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Evaluation of Ventilation Strategies in New Construction Multifamily Buildings

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Consortium for Advanced Residential Buildings

July 2014

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Evaluation of Ventilation Strategies in New Construction Multifamily Buildings

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Definitions

CARB	Consortium of Advanced Residential Buildings
CFM	Cubic Feet per Minute
CFM50	Cubic Feet per Minute Flow at A Test Pressure of 50 Pascals
CFM50/ft^2	CFM at a Test Pressure of 50 Pascals per Square Foot of Enclosure Area
ERV	Energy Recovery Ventilator
HVAC	Heating, Ventilation, and Air Conditioning
HRV	Heat Recovery Ventilator
kWh	Kilowatt-hour
LEED	Leadership in Energy & Environmental Design
MUA	Make-Up Air
OA	Outdoor Air
Pa	Pascal
PTAC	Packaged Terminal Air Conditioner
SWA	Steven Winter Associates
TAB	Testing and Balancing
W	Watt

Executive Summary

In multifamily buildings, particularly in the Northeast, exhaust ventilation strategies are the norm as a means of meeting both local exhaust and whole-unit mechanical ventilation rates required by ASHRAE 62.2 (ASHRAE 2010b). Through this research and their role in multifamily program implementation work in the region, Consortium for Advanced Residential Buildings (CARB) researchers believe that the majority of high performance, new construction, multifamily housing in the Northeast uses one of four general strategies for ventilation:

1. Continuous exhaust only with no designated supply or make-up air (MUA) source
2. Continuous exhaust with ducted MUA to apartments
3. Continuous exhaust with supply through a MUA device integral to the unit heating, ventilation, and air conditioning system
4. Continuous exhaust with supply through a passive inlet device, such as a trickle vent.

CARB researchers have also seen a subset of the first category, where the doors between interior corridors and apartments are undercut to allow MUA to flow from the corridor into the apartment. The general strategy is to pressurize the corridor using supply air and depressurize the apartments through continuous local exhaust. Though in many building codes this practice is essentially prohibited for reasons of fire safety, it is still a relatively common practice.

Insufficient information is available to designers on how these various systems are best applied. Product performance data are based on laboratory tests, and the assumption is that products perform similarly in the field. Since all ventilation systems are designed to work within a specific operating environment, proper application involves matching expected performance at expected building pressures. Still, in the case of passive ventilation systems that are dependent on environmental conditions, there is no guarantee that those conditions exist consistently in the finished building. This research effort sought to provide field validation of system performance. The performance of four substantially different strategies for providing MUA to apartments was evaluated.

Testing indicated that there is considerable variation in the amount of MUA provided by passive devices (System 4). Since operation of these devices is based on a pressure difference, any factors that affect the pressure across the device directly affect the flow. The role of wind is clearly visible by the short-term fluctuation of the pressure monitoring results. The airtightness of the apartment plays a major role in the performance of these devices. A well-sealed and compartmentalized apartment is needed in order to establish an adequately depressurized space.

In the case of the PTAC MUA fan (System 3), it was found that this strategy provided supply flows that were approximately 15% of the MUA. The balance of MUA was split roughly in half between leakage around the apartment door and other sources of infiltration. Despite the poor performance, this strategy still offers promise. Several changes in the system design could significantly improve the performance. In addition, a tight, well-compartmentalized building would result in a greater pressure differential, which the MUA fan experiences, and thus a greater flow through the fan.

Active MUA strategies (System 2), such as dedicated supply air from a central rooftop unit, can be highly effective at delivering specified quantities of MUA to apartments; however, a thorough testing and balancing process is required. In the units tested under this study, the performance varied from 12% to 132% of the design. This wide range indicates the need for clear, well-defined specifications and careful construction oversight with commissioning and verification of system performance.

Testing of local exhaust-only (System 1) indicated that approximately 25% of the MUA for apartment exhaust was being drawn from the corridor through leakage around the door, while the remainder came from other sources of infiltration. This is most likely a combination of infiltration from the exterior, from other apartments, and from interstitial spaces. With so many potential sources of MUA, it is not accurate to assume that one source predominates. While some factors that influence air movement can be controlled, most cannot. As a result, this strategy does not consistently deliver adequate MUA.

In order for a MUA strategy to function properly, it is necessary that the exhaust system operate as designed. On several occasions, it was observed that exhaust fans were not performing at their design levels. CARB also found situations where the same model fan was installed in each apartment, yet the performance was drastically different. These issues are the result of poor design, poor installation, or a combination of the two. Again, thorough testing and commissioning help to prevent these issues and ensure proper function of both exhaust and MUA systems.

The airtightness of an apartment plays a major role in the performance of MUA systems, especially when passive strategies are employed. Further study should be conducted to determine the minimum level of air sealing necessary to ensure performance. This is particularly important in maintaining pressure differentials and minimizing fluctuations due to environmental conditions.

1 Problem Statement

In multifamily buildings, particularly in the Northeast, exhaust ventilation strategies are the norm as a means of meeting both local exhaust and whole-unit mechanical ventilation rates required by ASHRAE 62.2. According to this Standard, an exhaust system is "one or more fans that remove air from the building, causing outdoor air to enter by ventilation inlets or normal leakage paths through the building envelope." If participating in a high performance building program, like ENERGY STAR® Certified Homes, exhaust ventilation system flow rates must be verified in the field to demonstrate compliance with ASHRAE 62.2 ventilation rates, but the source and quantity of make-up air (MUA) is rarely addressed. Although ENERGY STAR Certified Homes, Version 3, Rev. 07, requires that "ventilation air comes directly from outdoors, not from adjacent dwelling units, garages, crawlspaces, or attics," dedicated MUA is not explicitly required, and the source and quantity are not verified (EPA 2010). The issue of where the "fresh" air is coming from is gaining significance as airtightness standards for enclosures become more stringent, and the "normal leakage paths through the building envelope" disappear.

Even with few data available to support it, some high performance building programs, such as the U.S. Green Building Council's Leadership in Energy & Environmental Design (LEED) for Homes and the New York State Energy Research and Development Authority's Multifamily Performance Program, have recognized the importance of MUA. These programs have already included additional prescriptive requirements for MUA strategies, beyond what is required by ASHRAE 62.2, but still without any commissioning requirements to verify that the MUA system actually works. For example, LEED for Homes Mid-Rise requires that "outdoor air must be provided to each unit directly from the outdoors" (LEED 2010). While ASHRAE 62.2-2010, Section 6.1.1 accepts a ventilation system design that "explicitly requires transfer air from corridors into units," LEED for Homes Mid-Rise explicitly prohibits "systems that rely on transfer air from pressurized hallways or corridors, adjacent dwelling units, attics, etc." Other programs, like ENERGY STAR's Multifamily High Rise Program, are waiting for building research to inform their ventilation requirements.

As the industry waits for research results, exhaust ventilation approaches and corresponding MUA strategies (if any) are being implemented in high performance new construction multifamily buildings to meet program or code requirements, but a lack of clear guidance is resulting in poor implementation of ventilation systems despite the best intentions of the programs or standards cited above. Provisions for MUA, without depending on infiltration, come in many forms, ranging from fully ducted systems that deliver MUA directly to apartments, to designed holes in the envelope such as trickle vents, or outdoor air (OA) dampers tied to the space conditioning system. Passive systems are some of the least expensive options for providing MUA directly to apartments, but not enough is known about how effective they actually are. Pressurizing corridors by oversizing corridor space conditioning systems to provide an indirect source of MUA to apartments is a controversial but common practice that, thus far, has led to high energy use with no data to justify the perceived indoor air quality benefit to the apartment.

As ventilation rates increase along with air-tightness requirements, the MUA issue is only going to be exacerbated. Joe Lstiburek's article "Unintended Consequences Suck" in the June 2013 *ASHRAE Journal* expounds upon this (Lstiburek 2013). However, regardless of the ventilation design rate being implemented, design support to improve the performance of multifamily mechanical ventilation systems is warranted.

Insufficient information is available to designers on how these various systems are best applied. Product performance data are based on laboratory tests, and the assumption is that products perform similarly in the field. Since all ventilation systems are designed to work within a specific operating environment, proper application involves matching expected performance at expected building pressures. Still, in the case of passive ventilation systems that are dependent on environmental conditions, there is no guarantee that those conditions exist consistently in the finished building. Evaluation is needed to validate system performance in the field.

1.1 Previous Research

Steven Winter Associates/the Consortium for Advanced Residential Buildings (SWA/CARB) have been researching residential ventilation systems for more than a decade. In 2006, CARB tested and compared ventilation systems in high performing single-family homes in south Chicago, to evaluate performance and cost effectiveness (Aldrich 2006). In 2008, SWA evaluated the performance of self-balancing air dampers in multifamily central exhaust ventilation systems. The importance of air sealing the exhaust duct work was evident and methods including the Aeroseal technology were examined. This research was funded by the Partnership for Advancing Technology in Housing Program and the report was published by the National Association of Home Builders Research Center. The work was frequently cited by Building Science Corporation in its ventilation research study performed as part of an energy retrofit of an existing Philadelphia multifamily building (BSC 2012).

In 2009, SWA, Camroden Associates (Terry Brennan), and the National Center for Healthy Homes developed two best practice guides for exhaust-only systems in multifamily buildings applicable to both new construction and retrofits. These guides provide a blueprint for designing and implementing exhaust-only ventilation systems in multifamily buildings that meet ASHRAE 62.2 local exhaust and whole-unit ventilation rate requirements (NCHH 2009a, 2009b).

In 2013, CARB again evaluated ventilation systems in single-family homes to determine performance and cost effectiveness; however, this time the focus was retrofits of existing homes (CARB 2013). Neither the Building Science Corporation research nor these SWA/CARB research projects evaluated the source or quantity of the MUA.

In 2010, SWA performed testing in a multifamily building that had taken the extra step to pair exhaust ventilation with appropriately sized trickle vents, in order to provide a dedicated source of MUA. To support the development of the ENERGY STAR Multifamily High Rise program, EPA funded SWA to perform similar ventilation research in three additional midrise multifamily buildings. Through this work, a repeatable protocol for evaluating the performance of the compartmentalized apartment/unitized ventilation design has been developed and further refined for the current research.

The Canadian Mortgage and Housing Corporation has conducted considerable research on residential ventilation systems. A survey of corridor ventilation systems in midrise and high-rise multifamily buildings found that actual corridor and exhaust flows were considerably lower than the design levels. Environmental conditions, building airtightness, and compartmentalization all affected the flows. The study found that designers assumed MUA would be provided from the corridor and infiltration; however, little was done in the design or construction to ensure this.

Further research by the Canadian Mortgage Housing Association has shown that ventilation systems can be affected by a complex interaction of factors. Under- and overventilation are common occurrences. In corridor supply systems it has been found that much of the air bypasses the apartments and exits through stairwell, elevator shafts, and other points. In the study, four alternative ventilation strategies were evaluated (CMHC 2003), including passive vents and three variations of heat recovery ventilator (HRV) systems. It was found that passive vents were susceptible to wind and stack pressures and require compartmentalization of apartments to work properly. HRVs performed well, but were expensive and required greater maintenance.

Another study looked at the impacts of corridor ventilation on building energy consumption. The common notion this study examined was the belief that corridor supply systems can displace space heating by pressurizing the building. The results of the study disprove this concept. The corridor system did not displace significant amounts of infiltration or space heating load. The conclusion was heated air form the corridor system was finding direct routes to the outside and bypassing most areas.

Building Science Corporation has found that central ventilation systems in multifamily buildings often have poor overall performance. It recommend compartmentalizing apartments, sealing ductwork, and installing variable-speed, pressure-controlled fans with electronically commutated motors. The resulting system can improve performance and reduce heating energy and fan electric energy.

1.2 Research Questions

The following research questions were the focus of this project:

- What type of exhaust ventilation systems and corresponding MUA strategies (if any) are being implemented in high performance new construction multifamily buildings to meet whole-unit ventilation rates of ASHRAE 62.2?
- How can the air delivery performance of passive MUA strategies such as trickle vents, OA dampers, or door undercuts be measured and quantified in actual installations? How variable is the performance and what are the key factors that affect it—apartment location, extent of compartmentalization, season, etc.?
- Do the MUA strategies for apartments, both passive and active, function as designed when installed in actual buildings?
- Can specifications be developed to better ensure proper performance from all MUA strategies?
- What is the energy cost associated with the fan power of mechanical supply systems?
- Considering the choices for various ventilation approaches and the factors impacting their cost-effectiveness—material cost, efficiency, and performance—under what conditions is each system optimal?

2 Technical Approach

2.1 Make-Up Air Ventilation Strategies

This research project evaluated the performance of four substantially different strategies for providing MUA to apartments:

- No direct MUA supplied to apartments
- MUA through ducted supply air
- MUA through HVAC supply (i.e. packaged terminal air conditioner [PTAC] OA damper)
- MUA through passive vents.

2.1.1 Type 1: No Direct Make-Up Air Supplied to Apartments

In multifamily buildings, both high-rise and low-rise, although local mechanical exhaust and whole-unit ventilation may be provided, there might not be a provision for direct MUA to the apartments (see Figure 1). In the case of buildings constructed to low-rise residential building codes with no common spaces (e.g., townhouses), MUA may be assumed to come from air leaks in the exterior envelope. Also, when a building is designed with a common hallway and interior apartment entries, OA may be delivered to corridors but none is supplied directly to apartments. The intention, however controversial, may be that this air passes into apartments indirectly through door undercuts.

Figure 1. Example of a building with no direct MUA to apartments

Newer building codes for high-rise buildings essentially prohibit this latter approach, in part because it is not compatible with fire-resistant construction principles that call for complete separation of apartments from each other and from common spaces. ASHRAE Standard 62.1-2010 calls for very little corridor ventilation (0.06 CFM/ft^2 of corridor area), removing the rationale for pressurizing corridors with high amounts of OA. Still, a very common design for high-rise buildings calls for apartments with exhaust-only ventilation, no provision for direct supply air, and the expectation that at least some MUA will be supplied by the overventilated corridors. This research assesses whether corridor air makes its way into apartments through air leakage around the door frame and door undercut, intentionally or not.

2.1.2 Type 2: Make-Up Air Through Ducted Supply Air

This system type generally has continuous in-unit or central exhaust from apartments and continuous central fresh MUA directly supplied to each apartment (see Figure 2). In some instances, the supply air is provided by an energy recovery ventilator (ERV) or HRV that captures energy from central apartment exhaust; in others, it can be provided by the same space conditioning system serving the corridor. Verifying the delivery of MUA to apartments is straightforward, involving measurement at supply registers within the apartment. Research goals for this system type included verifying supply air delivery rates, making measurements of power consumption of the unit's exhaust and supply fans, and measuring the heat recovery efficiency (if present).

Figure 2. Example building with central ducted supply (left) and a central supply unit (right)

2.1.3 Type 3: Make-Up Air Through HVAC Supply

This system type uses the heating and/or cooling system of individual apartments as the source of MUA delivery through one of a variety of methods. In buildings with PTACs, MUA can be provided either through passive OA dampers that draw in air during normal blower operation or through a dedicated, powered OA supply fan in each PTAC unit (see Figure 3). The strategy is similar for buildings with fan coils or with ducted in-apartment air handlers using air cyclers or other integrated fresh air devices.

Figure 3. Example of a building with MUA from PTACs

2.1.4 Type 4: Make-Up Air Through Passive Vents

This system type uses engineered passive vents in the exterior envelope to provide MUA from outside. Exhaust in apartments is provided by either central or in-unit fans operating continuously. The negative pressure that these fans create is meant to draw MUA into the apartment through these passive vents.

The research focus for this system type is the functioning of passive vents under various pressure conditions. Since the passive vents are meant to operate in a general environment of negative apartment pressure, the research assessed whether these negative pressures prevail through a variety of environmental conditions.

2.2 Factors Affecting Ventilation System Performance and Choice of Measurements

Many factors affect the performance of a ventilation system and its ability to deliver fresh air to apartments, including elements of the proposed building design, its as-built construction, and human and environmental interaction with the building during occupation (see Table 1). Because the tests chosen for evaluation of performance in the study buildings are only a sample of a large number of possible tests, this study cannot provide final conclusions for ventilation systems of every type.

Table 1. Factors Affecting Ventilation Performance

Design Factors	• **Overall ventilation scheme** • Supply and exhaust design flow rates • Choice of ventilation equipment • Size and shape of building • Choice of building materials and techniques
Construction Factors	• Quality of ventilation equipment and duct installation • Airtightness of the building's exterior envelope and interior partitions
Environmental Factors	• Indoor and outdoor temperature • Wind pressures
Human Factors	• Operation of ventilation system's "modes" (high, low, etc.) • Resident operation of windows and other air pathways • Temperatures of building spaces

The tests below were chosen to evaluate construction and environmental factors in this study where possible. No attempt was made to quantify design factors because they are too varied to consider in this study. The influence of human factors was not adequately prepared for in this study and led to difficulty in evaluating some of the other factors. Further studies should more fully anticipate their influence.

2.3 Building Descriptions and Information

Test buildings were selected that represented each of the four ventilation strategies. Selection was based on construction schedules and owner enthusiasm for participating in this study. The aim was to choose buildings that had just completed construction, but were not yet fully occupied. This was to facilitate initial testing in the apartments. All of the test buildings in this study completed construction between late 2012 and 2013.

2.3.1 Type 1 Building: No Direct Make-Up Air Supplied to Apartments

The "No Direct Make-Up Air" test building is part of a senior housing complex in the greater Albany area of New York. The complex consists of a central building and numerous residential buildings. The structures are all connected; however, each building is separated by fire doors. The portion of the complex that was used for testing is circled in Figure 4. The apartments where pressure monitoring was conducted are highlighted in yellow. The three numbers in each box indicate the apartment number on each floor, lowest being floor 1, highest being floor 3.

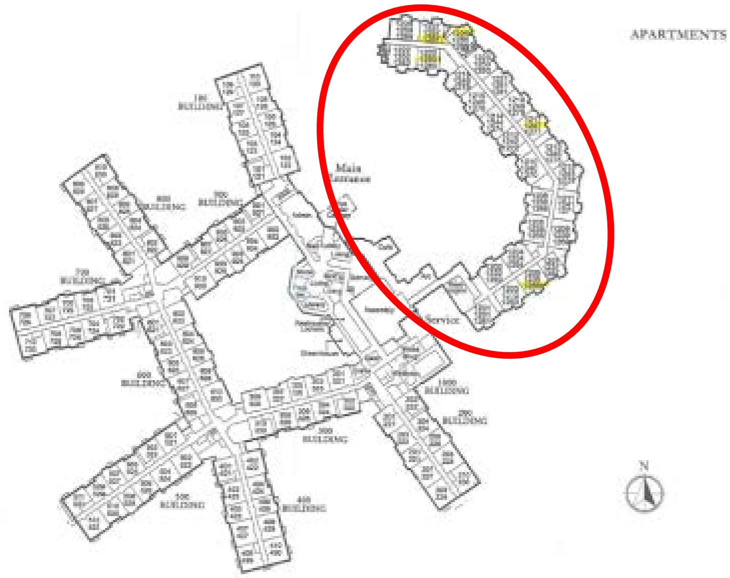

Figure 4. Apartment layout of test building "Type 1"

The test building is three stories tall. There is a corridor (~3,800 ft^2) that runs the length of the building, one elevator bank with two elevators, and four stairwells at the ends and midpoints of the building. Each floor has 26 apartments, two storage rooms, two lobbies, three garbage rooms, and two janitor closets.

Ducted OA is supplied to the corridors by nine vents on each floor, with a design supply of 850 CFM, or 0.22 CFM/ft^2. Although ASHRAE 62.1 requires a minimum of only 0.06 CFM/ft^2 for corridors, the system was intentionally designed to provide an additional 20–30 CFM per apartment, to indirectly provide MUA to the units (ASHRAE 2010a). In addition to the corridor ventilation, there is supply to each storage room (designed at 250 CFM/floor), exhaust from the three garbage rooms (designed at 420 CFM/floor), and exhaust from the two janitor closets (designed at 100 CFM/floor).

To meet the local exhaust and whole-unit ventilation rates required by ASHRAE 62.2, each apartment has a bathroom exhaust fan with occupancy-sensor boost that exhausts directly through the exterior wall of the apartment. When motion is detected in the bathroom, the fans ramp up from a low continuous ventilation rate of ~30 CFM to a high boost. In addition, kitchens in apartments are equipped with range hoods that exhaust directly to the exterior. The range hoods have three settings: high, low, and off; and are manually operated.

In theory, the design supplies 5,250 CFM of OA to the corridors and common spaces, and exhausts only 1,560 CFM from the garbage rooms and janitor closets, which should leave the corridor positively pressurized, with more than 40 CFM of OA per apartment.

2.3.2 Type 2 Building: Make-Up Air Through Ducted Supply Air

Two buildings were selected that represent the "Type 2" strategy. Both buildings are located in eastern Massachusetts. Both were existing former industrial buildings that were completely rehabilitated. Each building participated in utility conservation programs and the LEED for

Homes certification process during its construction. Participation included testing of apartment airtightness and testing and balancing (TAB) of heating, ventilation, and air conditioning (HVAC) system flows. Building #1 is four to five stories with 62 apartments, while Building #2 is five stories with 64 apartments. Each building has a central ERV on the roof that continuously exhausts air from apartment bathrooms and kitchens and delivers fresh MUA back to each apartment and corridor.

To meet the local exhaust ventilation rates required by ASHRAE 62.2, each apartment bathroom was designed to exhaust 25–30 CFM continuously and each apartment kitchen was designed to exhaust 50–60 CFM continuously, with the exception of the few units on the fifth floor in Building #1, where the kitchens are intermittently vented through the roof and not attached to the ERV. To meet the whole-unit ventilation rates of ASHRAE 62.2 and the prescriptive OA requirements for LEED for Homes certification, the design called for 50–90 CFM of MUA, ducted directly into the apartment. By design, the supply to the apartments was not intended to provide the same CFM as exhausted, but rather to meet the whole-unit ventilation rates of ASHRAE 62.2, which are lower than the continuous local exhaust requirements. Typical floor plans of both buildings are shown in Figure 5 and Figure 6.

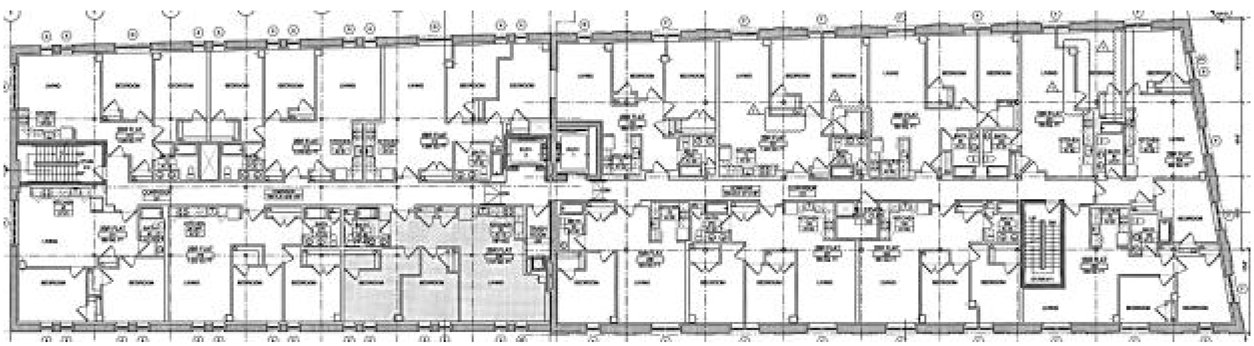

Figure 5. Typical floor plan of test building #1 of "Type 2"

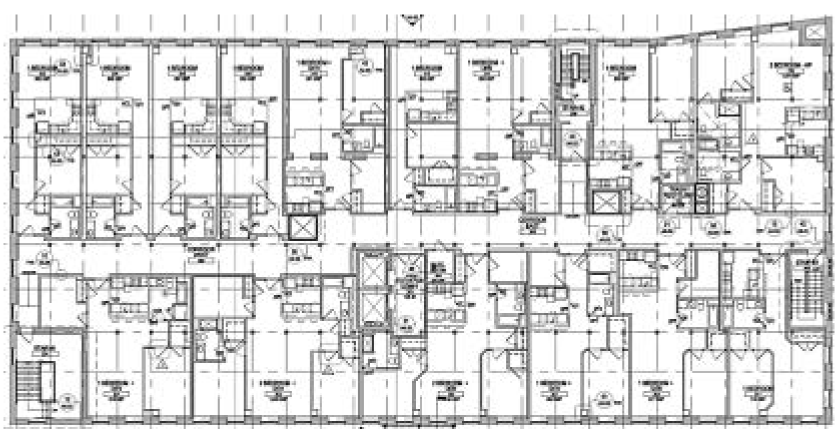

Figure 6. Typical floor plan of test building #2 of "Type 2"

2.3.3 Type 3 Building : Make-Up Air Through HVAC Supply

The "Type 3" test building is part of a senior housing complex in Westchester County, New York (Figure 7). It is a four-story, L-shaped building. There are 17 apartments per floor. There are a laundry room, a two-elevator bank, and three stairwells per floor. A typical floor plan is shown in the figure below. Pressure monitoring was conducted in apartments P and R on floors 2, 3, and 4. The locations of these apartments are indicated by the shaded blue boxes.

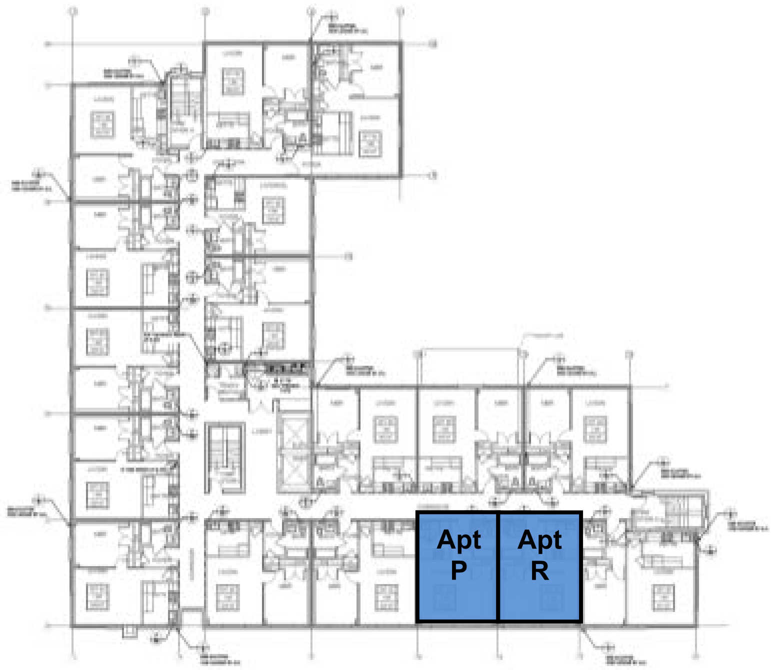

Figure 7. Typical floor plan of test building "Type 3"

The building participated in LEED for Homes Certification and the New York State Energy Research and Development Authority's Multifamily Performance Program during its construction, which required a provision for OA and included testing of apartment airtightness and TAB of HVAC system flows. The apartments are heated and cooled by PTACs with hot water coils. To meet the local exhaust required by ASHRAE 62.2, each apartment has an inline exhaust fan that draws air from the kitchen and bathroom. These fans operate continuously and vent directly to the exterior. The design calls for 30 CFM from the kitchen and 25 CFM from the bathroom. To provide MUA to meet the whole-unit ventilation rates, a PTAC with an OA damper and powered-fan was installed, which was intended to provide 40 CFM continuously, whether or not the main PTAC blower fan was running. Studio apartments have one PTAC, while one-bedroom units have two. All PTACS are equipped with fresh air kits.

2.3.4 Type 4 Building: Make-Up Air Through Passive Vents

The "Type 4" test building is located in the Bronx, New York. It is a five-story, T-shaped building. There are 13 apartments per floor. There are a laundry room, a refuse room, a storage room, an elevator bank, and two stairwells per floor. A typical floor plan is shown in Figure 8. Pressure monitoring was conducted in apartments 3F, 4K, 4L, 4M, 5A, and 5H.

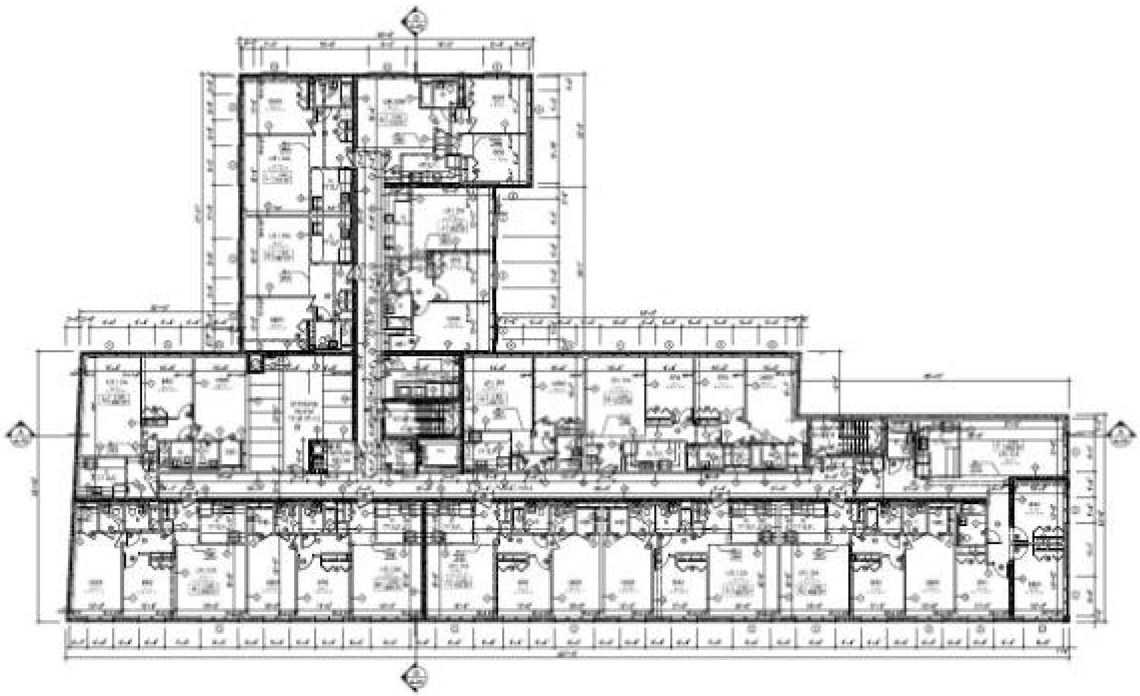

Figure 8. Typical floor plan of test building "Type 4"

The building participated in LEED for Homes Certification and the New York State Energy Research and Development Authority's Multifamily Performance Program during its construction, which required a provision for OA and included testing of apartment airtightness and TAB of HVAC system flows. The apartments are heated by hydronic baseboard convectors. To meet the local exhaust and whole-unit ventilation rates required by ASHRAE 62.2, the apartments are ventilated by inline fans drawing from kitchens and bathrooms and operating continuously. MUA is intended to come from trickle vents installed in window frames. There is one trickle vent in each living room and one per bedroom. It is not clear how the trickle vents were "sized" or selected for this building. They are all the same make and model.

2.4 Measurements and Tests

The tests listed in Table 2 were used in the analyses of the different ventilation strategies. For each building type they can be grouped into three main stages: detailed tests on building components, pressure monitoring in the winter, and pressure monitoring in the summer. For each building type, at least one building was tested in detail. Minimum sampling rates for each test are also shown below. These rates were determined based on the availability of previous test data and access to units for additional testing. Pressure monitoring was conducted for 2 weeks during the winter and 2 weeks during the summer. The length of the sampling period was based on the availability of equipment, availability of occupied units, and need to collect data that are representative of the season. The aim was to make the sampling period as long as possible, while still being able to monitor all of the buildings.

Table 2. Measurements and Sampling Rates at Each Building Type

Test	Number of Samples per Building Type (Percentage)			
	No Direct MUA Supplied to Apartments	MUA Through Ducted Supply Air	MUA Through PTAC	MUA Through Passive Vents
Apartment Blower Door Testing	27 (35%)	29 (23%)	9 (15%)	9 (14%)
Ducted MUA Supply Flows to Apartment		45 (36%)		
Corridor Supply Flows	31 (94%)			
Door Leakage Airflow	8 (10%)		7 (11%)	5 (8%)
PTAC OA Damper Airflows			5 (8%)	
Passive Vent Testing				5 (3%)
Apartment Exhaust Flows	11 (14%)	45 (36%)	6 (10%)	14 (22%)
Pressure Monitoring	5 (6%)		5 (8%)	5 (8%)

Details for the tests designed to provide data on various aspects of building and ventilation performance are given in Section 2.4.1 through Section 2.4.6. For improved context, details on the tests specific to a particular building type are provided in Section 3.

2.4.1 Apartment Blower Door Testing

Apartment airtightness (compartmentalization) is an important aspect of high performance construction, impacting the function of ventilation systems and other airflow patterns in an operating building. Evaluating apartment blower door data alongside ventilation performance measurements reveals correlations between the two. Buildings selected for evaluation have recently participated in high-performance building programs, where single-point, single-unit unguarded depressurization tests were conducted at 50 Pa, for more than 10% of the units.

2.4.2 Supply and Exhaust Flow Testing

The proposed testing involves using an orifice/pressure box or powered flow hood to measure airflow at apartment ventilation supply and exhaust registers, and comparing this to design values (see Figure 9). Airflow at corridor supply registers and common area exhaust registers will also be tested by this method.

Figure 9. Powered flow hood

2.4.3 Door Leakage Airflows

The testing apparatus for this experiment consists of a capture hood to encapsulate the door and capture airflow and a fan to impart a pressure on the hood and measure airflow. Readings are taken at different pressure drops across the door and the data analyzed to identify a basic curve for predicting airflow through a typical apartment door in the building (see Figure 10). These data are then combined with pressure monitoring results to infer the direction and magnitude of airflow across the apartment doors on a building-wide basis over time.

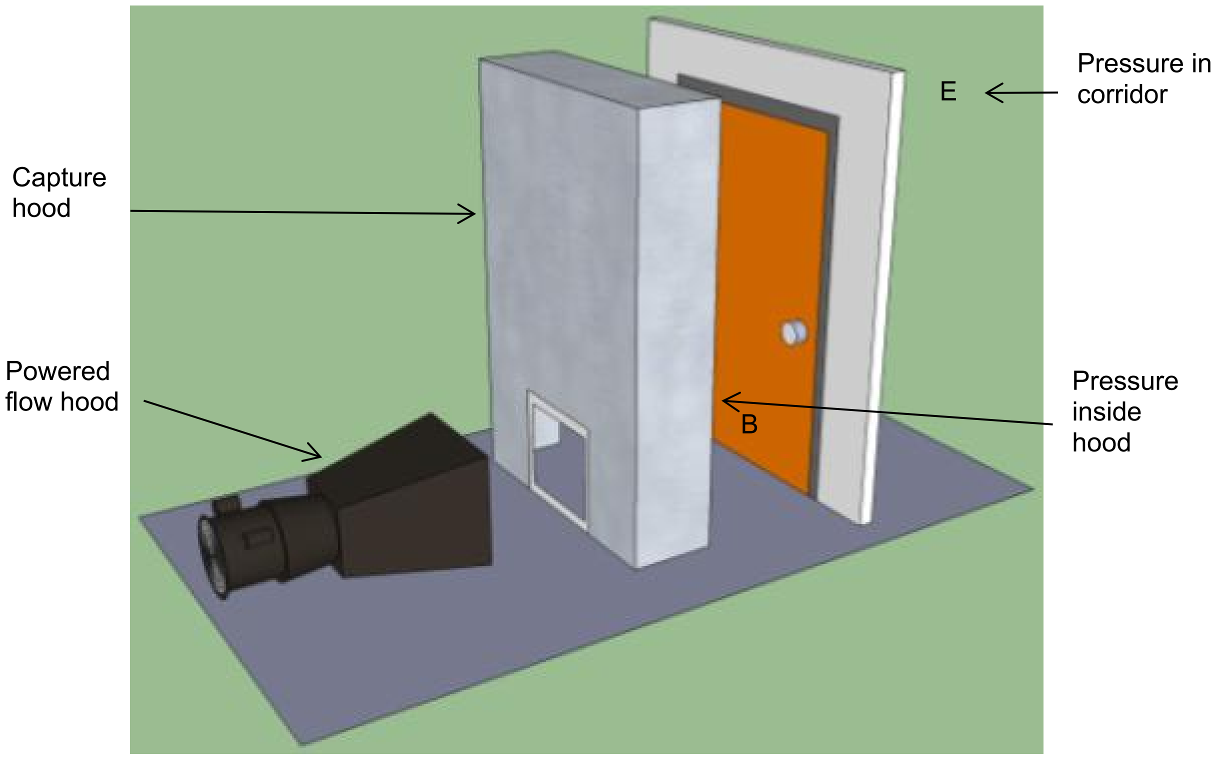

Figure 10. Setup for testing air leakage from a door frame

The testing apparatus is set up by constructing a capture hood from rigid polyisocyanurate foam board over the apartment entry door. This hood captures all airflow from the door frame and directs it to an opening where it is measured by a powered flow hood. A pressure difference across the door (A to B) is developed at several different levels. At each pressure difference, the powered flow hood measures the airflow. The powered flow hood is capable of both pressurization and depressurization tests but must be configured separately for either mode.

Door leakage in one of the test buildings in this study was measured using an alternate orifice plate method, because the above method had not been developed yet. The orifice plate method is described in more detail in Section 3.4.5 for the building in which it was used. Although the method was accurate, its setup was time consuming and cumbersome, leading to the need for an easier, faster way to measure leakage. The method described in this section is an improvement that was developed during the course of this study.

The two methods of measuring door leakage were not directly compared on the same building, but a check of the orifice plate method was made by comparing it to blower door results, as described in Section 3.4.5.

2.4.4 Pressure Monitoring

Airflow patterns in buildings are dependent on pressure differences. Understanding the major patterns of pressure fields is important to predicting the behavior of the airflow-related systems (mechanical, envelope, etc.) under various environmental and operational conditions. In most buildings during the winter, pressures prevailing on the exterior envelope are positive with respect to outside near the top of the building and negative at the bottom of the building, as illustrated in Figure 11. By comparing the results of flow testing with a "map" of pressure differences, the airflow through passive inlets and its variability can be predicted.

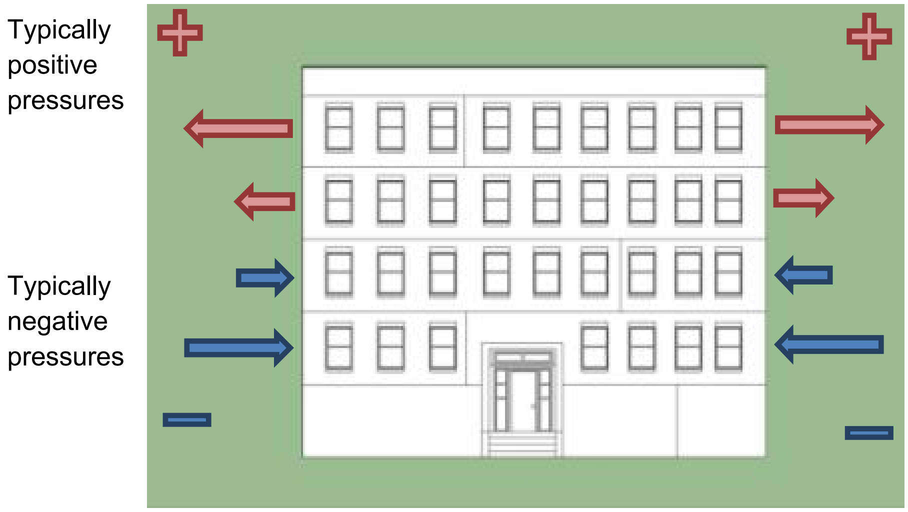

Figure 11. Typical pressure patterns in a multistory building in winter

An array of pressure sensors will be used to monitor pressure differences and predict general airflow patterns between key building areas. The following points will be measured with digital gauges and communicated to a central monitoring station: ground floor interior/exterior; apartments on lower, middle, and upper floors; and upper floor interior/exterior. A total of five points will be measured over a 1–2 week period. This test will be conducted twice; once during the winter and once during the summer season to observe the operating difference.

The goal of characterizing airflow at various pressures through trickle vents, apartment entry doors, and OA dampers of PTAC units is a predictable model of airflow patterns through these leakage points over time. By comparing the results of airflow testing with a map of pressure differences, the airflow through passive inlets can be predicted. Prevailing pressures monitored over time will indicate expected airflows.

2.4.5 Supply and Exhaust Fan Power Consumption

Fan electricity power consumption is estimated from product literature at the flow rates measured. The electricity use combined with the flow rate can be used to determine the relative fan efficiency in cubic feet per minute of air per Watt of electricity (CFM/W).

2.4.6 Factors Affecting the Measurement

In addition, environmental conditions play a large role in the operation of passive devices, the primary factors being wind and temperature. The role of wind is still clearly visible by the short-term fluctuation of the pressure monitoring results; however, the specific effects are difficult to quantify because of its intermittency and high variability. In addition, local wind data were not collected as part of this study.

There is no clear correlation between apartment location and flow through passive devices. In general, apartments on higher floors experience greater pressure variation due to wind; however, the specific geometry and situation of the building on its site enhance or detract from the impact of wind speed and direction. Location of trees, open spaces, setbacks, and other buildings all affect the local environment and can result in significant variations in building pressures for apartments on the same floor.

Occupant behavior is likely the largest influence on system behavior, but the effect is difficult to quantify or predict. Occupants may alter the operation of the ventilation system directly, for example by opening, closing, or blocking off vents, or turning on or off fans; or they may affect their operation indirectly by opening windows or adding or removing seals like weather-stripping to doors.

Occupant interaction with the ventilation systems can become a major challenge to measurement efforts, as additional efforts must be made to either record alterations to the systems by occupants, or to analyze the data and understand where occupant behavior is an influence. In this study, efforts were made to educate residents on the aims of the study and the requirements for participation. For example, residents were asked not to operate their windows during the study, but since CARB was not able to monitor them directly, there is no way to be certain that they were not. Future studies will need to record occupant interaction more directly if they are conducted in occupied buildings.

3 Results and Findings

The following subsections are organized according to the four MUA strategies discussed in the Technical Approach. The tests associated with each strategy and corresponding results are presented below.

3.1 Type 1: No Direct Make-Up Air Supplied to Apartments

3.1.1 Apartment Blower Door Testing

Blower door tests were conducted on 35% of apartments pursuant to utility incentive and green building program requirements. The building is built with an average apartment airtightness of 0.24 CFM50/ft^2 of enclosure area (or 5 ACH50) (see Table 3).

Table 3. Type 1 Building Apartment Airtightness Metrics

Measure	Unit Floor Area (ft^2)	CFM50	CFM50/ft^2 Enclosure	ACH50
Low	770	488	0.17	3.61
Average	1,018	767	0.24	5.06
High	1,115	990	0.30	6.87

3.1.2 Supply and Exhaust Flow Testing

The exhaust airflow of the bathroom fans was measured using an orifice/pressure box (Exhaust Fan Flow Meter from The Energy Conservatory). The average airflow from the bathroom fans during normal operation was 34 CFM. The average airflows from the first and second baths in "boost" mode were 91 and 92 CFM, respectively. The results are summarized in Table 4. Some of the variation in flows is due to the fact that two models of fans were used. One is designed for 30 CFM at low and 80 CFM on boost. The other fan type is designed for 50 and 130 CFM.

Table 4. Bathroom Exhaust Flows

Apartment (Floor)	Bath 1 Low Speed, Measured/Design, CFM)	Bath 1(Boost, Measured/ Design, CFM)	Bath 2 (Boost, Measured/Design, CFM)
1220 (1st)	31/30	Not tested	63/80
1221 (1st)	40/50	114/130	99/130
1227 (1st)	32/30	78/80	80/80
1229 (1st)	40/50	126/130	132/130
1248 (2nd)	30/30	68/80	79/80
1252 (2nd)	34/30	76/80	136/80
1255 (2nd)	30/30	81/80	Not tested
1257 (2nd)	32/30	83/80	74/80
1276 (3rd)	34/50	112/130	111/130
1283 (3rd)	35/30	78/80	72/80
1287 (3rd)	37/30	91/80	78/80
Average	**34**	**91**	**92**

The exhaust flow from the kitchen range hood was not measured due to the size of the hood and the fact that it operates only when switched on by residents. It is rated for 220 CFM.

The corridor and storage room supply flows and garbage exhaust flows were measured using a powered flow hood. Supply flows to the lobbies and server rooms and exhaust from janitor closets were not measured. Measured supply flows were 15%–60% below design airflow.

Table 5. Measured Corridor Supply Flows (CFM) by Floor

Location	Floor 1	Floor 2	Floor 3	Design
1	84	72	62	100
2	64	72	55	100
3	87	83	74	100
4	86	76	86	100
5	71	81	82	100
6	93	83	93	75
7	59	93	70	75
8	100	66	72	100
9	75	80	80	100
CFM/Floor	719	706	674	850
CFM/Apartment	27.7	27.2	25.9	32.7

Table 6. Storage Room Supply Flows (CFM) by Floor

Location	Floor 1	Floor 2	Floor 3	Design
Storage 1	84	67	51	150
Storage 2	85	65	53	100
CFM/Floor	169	132	104	250

Table 7. Garbage Room Exhaust Flows (CFM) by Floor

Location	Floor 1	Floor 2	Floor 3	Design
Garbage 1	107	147	145	130
Garbage 2	150	111	143	120
Garbage 3	234	300+	300+	170
CFM/Floor	491	558+	588+	420

When measuring the exhaust flows of the garbage rooms, the flow exceeded the 300 CFM limit of the powered flow hood (and the design) in several locations. It is estimated that the flow ranges from 100 to 400 CFM for each of the three garbage rooms on each floor, for total exhaust flow per floor of 500–600 CFM, which is 20%–40% over design. The result is a net supply of approximately 11 CFM per apartment, which is significantly lower than the design rate. As a result, the corridor is less pressurized than the design specification.

3.1.3 Door Leakage Airflows

As described in Section 2.2.3, the test apparatus for this experiment consists of a capture hood to encapsulate the door and capture airflow, and a fan to impart a pressure on the hood and measure airflow. Using a smoke pencil, the airtightness of the seal around the doorframe was verified (see Figure 12). Readings were taken at different pressure drops across the door (*A* to *B* in Figure 13) and the data analyzed to identify a basic curve for predicting airflow through a typical apartment door in the building. These data are later combined with pressure monitoring results to infer the direction and magnitude of airflow across the apartment doors on a building-wide basis over time.

Figure 12. Typical door weather-stripping coverage

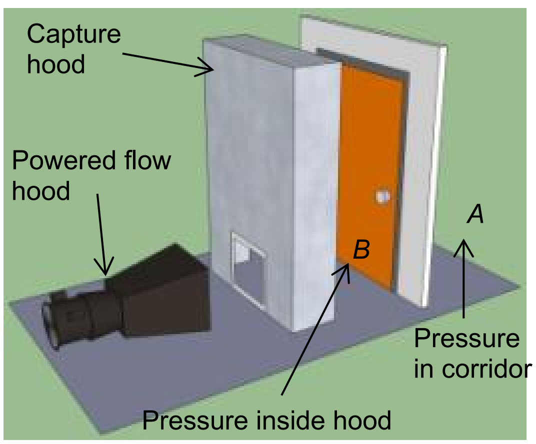

Figure 13. Concept for testing air leakage from a door frame (left) and actual test in progress (right)

The test was performed in both pressurization and depressurization modes on seven doors. The results were often similar, with the pressurization test usually slightly higher. One reason for this might be that the weather-stripping on the doorframes is more effective in one direction than in another. That is, in one direction the weather-stripping is held closed by air pressure, while in the other direction it is pushed slightly open. It is also likely that due to the shape of the door gap, flow is greater in one direction than the other at an equivalent pressure. Results from a single door test are shown in Figure 14 for an example.

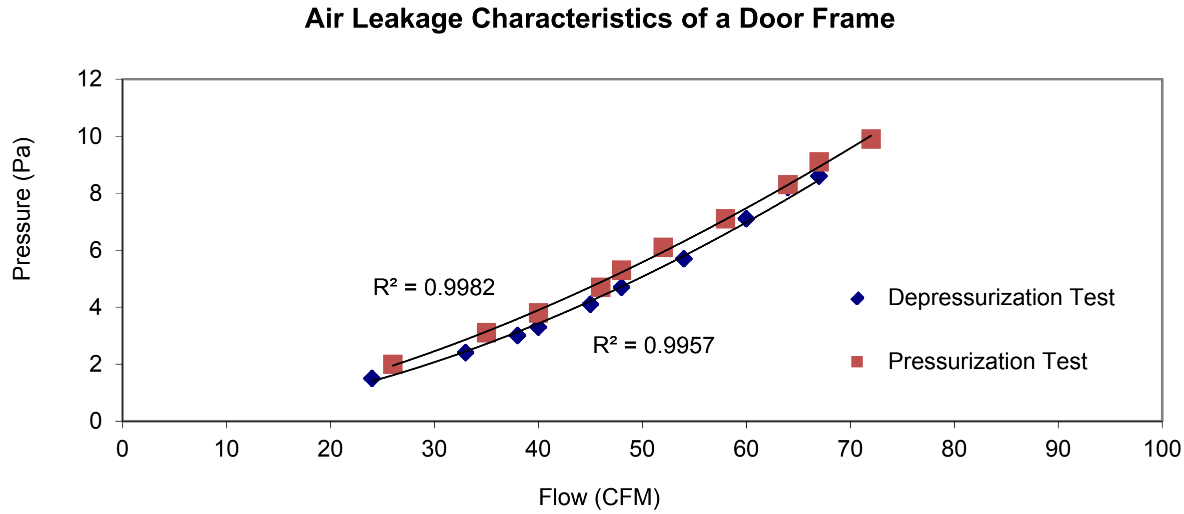

Figure 14. Results of air leakage test from a single door

Plotted together, the results from seven doors tested, both by pressurization and depressurization, are shown in Figure 15.

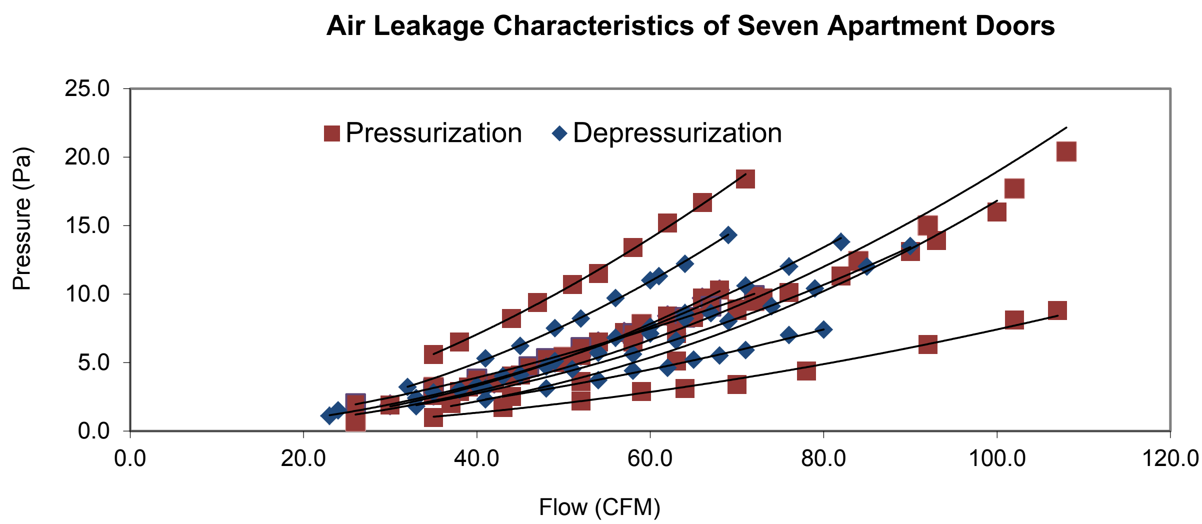

Figure 15. Results of air leakage test from all doors tested

The leakage values from all eight doors tested are given in terms of CFM50 below, with the results of their enclosure testing, also at 50 Pa, for context. Since the enclosure testing utilized the door for the blower door fan, the sum of the two columns represents the true total apartment enclosure leakage.

Table 8. Tabulated Results of Door Air Leakage Tests (CFM50)

Apartment (Floor)	Depressurization	Pressurization	Average (CFM50)	Apartment Air Leakage (CFM50)
1222 (1st)	184	195	190	958
1252 (2nd)	131	143	137	616
1255 (2nd)	115	126	121	695
1257 (2nd)	238	274	256	488
1259 (2nd)	124	Not tested	124	980
1282 (3rd)	123	152	138	761
1283 (3rd)	176	184	180	700
1287 (3rd)	156	160	158	518
Average	**156**	**176**	**165**	**767**

The data show that most of the doors had an equivalent leakage area at 4 Pa of 10–11 in.^{2}. Of the entire sample set measured through both pressurization and depressurization, the average leakage amounts to an equivalent leakage area of 12.7 in.^{2}.

The flow from door leakage is calculated using the orifice flow equation.

$$Q = C\Delta P^{\,n} \quad (1)$$

Where:

Q is leakage through the door gaps (in CFM).
C is the flow coefficient.
ΔP is the pressure difference between inside and outside of the test system (in Pascals).
n is the pressure exponent.

Using a linear regression on the logarithm of pressure and flow readings, the pressure exponent n and flow coefficient C can be derived for each door, measured by both pressurization and depressurization. When the average pressure exponent n and flow coefficient C from all the tested doors is determined, the performance of a typical door can be predicted at any commonly experienced pressure in the building over time. This information is used in conjunction with long-term pressure monitoring to infer the direction and magnitude of flow through these openings over time. The equation used to calculate flow through the door gaps is as follows:

$$Q = 22.366 * \Delta P^{\,0.5097} \quad (2)$$

The results of this equation evaluated at a variety of building pressures are shown superimposed on the data in Figure 16.

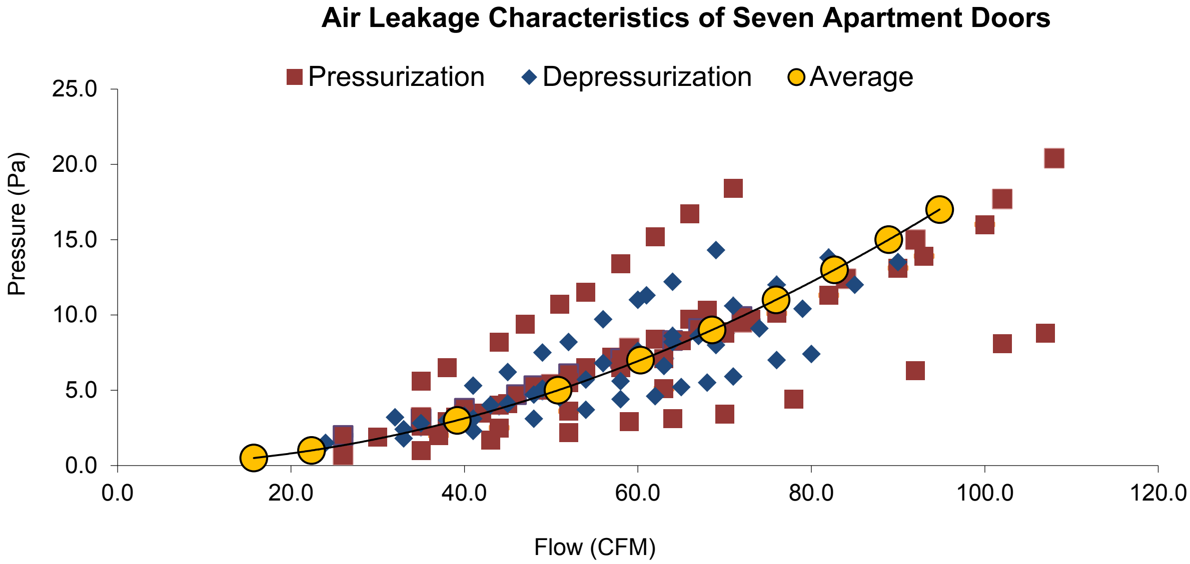

Figure 16. Results of air leakage test from all doors tested and average door performance

The results of this testing show that air flows through the apartment door very easily in spite of efforts to weather-strip the gaps around the door frame. No door sweep was installed, so it is assumed that the majority of the air leakage is through the door undercut, measured to be approximately 3/8" along the bottom. If even a small pressure difference exists between the apartment and the corridor, air flows into or out of the apartment.

To evaluate the airflow during "typical" operating conditions rather than specific pressure differences, the airflow through the eight apartment doors was recorded under four scenarios: first, with apartment exhaust fans "off" (although one bathroom, "Bath 1," remains on at low continuous rate only, ~34 CFM); second, with one bath fan, "Bath 1," on boost mode (~91 CFM); third, with both bath fans on boost mode (~183 CFM); and fourth, all fans running (~400 CFM), including the range hood operating on high.

While the design expectation was that the first scenario, with just the one bath fan running at low, should draw in 30 CFM of MUA from the corridor, three of eight units measured 0 CFM across the door in this condition. The average airflow through the apartment door due to the operation of an additional fan is shown in Figure 17 and ranges from 9 CFM to 61 CFM, while the exhaust fan airflows range from 34 CFM to 400 CFM, respectively. During the tests, the doors to the bathrooms and bedrooms were left open, offering the least restriction to airflow possible and the most airflow under the door.

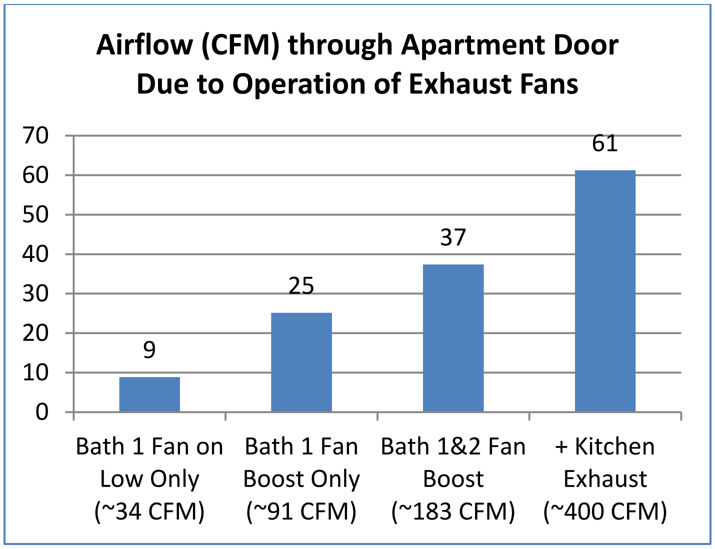

Figure 17. Incremental door airflow under various scenarios

It appears that the first bath fan (generally the "master bath" in this building) is responsible for more airflow when in boost mode, but more likely its operation diminishes the additional effect of another bath fan. The range hood appears to have quite an effect, likely due to its proximity to the apartment door. Although its airflow was not measured, it is rated for approximately 220 CFM at its high-speed setting, compared to the ~92 CFM measured in each bathroom when in "boost" mode.

Compared to the flow measured through the corridor door, it is clear that while some of the MUA for these exhaust fans comes through the apartment door as intended (~15%–25%), a good deal more comes from other places—probably a combination of the exterior envelope, duct leakage, and leaks from other apartments and the walls adjacent to the corridor. Based on these short-term results, it is clear that the 30 CFM of MUA supplied to the corridor intended for each apartment, does not manage to make it into the apartment, through the door undercut or other door frame leakage, while the whole-unit ventilation system is in typical continuous operation, but rather only when both bath fans are in boost mode (see Table 9).

Table 9. Average Apartment Supply and Exhaust Flows

Scenario	Measured Exhaust (CFM)	Door Leakage Supply (CFM)	Unaccounted Supply (CFM)
Base: Bath Fan 1 on Low	34	9	25
Both Bath Fans on Boost	183	37	146

3.1.4 Pressure Monitoring: Cooling Season

Pressure monitoring was conducted in August in five apartments, as highlighted in Figure 7. The pressure of the apartment with respect to the corridor was logged over a period of approximately 2 weeks. A negative pressure indicates that the apartment was depressurized with respect to the corridor. Data samples were taken each minute. The average for each hour was determined and plotted in Figure 18.

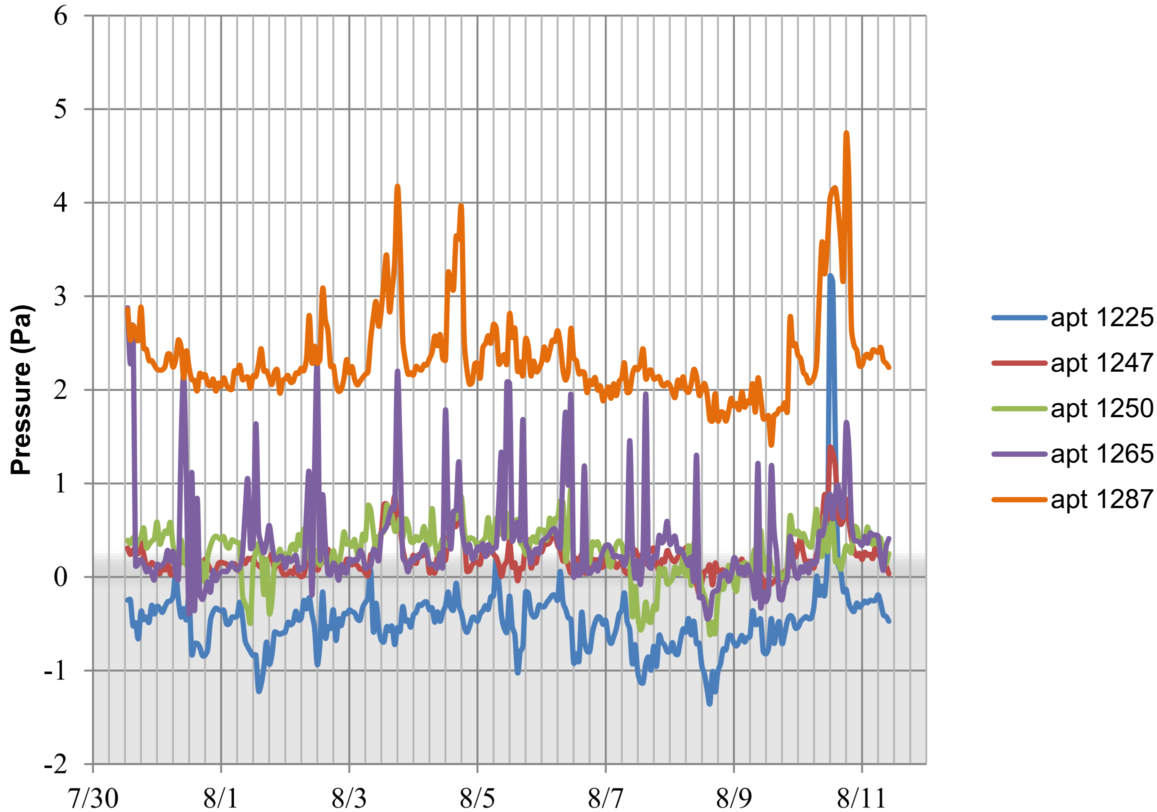

Figure 18. Apartment pressure with respect to corridor—cooling season

Of the five apartments, four had an average pressure > 0, which indicates that air flows through the door predominantly, and surprisingly, from the apartment to the corridor. Apartment 1225, on the ground floor, was the only apartment that was consistently depressurized. The initial hypothesis was that all apartments would be slightly depressurized with respect to the corridor, but the opposite was true.

One possible explanation is that bath fans operate continuously at a low level and switch to boost mode when the occupancy sensor detects motion. Since the units were unoccupied, the fans were all most likely operating at the low level. This level exhausts considerably less air than the boost mode. In addition, although the corridors have ducted supply air (measured below design at about 700 CFM per floor), the garbage rooms and janitor closets on each floor collectively exhaust more than design, and almost the same volume of air (500–600 CFM). The garbage rooms are compartmentalized to a degree; however, it is likely that a portion of the air they exhaust is drawn from the corridors.

The door airflow relationship was then applied to the pressure monitoring data to quantify the airflow across the apartment door. The equation for the average door was used in conjunction with the data from the five apartments that were monitored. A portion of the results is plotted in Figure 19. Only 1 week is plotted to provide higher resolution so that the daily fluctuation are more visible.

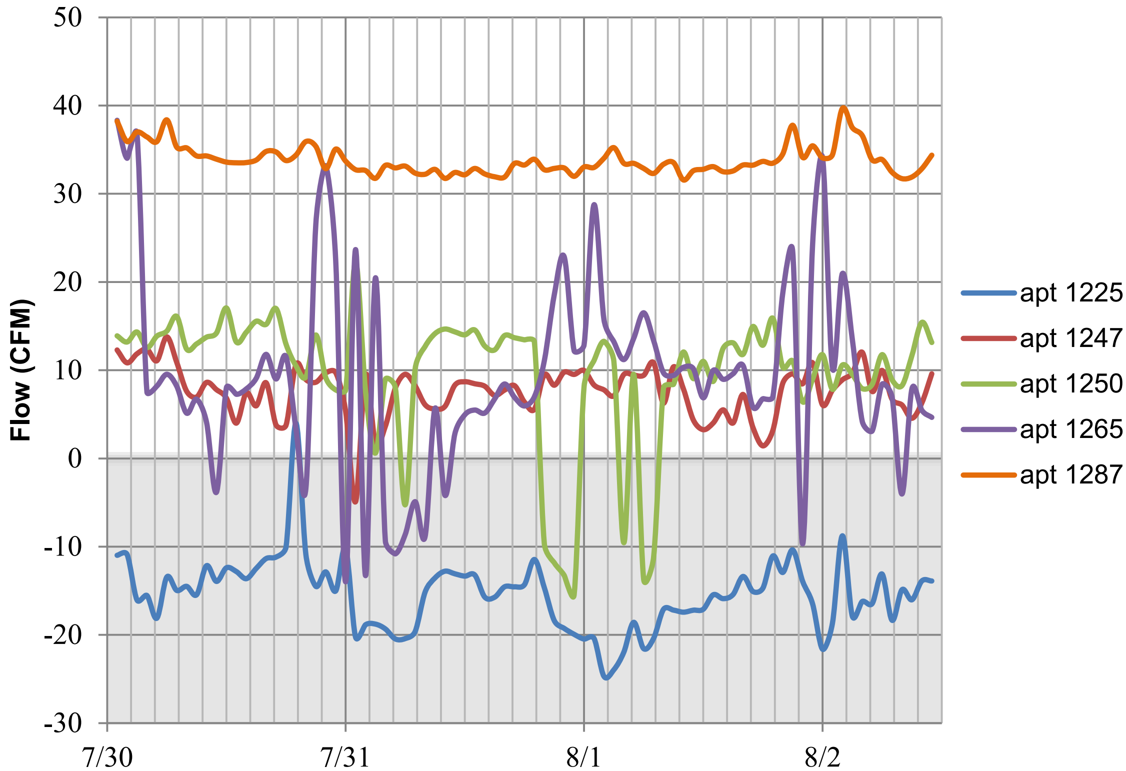

Figure 19. Airflow across apartment door. Positive values indicate flow from apartment to corridor.

The flow across the apartment doors ranged from 24 CFM into the apartment to 40 CFM out. There was considerable variation between apartments and over time within individual units. Only one apartment maintained an average flow into the unit. The remaining four all exhibited net airflow from the apartment to the corridor. This confirms the short-term results—that the intended MUA supplied to the corridor for the apartments does not manage to make it into the apartment, through the door undercut or other door frame leakage, while the whole-unit ventilation system is in typical continuous operation. It also unexpectedly identified airflow from the apartments into the corridor.

The pressure of the apartment with respect to outdoors was also measured. The results are shown in Figure 20.

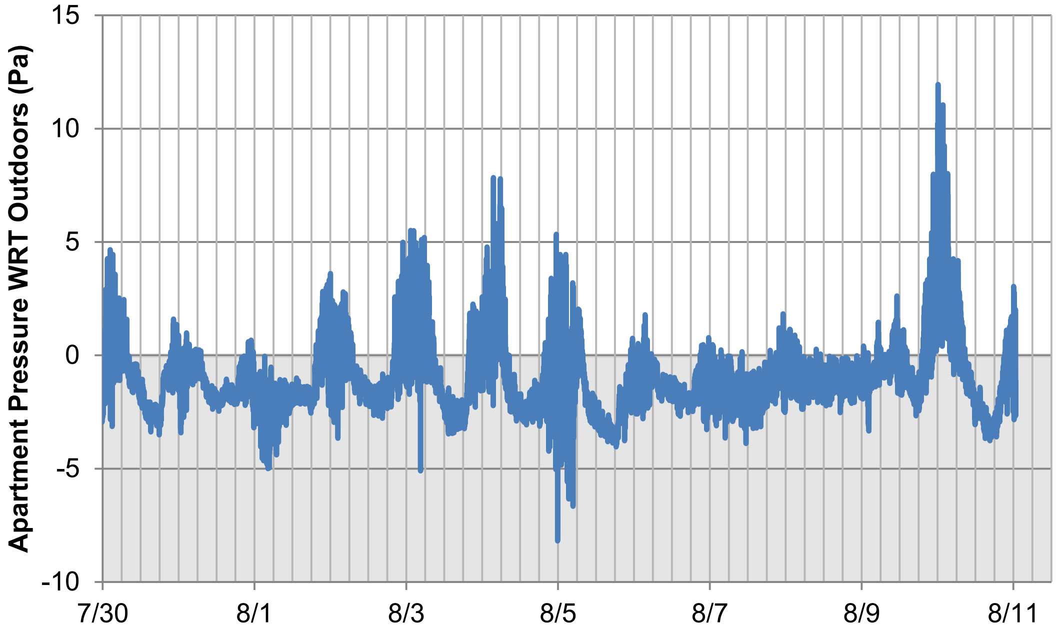

Figure 20. Apartment pressure with respect to outdoors—cooling season

Again, the pressure fluctuates considerably, from –7.5 Pa to +12 Pa. This is likely a result of external conditions—wind, temperature, and opening and closing of stairwell and corridor doors—and the fact that the apartments, while meeting the current airtightness thresholds for various programs, are not sufficiently compartmentalized with respect to air movement to be able to draw in MUA from its intended source.

3.1.5 Pressure Monitoring: Heating Season

Pressure monitoring was conducted again in late November in five apartments. Four of the five apartments were the same as those used for the cooling season monitoring. In both seasons, the apartments were unoccupied. The pressure of the apartment with respect to the corridor was logged over a period of approximately 2 weeks. A negative pressure again indicates that the apartment was depressurized with respect to the corridor. The average hourly pressure for each apartment with respect to the corridor is plotted in Figure 21.

Of the five apartments, only one, Apartment 1287, was consistently depressurized with respect to the corridor. Unlike the consistently depressurized apartment from the cooling season monitoring, this apartment was located on the top floor of the building. The other four apartments were either neutral or slightly pressurized. This indicates, with the exception of Apartment 1287, there is no MUA being provided from the corridor via doorframe leakage or the door undercut. In fact, there is small net flow of air from many apartments into the corridor.

The pressure in an apartment with respect to the ambient outdoor pressure was also measured in two apartments. Apartment 1220 is located on the first floor and Apartment 1265 is on the third. The results are shown in Figure 22.

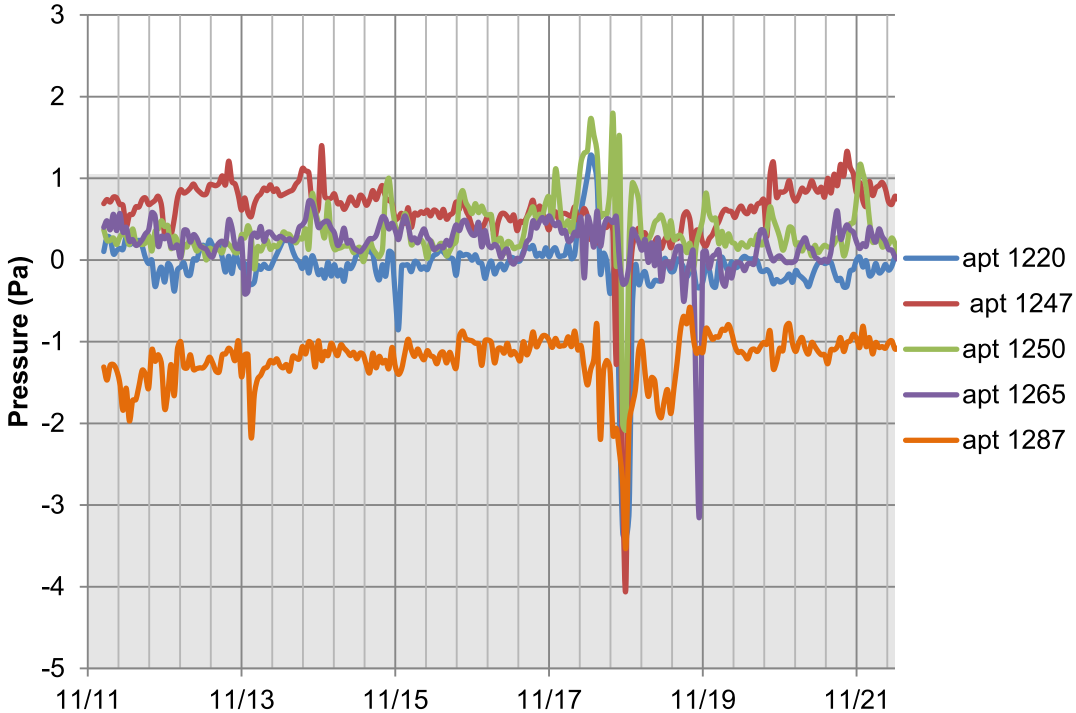

Figure 21. Apartment pressure with respect to corridor—heating season

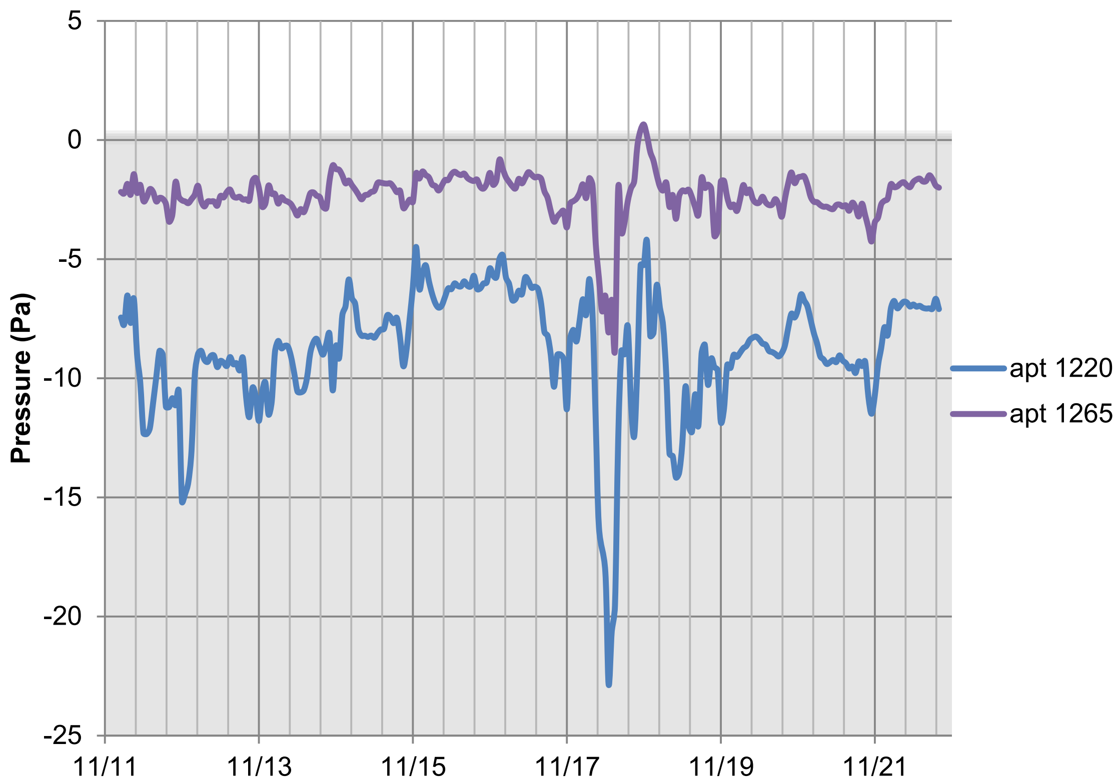

Figure 22. Apartment pressure with respect to outdoors—heating season

Both apartments are consistently depressurized with respect to the outdoors, indicating a net flow of air into the apartment from outside. The first floor unit exhibits a greater pressure difference across the exterior wall, which is likely a result of stack effect in the building.

The pressures with respect to outside and corridor for two apartments are shown in the following two figures. In both instances, there is negligible pressure across the apartment-corridor boundary and a significant pressure across the apartment-outdoor wall. This indicates that the majority of the MUA for these units is being drawn from outdoors, through the exterior wall.

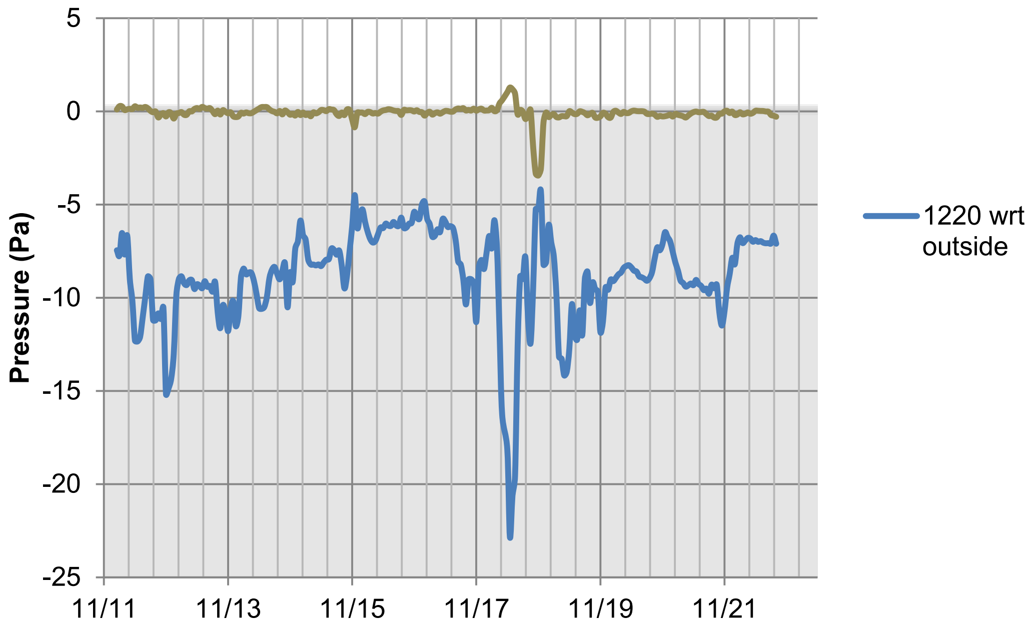

Figure 23. Apartment 1220 pressure with respect to outdoors and corridor—heating season

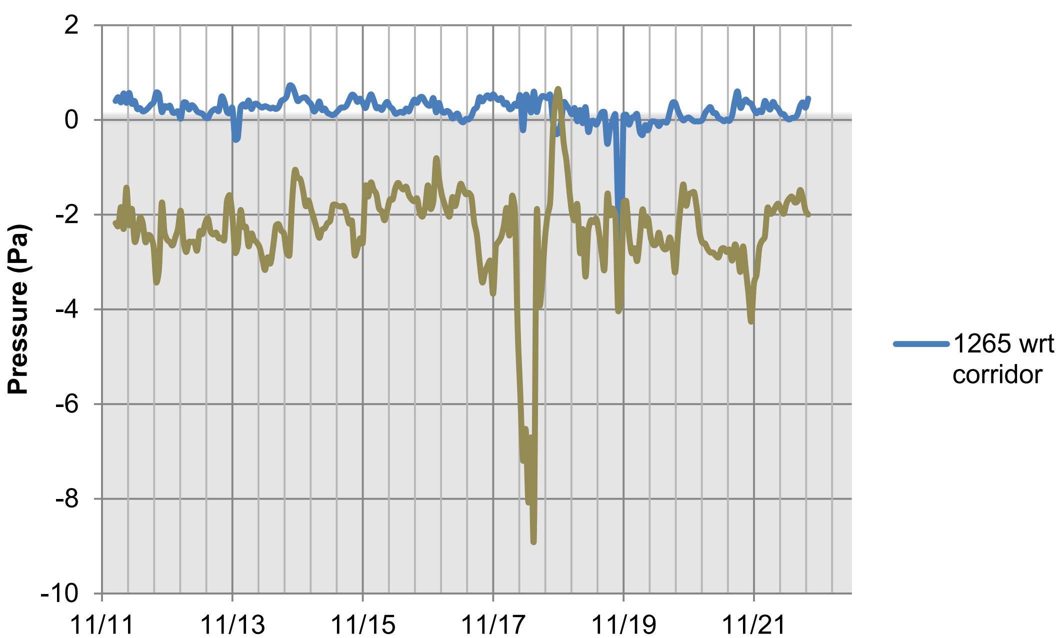

Figure 24. Apartment 1265 pressure with respect to outdoors and corridor—heating season

3.1.6 Fan Power Consumption

The performance specifications of each fan are summarized in Table 10 and Table 11. Due to the location of the exhaust fans in the units, the power could not be easily measured. As a result, the rated power and rated flow were used and applied to the measured flow. The power consumption is assumed relatively constant over the operating pressures.

Table 10. Exhaust Fan Performance—Power and Flow

Fan Type	Rated Power (W)	Rated Flow (CFM)	Measured Flow (CFM)	Measured CFM/ Rated W
Type 1: Low	2.4	50	38	15.8
Type 2: Low	3.2	30	33	10.3
Type 1: Boost	11.9	130	117	9.8
Type 2: Boost	7	80	79	11.3

For the purposes of comparison, it can be assumed that the fans operate for the vast majority of the time at low. Therefore, the average performance for this system is 13.1 CFM/W.

The performance specifications of the supply fans are summarized in Table 11. The measured flows could not be reliably assigned to the appropriate fan; therefore, they are not included in the table.

Table 11. Supply Fan Performance—Power and Flow

Fan Type	Rated Power (W)	Rated Flow (CFM)	Rated CFM/ Rated W
VU-1	1491.4	3200	2.1
VU-2	372.9	1050	2.8
VU-3	372.9	1000	2.7

3.2 Type 2: Make-Up Air Through Ducted Supply Air

3.2.1 Apartment Blower Door Testing

Blower door tests were conducted on a sample of apartments in the two buildings. Both buildings have an average apartment airtightness of 0.30 CFM50/ft^2 of enclosure area (see Table 12 and Table 13). The first digit of the apartment number also indicates the floor level; however, many fourth-floor apartments were two-story units, with living space on the fifth floor.

Table 12. Type 2 Building #1 Apartment Airtightness Metrics

Apartment	Floor Area (ft^2)	Wall Height (ft)	CFM50	CFM50/ft^2 Enclosure	ACH50
108	1,114	12	1,337	0.34	5.8
206	990	12	396	0.11	2.0
209	1,114	12	1,337	0.34	6.3
210	996	13	1,374	0.39	6.9
212	1,018	13	1,425	0.39	7.2
213	1,059	13	1,483	0.40	7.0
214	1,056	12	1,331	0.36	6.3
302	970	12	485	0.14	2.5
400	730	10	993	0.34	6.8
403	1,331	10	932	0.22	4.2
408	1,559	10	1,195	0.22	4.6
417	1,115	12	1,516	0.39	6.8
Average	**1,088**	**12**	**1,150**	**0.30**	**5.5**

Table 13. Type 2 Building #2 Apartment Airtightness Metrics

Apartment	Floor Area (ft^2)	Wall Height (ft)	CFM50	CFM50/ft^2	ACH50
102	1202	10.5	1,441	0.44	6.9
103	1,180	10.5	1,419	0.47	6.9
117	1,316	10.5	1,463	0.32	6.4
201	918	11.0	580	0.17	3.5
205	1,156	11.0	798	0.20	3.8
208	652	11.0	480	0.18	4.0
218	1,201	11.0	965	0.24	4.4
302	1,297	11.0	1,108	0.26	4.7
303	1,253	11.0	871	0.21	3.8
309	1,004	11.0	884	0.25	4.8
312	833	11.0	907	0.29	5.9
401	925	8.5	1,140	0.33	8.7
404	1,119	8.5	1,147	0.30	7.2
407	920	8.5	1,288	0.40	9.9
417	1,487	8.5	1,653	0.35	7.9
422	1,138	8.5	1,634	0.43	10.1
Average	**1,110**	**10.0**	**1,122**	**0.30**	**6.2**

3.2.2 Supply and Exhaust Flow Testing

The supply and exhaust flows were measured in a sample of apartments in both test buildings using a powered flow hood and compared to the design rates. The net differences between the supply and exhaust flows were also calculated, with negative values indicating that exhaust flow exceeded the supply flow, an expected result based on the design. The results are presented in Table 14 and Table 15.

Table 14. Building #1—Actual and Design Supply and Exhaust Flow

Apt	Kitchen Exhaust (CFM)			Bathroom Exhaust (CFM)			Supply (CFM)			
	Actual	Design	%	Actual	Design	%	Actual	Design	%	Net
102	23	50	46%	14	25	56%	28	75	37%	-9
105	17	60	28%	12	30	40%	37	90	41%	8
108	<8	60	<13%	<8	30	<27%	23	90	26%	7
110	<8	60	<13%	<8	30	<27%	63	90	70%	47
112	<8	60	<13%	<8	30	<27%	25	90	28%	9
204	16	60	27%	6	30	20%	34	90	38%	12
209	25	60	38%	14	30	47%	46	90	51%	7
212	33	60	55%	22	30	73%	60	90	67%	5
213	31	60	52%	20	30	67%	63	90	70%	12
214	28	60	47%	13	30	43%	65	90	72%	24
301	19	60	32%	11	30	37%	47	90	52%	17
303	18	50	36%	6	25	24%	43	75	57%	19
304	14	60	23%	7	30	23%	11	90	12%	-10
305	15	60	25%	11	30	37%	25	90	28%	-1
309	30	50	50%	18	25	72%	45	75	60%	-3
312	29	60	48%	21	30	70%	60	90	67%	10
401	Vented	Range	Hood	23	25	92%	67	75	89%	44
403	Vented	Range	Hood	16	25	64%	66	50	132%	50
404	DNT	50	NA	14	25	56%	57	75	76%	NA
405	Vented	Range	Hood	14	25	56%	43	50	86%	29
407	23	50	46%	13	25	52%	66	75	88%	30
408	Vented	Range	Hood	15	25	60%	55	50	110%	40
Avg			40%			52%			62%	

Table 15. Building #2—Actual and Design Supply and Exhaust Flow

Apt	Kitchen Exhaust (CFM)			Bathroom 1 Exhaust (CFM)			Bathroom 2 Exhaust (CFM)			Supply (CFM)			
	Act	Des	%	Act	Des	%	Act	Des	%	Act	Des	%	Net
101	13	50	26%	16	25	64%	15	25	60%	DNT	85	NA	NA
106	28	50	56%	15	25	60%	16	25	64%	DNT	85	NA	NA
110	18	50	36%	17	25	68%	(No Bath #2)			DNT	70	NA	NA
113	27	50	54%	18	25	72%	20	25	80%	DNT	85	NA	NA
114	25	50	50%	15	25	60%	(No Bath #2)			29	50	58%	–11
116	26	50	52%	16	25	64%	15	25	60%	45	75	60%	–12
201	27	50	54%	13	25	52%	(No Bath #2)			42	75	56%	2
203	26	50	52%	20	25	80%	20	25	80%	47	75	63%	–19
208	29	50	58%	18	25	72%	(No Bath #2)			26	50	52%	–21
210	24	50	48%	17	25	68%	(No Bath #2)			23	50	46%	–18
216	22	50	44%	20	25	80%	(No Bath #2)			30	50	60%	–12
301	23	50	46%	14	25	56%	(No Bath #2)			27	50	54%	–10
304	29	50	58%	17	25	68%	DNT	25	NA	47	75	63%	NA
307	27	50	54%	22	25	88%	DNT	25	NA	47	75	63%	NA
312	36	50	72%	17	25	68%	(No Bath #2)			26	50	52%	–27
401	25	50	50%	15	25	60%	15	25	60%	38	90	42%	–17
404	23	50	46%	16	25	64%	12	25	48%	43	90	48%	–8
405	29	50	58%	19	25	76%	16	25	64%	45	90	50%	–19
406	27	50	54%	14	25	56%	16	25	64%	41	90	46%	–16
409	18	50	36%	18	25	72%	19	25	76%	45	90	50%	–10
413	36	50	72%	21	25	84%	20	25	80%	43	90	48%	–34
418	29	50	58%	26	25	104%	23	25	92%	47	90	52%	–31
422	27	50	54%	17	25	68%	18	25	72%	76	90	84%	14
Avg			52%			70%			66%			55%	

Despite their best intentions to provide a dedicated source of MUA, Table 14 and Table 15 illustrate one of the challenges with designing and installing ducted ventilation systems: the performance of the system falls short of the design specifications without proper commissioning. Neither exhaust nor supply measurements were close to the design flows, meaning that the recommended ventilation rates were not achieved. Exhaust airflow, in some units of Building #1 and most units of Building #2, exceeded the supply airflow, as expected, which means there are still unidentified sources of MUA. Although LEED for Homes Certification required designing the system to meet ASHRAE 62.2, there was no requirement for measured airflows to actually comply.

The results above were compared to TAB reports from contractors for both buildings. In the view of CARB investigators, the veracity of at least one TAB report is highly suspect for several reasons. First, it is highly suspect that the total flow is exactly the same as designed, which unfortunately is extremely unusual in most buildings. All of the individual register measurements for exhaust CFM were exactly 5 CFM above, 5 CFM below, or exactly on the target, which is also highly unusual. If the measuring device used was only capable of 5 CFM increments, it is not precise enough to be used for this type of low-flow balancing work. Lastly, CARB results show that measured flow decreases with increasing distance from the MUA fan, which is a pattern consistent with leaky ductwork. By contrast, the TAB results show no pattern at all, instead reporting nearly perfect results randomly distributed throughout. These factors point to clear fabrication of the reported results.

3.2.3 Supply and Exhaust Fan Power Consumption

The power ratings for the supply and exhaust fans are summarized in Table 16. Actual field measurements were not made due to access issues.

Table 16. Supply and Exhaust Fan Power

Fan Type	Rated Power (W)	Rated Flow (CFM)	CFM/W
Exhaust Central	1,119	3,200	2.9
Supply Central	1,492	3,200	2.1

3.3 Type 3: Make-Up Air Through HVAC Supply

3.3.1 Apartment Blower Door Testing

Blower door tests were conducted on 15% of apartments pursuant to LEED program requirements. Apartments are numbered by floor (first through fourth) and letter. The building is built with an average apartment airtightness of 0.29 CFM50/ft^2 of enclosure area (see Table 17).

Table 17. Type 3 Building Apartment Airtightness Metrics

Apartment	Floor Area (ft^2)	Wall Height (ft)	CFM50	CFM50/ft^2	ACH50
1C	625	9.33	657	0.30	6.76
1K	625	9.33	614	0.28	6.32
2B	625	9.33	636	0.36	6.54
2E	625	9.33	623	0.28	6.41
2F	475	9.33	526	0.24	7.12
2R	625	9.33	580	0.32	5.97
3R	475	9.33	537	0.24	7.27
4A	625	9.33	610	0.34	6.27
4F	475	9.33	471	0.22	6.37
Average	**575**	**9.33**	**583.8**	**0.29**	**6.56**

3.3.2 Supply and Exhaust Flow Testing

The exhaust flows from the bathroom and kitchen registers were measured using a powered flow hood. The average total exhaust airflow from the apartments tested was 57 CFM, compared to the design of 55 CFM. The results are summarized in Table 18.

Table 18. Apartment Exhaust Flow Test Results

Apartment	Kitchen (CFM)	Design (CFM)	Bathroom (CFM)	Design (CFM)	Total (CFM)	Design (CFM)
2R	26	30	26	25	52	55
3R	19	30	19	25	38	55
3P	27	30	28	25	55	55
3E	25	30	29	25	54	55
4F	22	30	56	25	78	55
4P	34	30	31	25	65	55
Average	**25.5**	**30**	**31.5**	**25**	**57**	**55**

In the common corridor, there is one supply register per floor. This is designed to provide conditioned air to the corridors only, and is not intended to supply MUA to the apartments. They are located at the northwest end of each corridor, near Stair A. The construction drawings indicate 140 CFM from each of these registers. This equates to slightly more than 8 CFM per apartment. The actual airflow was not measured because a good seal with the powered flow hood was not possible due to the trim and molding around the register.

3.3.3 Door Leakage Airflows

Although not designed as a source of MUA to the apartment, flow through the door was measured the same way as described in Section 2.2.3.

The apartment doors have weather-stripping around the sides and top, but do not have a door sweep at the bottom. There is approximately a ⅜-in. gap between the bottom of the door and the threshold, as shown in Figure 25.

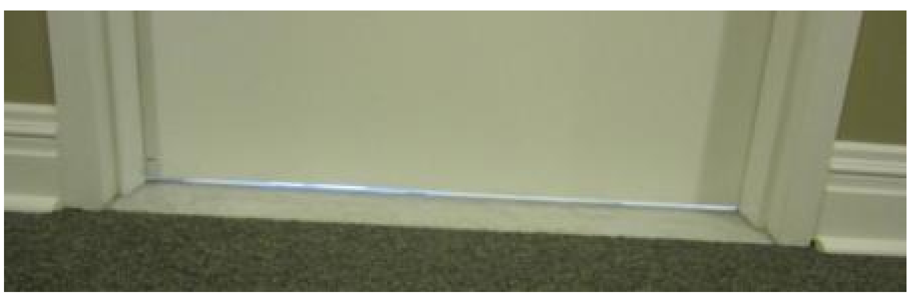

Figure 25. Apartment door—gap between door and threshold

The leakage values from seven doors tested are given in Table 19 in terms of CFM50, and the results of their blower door tests, when available. Compared to the building tested in Type 1, where the door undercut was somewhat intended to allow MUA into the apartments, these doors show 30% higher airflow across the door at 50 Pa.

Table 19. Tabulated Results of Door Air Leakage Tests (CFM50)

Apartment	Depressurization	Pressurization	Average	Apartment Air Leakage
2R	213	209	211	580
3R	220	203	211	537
3P	187	209	198	
3E	276	255	266	
4R	359	221	290	
4F	113	150	132	471
4P	204	189	196	
Average	**225**	**205**	**215**	

Figure 26 depicts the results of the individual door tests, along with a dataset that represents the average of all the data.

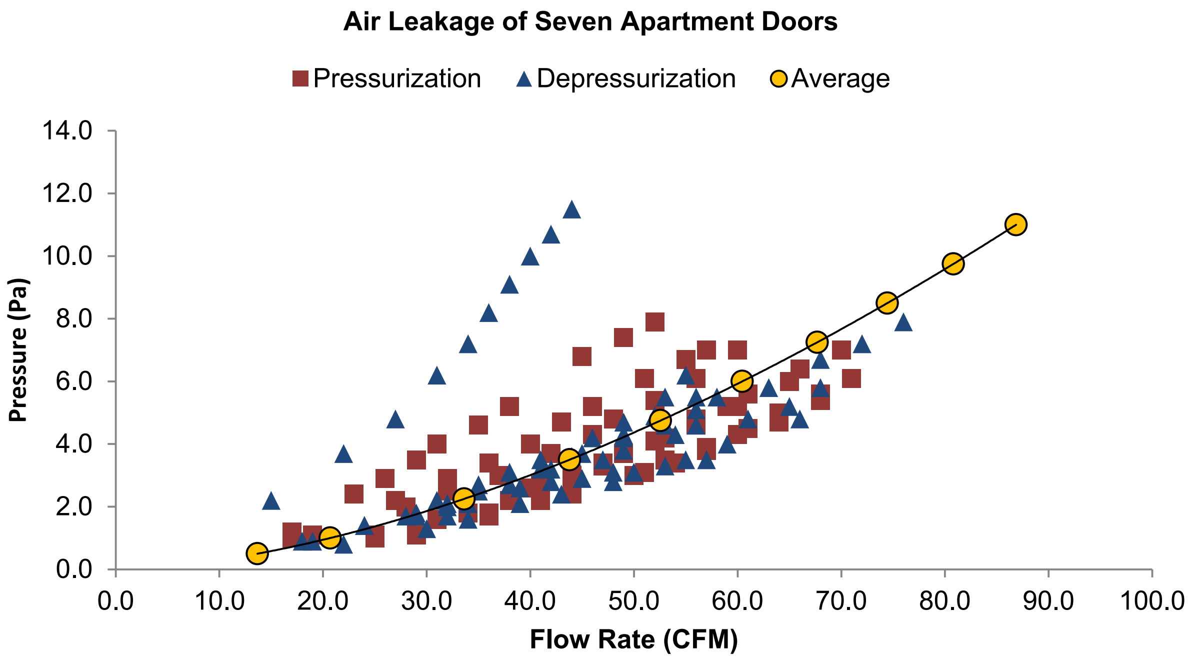

Figure 26. Results of air leakage test from all doors tested and average door performance

The results of this testing show that air flows through the apartment door very easily and can be correlated to the pressure difference between the apartment and the corridor (see Section 3.3.6).

3.3.4 Packaged Terminal Air Conditioning Make-Up Air

Manufacturers of PTACs have for many years included “fresh air dampers” and other devices that passively admit OA and incorporate it into their airstream. These work on a similar principle to passive or “trickle” vents, in that airflow through them is dependent on building pressures. More recently, manufacturers have also begun to offer fresh air kits, with a small dedicated supply air fan to provide a continuous flow of OA, regardless of main unit operation. Because the fans are small, it is likely that their performance will still be affected by prevailing pressures in the building.

To test the airflow through the PTAC fresh air kit, a custom-made device which combines a powered capture hood and an orifice plate was used. The device is shown in Figure 27 and represented diagrammatically in Figure 28.

Figure 27. Testing apparatus for measuring airflow through PTAC fresh air kit (cover removed)

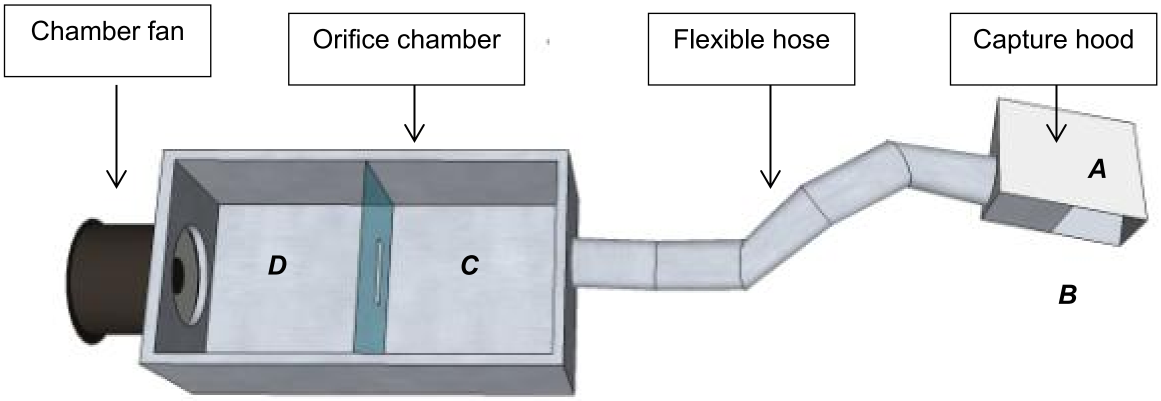

Figure 28. Diagram of apparatus for measuring airflow through PTAC fresh air kit

When the pressure in the hood (*A*) is zero with respect to the ambient pressure around it (*B*), the flow going into the hood equals the flow leaving the hood. No pressure is placed on the outlet of the object being tested, and the effect of placing the hood over the test object is minimized. In order for the pressure in the capture hood to reach zero, suction must be placed on the orifice chamber by the chamber fan. A pressure drop across the orifice plate develops (*C* to *D*), and this can be measured to determine flow. The goal is to isolate and capture airflow only from the dedicated fresh air kit, not from other leakage pathways in the PTAC such as gaps between the unit and its through-wall sleeve.

The procedure was repeated with higher and lower pressures inside the capture hood (delta between *A* and *B*), to simulate various pressure environments in which the device must work.

Measurements were taken at a variety of pressures in two series; one with a 3-in.^{2} test orifice and one with a 4-in.^{2} test orifice. The results (shown in Figure 29) were similar, with good correlation between airflow and pressure.

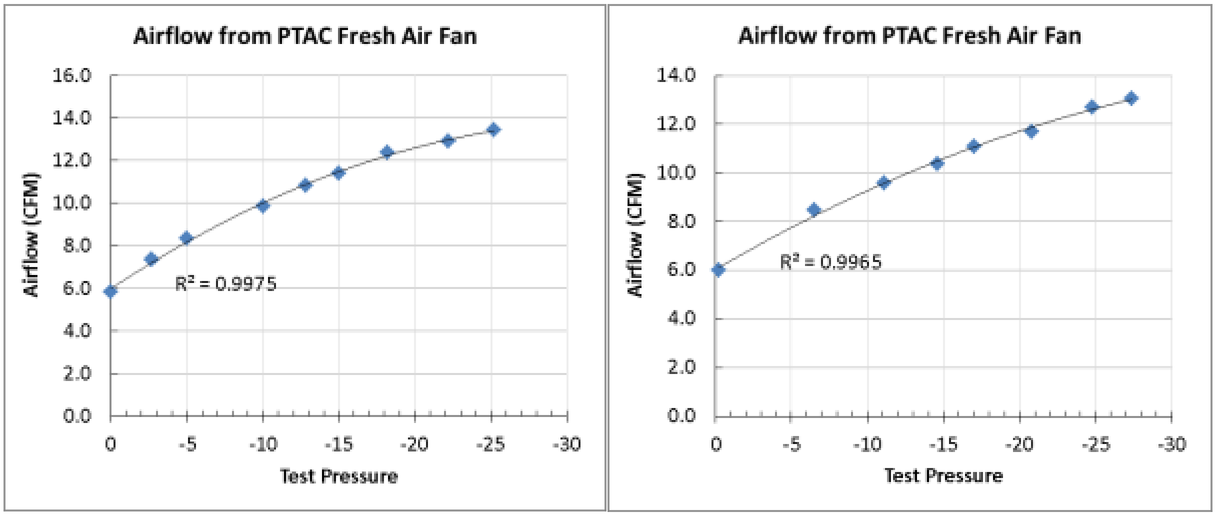

Figure 29. Results from 3-in.^{2} orifice (L) and 4-in.^{2} orifice (R)

The results of the 3-in.^{2} and 4-in.^{2} orifice tests were then plotted together. The results are shown in Figure 30.

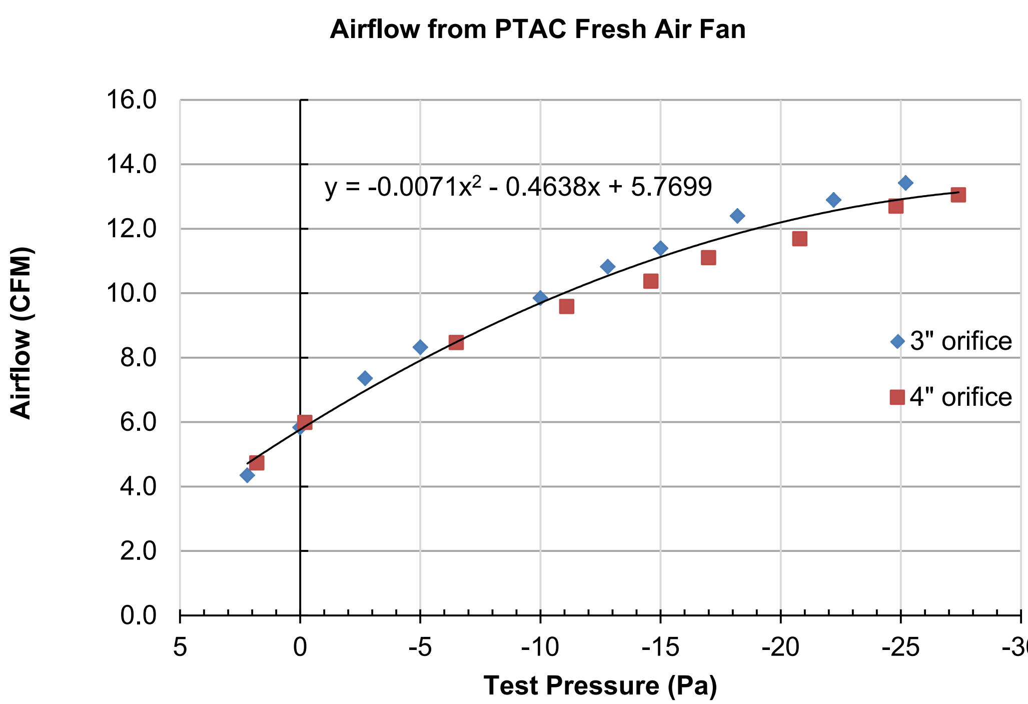

Figure 30. Combined results from both tests

The equation from the best-fit curve can be used to infer the airflow through the PTAC fresh air kit at any potential building pressure. When combined with long-term pressure monitoring, the direction and magnitude of airflow through the PTAC fresh air kit can be inferred (see Section 3.3.6).

The pressure that the PTAC fresh air fan experiences is affected by the operating conditions of the apartment, in particular the operation of exhaust fans, PTAC fresh air fan, and PTAC blower fan. For example, when the PTAC's main blower is running, the pressure near the fresh air fan drops considerably, allowing the fresh air fan to deliver more flow. To measure the effect of these conditions, a static pressure probe was placed in the PTAC cabinet, at the outlet of the fresh air fan. This pressure and the pressure with respect to outdoors were recorded over time. This setup is shown in Figure 31. The right image shows the static pressure probe placement in the blower cabinet. The flow through the fresh air fan was then calculated using the equation developed in Figure 30 from the orifice plate/capture hood tests.

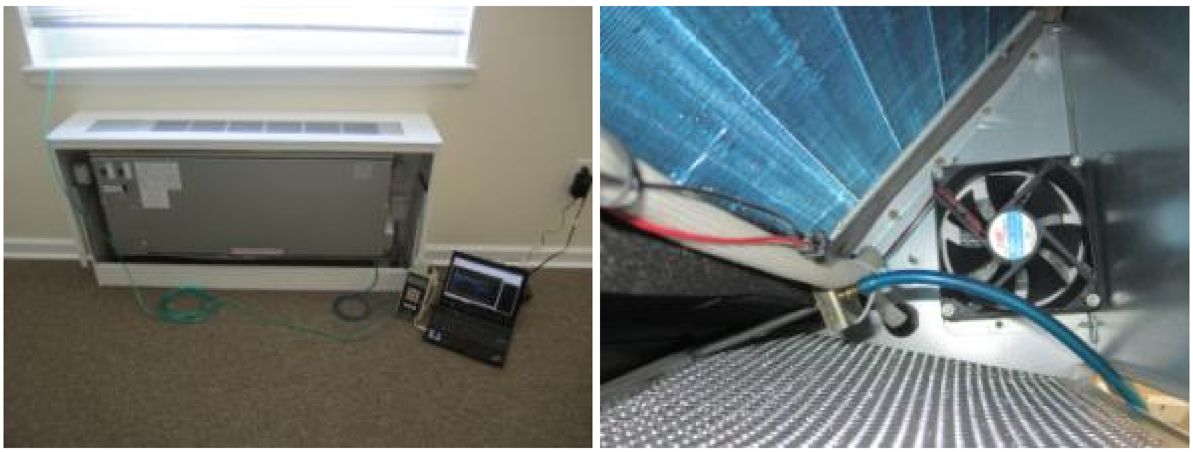

Figure 31. Setup for measuring pressures inside the PTAC blower cabinet

A summary of the various conditions and results of the tests is shown in Table 20.

Table 20. Effect of Apartment Operating Conditions on Pressure at Outlet of PTAC Fresh Air Fan

Nominal Operating Conditions	Exhaust Fans	Fresh Air Fan	PTAC Blower Fan	Average Pressure (Pa)	Flow (CFM)
All Off	OFF	OFF	OFF	–1.5	6.5
Exhaust Fans On	ON	OFF	OFF	–1.4	6.4
OA Kit On	ON	ON	OFF	–2.2	6.8
Blower Low	ON	ON	LOW	–3.7	7.6
Blower High	ON	ON	HIGH	–5.6	8.6

During the time of the tests, under "all off" conditions, the area in front of the PTAC fresh air fan was slightly depressurized with respect to outside. This resulted in a flow of approximately 6.5 CFM into the apartment. Although it was expected that the operation of the exhaust fans would result in further depressurization of the apartment, when the exhaust fans were turned on (via the circuit breaker) the pressure actually increased slightly. This unexpected result is likely due to variations in building conditions (opening and closing of doors) and atmospheric conditions (wind). When the PTAC fresh air fan was energized, the pressure in the cabinet fell with respect to outdoors. This is expected, as the fan is designed to draw air from outside into the blower cabinet; however, the increase in airflow was less than 0.5 CFM, and nowhere near the expected airflow of 40 CFM. Energizing the PTAC blower caused further depressurization of the sample zone, with lower pressures being correlated to the higher blower speed. This is the result of the fan drawing air from the lower region of the cabinet and pulling it upward. The result of the blower set to high is an increase of 26%, or approximately 1.9 CFM, over the "OA Kit On" condition. Thus, the operation of the apartment, in particular the PTAC blower, has a direct impact on the pressure the PTAC fresh air fan experiences, and therefore the amount of air delivered, which, at 8.6 CFM with all fans running, still falls very short of the design of 40 CFM.

3.3.5 Pressure Monitoring—Cooling Season

Pressure monitoring was conducted in July in five apartments: 2R, 3P, 3R, 4P, and 4R. These apartments are on floors 2, 3, and 4. Apartments P and R are adjacent to each other and located on the southern exposure of the building.

The pressure at the outlet of PTAC fresh air fan with respect to outdoors was logged over a period of approximately 2 weeks. A negative pressure indicates that the apartment was depressurized with respect to outdoors. Data samples were taken each minute. The average for each hour was determined and plotted in Figure 32.

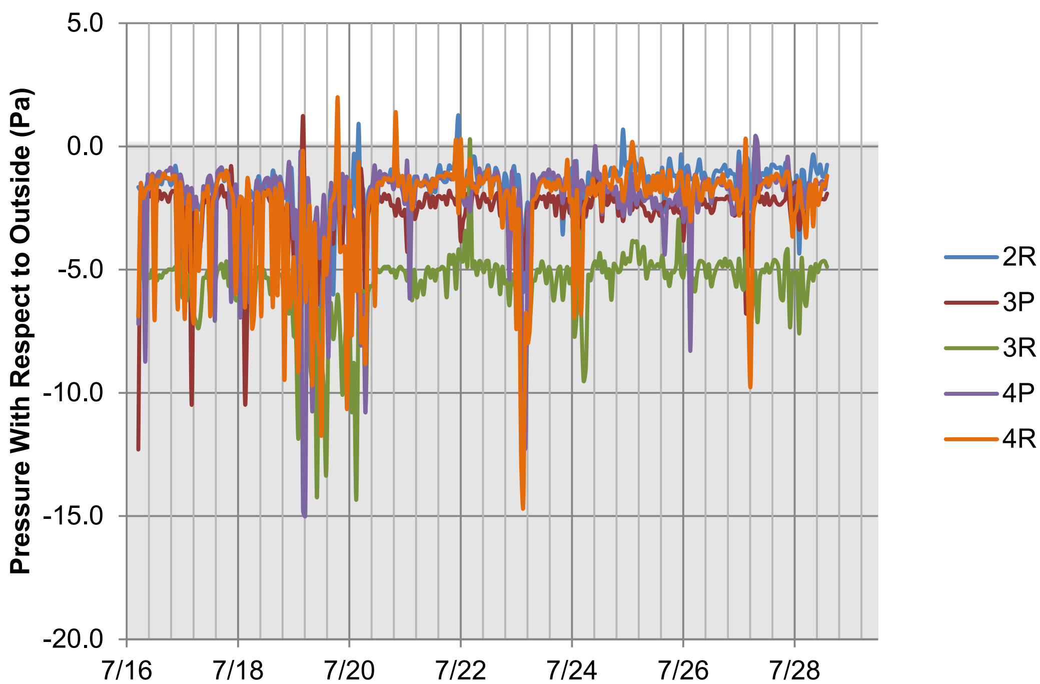

Figure 32. Pressure at outlet of PTAC fresh air fan with respect to outdoors

The data indicate that the apartments are depressurized with respect to outdoors for the vast majority of the time. In addition, it appears that the pressure fluctuates between +2 Pa and

–15 Pa. The data for a single day are shown in Figure 33 to better illustrate trends between apartments.

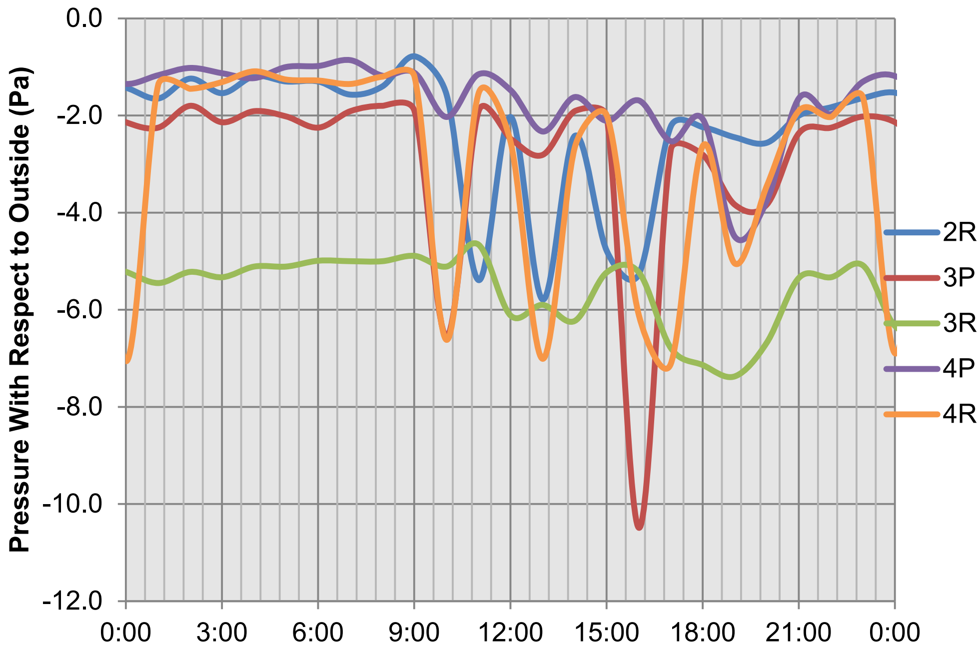

Figure 33. Pressure at outlet of PTAC fresh air fan with respect to outdoors, single day

It should be noted that the blower on the PTAC in apartment 3R was set to "High." On this setting, the blower runs continuously at high speed. The blowers in the other apartments were set to "Auto," which means they operate in response to calls from the thermostats. In the previous section, it was found that the blower operation directly affects the pressure the fan experiences. The pressure monitoring data confirm those findings, as the readings from 3R were overall, consistently more negative than the other readings.

In addition to monitoring pressure, the apartment temperature and PTAC operation was recorded for each of the five apartments. To measure PTAC operation, a temperature data logger was placed on the cooling side of the unit. A drop in temperature for this logger was inferred to mean the PTAC was in operation. Figure 34 is a plot of pressure, apartment temperature, and PTAC temperature for apartment 4R over 1 day.

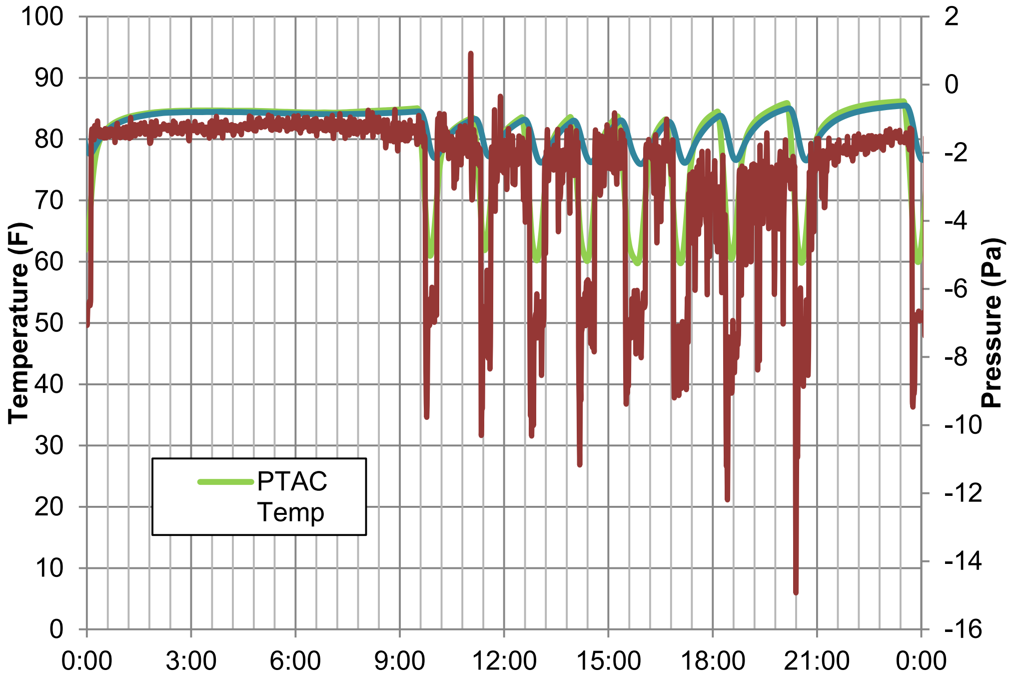

Figure 34. Apartment 4R—pressure, apartment temperature, and PTAC temperature

As expected, PTAC temperature (green line) and apartment temperature (blue line) are directly correlated. When the apartment temperature reaches approximately 82°F, the PTAC turns on and runs until the apartment temperature falls to about 78°F. This cyclic operation happens throughout the day. The more interesting relationship is between the PTAC operation and pressure at the fresh air kit fan (red line). It was observed that the two are also correlated. When the PTAC is off, the pressure fluctuates around –2 Pa. When the PTAC is operating, the pressure falls to –7 to –9 Pa. Again, this confirms that PTAC operation has a direct effect on pressure. The minor variations in pressure are most likely due to fluctuations in atmospheric conditions, predominately wind.

An additional pressure monitoring station, consisting of two DG-700 manometers and a laptop running Teclog, was established in apartment 3P. This station was used to measure the ambient pressure of the apartment with respect to outdoors and with respect to the corridor. It was also used to measure the pressure of apartment 3R with respect to the corridor. Data were collected every minute. The hourly averages are plotted in Figure 35.

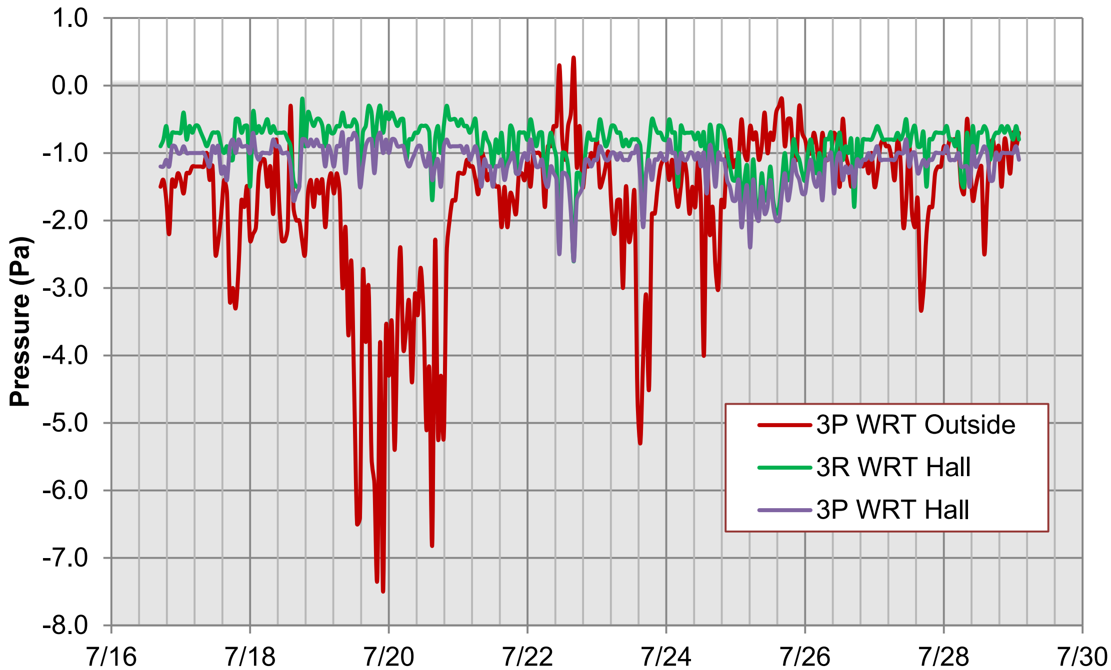

Figure 35. Apartment pressures with respect to outdoors and corridor

In order to better visualize the trends, a single day is shown in Figure 36, below.

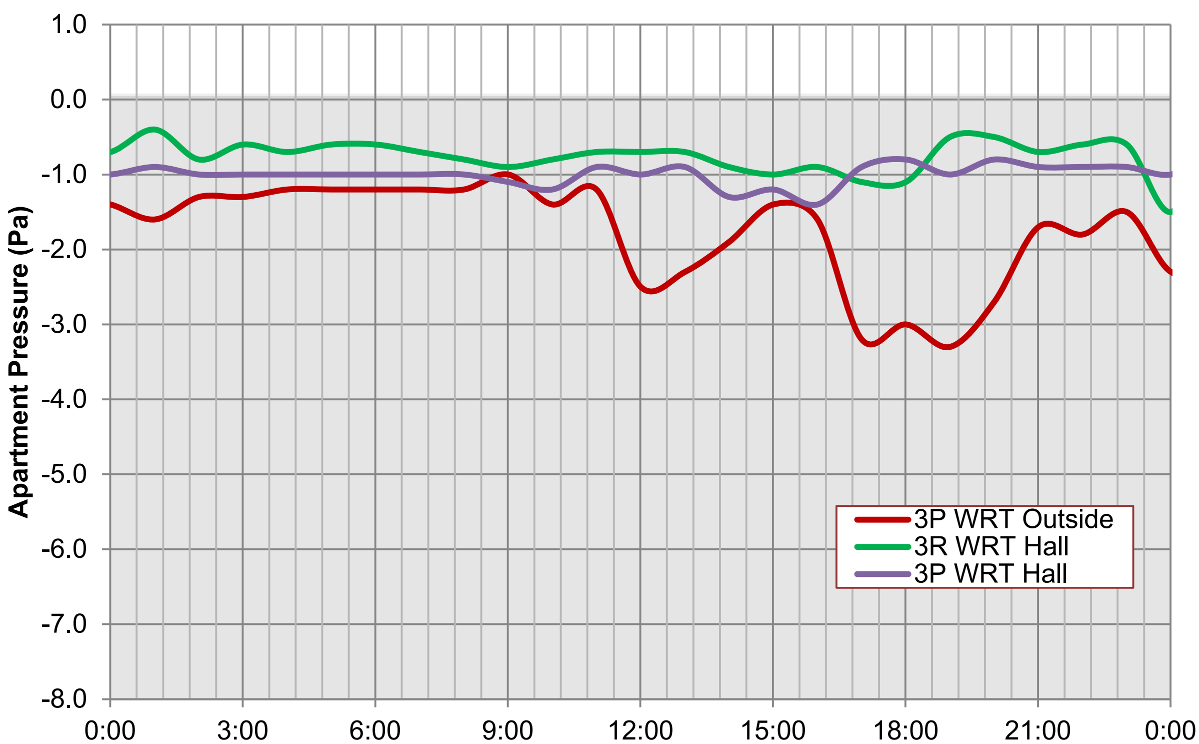

Figure 36. Apartment pressures with respect to outdoors and corridor—single day

Both apartments maintain a slight depressurization with respect to the corridor. When the results of the pressure monitoring are combined with the findings from the door leakage and PTAC tests, pathways of air movement into and out of the apartment can be established. In the two apartments where both of these parameters were measured, significantly more air is exhausted by the bath and kitchen fans, than is supplied through door leakage and PTAC fresh air fan combined. This means that again, despite the best intentions of the high performance building program and the design team, additional air is being drawn from unintended spaces, such as adjacent apartments, interstitial cavities, and unintended holes in the exterior wall.

Table 21 presents the supply flows as a percentage of the total flow being exhausted from the apartment. Although it was the intended source for MUA, the PTAC fresh air fan is responsible for a relatively small percent of the MUA. The majority comes from a combination of flow under and around the door and unknown sources of infiltration. Even though the door was not intended as a pathway for MUA, it actually provides a higher percentage than the intended source, and even a higher percentage than the door in the Type 1 building, where it was the intended source.

Table 21. Average Apartment Supply Flows as Percentage

Apartment	PTAC OA	Door Leakage	Unknown
3P	13%	41%	46%
3R	23%	48%	30%

Table 22 compares the design flow through the PTAC fresh air fan to the average measured hourly flow.

Table 22. Actual and Design Supply Flows From PTAC Fresh Air Fan

Apartment	PTAC OA Actual (CFM)	PTAC OA Design (CFM)	Actual/Design %
3P	7.1	40	18%
3R	8.6	40	22%
4R	7.1	40	18%
2R	6.6	40	17%
4P	6.9	40	17%

The overall average installed performance of the fresh air fan was approximately 20% of the design specification. The average hourly flows across the five apartments ranged from 4.9 CFM to 14.3 CFM. This represents 12%–36% of the design.

3.3.6 Pressure Monitoring—Heating Season

Pressure monitoring was conducted again in December in the same five apartments. The apartments were monitored for approximately 2 weeks. All five apartments were occupied during the heating season monitoring period. The PTACs and PTAC blowers were all initially set to “auto” mode. The tenants were asked to keep the blowers on auto; however, no request was made regarding the PTAC operation. As a result, some tenants manually switched the PTAC off during warmer periods, which means that the blower was also off for these times.

The pressure at the outlet of the fresh air kit with respect to outdoors was recorded in the five sample apartments. The sampling period spanned 2 weeks, including the Thanksgiving holiday. Unfortunately, it became apparent that several factors must have been at play during this period, such as occupancy of the apartment and by extension, the PTAC blower settings, thermostat set points, and possible open windows. This made interpreting the data difficult and led CARB to limit the analysis to a shorter period when it was certain those variables had been accounted for. The behavior of the apartments mirrors more closely that of the summer monitoring period. The snapshot of the data is presented in Figure 37. A negative pressure indicates the cabinet is depressurized and with respect to outside.

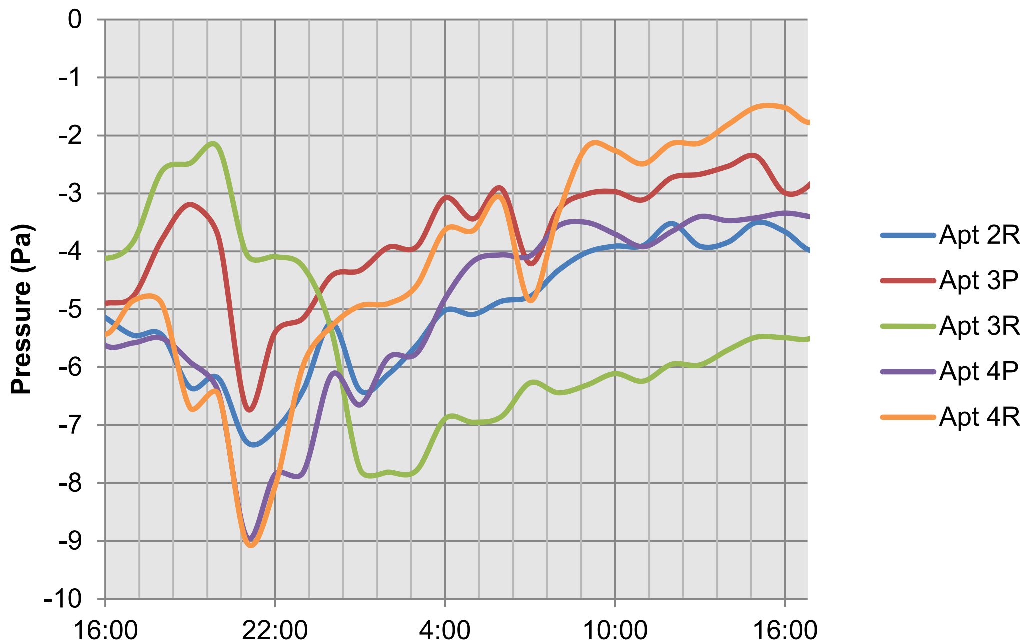

Figure 37. Pressure at outlet of PTAC fresh air fan with respect to outdoors—heating season

The results indicate that the outlet of the fresh air fan was negatively pressurized with respect to outdoors, which means air is being drawn in though the system. The performance of the systems is relatively consistent, with a maximum variation between apartments of 4 Pa. The subtle variation in pressure over the course of the day can most likely be attributed to environmental conditions.

In addition, the pressure between the apartment and corridor was logged in two apartments. The results are presented in Figure 38 and Figure 39.

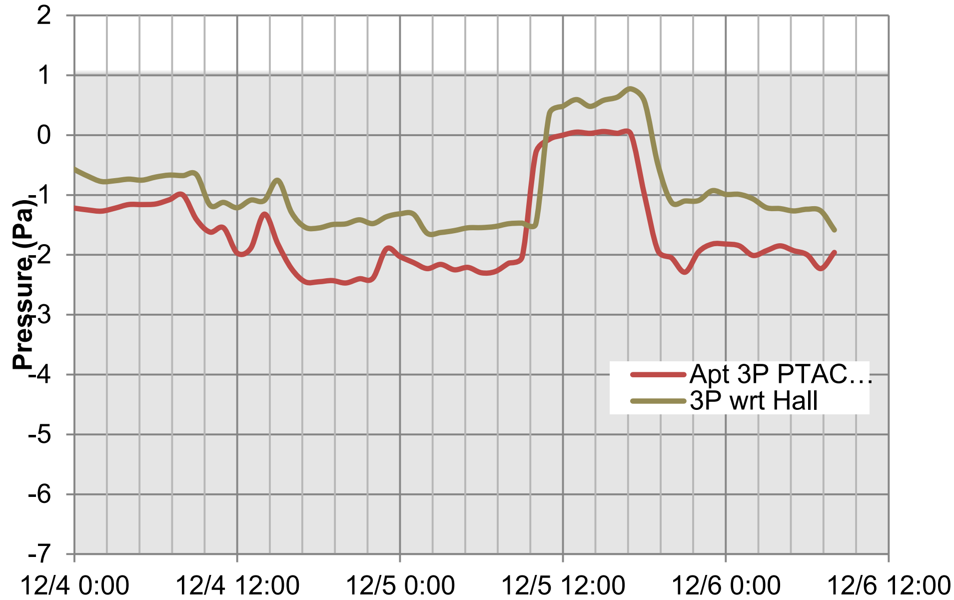

Figure 38. Apartment 3P pressures with respect to outdoors and corridor—heating season

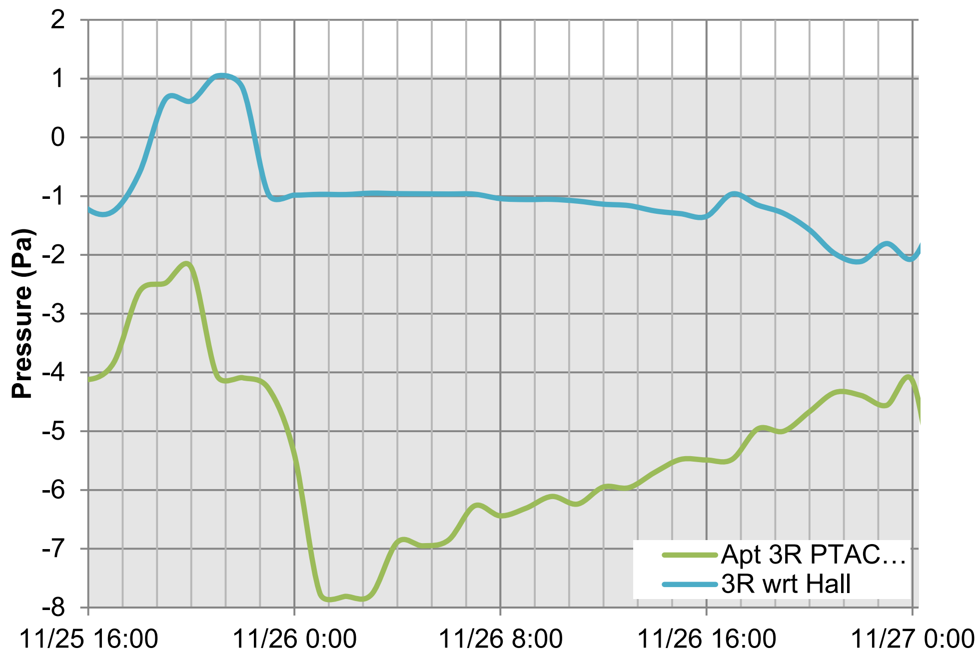

Figure 39. Apartment 3R pressures with respect to outdoors and corridor—heating season

In both cases, the PTAC and apartment follow similar trends; however, the apartment is slightly more pressurized than the PTAC. This is to be expected as the PTAC blower and fresh air fan reduce the pressure in the PTAC cabinet.

These data were combined with the equations obtained for airflow across the door and PTAC at various pressures, to develop a more complete understanding of air movement in these two apartments. These results are summarized in Table 23.

Table 23. Average Apartment Exhaust and Supply Flows (CFM)

Apartment	Exhaust	PTAC OA	Door Leakage	Unknown
3P	55	6.6	22.6	25.8
3R	38	8.5	14.9	14.6

Similar to the results from the cooling season, the PTAC OA kit is responsible for a relatively small amount (12%–22%) of MUA. The majority comes from the corridor door and miscellaneous sources of infiltration.

3.3.7 Supply and Exhaust Fan Power Consumption

The power ratings for the supply and exhaust fans are summarized in Table 24. Actual field power measurements were not made due to access issues. The measured flow was determined during the cooling season.

Table 24. Supply and Exhaust Fan Power

Fan Type	Rated Power (W)	Rated Flow (CFM)	Measured Flow (CFM)	Measured CFM/ Rated W
Supply PTAC Fan	2.4	40	8.6	3.6
Apartment Exhaust Fan	36	55	57.0	1.6

3.4 Type 4: Make-Up Air Through Passive Vents

3.4.1 Apartment Blower Door Testing

Blower door testing was conducted in nine apartments. The results show that apartments in this building are generally well compartmentalized, with an average total leakage rate of 0.10 CFM50/ft^2 of apartment enclosure. The results of the test are summarized in Table 25.

Table 25. Type 4 Building Apartment Airtightness Metrics

Apartment	# Beds	Flow (CFM50)	Apartment Volume (ft^3)	ACH50
2B	2	312	6600	2.8
2L	1	248	5496	2.7
3C	2	244	7376	2.0
3G	3	310	9120	2.0
4J	2	387	6504	3.6
4M	1	209	7920	1.6
5B	2	249	7376	2.0
5F	3	423	10840	2.3
5K	2	356	5616	3.8
Average				2.5

3.4.2 Supply and Exhaust Flow Testing

Each apartment in this building is equipped with a single inline exhaust fan serving multiple registers, one in each bathroom and kitchen. Each register is outfitted with an automatic balancing damper to limit the airflow from each register and balance airflow among them. Exhaust rates were measured from each register in 14 apartments. The results are summarized in Table 26 below.

Table 26. Type 4 Exhaust Flow Measurements

Apartment	# of Bedrooms	Exhaust Flow (CFM)			Total Flow (CFM)	Design CFM
		Kitchen	Bath 1	Bath 2		
1A	2	7	32	–	39	105
1D	3	21	40	21	82	125
2A	2	33	23	22	78	125
2B	2	34	19	37	90	125
2D	2	37	21	13	71	125
2F	3	35	18	20	73	125
2L	1	52	25	–	77	125
3C	2	40	24	25	89	125
3G	3	25	24	19	68	125
4J	2	42	23	–	65	105
4M	1	41	23	–	64	105
5B	2	37	15	16	68	125
5F	3	35	20	9	64	125
5K	2	54	30	–	84	105
Average		27			72	

The average flow rate from an exhaust register was 27 CFM. The design calls for 20 CFM from bathrooms and 85 CFM from kitchens for a total of 105–125 CFM per apartment, depending on the number of bathrooms. Measured airflows in kitchens average 44% of design, while those from bathrooms average 113% of design. Difficulties specifying and constructing very small multibranch exhaust systems can account for much of this variation. In both one-bathroom and two-bathroom units, the same exhaust fan was specified but at different static pressures.

Automatic balancing dampers and newer fans that self-correct for installation variances may be able to help limit imbalances. In this building, automatic balancing dampers were used in both kitchen and bathroom registers. In kitchens, maximum flows were 68% of design. The dampers were either incorrectly specified or were unable to limit flows in bathrooms to design levels. Flows in bathrooms were up to 200% of design of 20 CFM.

3.4.3 Passive Vent Testing

The test building uses trickle vents, a type of passive vent, to provide fresh air to apartments based on the pressure difference between inside and outside. A photo of one type of trickle vent is shown in Figure 40 (left) below, and another one shown in a typical installation in a window frame in the Figure 40 (right).

Figure 40. Common trickle vent (left) and installation in a window frame (right)

Trickle vents are tested by their manufacturers to determine their performance at various pressures or wind speeds, giving designers information about how the devices can be properly applied in their buildings.

In the test building, trickle vents were tested to characterize their performance as installed. Five trickle vents were tested by inducing a pressure difference on either side and measuring the airflow. A capture box was sealed around each vent and a fan was used to create a pressure on one side. The pressure on the inside and outside aspect of each vent was measured with manometers and the calibrated fan was used to measure the airflow. A photo of the testing apparatus is in Figure 41.

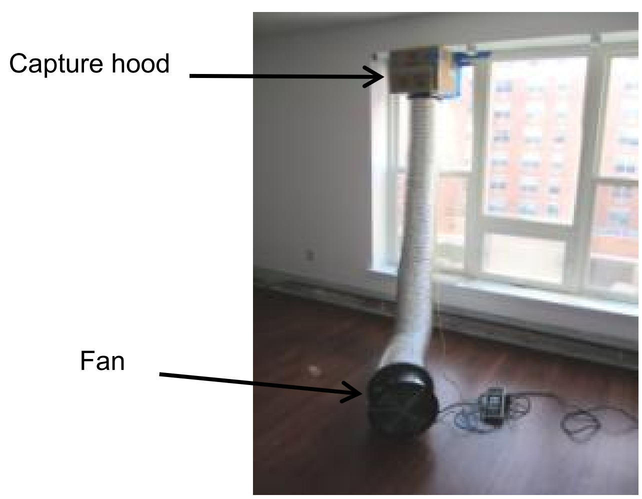

Figure 41. Setup for testing airflow through passive vents

Five separate vents were tested by this method and the results are shown together in the chart below. Airflow through the vents was measured at a variety of pressures. A clearly recognizable pattern is shown. The first trickle vent was tested under both positive and negative pressures, and the results were almost identical. The remaining four vents were tested only under negative pressure, and only results from the negative-pressure tests are displayed in Figure 42.

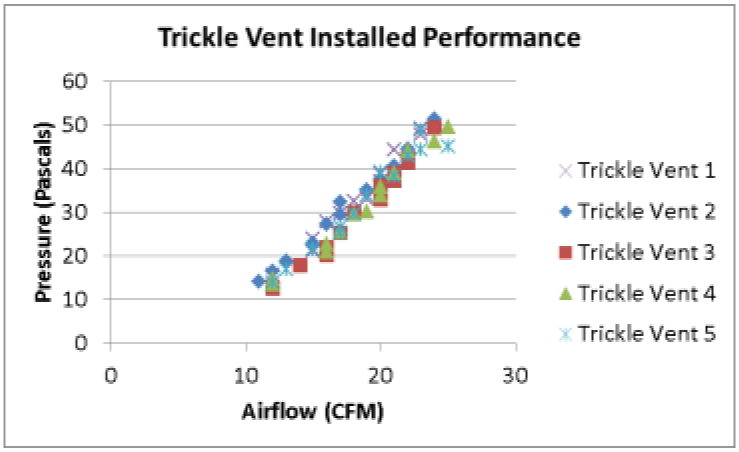

Figure 42. Trickle vent flow at varying pressures

The results show that trickle vents in this building are capable of airflow to an apartment but that a significant pressure difference across the vent is required. For example, if 25 CFM of MUA is desired, a pressure difference of nearly 50 Pa is required, roughly equivalent to a 20 mile-per-hour wind. Obviously consistent wind cannot be depended on, and using mechanical equipment to create a 50-Pa pressure difference would possibly present many unintended consequences. The results show that the commonly used trickle vents installed in most buildings as currently built are unlikely to provide rates of supply air anywhere equivalent to exhaust rates. The trickle vents are too small or too few, and the pressures commonly developed are much too weak to draw enough air from them.

It should also be mentioned that trickle vents must be installed well to function as intended. In a building evaluated by CARB for other studies, the lack of measured performance from a trickle vent prompted an investigation of the installation. Upon removing the vent cover from the window frame, closer examination revealed significant blockage of the air pathway through the layers of the window frame, caused by poor manufacturing technique. Obviously defects like this negatively impact the function of the vents.

Figure 43. Cut for trickle vent in window frame (left), trickle vent removed. Secondary holes drilled through frame to allow air passage (right)

The data gathered from testing airflow through the trickle vents in the test building are used to model how they function as a source of MUA over time. Using a linear regression on the logarithm of pressure and flow readings from all five vents of the same make and model, the pressure exponent *n* and flow coefficient *C* was derived and equation used to calculate flow through the vents is as follows:

$$Q = 2.768 * \Delta P^{\,0.551} \quad (3)$$

3.4.4 Door Leakage Airflows

Each door between apartments and corridors has a door sweep, but the sweep is not always tight to the door saddle. In addition, the door jambs and header do not typically have weather-stripping. As a result, significant gaps allow relatively easy passage of air between apartments and corridors. Simple measurements of the space around the door frames showed approximately 22 in.^{2} of gap around them. Equipment for testing the doors with a rigid capture hood the same way as other buildings in this study was not available, so doors were tested in two other ways to quantify the amount of leakage area.

Using a blower door procedure to depressurize the apartment through a window, the apartment/corridor door gap was repeatedly taped and untaped to observe the difference in measured flow through the blower door. A difference of approximately 205 CFM50 was recorded in tests on two apartments, roughly equivalent to 20 in.^{2} of leakage.

Another approach used a sharp-edged orifice and pressure measurements to estimate door gap size and airflow due to normal operating conditions in the apartment. A plastic shroud was taped over the door frame, and a plate with a sharp-edged orifice was fixed to the shroud. An illustration is provided in Figure 44.

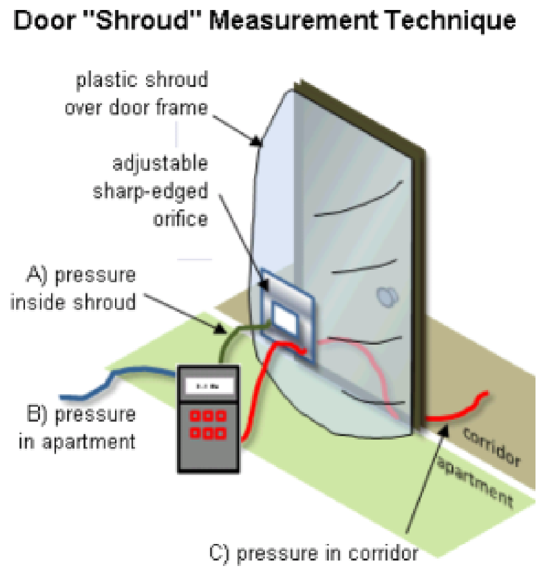

Figure 44. Setup for testing airflow through door gap with a plastic shroud and orifice plate

The pressure difference between the inside of the apartment (B) and in the corridor (C) was kept at 1–2 Pa by adjusting the orifice size, reducing the restricting effect of the shroud on the door but keeping airflow through it within a measurable range (see Table 27). The pressure difference across the plate was measured by subtracting the pressure inside the plastic shroud (A) from the pressure inside the apartment (B). Using a coefficient of discharge of 0.61 for the orifice plate, the flow at the measured pressure difference across the door yielded airflow estimates.

Table 27. Test Results Showing Calculated Leakage From a Plastic Shroud

Unit	Pressure Difference Across Orifice (A-B)	Corridor Pressure WRT Apt (C-B)	Orifice Size (in.^{2})	Calculated Flow (CFM)	Apartment Exhaust Fan Operation	Calculated Leakage Area (in.^{2})
3A	4.0	1.2	27	60.0	Fans On	24.6
3B	1.3	1.7	2	2.5	Fans Off	n/a
3C	3.1	1.2	27	52.8	Fans On	26.3

Measurements were taken in three apartments, two with their continuous exhaust fans running, and one with the exhaust fan disabled. All three apartments were neighbors on the same floor.

The airflow measurements indicate that operating the unit exhaust fans has a significant effect on the amount of air being drawn from the corridor door in these apartments. In the apartments with bath fans running, 53–60 CFM is drawn through leakage around the door. In the apartment without the fan operating, only 2.5 CFM is drawn through leakage around the door, illustrating the difference that the local exhaust makes in depressurizing the apartment. Due to the small values recorded, it was not possible to calculate the leakage area of this door.

The area of the gap around the door can be determined by using the measurements above. By subtracting the measured pressure drop across the apartment boundary (C–B) from the pressure drop across the shroud (A–B), the pressure drop across the door itself (A–C) can be determined. Using this pressure drop and the flow measured through the orifice, one can find the area of the door gap. The average area of leakage around the doors calculated by this method is 25.5 in.^{2}

$$A = Q/C_d * (2\Delta P/\rho)^{11.5} * 1.36697 \quad (4)$$

Where:

A is the leakage area of the door
Q is leakage through the door gaps (in CFM)
C_d is the coefficient of discharge
ΔP is the pressure difference between inside and outside of the test system (in Pascals)
ρ is the air density (in kg/m^3)

3.4.5 Pressure Monitoring

Pressure monitoring was undertaken in several building spaces with the intent of understanding the airflow patterns between building spaces and between the building and outside. Data were gathered on 1-second intervals, and then averaged over every hour to give a general picture of pressure in the spaces over time. Data were collected during a shoulder season with a mix of warm and cool weather. Two of the apartments were unoccupied for at least 1 week, while the rest were occupied. Definite patterns emerge when comparing the occupied apartments to the unoccupied apartments.

Figure 45 shows the pressure in several apartments throughout the building as well as the hallway, all with respect to a single outdoor reference pressure. The chart shows vacant apartments were more negatively pressurized than those apartments with tenants living in them. Apartment 4L was unoccupied and vacant for the entire monitoring period, while Apartment 4M was unoccupied until November 2, 2013, when a tenant moved in and occupied the space.

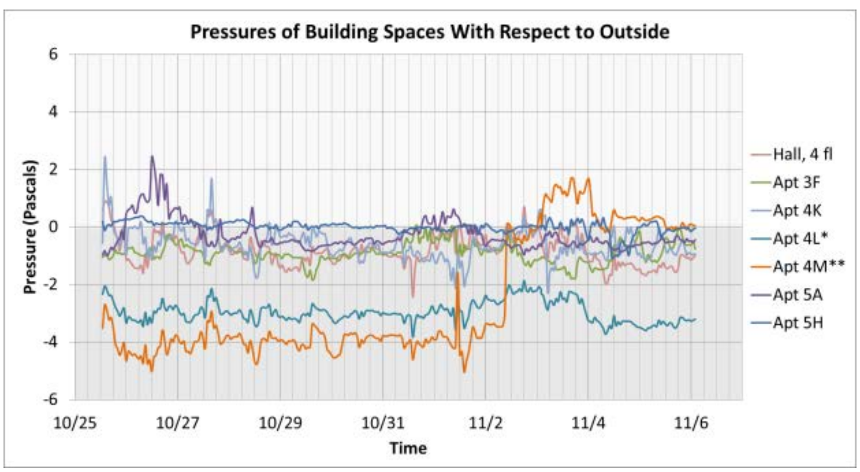

Figure 45. Pressure in several building spaces over time

*Apt. 4L was unoccupied for the entire monitoring time.
**Apt. 4M was unoccupied until November 2.

In this occupied building, both tenants and the resident superintendent were unaware of the presence or function of the trickle vents installed in their windows. Several complained of a "stuffy" environment, and preferred to use their windows to ventilate the apartment. In Figure 46, one can see the direct effect of an open window on the pressure in the apartment. Apartment 5H was observed with open windows at each visit, and the resident explained that he preferred more fresh air than could be provided by the trickle vent. The pressure in this apartment is essentially neutral with respect to outside, showing free exchange of air with the outside.

Other occupied apartments kept their windows closed more habitually, according to interviews with tenants. One can see a trend of generally lower pressure with respect to outside in the apartment on the third floor, while apartments on higher floors have somewhat higher pressures. This concurs with a general pattern common to buildings in cooler weather, as stack effect increases pressure on upper floors while lowering it on lower floors with respect to outside.

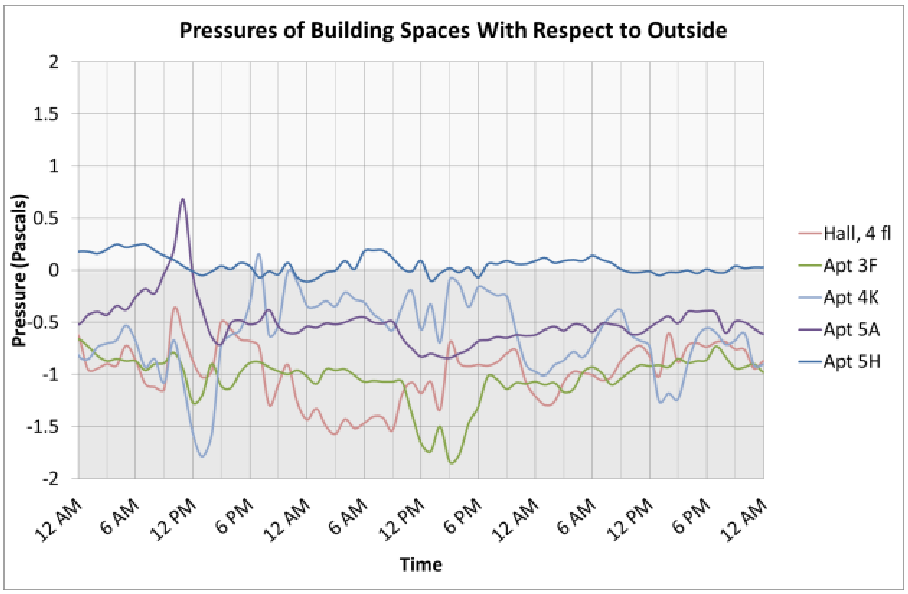

Figure 46. Pressure data logged in building spaces over a 24-hour period

Pressures between apartments and their neighboring hallways were also recorded (Figure 47). It appears that vacant apartments are significantly more depressurized relative to the hallway than occupied apartments. This indicates that air predominantly flows into apartments from the corridors in unoccupied apartments. This concurs with earlier testing that measured the flow of air through the corridor door in an unoccupied apartment was 53–60 CFM. In occupied apartments, open windows obviously dominate the airflow dynamics. In this study building as well as many others, residents open windows to combat localized overheating in their apartments.

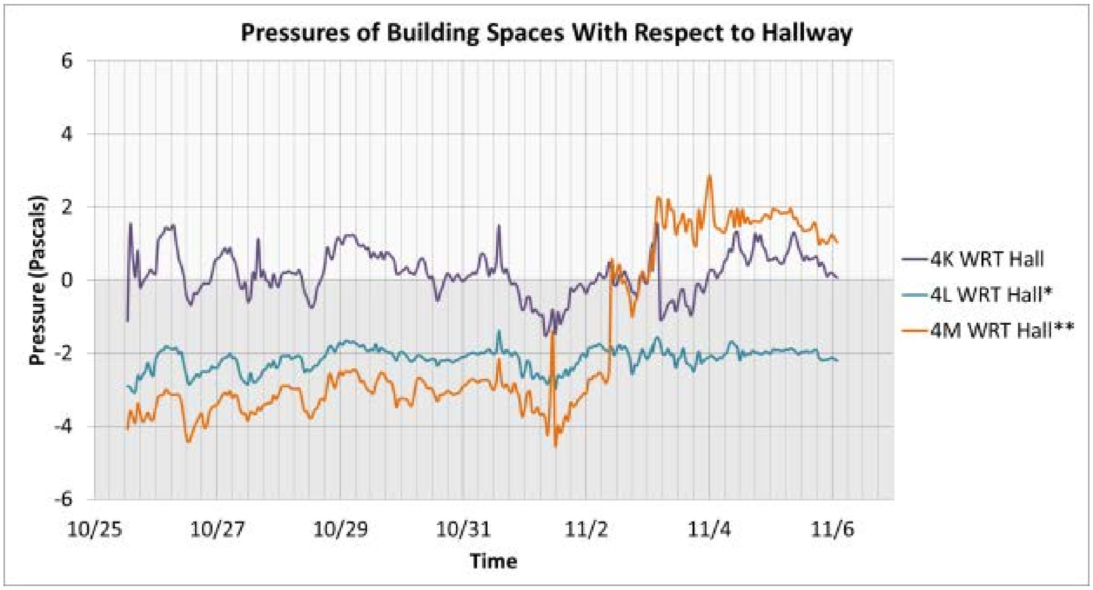

Figure 47. Pressures in apartments with respect to hallway

*Apt. 4L was unoccupied for the entire monitoring time.
**Apt. 4M was unoccupied until November 2.

The equation for an orifice opening can be used by applying the pressures measured through logging, to the area of the door leakage measured in previous tests

$$Q = A * C_d * (2\Delta P/\rho)^{0.5} * 1.36697 \quad (5)$$

Where:

Q is leakage through the door gaps (in CFM).
A is the leakage area of the door
C_d is the coefficient of discharge
ΔP is the pressure difference between inside and outside of the test system (in Pascals)
ρ is the air density (in kg/m^3)

This equation was used to calculate the airflow through the door at any given time if the pressure is known. Applying this to the pressure logging data, the bulk flow of air into or out of the apartment can be determined. Table 28 shows these data for three apartments. Data from apartment 4K, in which windows were opened occasionally, are in contrast to the data from apartments 4L and 4M, which were unoccupied with their windows closed.

The data show that the two unoccupied apartments are drawing significant air from the corridors, while the occupied Apartment 4K in fact is sometimes delivering air into the corridor. The pressure in this apartment fluctuates widely, and flows are significant in either direction, possibly caused by the operation of the windows. At times, the apartment draws a significant amount of air from the corridor (up to 39 CFM) while at other times, it sends air in the other direction (up to 45 CFM into the corridor). Since neighboring apartments on the same floor are consistently negatively pressurized with their windows closed, it is assumed that the cause of the wild swings of pressure and airflow in the other direction are the result of opening and closing windows.

Table 28. Summary Flow Data From Apartment/Corridor Doors

	Apt 4L	Apt 4M	Apt 4K*
Average	55	66	–13
Maximum	65	78	39
Minim	44	55	–45
Tested Condition	Unoccupied	Unoccupied	Occupied

*Negative numbers indicate flow from apartment into corridor

The logged data from Apartment 4K are quite variable, illustrating the impact of opening windows on the pressure dynamics of the building. In the chart below, there is an obvious correlation between the pressure in the apartment with respect to outside and with respect to the corridor. Most notably, when the pressure in the apartment with respect to outdoors jumps toward zero, it indicates an open window and the pressure with respect to the hallway increases to positive territory. These events are marked by air flowing from the apartment into the corridor for a time, as indicated by the directional arrows in Figure 48. In this building, apartments with their windows open may vent air into the corridor, while apartments with their windows closed draw air from the corridor.

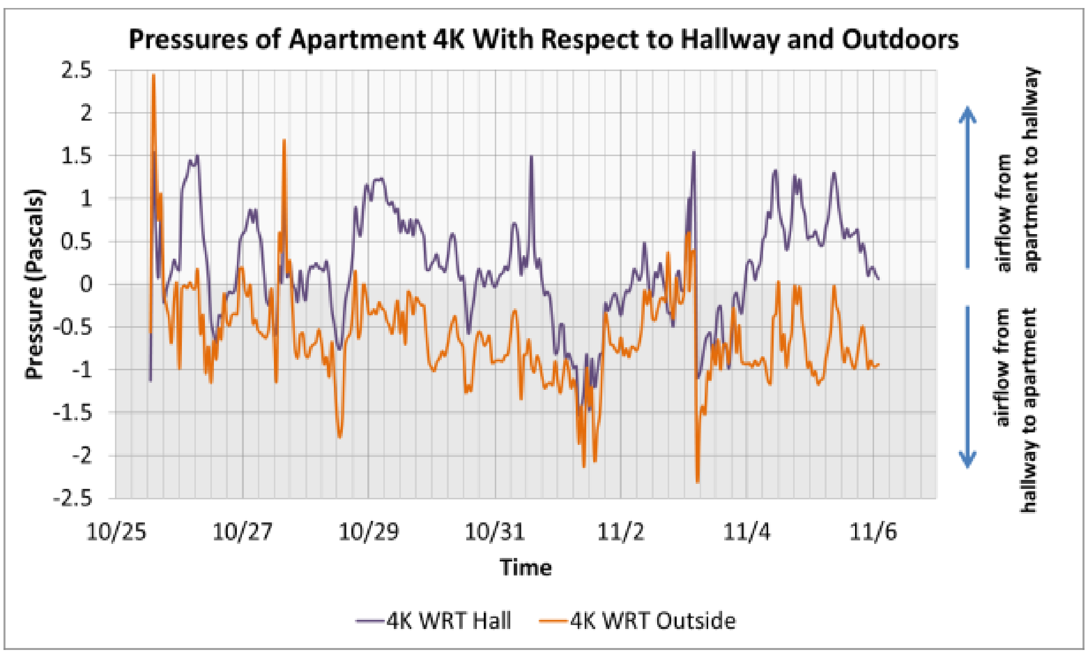

Figure 48. Pressures in apartment with respect to hallway and outdoors

Comparing corridor door airflows to those originating from trickle vents, it is clear that more identified MUA originates from corridors in this building than from outside, or at least through trickle vents from the outside (see Table 29). The average trickle vent delivered about 5 CFM at the pressures commonly experienced in apartment 4L, an unoccupied apartment. In apartment 4M, another unoccupied apartment, the average flow was almost 6 CFM per trickle vent.

Table 29. Summary Flow Data From Trickle Vents

Trickle Vent Flows (CFM)						
Apartment	**Apt 4L**	**Apt 4M**	**Apt 4K**	**Apt 3F**	**Apt 5A**	**Apt 5H**
From Single Trickle Vent						
Average	5	5.9	1.9	2.5	1.1	–0.1
Maximum	3.9	4.8	–4.5	–0.5	–4.5	–1.6
Minimum	5.8	6.7	4.3	3.9	2.8	2.9
From All Trickle Vents in Apartment						
# Beds	1	1	2	3	2	1
# Trickle Vents	3	2	4	5	3	2
Total Flow	15.1	11.9	7.4	12.6	3.3	–0.2
Tested Condition	Unoccupied	Unoccupied	Occupied	Occupied	Occupied	Occupied

Data from Apartment 4M are taken from the unoccupied period only.
Negative numbers indicate flow from the apartment out the trickle vents to outside.

In summary, for apartments in which no windows were opened during the monitoring period, airflow from the corridor into the apartments dominates the MUA pattern (see Table 30). These flows are several times higher than those measured from trickle vents.

Table 30. Identified Sources of MUA in Apartments (CFM)

	Apt 4L	**Apt 4M**	**Apt 4K**
Air From Corridor Door	54.8	66.1	–13.2
Air From Trickle Vent	15.1	11.9	7.4
Measured Apartment Exhaust	36	38	49
Tested Condition	Unoccupied	Unoccupied	Occupied

3.4.6 Exhaust Fan Power Consumption

The exhaust fans used in this building are Panasonic WhisperLine FV-10NLF1, nominally 120-CFM fans. Product literature lists fan efficiency at no less than 3.3 CFM/W, resulting in a maximum power consumption of 21.8 W at the average measured exhaust flow rate.

4 Discussion

Of the four strategies tested, all delivered varying degrees of MUA; however, none consistently delivered their design flow rates. That does not imply that these strategies are ineffective; it simply means that the installations tested for this study were not executed properly. The following discussion aims to provide criteria and specifications needed for each strategy to deliver design flow rates and then provides a side-by-side comparison of the four.

4.1 Type 1: No Direct Make-Up Air Supplied to Apartments

This type of ventilation strategy is commonly found in multifamily construction. Local exhaust is provided with no provision for MUA, which is assumed to come from the exterior envelope as in low-rise residential construction. Alternatively, MUA may be provided to a “pressurized” corridor and assumed to transfer to the apartment through door leakage around the apartment door. In the test building, the common area ventilation system was intentionally oversized to provide OA for the corridors and the apartments. In practice, more air than expected was exhausted from common areas, and almost balanced the supply. The corridors were essentially unpressurized by the common area ventilation systems. Still, testing indicated that approximately 25% of the MUA for apartment exhaust was being drawn from the corridor through leakage around the door, while the remainder came from other sources of infiltration. It was outside the scope of this study to identify all sources of infiltration; however, it is most likely a combination of infiltration from the exterior, from other apartments, and from interstitial spaces.

With so many potential sources of MUA, it is not accurate to assume that one source predominates. While some factors that influence air movement can be controlled, most cannot. As a result, this strategy does not consistently deliver adequate MUA. In addition, as construction moves toward tighter buildings, the source of MUA will shift toward the weakest pressure planes, which will likely be interior spaces.

4.2 Type 2: Make-Up Air Through Ducted Supply Air

This strategy of ventilation was effective at delivering MUA to many apartments. The percent of supply to exhaust ranged from 38% to 105%. However, it failed to meet design rates in most cases. This highlights the need for close oversight during construction and a thorough commissioning process.

Though challenges exist, it is possible to design and construct this system to meet the specified flow rates. Numerous factors, including poor ductwork design, duct leakage, undersized fans, poor installation, and imbalanced risers, can contribute to the subpar performance. A skilled and motivated ventilation contractor is imperative in creating a properly functioning system.

Independent testing and verification is also important in helping to establish a system that performs properly. While a TAB contractor may be used, it is equally important to verify the results. There was considerable discrepancy between CARB’s field measurements and the TAB report, which consistently reported the system as performing within 5%–10% of design. CARB measurements showed that the system consistently underperformed by 30%–60%. Discussion in Section 3.2.3 gives more detail on the possible reasons for this discrepancy.

4.3 Type 3: Make-Up Air Through HVAC Supply

This somewhat novel ventilation strategy is innovative but ultimately was not effective at delivering MUA to apartments. The strategy provided supply flows that were approximately 15% of the MUA. The balance was split roughly in half between leakage around the door and other sources of infiltration. Despite the poor performance, this strategy still offers promise.

Three changes in the system design would significantly improve the performance. The first is to construct a tight, well-compartmentalized building. The building tested for this study was relatively tight; however, the gap beneath the apartment doors significantly reduced the overall apartment tightness. This is generally not taken into account when the apartment is tested because the blower doorframe is typically placed in the door opening. Installing weather-stripping and a door sweep would help to ensure that the door does not contribute to air infiltration. A tighter apartment results in a greater pressure differential that the MUA fan experiences. This results in greater flow through the fan.

The last two improvements pertain to the design of the MUA kit. The path from outside to inside, through the kit, is rather long and subject to substantial pressure drops. Moving from outside to inside the following components are encountered: exterior damper, mesh screen, several feet of corrugated plastic tubing, one foot of insulated ductwork, and a 1-in. thick filter. Reducing this path and the number of pressure drops would result in higher flow rates.

Last and most importantly is the fan itself. The one used in the MUA kit is a simple 12-V computer fan. There is a wide variety of these fans available with an equal array of performance curves. The fan curve could not be obtained for the particular model used in the MUA kit; however, qualitative testing showed that it did not perform well under high static pressure. Future versions of this system should consider using a fan that is designed to operate under higher static pressure. Ideally, the fan should be sized for the operating characteristics of the system. It is likely that if all three improvements are made, the performance will improve and substantially more MUA will be delivered. It is conceivable that design level ventilation could be achieved with an improved system

4.4 Type 4: Make-Up Air Through Passive Vents

This type of ventilation strategy requires near-complete control over all elements of air movement in a building in order to function well. Apartments must be substantially airtight so that alternate pathways for air movement can be minimized. It is beyond the scope of this study to quantify what levels of airtightness are necessary for typical passive vents to function properly, but the results of this study show that even in apartments of better-than-average airtightness, performance from passive vents is difficult to ensure.

Testing showed that at an average apartment airtightness of about 0.10 CFM50/ft^2, continuous in-unit exhaust fans drawing 36–45 CFM were able to depressurize the apartment to about 3–4 Pa. This is enough to draw 11.5 CFM from trickle vents compared to 41 CFM of exhaust, resulting in controlled MUA ratio of 28% (see discussion of “controlled MUA fraction” in Section 4.5 below). Through pressure monitoring, it became immediately clear that opening windows in an apartment completely eliminates any such depressurization.

This may be a moot point, because opening the window clearly promotes significant air exchange between the apartment and outside, and hopefully this means that fresh air makes its way into the apartment. However, it also became apparent from pressure monitoring that the airflow between the apartment and the corridor was highly affected by the opening and closing of windows, and that the direction of airflow is not easily predictable or controllable. This means that an apartment with open windows could end up supplying polluted air to the corridor and to other units, or that it could draw polluted air from the corridor inward, depending on the prevailing pressures in the building at that time.

4.5 The Relationship Between Apartment Airtightness and Make-Up Air

The Type 4 strategy of providing ventilation, while probably the lowest cost in terms of construction and operation, is also probably the most difficult to execute well, requiring above-average levels of attention to air-sealing details. The apartment airtightness necessary is not commonly seen in multifamily residential construction.

To illustrate this point, consider a building with trickle vents. In order to keep trickle vents to a reasonable size, the apartment in which they are installed must be at a sufficient negative pressure to draw air from the vent, and therefore the apartment must be relatively airtight to develop that pressure. This shows that a balance must be struck between realistic targets for depressurization and trickle vent size (see Table 31). The apartments monitored for this study were maintained at a negative pressure of 3–4 Pa. In order to deliver 30 CFM to an apartment at a pressure of 4 Pa, a trickle vent must have 25 in.^{2} of open area. This is akin to having a 2-ft wide window open by 1 in. For comparison, the trickle vents tested in the Type 4 building had an opening of about 4 in.^{2} per vent.

Table 31. Area of Trickle Vents Required at Various Pressure Differences To Deliver 30 CFM

Pressure Difference (Pa)	Trickle Vent Area Required (in.^{2})	Minimum # Common Trickle Vents Required at 4 in.^{2} Each
3.0	29.1	8
4.0	25.2	7
5.0	22.6	6
6.0	20.6	6
7.0	19.1	5
8.0	17.8	5
9.0	16.8	5
10.0	16.0	4

Obviously, caution should be exercised before specifying 25-in.^{2} engineered "holes" in the exterior envelope, but this illustrates the tradeoff that must be weighed before system selection.

As an example, to meet ASHRAE 62.2-2010 standards for a studio apartment in this building, 30 CFM of ventilation would be required. The exhaust fan used in this building is capable of working against 155 Pa static pressure at that flow rate. Given that ductwork, registers, and exterior louvers in the exhaust system each detract from that figure, the amount available to depressurize the apartment as needed to make trickle vents function is not large.

In a basic blower door test, all sides of a test space are depressurized to an equal degree (see Figure 49). In a single-family home, the leakage quantified relates fairly directly to indoor-outdoor airflow and energy use. In multifamily buildings, however, the leakage figures determined from this process are not directly indicative of either airflow patterns or energy impacts.

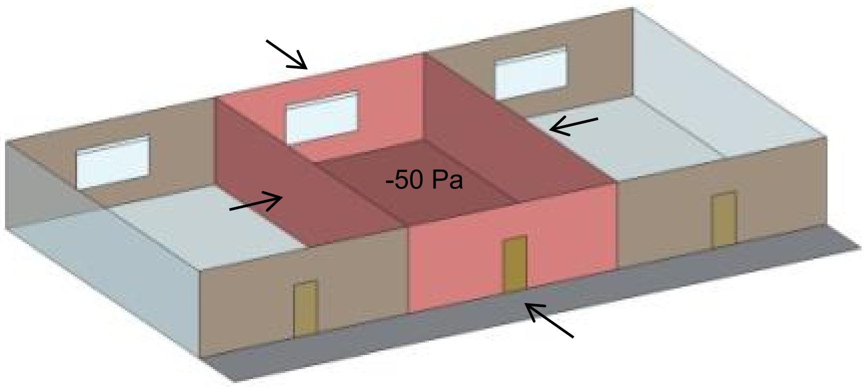

Figure 49. All sides of an apartment contribute to leakage in a blower door test

Not all surfaces of an apartment leak equally under the artificial conditions of a blower door test, and this is even truer in normal operating conditions. Though data indicating the leakage rates of separate surfaces are difficult to obtain, it is safe to say that interior demising walls leak considerably more than exterior walls or typical floors or ceilings, especially those made of monolithic slabs of concrete. Still, even though demising walls are leaky, they do not often experience the major pressure differences that induce leakage if they are served by equally operating mechanical systems (see Figure 50). In the test building, every apartment had a relatively similar rate of exhaust and a similar operating pressure. Air does not move across the shared apartment walls if the pressure in both apartments is the same. The leakage and MUA therefore come mostly from the exterior or the corridor/apartment wall.

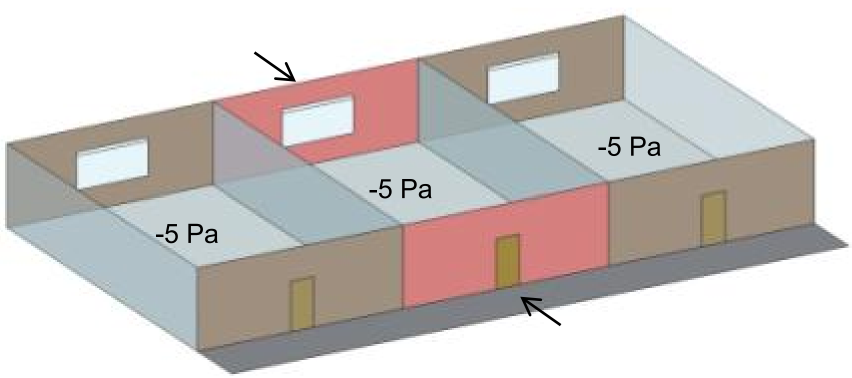

Figure 50. Pressure differences on select surfaces in normal building operation

The tests performed in this study to quantify corridor door leakage found that the doors leaked about 200 CFM50. Converting this to leakage at an apartment's typical operating pressure of –4 Pa, this equates to about 57 CFM, about the same value as the tests that measured door airflow under actual operating conditions. Clearly the corridor door can be by far the biggest point-source of MUA in the apartment, whether intentional or not.

Of course, if any apartment comes under different operating conditions because of a malfunction or change in the operation of another apartment, air movement occurs across the shared walls. For example, if the exhaust fan in a smoker's apartment stops working, not only is the smoke not exhausted from the apartment, but the working exhaust systems in nearby apartments draws that smoke into their own apartments. Compartmentalization is very important to prevent this situation.

Creating an apartment that is capable of producing flow from trickle vents and only trickle vents would prove to be quite difficult. In Table 32, a theoretical scenario based on test results from the test building is shown. Current leakage levels and distributions are shown, compared to target levels for a scenario in which trickle vents could work. Leakage sources from the blower door test are identified, along with assumptions for the share of the total leakage due to each envelope component. From leakage tests done on these building components, the following have been identified. The door and trickle vents combined account for almost as much leakage as the entire envelope combined.

Table 32. Leakage Sources of Tested Apartment

Leakage Test Results	CFM50	Source
Envelope	300	Blower door test
Door	200	Door leakage test
Trickle Vents	75	Depressurization test
Total	575	

Identifying the share that each surface of the apartment accounts for of the envelope leakage figure, the estimated contribution of each is given below in CFM50. As mentioned before, not all envelope leakage paths identified during the blower door test allows air through in actual building operation. For example, the pressure difference between apartments is close to zero during normal building operation so no MUA is taken from this space. In the table below, those surfaces which contribute to air movement during normal building operation are indicated by an asterisk. The share of each building component in actual operation is shown in the table as well. The pressure that a typical apartment experiences in this building as currently built is about 4 Pa. At this pressure, the various envelope components pass considerably less air, shown in the columns labeled "Actual Operation." The total air exchanged through all envelope components is 106 CFM.

The target envelope leakage numbers required to obtain most MUA from trickle vents are substantially lower. Leakage from all other building components must be minimized so that the greatest pressure is exerted on the trickle vents. They should be the leakiest component of the envelope. In the scenario in Table 33, the total envelope leakage including leakage from the corridor door and the trickle vents is 179 CFM50, which is extremely airtight. Such an airtight apartment would elevate the pressure in the apartment to perhaps 10 Pa, drawing 76 CFM of MUA total, with the majority coming from trickle vents.

Table 33. Current and Proposed Building Characteristics for Properly Functioning Trickle Vents

	Current				Target			
	Total Leakage		Actual Operation		Total Leakage		Actual Operation	
Leakage Source	Share	CFM50	Pressure	CFM	Share	CFM50	Pressure	CFM
Floor	2.5%	14	0	0	3%	10	0	0
Ceiling	2.5%	14	0	0	3%	10	0	0
Ext. Wall*	7%	40	4	11	7%	20	10	9
Corridor Wall*	10%	58	4	16	13%	40	7	15
L Wall	15%	86	0	0	17%	50	8	0
R Wall	15%	86	0	0	17%	50	0	0
Door*	35%	201	4	57	7%	20	7	7
3 Trickle Vents*	13%	75	4	21	34%	101	10	45
		575		**106**		**300**		**76**

*indicates a surface that contributes to air exchange during normal building operation.

Attaining tightness levels this high is beyond the reach of everyday construction practices. This building, as currently built, has blower door results that are considered very airtight. The average airtightness of apartments in the building is 2.5 ACH50, and the leakage ratio is 0.11 CFM50/ft^2 of enclosure area. To put this in perspective, these levels are already approximately one third of the current requirement in the ENERGY STAR Multifamily High Rise program. The proposed level of airtightness for the envelope components is broken down in Table 34. Leakage from the envelope is minimized to 179 CFM50 for an 800-ft^2 apartment, or 0.067 CFM50/ft^2 of enclosure area.

Table 34. Proposed Leakage Levels for Functioning Trickle Vent

Leakage Targets	CFM50
Envelope	179
Door	20
Trickle Vents	101
Total	**300**

Though there is no specific threshold of apartment airtightness required, the proper functioning of the system under varying environmental and operational conditions is highly dependent on compartmentalization. The airtightness of the envelope must be minimized to avoid transfer of air between apartments when a window is opened in a neighboring apartment, for example. As demonstrated in this relatively tight building, opening the window in an apartment significantly affects pressure in its neighbors. The alternative to compartmentalization is to ensure that all apartments are held at the same pressure regardless of windows opening, fans turning on and off, etc., which is not practical.

This discussion seeks to point out that although there is no specific standard for how airtight an apartment must be to benefit to the function of the ventilation system, in general tighter apartments afford more control over the source of MUA through ever-changing environmental conditions. Table 35 illustrates where MUA is sourced at two levels of airtightness in a model apartment.

Table 35. Two Scenarios of Apartment Tightness and MUA Sources

	Scenario 1 As Currently Built	Scenario 2 Proposed
Envelope	299	79
Door	201	20
Trickle Vents	75	101
Total Leakage	575	200
CFM50/ft^2	0.11	0.03
# Times Tighter Than ENERGY STAR	3	10
CFM From Trickle Vent	21	45
CFM From Other	85	20
% MUA From Trickle Vent	20%	69%
% MUA From Other	80%	31%

In the first scenario, based on actual measurements of the building in this study, the total leakage of an apartment may be 575 CFM50, including leakage from the envelope, the corridor door, and trickle vents. This total leakage equates to 0.11 CFM50/ft^2 of apartment envelope, about 3 times tighter than the current ENERGY STAR for Multifamily High Rise standard.

In this scenario, three trickle vents, each 4 in.^{2} in area, bring in 21 CFM total, or 20% of MUA, while 85 CFM or 80% of MUA comes from other unidentified sources such as the shared walls, floor, ceiling, corridor door, and exterior wall.

In the second scenario, the apartment is tightened by weather-stripping the corridor door so that it leaks only 20 CFM50, the trickle vents are enlarged to 13 in.^{2}, and the rest of envelope leakage is minimized to only 79 CFM50 (see Table 35). Under normal operating conditions, 45 CFM (69%) of MUA would come from trickle vents, while only 20 CFM (31%) comes from unidentified sources.

Obviously making an apartment 10 times tighter than the ENERGY STAR standard will be no easy task, but if this threshold is ever reached by advancing the art and science of compartmentalization, there is good reason to hope that apartment exhaust will be made up in large part by fresh, controlled air sources.

4.6 Comparison of Different Strategies

The following section aims to provide a means of comparing the four MUA strategies. Each strategy was applied to two theoretical apartments: a 450-ft^2 studio and a 750- ft^2 two-bedroom apartment. Based on ASHRAE 62.2-2010, 30 CFM and 45 CFM of whole-unit ventilation are required, respectively (ASHRAE 2010b). (ASHRAE 62.2-2013 requires slightly higher levels; however, the units evaluated were constructed prior to 2013 so the 2010 rates were used for this comparison.) The fan performance metric (supply CFM/W) that was developed for each strategy was applied to the two theoretical apartments to determine the electricity requirement necessary to provide the required MUA. The results are presented in Table 36.

Table 36. Comparison of Ventilation Strategy Fan Power Applied to Two "Sample" Buildings

Strategy	Fan Type	Total Fan Power* (Rated W)	Measured Airflow (CFM)	CFM/W	Total Fan Power (W) for Studio (30 CFM)	Total Fan Power (W) for 2-Bedroom (45 CFM)
Type 1: No Direct MUA Supplied To Apartments	Individual apartment exhaust fan	3.2**	9.7	3.0	9.9**	14.8**
Type 2: MUA Through Ducted Supply	Central supply	1,119	1,792	1.6	42.3	63.5
	Central exhaust	1,492	1,898	1.3		
Type 3: MUA Through HVAC Supply	PTAC supply fan	2.4	4.1	3.6	15.8	20.0
	Apartment exhaust fan	36	57	1.6		
Type 4: MUA Through Trickle Vents	Individual apartment exhaust fan	21.8**	11.5	0.5	56.9**	85.3**

*Values estimated from manufacturer or design literature.
**Type 1 and Type 4 both use the same type of fan. The variation in power is due to individual product selection. Had the fan from Type 1 been used in Type 4, the values would be significantly lower.

The data in the Table 36 should be viewed with the understanding that it contains a mix of both tested values and manufacturer design values. Due to difficulty in accessing several of the fans, all of the values for fan power were taken from manufacturer literature. The values for airflow were all directly measured or derived from measurements. In the case of Type 1: exhaust only, the fan depressurizes the apartment and results in flow from the corridor into the apartment. Therefore, the measured airflow represents the amount of air coming through the door undercut. For Type 3: HVAC supply, the total fan power is the sum of the existing exhaust fan and the power required by the PTAC fan to supply the requisite amount of fresh air. These values were determined from tests conducted on studio apartments in the building, which have one kitchen exhaust, one bath exhaust, and a single PTAC supply. Values for one- and two-bedroom units would be slightly different due to variations in the number of baths and PTACs; however, these units were not tested under this study.

Comparing one system to another with finality is difficult because none of the buildings actually performed as designed. In the case of passive vents, the proper functioning of the vents is very dependent on the airtightness of the building envelope. The only building type in which verifying performance is relatively straightforward is Type 2: ducted supply, but even this was shown through measurements to fall considerably short of the target.

It should also be understood that these values are only valid for the equipment used in the buildings in this study, and should not be taken as universally representative of all buildings of the same type. For example, the mechanical equipment for Types 1 and 4 are substantially similar—small, unitized exhaust fans located in the bathrooms of each apartment—but because of a choice of fan equipment, those in the Type 4 study building consume considerably more electricity than those in the Type 1 building. Design choices have an impact on the performance of every project, and these data should be taken as examples only.

Type 1 has been included in the table for reference; however, it does not reliably deliver fresh air, as demonstrated in the tests. Types 2 and 3 include the power requirements of the supply and exhaust fans, since these systems require both fans to function properly. Of the three remaining strategies that have potential to reliably provide MUA, Type 3 performs the best with regards to electric energy requirements; however, the power requirements needed for the supply fan would likely be greater than those noted in the table because a different fan would need to be used to deliver the needed flow. Types 2 and 4 require significantly more fan energy; however, the ventilation performance of Type 4 is likely to be more inconsistent and subject to environment factors than Type 2.

Although Type 2 requires more electric energy than Type 3, it has the potential to conserve thermal energy by tempering the supply of outdoor MUA with energy recovered from the exhaust air through the ERV. It should be noted that Type 2 does not require energy recovery. It is possible to provide ducted supply and separate exhaust without an HRV or ERV. Types 3 and 4 both deliver MUA from the outside; however, the comparison between their thermal performances is not a simple process.

Table 37 shows a comparison between the total exhaust removed from the apartment and the supply air from known sources. The ratio of known supply air to exhaust air is the controlled MUA fraction. The MUA through ducted supply is the best performer of the group, with a 71% controlled MUA fraction. This means that every CFM of exhaust is matched by 0.7 CFM of fresh air supply. The worst performer of the group was the PTAC MUA supply, with every CFM of apartment exhaust matched by less than 0.1 CFM of supply. The two passive MUA strategies (Types 1 and 4) both had a controlled MUA fraction of about 28%. In addition, for reference only, the ASHRAE 62.2-2010 whole-building ventilation rate is included for the apartments. This value is determined from ASHRAE 62.2-2010 Table 4.1a and is based on the floor area and number of bedrooms in each apartment. One-bedroom apartments with less than 1,500 ft^2 have OA ventilation requirements of 30 CFM, and two- and three-bedroom apartments with less than 1,500 ft^2 have OA ventilation requirements of 45 CFM. Although exhaust only strategies are accepted by ASHRAE 62.2, the ideal ventilation design would provide MUA from the outdoors that met these ventilation rates. Again, Type 2 is the best performer in this regard.

Table 37. Comparison of Supply Air Delivered by Each Ventilation Strategy

Strategy	ASHRAE 62.2 Whole-Building Ventilation Rate (CFM)	Average Supply Air Delivered (CFM)	Average Total Continuous Exhaust (CFM)	Average Controlled MUA Fraction (Supply Delivered/ Exhaust)
Type 1: No Direct MUA Supplied to Apartments	30–45	9.7	34	28.5%
Type 2: MUA Through Ducted Supply	30–45	37.9	53	71.4%
Type 3: MUA Through HVAC Supply	30	4.1	57	7.2%
Type 4: MUA Through Trickle Vents	30–45	11.5	41	28.0%

These data do not indicate the expected performance of every building that uses one of these strategies, but it is illustrative of the challenges in making each one work well. Clearly, construction quality of these particular buildings was a large factor in performance. CARB suspects that better unit compartmentalization and better construction of the ventilation systems would help the performance of each of these strategies.

Table 38 summarizes the general aspects of each type of ventilation system studied in this report. Material costs (not including installation labor) were estimated by the following methods:

- The cost of exhaust-only systems was estimated based on wholesale prices for continuously operated exhaust fans such as the Panasonic WhisperGreen fan, the model used in the study building.
- The cost of ducted ERV/HRV systems was estimated based on conversations with the developer of the two buildings in this study. The figure includes the main air handler cost and associated ductwork.
- The cost of PTAC OA fans was based on comments by the manufacturer on the additional cost for the optional package added to their typical PTAC unit.
- Costs for the trickle vents are based on comments by several developers in the New York City area who regularly use the devices, but does not include the cost of installation in a window.

Fan energy estimates are based on manufacturer's data relating fan performance in CFM with power consumption. The power consumption is based on 30 CFM of exhaust being removed and 30 CFM of fresh air being delivered. These estimates are based on manufacturer's data of the equipment used in the study buildings, and the actual power consumption of a real building is different based on system design, product selection, and construction.

- For Type 1, Exhaust Only, fan power is the estimate of a typical in-unit exhaust fan such as the Panasonic WhisperGreen at the design levels of ventilation used in the study building. No dedicated supply is provided, so no power consumption for supply is accounted for.
- For Type 2, Ducted Supply, fan power was estimated based on manufacturer's data for fan power consumption at design airflows for both supply and exhaust fans in the central rooftop unit.
- For Type 3, PTAC OA Fan, the estimate is based on the power consumption of the small fresh air supply fan as well as a typical in-unit exhaust fan, in a design similar to that of the study building.
- For Type 4, Trickle Vents, fan power is the estimate of a typical in-unit exhaust fan at the design levels of ventilation used in the study building. No dedicated supply is provided, so no power consumption for supply is accounted for.

This analysis of ventilation system efficiency is simplified, and it ignores factors such as heat or energy recovery efficiency of an HRV/ERV unit. It also ignores certain likely effects on building efficiency such as the interaction between infiltration and ventilation in buildings with exhaust-only systems. Discussions of these interactions (Roberson 2004) are beyond the scope of this study.

The controlled MUA fraction is the ratio of measured supply CFM from known sources to measured exhaust CFM. The ideal ratio would be 1 CFM supply to 1 CFM exhaust, with every unit of air drawn from the apartment replaced by a unit of fresh air of known origin. Passive systems and those that rely on pressure differences to draw air through building spaces (Types 1 and 4) are at a disadvantage to ducted or forced air systems (e.g., Types 2 and 3), because they rely on very tight interzone air barriers and clear passive MUA pathways to function. In all likelihood, the controlled MUA fraction of passive systems will never be 100%, meaning there will always be air drawn from unintended spaces such as other apartments, hallways, and other building spaces.

In Table 38, the only system that was proven to deliver the designed amount of fresh air at a rate equal to the exhaust was the ducted supply system, though for any given apartment, that depends directly on the quality of the distribution system. This is borne out in the testing results, that show that for any given apartment, the controlled MUA fraction was anywhere between 40% and 105%. It should be reiterated that the table states results for the buildings tested in this study, and that a new building could fare better or worse depending on construction quality.

Table 38. Comparison of Ventilation Strategies

	Type 1 Exhaust Only	Type 2 Ducted Supply	Type 3 PTAC OA Fan	Type 4 Trickle Vents
Material Cost (Estimated)	\$150–\$200/fan	\$800–1,200/apartment	\$90 more than standard PTAC	\$40/vent
Fan energy per Studio Apartment (24/7 Operation; Estimated)	87 kWh/year (apartment exhaust fan)	371 kWh/year (supply and exhaust fans)	139 kWh/year (OA fan and exhaust fan)	498 kWh/year* (apartment exhaust fan)
Controlled MUA Fraction (Tested Results)	20%–45% (from door gap)	40%–105%	5%–25%	15%–40%
System Pros	• Inexpensive • Little to no maintenance required	• Supply air is provided in a controlled and measurable way • Provides the opportunity for filtration and heat recovery or air • Single, easily monitored fresh air device	• Relatively inexpensive • Provides some opportunity for filtration • Supply air is drawn through heating/cooling element which tempers it, results in improved comfort	• Relatively inexpensive • Little to no maintenance required
System Cons	• No designated source of supply air • Results in air being drawn from corridor, other apartments and interstitial spaces • May cause complaints of odors from other units	• Expensive material cost • Annual operating costs are higher than other methods • HRV/ERV requires routine maintenance	• Fan is not capable of operating against high static pressure • Building conditions can overwhelm fan, resulting in reduced supply flow • Filter requires periodic changing and is not easily accessible	• Flow is subject to changing building pressures • Requires very tight construction to function properly • Building operation can result in low or reversed flows

*This value is a result of product selection. Had a fan similar to Type 1 been used the value would be significantly lower.

5 Preliminary Conclusions

This project sought to answer the following research questions:

- What exhaust ventilation and corresponding MUA strategies (if any) are being implemented in high performance new construction multifamily buildings to meet whole-unit ventilation recommendations of ASHRAE 62.2-2010?

  Through this research and CARB's role in multifamily program implementation work in the region, CARB researchers believe that the majority of high performance, new construction, multifamily housing in the northeastern United States use one of four general strategies for ventilation:

  1. Continuous exhaust only, with no designated supply or MUA source
  2. Continuous exhaust with ducted MUA to apartments
  3. Continuous exhaust with supply through a MUA device integral to the unit HVAC
  4. Continuous exhaust with supply through a passive inlet device such as a trickle vent.

  CARB researchers have also seen a subset of the first category, where the doors between interior corridors and apartments are undercut to allow MUA to flow from the corridor into the apartment. The general strategy is to pressurize the corridor using supply air and depressurize the apartments through continuous local exhaust. Though in many building codes this practice is essentially prohibited for reasons of fire safety, it still continues as either a designed MUA strategy or as a poorly enforced interpretation of building code. The third and fourth strategies, although not intentional, showed significant MUA supplied through leakage around the door.

  These four main system types are representative of common ventilation strategies in the northeastern U.S. green building market. Each of the study buildings had participated in a green or energy efficiency standard such as LEED or ENERGY STAR. One commonality of all of the study buildings was the requirement that each design contain some way for fresh MUA to enter the apartment. The range of buildings is not meant to be exhaustive, but it is representative of the building stocks that CARB has worked with, including low-rise, midrise, and high-rise building types.

- How can the air delivery performance of passive MUA strategies such as trickle vents, fresh air dampers, or door undercuts be measured and quantified in actual installations? How variable is the performance and what are the key factors that affect it—apartment location, extent of compartmentalization, season, etc.?

  CARB's approach centered on inducing pressures that are not present in normal building operation, for the purposes of measuring flows within the normal range of common testing equipment. The contrivances constructed for this purpose amounted to in-field laboratory-style testing of the passive devices through a range of conditions. This level of rigor is not practical for wide use. Given the inability to quantify installations in the field, thorough installation guidelines, which address building airtightness, exhaust levels, and other factors, should be developed to ensure passive vents perform as designed.

In the future, the in-field performance of passive MUA devices should likely be verified through qualitative methods—visual inspection and simple functional performance tests—rather than quantitative methods. Laboratory tests conducted by manufacturers or third parties should be relied on for design. In addition, clear specifications for the installation and operating parameters of these devices should be established by the manufacturers. Manufacturer documentation of minimum building requirements, such as apartment airtightness and local exhaust rates, should be provided and correlated to device performance.

From the tests, there is considerable variation in the amount of MUA provided by passive devices. Since operation of these devices is based on a pressure difference, any factors that affect the pressure across the device directly affect the flow. The airtightness of the apartment plays a major role in the performance of these devices. A well-sealed and compartmentalized apartment is needed in order to establish an adequately pressurized space.

In addition, environmental conditions play a large role in the operation of passive devices, the primary factors being wind and temperature. The role of wind is still clearly visible by the short-term fluctuation of the pressure monitoring results, however, the specific effects are difficult to quantify because of its intermittency and high variability. In addition, local wind data were not collected as part of this study.

There is no clear correlation between apartment location and flow through passive devices. In general, apartments on higher floors experience greater pressure variation due to wind; however the specific geometry and situation of the building on its site enhance or detract from the impact of wind speed and direction. Location of trees, open spaces, setbacks, and other buildings all affect the local environment and can result in significant variations in building pressures for apartments on the same floor.

- Do the MUA strategies for apartments, both passive and active, function as designed when installed in real-world buildings?

  Active MUA strategies, such as dedicated supply air from a central rooftop unit, can be highly effective at delivering specified quantities of MUA to apartments; however, a thorough TAB process is required. In the units tested under this study, the performance varied from 12% to 132% of the design. This wide a range indicates the need for clear, well-defined specifications and careful construction oversight. In addition, commissioning and verifying system performance are also important to a well-performing system. In the case of PTACs with MUA kits, the products need improvement in order to function as intended. With revision and product quality control, there is ultimately no technical reason that this design cannot work.

The performance of passive MUA strategies, such as door undercuts and trickle vents, is considerably more variable and, based on current practices, is not meeting the design intent. It should be reiterated that door undercuts are not a reliable or safe method of providing MUA and are not recommended. Under specific conditions, it is possible for trickle vents to provide design-level supply; however, the challenge is to maintain the required conditions under a variety of environmental and operating situations. Since this strategy is passive by definition, it is difficult to implement them to perform as designed under all conditions that a building experiences over the course of a year. CARB found the performance ranged from about 10%–35% of design.

While there is no technical reason that passive strategies cannot function, the designs are very difficult to execute in the real world, requiring levels of compartmentalization that are not common to typical construction. In addition, it is clear that there is a significant lack of understanding on the part of building designers as to what performance levels can be expected from passive vents when installed in a real building. For example, the trickle vents used in the study building have performance data available in units of wind speed, not pressure.

Little guidance is given in product literature on how to translate performance data of passive vents into a working design. If they are to be used effectively, much more data are needed to demonstrate the real-world performance of the vents, the typical pressures that can be expected in apartments, and guidelines for the required airtightness of apartments.

- Can specifications be developed to better ensure proper performance from all MUA strategies?

Clear, well-defined specifications can be developed to ensure proper performance from all MUA strategies, but this study did not yield enough data to conclusively define what those specifications should be. In the future, specifications should focus on air sealing, compartmentalization, ventilation system performance, and general construction quality.

The airtightness of an apartment plays a major role in the performance of MUA systems, especially when passive strategies are employed. Further study should be conducted to determine the minimum level of air sealing necessary to ensure performance. This should be expressed as a common metric, such as $CFM50/ft^2$. In addition to air sealing of apartments, it is important to ensure compartmentalization of other building spaces. This is particularly important in maintaining pressure differentials and minimizing fluctuations due to environmental conditions. It may be difficult to provide a specific metric, but a qualitative standard and general guidance can be developed.

In order for a MUA strategy to function properly, it is necessary that the exhaust system operate as designed. It was observed several times where exhaust fans were not performing at the design levels. CARB also found situations where the same model fan was installed in each apartment, yet the performance was drastically different. These issues are the result of poor design, poor installation, or a combination of the two.

Thorough construction quality control, testing, and commissioning help to prevent these issues and ensure proper function of both exhaust and MUA systems. Along the same lines, strong construction oversight of the general process should be included as part of the guidance.

- What is the energy "penalty" of mechanical supply systems?

  All ventilation strategies result in electricity and thermal energy penalties. As previously mentioned, the thermal analysis is beyond the scope of this study. The electricity penalty of ventilation is the result of the energy required to run the fans. Mechanical supply systems employ both supply and exhaust fans; therefore, the electricity requirements are greater than passive strategies, which only utilize exhaust fans.

  The electricity requirements of each system are summarized in Table 36. The fan energy estimates are based on a mix of manufacturer's data for electricity consumption and tested data for delivered CFM of fresh air. This leads to expected results, such as the mechanical supply (Type 2) requiring approximately 2.7 times more fan electricity than the passive strategy (Type 4). It also leads to an unexpected result where the MUA through HVAC system (Type 3) requires slightly more electricity per CFM than the mechanical supply, due to the weak performance of the fresh air fan.

  This estimate also does not take into account distribution issues of the ducted supply system. For example, additional fan power would be required to increase pressure and flow in the distribution system to overcome duct leakage and deliver design airflows at the farthest registers where they are too low. Instead of analyzing this scenario, the total airflow of the system as measured in the field was compared to the rated electricity consumption at design flow.

  There are obvious shortcomings with this approach, but due to the difficulty of measuring fan electricity consumption, particularly of many small fans in buildings without central systems, a full comparison of field-measured flow and power consumption was not possible. Future studies may take this into account.

- Considering the choices for various ventilation approaches and the factors impacting their cost effectiveness—material cost, efficiency, and performance—under what conditions is each system optimal?

  All approaches evaluated in this study have the potential to deliver effective ventilation, but each has benefits and drawbacks. Choosing which system is best for a particular building depends on more than its effectiveness. For a building design already including PTACs, the lowest first-cost option is certainly to use PTACs with an improved fresh air kit. For building designs that more readily allow for penetrations in the exterior walls, unitized exhaust fans and passive inlet vents may be the most appropriate. It also should be straightforward to construct a ducted supply system that delivers the appropriate ventilation, using established principles.

Material costs and operating costs for each approach in this study have been discussed. Although Type 4 was the most expensive in terms of fan energy, it represents only one type of fan. A more efficient model could have been used, which would result in substantially less energy consumption. Considering that, the most expensive approach is then the centrally ducted supply design, whether through a supply-only unit or an HRV or ERV. Extra ductwork, equipment, and lost floor area are all costs not incurred by other approaches. On the other end of the spectrum, a system design in which no dedicated supply system is installed is the least expensive. In terms of operating costs, the same is basically true. Those systems that utilize only exhaust and have no dedicated supply are the least energy intensive to run. Those that have dedicated supply fans are the most energy intensive.

Performance of any of the ventilation approaches is highly dependent on thoughtful design and quality construction. Tight and well-balanced ductwork is also critical, and can mean the difference between an efficient, high performance system and an expensive but ineffective one. Obtaining effective performance from a system with ducted supply is well understood, utilizing tried and tested principles. The duct system must be well designed and laid out, very tightly sealed, and well balanced. Obtaining top performance from other ventilation approaches is somewhat less straightforward. The current generation of PTACs with fresh air kits is not able to deliver the desired quantities of fresh air. Still, the approach is innovative and improving the design should make it more effective.

For all ventilation systems, but particularly for exhaust-only systems such as those with no ducted supply or with passive inlet vents, controlling where fresh MUA originates is difficult. This is borne out by the results of this testing, which found that the controlled MUA fraction, or the supply rate of MUA of known origin to the exhaust rate, ranges greatly from less than 50% to more than 150%, even in the same building.

The discussion in Section 4.5 on the necessity of compartmentalization does not apply only to buildings with passive vents. CARB believes that all buildings will achieve better control over airflow through compartmentalization and better HVAC construction. Any ventilation system studied in this report has the potential to serve a building well. Each strategy has benefits and costs that make it more appropriate for one building but not another. There is no “best” ventilation system but rather a collection of best practices for any given approach. Table 39 shows situations in which each type of ventilation system would be well suited.

Table 39. Optimal Conditions for Each Ventilation System Type

System Type	Conditions Under Which Each System Is Optimal
Type 1. Exhaust Only	• Not recommended for multifamily buildings with common hallways. Low-rise buildings with no common hallway; exterior entries
Type 2. Ducted Supply	• Buildings where exterior ventilation penetrations are not allowable. • Buildings where filtered fresh air is a design requirement. • Very tall buildings that must overcome significant stack effect.
Type 3. PTAC OA Fan	• Buildings with PTACs as basis of design.
Type 4. Trickle Vents	• Buildings with very airtight apartments. • Shorter buildings (4 or fewer stories) in which stack effect is less of an issue.

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