.S. Department of Energy

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# Multifamily Ventilation Retrofit Strategies

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## Definitions

| | |
|---|---|
| ACH 50 | Air changes per hour at 50 pascal test pressure (hour$^{-1}$) |
| ASHRAE | American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. |
| BSC | Building Science Corporation |
| CAR | Constant airflow regulator |
| CDD | Cooling degree day |
| CEE | Center for Energy and Environment |
| cfm | Cubic feet per minute |
| cfm 50 | Cubic feet per minute at 50 pascal test pressure |
| CMHC | Canada Mortgage and Housing Corporation |
| DOE | U.S. Department of Energy |
| ECM | Electronically Commutated Motor |
| EF-[x] | Exhaust fan [unit number] |
| EqLA | Equivalent leakage area (Canadian General Standards Board) |
| ETS | Environmental tobacco smoke |
| h | Hour |
| HDD | Heating degree day |
| hp | Horsepower |
| HRV | Heat recovery ventilator |
| kBtu | Thousand ($10^3$) British thermal units |
| kW | Kilowatt |
| kWh | Kilowatt-hour |
| KPHL | Philadelphia International Airport weather station |
| nACH | Natural air changes per hour (hour$^{-1}$) |

| | |
|---|---|
| NAHBRC | National Association of Homebuilders Research Center |
| L | Liter |
| $m^2$ | Square meter |
| MAU | Makeup air unit |
| MMBtu | Million ($10^6$) British thermal units |
| mph | Miles per hour |
| Pa | Pascal |
| rpm | Revolutions per minute |
| s | Second |
| SIR | Savings-to-investment ratio |
| TREAT | Targeted Retrofit Energy Analysis Tool |
| VA | Volt-amps |
| VDC | Volts, direct current |
| VFD | Variable frequency drive |
| W | Watt |
| WRT | With respect to (used to reference pressure measurements) |

# Executive Summary

In multifamily buildings, central (typically rooftop) ventilation systems often have poor overall performance, overventilating some portions of the building (resulting in excess energy use), while simultaneously underventilating other portions of the building (resulting in diminished indoor air quality). These issues are often tied to multistory stack effects (warm air rising at cold outdoor conditions), and a lack of compartmentalization (airtightness) between floors and between units. These issues are exacerbated by the presence of multistory shafts (e.g., elevator shafts, stairwells, and ventilation shafts). Central corridor supply and makeup air systems combined with rooftop central exhaust systems are particularly problematic. The recommended solution is to isolate the units from one another and from corridors, shafts, elevators, and stairwells by means of greater airtightness.

Duct sealing of exhaust shafts has significant energy benefits. Codes require minimum exhaust flows from spaces (kitchens and bathrooms). Leaky exhaust duct shafts pull additional exhaust air out of interstitial spaces (i.e., “stealing” air), which does not help meet the minimum exhaust requirements and results in overventilation.

Building Science Corporation performed a series of field tests at a mid-rise test building with Innova Services Corporation, which is a Philadelphia-based firm that works in the affordable housing industry. The test building was undergoing a major energy audit and retrofit that was completed over the course of 2011 and 2012. Ventilation upgrades were one component of the retrofit, which also included lighting, space heating, domestic hot water, and appliance upgrades.

The retrofit exhaust ventilation system replaced the existing rooftop fans with variable-speed, pressure controlled, electronically commutated motor rooftop units. Apartment unit exhaust registers were changed to localized powered exhaust fans, controlled by wall switch timers, to supply ventilation on an as-needed or timed basis. When the unit exhaust fan is off, some limited baseline ventilation occurs through the fan damper; when a unit exhaust fan is turned on to respond to pollutant loads, the rooftop exhaust rate increases (maintaining negative pressure in the shaft).

The corridor ventilation system was intended to replace a non-operational rooftop makeup air system, which was deactivated because of excess energy costs associated with heating large airflows. The retrofit system switches to floor-by-floor ventilation, tempering ventilation supply air with indoor air to avoid cold air complaints.

Pre-retrofit air leakage was measured in two exhaust duct shafts: leakage was more than double recommended levels (per Zuluaga and Fitzgerald 2010). The fan depressurization leakage measurements were 26% and 13% of the nominal (callout) flow, using the cfm 50 (cubic feet per minute at 50 pascal test pressure) leakage metric. Summed unit exhaust airflows were compared with the rooftop airflow measurements, providing a “calculated leakage” that correlated reasonably well with the nominal leakage.

Airflows from the units and the rooftop fans were compared to the nominal plan callouts. Unit airflows were lower than callouts (78% weighted average), while rooftop airflows were higher than callouts (109% on average). The mismatch between rooftop and unit flows shows the effect of exhaust shaft duct leakage.

Unit air leakage was measured with depressurization testing, showing high air leakage and poor compartmentalization. Much of the leakage appeared to be above the suspended ceiling: air sealing details required for fire rating of the demising walls were never completed.

In the post-retrofit testing, exhaust airflows were measured at the rooftop unit and in the apartment units, with individual unit exhausts turned on and off. Although rooftop measurements had high uncertainty because of wind effects, it appears that the rooftop fan correctly increases its flow when additional unit exhaust fans are turned on. Airflows at the unit exhausts matched expected patterns, including some airflow (bypass) through the unit exhaust fan's damper with the unit off and higher flow with the unit on. Rooftop exhaust fan airflows were roughly 50% of original plan callout values, but met ASHRAE 62.1 and 62.2 targets (ASHRAE 2010a, 2010b).

Power draw measurements show a substantial improvement in fan efficiency: calculated efficiency based on this measurement was 10–20 cfm/W, compared to the pre-retrofit state of 1.3– 2.1 cfm/W. This is ascribed to improved efficiency of the fan motor and the reduction in airflow (40%–60% of original design), the latter which results in effectively oversized ductwork. Efficiency levels this high should not be expected with a new duct system sized for the measured flows. These metrics do not include the contribution of the unit exhaust fans (at 12 W each).

Similar to the pre-retrofit measurements, calculated duct leakage could be estimated from the difference between rooftop and unit exhaust measurements. The calculated duct leakage (as a percentage of flow from the rooftop fan) is 40%–50% with the unit exhausts off and 15%–25% with the unit fans on. Although the "unit fans off" calculated duct leakage is a very high fraction of the flow (40%–50%), at Exhaust Fan-1, for example, the absolute value (85–100 cfm) is comparable to or less than the calculated duct leakage in the pre-retrofit system (110 cfm). The roof curb connection was one significant source of duct leakage that was corrected in the retrofit. No duct sealing was implemented beyond rooftop curb work, such as aerosol-based sealant or hand-applied mastic to accessible portions.

Monitoring equipment was installed on two exhaust fans. A correlation was seen between fan speed variations and wind events. There was also a diurnal variation in fan speed on a cycle that matches typical occupancy, with low variations during sleeping hours (10 p.m. to 6 a.m.), and greater variations during the day.

The retrofit corridor supply ventilation system was installed and tested; basic function is as per design, with outdoor supply air being tempered or diluted with interior air (at ratios of 1:2 to 1:3.5) for occupant comfort. The system, however, had relatively high static pressures and relatively low fan efficiencies (0.9 cfm/W for net outside air).

Some limited conclusions can be drawn from the collected data. If the reduction in ventilation flow is applied across all fans, heating energy savings are estimated at roughly 4,000 therms/yr, which can be compared with wintertime heating use estimated at 16,000 therms/yr. The electrical savings resulting from upgraded fans (and reduced ventilation rates) are also significant, changing from roughly 4,500 kWh/month to 290 kWh/month in fan use energy, including the estimated contribution of unit exhaust fans.

# 1 Introduction

In multifamily buildings, central (typically rooftop) ventilation systems often have poor overall performance, overventilating some portions of the building (resulting in excess energy use), while simultaneously underventilating other portions of the building (resulting in diminished indoor air quality). At this point, there are some tested and recommended solutions for solving these issues in both new construction and retrofit situations.

The recommended retrofit solutions, however, have ramifications in terms of installed cost and simultaneous access to multiple units to execute the retrofit. Alternate solutions, involving variable-speed rooftop exhaust fans and individual unit powered exhaust fans, can be considered. This research project examined the performance of existing multifamily ventilation central systems and explored alternative solutions in retrofit situations. Engineering calculations and field-testing of components and systems were used to complete this work.

Building Science Corporation (BSC) performed this research with Innova Services Corporation ("Innova"), a Philadelphia--based firm that works in various sectors of affordable housing, including construction project management, general contracting, and building retrofit services.

This research on multifamily ventilation systems was conducted at a building retrofit project that was recently completed. The test building was the James J. Wilson Mercy-Douglass Residences,[1] which is senior housing constructed in the mid-1980s (see Figure 1).


**Figure 1. Mercy-Douglass Residences overhead view (L) and site conditions (R)**

[1] 4511 Walnut Street, Philadelphia, PA, 19139

# 2 Multifamily Building Ventilation Background

## 2.1 Stack Effect, Ventilation, and Compartmentalization

The dominant forces causing air movement in buildings are wind, temperature difference-induced stack effects (otherwise known as natural buoyancy), and mechanical pressurization and depressurization (Straube and Burnett 2005; Hutcheon and Handegord 1995).

Taller buildings are often dominated by stack effect. Wilson and Tamura (1968) and Hutcheon and Handegord (1995) discuss the fundamental physics. The simplified consequences of stack effect are shown in Figure 2. In cold weather, outdoor air infiltration occurs on lower floors and interior air exfiltration occurs on upper floors. Research has shown that in cold climates in the winter, stack effect dominates over wind effects (Feustel and Diamond 1996; Palmiter et al. 1995; Francisco and Palmiter 1994).

If there is interior leakage between floors (common in the stock of multifamily buildings), upper floors are effectively “ventilated” with air from lower floors (i.e., replacement air comes from other units), as shown in Figure 2. This results in odor and pollutant transfer, compromised smoke control and fire safety, highly varying rates of air change between floors, difficulties in maintaining even temperature set points (especially in buildings without zoned controls or thermostats), and excess energy use.

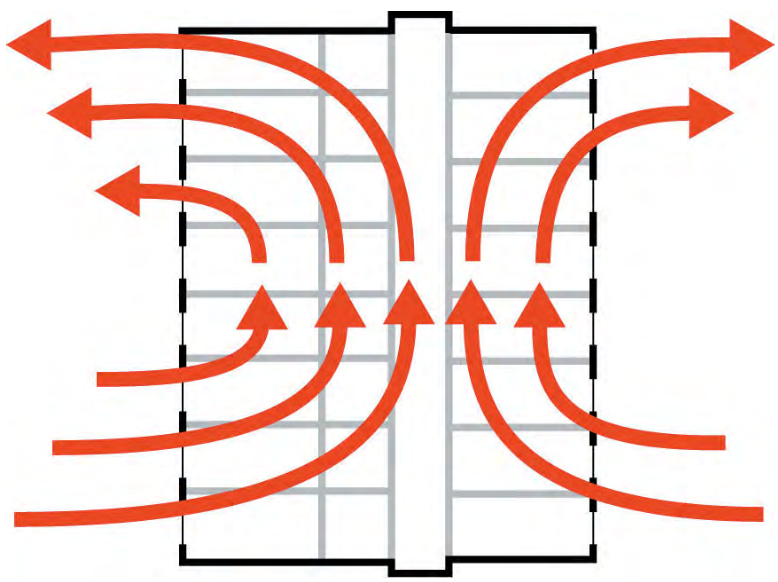

**Figure 2. Stack effect in multifamily buildings (simplified)**

Stack effect problems are exacerbated by the presence of multistory shafts, such as elevator shafts, stairwells, and ventilation shafts. These shafts have stack-driven pressure differences across their walls, resulting in an additional potential air transfer path (Figure 3). Note that if the shaft is a multistory mechanical duct, the stack effect pressures will be superimposed on the mechanically induced pressures on a seasonal basis, resulting in uneven distribution of ventilation flows. Upper floor units are typically overventilated in wintertime because of combined stack and mechanical pressures.

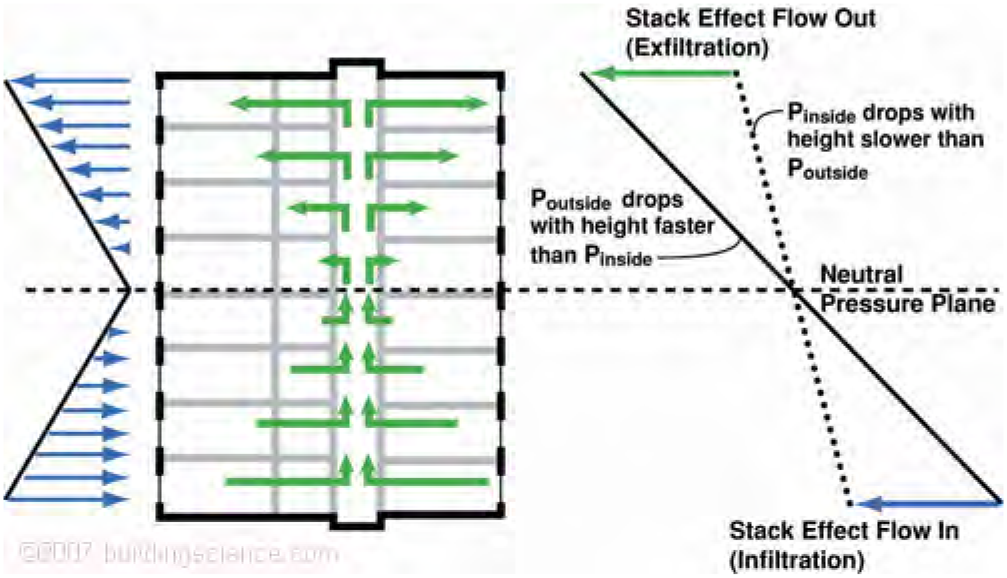


**Figure 3. Stack effect in multifamily buildings (simplified), showing shaft effects**

The solution proposed by Lstiburek (2005) and others is to isolate the units from one another and from the corridors, shafts, elevators, and stairwells, by means of greater airtightness or compartmentalization (Figure 4). This limits stack effects largely to the floor-to-ceiling height difference of a given unit, as opposed to stack acting over the height of the building. Elevators should be located in vestibules, lobbies, or other airlocks to isolate them from corridors.

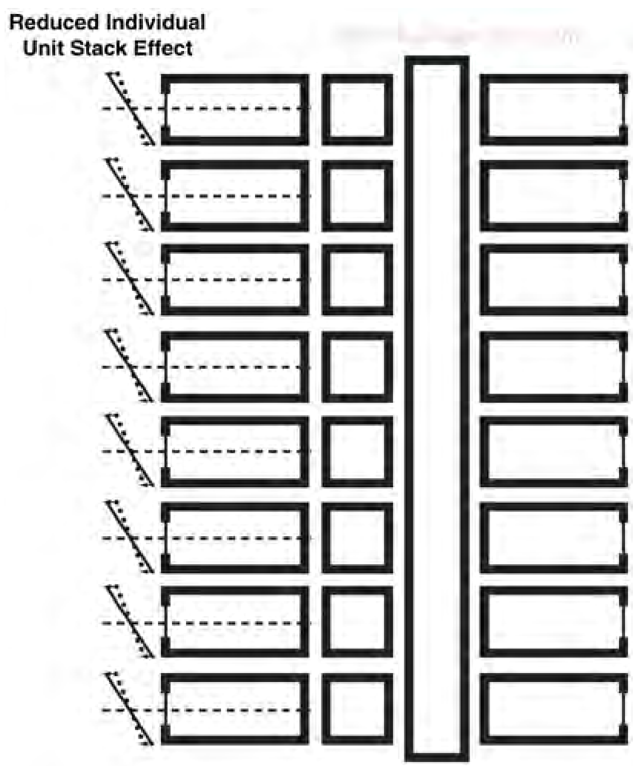


**Figure 4. Idealized compartmentalized multifamily building, showing stack per floor**

Figure 5 shows the air barrier compartmentalization concept. Each unit is isolated from adjacent units and from the exterior by an air barrier system with a maximum air leakage rate of 2.0 L/(s·m$^2$) at 75 Pa, which is equivalent to 0.30 cfm at 50 Pa/ft$^2$ of enclosure (cfm 50/ft$^2$). The interunit separation must also meet the specific fire resistance rating requirement for the given separation.

Compartmentalization also reduces overall air leakage through the building enclosure by limiting stack effect pressures across the exterior enclosure to those associated with one compartmentalized unit's height. This is shown in concept by comparing Figure 3 with Figure 4.

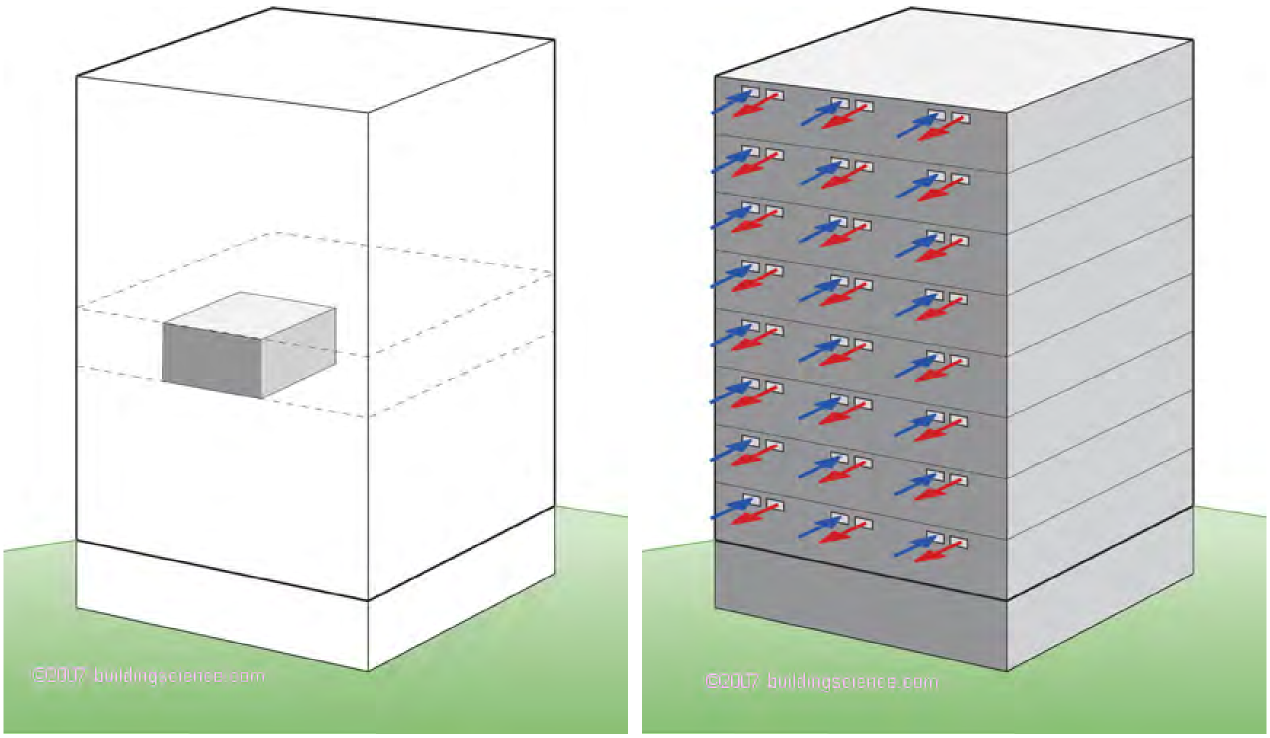


**Figure 5. Ideal unit compartmentalization (L) and individual unit ventilation supply/exhaust (R)**

This compartmentalization principle can be applied to ventilation systems as well. Ideally, ventilation air would be supplied and exhausted through the exterior wall (as shown in Figure 5, right), not across interior pressure boundaries, which compromises compartmentalization.

Individual unit ventilation systems have a further benefit in that they can be controlled on a unit-by-unit basis, either by the occupant or by building management. A central ventilation system, in contrast, typically provides a constant exhaust rate for all units at all times, resulting in overventilation in some units and underventilation in others, assuming diversity of pollutant loads. For instance, a temporarily unoccupied unit would be overventilated if operated identically to an occupied unit. Of course, overventilation has an associated energy penalty.

For reference, the calculated stack effect pressure over a 30-ft and 40-ft height is graphed against exterior temperature in Figure 6. Various weather conditions for Philadelphia are shown, including the 99.6% design temperature (12.6°F), and the three lowest monthly average temperatures (December–February; 33°–38°F). This shows the expected range of stack pressures operating across low- and mid-rise multifamily buildings. The most common wintertime stack pressures would be centered on the 8- to 12-Pa range, based on monthly average temperatures.

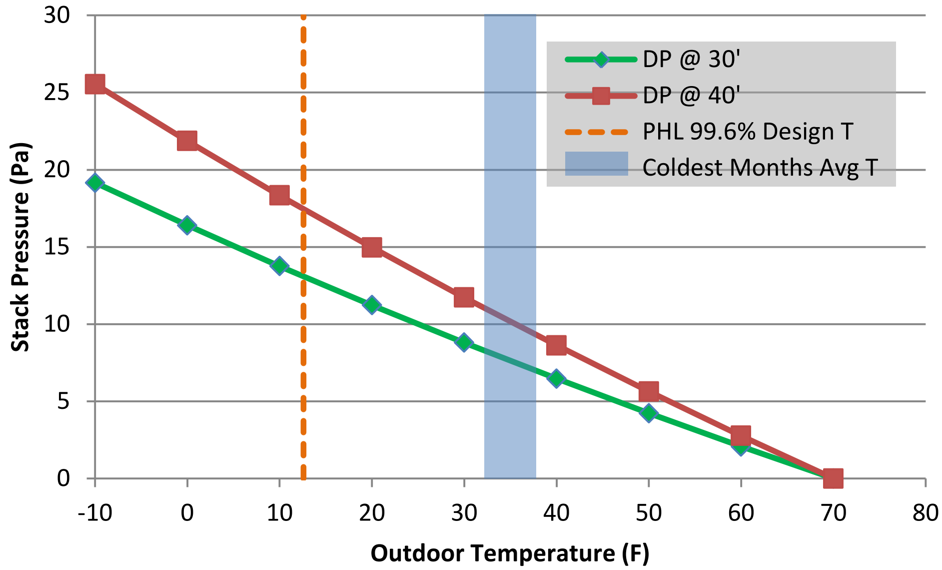


**Figure 6. Stack effect pressures for 30-ft and 40-ft heights, with Philadelphia weather conditions**

## 2.2 Literature Review

In existing multifamily buildings, research indicates that many such buildings are significantly overventilated as a result of using central corridor supply and makeup air systems combined with rooftop central exhaust systems. At the same time, other parts of the buildings are underventilated (Canada Mortgage and Housing Corporation [CMHC] 2005, 1999). The research suggests that this overventilation results in high energy costs; major discomfort; poor control of indoor air quality; and poor part load humidity control.

The Center for Energy and Environment (CEE; 2004) performed a major study on controlling environmental tobacco smoke (ETS) in six multistory multifamily buildings. The study involved a variety of measurements, including unit air leakage, ventilation airflows and pressurization, and direct measurement of interunit contaminant transfer (using a tracer gas and a perfluorocarbon tracer). Remedial air sealing was performed on units and post-retrofit tests were conducted. These retrofits significantly reduced contaminant transfer. The CEE research team also observed that controlling the ventilation system is crucial; it was found to be nonfunctional or badly out of specification in many cases. When designing centralized exhaust systems, the CEE authors expressed preference for systems that would exhaust all units constantly, as opposed to intermittent exhausts that would respond to load. The latter system results in pressure differentials between units when exhaust fans are run. This can increase airflow (and thus contaminant transfer) between units.

The National Association of Homebuilders Research Center (NAHBRC; 2008) studied the use of constant airflow regulators (CARs) as a method for improving performance of centralized ventilation systems in multifamily buildings. The study included an excellent overview of the topic of ventilation rates in multifamily buildings, and the issues of the energy penalties of overventilation. It identified CARs as a solution to uneven distribution of ventilation resulting from stack effect, wind pressures, system imbalances, and unit pressurization or depressurization. Exhaust systems with wide variations in flows (pre-retrofit) had post-retrofit airflows consistently close to specifications. The NAHBRC authors concluded that CARs are an excellent solution for overventilation; however, underventilation is a system design issue that these devices cannot solve. In addition, one issue encountered in a retrofit installation was that the exhaust shaft was sufficiently leaky that the rooftop exhaust fan could not provide sufficient negative pressure at the furthest registers for the CARs to function correctly. Retrofit sealing of the exhaust shaft was necessary to make the system function as designed.

Zuluaga and Fitzgerald (2010) gave a more detailed presentation of the work discussed in NAHBRC (2008). One topic discussed in detail was air leakage and remedial sealing of centralized exhaust shafts. Codes and other authorities require certain minimum exhaust airflows from various spaces (kitchens and bathrooms). Leaky exhaust duct shafts pull additional exhaust air out of interstitial spaces in the building, which does not help meet the minimum exhaust requirements. This results in overventilation of the building (i.e., the leaky ducts “steal” air), because the rooftop exhaust fan must remove an excess airflow to meet code minimums in bathrooms and kitchens. The NAHBRC authors show typical leakage locations in exhaust shafts and various methods of retrofit air sealing, including manual mastic/foam, aerosol-based sealing, and remote sealing with video cameras. They present solid guidance for retrofitting central exhaust systems, including cleaning, sealing, and installing dampers (CARs).

## 2.3 Ventilation Energy in Context

Ventilation—and more importantly, overventilation—can have significant effects on overall heating and cooling performance. This is particularly true for multifamily buildings, given that enclosure loads are a smaller portion of the total load (relative to single family housing) because of reduced exterior exposure.

Zuluaga and Fitzgerald (2010) estimated that 1 cfm of ventilation load has an associated space conditioning cost of roughly $1–$2 in a New York City (Zone 5) climate. This calculation was rechecked using Philadelphia hourly typical meteorological year (TMY 3) data, assuming that

$$H\ (\text{Btu/h}) = 1.08 \times Q\ (\text{cfm}) \times \Delta T\ (°\text{F}).$$

Table 1 shows the results expressed as the impact of 1 cfm of air exchange (without heat recovery), operating 24/7/365 with 70°F indoor conditions, in terms of heating energy only.

**Table 1. Energy Impact of 1 cfm of Air Exchange on Heating[a]**

| Metric | Amount |
|---|---|
| Heating Energy | 161,352 Btu/yr (1.6 therms) |
| Heating Efficiency | 85% (assumed) |
| Annual Cost @ $1.50/Therm Gas | $2.85 |
| Annual Cost @ $1.00/Therm Gas | $1.90 |

[a] Assuming Philadelphia typical meteorological year (TMY 3) climate

These air exchange figures should be applied to the net total of ventilation (or overventilation) and air leakage. The total airflow (cfm) should not be calculated as the simple addition of infiltration airflow and ventilation airflow through the fan. Instead, the net ventilation provided by an exhaust-only system is roughly half the fan's rated capacity as per the "half fan" rule (Palmiter et al. 1990; discussed in detail by Roberson 2004). Therefore, reducing exhaust ventilation rates would likely only reduce air exchange by half the change in fan flow.

To put the effect of ventilation (and overventilation) in context, BSC performed basic calculations to show the relative contributions of various enclosure components to heating loads. The contributions to heating energy use were calculated for a small apartment (900 $ft^2$, 1 bedroom, one exposed wall, adiabatic floor and ceiling), for the following components: opaque wall area, glazing, infiltration (unintentional air exchange), and ventilation plus overventilation. The results are expressed in terms of UA value (Btu/h·°F), to apply these concepts as universally as possible across various climate zones and conditions. Note that this solely examines heating energy performance, which is only a portion of the total energy use for multifamily buildings.

A typical overventilation rate was estimated based on the information from Zuluaga and Fitzgerald (2010), where actual ventilation was provided at 180% of recommended levels, even accounting for underventilation in some units. As is typical for these systems, there was an uneven distribution of ventilation air over the height of the building.

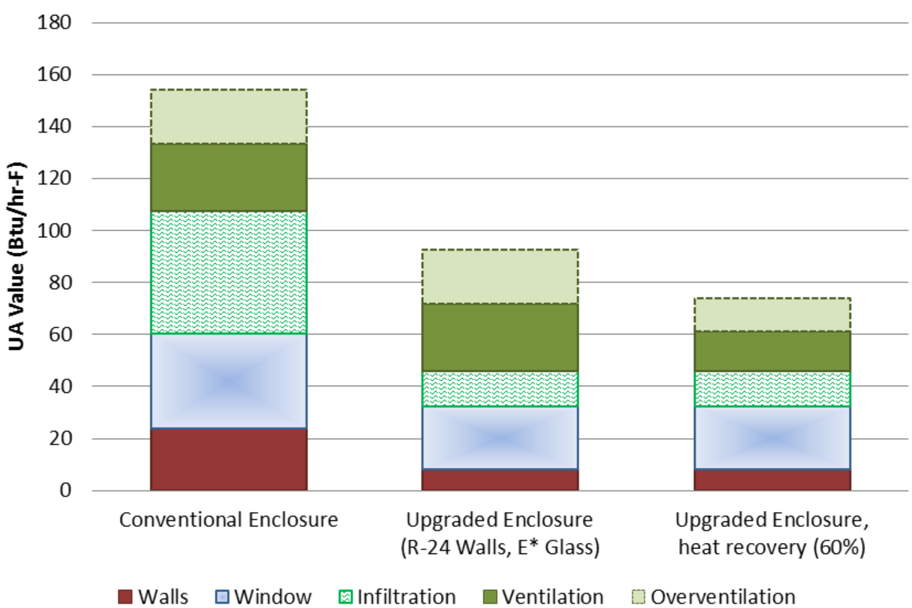


**Figure 7. Relative contributions of opaque wall, glazing, ventilation, and infiltration (UA values)**

In Figure 7, the "conventional enclosure" option includes steel stud framing with fibrous insulation in the stud cavities (R-8 overall opaque R-value), the windows are aluminum frame with thermal breaks (U = 0.45), infiltration is 0.35 natural air changes per hour (nACH), and ventilation is provided at the ASHRAE Standard 62.2 rate (ASHRAE 2010b).

The "upgraded enclosure" option includes wood 2 × 6 framing with 1.5 in. of polyisocyanurate exterior rigid insulating sheathing (R-24 overall opaque R-value), ENERGY STAR-compliant windows (U = 0.30), infiltration of 0.1 nACH, and ventilation at the ASHRAE Standard 62.2 rate.

The "upgraded enclosure, heat recovery" option reduces the magnitude of the ventilation energy by applying a heat recovery ventilator (HRV) with an efficiency of 60%.

Overall, as the enclosure is improved, the ventilation/overventilation and infiltration portions of the load become more and more dominant. Specifically, overventilation is comparable to the heating load through the ENERGY STAR windows alone, and is greater than the heating load through well-insulated exterior walls. Although HRV use reduces the overventilation penalty, the measures proposed in this research have the opportunity to substantially reduce overventilation, which would be a significant improvement.

# 3 Project Retrofit Plan

## 3.1 Overview

The ventilation upgrade that was implemented at Mercy-Douglass Residences was a component of a major energy audit and retrofit that was completed over the course of 2011–2012. The retrofit project was performed under the auspices of the Philadelphia Housing Development Corporation's weatherization program as a pilot project for multifamily residential structures. Under the program, a request for qualifications was issued for project management and consultation services that included performance of energy audits and the oversight of contractor selection to perform energy efficiency retrofits using funds from the American Recovery and Reinvestment Act of 2009. Innova was awarded the contract based on its satisfaction of the request for qualifications requirements and experience in the multifamily residential energy sector. After the contract award, the Philadelphia Housing Development Corporation (in consultation with Innova) identified the Mercy-Douglass Residences as an ideal pilot project for the program based on the age and condition of its mechanical systems.

For reference, the work other than ventilation included the following (Innova 2011):

- Lighting: Exterior lighting upgrade, light-emitting diode exit signs, compact fluorescent lamp package, stairwell lighting upgrade, common area lighting upgrade
- Heating use reductions: space heating boiler upgrade (atmospheric cast iron boiler to condensing sealed-combustion boiler; see Figure 8), space heating loop distribution upgrade (installation of variable frequency drive (VFD) pumps to account for varying flow restrictions from thermostatic radiator valve cycling), air sealing
- Other (water and appliances): domestic hot water boiler upgrade, low-flow plumbing devices, refrigerator upgrade.

**Figure 8. Replacement of atmospheric boilers (L) with condensing sealed-combustion boilers (R)**

The work that was done in this retrofit was constrained by programmatic limitations. Energy cost savings measures were required to meet cost-effectiveness requirements in order to be funded under various government programs (minimum savings-to-investment ratio [SIR] of 1.0 for U.S.

Department of Energy [DOE] requirements). Some measures that were proposed and rejected for not meeting these cost-effectiveness requirements included replacement windows, a roof replacement, apartment lighting upgrades, and parapet repairs.

The BSC/Innova research team believed that the current simulation software used for analysis (Targeted Retrofit Energy Analysis Tool [TREAT] building analysis software) might not truly capture the effect of some upgrades because of limitations in inputs and algorithms. Although there was some discussion about modifying the simulation inputs, the timeline for this work was not amenable to further changes once the process was set in motion, so this approach was not pursued. Specifically, the audit and the TREAT model results are sent to the program operator, who in turn sends it to the state funding agency. Once the approvals are given for the modeled scope, the work is put out for bid. At that point, the only way to change the scope is to have the auditor remodel the savings, revise the audit, and seek all the approvals again.

Note that BSC did not perform existing retrofit whole-building energy modeling in this project; Innova conducted the energy analysis based on TREAT simulation software for the test building as a component of its full energy audit (Innova 2011). Note that Building Energy Optimization analysis is not directly relevant to this project because the software has difficulty handling multifamily inputs, especially floor-over-floor construction. BSC's previous work modeling multifamily buildings using Energy Gauge USA (Parker et al. 1999) demonstrated that groupings of units could be combined for reasonable results (BSC 2008); however, more explicit modeling with DOE-2 based tools would be a more defensible approach.

### 3.2 Pre-Retrofit Energy Performance

To gain a better understanding of the pre-retrofit energy performance of the Mercy Douglass Residences, the energy consumption data taken from the energy audit are included here. The monthly energy use is plotted here with heating degree days (HDD) and cooling degree days (CDD); data were available for a year spanning 2009–2010. Natural gas is used for space heating and domestic/service hot water. Electricity is submetered per apartment unit, which includes appliances, typical plug loads, and cooling via through-the-wall air conditioners (operated at the occupant's discretion). The building has no central space cooling.

The energy use is first plotted in terms of monthly cost in Figure 9, subdivided into electricity and natural gas. The figure shows that the electrical baseline is a large fraction of the total cost, and a significant cost is associated with space heating (as shown by the correlation between wintertime gas use and HDD). Domestic/service hot water use can be approximated by examining gas consumption during the nonheating months (a "baseline" of use). Based on this assumption, domestic hot water usage appears to be quite small relative to the space heating loads. Electricity use increases moderately during summertime cooling periods (correlating to CDD); however, it is small relative to the baseline usage.

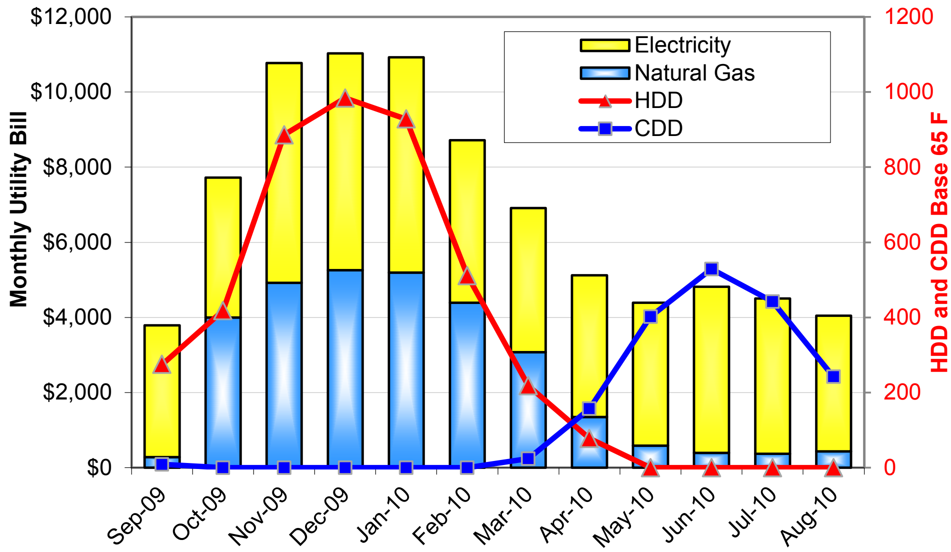


**Figure 9. Pre-retrofit energy performance, monthly energy cost, with HDD/CDD**

The same information is plotted in terms of site energy (Figure 10) and source energy (Figure 11), using the site-source factors from Deru and Torcellini (2007). As would be expected, when converted to source energy, electricity becomes a larger overall energy load relative to gas use (2,186 MMBtu/year gas versus 4,823 MMBtu/year electricity source energy).

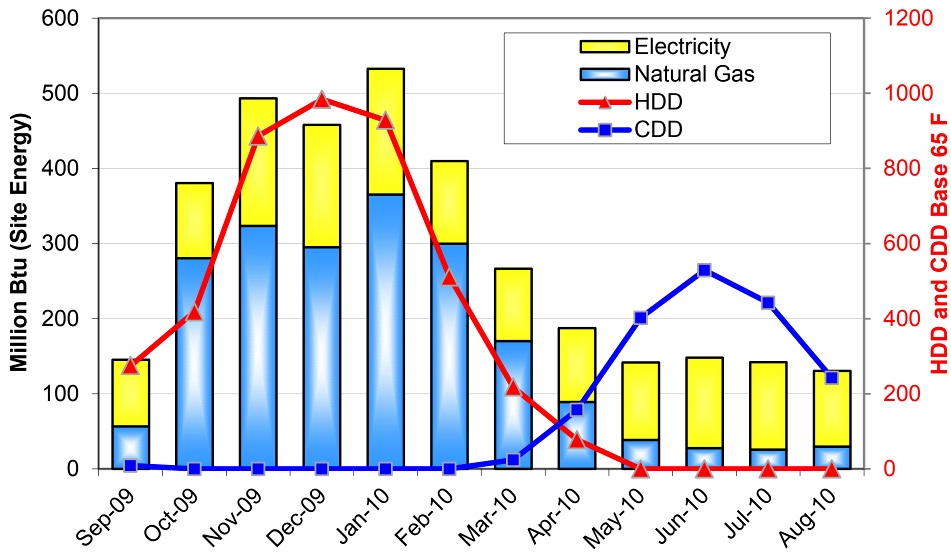


**Figure 10. Pre-retrofit energy performance, monthly site energy use, with HDD/CDD**

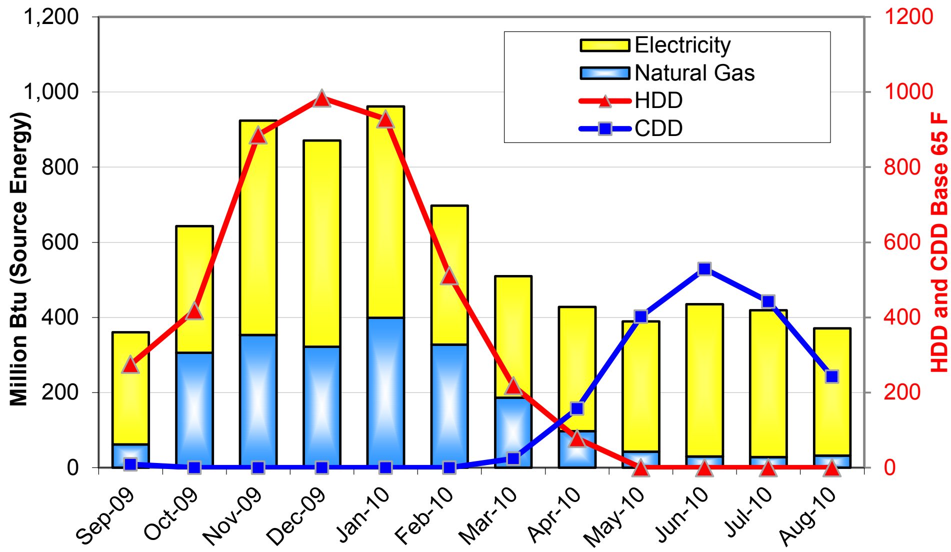


**Figure 11. Pre-retrofit energy performance, monthly source energy use, with HDD/CDD**

Another pattern that is visible in these graphs is the significant increase in electrical consumption during the winter months, which is even higher than the summertime cooling increase. This is shown more clearly in the plot of electrical use (Figure 12).

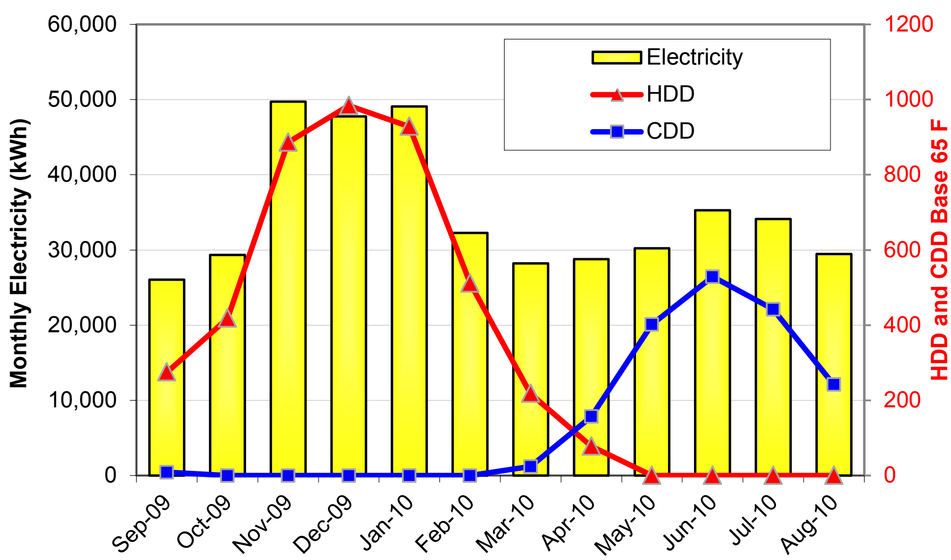


**Figure 12. Pre-retrofit energy performance, monthly electricity use, with HDD/CDD**

This increase correlates very well with the coldest months; Innova (2011) gave the following explanation for this increase:

> *Baseline usage accounts for the bulk of electrical consumption at Mercy Douglass, at approximately 85% of total consumption. There is a moderate increase over baseline in summer months owing to the use of through-wall air conditioners.*

*An unusually large increase in the months of November, December and January was not accounted for by management, but is likely due to problems with the space heating loop pumps, which have been experiencing failures and are subject to frequent repair, according to maintenance staff. In addition, shortened winter daylight hours produce longer operational periods of exterior and apartment lighting.*

The electrical use was further broken down into common space (which would include the space heating loop pumps) and the tenant spaces (average of 10 units multiplied by total number of units), as shown in Figure 13.

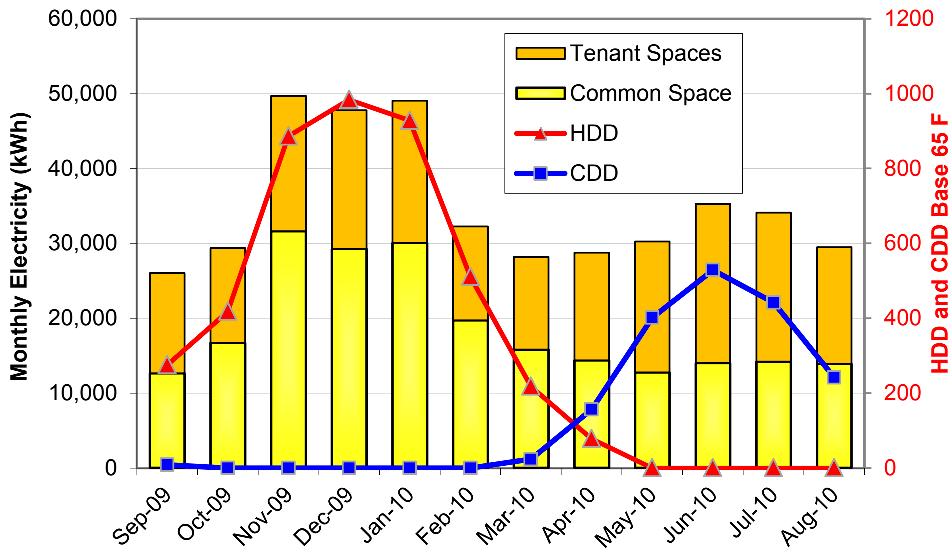


**Figure 13. Pre-retrofit energy performance (common + tenant) electricity use, with HDD/CDD**

The common space wintertime increase is roughly 15,000 kWh/month; assuming a constantly running load, this is equivalent to a continuous 20-kW load, which is exceptionally high. Improper control of the space heating loop pumps is a plausible explanation: two 3-hp heating loop pumps are called out on the plans. Assuming 746 W/hp and 25% motor efficiency (the low end of the scale), this would be a continuous load of 18 kW.

The tenant spaces, though, are also contributing to the wintertime increase in electrical consumption, as shown in Figure 14. Some of the tenant units show a substantial wintertime spike; others show no wintertime rise. One explanation is the use of electric resistance heaters in some apartment units in the winter.

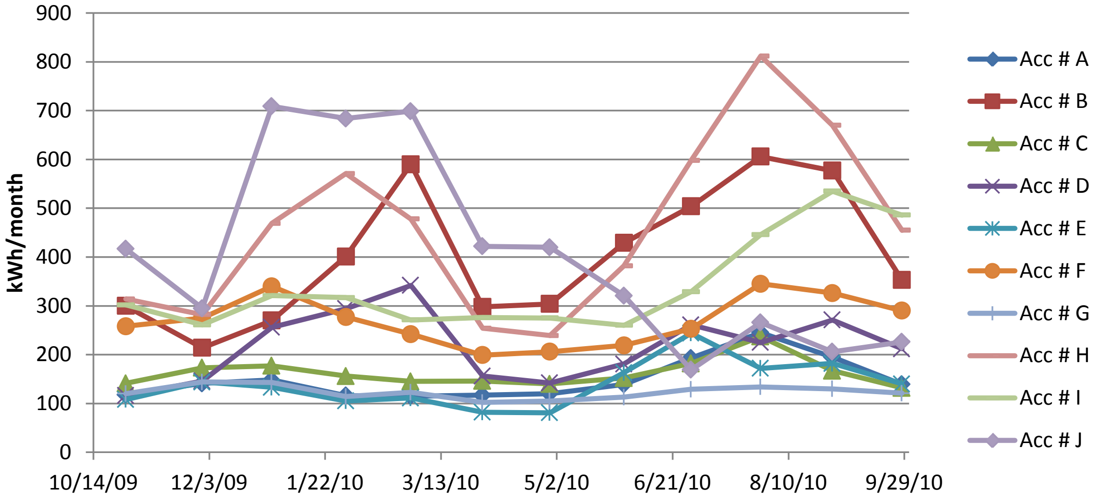


**Figure 14. Pre-retrofit energy performance electricity use (tenant space unit monthly use)**

Overall, the analysis shows that heating is a strongly dominant load, in terms of either energy cost or source energy. Ventilation efficiency measures will improve heating season performance.

### 3.3 Exhaust (Kitchen and Bathroom) Ventilation Plan

The existing exhaust ventilation system consists of multiple rooftop exhaust fans, connected to exhaust registers located in the bathrooms and kitchens (Figure 15 and Figure 16). The vertical riser from the fan splits into horizontal branches, in turn connecting multiple parallel shafts. In all, there are 12 rooftop exhaust fans at the building, with a combined nominal exhaust rate of 9,150 cfm. The rooftop exhaust fans are run constantly at a fixed speed.

A given shaft/fan handles only kitchen exhausts or bathroom exhausts; the two types of exhausts are not mixed in any shaft (see Figure 16).

**Figure 15. Rooftop ventilation system components (L) typical kitchen exhaust grille (R)**

The kitchens are exhausted via a wall register (Figure 15); no separate range-top hood is installed (e.g., recirculating hood for grease capture).


**Figure 16. Typical floor plan, showing kitchen/bath exhaust systems and risers**

The bathrooms are exhausted through ceiling registers; typically, flexible duct joins the register to the exhaust trunk (Figure 17).

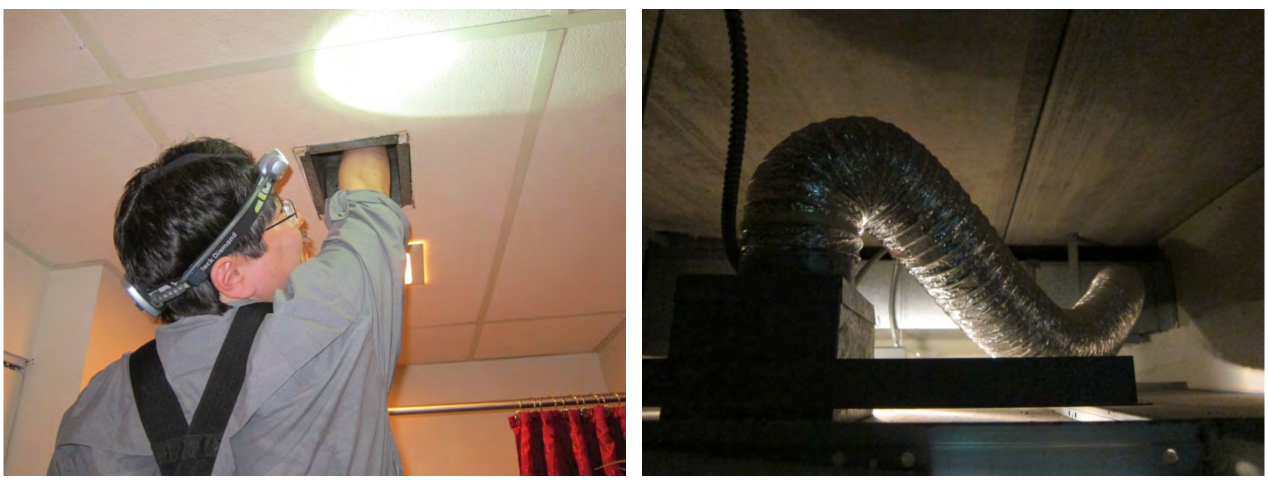

**Figure 17. Typical bathroom register (L) with flexible duct connection to exhaust trunk (R)**

The issues with the existing exhaust system are described by Innova (2011):

> *Rooftop ventilators are exhausting conditioned air 24/7, increasing demand on unit heating and cooling and depressurizing the apartments and corridors. "Stale" air is being drawn from corridors into apartments, rather than fresh air via infiltration points, as evidenced by tenant complaints of odors from other apartments.*

The rooftop corridor makeup air fan is not being run because of high operating costs, which contributes to these tenant odor complaints.

The options considered in the retrofit included unit-by-unit exhaust ventilation, HRV (either unit-by-unit or central), and the selected ventilation strategy (variable speed rooftop exhaust fans with intermittent unit exhaust fans).

### 3.3.1 Unit-by-Unit Exhaust-Only Ventilation

One alternative to this central exhaust system is to abandon or replace this system with individual unit-controlled ventilation in compartmentalized apartment units. Innova (2011) described this, shown in Figure 18, as an alternate measure that was not selected in this retrofit.

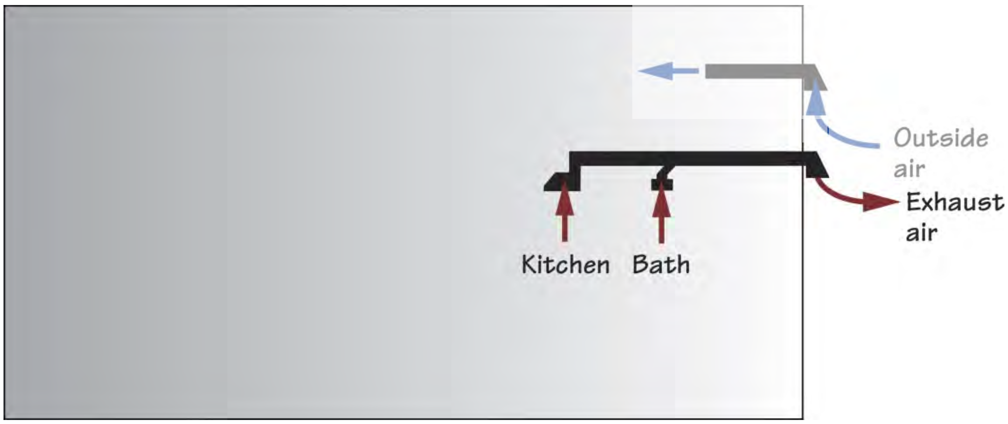


**Figure 18. Conceptual design of individual unit exhaust systems**

Innova's discussion of this alternative follows:

> *Localize Apartment Exhaust (Alternate to "Revise Apartment Exhaust"): weatherstrip and install sweep on apartment entry doors to isolate apartments from corridor; install ENERGY STAR bathroom and kitchen exhaust fans with backdraft dampers operated by an air cycler for each fan (basis of design: AirCycler SmartExhaust), programmed to produce 200% of the ASHRAE minimum ventilation requirement via infiltration; run individual ducts for each fan above unit drop ceiling where available and build a ceiling soffit through the apartment that will house both ducts leading them to an exterior mounted exhaust manifold; create one penetration on the exterior wall for the manifold vent; terminate vent with rainproof screened vent cap; air seal the abandoned riser seal risers; demo existing roof exhaust fan and patch roof, including insulation.*
>
> *Perform blower door-guided air sealing to ensure infiltration rate at no more than 200% of ASHRAE minimum ventilation for each apartment. Requires engineering to determine fresh air recharge requirements and supply rates.*

This alternative was rejected in the retrofit plan because it requires wall penetrations (with associated flashing) through the exterior wall of each unit. These penetrations add substantially to the cost, especially in a retrofit situation (as opposed to new construction, where there is no existing ductwork to use).

### 3.3.2 Heat Recovery Ventilation Options

Another high performance option is the use of HRVs, either on a unit-by-unit basis, or as a central system. As discussed in Section 2.3, this strategy can significantly reduce ventilation loads.

Individual unit HRVs (Figure 19), however, suffer from the same issue described for individual unit exhaust ventilation. Their installation costs are high in retrofit cases because of the requirement for outside penetrations.

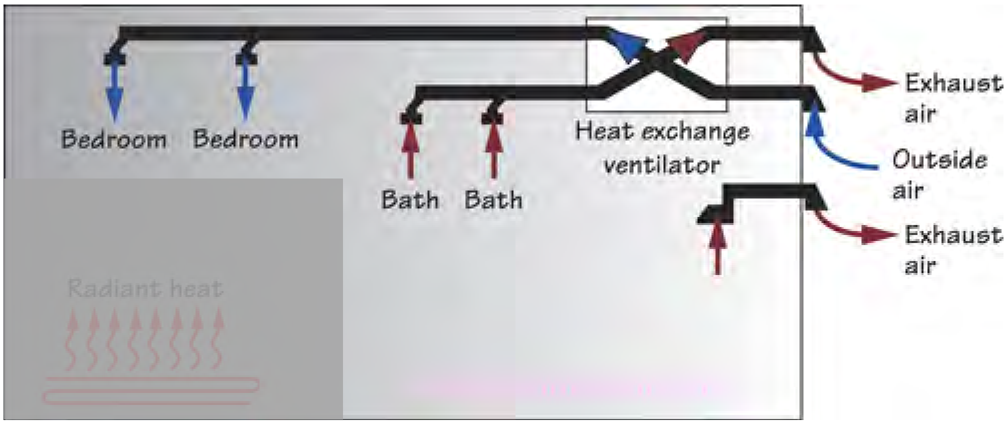


**Figure 19. Conceptual design of individual unit HRV ventilation**

A central HRV system can deliver excellent performance (with some caveats); however, it requires a fully ducted supply and exhaust system that connects each apartment unit to the rooftop unit (see Figure 20). Retrofitting a second set of ductwork into an existing building is typically not feasible in terms of cost. The representative images of a central HRV system in Figure 20 are from a different project (not the current Innova work).

**Figure 20. Rooftop HRV, with supply/exhaust ducts (L); supply and exhaust ductwork in corridor (R)**

### *3.3.3 Selected Ventilation Strategy*

The proposed retrofit was structured as follows (Innova 2011):

> *Revise Apartment Exhaust: weatherstrip and install sweep on apartment entry doors to isolate apartments from corridor;*
>
> *Install ENERGY STAR bathroom and kitchen exhaust fans with backdraft dampers operated by an air cycler for each fan (basis of design: AirCycler SmartExhaust or equal), programmed to produce 200% of the ASHRAE minimum ventilation requirement via infiltration;*
>
> *Inspect riser ducts and perform air sealing as required to minimize leakage.*
>
> *Remove existing 24/7 rooftop exhaust fans and replace with VFD-operated "mart" fans, controlled by pressure sensor that maintains a negative pressure in the riser with respect to the exterior in response to operation of apartment exhaust fans (basis of design: Greenheck Vari-Green motor and GreenVent pressure control system or equal).*
>
> *Perform blower door-guided air sealing of apartments to ensure infiltration rate at no more than 200% of ASHRAE minimum ventilation requirement. Requires engineering to determine fresh air recharge requirements and supply rates.*

To further explain this statement, the ventilation loads of the 24/7 constant-speed exhaust fans were reduced by replacing the rooftop fan units with variable-speed exhaust fans. These fans can be controlled manually or with a 0–10 VDC(volts direct current) control signal The plan described in the Innova (2011) excerpt is to use a pressure sensor to maintain constant negative pressure in the exhaust system ductwork (Greenheck Fan Corporation 2010):

> *Greenheck's GreenVent Constant Pressure Control System - This is a system of integrated controllers. The controllers will monitor the pressure in a duct and then appropriately adjust the speed of the fan to maintain a slight negative or positive pressure in the duct work. This system is very similar to what is also known as a MDVS or Modulating Dryer Venting System. A pressure tap measures the static pressure in a riser (chase) that has multiple fans or dryers blowing into it. As more of the fans are turned on, the pressure in the riser goes up. The pressure transducer signals the controller which then speeds up the Vari-Green fan.*

At the unit terminals, some possible system variants include the following:

- Constant airflow devices at the register terminals (American Aldes Constant Airflow Regulator or similar), which maintain a constant airflow over a wide range of static pressures, thus eliminating stack effect overventilation, and problems due to poorly balanced systems. This was the approach espoused by NAHBRC (2008) and Zuluaga and Fitzgerald (2010). These would be set to run at a constant exhaust rate, which would not make use of the variable speed features of the rooftop fan. In addition, they add static resistance to the system, increasing fan power consumption.

- Constant airflow devices, combined with motorized dampers (American Aldes ZRT Zone Control Exhaust Terminal or similar), controlled by wall switches and/or timers, to provide ventilation on an as-needed or timed basis. This would result in a ventilation flow which varies over the course of the day, which dovetails well with the use of a variable speed rooftop fan. Note that these are motorized dampers (which open and close), but with no fan at the unit terminals.
- Localized powered exhaust fans used at the apartment unit exhaust points, controlled by wall switch timers, to provide ventilation on an as-needed or timed basis. This would result in a ventilation flow which varies over the course of the day, which dovetails well with the use of a variable speed rooftop fan. The expected behavior was that there would be some leakage through the fan in its passive state, with increased flow when the fan is turned on.

The costs for motorized dampers with constant airflow devices were compared to those of individual unit exhaust fans. The prices were comparable; given the greater availability of high-quality ENERGY STAR-rated exhaust fans, this system was selected, as shown in Figure 21.

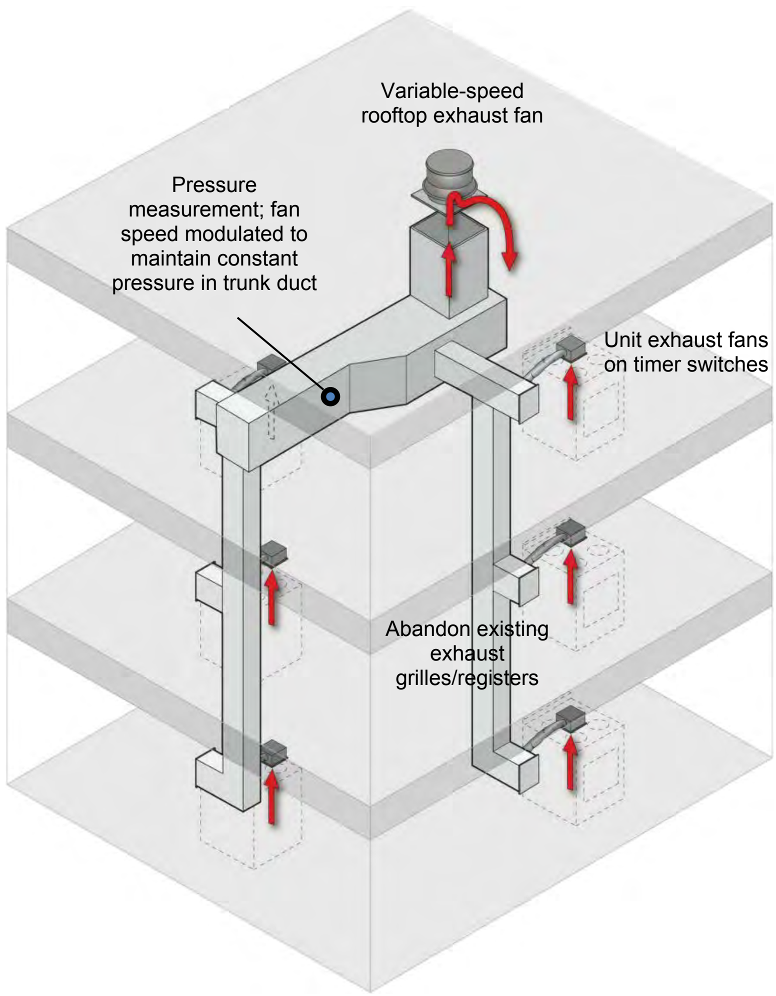


**Figure 21. Geometry of proposed exhaust system retrofit with individual exhaust fans**

The energy audit simulations (Innova 2011) examined the effect of this exhaust ventilation upgrade (see Figure 24 Item 11-Revise Apartment Exhaust). It showed a SIR value of 1.01 (meeting the Pennsylvania Housing Finance Agency's threshold of 1.0), with significant associated savings (691 MMBtu/yr or more than $10,000/yr).

### 3.4 Supply (Corridor) Ventilation Plan

The corridor makeup air system's original design supplied preheated air at the corridors via a centralized ductwork system. The corridor air is supplied by a rooftop-mounted gas-fired makeup air unit (MAU; see Figure 22), connected to a vertical shaft, which in turn feeds the corridors floor by floor through ceiling registers. This results in pressurized corridors, which in turn supply makeup air to units via undercut doors.

As noted in the energy audit report (Innova 2011), however, this system had been taken out of service because of excessive energy costs associated with direct heating of large volumes of makeup air (6,070 cfm constant airflow, 500 kBtu/h output, 5-hp blower motor). Furthermore, this rooftop unit provides no cooling. Finally, use of corridor pressurization has been documented to deliver poor distribution to dwelling units (Zuluaga and Fitzgerald 2010; Lstiburek 2005; CMHC 1999).

> *Existing rooftop make-up air unit has been disabled for approximately two years, resulting in poor indoor air quality and a fire safety hazard due to depressurization. (Innova 2011)*

**Figure 22. Nonoperational rooftop MAU**

The proposed retrofit to corridor ventilation was as follows (Innova 2011):

> *Corridor ventilation upgrade (Localize Corridor Ventilation): disable rooftop make up air system, insulate and air seal corridor supply registers and central corridor exhaust registers; install blocking and air sealing where supply and exhaust ductwork penetrates each floor.*
>
> *Create a wall penetration above the drop ceiling at the end of each corridor, install a PVC "T" open to the corridor, connected to the exterior penetration and the intake side of radon exhaust-type fan [in-line fan] (basis of design: Radon*

*Away GP201 or equal) to create a mix of conditioned corridor air and fresh outside air.*

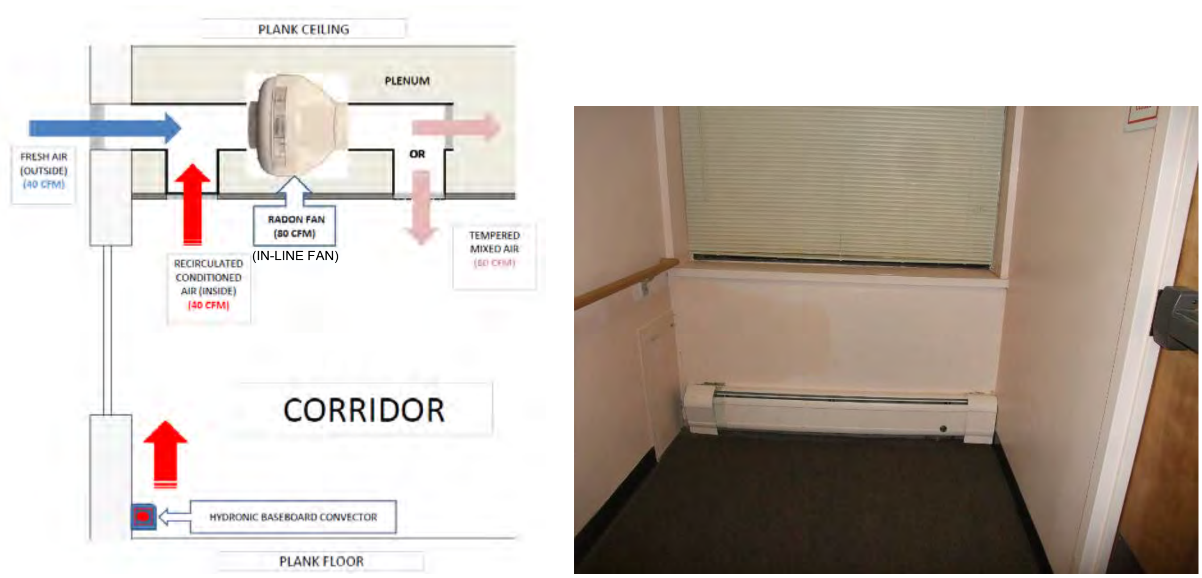


**Figure 23. Preliminary sketches of corridor ventilation (L), and corridor baseboard (R)**

The interior corridor air intake is placed near the hydronic baseboard at the ends of the corridors to boost the temperature of the recirculated air. The hydronic baseboard (shown in Figure 23, right) was an existing portion of the building's heating system.

*Distribute mixed air from an outlet using the drop ceiling as a plenum; replace one ceiling tile with a grate to distribute air to corridor.*

*Requires engineering to determine corridor loads and correct rate of supply (Innova 2011).*

This upgrade switches to floor-by-floor ventilation, tempering ventilation supply air with indoor air to avoid cold air complaints. Note that this upgrade abandons the multistory shafts, which are associated with stack-driven airflow problems (Lstiburek 2005).

The actual retrofit did not use the drop ceiling to distribute supply air as shown in Figure 23; instead, it was connected to the existing hallway supply ventilation ductwork and registers located within the drop ceiling. This ductwork was isolated from the central shaft to create floor-by-floor ventilation. In addition, the diagram shows a 1:1 dilution ratio (indoor:outdoor air). This was changed to a higher ratio during the planning process, to increase wintertime supply air temperature.

The summary of the energy audit simulations is given in Figure 24 (Innova 2011), with the corridor ventilation system highlighted. Although it only shows a SIR value of 0.3 (below the Pennsylvania Housing Finance Agency's threshold of 1.0), it is a health and safety measure, as noted in the audit. Furthermore, definite savings are associated with this measure (51 MMBtu/yr or $777/yr).

**Recommended Measures**

| | Measure Description | Qty. | Cost per Unit | Estimated Installed Cost | Annual Energy Savings | | Annual Energy Savings | | Annual Water/ Sewer Savings | | Annual Cost Savings | Simple Payback | S.I.R. (PV) | Life Cycle Savings | Measure Life |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | MMBTUh | $ | kWh | $ | 1000 gals | $ | $ | years | | $ | |
| | **Energy Saving Measures** | | | | | | | | | | | | | | |
| 1 | Low flow plumbing devices | 61 | $154 | $9,368 | 67 | 1,017 | 0 | 0 | 901.7 | $10,729 | $11,746 | 0.8 | 7.81 | $63,813 | 7 |
| 2 | Exterior lighting upgrade | 61 | $65 | $3,976 | 0 | 0 | 3,066 | 383 | 0.0 | $0 | $383 | 10.4 | 1.15 | $599 | 15 |
| 3 | LED Exit signs | 61 | $65 | $3,975 | -11 | -159 | 6,307 | 788 | 0.0 | $0 | $630 | 6.3 | 1.89 | $3,542 | 15 |
| 4 | CFL Package | 61 | $124 | $7,550 | -28 | -417 | 17,267 | 2,158 | 0.0 | $0 | $1,741 | 4.3 | 1.62 | $4,671 | 8 |
| 5 | Space heating boiler upgrade | 61 | $1,172 | $71,500 | 408 | 6,166 | 0 | 0 | 0.0 | $0 | $6,166 | 11.6 | 1.50 | $35,874 | 25 |
| 6 | Air sealing | 61 | $92 | $5,593 | 44 | 660 | 0 | 0 | 0.0 | $0 | $660 | 8.5 | 1.26 | $1,429 | 13 |
| 7 | Refrigerator upgrade | 61 | $629 | $38,381 | -47 | -706 | 33,489 | 4,186 | 0.0 | $0 | $3,480 | 11.0 | 1.08 | $3,163 | 15 |
| 8 | Stairwell lighting upgrade | 61 | $126 | $7,687 | -9 | -131 | 5,163 | 645 | 0.0 | $0 | $514 | 15.0 | 0.80 | -$1,553 | 15 |
| 9 | DHW boiler upgrade | 61 | $548 | $33,413 | 138 | 2,085 | 0 | 0 | 0.0 | $0 | $2,085 | 16.0 | 1.09 | $2,896 | 25 |
| 10 | Space heating loop distribution upgrade | 61 | $1,372 | $83,680 | 339 | 5,125 | 6,479 | 810 | 0.0 | $0 | $5,935 | 14.1 | 0.61 | -$33,053 | 10 |
| 11 | Revise Apartment Exhaust | 61 | $1,858 | $113,348 | 691 | 10,438 | 23,483 | 2,935 | 0.0 | $0 | $13,373 | 8.5 | 1.01 | $724 | 10 |
| | **Health & Safety Measures** | | | | | | | | | | | | | | |
| H1 | Corridor Ventilation Improvement | 61 | $616 | $37,563 | 51 | 777 | 0 | 0 | 0.0 | $0 | $777 | 48.4 | 0.31 | -$26,009 | 20 |
| H2 | Common area lighting upgrade | 61 | $253 | $15,433 | -16 | -236 | 9,583 | 1,198 | 0.0 | $0 | $962 | 16.0 | 0.74 | -$3,949 | 15 |

**Figure 24. Recommended measures and cost effectiveness (Innova 2011)**

## 3.5 Duct Sealing Options

A component of the test plan was to measure the existing exhaust riser ducts for air leakage; the retrofit plan included provisions for improving shaft airtightness:

> *Inspect riser ducts and perform air sealing as required to minimize leakage (Innova 2011).*

One option for air sealing is a remote shaft spray mastic system, developed by Consolidated Environmental, Inc., and shown in Figure 25. A segmented pole is lowered down through the rooftop fan opening; a remote camera allows inspection of the exhaust shaft for seams and penetrations. Targeted retrofit sealing is accomplished using spray-applied mastic, as shown in Figure 25 (right)


**Figure 25. Remote shaft-sealing spray mastic system**

***(Photo from Consolidated Environmental, Inc.)***

The exhaust duct system's geometry, however, was not amenable to this retrofit method (refer to Figure 21). The exhaust riser is not a straight vertical shaft. Instead, the shaft splits into multiple parallel risers, which would not be accessible from the rooftop opening.

An alternate duct sealing solution is the use of a commercially available aerosol-based duct sealing system, as described by Modera et al. (1996). This technique involves the injection of a fine aerosol spray of a vinyl-acetate (water-based) polymer that preferentially deposits on leakage locations (see Figure 26). The manufacturer furnishes studies showing significant reductions in exhaust shaft leakage (from 326 cfm 25 to 12 cfm 25 in a Boston-area study). Zuluaga and Fitzgerald (2010) present results showing a reduction from 220 cfm 25 to 19 cfm 25 in one building, and from 1,606 cfm 25 to 30 cfm 25 in another building. These results essentially tighten the ducts enough that leakage is close to insignificant.


**Figure 26. Aerosol duct sealing of residential HVAC system (L); with close-up of equipment (R)**

This premium performance, though, can have a high associated cost. On a project in eastern Pennsylvania, Innova was initially quoted a price for $6,000 per six-story shaft, for a building with 20 exhaust risers ($120,000 project cost for upgrade). The manufacturer of the aerosol duct sealing system commented that, based on the known information, this pricing is on the high side. In addition, another contractor subsequently gave a bid price of $1,000 per shaft. Noted that this price incorporated the aerosol sealant work into a larger scope of work.

# 4 Pre-Retrofit Performance Testing

BSC worked with Innova for 2 days of pre-retrofit performance testing on Mercy Douglass in mid-June 2011. The team measured exhaust shaft performance (including airflow, power draw, and duct leakage), and performed air leakage testing on individual units.

## 4.1 Exhaust Ventilation System

Exhaust shaft testing included duct air leakage testing, and airflow testing.

**Figure 27. Typical rooftop exhaust units (L); cover removed from exhaust fan (R)**

### *4.1.1 Exhaust Shaft Leakage Testing*

The exhaust shafts were then tested for air leakage, using fan depressurization and pressurization testing from the roof curb (Figure 28).

**Figure 28. Air leakage testing of exhaust fan (EF) shaft 5 (EF-5)**

Air leakage was measured at two shafts, with the following characteristics. The flow callouts are specified flows from the mechanical plan.

- EF-1: exhaust from six unit kitchens at 60 cfm each; 360 cfm at 0.30-in. external static pressure, 1/6-hp fan

- EF-5: exhausts from six unit bathrooms at 70 cfm each, and two common space bathrooms at 200 cfm each; 820 cfm at 0.50-in. external static pressure, ¼-hp fan.

Duct leakage testing was done with manual multipoint testing, with test pressures ranging from 60 Pa to 25 Pa. Initial testing on EF-1 revealed that pressurization testing tended to blow off register sealing tape. To avoid this problem, the team then chose to solely rely on depressurization testing. These exhaust shafts are run solely under negative pressure (unlike conventional HVAC systems, which have positive and negative pressures); therefore, depressurization testing should accurately capture operating leakage.

One shortcoming of the testing of EF-1 was that the installation of the connection plate (corrugated cardboard) covered the void spaces between the roof curb and the sheet metal duct; these voids or open corners are shown in Figure 29. As the dust marking patterns show, airflow from these corners influences airflow into the fan, reflecting the fact that leakage occurs in operation. Therefore, the measurement at EF-1 must account for this additional duct leakage. Given that the relative flexible cardboard was pulled flat against the open corners in depressurization testing, though, this leakage may be smaller than the physical size of these holes would suggest. EF-5 was tested with the connection solely to the metal duct (Figure 28).


**Figure 29. Open corners at exhaust shaft rooftop curb (L), with dust marking patterns (R)**

Significant leakage was noted around the duct boot attachment through gypsum board (similar to observations by Zuluaga and Fitzgerald [2010]); air leakage is evidenced by the dust deposition under the sheet metal register outline (see Figure 30, left). The junction from the sheet metal to drywall was sealed with foil tape (see Figure 30, right), and the shafts were retested.

**Figure 30. Kitchen exhaust boot-to-drywall as found (L) and retrofit seal (R) state**

Testing continued with EF-5; however, one shortcoming of this testing was that inadvertently, the spring-operated louvers at the top of the exhaust shaft were not blocked open, as was done on EF-1 (see Figure 31). In operation, these louvers normally open because of fan negative pressure. The louvers are designed to close if the fan loses power.

The flow versus depressurization curve obtained at EF-5 demonstrated that the louvers were closing incrementally as the multipoint fan depressurization dropped from 60 Pa to 25 Pa. As a result, multipoint testing from this shaft was ignored and only the highest pressure was used, assuming that the louvers were at their most open position at this test point.

**Figure 31. Spring-loaded louvers on exhaust fan rooftop curb blocked open at EF-1 testing**

The multipoint air leakage test for EF-1 is shown in Figure 32; it is evident that leakage was decreased substantially by sealing the kitchen exhaust boots to the gypsum board.

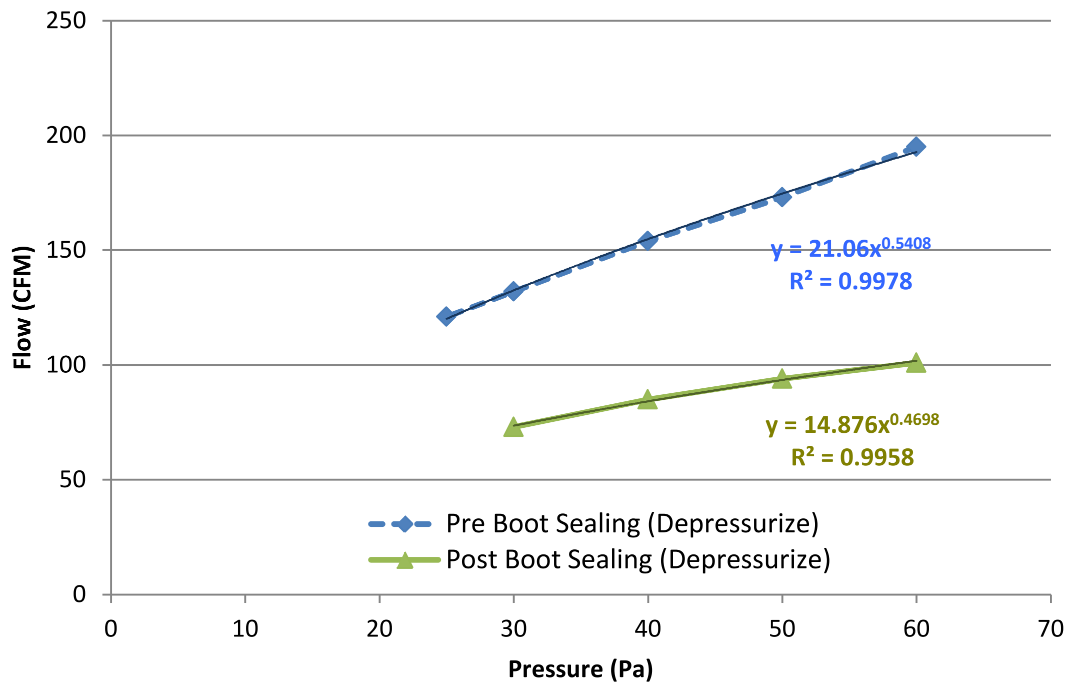


**Figure 32. Multipoint air leakage data for EF-1 with pre- and post-register boot sealing**

To interpret the data, the shaft leakage rates can be quantified relative to metrics proposed by Zuluaga and Fitzgerald (2010), shown in Table 2. Note that the metric used is cfm at 50 Pa test pressure (cfm 50), divided by the number of floors served.

**Table 2. Exhaust Shaft Leakage Qualitative Guidelines**

| Description | Metric |
|---|---|
| "Good" | 5 cfm 50/floor |
| "Typical" | 10 cfm 50/floor |
| "Bad" | 15+ cfm 50/floor |

Source: Zuluaga and Fitzgerald (2010)

Based on test data, cfm 50 values were calculated. Table 3 shows the results, normalized both by number of floors and by nominal flow (as per mechanical plans, not measured flow).

**Table 3. Shaft Air Leakage Measurements With Register Boots Unsealed and Sealed**

| Shaft | cfm 50 (Unsealed) | cfm 50 per Floor (Unsealed) | cfm 50% of Flow (Unsealed) | cfm 50 (Sealed) | cfm 50 per Floor (Sealed) | cfm 50% of Flow (Sealed) |
|---|---|---|---|---|---|---|
| EF-1 (Kitchen) | 175 | 58 | 49% | 93 | **31** | 26% |
| EF-5 (Bath) | 175 | 58 | 21% | 103 | **34** | 13% |

In all cases, the exhaust shaft leakiness was substantially worse than the bad metric provided by Zuluaga and Fitzgerald (roughly double the value). Although the sealing of the boots improved shaft tightness substantially, it is still above typical levels. These shaft metrics, though, are not a completely fair comparison, given the geometry of the shafts at this building. The two parallel risers are a system with more joints and surface area compared to straight vertical shafts. Normalizing leakage by the number of floors served gives no normalization for serving multiple exhaust points per floor; the metrics in Table 2 were developed assuming minimal lateral distribution. A metric of cfm 50 leakage as a percentage of nominal flow, which normalizes for system size, might be an alternate metric to consider. This would be analogous to metrics used in residential HVAC duct system leakage testing.

These cfm 50 numbers can be translated into EqLA (Equivalent Leakage Area, a Canadian General Standards Board-developed metric at 10 Pa), to provide an order of magnitude of the aggregate hole size. For the post-sealed boot state, the EqLA values were 9.6 $in^2$ (EF-1) and 10.6 $in^2$ (EF-5).

The decrease in shaft leakage associated with sealing the bathroom shaft boots (EF-5) was smaller than in the kitchens (EF-1), given that the registers were through suspended ceilings tiles (not gypsum board), with a limited ability to improve the seal.

Examination of the ductwork revealed that the sheet metal joints were sealed with limited amounts of mastic (see Figure 33); however, there were many other unsealed joints, as well as inaccessible joints, which would have been difficult to seal during construction.

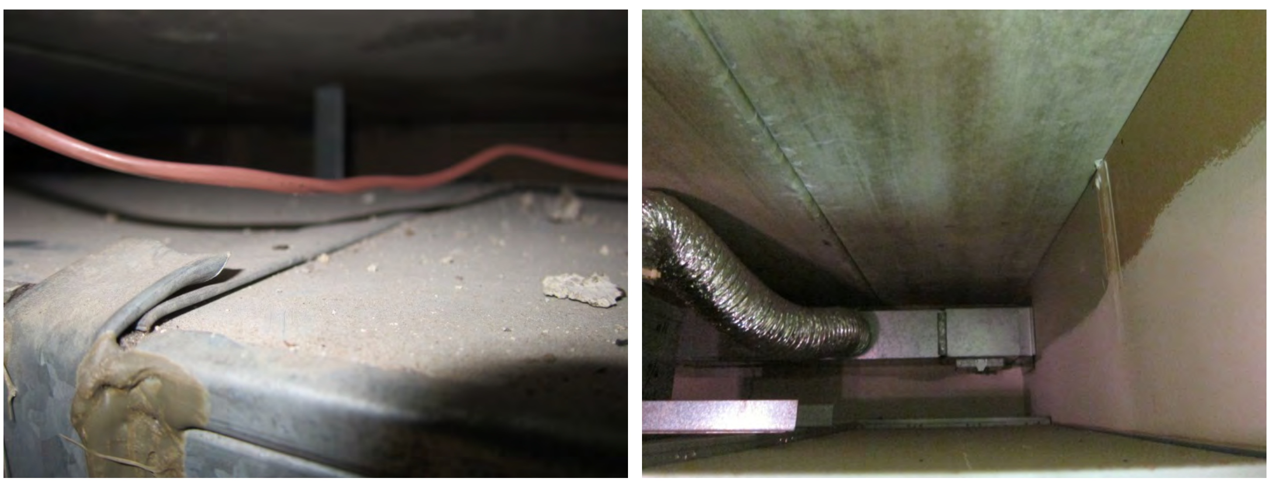

**Figure 33. Limited mastic sealing at sheet metal joints (L); connection to flex runouts (R)**

The geometry of the shafts is such that "remote sealing" (refer to Figure 25) from the rooftop shaft access is not a viable option. The ductwork immediately turns and branches into two parallel risers after entering the building, eliminating the direct access seen in other buildings. Either manual sealing of the accessible ductwork (with limited improvement) or aerosol sealing (see Figure 26) would appear to be the only available options.

### *4.1.2 Exhaust Airflow Testing (Rooftop Units)*

Exhaust fan airflow testing included airflow at both the rooftop units and at individual exhaust grilles within the units. The results of these tests were then correlated with each other.

Rooftop exhaust fans were measured using a powered flow capture enclosure or box, with a pressure nulling method (see Figure 34). This is essentially an expanded version of methods described by The Energy Conservatory (2001). The use of a powered flow capture hood eliminates insertion losses (common with nonpowered hoods), which is the change in actual airflow resulting from the increased pressure resistance from inserting the measurement device.

The capture enclosure is constructed from rigid board insulation and a light lumber frame, with all joints taped. The open side is sealed to the roof with foam gasket material on the edges, with weights added to the enclosure to compress the gaskets. The gravel ballast is removed at the roof deck to improve the air seal.


**Figure 34. Powered flow capture enclosure for rooftop exhaust fans showing construction**

A calibrated fan is connected to an opening in the enclosure, set up to depressurize. A static pressure probe is installed to measure the pressure within the enclosure (see Figure 35, left); the fan is adjusted to a zero pressure with respect to (WRT) ambient. This “pressure nulling” method relies on the fact that when the airflow into a closed container is equal to the airflow out, the pressure difference of the enclosure to ambient will be zero. The flow through the calibrated fan is then recorded as the flow from the rooftop exhaust fan.

**Figure 35. Static pressure probe in enclosure (L); measurement of bypass leakage (R)**

One potential source of inaccuracy is leakage at the gasketed seal at the roof deck, given the irregular surface of the built-up roof. One advantage of this nulling method, however, is that there is minimal pressure difference (zero target) across this gasket. This was corroborated by a measurement of zero velocity at the seal during testing (Figure 35, right).

Another source of inaccuracy that affected results was that to null the enclosure to a zero pressure, a constant reference pressure is preferred. Unfortunately, during the testing, wind gusting resulted in pressure variations, so time averaging was required to obtain results. Wind variations were slightly reduced by placing the reference pressure tap in a semishielded roof mechanical penthouse.

The following exhaust fans were tested for airflow; they included those tested for duct leakage (EF-1 and EF-5), as well as an additional unit (EF-2):

- EF-1: exhaust from 6 unit kitchens at 60 cfm each;
  360 cfm at 0.30-in. external static pressure, 1/6-hp fan
- EF-2: exhaust from 12 unit bathrooms at 70 cfm each; 840 cfm at 0.37-in. external static pressure, ¼-hp fan
- EF-5: exhausts from 6 unit bathrooms at 70 cfm each and
  2 common space bathrooms at 200 cfm each; 820 cfm at 0.50-in. external static pressure, ¼-hp fan.

In addition, amperage and voltage of the fan were measured (see Figure 36, left), which were used to calculate apparent power (volt-amps [VA]). If an assumed power factor of 0.85 is applied, this gives an estimate of true power (in watts). This allows cubic feet per minute per watt to be calculated for these fans. Table 4 presents the results.

At EF-2, the initial results were far below the rated flow; examination of the fan revealed that the fan belt was cracked and extremely loose (see Figure 36, right, and EF-2 (Bath)-Loose in Table 4). A second set of measurements was taken with the belt tightened (EF-2 (Bath)-Tight in Table 4). Power measurements were taken only after tightening the belt.

**Table 4. Exhaust Fan Airflows (via Rooftop Capture Hood) With Power Draw Estimates**

| Shaft | cfm | Amps | Volts | VA (Apparent Power) | Watts (True Power) | cfm/W |
|---|---|---|---|---|---|---|
| EF-1 (Kitchen) | 480 | 3.60 | 119 | 428 | 364 | 1.3 |
| EF-2 (Bath)-Loose | 250 | – | – | – | – | – |
| EF-2 (Bath)-Tight | 540 | 3.80 | 119 | 452 | 384 | 1.4 |
| EF-5 (Bath) | 720 | 3.40 | 119 | 405 | 344 | 2.1 |

**Figure 36. Measurement of amperage draw (L); loose fan belt at EF-2 (R)**

### *4.1.3 Exhaust Airflow Testing (Unit Exhausts)*

Exhaust register airflows were measured at two locations in each accessible unit (kitchen and bathroom), in 12 units in the building (see Figure 37). All units in the building are one bedroom or studio units; each has a wall exhaust register in the kitchen (60-cfm callout on plans), and a ceiling exhaust register in the bathroom (70-cfm callout on plans). Both are set to run continuously at these flows. Measurements were completed using a flow capture hood (a nonpowered thermo-anemometer-based unit).

**Figure 37. Airflow testing of unit exhausts with flow capture hood; kitchen (L) and bath (R)**

The exhaust shafts are set up so that any given exhaust fan only handles kitchens or bathrooms; the registers are "ganged back" to back to draw from units (see Figure 38 for individual shaft geometry and refer to Figure 16 for floor plan and shaft layout). Consequently, access to these apartment units provided complete flows for two exhaust shafts (EF-1 and EF-5), and incomplete flows for two additional exhaust shafts (EF-2 and EF-6; see Figure 16).

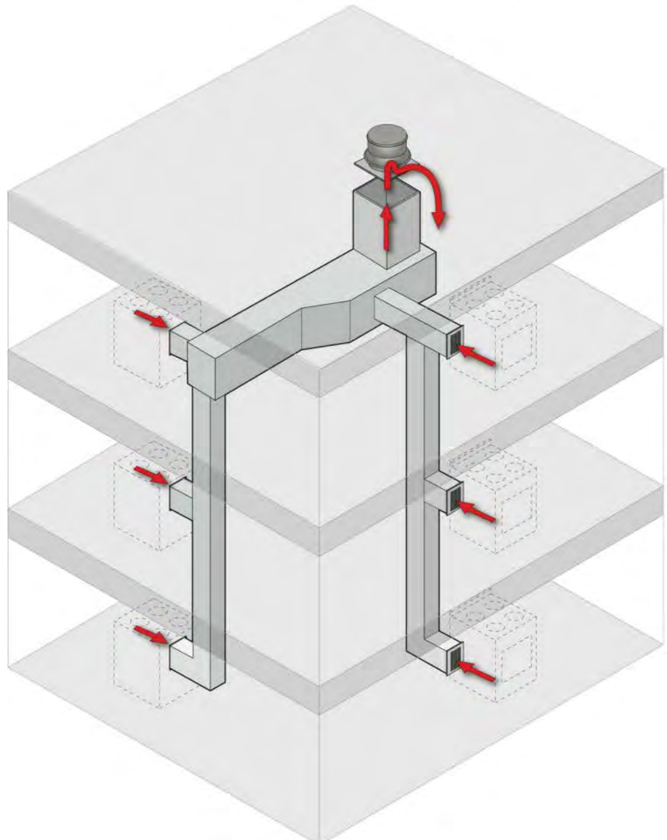

**Figure 38. Geometry of EF-1 (kitchen) shaft (six back-to-back kitchens)**

These results were tabulated and compared to the plan callouts, as shown in Figure 39 and Figure 40.

- Average unit exhaust airflow (kitchen + bathroom) was 96 cfm (±18 cfm, 1 standard deviation), ranging from 68 to 121 cfm.
- The plan callouts are for 130-cfm continuous exhaust per unit (70-cfm bathroom + 60-cfm kitchen); all units were measured lower than this level.
- The airflows can be compared to the ASHRAE 62.2 rates (ASHRAE 2010b; assuming no or one bedroom), which range from 15- to 25-cfm continuous flow.
- The airflows can be compared with ASHRAE 62.1 rates (ASHRAE 2010a), which range from 45- to 60-cfm continuous flow.

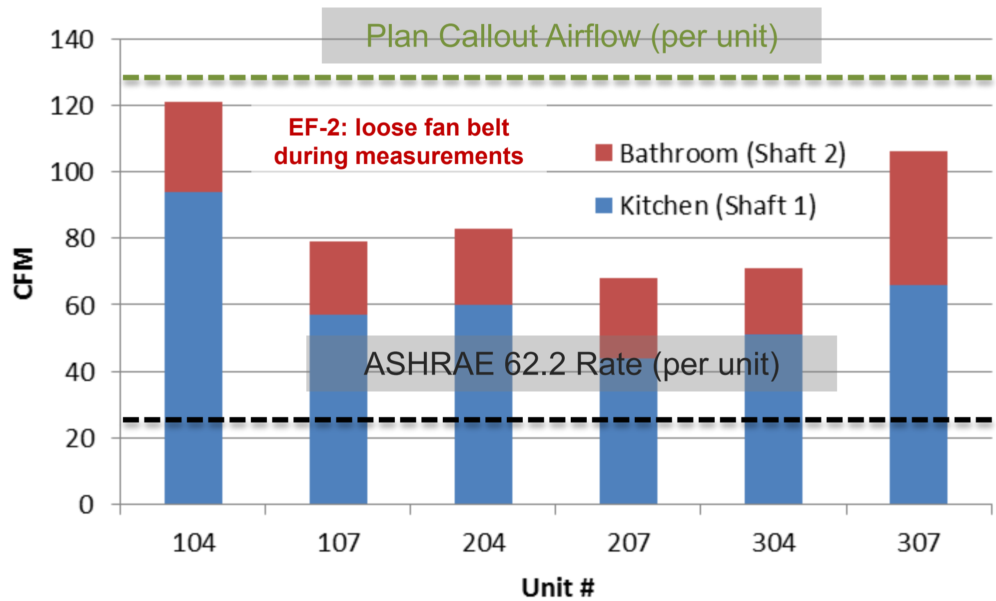


**Figure 39. Unit airflows for bathroom and kitchen exhaust fans, shafts 1 and 2**

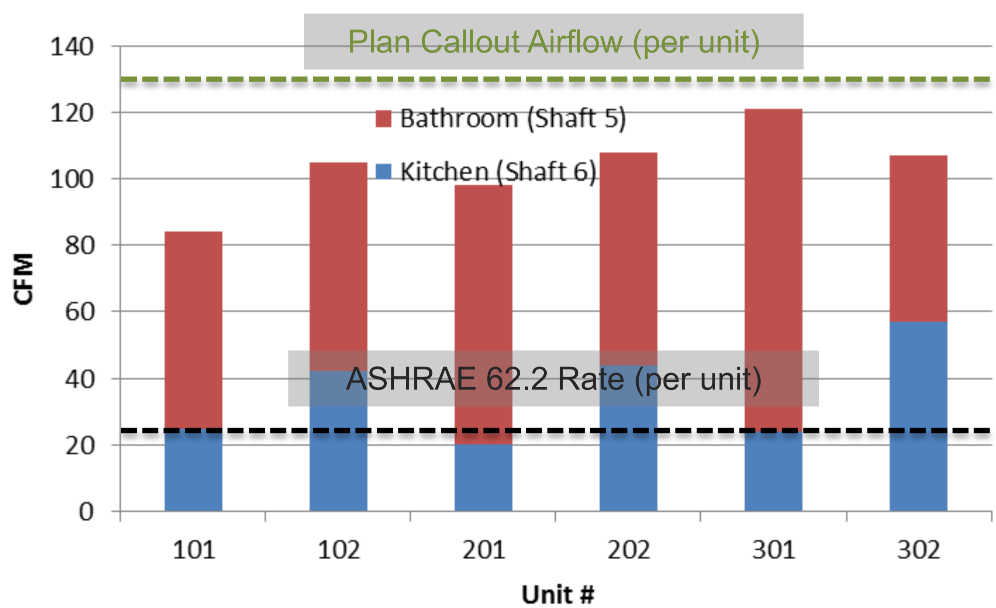


**Figure 40. Unit airflows for bathroom and kitchen exhaust fans, shafts 5 and 6**

For reference, the ASHRAE 62.1 and 62.2 rates for a selection of apartment units are given in Table 5. Note that figures are given for both 62.1-2007 and 62.1-2010.

Overall, airflows are consistently lower than plan callouts, but much higher than ASHRAE 62.2 requirements (resulting in a significant increase in energy consumption). On one shaft, the rooftop exhaust unit had an extremely loose fan belt (refer to Figure 36), resulting in very low flows (EF-2, 26-cfm/register measured typical, versus 70-cfm/register callout). EF-6 appears to have a low flow condition as well, but the rooftop exhaust was not inspected.

**Table 5. ASHRAE Standard 62.1 and 62.2 ventilation flows for selected units**

| Unit | Bedrooms | ASHRAE 62.2-2010 | ASHRAE 62.1-2007 | ASHRAE 62.1-2010 |
|---|---|---|---|---|
| **108** | 0 | 13 | 31 | 46 |
| **121** | 1 | 24 | 46 | 63 |
| **202** | 1 | 24 | 45 | 62 |
| **208** | 1 | 21 | 31 | 46 |
| **304** | 1 | 24 | 46 | 62 |
| **307** | 1 | 24 | 45 | 61 |

Source: ASHRAE (2010a, 2010b)

No particular pattern was seen in the distribution of exhaust flows. A common problem is overventilation of upper floor units (close to the rooftop fan) versus underventilation of lower floor units. Temperatures during these measurements, though, were close to interior temperatures (60°–80°F), indicating that stack effect-driven airflow would be minimal (2–5 Pa).

#### *4.1.4 Exhaust Airflow and Duct Leakage Analysis*

The individual unit exhaust flows and rooftop exhaust fan flows were graphed together for the two shafts that were completely measured (EF-1 and EF-5), as shown in Figure 41 and Figure 42. The unit exhausts were summed and the difference between this total and the rooftop fan was assumed to be duct leakage from interior interstitial spaces. This difference is referred to as "calculated leakage," and is shown as "Leakage" (with a dotted outline) in the graphs below.. Total exhaust fan airflows were in the range of 80%–85% of the unit total airflows, with the missing 15%–20% of flow assumed to be the operating duct leakage.

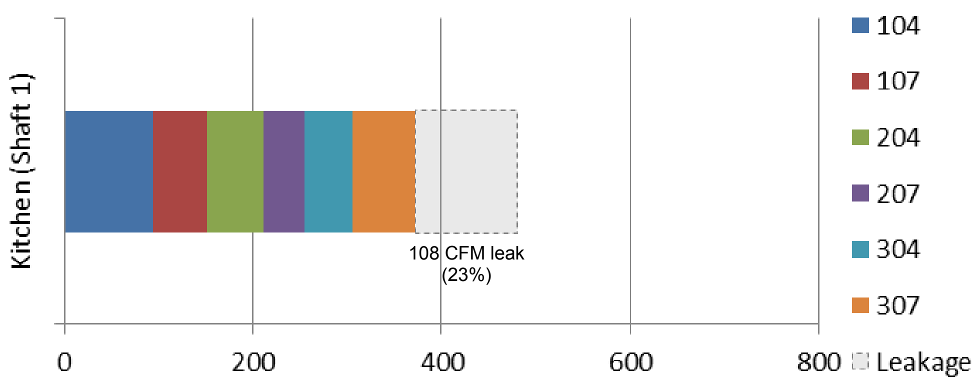


**Figure 41. Unit airflows compared to rooftop fan airflow, EF-1 (kitchens)**

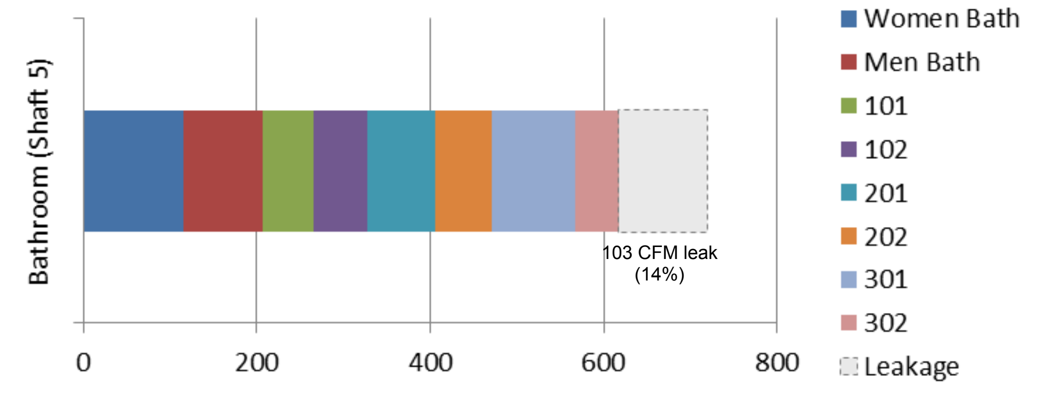


**Figure 42. Unit airflows compared to rooftop fan airflow, EF-5 (bathrooms)**

Although unit and rooftop flows were measured for EF-2, the unit measurements were taken before tightening the fan belt. As a result, calculations from these measurements would be mostly irrelevant.

Table 6 compares these calculated leakage figures and the measured leakage (using depressurization testing with the register boots sealed, called out as “dep. test”).

**Table 6. Comparison of Shaft Air Leakage Measurements and Calculated Leakage**

| Shaft | cfm 50 (Dep. Test) | cfm 50 per Floor (Dep. Test) | cfm 50 % of Flow (Dep. Test) | Calculated Leakage (cfm) | Rooftop Sirflow (cfm) | Calculated Leakage % of flow |
|---|---|---|---|---|---|---|
| **EF-1 (Kitchen)** | 93 | 31 | **26%** | 108 | 480 | **23%** |
| **EF-5 (Bath)** | 103 | 34 | **13%** | 103 | 720 | **14%** |

The results are surprisingly comparable, given the uncertainties in these measurements. This could be considered evidence (admittedly inconclusive) that exhaust shaft cfm 50 measurements are comparable to operating leakage, assuming that low static pressure connections (such as the register boots) are sealed.

The measured airflows (rooftop and unit) can be compared to the nominal callouts from the plans, as shown in Table 7. Note again that at EF-2, the unit flows were measured before fan belt tightening and the rooftop unit was measured after belt tightening. As a result, only the latter is shown.

There is substantial variation above and below the callout/nominal flows. On average, unit flows are below callouts (78%), and rooftop unit flows are above callouts (109%). This shows the effect of exhaust shaft duct leakage, which results in excess air removal (with an associated energy penalty) to meet minimum exhaust flow requirements.

**Table 7. Comparison of Measured Airflows and Nominal Plan Callouts**

| Shaft | Nominal Callout (cfm) | Unit Sum Measured (cfm) | Unit Flow % of Callout | Rooftop Measured (cfm) | Rooftop Flow % of Callout |
|---|---|---|---|---|---|
| EF-1 (Kitchen) | 360 | 372 | 103% | 480 | 133% |
| EF-2 (Bath) | 420 | – | – | 540 | 129% |
| EF-5 (Bath) | 820 | 617 | 75% | 720 | 88% |
| EF-6 (Kitchen) | 360 | 212 | 59% | – | – |
| Weighted Average | | | **78%** | | **109%** |

## 4.2 Unit Air Leakage Testing

Unit air leakage was tested with depressurization testing. A blower door was installed in the unit's doorway to the corridor, and the corridor was connected to the exterior by opening the rooftop door to provide pressure relief (see Figure 43). Six units were tested. The sample included top- and middle-floor units, and both corner and middle units. The relative geometry of the tested units is shown in the sample floor plan (Figure 44).

These tests only measured total leakage of the units (both to interior and exterior). Nulling testing was not performed because of access and timing issues. Nulling testing would have isolated leakage to the exterior from interunit leakage (i.e., compartmentalization failures).

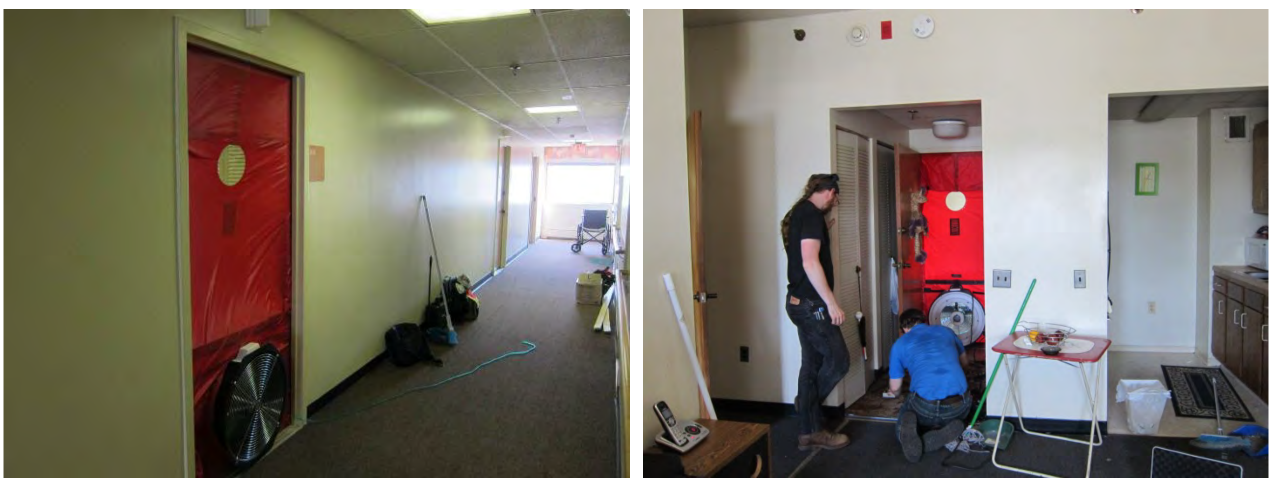

**Figure 43. Air leakage testing of units from hallway (L) and interior of unit (R)**

The results are shown in Table 8 in raw form (cfm 50), as well as normalized by volume (air changes per hour at 50 Pa [ACH 50]) and surface area (cfm 50/ft$^2$ of unit enclosure). There are a variety of exposures and unit sizes; the area exposed to the exterior is also calculated for reference (including wall and roof area).

**Table 8. Unit Airtightness Measurements With Normalized Leakage**

| Unit | cfm 50 | Floor Area | Volume ($ft^3$) | Surface Area ($ft^2$) | Surface Area-Exterior ($ft^2$) | ACH 50 | cfm 50/$ft^2$ Enclosure |
|---|---|---|---|---|---|---|---|
| **108** | 939 | 597 | 5,375 | 2,103 | 81 | 10.5 | 0.45 |
| **121** | 1,104 | 883 | 7,945 | 2,838 | 248 | 8.3 | 0.39 |
| **202** | 1,094 | 861 | 7,747 | 2,782 | 242 | 8.5 | 0.39 |
| **208** | 885 | 597 | 5,375 | 2,103 | 81 | 9.9 | 0.42 |
| **304** | 1,216 | 871 | 7,838 | 2,807 | 1,404 | 9.3 | 0.43 |
| **307** | 1,246 | 855 | 7,693 | 2,768 | 1,091 | 9.7 | 0.45 |

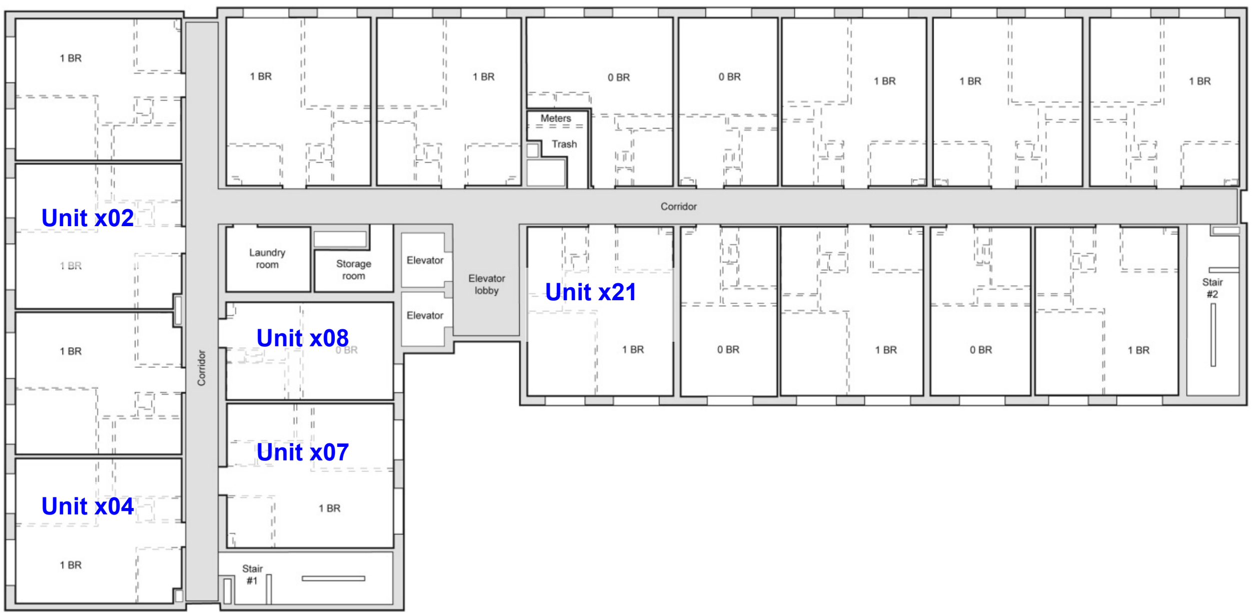


**Figure 44. Tested units highlighted on typical floor plan**

The results were relatively consistent between units. Average leakage was 9.4 ACH 50 (±0.8, 1 standard deviation), or 0.42 cfm 50/$ft^2$ enclosure surface area (±0.03, 1 standard deviation). There did not appear to be any significant correlation between unit exposure (corner versus middle, or lower floor versus upper floor) and overall air leakage.

These results can be compared, for instance, with the Leadership in Energy and Environmental Design Mid-Rise compartmentalization leakage metrics of 7.0 ACH 50 (basic prerequisite), and 4.0 ACH 50 (credit for ETS control). Another comparison is Lstiburek's (2005) recommendations for compartmentalization of 0.30 cfm 50/$ft^2$ enclosure surface area. It is clear that the air leakage of these units (mid-1980's construction) is higher than recommended levels.

Although this is an admittedly limited sample, these measurements do not corroborate the observations of CEE (2004). In that study, the investigators measured large differences between units within the same building (factor of two air leakage difference between leakiest and tightest). The CEE researchers observed this large range of leakage only at some of their test buildings (four out of six).

In addition, in the BSC/Innova study, interzonal pressure measurements/mapping was used to characterize the leakage paths in these units, as shown in Figure 45.

**Figure 45. Interzonal pressure measurements (suspended ceiling, L; mechanical access, R)**

The results for three dwelling units are shown in Tables 9, 10, and 11. All measurements were conducted with the unit at 50 Pa with respect to (WRT) the exterior; the pressure difference/ΔP is the interstitial space with respect to the dwelling unit.

**Table 9. Interzonal Pressure Difference Measurements, Unit 307 (WRT Interior Space)**

| Location | Pressure Difference/ΔP |
|---|---|
| Suspended Ceiling, Kitchen | 25 Pa |
| Suspended Ceiling, Bathroom | 25 Pa |
| Shaft Around Kitchen Exhaust | 29 Pa |
| Demising Wall Stud Cavity | 34 Pa |

**Table 10. Interzonal Pressure Difference Measurements, Unit 304 (WRT Interior Space)**

| Location | Pressure Difference/ΔP |
|---|---|
| Suspended Ceiling, Kitchen | 37 Pa |
| Suspended Ceiling, Bathroom | 37 Pa |
| Shaft Around Kitchen Exhaust | 36 Pa |
| Demising Wall Stud Cavity | 40 Pa |
| Mechanical Access Hatch | 40 Pa |
| Tee Wall Electrical Penetration | 9 Pa |

**Table 11. Interzonal Pressure Difference Measurements, Unit 208 (WRT Interior Space)**

| Location | Pressure Difference/ΔP |
|---|---|
| Suspended Ceiling, Bathroom | 29 Pa |

Conclusions from these measurements included the following:

- The space above the suspended ceilings is significantly outside of the unit's air barrier (50%–75%). As a result, the leaky ceiling tile plane inadvertently forms a significant portion of the unit's air barrier. This also implies that significant air leaks are present in the space above the suspended ceiling (to adjacent units or exterior).
- The rated shaft around the kitchen exhaust ductwork is significantly (60%–70%) outside of the unit; therefore, any holes connecting the unit to the space inside the shaft will result in a loss of compartmentalization.
- The space within the mechanical chase at the perimeter of the top floor (the mechanical access hatch seen in Figure 45) is significantly outside of the unit's air barrier (~80%). This measurement does not differentiate, however, whether leakage is to adjacent units or to the exterior (via an air barrier failure to the roof). Given the construction of the detail (see Figure 46), it is quite possible that this is leakage to the parapet, to the outdoors, or both. This leakage could be a significant energy penalty.
- The unit interior partition wall is substantially (82%) within the unit in terms of air barrier continuity.

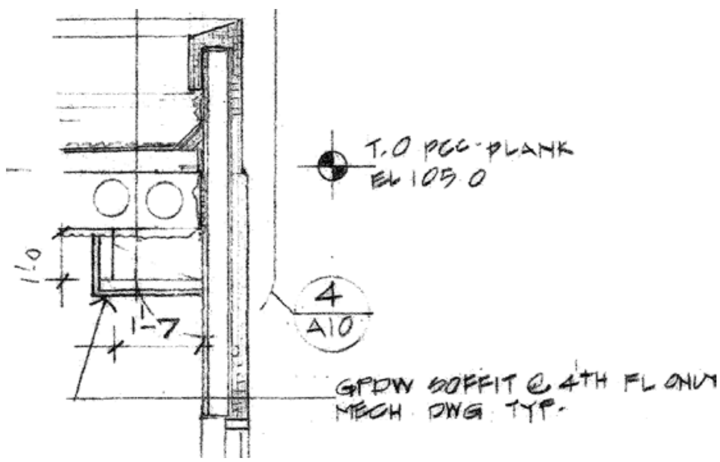


**Figure 46. Top floor mechanical soffit and parapet detail (Section A10.10)**

Figure 47 shows some examples of the lack of air barrier continuity above the suspended ceiling.

**Figure 47. Lack of air sealing at demising wall to concrete plank (L) and pipe penetration (R)**

Although the rated demising wall gypsum board correctly extends to the underside of the concrete plank floor, there is no fire caulking or other sealing detail at the connection between these two air barrier components (Figure 47, left). In addition, there are significant compartmentalization air barrier failures at mechanical penetrations, such as plumbing pipes (Figure 47, right) and duct penetrations (Figure 48).

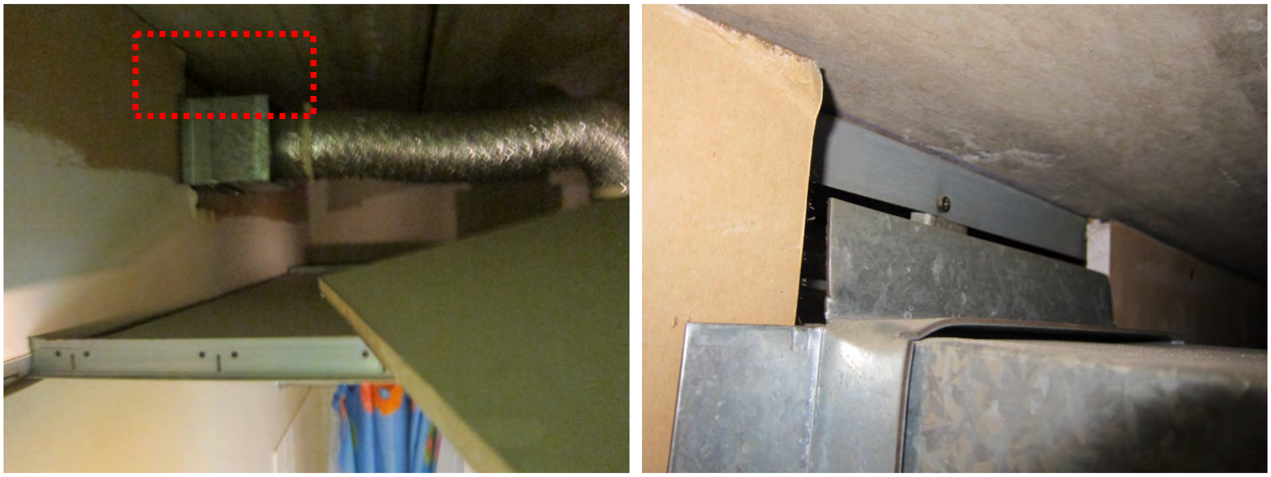

**Figure 48. Exhaust duct penetration at demising wall, showing lack of air barrier continuity**

Given the construction of the floor/ceiling assembly (hollow core concrete plank), it is assumed that the floor plane is relatively airtight, except at the penetrations such as plumbing and mechanical penetrations and shafts.

Retrofit air sealing between units would benefit indoor air quality and unit compartmentalization; this could be performed in an accessible but hidden space (dropped ceiling). For instance, a liquid spray-applied fire-rated sealant (see Figure 49 for an example from another project, not Mercy Douglass) could be used to retrofit fire continuity to the rated assembly, as well as create a more effective air barrier.

**Figure 49. Liquid spray-applied fire-rated sealant**

Building management was unaware of these legacy construction deficiencies; they have since been apprised of their extent and importance.

# 5 Post-Retrofit Performance Testing

BSC worked with Innova on post-retrofit performance testing of Mercy Douglass in mid-November 2011 (one prototype shaft), and again in June 2012. The team measured exhaust shaft performance (including airflow, power draw, and duct leakage) on several shafts retrofitted with variable-speed pressure-controlled exhaust fans. The corridor supply fans were characterized and interunit pressure measurements were taken. Fan speed monitoring equipment was installed on two rooftop exhaust fans. Data were collected for 5 months.

## 5.1 Exhaust Ventilation System

The site work on the exhaust system included inspecting the installed system, measuring the airflow of the rooftop exhaust fan and the unit exhaust fans, and installing data monitoring equipment on the exhaust fan controllers.

### *5.1.1 Exhaust Ventilation System Retrofit Overview*

Figure 50 depicts a retrofitted rooftop exhaust fan with a variable-speed electronically commutated motor (ECM) (described earlier).


**Figure 50. Variable-speed exhaust fan with cover removed (L), with controller box (R)**

Note that it is a direct-drive (not belt drive) unit, which eliminates the belt maintenance and low-airflow issues discovered during pre-retrofit testing.

The control system includes the control box (Figure 50, right), which controls the fan speed. The controller receives input in turn from a pressure transducer, which measures trunk duct pressure (Figure 51). The same model rooftop fan was used in all cases. The controller can be set to a target speed (or duct pressure and flow) to match each shaft's required flow.


**Figure 51. Duct pressure transducer and static pressure probe on top floor trunk duct**

The exhaust registers were replaced with ceiling-mounted individual exhaust fans in the kitchens and bathrooms, controlled by an occupant-operable timer switch (see Figure 52). The concept is that with the unit fan turned off, passive flow (induced by the rooftop unit) occurs through the unit fan. When the unit exhaust fan is turned on, the exhaust rate is boosted from the passive flow level, with the rooftop exhaust fan maintaining negative pressure in the ductwork.

The bathroom fans are hard-wired to the lights, to activate the fan when the bathroom is occupied. The kitchen fans are controlled by an independent wall switch. The timer duty cycle was not set during field work. The timed flow should be adjusted to cycle the unit exhaust fans to meet ASHRAE 62.1 or 62.2 (2010a, 2010b) requirements. The setting can be determined based on the measured airflows.


**Figure 52. Bathroom dwelling unit exhaust fan (L) and controller timer switch (R)**

### *5.1.2 Exhaust Ventilation Airflow Testing (Rooftop Unit)*

Rooftop exhaust fan airflows were measured with the same flow capture enclosure used in the pre-retrofit measurements, as shown in Figure 53. Multiple exhaust shafts were measured during the two trips.

One difference, however, was that the flow measurements were run using automated controls and software available from the testing equipment manufacturer (see Figure 54). The system was set to modulate the calibrated fan pressure to achieve a zero pressure difference between the flow capture hood and ambient conditions. One advantage of this system is that it yields a complete record of the test period (shown below in Figure 57 and Figure 58).

**Figure 53. Powered flow capture hood, showing duct testing fan**

**Figure 54. Computerized flow capture hood testing (L), showing manometer (R)**

One observation during this testing was that cold ambient conditions during the November trip allowed an infrared camera to be used to locate air leakage. Specifically, a concern with the rooftop flow capture enclosure is that bypass leakage is occurring at the seal between the enclosure and the roof deck. Infrared images, though, showed no clear signal of outward warm air leakage at this joint (see Figure 55). Inward leakage, however, would not be visible. Note that the reflective low-emissivity foil facing of the rigid foam insulation creates infrared reflections in this image.

The lack of air leakage is consistent with the fact that the net zero pressure between box and ambient conditions would minimize the leakage. For comparison, Figure 56 shows an infrared image of the heated air leaving the calibrated fan.

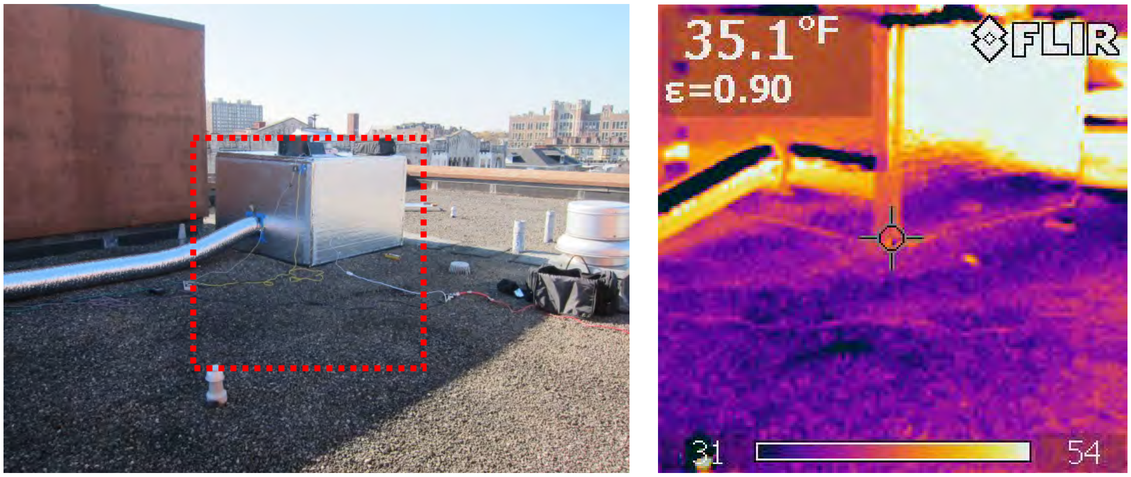


**Figure 55. Powered flow capture hood with infrared, showing minimal leakage at seal**

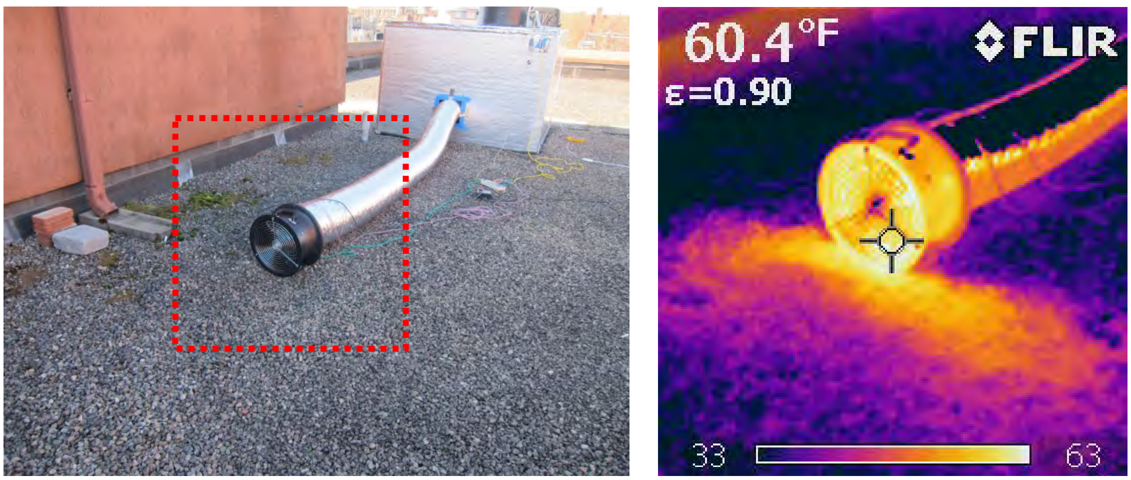


**Figure 56. Powered flow capture hood with infrared, showing output airflow heat signature**

Some measurements on EF-1 from the November trip are shown in Figure 57. The initial measurement was a baseline period, with the rooftop exhaust fan running, but the individual apartment unit exhaust fans were all turned off. Then, the individual exhaust fans were incrementally turned on and measured, progressing downward in the building. After a measurement period during which all fans were running, the individual exhaust fans were incrementally turned off and measured. This was followed by a final baseline measurement (no individual unit fans running).

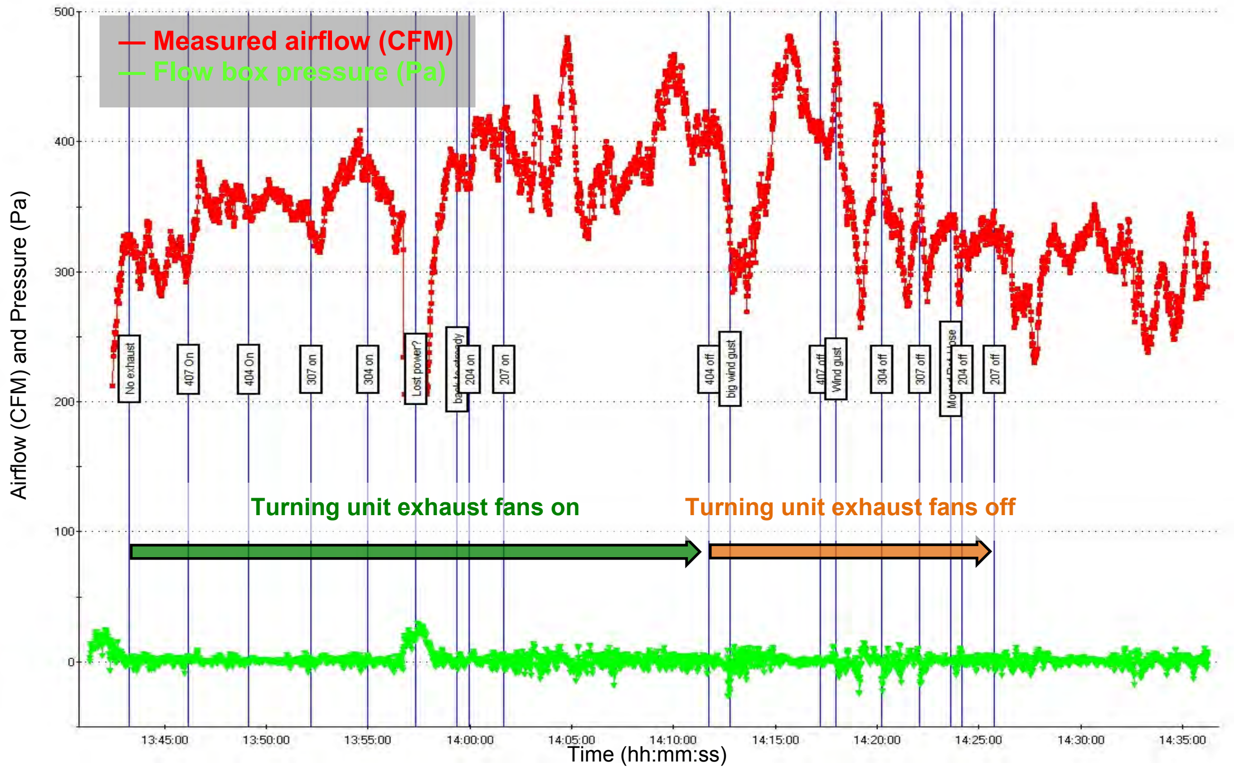


**Figure 57. EF-1 automated flow and pressure measurement (November trip, final test)**

As the results demonstrate, there is a great deal of variation in the measurement resulting from wind effects. Hourly wind speeds averaged 10 mph during this November testing, with gusts in the 20-mph range. This caused a great deal of variation in the pressure measurement from ambient conditions to the flow enclosure, resulting in these variations in airflow measurement. For instance, at the "all fans on" condition, the airflow measurement was 394 cfm ± 34 cfm (±1 standard deviation). At the "all fans off" condition, the airflow measurement was 299 cfm ± 28 cfm (±1 standard deviation). The effect of wind can be seen specifically at marker positions ("big wind gust"), showing tremendous changes in measurements in periods when the exhaust system was operating at steady-state conditions.

A similar set of measurements was done on EF-7 during the June 2012 site work (see Figure 58). Wind speeds were lower (0–5 mph), and measured flows had lower oscillation and uncertainty. EF-7 handles a larger number of exhausts with a higher target airflow. With all unit exhaust fans on, the rooftop measurement fan's capacity was exceeded by the exhaust flow, resulting in the anomaly seen after "turning unit exhaust fans on" in Figure 58.

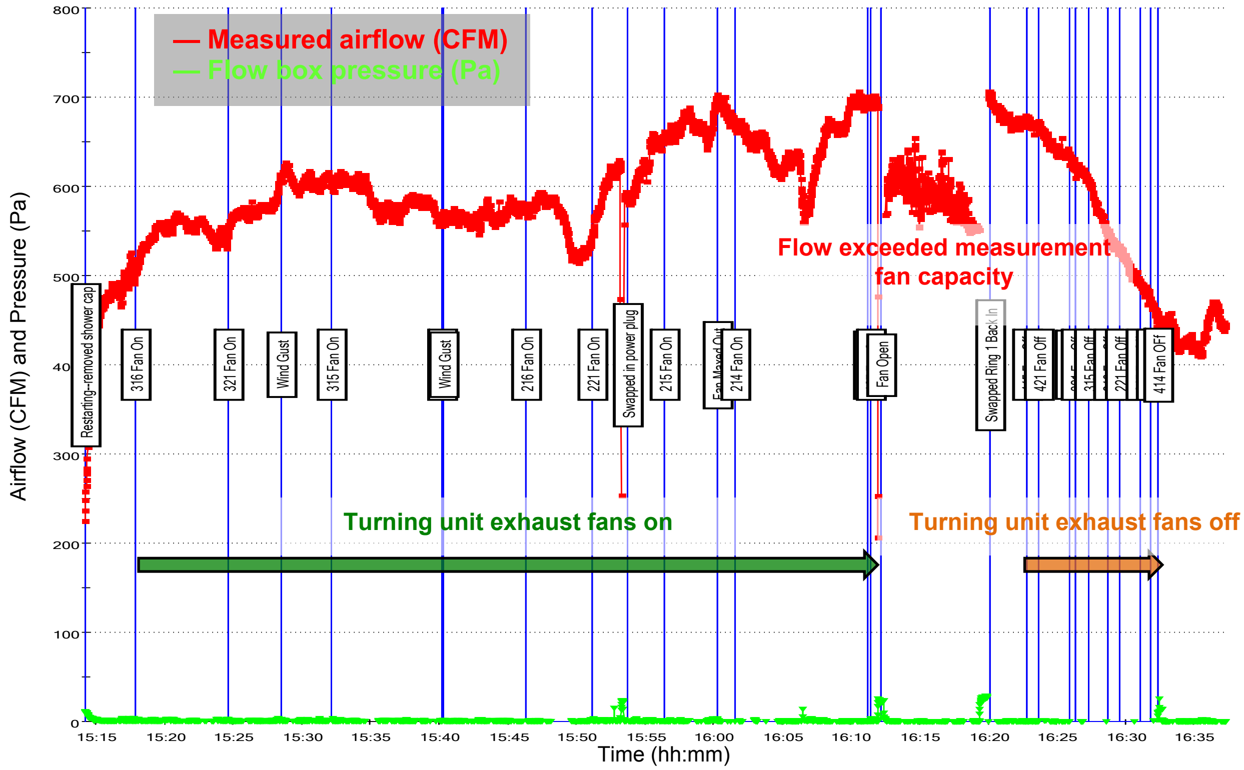


**Figure 58. EF-7 automated flow and pressure measurement (June trip test)**

Overall, there is a reasonable pattern, where turning on individual exhaust fans increases airflow through the rooftop unit. This is consistent with the pressure-controlled variable-speed fan increasing its speed to maintain a constant negative pressure as the individual unit exhaust fans add airflow into the shaft. For instance, in Figure 59 (which zooms in on a portion of a June test), a gradual but distinct decrease in rooftop unit fan flow is seen after "204 off" and "207 off." Discerning the changes in flow with each incremental added fan, however, is beyond the resolution of these measurements.

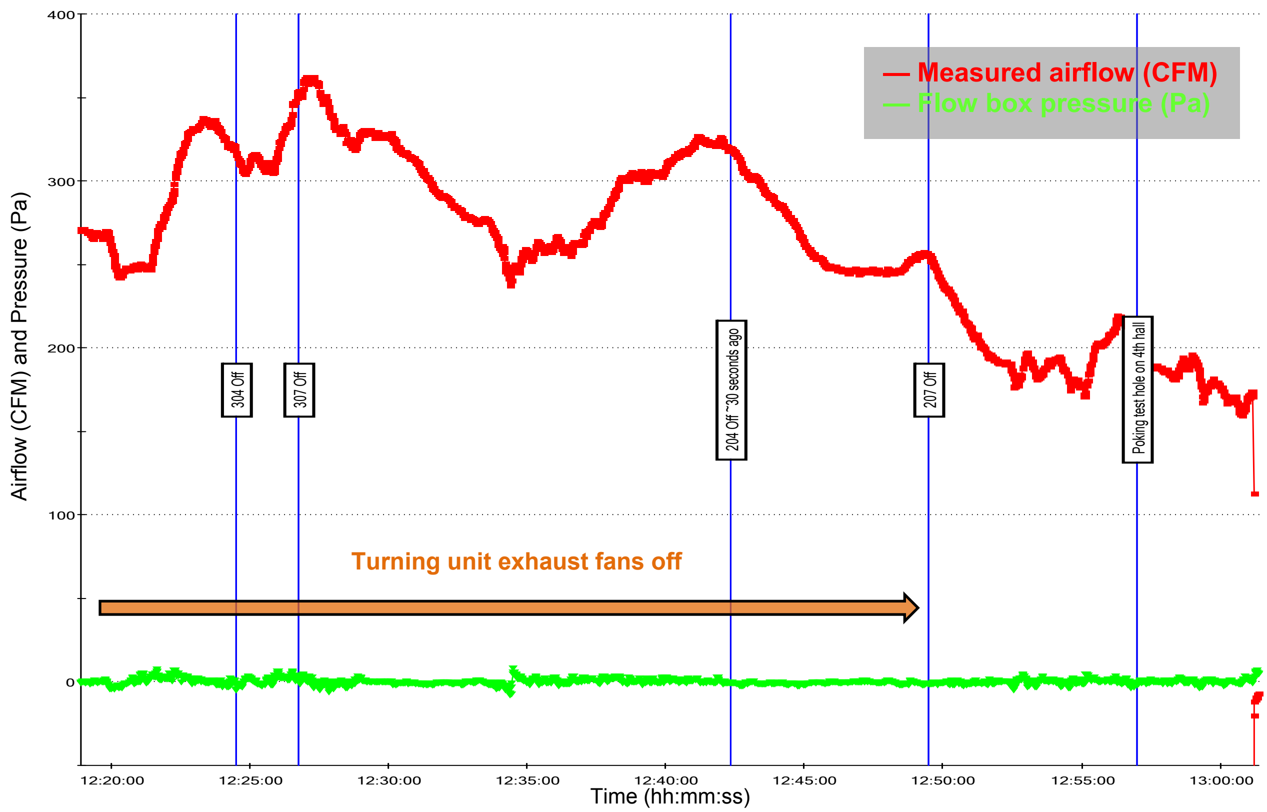


**Figure 59. Automated flow and pressure measurement (Day 2 test detail)**

Rooftop airflow measurements were taken for five exhaust shafts (including EF-1 and EF-7). The remaining three measurements were "single point" flow measurements, without intentional cycling of the unit exhaust fans. The status of the unit exhaust fans was unknown in this measurement, but based on observations in the units, the occupants seldom run the fans. The results are plotted with the original plan airflow callouts (130 cfm per unit: 70 cfm bath + 60 cfm kitchen) in Figure 60.

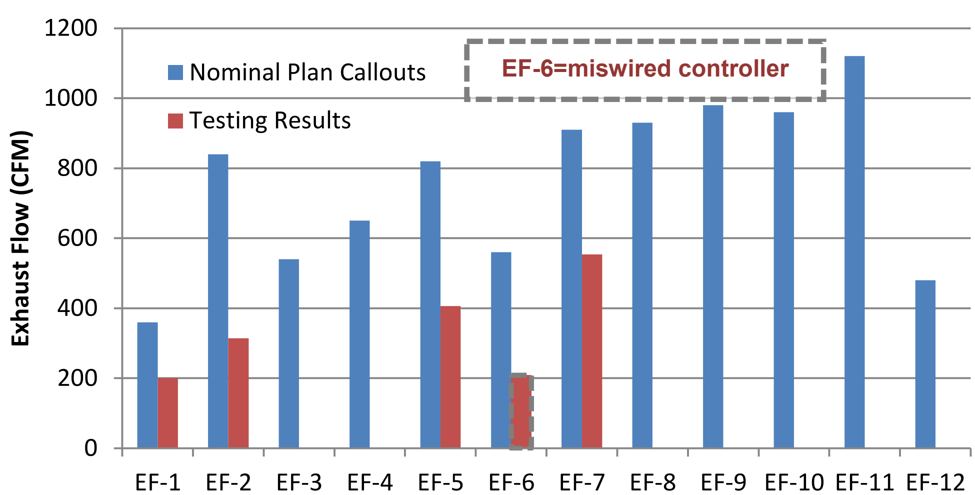


**Figure 60. Exhaust fan rooftop airflow test results**

The airflows were significantly reduced, to roughly 50% (weighted average) of the original plan callouts (closer to ASHRAE 62.1/62.2 rates; see Table 3). As shown by the measurements in Figure 57, Figure 58, and Figure 59, these rates would increase when unit exhaust fans are run. EF-6 has a miswired controller, resulting in a low-flow situation. The team is now addressing this issue as a punch list item. Low-flow issues with rooftop exhaust fans (e.g., EF-2) can be solved by increasing the controller static pressure set point, resulting in higher flow.

Amperage measurements were also taken (see Figure 61, left), corresponding to airflow measurements.

**Figure 61. Amperage measurements at rooftop exhaust fan (L); temporary seal of roof curb (R)**

The calculated results are shown in Table 12, with the pre-retrofit EF-1 results given for comparison. Note that in the power calculations, a power factor of 0.75 was assumed for the variable-speed (electronically commutated motor) fan, as opposed to 0.85 for the pre-retrofit (permanent split capacitor) motor fans (Greenheck 2011; a company representative recommended a power factor of 0.72 to 0.76 depending on the speed, horsepower, and voltage).

**Table 12. Exhaust Fan Airflows (via Rooftop Capture Hood) With Power Draw Estimates**

| Exhaust Fan # | Callout cfm | Measured cfm | Amps | Watts | cfm/W | % of Callout |
|---|---|---|---|---|---|---|
| EF-1 Pre Retrofit | 360 | 480 | 3.6 | 321 | 1.5 | 133% |
| EF-1 | 360 | 200 | 0.23 | 21 | 9.7 | 56% |
| EF-2 | 840 | 314 | 0.21 | 19 | 16.8 | 37% |
| EF-5 | 820 | 406 | 0.20 | 18 | 22.7 | 50% |
| EF-6 | 560 | 209 | 0.10 | 9 | 23.4 | 37% |
| EF-7 | 910 | 554 | 0.20 | 18 | 31.3 | 61% |

If these measurements are correct, this fan shows an order of magnitude improvement in the fan efficiency (in cubic foot per minute per watt) for the exhaust system. Part of the efficiency gain can be attributed to the greater electrical efficiency of the new fan motors. Significant efficiency gains, however, result from lowering the airflow through a now-oversized duct system. The measured airflows were 40%–60% of the plan callout value. Assuming power input varying with the cube of flow (typical fan rule), a 50% airflow reduction results in an 88% reduction in power input. As a result, efficiency levels this high should not be expected with a new duct system sized for the measured flows.

These amperage measurements were also conducted as individual unit exhaust fans were turned on and off, resulting in varying rooftop exhaust fan flow. No significant variation in amperage was observed, however, as unit fans were switched on and off. This might be due to the fact that the powered unit fans effectively reduce the static pressure that the rooftop fan needs to overcome at a given airflow. These measurements only assume the electrical use contribution of the rooftop fan; incremental addition of the unit exhaust fans (at 12 W each) will reduce the cubic foot per minute per watt metric.

Significant differences in flow were seen after temporarily sealing the open corners of the curb (see Figure 61, right). The reduction in flow after sealing the corners (from 325 cfm to 200 cfm) indicates that significant amounts of the total fan flow were being lost to this easily accessible duct leakage.

In addition, measurements were taken with a handheld manometer at the pressure transducer measurement (Figure 52) to verify its calibration. The measurements showed pressures consistent with the system set point (–25 Pa/–0.1-in. water column).

### 5.1.3 Exhaust Ventilation Airflow Testing (Unit Exhaust Fans)

Similar to the pre-retrofit work, airflow was measured with a flow capture hood at the apartment unit bathrooms and kitchens (Figure 62, left). A certain amount of airflow was expected with the unit exhaust fan turned off, which would increase as the unit fan was turned on. Consequently, two measurements were required at each fan. In addition, exhaust system pressure (upstream of the unit exhaust fan damper) was measured with a handheld manometer (Figure 62, right).

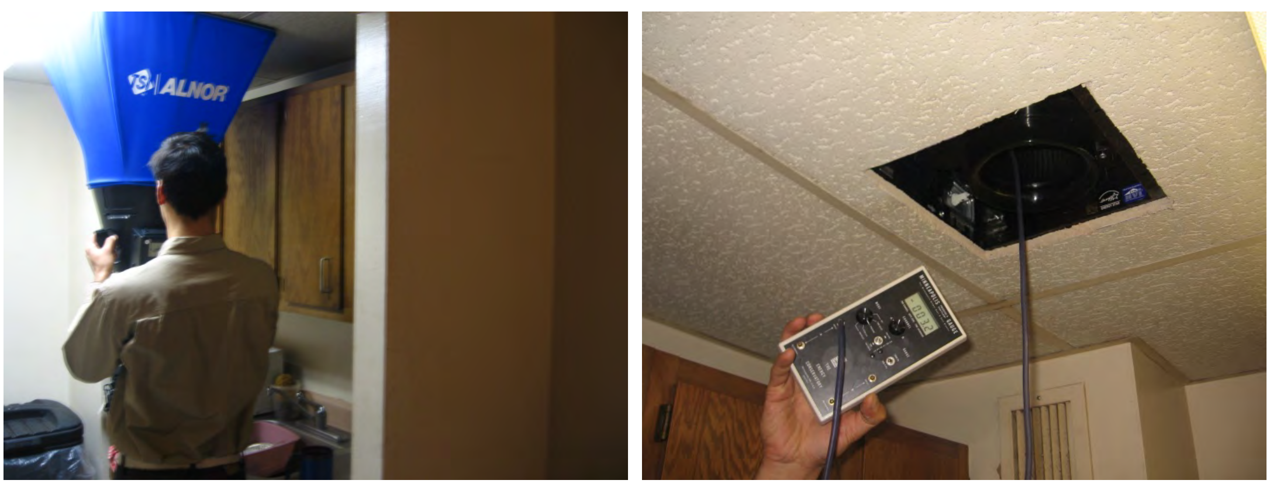


**Figure 62. Airflow measurement at kitchen exhaust fan (L) and duct pressure measurement (R)**

In the November 2011 work, EF-1 was measured in detail. Measurements were taken both as the unit exhaust fans were incrementally turned on (progressing down the building), and then as the unit exhaust fans were turned off (also progressing down the building). Measurements were taken in each case with the fan on and off, as shown in Figure 63 and Figure 64. Average airflows for both sets of measurements were 18 cfm (±5 cfm) unit fan off and 48 cfm (±5 cfm) unit fan on.

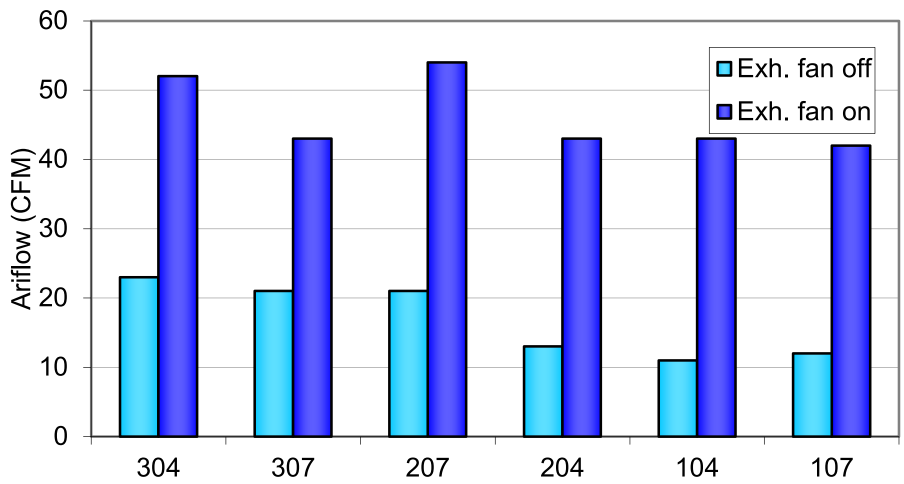


**Figure 63. EF-1 airflow measurement of individual unit exhaust fans, turning unit fans on**

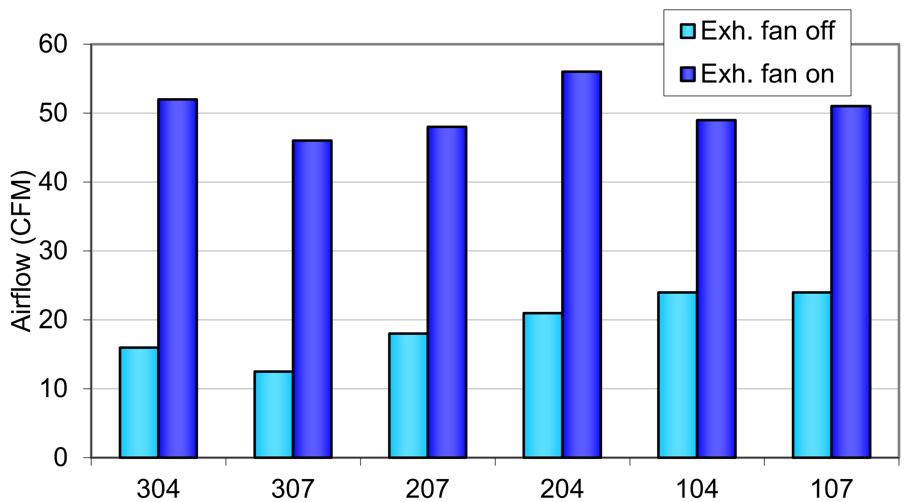


**Figure 64. EF-1 airflow measurement of individual unit exhaust fans, turning unit fans off**

There appears to be some type of pattern in the fan-off versus fan-on measurements. As more individual exhausts were turned on or off, it appeared that the rooftop fan flow changed the passive flow through the unit fan opening. The reason for this change is not clear; the physical pressure response in the ductwork system is close to instantaneous (seconds or less). It might be a transient effect correlated to changes in rooftop fan speed. It seems odd, though, for the fan speed to change over the course of tens of minutes, unless the controller algorithm is set to ramp fan speeds very slowly.

The pressure measurements through inactive unit exhaust fans (as per Figure 62, right) are shown in Table 13 and Table 14. These measurements were taken in the process of turning the unit exhaust fans on and off, respectively. The pressure measurements are consistent with the airflows graphed in Figure 63 and Figure 64.

**Table 13. Exhaust Duct Pressures, Turning Unit Exhausts On**

| Location | Pressure Difference/ΔP |
|---|---|
| Pressure Transducer | –25 Pa |
| Unit 307 | –6 Pa |
| Unit 207 | –2 Pa |
| Unit 104 | –0.5 Pa |

**Table 14. Exhaust Duct Pressures, Turning Unit Exhausts Off**

| Location | Pressure Difference/ΔP |
|---|---|
| Pressure Transducer | –25 Pa |
| Unit 307 | –6 Pa |
| Unit 207 | –10 Pa |
| Unit 104 | –9 Pa |

A similar set of measurements was taken on EF-7 in the June 2011 work. The results, shown in Figure 65, were comparable. Note that EF-7 has many more connected drops than EF-1 (13 bathrooms, as opposed to 6 kitchens), with a higher overall airflow. Some anomalies are seen in the data. For example, Unit 315 had a fan that was not connected to electrical power, and Unit 113 had an obstruction in the ductwork.

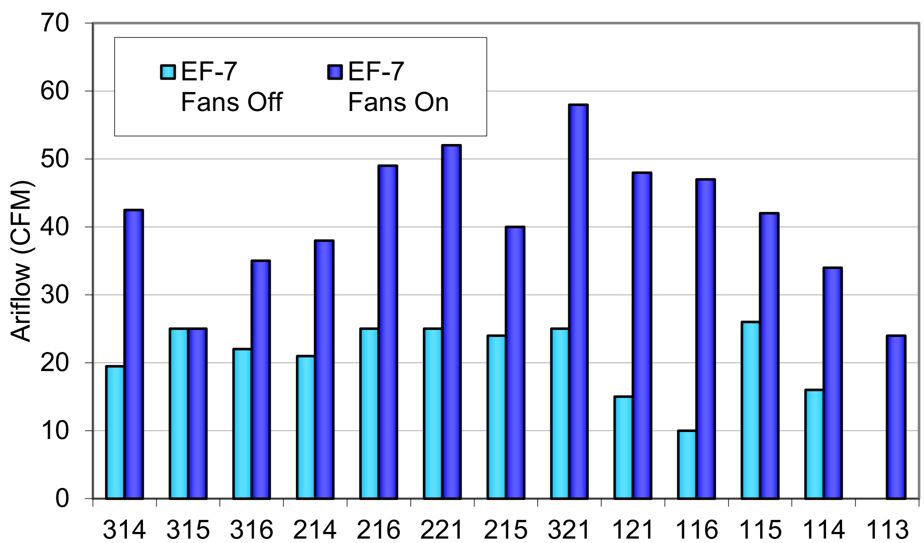


**Figure 65. EF-7 airflow measurement of individual unit exhaust fans, turning unit fans on**

Average airflows were 21 cfm (±5 cfm) with the unit fan off and 41 cfm (±10 cfm) with the unit fan on.

In the June 2011 field work, the passive flow through both kitchen and bathroom unit exhaust fans were measured to determine total flow per unit, as shown in Figure 66. Several kitchen exhaust fans were not accessible during this testing, so the average of other measurements is shown in the graph as a placeholder ("not accessible").

Average airflow was 37 cfm per unit (omitting the zero values; ±12 cfm standard deviation), with the unit exhaust fans off.

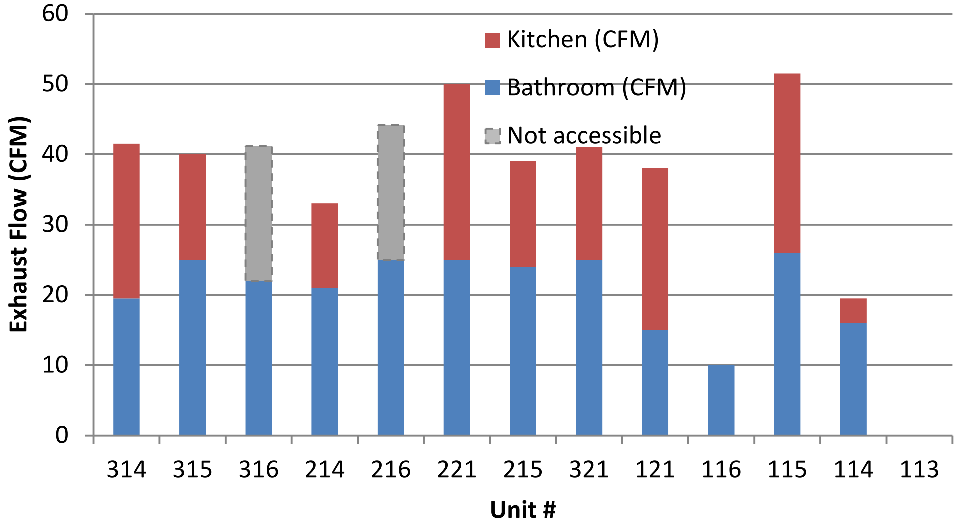


**Figure 66. Passive flow through unit exhaust fans (includes EF-6, EF-7, and EF-8 flows)**

For reference, the ASHRAE 62.2 requirement for the units (assuming zero or one bedroom) ranges from 15- to 25-cfm continuous flow; Innova generally targets 200% of this rate. It appears that the passive flow through the inactive unit exhaust fans is typically sufficient to meet this Innova target (as well as ASHRAE 62.2 rates); however, this is only a sampling of two exhaust systems. Additional measurements and commissioning are recommended before setting the operational state of the system.

### *5.1.4 Exhaust Airflow and Duct Leakage Analysis*

Similar to pre-retrofit testing, the rooftop exhaust fan measurement and unit exhaust airflows were plotted together, resulting in a calculated/estimated duct leakage. But because the rooftop exhaust airflows were measured under less-than-ideal (windy) conditions, the calculated duct leakage should be regarded only as an estimate.

The results are shown for turning on unit exhaust fans in Figure 67 and for turning them off in Figure 68. The two cases are similar, but with some differences in summed airflows.

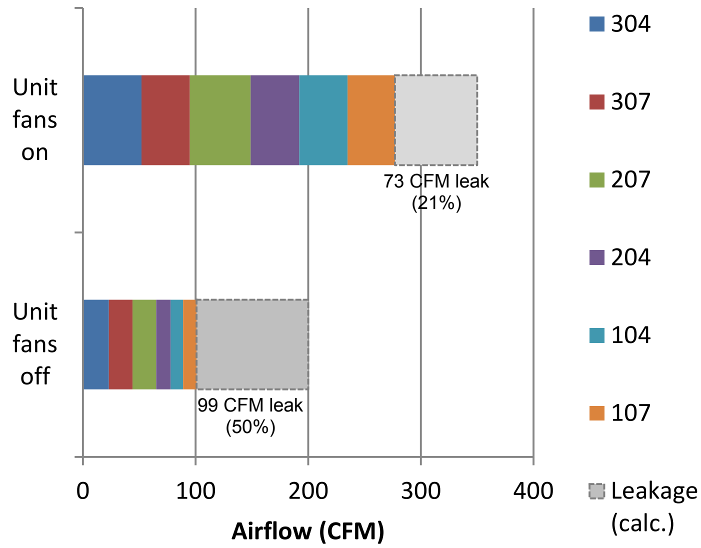


**Figure 67. EF-1 unit airflows and rooftop fan airflow (calculated duct leakage), turning unit fans on**

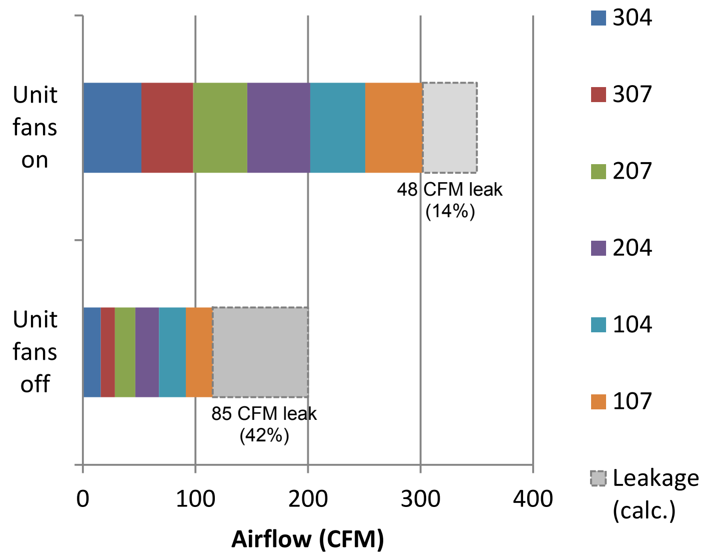


**Figure 68. EF-1 unit airflows and rooftop fan airflow (calculated duct leakage), turning unit fans off**

The same measurements were done for EF-7, with results shown in Figure 69.

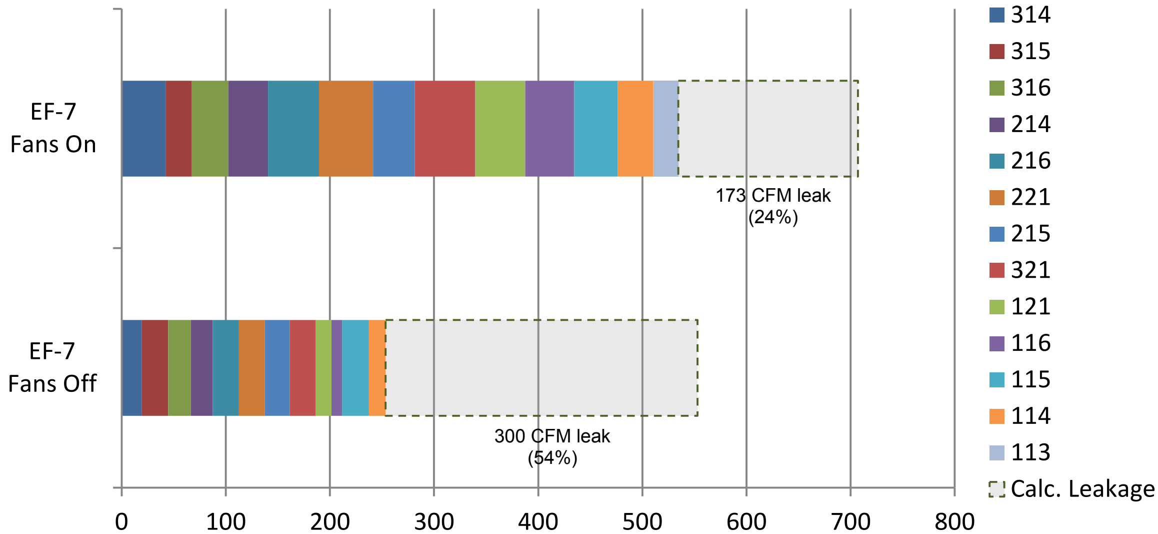


**Figure 69. EF-7 unit airflows and rooftop fan airflow (calculated duct leakage), turning unit fans on**

The calculated duct leakage (as a percentage of flow from the rooftop fan) is 42%–54% with the unit exhausts off, and 14%–24% with the unit fans on.

At EF-1, this can be compared with the previous leakage metrics of 23% (calculated duct leakage before retrofit work) and 26% (cfm 50 duct leakage measurement divided by nominal flow). Although EF-1's "unit fans off" calculated duct leakage is a very high percentage of flow (40%–50%), the absolute value (85–100 cfm) is comparable with or less than the calculated duct leakage from the pre-retrofit system (110 cfm; see Figure 41). EF-7's calculated leakage, however, is more than half the rooftop flow. Overall, this shows that there would have been a benefit to retrofit exhaust shaft duct sealing.

### *5.1.5 Exhaust Ductwork Air Leakage and Sealing*

During the November test, exterior temperatures were cold enough to demonstrate warm air leakage occurring at the unsealed corners of the rooftop exhaust curb, as shown in Figure 70.

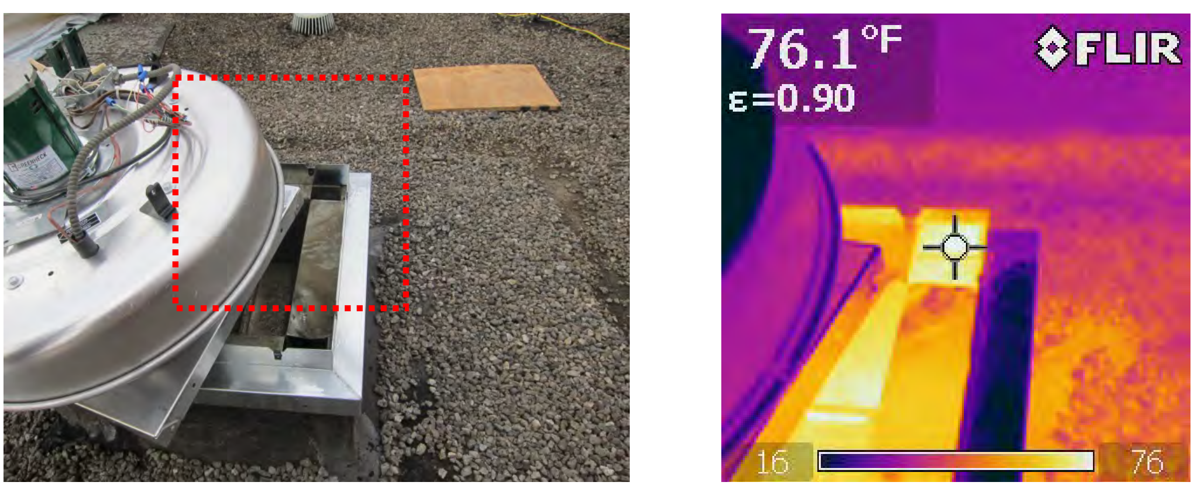


**Figure 70. Stack-driven air leakage at unsealed corners of exhaust shaft roof curb**

This detail was not addressed on the prototype, so it was temporarily sealed during testing using foil tape (see Figure 61). This demonstration, however, helped convince all stakeholders that this was a useful and required component of the retrofit. In addition, the change in airflow (from 325 to 200 cfm) showed that operating leakage at these corners can be significant.

The retrofit used sheet metal and duct mastic to form an effective seal at the corners and to provide a connection from the opening to the newly installed roof curb, as shown in Figure 71.

**Figure 71. Mastic and sheet metal retrofit air sealing of exhaust shaft roof curb**

One post-retrofit shaft (EF-3; 9 kitchens) was tested for duct leakage, as shown in Figure 72. Depressurization testing was used. No pre-retrofit test is available for comparison.

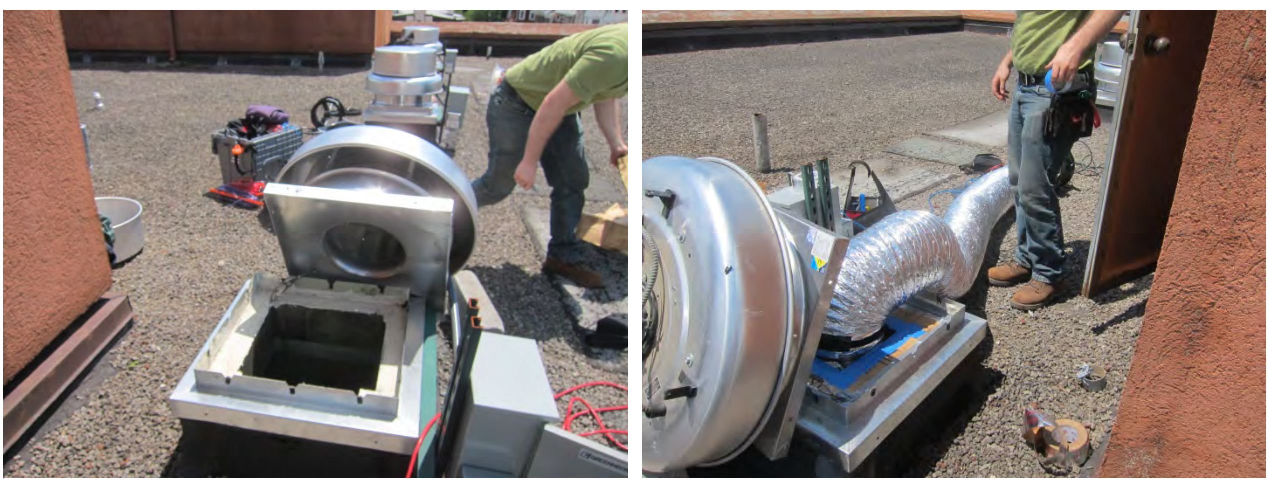

**Figure 72. Duct leakage testing of EF-3 (post-retrofit)**

The resulting multipoint test on EF-3 is shown in Figure 73. Leakage (296 cfm 50) was substantially higher than that measured during the pre-retrofit tests on EF-1 and EF-5 (93 and 103 cfm 50, respectively). This high leakage is not explained by the size of the system (EF-5 is larger than EF-3). This metric also shows high leakage when normalized by floor: 99 cfm 50/floor, versus bad as 15+ cfm 50/floor (Zuluaga and Fitzgerald 2010; see Table 2). The source of this leakage was not determined in this testing; much of the exhaust system is not accessible because it is located within fire-rated shafts.

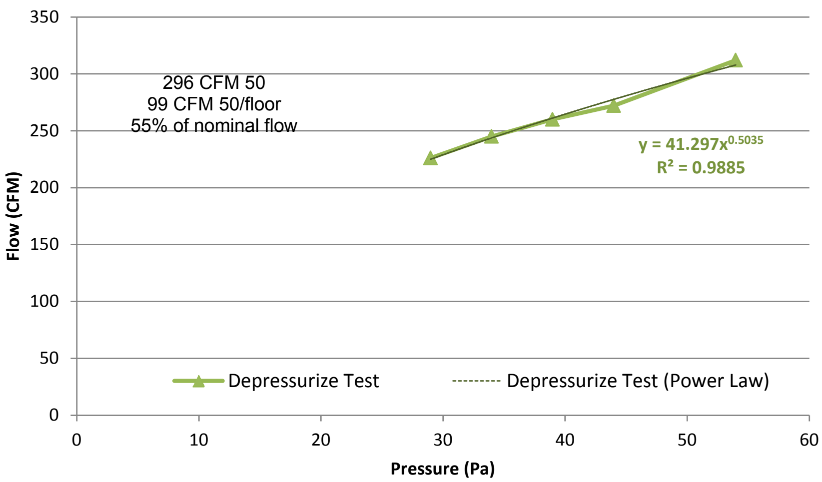


**Figure 73. Multipoint air leakage data for EF-3, post-retrofit**

No additional duct sealing, such as aerosol-based sealant or hand-applied mastic to accessible portions, was implemented beyond the rooftop curb work..

The spring-loaded louvers were removed from the roof curb, a step that reduces the static pressure drop of the ductwork system and improves fan efficiency. Measurements were taken with the louvers in their spring-loaded position and blocked open. Rooftop fan wattage dropped from 20–30 W to 13–18 W. Fan speed (percentage of maximum rpm, as shown on the controller display) also dropped with the louvers pinned open.

### *5.1.6 Unit Pressure Differences with Exhaust Fan Operation*

One risk when using intermittent exhaust fans in a multifamily building is the potential for pressure differences causing unit-to-unit contaminant transport. For this reason, pressure differences between two adjacent units were measured while cycling the unit exhaust fans on and off in various combinations, as shown in Figure 74.

**Figure 74. Interunit pressure difference measurement**

The pressures of both units with respect to the corridor were monitored, and the pressure difference from one unit to the other was calculated and plotted in Figure 75. Positive values show flow from 302 to 303, and negative values in the opposite direction.

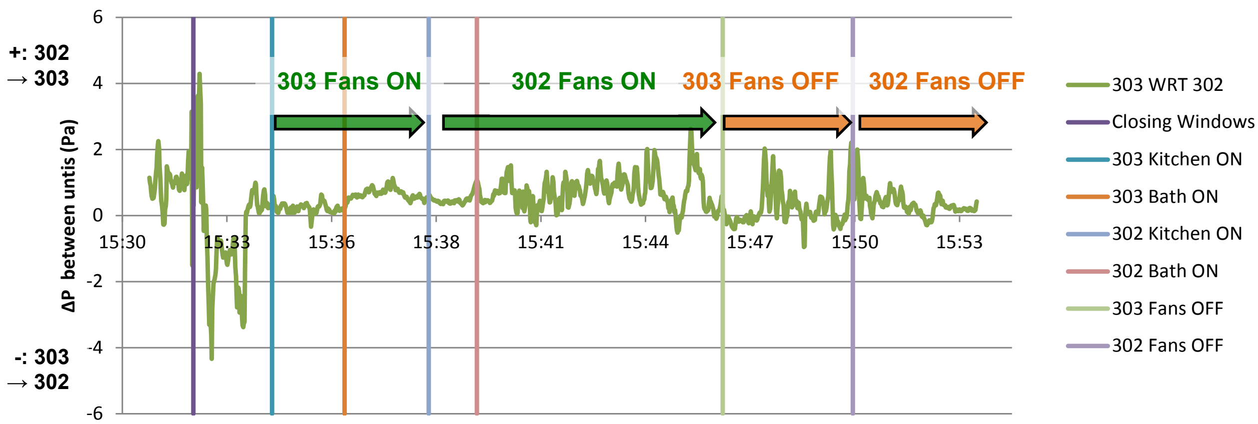


**Figure 75. Interunit pressure difference measurement**

There is no clear shift in pressure while turning unit exhaust fans on and off; instead, the pressure differences are dominated by intermittent wind effects, based on the pressure variations seen in the unit-to-corridor measurements.

Measurements of exhaust airflows with unit exhaust fans turned on and off are shown in Figure 76; the “Fan ON” bar indicates the flow added when the unit fan is on. These measurements can be combined with previous measurements of unit airtightness to calculate the expected change in unit pressure. The added airflow (state change) is 35–50 cfm. The expected pressure change for an apartment unit would be under 1 Pa, which is consistent with the lack of pressure response from turning fans on and off. Wind and stack effect induce larger interunit pressure differences; higher airflows and more airtight apartment units would result in a larger pressure response.

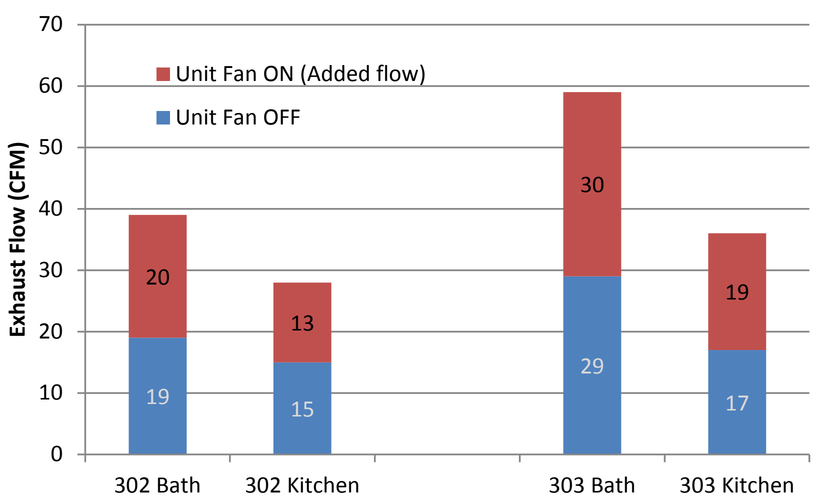


**Figure 76. Unit exhaust airflows with unit fan turned on and off**

### 5.1.7 Exhaust Ventilation System Monitoring: Field Installation

In addition to this field testing, monitoring equipment was installed on two exhaust fans to measure the voltage output signal of the variable-speed fan controller (Figure 77). The intent was to measure the variation in fan speed, which would give some insight into the range of variable-speed operation and the potential savings associated with modulating fan speed to meet demand.

**Figure 77. Installation of voltage data logging equipment on variable speed fans**

Data were collected from two exhaust fans:

- EF-1: exhaust from 6 unit kitchens, original design 60-cfm each; 360 cfm at 0.30-in. external static pressure, 1/6-hp fan
- EF-7: exhaust from 13 unit bathrooms, original design 70-cfm each; 910 cfm at 0.50-in. external static pressure, ⅓-hp fan

Data were recorded at 3-min intervals, and the data collection period ran from January 2012 to May 2012.

### 5.1.8 Exhaust Ventilation System Monitoring: Results and Analysis

The collected fan data were plotted with online weather data for the Philadelphia International Airport weather station (KPHL). The results were graphed in terms of fan speed (rpm), based on the conversion from control voltage to rpm provided by Greenheck (2010):

> *Control wire inputs - A motor with control wires that will accept a 0-10 VDC analog control signal. The active range is 2-10 with 2 VDC correlating to 350 rpm and 10 translating to the max speed the motor can spin (typically 1725) This option allows, controls by others, to control the speed of the fan, such as a Building Management System.*

Greenheck also provides fan curves, correlating rpm with flow (cfm) at various static pressure levels. The calculated airflows, however, were completely inconsistent with the airflow measurements done on site, even accounting for high static pressures (Figure 78):

- EF-1 calculated flows: 2140 cfm max/375 cfm min/927 cfm average at 0.125-in. water column (31 Pa) static pressure; system set to operate at 0.1-in. water column (25 Pa)
- EF-1 site measured flows: 200 cfm with unit exhaust fans off; 350 cfm with unit exhaust fans on

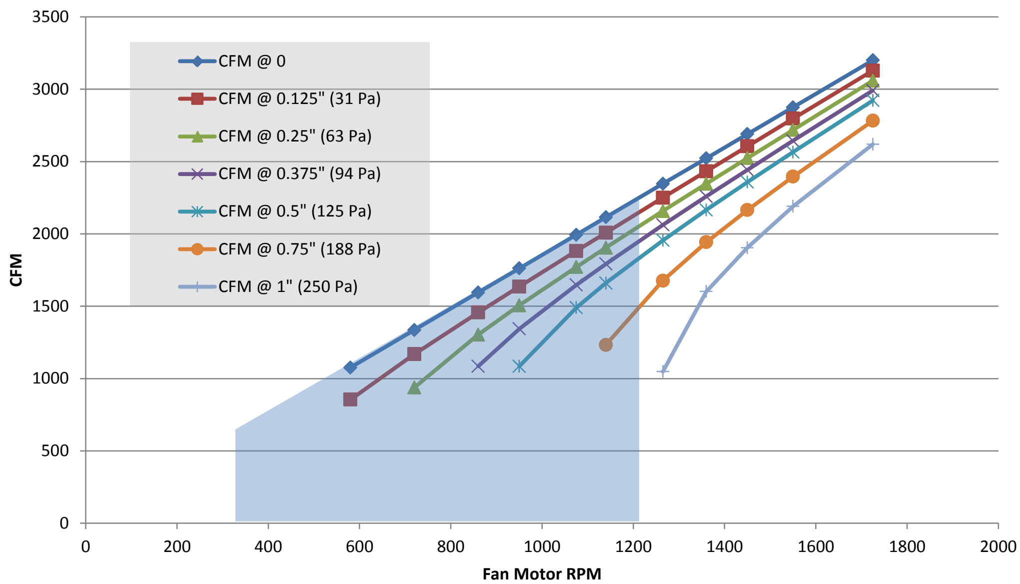


**Figure 78. Greenheck motor rpm versus cfm at various static pressures (rpm range highlighted)**

As another approach, during the short-term EF-7 site measurements, the control voltage was logged at every second, and correlated with measured fan flows, as shown in Figure 79.

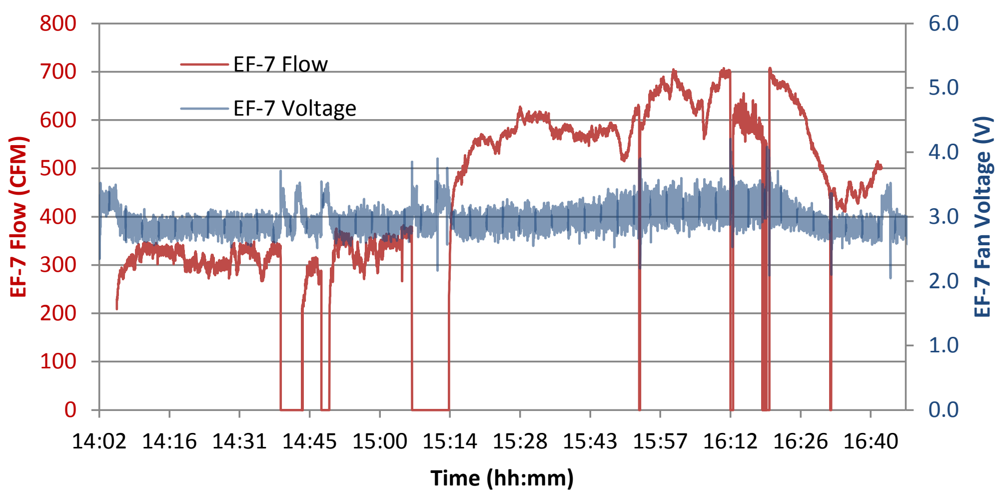


**Figure 79. EF-7 measured flow (cfm) and control voltage (1-s data)**

Although there appears to be some correlation between the two measurements, when the values were plotted against each other, the results had minimal correlation ($R^2 = 0.0002$).

For this reason, the results have been left as rpm measurements, pending better correlation between voltage and airflow. One possible explanation for the mismatch between static pressure and airflow (i.e., fan curve) measurements is system effect (i.e., velocity losses caused by turbulence), as described by Page (2011). The exhaust ductwork systems have a hard 90-degree tee or ell connecting to the exhaust fan riser, which would result in significant turbulence.

An initial plot compared fan speed with exterior temperature (Figure 80). The BSC/Innova team expected that the pressure controller would compensate for stack effect variations. Little correlation is evident, however, in data covering winter and early summer conditions. Arguably, fan voltage amplitude variations are smaller during warmer weather.

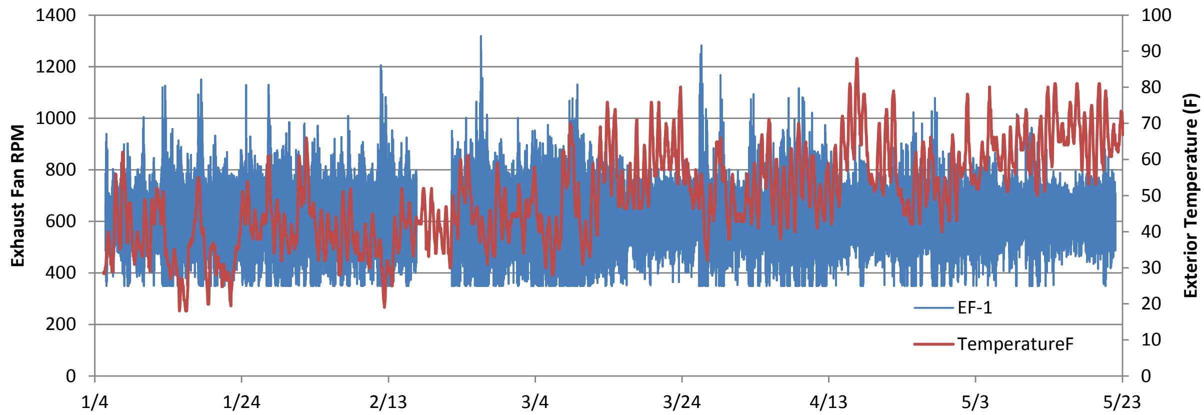


**Figure 80. EF-1 fan speeds with hourly exterior temperatures for KPHL weather station**

The fan speed was also plotted with wind speed (Figure 81). Although there appears to be a weak correlation, where extreme wind conditions are accompanied by larger variations in fan speeds, it is by no means a one-to-one correlation.

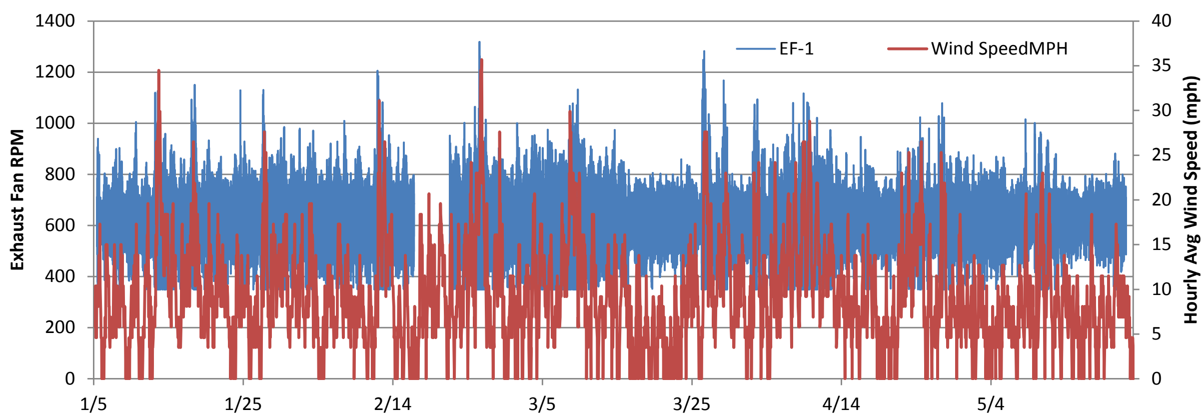


**Figure 81. EF-1 fan speeds with hourly exterior wind speeds for KPHL weather station**

A similar pattern was seen for EF-7, as shown in Figure 82.

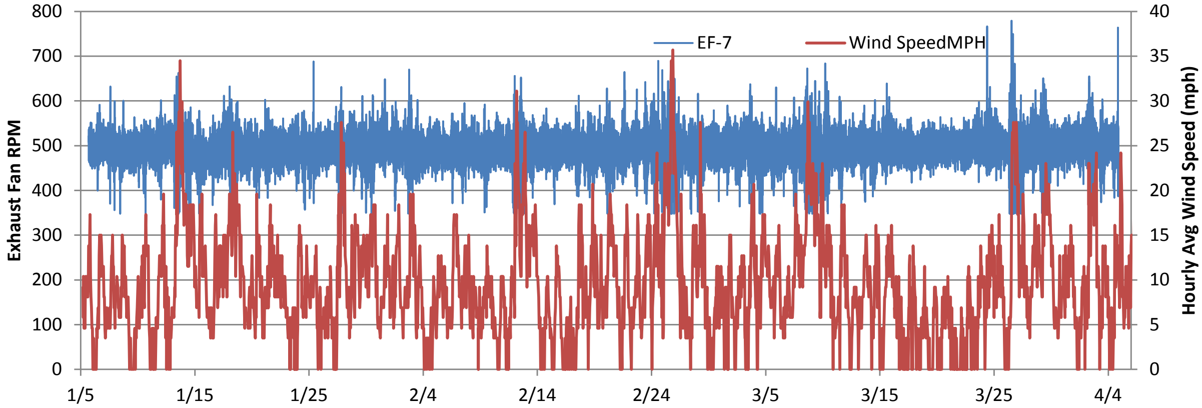


**Figure 82. EF-7 fan speeds with hourly exterior wind speeds for KPHL weather station**

It is important to remember that the wind data plotted here are hourly averages, from a weather station away from the test site (Philadelphia International Airport). The wind data do not capture the effect of localized wind gusts, which might be captured by voltage measurements, given the 3-min data collection intervals.

Wind gust speed is also plotted with fan speed for reference (Figure 83); again, large wind gusts are accompanied by larger variations in fan speeds. In addition, a period of low fan speed variability (late March 2012) correlates to a lack of wind gusts.

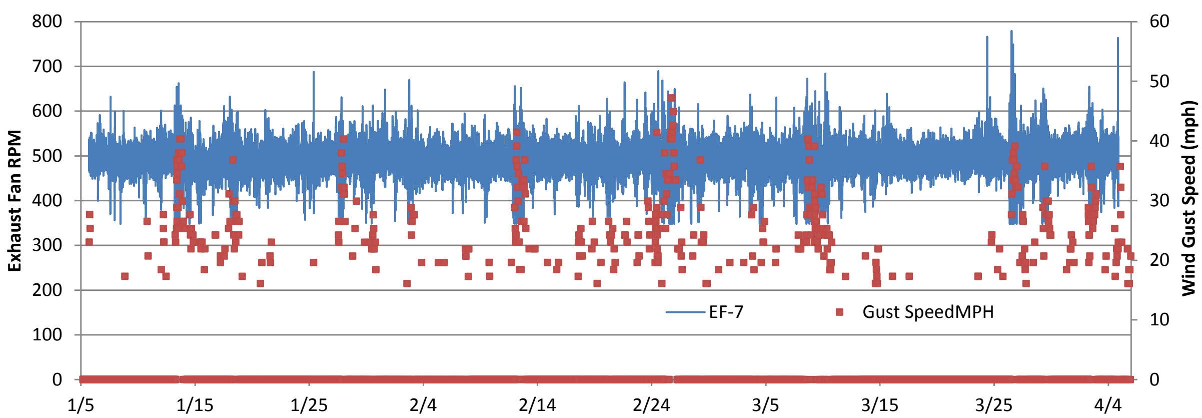


**Figure 83. EF-7 fan speeds with wind gust speeds for KPHL weather station**

Another observed pattern was a general diurnal variation, as shown in Figure 84, which plots several days in February. There is greater variation in fan speed (above and below the average) on a cycle that matches typical occupancy, with low variations during sleeping hours (10:00 p.m. to 6:00 a.m.), and greater variations during the day.

The fact that the diurnal pattern is a variation (above and below the average rpm) is unexpected: the expected pattern would be an increase above the average during the day (because unit exhaust fans might be operating). This might be due to the fan control algorithm varying above and below the set point after ramping to maintain a constant pressure.

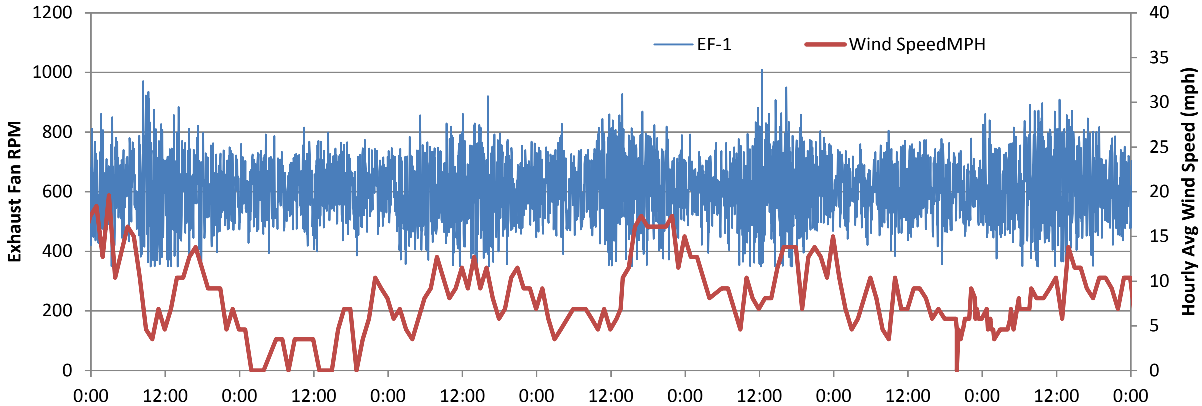


**Figure 84. EF-1 fan speeds for 02/03/12–02/09/12, showing diurnal variation**

In addition, the speed range of EF-7 is much smaller than that of EF-1. This is clear from a visual inspection of the data, as well as a histogram of measured voltages (see Figure 85). Several theories were proposed for this behavior.

One theory is that EF-1 is a kitchen shaft and EF-7 is a bathroom shaft. The bathroom exhaust fans are ganged with the lights, so they would be operated during occupancy. In comparison, the kitchen exhaust would be run at the discretion of the tenant. This might mean that EF-1 would have more variable or "spiky" behavior.

Another theory is that EF-7 is a much larger system (13 bathrooms; 910 cfm nominal) than EF-1 (6 kitchens; 360 cfm nominal). Therefore, given EF-7's larger ductwork system, any given unit bathroom exhaust would have a much smaller effect on the system pressure (and thus changes in rooftop fan speed) than a given unit exhaust in EF-1.

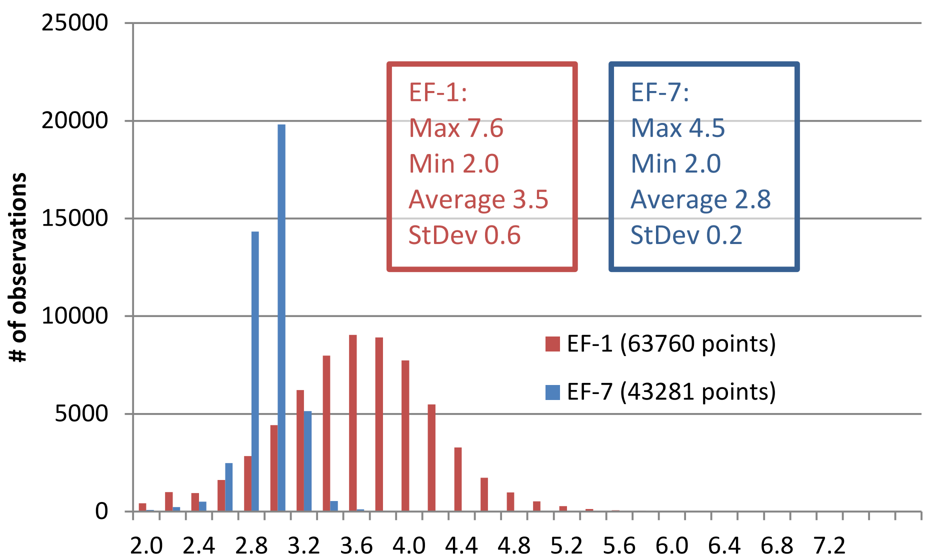


**Figure 85. Voltage measurement histogram for EF-1 and EF-7, with statistics**

## 5.2 Corridor Supply Ventilation System Design and Testing

As described in previous sections, the building's original corridor ventilation system (rooftop gas-fired MAU; refer to Figure 15) is not operational because of its operating cost and excessive ventilation rate. As a result, a floor-by-floor corridor ventilation system was designed as a replacement to eliminate floor-to-floor connections inherent to centralized ventilation systems.

### *5.2.1 Design Intent and Execution*

One of the first issues dealt with in the design was the ventilation rate. The ventilation rate for corridors stated in ASHRAE/ANSI Standard 62.1 (ASHRAE 2010a) is 0.06 cfm/ft$^2$. Assuming a corridor area of 1470/ft$^2$ per floor, this is equal to a ventilation rate of 88 cfm/floor.

To provide acceptable supply air temperatures in a cold climate (DOE Zone 4), however, either preheating or tempering is required. Dilution of the supply air with interior air was selected. Although it has diminished fan efficiencies ($cfm_{outside\ air}$/W), it is simpler to install than systems involving duct heaters. Using HRV could also produce warmer delivery temperatures (in addition to overall energy benefits); however, it was not chosen for reasons explained next. A dilution ratio of 3:1 was recommended, which results in an overall target flow of 352 cfm (264 cfm dilution air:88 cfm outside air).

One obstacle to this simple corridor ventilation system was a requirement from the local engineer hired by the mechanical contractor. The engineer required that the supply ventilation system account for the exhaust flows of the two electric dryers in the common laundry room that is located on each floor. The nominal callout for each dryer is 214 cfm; adding two dryers and the ASHRAE 62.1 corridor ventilation rate (88 cfm) results in 516 cfm per floor (~2,000 cfm/floor assuming 3:1 dilution). The engineer insisted on this additional flow, even though the dryers are operated intermittently.

Innova has previously measured dryer exhausts in the range of 50–70 cfm in multiple projects. With these airflows, the overall outside air requirement drops to roughly 210 cfm per floor (832 cfm, assuming 3:1 dilution).

In the end, a compromise value was chosen based on 200 cfm for two dryers (100-cfm each), plus 17 cfm (50-cfm elevator exhaust divided by 3 floors), or 217 cfm per floor. This results in an outdoor air ventilation rate of 305 cfm per floor, after adding corridor ventilation (88 cfm). A lower dilution rate was selected to reduce fan size (2:1), giving an overall fan flow of 914 cfm. Table 15 summarizes these results.

**Table 15. Corridor Ventilation Rates, With Dilution Rates and Total (Diluted) Fan Flow**

| Description | Corridor (cfm) | Laundry (cfm) | Total (cfm) | Dilution Ratio | Fan Flow (cfm) |
|---|---|---|---|---|---|
| ASHRAE 62.1 Corridor Only | 88 | 0 | 88 | 3:1 | 352 |
| Two Dryers st Nominal Flow | 88 | 428 | 516 | 3:1 | 2,064 |
| Two Dryers at Measured Flow | 88 | 120 | 208 | 3:1 | 832 |
| Compromise Values | 88 | 217 | 305 | 2:1 | 914 |

The team faced another limitation; there is only limited height available in the existing suspended ceiling. There is a vertical clearance of roughly 14 in., and an inline fan that meets the ~900 cfm flow requirement is 15 in. in diameter. To meet this geometry requirement, a system that uses two ~450 cfm inline fans in parallel was chosen.

Figure 86 shows a schematic of the corridor ventilation system.

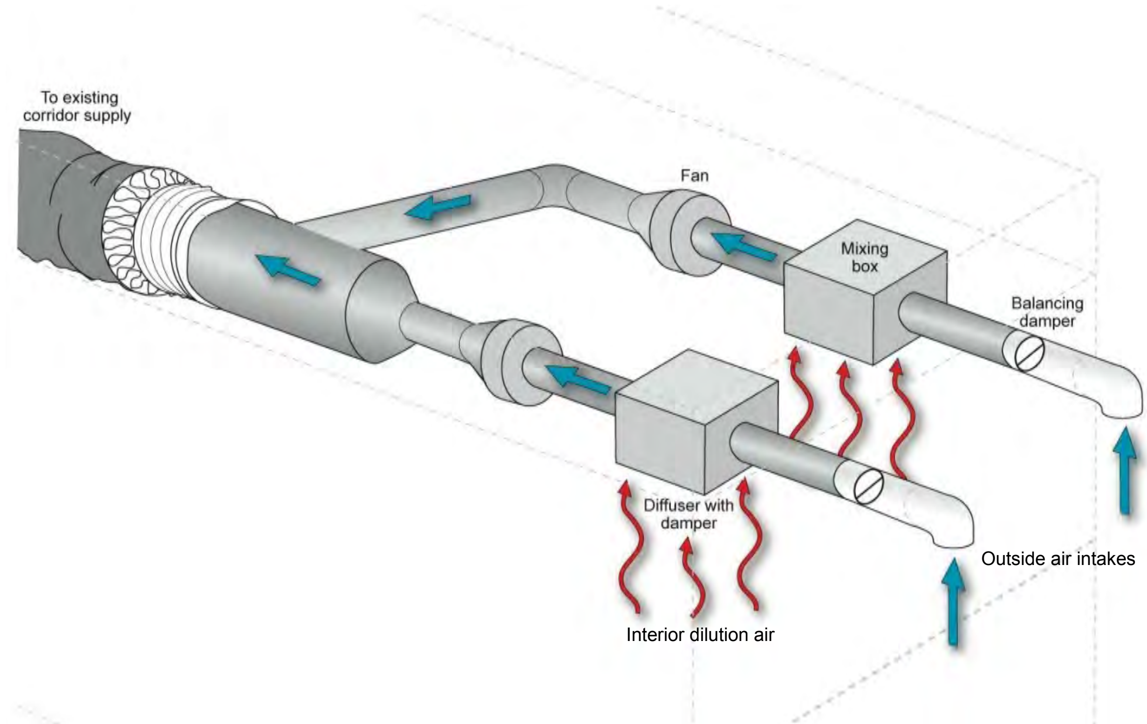


**Figure 86. Schematic of corridor ventilation system**

Outdoor air is drawn from two intakes at the exterior wall end cap of a hallway, and brought into mixing boxes to achieve dilution with interior air. Balancing dampers and ceiling diffusers with dampers are used to control the mixing ratio of this supply air. The mixed outside air is then connected to the existing corridor supply system, which was isolated from the multistory shaft connected to the rooftop MAU. The existing ductwork system was designed to supply roughly 1,500 cfm/floor, so the system is sized generously for the ~900 cfm now being supplied.

Based on examinations of preliminary plans, BSC advised the team to increase duct sizes because of the high velocities predicted based on the target flows. Note, however, that inline fans are often suitable for high static pressure applications such as radon mitigation systems.

### *5.2.2 Results and Analysis*

Images of the installed system are shown in Figure 87, Figure 88, and Figure 89, including views from the exterior, the system in the suspended ceiling, and the diffusers for interior dilution air.

**Figure 87. Corridor ventilation exterior view (L) and connections above suspended ceiling (R)**

**Figure 88. Inline fans and registers in suspended ceiling**

**Figure 89. Flexible duct connection (L) and wye connection (R)**

The system was tested for airflow. The exterior intakes were not accessible for flow hood measurements, so airflow measurements were taken at the intake registers (for interior dilution air), and at the supply ventilation registers. The locations of these ceiling registers are shown on a typical floor plan in Figure 90.

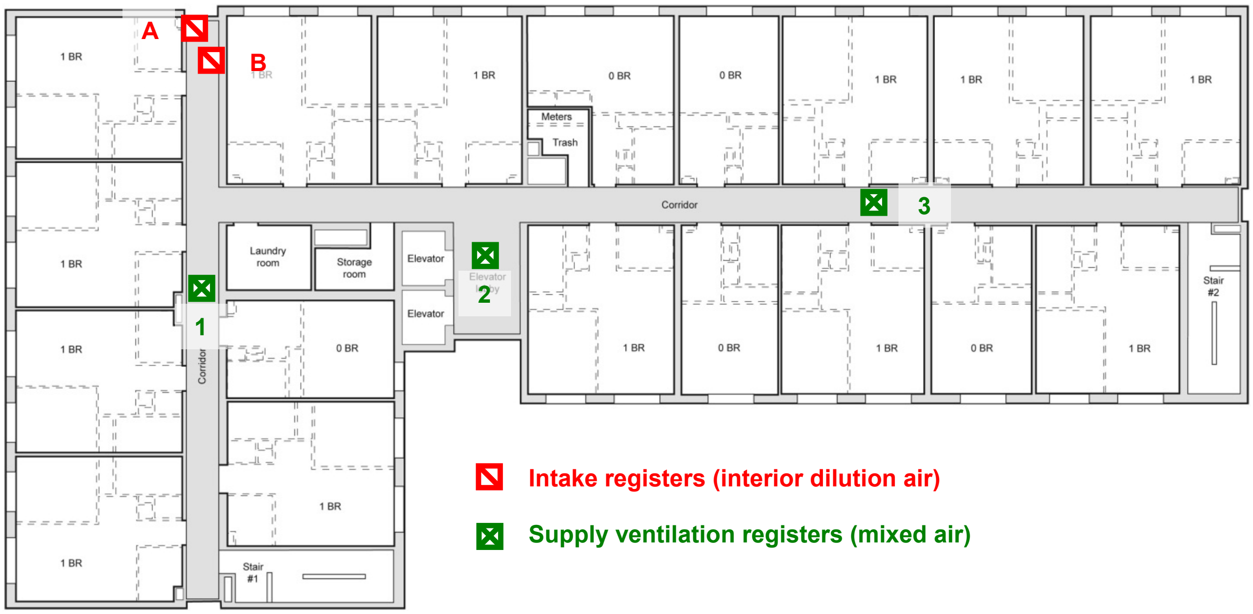


**Figure 90. Schematic of supply ventilation registers and interior dilution air intakes**

The results are shown in Figure 91. The outlets were summed, and then compared with the sum of the interior intakes. The difference is nominally the outdoor supply airflow (labeled "Outside Air (Calc.)"), minus effects of duct leakage (which were not measured). Duct leakage in this system might be significant.

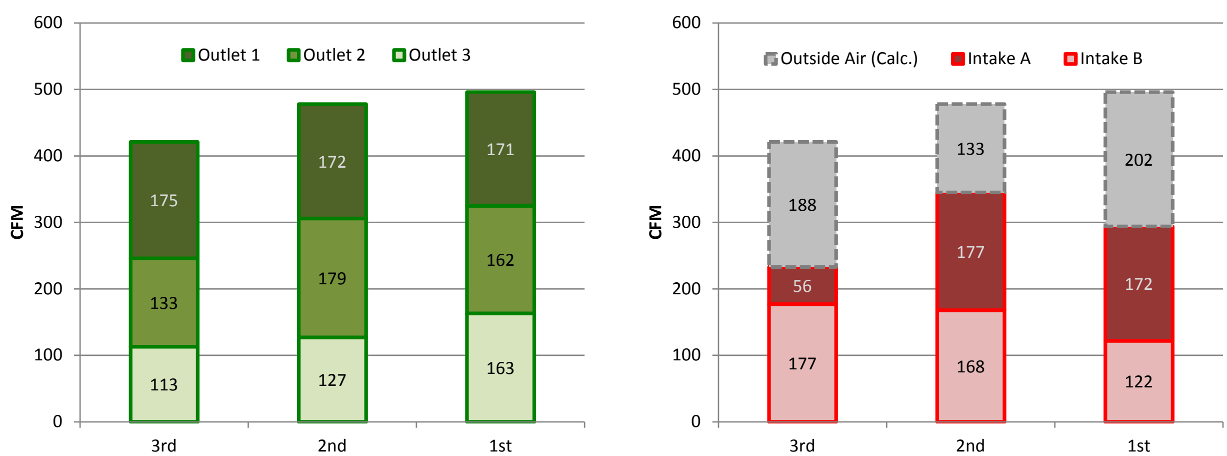


**Figure 91. Ventilation outlet (L) and intake (R) flow measurements, with calculated outside air**

The summed outlet flows are in the 420- to 500-cfm range. Assuming the calculated outside airflows shown in Figure 91, these are dilution ratios of 2.2:1, 3.6:1, and 2.5:1, respectively, for the three systems, which will produce reasonable wintertime delivery temperatures. This is substantially lower, though, than the target of 900 cfm (total airflow). The calculated outside airflows (130 to 200 cfm) are lower than the design target (300 cfm), but higher than the 90 cfm required by ASHRAE 62.1 for corridor ventilation.

Fan power consumption and static pressure were measured at the third-floor system. Fan wattage was roughly 100 W each (nameplate rated 144 W); assuming the measured airflows, this is 2.1 cfm/W through the fan (outside and tempered indoor air), and 0.9 cfm/W for net outside air. The outside air efficiency is comparable to non-electronically commutated motor (ECM) residential-scale HRV efficiencies (0.5 to 1 cfm/W non-ECM HRV; ~2 cfm/W ECM HRV).

Static pressures of the two inline fans were measured, and the total airflow was calculated ("Calc. tot. cfm"), using the manufacturer's fan curve. Outdoor airflows were recalculated assuming the fan curve numbers; these results are shown in Table 16.

**Table 16. Corridor Supply Fan Static Pressures**

| | Return Static P | Supply Static P | ΔP (Pa) | ΔP (IWC) | Hall cfm | Calc. Tot. cfm | Calc. Out. cfm |
|---|---|---|---|---|---|---|---|
| **LH Inline Fan** | –304 Pa | +132 Pa | 436 Pa | 1.74 | 56 | 90 | 34 |
| **RH Inline Fan** | –90 Pa | +44 Pa | 134 Pa | 0.54 | 177 | 400 | 223 |
| **Total** | | | | | 233 | 490 | 257 |

Notes: LH=left hand; RH=right hand; P = pressure; ΔP=pressure difference; IWC = inches water column

The calculated total airflow (490 cfm) is greater than the sum of the supply register (420 cfm), which can be attributed to duct leakage on the supply (positively pressurized) side. Assuming this calculated total airflow, fan efficiencies change to 2.4 cfm/W through the fan (outside and tempered indoor air), and 1.3 cfm/W for net outside air. The tempering ratio, however, drops from 2.2:1 to 1.1:1. Duct leakage in the corridor supply system hinders distribution of ventilation air but not overall performance. This supply leakage goes to the suspended ceiling space, which in turn leaks into the conditioned space.

# 6 Analysis, Conclusions, and Further Work

## 6.1 Summary of Key Measurements

Some key measurements from this research are summarized in the sections that follow.

### *6.1.1 Pre-Retrofit Testing*

Pre-retrofit air leakage was measured in two exhaust duct shafts and found to be more than double recommended levels (Zuluaga and Fitzgerald 2010). The fan depressurization leakage measurements were 26% and 13% of the nominal (callout) flow, using the cfm 50 leakage metric. Summed unit exhaust airflows were compared with the rooftop airflow measurements, providing a "calculated leakage." These values correlated reasonably well with the nominal leakage, at 23% and 14% for the two shafts. Although the results are surprisingly comparable, given the uncertainties in these measurements, they should not be considered definitive evidence.

Airflows from the units and the rooftop fans were compared to the nominal plan callouts. Unit airflows were lower than callouts (78% weighted average); rooftop airflows were higher than callouts (109% on average). For reference, the callout ventilation rates (with properly functioning rooftop fans) were higher than code-mandated rates (ASHRAE 62.1 [2010a] or 62.2 [2010b]). The mismatch between rooftop and unit flows shows the effect of interior duct leakage that draws air from interstitial spaces, without necessarily solving interior pollutant problems, resulting in overventilation energy penalties.

Unit air leakage was measured with depressurization testing, showing high air leakage (average of 9.4 ACH 50, or 0.42 cfm 50/ft$^2$ enclosure) and poor compartmentalization. These results can be compared with the Leadership in Energy and Environmental Design Mid-Rise compartmentalization leakage metrics of 7.0 ACH 50 (basic prerequisite), and 4.0 ACH 50 (credit for Environmental Tobacco Smoke control). Much of the leakage appeared to be above the suspended ceiling; air sealing details required for fire rating of the demising walls were never completed. In addition, there was air leakage from the units into the fire-rated shafts that contain the exhaust ductwork.

### *6.1.2 Post-Retrofit Testing*

The retrofit installed variable-speed pressure-controlled rooftop exhaust fans on the existing exhaust shafts. The shafts are connected to multiple individual unit exhaust fans with occupant-operated timer switches. The rooftop fan is set to maintain a constant negative pressure in the exhaust duct. As individual apartment unit fans are turned on, fan speed is increased to maintain pressure. When the unit exhaust fan is off, some limited baseline ventilation occurs through the fan damper. When a unit exhaust fan is turned on to respond to pollutant loads, the rooftop exhaust rate increases (maintaining negative pressure in the shaft).

Airflows were measured at the rooftop unit and in the apartment units, with individual unit exhausts turned on and off. Although rooftop measurements had high uncertainty because of wind effects, it appears that the rooftop fan correctly increases its flow in response to additional unit exhaust fans being turned on. Discerning the changes in flow with each incremental added fan, however, is beyond the resolution of these measurements. Baseline (no unit exhaust running) exhaust ventilation rates were significantly reduced relative to original plan callout levels (~40%–60%).

Power draw measurements appeared to show a substantial improvement in fan efficiency. Calculated efficiency based on this measurement was 10–20 cfm/W, compared to the pre-retrofit efficiency of 1.3 to 2.1 cfm/W—an order of magnitude improvement. This is ascribed to both improved efficiency of the fan motor and the reduction in airflow (40%–60% of original design), which results in effectively oversized ductwork. Efficiency levels this high should not be expected with a new duct system sized for the measured flows. These metrics do not include the contribution of the unit exhaust fans (at 12 W each).

Airflows at the unit exhausts were as expected. With the unit exhaust fan off, there was some airflow (bypass) through the fan's damper. When the unit exhaust fan was turned on, a higher flow was measured. These measurements were typically about 20 cfm (unit fan off) and in the range of 40–50 cfm (unit fan on). The flow rates can be compared with ASHRAE 62.1 (45–60 cfm) and ASHRAE 62.2 (15–25 cfm); note that there are two exhausts per unit (kitchen and bathroom).

Similar to the pre-retrofit measurements, calculated duct leakage could be estimated from the difference between rooftop and unit exhaust measurements. The calculated duct leakage (as a percentage of flow from the rooftop fan) is 40%–50% with the unit exhausts off, and 15%–25% with the unit fans on. Although the unit fans off calculated duct leakage is a very high fraction of the flow (40%–50%), at EF-1 (as an example) the absolute value (85–100 cfm) is comparable to or less than the calculated duct leakage from the pre-retrofit system (110 cfm). EF-7's calculated leakage, however, is more than half the rooftop flow. Overall, this shows that there would have been a benefit to retrofit exhaust shaft duct sealing.

Duct leakage was directly measured in one post-retrofit shaft; it was very high (300 cfm 50 or 99 cfm per floor). The source of this leakage was not determined in this testing because much of the exhaust system is inaccessible (located within fire-rated shafts). No duct sealing, such as aerosol-based sealant or hand-applied mastic to accessible portions, was implemented beyond rooftop curb work.

One risk when using intermittent exhaust fans in a multifamily building is the potential for pressure differences causing unit-to-unit contaminant transport. Measurements indicated that unit pressures induced by intermittent exhaust fans were smaller than wind and stack pressures. Of course, higher airflows and tighter units would result in a larger pressure response.

Monitoring equipment was installed on two exhaust fans to measure the voltage output signal of the variable-speed fan. Data were collected from January 2012 through May 2012. Although the manufacturer provides correlations between control voltage, fan rpm, and airflow (cfm), the measurements do not correspond to the range of measurements seen in the field. Results were only presented, then, in terms of rpm data.

General patterns could be discerned from the voltage measurements. When measurements were correlated against local weather data, a weak correlation could be seen between wind speed and fan control voltage. This is reasonable for a fan controlled by pressure differentials. Little correlation was seen between ambient temperature and fan speeds; arguably, fan voltage amplitude variations are smaller during warmer weather. There was a general diurnal variation in fan speed on a cycle that matches typical occupancy, with low variations during sleeping hours (10 p.m. to 6 a.m.), and greater variations during the day.

Retrofit corridor supply ventilation fans were designed to replace the nonoperational rooftop MAU, which was disabled because of operating expense. A floor-by-floor system that met ASHRAE 62.1 corridor ventilation rates was implemented, plus makeup air for common laundry spaces.

The system was installed and tested. Basic function was as per design, with interior air tempering or diluting the outdoor supply air (at ratios of 2:1 to 3.5:1) for occupant comfort. The system, however, had relatively high static pressures and relatively low fan efficiencies (0.9 cfm/W for net outside air).

## 6.2 Analysis and Conclusions

Some limited conclusions can be drawn from the collected data, extrapolating from the systems that were measured during post-retrofit field work. The energy impact of the reduced ventilation flows were calculated based on the plan callouts and field measurements. Rooftop airflows are used (as opposed to unit airflows), which captures the overventilation effects due to exhaust duct leakage.

Based on the study assumptions, the reduction in ventilation airflow could be on the order of a quarter of the heating energy use (see Table 17). Because multiple energy saving measures were implemented, though, it will be difficult to disaggregate ventilation upgrade benefits from other heating system upgrades.

**Table 17. Extrapolated Savings From Reduction in Ventilation Airflows**

| Measurement | Value |
|---|---|
| Exhaust Airflow From Plans | 9,150 cfm |
| Rooftop Exhaust Measurement Relative to Callout | 109% |
| Extrapolated Pre-Retrofit Rooftop Exhaust Ventilation Rate | **9,951 cfm** |
| Weighted Average Rooftop Exhaust % of Callout (Post-Retrofit, Unit Fans Off) | 50% |
| Normalized Flow for Whole Building (All Exhaust Fans) | 4,575 cfm |
| Unit Exhaust Fans Run 3 H/D, Time Average of Added Flow | 404 cfm |
| Extrapolated Post-Retrofit Rooftop Exhaust Ventilation Rate | **5,445 cfm** |
| Percentage of Original Rate | 55% |
| Heating Load of 1 Cfm Air in Philadelphia Climate | 1.61 therms |
| Gas Reduction From Ventilation Change at 90% Efficiency and Half-Fan Rule | 4,040 therms |
| Wintertime Gas Consumption (Estimated Heating Use), Pre-Retrofit Data 2009–2010 | 16,362 therms |

Calculations can also be made for the reduction in exhaust fan wattage, as shown in Table 18.

**Table 18. Extrapolated Savings From Reduction in Exhaust Fan Wattage**

| Measurement | Value |
|---|---|
| Exhaust Fan Efficiency, Pre-Retrofit (Average of 3 Fans) | 1.6 cfm/W |
| Exhaust Fan Efficiency, Post-Retrofit (1 Fan Data) | 20 cfm/W |
| Wattage Draw of Pre-Retrofit System (24/7/365 Runtime) | **6,200 W** |
| Wattage Draw in Post-Retrofit System (Rooftop Units Only, 24/7/365 Runtime) | 213 W |
| Unit Exhaust Fan Wattage (One Fan) | 12 W |
| Unit Exhaust Fan Wattage With 3 Hours/Day Runtime, Averaged (All Fans) | 183 W |
| Wattage Draw of Post-Retrofit System (Including Unit Fans) | **396 W** |
| | |
| Pre-Retrofit Exhaust System Electricity Use | 4,524 kWh/month |
| Post-Retrofit Exhaust System Electricity Use | 289 kWh/month |
| Baseline Electrical Use From 2009–2010 Energy Use Data | 30,000 kWh/month |

The combination of reduced exhaust airflow (in an oversized duct system) and more efficient fans results in substantial electrical energy savings, assuming that field measurements are representative of the system as a whole.

One slight weakness of the implementation was the lack of commissioning of the variable-speed fans. All fans were left at their default setting of 0.10-in. water column /25 Pa at the trunk duct. This did, however, produce very reasonable flows for most of the exhaust shafts that were measured. This system would ideally be commissioned by setting a static pressure set point that provides consistent draws through the individual exhaust fans in their "passive" mode (e.g., ~20 cfm/opening in the measured system).

In addition, the timer switches were not commissioned, but given that target exhaust flows were being achieved in the passive (unit exhaust fan off) state, additional timer-based runtime of the unit exhaust fan is not necessary. The unit exhaust fans can still be operated at the occupant's discretion to address pollutant loads.

The lack of systematic exhaust shaft duct sealing was a missed opportunity in this retrofit project; for example, the duct leakage in the post-retrofit shaft was very high. Given the geometry of the ductwork system, aerosol-based duct sealing would have been the best candidate for this work, and would have reduced the overventilation caused by exhaust shaft leakage.

## 6.3 Further Work

If resources are available for further field work at Mercy Douglass Residences, the following activities could be worthwhile.

Given the uncertainty in the correlation between measured control voltages and airflow (cfm), fan speed (rpm) for the variable-speed fans might be directly measured using a handheld strobe tachometer. Control voltage could be measured at the same time.

Examination of the post-retrofit energy bills (gas and electricity) would reveal indications of overall reductions in gas heating energy use, domestic hot water energy use, and common space electricity use (rooftop exhaust fans and heating loop pumping energy). It also might give more insight into the wintertime electrical peak use seen in pre-retrofit data.

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