FINAL REPORT
IMPROVING AIR QUALITY, ENERGY EFFICIENCY, AND GREENHOUSE GAS REDUCTIONS THROUGH MULTIFAMILY UNIT COMPARTMENTALIZATION

Prepared By:

Mark Modera (Principal Investigator)
Scott Adler
Curtis Harrington
Western Center for Cooling and Efficiency
University of California
215 Sage Street, Suite 100
Davis, CA 95616

Deborah H. Bennett (Principal Investigator)
Rebecca Moran
Department of Public Health Sciences
School of Medicine
One Shields Avenue
University of California, Davis
Davis, CA 95616

Marian Goebes (Co-Investigator)
TRC Advanced Energy
436 14th St., Suite 1020
Oakland, CA 94612

Prepared for the:

California Air Resources Board and the California Environmental Protection Agency

January 9, 2023

DISCLAIMER

The statements and conclusions in this Report are those of the contractor and not necessarily those of the California Air Resources Board. The mention of commercial products, their source, or their use in connection with material reported herein is not to be construed as actual or implied endorsement of such products.

ACKNOWLEDGMENTS

The authors would like to acknowledge:

- The builders and developers who allowed us to conduct field testing in their buildings.
- The valuable input and guidance from Qunfang (Zoe) Zhang and Patrick Wong of the California Air Resources Board. This project would not have been possible without their support and expertise.

This report was submitted in fulfillment of contract number 19RD013 "Improving Air Quality, Energy Efficiency, and Greenhouse Gas Reductions through Multifamily Unit Compartmentalization", by the University of California Davis under the sponsorship of the California Air Resources Board. Work was completed as of October 30, 2022.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

To assess the impacts of compartmentalization or airtightness on indoor air quality (IAQ), energy efficiency and greenhouse gas (GHG) emissions, three new-construction multifamily buildings in California were tested. One building targeted a compartmentalization level of 0.3 cfm_{50}/ft^2, the second building targeted a level of 0.23 cfm_{50}/ft^2 (LEED requirement), and the third used balanced ventilation, representing different means of compliance with the 2022 California Building Code. The testing showed that all buildings were tighter than required by current Building Code, with an average unit air leakage of 0.16 cfm_{50}/ft^2, indicating a tighter leakage requirement than current code requirement is achievable. Inter-unit transfer of pollutants was very small for gaseous pollutants and indiscernible for fine particles ($PM_{2.5}$). Simulations using CONTAM showed that tightening increased concentrations of pollutants generated within a unit due to decreased infiltration from outdoors, but decreased inter-unit air pollutant transfer, suggesting that both types of pollutant generation need to be addressed. Annual energy savings from compartmentalization simulated with CONTAM and EnergyPlus indicated 4-6% energy savings and GHG reductions depending on climate zone and ventilation strategy. Simulations also indicated significant energy and GHG savings from reduced fan power when going from balanced to unbalanced ventilation, or from reduced thermal losses when adding a heat exchanger to balanced ventilation.

EXECUTIVE SUMMARY

Background

Title 24-2019, which took effect January 1, 2020, has a requirement that all new-construction multifamily units either: a) meet a compartmentalization requirement (total unit leakage) of 0.3 cfm at 50 Pa per square foot of apartment (unit) enclosure area (0.3 cfm50/ft^2, which is also required by the American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE) Standard 62.2-2019), or b) provide balanced ventilation (equal supply and exhaust flows) to each dwelling unit. While this requirement is a step in the right direction, it falls short of providing what is likely needed to ensure good IAQ and to adequately promote GHG reduction. The IAQ, energy use, and GHG impacts of this requirement need to be evaluated.

Objectives and Methods

The overall objective of this research was to investigate IAQ, energy and GHG impacts of different levels of compartmentalization (airtightness) and ventilation strategies in new multifamily buildings in California. The specific objectives were as follows:

- Measure the distribution of total air leakage of units in the same building
- Measure the distribution of mechanical ventilation flow rates at grilles for units in the same building
- Measure inter-unit pollutant transfer from units with different levels of air tightness
- Measure overall air change rates in units with different levels of air tightness
- Model air transfer paths using different total leakage levels, supply fan flows and exhaust fan flows to test the impact of compartmentalization on air and pollutant transfer rates
- Model energy usage and GHG emissions for different levels of air tightness and ventilation strategies
- Analyze field test results and modeling results to determine impacts of compartmentalization on IAQ, energy savings, and GHG reduction

Three mid-rise new-construction multifamily buildings in California were recruited to conduct field measurements, including two buildings targeting compartmentalization (one targeting a level of 0.3 cfm50/ft^2 (current Building Code), and the other targeting 0.23 cfm50/ft^2 (Leadership in Energy and Environmental Design (LEED) requirement), and one NOT targeting compartmentalization but rather using modular construction with a balanced ventilation system. Field testing included one-time measurements of total unit leakage and exhaust and/or supply grille flow rates in 10 to 14 units of each building, as well as controlled field experiments to measure air change rates, inter-unit air transfer between the units and outdoors as well as between units. Field measurements and data from the literature were used in simulation models to explore the applicability of the field results to multifamily buildings with three different compartmentalization levels (0.15 cfm50/ft^2, 0.3 cfm50/ft^2, and 0.45 cfm50/ft^2), and three different ventilation systems (exhaust-only, supply-only and balanced) in four climate zones (Sacramento, San Francisco, Los Angeles and Fresno). The performance parameters modeled included unit air change, unit ventilation flows, source of air entering units, gaseous pollutant exposure (from both generation within a unit and inter-unit pollutant transfer), energy savings/penalties related to space conditioning and fan energy, and GHG emissions.

Results

All the units tested in three new-construction multifamily buildings had leakage levels well below the compartmentalization requirement of 0.3 cfm_{50}/ft^2, with an average unit leakage level of 0.16 cfm_{50}/ft^2. Note that two of the buildings were targeting compartmentalization (one targeting a level of 0.3 cfm50/ft^2, and the other targeting 0.23 cfm50/ft^2 (LEED target)), and the third building used modular construction with balanced ventilation, therefore these buildings represented new construction buildings that meet the requirements in Title 24-2019, but do not represent traditional (site-built) construction (i.e., that is not targeting compartmentalization or using balanced ventilation). For in-situ construction, each adjoining surface between units was responsible for 7-20% of total unit leakage, and for modular construction there was virtually no horizontal air leakage to the adjacent units, apparently due to double walls, and had 7-11% of their air leakage with the units above or below. The units were also found to be fairly consistent in their leakage levels within a building, with standard deviations between 10-15%.

The mechanical ventilation flow measurements indicated more variability between buildings, with two buildings running at 0.6-0.7 Air Changes per Hour (ACH), and one building having continuous mechanical ventilation flows much greater than required (measured ventilation flows corresponding to 2.4 ACH). This means that fan energy and HVAC loads in that building could be decreased considerably by lowering ventilation flows to the minimum requirement as in Title 24, Part 6, section 160.2. For that same building, unfiltered supply flows were problematic, as outdoor pollutants were transferred directly indoors.[1] Also, there was much more variation in mechanical ventilation flows between units in some buildings, with standard deviations ranging from 5% to 33%. These variations impact both mechanical ventilation rates and pressure differences between units, likely resulting in increased transport between units.

Inter-unit transfer of pollutants was measured to be very small for gaseous pollutants and indiscernible for particulate matter with diameters less than 2.5 micrometers (PM2.5) in these buildings. This was true even when turning on the kitchen exhaust fans in the units adjacent to the source unit while not turning on the fan in the pollutant source unit, which created significant depressurization of the adjacent units relative to the source unit (2-14 Pa, 8.6 Pa average versus 1.3 Pa average with kitchen exhaust fans off). Although these pressure differences created flows from the source unit into the adjacent units, they also increased flows from outside, thereby diluting the pollutant concentration that had transferred from the source unit to the adjacent units.

Compartmentalization was modeled in CONTAM to analyze impact on outdoor air infiltration and air transfer between units for various ventilation strategies. Tightening units slightly increased the concentrations of pollutants generated within a unit (increasing by roughly 10% if tightened from 0.45 cfm_{50}/ft^2 to 0.15 cfm_{50}/ft^2), but significantly decreased the concentrations of pollutants transferred from other units (decreasing concentrations by a factor of 3 to 11 when tightened from 0.45 cfm_{50}/ft^2 to 0.15 cfm_{50}/ft^2). In general, leakier units had higher ventilation rates, leading to greater pollutant dilution and lower concentrations of pollutants, but leakier units were more likely to receive air from other units. However, for intermittent pollutants generated within a unit, such as NO_2 generated from cooking with a gas stove, pollutant concentrations were more impacted by whether the resident used their kitchen exhaust fan while cooking than by the compartmentalization level (60-260% increases due to turning off the fan, versus 10% decreases associated with tripling the leakage from 0.15 cfm50/ft^2 to 0.45 cfm50/ft^2). Occupants that do not run their range hoods while cooking can have 1-hour NO_2 concentrations greater than 100 ppb, which exceeds the level of the National Ambient Air Quality Standard (NAAQS) for one-hour NO_2. Secondhand

[1] This project was constructed under Title 24-2016, which did not require filtration of outdoor air for this ventilation unit, because it does not have ductwork. Beginning in the 2019 version of Title 24 Part 6, projects are required to provide MERV 13 filtration of outside air, which should mitigate this problem.

smoke transfer was reduced by 20% when moving from 0.45 cfm_{50}/ft^2 to 0.30 cfm_{50}/ft^2, and an additional 33% when moving from 0.30 cfm_{50}/ft^2 to 0.15 cfm_{50}/ft^2.

Energy modeling in EnergyPlus suggests that compartmentalization could save between 4-6% of building HVAC energy and HVAC GHG emissions, calculating percentages relative to a building with 0.45 $cfm50/ft^2$ and balanced ventilation. While fan energy can be saved from opting for a one-fan, supply-only or exhaust-only system instead of a two-fan balanced system, energy savings from a heat exchanger made a balanced system preferred in climate zones that required a significant heating and/or cooling, such as the Central Valley, in terms of overall energy savings and GHG emission reduction. Furthermore, to achieve the maximum energy savings, buildings need to take advantage of "free-cooling" conditions when increasing the flow of outdoor air into the building can provide natural cooling. This can be achieved with windows that occupants can open or by installing ventilation controls, such as economizers or heat recovery bypass, to automate the process. If occupants are assumed to not take advantage of free cooling, the energy and GHG savings associated with compartmentalization were reduced to 1-2%, however such an assumption seems unreasonable, as it makes San Francisco a cooling-dominated climate. It should be noted that the study results would be affected in the case of a growing number of wildfire smoke days. Also, using window openings is not recommended during high air pollution events such as wildfire. In addition, a cost-effectiveness analysis was not part of the scope for this contract; however, there is a current project on this topic by the Codes and Standards Enhancement team for supporting updates to the CA building codes.

Conclusions

Based upon our limited sample it appears that new multifamily buildings in California that target a compartmentalization value of 0.3 cfm_{50}/ ft^2 should be able to achieve a tighter requirement of 0.2 cfm_{50}/ ft^2, as 95% of units tested in the three buildings were tighter than 0.2 cfm_{50}/ft^2. In these same buildings, measurements indicated that ventilation flows were not always adjusted to the minimum flow requirement, which suggests an opportunity to save energy. Compartmentalization is estimated to save 4-6% of building HVAC energy and HVAC GHG emissions. Using heat exchangers and ventilation controls could provide further energy savings and air quality improvements and warrant further study.

On the IAQ side, the field measurements indicated minimal transfer of gases, and unmeasurable transfer of particulates between units. On the other hand, the CONTAM simulations indicated that using compartmentalization slightly increased the concentration of pollutants generated within a unit (~10%), but significantly decreased the concentrations of pollutants coming from other units by a factor of 3 to 11 times. However, we cannot forget the need for ventilation for diluting pollutants generated within a unit. For example, for pollutants generated in a unit by cooking, not using a kitchen exhaust hood increases pollutant concentrations by 60-260%. This suggests a need for strengthening the requirement on kitchen ventilation, such as automated kitchen exhaust hood fan operation, similar to moisture activated bathroom exhausts commonly found in Europe.

Chapter 1: Introduction

Since the early 1900s, air quality has been a defining challenge for California. In the summer of 1943, smog reduced visibility to only three blocks in Los Angeles and residents suffered from burning eyes and lungs, as well as nausea [1]. California responded by establishing tailpipe emission standards, which led to the development of the catalytic converter in the 1970s [1]. Although aggressive air pollution control programs have improved air quality in California, in many regions around the state air pollution levels remain unhealthy, consistently ranking among the worst in the nation [2]. The increase in vehicle miles traveled, average temperatures, and wildfire smoke present additional challenges that need to be combated to continue the trend towards cleaner air for all.

Elevated levels of outdoor pollutants can also deteriorate indoor air quality (IAQ) when outdoor air enters units either intentionally (supply ventilation) or unintentionally (infiltration). Awareness of IAQ has been growing for decades with COVID-19 alerting the general public to the need for fresh and filtered air. Some examples of sources of pollutants generated within indoor spaces include NO_2 from gas stoves, formaldehyde emitted from building materials and furniture, or emissions from cigarette smoke, which includes both gases such as benzene or particles. Outdoor air pollution can also infiltrate into the indoor environment. For gases, the indoor concentrations are generally not reduced from outdoor levels when the air travels to the indoor environment except reactive gases such ozone, while for outdoor PM, some of the particles are removed as the air transfers through the building shell. Both $PM_{2.5}$ and NO_2 are criteria pollutants with many known health impacts. Benzene and formaldehyde are air toxics, with benzene being a known human carcinogen and formaldehyde being a probable human carcinogen.

Air quality is also an environmental justice issue, as disadvantaged communities are generally located near pollution sources, such as highways and power plants [3]. Furthermore, low-income populations often live in multifamily housing that can have poor IAQ due to leakage between units. Unlike single-family homes, which only exchange air with the outdoors, multifamily units contain airflow connections to other units, allowing unwanted transfers of air, pollutants, odor, noise, and pests. Typical leakage pathways include elevator/air shafts, stairwells, plumbing and electrical chases, and HVAC equipment [4]. Therefore, improving IAQ in multifamily buildings is an important component to address environmental disparity [5].

Compartmentalization involves sealing each multifamily unit (i.e., apartment, condominium, etc.) from adjacent units, other interior spaces, and the exterior, such that each unit is effectively its own compartment – which can provide IAQ benefits by reducing pollutant transfer between units and improving comfort through reduced noise and odor transfer. It also reduces energy use and GHG emissions through reduced air infiltration from the exterior. Today's energy policy is continuing to change the built environment. California's climate goals call for GHG emission reductions in all sectors of the economy [6]. Buildings account for roughly 25% of the state's GHG emissions and are proposed to be decarbonized through increased efficiency and electrification [7]. With increasing work-from-home jobs and rising electricity and gas prices, measures that both improve indoor environmental quality and save energy are essential. However, compartmentalization is not standard practice, which is principally due to a lack of data quantifying IAQ, energy and GHG impacts at different levels of compartmentalization.

1.1 Study Objectives

Beginning with the 2019 version of Title 24, Part 6, California has required that all newly constructed multifamily dwelling units either meet a compartmentalization target of 0.3 cfm50/ft^2, or have balanced ventilation. The compartmentalization requirement of 0.3 cfm50/ft^2 is also in the ASHRAE 62.2 standard for

Residential Ventilation and IAQ, and in several programs such as LEED and ENERGY STAR. However, in the literature, there are no experimental data available that quantify IAQ or health impacts from compartmentalization. Research in this area is necessary to address this lack of data and provide information on how compartmentalization requirements affect indoor air pollutant concentrations, energy use, and GHG emissions in multifamily buildings. Such data are critical to inform the development of modern building standards in support of meeting California's air quality, climate, and energy efficiency goals.

The main objective of this study is to obtain data and perform analyses to assess the IAQ, Energy and GHG impacts of different levels of compartmentalization (air tightness) of units in new mid- or high-rise multifamily California buildings. The specific aims of the study were to:

- Measure the distribution of total air leakage for units in newly built multifamily buildings
- Measure the distribution of mechanical ventilation flow rates at grilles for units in newly built multifamily buildings
- Measure overall air change rates in units with different levels of air tightness
- Measure inter-unit pollutant transfer rates in units with different levels of air tightness
- Model air transfer paths for different levels of air tightness and ventilation strategies
- Model energy usage and GHG emissions for different levels of air tightness and ventilation strategies
- Analyze field test results and modeling results to determine impacts of compartmentalization on IAQ, energy savings, and GHG reduction.

1.2 Background

1.2.1 Multifamily Buildings

Multifamily buildings refer to structures that contain multiple dwelling units. Multifamily buildings are categorized as low-rise, mid-rise, or high-rise, and can also be mixed-use. Low-rise buildings, such as townhouses, are generally three or fewer stories. Mid-rise buildings, such as college dormitories, are generally between five and nine stories. High-rise buildings are generally ten or more stories. Mixed-use buildings have businesses on the ground floor with residential units on the floors above.

Multifamily buildings account for almost half of new-construction residential starts in California each year [8]. Since they differ substantially in construction and operation from single-family homes, multifamily buildings follow their own set of codes and standards. However, inadvertent airflow "leakage" pathways between zones are potentially problematic for IAQ and energy efficiency in multifamily buildings.

1.2.2 Construction Practices

Structures are typically built from wood, concrete, and steel and must follow the International Building Code based on function and height [9]. Today, the construction landscape is being reimagined with labor shortages propelling innovation in construction practices [10].

Because one of the projects tested in this study used modular construction, this section provides a short description of that practice. Modular construction refers to prefabrication, offsite construction of building components that are later assembled onsite, and is on the rise as a construction technique [11]. Instead of constructing a building from the ground up (foundation, then walls, then roof) as is done by traditional construction companies, prefabrication construction delivers pre-assembled components to be assembled at the job site. Modular construction is a type of prefabrication where three-dimensional "modules" are delivered to be assembled onsite like LEGO building blocks. According to modular construction proponents, the major advantages of prefabrication are increased construction speed and decreased construction costs [12].

Modular construction also has the potential to improve IAQ. Modules that are manufactured offsite can be inherently sealed as individual units. When joined together, units have two walls separating them from their neighbors. This double barrier should be better at limiting air and pollutant transfer than traditional construction with a single common wall. However, modular construction still requires sealing at the job site, as electrical, plumbing, and HVAC equipment require penetrations between zones, which can undo earlier sealing efforts and create unwanted leakage pathways. There is also the question about increased material usage and associated costs with this type of construction.

1.2.3. Ventilation

Ventilation is the process of providing outdoor air and exhausting stale air, throughout a building. More broadly, HVAC systems are responsible for providing air at a comfortable temperature and humidity, and ideally free of harmful concentrations of pollutants. In commercial office and retail buildings, this is generally achieved by bringing in outdoor air through the HVAC equipment, heating or cooling that air, and filtering that air. In the case of multifamily buildings, since the 2008 version of Title 24, Part 6, newly constructed multifamily dwelling units have been required to provide whole dwelling unit ventilation, meaning a mechanical system for bringing in outdoor air at a minimum rate that varies by unit size and number of bedrooms. Multifamily buildings use a variety of strategies for providing whole dwelling unit ventilation. These include continuously operating bathroom exhaust fans for an exhaust-only strategy, dedicated outdoor air systems that provide outdoor air through a central ventilation strategy, individual heat recovery or energy recovery ventilation systems (HRVs or ERVs), packaged terminal heat pumps that can provide a fraction of outdoor air for ventilation purposes, and other strategies.

Imbalanced ventilation systems supply and exhaust air at different rates, or simply use one method. The difference between supply and exhaust flow rates is made up for through uncontrolled infiltration or exfiltration through the envelope of each zone. In single-family homes, imbalanced flows are balanced by exchanging air with the outdoors. In multifamily buildings, the situation is less transparent. The makeup air for an imbalanced system may originate from the outdoors or other indoor spaces since units share walls with the exterior and other interior zones.

Until recently, exhaust-only ventilation dominated multifamily building design [13]. These inexpensive and simple-to-install systems work by depressurizing a building. Fans continuously remove air from units while makeup air infiltrates through leaks in the unit’s envelope (or passive vents). The exhaust airflow rate in each unit is set to meet the ASHRAE minimum ventilation requirement [14]. However, concerns have been raised about the source of infiltration in exhaust-only buildings, as air coming from adjacent units may be undesirable from a health and comfort perspective [15].

Supply ventilation systems are common in commercial buildings. These systems work by pressurizing a building. Fans continuously blow air into a unit, causing air to leak out of the unit through “holes” in the envelope. Supply systems limit outdoor pollutants by pressurizing the zone and filtering supply air. However, occupant behavior in residential buildings, such as opening windows and operating intermittent kitchen fans, can interfere with this ventilation strategy. These actions can depressurize units down to or below the ambient pressure, inducing air and pollutants to flow from higher- to lower-pressure units.

Balanced ventilation systems have been proposed as a preferred ventilation option [16]. These systems, if properly designed and installed, maintain a neutral pressure between the inside and outside of a building. They typically supply air to bedrooms and living rooms and exhaust air from bathrooms (and perhaps the kitchen) at equal rates. Balanced systems are generally more expensive to install and operate than either exhaust or supply systems. However, by minimizing uncontrolled airflows, balanced systems provide opportunities to save energy (with heat recovery) and improve indoor air quality. However, over time balanced ventilation systems can become unbalanced for a variety of reasons. For example, debris that builds up on air filters can reduce supply flows if the filters are not regularly cleaned and replaced [17]. Additionally, balanced systems become unbalanced when intermittent kitchen or bathroom exhaust fans are in operation.

1.2.4 Airtightness & Airflow

Building leakage is characterized in terms of airtightness and airflow. Airtightness refers to the size (or inverse flow resistance) of unintentional openings ("leaks") in an envelope, while airflow refers to the movement of air through those leaks. Pressure differences determine the magnitude and direction of airflow between zones and are influenced by natural forces, mechanical ventilation, and occupant behavior.

Natural forces that promote leakage flows are wind and buoyancy. When wind blows it creates varying static pressures on the outside of a building, with higher pressures on the windward side and lower pressures on the leeward sides. It drives infiltration on faces with elevated pressure, and exfiltration on the other faces, as well as horizontal flows within the building along the pressure gradient [4]. Space conditioning from HVAC systems can also create pressure differences throughout a building by creating temperature gradients through the building. Indoor-outdoor temperature differences cause a buoyancy force, known as the "stack effect" [18]. In the winter, warm, less-dense indoor air rises, escapes through the roof, and is replaced by cold, more-dense outdoor air through the base. In the summer, the direction is reversed: exfiltration of cold indoor air occurs through the base and infiltration of hot outdoor air occurs through the roof. During the heating season, the stack effect is the dominant airflow driver in cold climates [19, 20].

Mechanical systems drive air leakage either into or out of a building depending on the ventilation strategy. Ventilation systems negatively pressurize a zone and drive infiltration if they exhaust more air than they supply, and positively pressurize a zone and drive exfiltration if they supply more air than they exhaust. Combustion appliances consume oxygen, thus depressurizing a zone and driving infiltration. Continuous or intermittent exhaust fans operate within the unit to remove air from bathrooms, kitchens, and clothes dryers. These unbalanced mechanical systems can cause pressure differences and leakage between units [19, 20]. For depressurized units, makeup air flows into the unit through all surfaces, delivering air from the outdoors, corridor, and neighbors. Operating all unit ventilation fans simultaneously (continuous systems) results in less inter-unit flow than intermittent operation; however, pressures are never completely uniform due to variations in ventilation flows and different sized units. Additionally, occupants can significantly affect unit pressures by opening or closing windows and doors, and operating bathroom or kitchen exhaust fans [4].

The air flow through a sharp-edged orifice can be calculated from its physical area using the Bernoulli equation. The Bernoulli equation is a mathematical expression, stating that an increase in the velocity of a fluid or gas occurs when its static pressure (or potential energy) decreases:

(1) $$\boldsymbol{P + \frac{1}{2}\rho v^2 + \rho g h = constant}$$

$$where\ P = pressure\ [Pa],$$

$$p = density\ [kg/m^3],$$

$$v = velocity\ [m/s],$$

$$g = 9.81\ [m/s^2], and$$

$$h = height\ [m]$$

Thus, pressure differences between zones induce airflows at a velocity proportional to the square-root of the pressure difference for inviscid flows that follow the Bernoulli principle. The airflow rate is the product of this velocity and the leakage area.

Assuming no change in height:

(2) $$\boldsymbol{P_1 + \frac{1}{2}\rho {v_1}^2 = P_2 + \frac{1}{2}\rho {v_2}^2}$$

and the Continuity equation:

(3) $$\boldsymbol{A_1 v_1 = A_2 v_2}$$

$$where\ A = area\ [m^2]$$

(4) $$\boldsymbol{v_2 = \sqrt{\frac{2(P_2 - P_1)}{\rho[(\frac{A_2}{A_1})^2 - 1]}}}$$

(5) $$\boldsymbol{A_2 v_2 = A_2 \sqrt{\frac{2}{\rho[(\frac{A_2}{A_1})^2 - 1]}}\sqrt{\Delta P}}$$

$$where\ A_2 v_2 = Q = airflow\ rate\ [m^3/s]\ and$$

$$A_2 \sqrt{\frac{2}{\rho[(\frac{A_2}{A_1})^2 - 1]}} = k\ (constant)$$

(6) $$\boldsymbol{Q = k\sqrt{\Delta P}}$$

For leakage sites that are not sharp-edge orifices, which is the case for most leaks in buildings, the flow does not follow Bernoulli's equation. The flow through building leaks can be described by a similar equation that is expressed as a power law:

(7) $$\boldsymbol{Q = C\Delta P^n}$$

$$where\ Q = airflow\ rate\ [m^3/s],$$

$$C = flow\ constant,$$

$$\Delta P = pressre\ difference\ [Pa], and$$

$$n = flow\ exponent$$

The flow exponent lies between 0.5 (Bernoulli flow or turbulent flow) and 1 (perfectly laminar flow) with models using a value in the middle, typically 0.65, based upon empirical data from many houses [21].

1.2.5 Envelope Leakage

Air barriers and air sealing help prevent leakage, which can save over 30% of a building's heating and cooling costs [22]. Minimizing air movement into and out of a building is primarily achieved through air sealing. Air sealing also limits the transfer of harmful pollutants, which travel through the air. The transfer of gaseous pollutants is reduced by reducing the total air flow, while the transfer of particulate pollutants is further reduced by filtering some particles as they pass through walls. However, a tradeoff exists. While air sealing decreases the flow of pollutants entering the unit from outdoors, it also decreases the removal of indoor pollutants, thus increasing the concentration of pollutants that are generated indoors, unless they are removed through local exhaust fans or other means.

Common leakage elements include doors, windows, vertical to horizontal surface interfaces, electrical boxes, plumbing vents, and HVAC ducts. These sites are generally manually sealed with caulk, gaskets, tape, and spray foam to reduce air leakage. Building wrap, which is a durable plastic material wrapped around the envelope during construction, is the most common and effective air barrier [22].

Building airtightness is measured by performing a blower-door test [23], which is also referred to as a fan-pressurization test. A blower door is a calibrated fan that mounts onto an exterior door. The fan blows air either into or out of the building/unit, pressurizing or depressurizing the zone relative to outside. The pressure difference causes air to flow through gaps, cracks, and other openings in the envelope. The fan flow required to maintain a constant pressure difference (typically 50 Pa) between inside and outside can either be normalized by volume (ACH50) or surface area ($cfm50/ft^2$) to determine a relative leakage metric [24].

A recent comprehensive study used semi-automated blower-door testing to quantify air leakage in multifamily buildings [25]. The survey spanned 25 low-rise buildings throughout six states in the Midwest and Northwest. All buildings had overall exterior leakage levels below their state-mandated requirements. All but one building were below 4 air changes per hour at 50 Pa (ACH_{50}), and 21 of those 24 buildings were below 3 ACH_{50}. The Pacific Northwest had the leakiest buildings, which is likely due to these states having less stringent exterior leakage limits. Nonetheless, this study suggests that the exterior envelopes of multifamily buildings are relatively air tight on an ACH basis relative to single family buildings. This is not surprising from a simple geometric perspective, as the surface to volume ratio is smaller for a larger shape (e.g. a larger building).

1.2.6 Unit Leakage

In general, while researchers are finding that exterior envelopes of new-construction multifamily buildings are relatively airtight, interior structures are often leaky [25]. When Bohac & Sweeney [25] performed total unit leakage tests on 25 multifamily buildings, none of the common-entry units, and only 29% of the garden-style units complied with a unit leakage requirement of 5 ACH_{50}. The average leakage value for a single unit was found to be 6.5 ACH_{50}.

The 2012 International Energy Conservation Code (IECC) includes a requirement that air leakage may not exceed 3 ACH_{50} in Department of Energy (DOE) Climate Zones 3 through 8 [26]. National Renewable Energy Laboratory (NREL) has conducted studies investigating the feasibility of achieving this airtightness requirement in US multifamily buildings. One study performed blower-door tests to measure air leakage in three projects in upstate New York [27]. The buildings were constructed in 2013 and all achieved ENERGY

STAR and LEED ratings. Only 11 of the 58 tested units met the IECC requirement with unit leakage testing. Another study testing whether buildings met the IECC requirement performed both unguarded and guarded blower-door tests to determine total leakage, leakage to the outdoors, and inter-unit leakage for five three-story townhouse buildings in Washington, D.C. [28]. Unguarded testing refers to a single-zone blower-door test for total air flow in the tested unit, while guarded blower-door testing refers to multi-zonal blower-door testing where one wall is pressurized/depressurized by the same amount on both sides, causing no air to flow through the wall. The difference in airflow between the guarded and unguarded tests equals the inter-unit air flowing through the guarded zone. None of the units came in under the 3 ACH_{50} target. Typical unguarded tests came in around 4.8 ACH_{50}. Though the number of air changes per hour in these units was well above the target, they were close to achieving the normalized 0.3 cfm_{50}/ft^2 compartmentalization level. The fact that middle units had more leakage area than end units and that guarded testing showed larger reductions in leakage for middle units than end units implies that total leakage was dominated by inter-unit leakage in this building. Despite these findings, many researchers claim that achieving a unit total leakage of 3 ACH_{50} in multifamily dwellings, though not easy, is manageable with thoughtful design, investment, and construction [27].

Tracer gas techniques facilitate mapping air flows throughout a building. Tracer gas testing introduces higher concentrations of a particular gas and measures the movement of the gas with sensors to determine air currents and leakage paths. Such airflow studies generally focus on air exchange with the outdoors, but can also be used to measure air exchange between units. A study on three low-rise multifamily buildings built in the late 1900s in the Pacific Northwest was conducted during typical heating conditions [20]. All three buildings were outfitted with gypcrete-on-plywood floors, making them nominally airtight. The study found that 13-26% of total airflow into a unit came from other units. Using perfluorocarbon tracer gas, another study of a six-story multifamily building in New Jersey reported similar inter-unit air exchange results, finding 22% of airflow was coming from other units [29].

The literature suggests that better building design can minimize air leakage by tightening units and implementing ventilation strategies that minimize pressure differences across zones. Building energy codes have reduced whole-building exterior air leakage in new-construction multifamily buildings, thus saving significant energy related to space conditioning [25]. It is important to consider that leaky buildings increase the ventilation rate, which can decrease the concentration of harmful pollutants generated indoors. Therefore, an energy-centric sealing approach could be misguided, especially during retrofits as reducing whole-building exterior air leakage could increase the concentration of pollutants generated within a given apartment and not address inter-unit leakage, and therefore could adversely affect the health of occupants. Instead, a holistic approach is required to improve all building performance metrics, including IAQ, energy efficiency, and occupant comfort.

1.2.7 Compartmentalization

Compartmentalization is the practice of sealing individual dwelling units from the exterior, neighboring units, and all other interior spaces, so that each unit is effectively its own "compartment" within a building. This practice is intended to: provide IAQ benefits by reducing pollutant transfer between units; improve comfort by minimizing noise and odor from neighbors; and save energy, and consequently GHG emissions, by limiting infiltration, thus decreasing the load on HVAC systems.

The current California Building Energy Efficiency Standards, Title 24-2022 and previous versions of Title-24, set no mandatory requirement for compartmentalization [30]. Title 24-2019 has a requirement that all new-construction multifamily units must either:

a) meet a compartmentalization requirement of 0.3 cfm_{50}/ft^2 of enclosure surface area, or
b) provide balanced ventilation

A 0.3 cfm_{50}/ft^2 airtightness level is also required by ASHRAE Standard 62.2-2019 [31]. While this new requirement is a step in the right direction, it needs to be evaluated to ensure it is promoting good IAQ and significant energy and GHG reductions.

The current Title-24 requirement for new-construction multifamily units above is potentially insufficient for promoting good IAQ and providing significant energy and GHG reductions. First, new-construction multifamily buildings can bypass compartmentalization by installing balanced ventilation systems. Although an improvement, balanced ventilation still allows for leakage between units and infiltration due to wind and stack effect. Second, the proposed value is based on apparent air-sealing feasibility instead of evidence that shows specific IAQ improvements. Compared to single-family homes, the 0.3 cfm_{50}/ft^2 level is rather leaky, as it corresponds to roughly 6-7 ACH_{50}. On the other hand, it is worth noting that the surface to volume ratio is higher in multifamily versus single-family construction. For these reasons, there may still be significant pollutant transfer between units at this leakage level, particularly given the extensive use of common conduits for plumbing and electrical service, and central-exhaust ventilation in new multifamily construction.

Fortunately, new sealing technologies are emerging that improve upon the traditional manual sealing process. The manual method has contractors search for leaks, seal them, and then guess whether units are tight enough to pass a blower-door test, which is labor intensive and imprecise. The emergence of new processes could greatly enhance and automate the sealing process. For example, testing of aerosolized sealant particles to seal leaks in building envelopes suggests that the process can achieve better levels of air tightness compared to manual sealing methods, with automated air-tightness verification, and at lower cost [32].

1.2.8 Indoor Air Quality & Pollutant Transfer

Air quality is directly linked to human health. IAQ is important because Americans, on average, spend about 90% of their time indoors where some pollutant concentrations can be more than double that of the outdoors [33, 34]. Potential adverse health impacts associated with indoor pollutants can be mild – irritated eyes, nose, and throat; to moderate – headaches, dizziness, and fatigue; to severe – respiratory diseases, heart diseases, and cancer [35].

In recent decades, indoor concentrations of many pollutants have increased due to energy-efficiency measures that lead to insufficient ventilation, as well as outgassing from new building materials and household products [36]. Unlike single-family homes that only exchange air with the outdoors, multifamily buildings have an additional pollution source from their neighbors. Even if IAQ-conscious occupants eliminate pollution sources within their own unit, they may still be subject to unhealthy levels of air pollution from their neighbors.

Harmful gases and particulate matter (PM) can enter apartment units from common areas and shared spaces, hallways, elevator shafts, and neighboring units. Pollutants can travel through ventilation systems, leaks in partitions, gaps around pipes, and openings in electric outlets. Exposures resulting from these transfers are important to consider because they can elevate concentrations of pollutants above acceptable levels and potentially expose occupants to secondhand smoke, which is considered unsafe at any level [37].
Secondhand smoke has been extensively studied because exposure to secondhand smoke has been associated with increases in both morbidity and mortality, specific links to cardiovascular disease, several cancers (such

as lung, breast, and nasal sinus), asthma, respiratory illness in children, low birth weight, and sudden infant death syndrome [38, 39, 40, 41, 37].

Survey data is commonly used to ask participants about their perceived exposure to secondhand smoke. Among a random sample of 341 young adults (18-26 years) in San Francisco County who did not smoke and lived in a non-smoking unit, 205 reported secondhand smoke drifting into their unit in the last 30 days, with those living in buildings with five or more units reporting drift more often relative to those living in buildings with fewer units [42]. A separate survey of 405 households in multifamily buildings found that 48% reported that secondhand smoke enters their unit at times, with 37% of those who reported secondhand smoke entering their units (18% of total respondents) indicating that the secondhand smoke bothered them a lot [43].

The total number of people potentially exposed to secondhand smoke coming from other units in multifamily buildings has been estimated by researchers synthesizing data across multiple sources [44]. Using data from the 2009 American Community Survey, the study estimated that 25.8%, or 79.2 million people live in multifamily housing in the United States (US). In California, 32%, or 11.8 million people live in multifamily housing. King et al. (2013) utilized the 2006-2007 Tobacco USE Supplement to the Current Population Survey to estimate the number of people living in multifamily housing who did not allow smoking in their residence, estimating a population of 62.7 million nationwide and 10.6 million in California. Using all published, peer-reviewed studies that assessed self-reported secondhand smoke infiltration in the past year, King et al. (2013) estimated that between 44% and 46.2% of smoke-free housing units within multifamily buildings had infiltration of secondhand smoke coming from other places in the buildings. From this, it was estimated that 27.6-28.9 million people nationwide have experienced secondhand smoke infiltration, with 4.6-4.9 million affected residents in California.

Other studies have measured increased secondhand smoke exposure for people living in multifamily housing. Using cotinine levels in urine (a biomarker for tobacco smoke exposure), researchers identified 5,002 children not living with smokers in the 2001-2006 National Health and Nutrition Examination Survey (NHANES) and found that 74% were exposed to secondhand smoke [45]. Furthermore, the study found that children living in apartments had an increase in cotinine of 45% compared to those living in detached houses.

Another study measured transfers of gases and secondhand smoke by utilizing measurements of both perfluorocarbon tracers (PFT) and nicotine [46]. Six buildings in Minnesota with up to eight units per building were studied. The methodology incorporated multiple PFT tracer gases, allowing researchers to determine airflow into a target unit from multiple adjoining units. The median fraction of the total air transferring to a unit from other units was 4.1%, ranging from 2.1% in a new building to 35.3% in a duplex built in the 1930s. Both the PFT and nicotine transfer rates were calculated based on the measurements of these compounds in the studied units. The PFT transfer rate was 2-11 times higher than the nicotine transfer rate, with a median transfer rate six times higher than that of nicotine. The authors reported that the nicotine transfer rate was lower due to strong sorption of nicotine versus the tracer gases. In other words, because the nicotine deposited on the surfaces in the receiving unit, the relative airborne concentration was lower than for the tracer gas, and therefore, the calculated transfer rate was lower.

Inter-unit transfer of secondhand smoke has been measured in multifamily buildings through detecting elevated PM levels [47]. $PM_{2.5}$ was measured in 30 units in 11 multifamily buildings that included both smoke-permitted (n=16) and smoke-free (n=14) units. $PM_{2.5}$ monitors were set up in the main living area as well as in a shared common hallway and outdoors, where possible, for 72 hours. Vapor phase nicotine was also measured in one building. The smoke-permitted units had higher $PM_{2.5}$ concentrations, with a median concentration of 20.2 $\mu g/m^3$, compared to the smoke-free units which had a median concentration of 8.3 $\mu g/m^3$, while the common hallways had a median concentration of 16.6 $\mu g/m^3$. The median $PM_{2.5}$ concentration on the outdoor patios was 8.6 $\mu g/m^3$, which was consistent with levels found in the smoke-free units. Two of the 14 smoke-free units showed evidence of secondhand smoke transfer, while six of the eight common hallways showed evidence of transfer from smoking units. Evidence of secondhand smoke transfer was based on examination of real-time concentration profiles – seeing an increase in the smoking unit followed by increases in hallways or other units.

CONTAM is a multizone IAQ and ventilation analysis program used to calculate airflows, contaminant concentrations, and personal exposure [48]. One study used CONTAM to simulate various interventions to determine if they might be effective at reducing exposure to pollutants in low-income townhouse units [49]. While most of the modeled interventions involved source reduction strategies, such as replacement of a faulty stove, others looked at the impact of changes to the building or ventilation systems, including operation of kitchen and bathroom exhaust fans, tightening the building envelope, and installing mechanical ventilation. Kitchen fan operation predicted decreases in exposure to carbon monoxide (CO), NO_2, and PM. Whole-building mechanical ventilation predicted decreases in concentrations of contaminants originating indoors and increases in concentrations of contaminants originating outdoors. Tightening the building envelope without upgrading mechanical ventilation was predicted to dramatically increase concentrations of pollutants originating indoors.

Another study used CONTAM to model $PM_{2.5}$ concentrations in a 32-unit, four-story multifamily building under three ventilation scenarios: infiltration-only (air entering via unintended openings due to natural driving forces of wind and buoyancy), whole building exhaust ventilation, and whole-building balanced supply/exhaust ventilation [50]. Scenarios include both author-defined high and low cooking sources with and without smokers, and considering interventions such as sealing, insulation, and HVAC filtration. The baseline results (without interventions) found that for all indoor source levels, the balanced ventilation system resulted in the lowest $PM_{2.5}$ concentrations, followed by the whole building exhaust ventilation system. The high-performance sealing and insulation interventions increased $PM_{2.5}$ concentrations in all ventilation scenarios, with the lowest increases in the balanced ventilation scenario. Improved HVAC filtration and local kitchen exhaust systems were able to largely mitigate the increased concentrations stemming from the sealing and insulation interventions, reaching in fact a lower concentration than the baseline scenario for the balanced ventilation system.

While targeted policies have decreased pollution sources (e.g., smoke-free housing), measured concentrations of certain pollutants have increased in some buildings due to outgassing from building materials and household products and the complexities of air sealing and ventilation systems [36]. Gaseous pollutants were found to be the primary concern for inter-unit transfer, as very little PM was detected to transfer between units [46]. The IAQ benefits of energy-efficient buildings is unclear, as the concentrations of pollutants originating outdoors is much lower, yet the concentrations of pollutants originating indoors can be higher [51]. While increased ventilation with filtration can dilute indoor pollutant concentrations, few studies exist on how different airtightness levels affect pollutant concentrations and transfer. Understanding this interaction between leakage levels and ventilation strategies is necessary to ensure the benefits of energy efficiency and IAQ are maximized.

1.2.9 Energy Usage & GHG Emissions

In the US, buildings account for approximately 40% of primary energy consumption [52, 53]. This translates to about 800 million metric tons of carbon dioxide equivalent ($MMTCO_2e$) per year, which are primarily generated from burning fossil fuels for heating [54]. Building codes and certification programs, like LEED, promote energy efficient buildings to save energy and reduce GHG emissions.

Each household in California uses roughly 60 million British thermal units (MMBTU) of energy per year [55]. While this number is about one third less than the US average, the average California household pays more for energy than the national average due to significantly higher energy prices in California [56]. Therefore, energy savings can directly benefit residents by lowering their energy bills and can more broadly benefit society by reducing GHG emissions and help mitigate climate change.

The average California family uses about 30% of their energy for heating and cooling [55]. This number too is less than the US average (approximately 40%) due to California's "mild" climate [52, 53]. However, California has 16 distinct climate zones (including coastal, desert, and alpine) with drastically different heating and cooling needs. The Building Energy Efficiency Standards (Title 24 Part 6) adjust requirements by climate zone to account for different meteorological conditions. As a result, space conditioning equipment and usage varies significantly throughout the state, and so too does the savings potential.

Air leakage is a significant source of energy loss in multifamily buildings [57, 28]. The stack effect induces uncontrolled airflows, creating uneven demands for space conditioning among units [58]. Analysis on a 12-story multifamily building in Pittsburgh found that the annual heating energy consumption on lower floors was 28% higher than the building mean [19]. This effect is amplified in climates with large temperature differentials between indoors and outdoors during summer and winter.

Two common energy savings measures are tightening a building and updating ventilation systems. Oversized ventilation systems are common in mid- to high-rise multifamily buildings to overcome structural flaws, such as air leaks, wind pressure, and stack effect [59]. Overcoming these flaws by eliminating leaks and installing appropriately sized ventilation equipment is a common retrofit. A cost-benefit analysis is frequently used to compare energy savings against the cost to evaluate the economics. In many instances, energy efficient measures are cost-effective for saving energy, reducing GHG emissions, and improving IAQ.

EnergyPlus is a whole-building energy simulation program used to model energy consumption [60]. A Canadian case study used this program to model the energy impacts of suite compartmentalization and improved ventilation for a 13-story multifamily residential building in Vancouver, which underwent a retrofit in 2020. [59]. The study modeled compartmentalized units with balanced ventilation and heat recovery systems. It found a 51% (48.5 $ekWh/m^2$) reduction in total annual heating energy, which corresponded to a 29% (20.2 tCO_2e) annual carbon footprint decrease (Note: the conversions will differ by fuel types and regions). While this study shows the potential for energy and GHG savings, it did not separate the effects of compartmentalization and improved ventilation. Therefore, no recommendations or information about the improvements from certain airtightness levels could be drawn. Another study also used EnergyPlus to demonstrate ways to reduce energy consumption in multifamily dwellings in California [61]. Proposed ventilation code changes (including leakage reduction and ventilation changes) were predicted to result in statewide annual savings of 1.66 MMBTUs and 7,800 MWh, with annual GHG reductions of 2,686 tons. However, only a small portion of these savings were estimated to come from compartmentalization, with most of the savings attributed to lowering the ventilation rate.

Other models have been developed to simulate potential energy savings for buildings. A Swedish paper presents a bottom-up model to assess energy saving measures and carbon dioxide (CO_2) mitigation strategies in office buildings [62]. Their Energy, Carbon and Cost Assessment for Building Stocks model assumes the building is a single thermal zone and uses heat balance equations to calculate the total energy demand. A convenient feature of this model is the cost-analysis output. For the Swedish residential sector, the model calculates that 12 energy savings measures can reduce energy consumption by 55% and associated CO_2 emissions by 63%. The most impactful measure was predicted to be heat recovery systems with an energy saving of 22%. Lowering the indoor temperature to 20 °C (68 °F), a reduction of 1.2 °C (0.2 °F), was predicted to reduce energy use by 14%. Each of four insulation measures (facades, windows, basements, and roofs) were estimated to save about 5% of energy use. Although this model is useful for identifying areas for potential energy savings, it has not been validated outside of Sweden and it does not include information on energy savings at different compartmentalization levels. Another study used Transient System Simulation Tool (TRNSYS), a detailed multi-zone building energy modeling program, to evaluate potential savings from tightening units [63]. The paper found air-tightening to be cost-effective for the studied residential building with energy savings between 3-36%. Although other models exist, EnergyPlus remains the most widely used and trusted energy modelling tool for general analysis.

Bohac and Sweeney modelled direct energy impacts associated with varying air leakage levels in low-rise multifamily buildings [25]. Their model used CONTAM to generate airflows, coupled with EnergyPlus to simulate heat transfer and energy use for a building. For the simulated Midwest cold climate and Northwest marine climate, they found heating and cooling savings between 5-15% of whole-building energy use intensity. Although Bohac and Sweeney do simulate multiple leakage levels, their model is not based on empirical results at different leakage levels, and their assumption that every unit in the building has the same leakage level is an oversimplification, which likely masks the true airflow, and consequently energy usage in the building.

Building energy efficiency continues to be an important topic, as this sector is a major consumer of energy and emitter of GHG. Retrofits to multifamily buildings often involve tightening the envelope to improve thermal performance and updating ventilation systems to improve air flows. Such retrofits are often cost-effective, but highly sensitive to climate zone, building configuration, and electricity costs. Modelling work in EnergyPlus shows clear energy savings from tightening the building envelope; however, the magnitude of enegy savings from of compartmentalization is understudied.

Chapter 2: Methods

This project involved building recruitment, field testing and modeling simulation using CONTAM and EnergyPlus, with methods discussed separately below. Any changes to the methods relative to what was originally proposed are noted in the relevant section.

2.1 Building Recruitment

The study team recruited buildings for the field testing by direct outreach to stakeholder contacts, using two overall methods. The study team:

1. Contacted multifamily project team members, including developers and architects. The subcontractor TRC leveraged its list of multifamily project team members that they have developed from decades of implementing multifamily programs in the State. The study team reached out to 52 contacts using this method. Typically, recruiters would email a contact, follow-up with a phone call, and follow-up with at least one more contact (email or phone).

2. Asked industry contacts about developers that might be interested in participating. The industry contacts then sent a recruitment email to the developers on our behalf. At least 11 industry contacts sent emails to multifamily project team members on behalf of the study team.

For both methods, the outreach email included a 2-page flyer that described the overall goals of the study, benefits to participating projects, and expectations for participants. While the study team contacted different types of project team members (e.g., developers, architected, raters) for recruitment, ultimately it was the developer making the final decision, and the developer always conferred with its general contractor. The main reason for projects not participating were:

1. Developers were interested, but the timeline for the research did not align with their construction schedule. For example, a project was too far along in its construction, or would be constructed too far in the future to fit the research schedule.

2. Developers declined the request because they were concerned, or their general contractors were concerned, about impacts to the construction schedule. With COVID-19 delays and supply chain issues, developers and contractors were already behind schedule. While the study team offered to collect data over the weekend, construction was often happening 6 to 7 days per week.

For interested projects, the study team provided a memorandum of understanding that provided more details on participation expectations and released participating projects from liability for damage done or injuries incurred by the study team. Four projects agreed to participate in the field research. One ultimately did not sign the agreement because of liability concerns. Because the three buildings that were recruited represented a mix of multifamily buildings (affordable and market-rate, different ventilation strategies), the study team conducted field testing in the three projects that signed the participation agreement. One limitation with recruitment was that the study team was not able to recruit a site-built project that was not pursuing compartmentalization. Most developers that were interested were targeting compartmentalization. The one recruited project that was not pursing compartmentalization used modular construction.

2.2 Buildings Evaluated

Three new-construction mid-rise multifamily buildings in the San Francisco Bay Area were recruited for field testing (summarized in Table 2.2.1). While all three were six-story residential buildings, each had distinct designs, unit sizes, mechanical equipment, and intended occupants. Two buildings targeted compartmentalization, and two used balanced ventilation.

Table 2.2.1 Overview of Three Multifamily Buildings Selected for Field Testing

	Building A	Building B	Building C
Location	Oakland, CA	El Cerrito, CA	San Jose, CA
Rate	Affordable	Market	Affordable
Number of stories	6 (1^{st} floor is parking)	6 (1^{st} floor is parking)	6 (1^{st} floor is parking)
Construction type	Site-built (traditional)	Modular	Site-built (traditional)
Airtightness Target	0.3 cfm_{50}/ft^2	N/A	0.23 cfm_{50}/ft^2 (LEED)
Ventilation System	Balanced with heat recovery as design intent, but exhaust was more than supply	Balanced	Exhaust

Building A

The first building is a six-story, rectangular multifamily apartment complex located in Oakland, CA (pictured in Figure 2.2.1). This classic wood-frame-construction building has a first-floor parking garage with a poured concrete slab separating the garage from the five upper residential floors. The building had electric heat pumps and electric stoves. The project's target tenants are low-income families with children and those who were formerly unhoused. The building consists of 59 units: 11 one-bedroom, 28 two-bedroom, and 20 three-bedroom. It was designed to meet Section 120.1 of Title 24 through the compartmentalization requirement (0.3 cfm_{50}/ft^2). Individual units have heat recovery ventilators (HRV) continuously supplying air to the bedroom(s) and exhausting air from the bathroom(s), however the system is imbalanced by design – exhausting more air than it supplies. Each unit also has an intermittent two-speed kitchen exhaust fan.

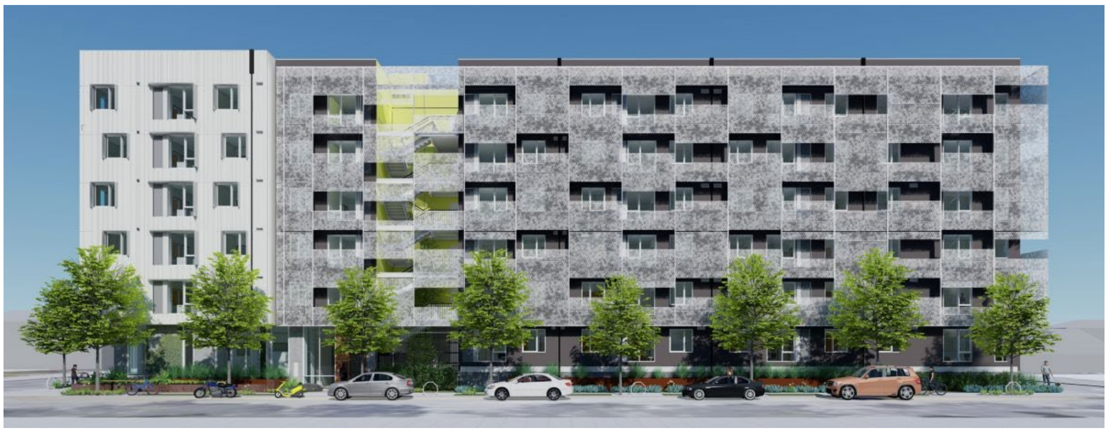


Figure 2.2.1 Computer generated architecture drawing of Building A.

Building B

The second building is a six-story, U-shaped multifamily apartment complex located in El Cerrito, CA (pictured in Figure 2.2.2). This modular-construction building has a first-floor parking garage with a poured concrete slab separating the garage from five upper residential floors. The building has mixed fuel: electric heat pumps and gas stoves. Units will be leased at market rate. The building consists of 156 units: 25 studio, 106 one-bedroom, and 25 two-bedroom. It was designed to meet Section 120.1 of Title 24 through balanced ventilation rather than compartmentalization. Common hallway supply systems bring fresh air into the living room and bedroom(s), while bathroom fans continuously exhaust air outside at an equal rate. Each unit also has an intermittent two-speed kitchen exhaust fan and a booster bathroom fan.

Figure 2.2.2 Computer generated architecture drawing of Building B.

Building C

The third building is a six story, E-shaped multifamily apartment complex located in San Jose, CA (pictured in Figure 2.2.3). The building is designed to LEED Platinum green standards. The classic-wood-frame construction building has a first-floor parking garage with a poured concrete slab separating the garage from five upper residential floors. The building has electric Packaged Terminal Heat Pumps (PTHPs) in each unit and electric stoves. This is an affordable housing development. The building consists of 135 units: 118 studio, 16 one-bedroom, and 1 two-bedroom. It was designed to outperform the Section 120.1 compartmentalization requirement of Title 24 by targeting a LEED level of compartmentalization (0.23 cfm_{50}/ft^2). Corridors are either open to the outdoors or depressurized with exhaust fans. Units run depressurized with continuous bathroom and kitchen exhaust fans. Makeup air is provided by the PTHP, which has an outside-air opening secured in the "open" position. The kitchen fans also have two-speed booster fans to increase flow to "low" or "high" while cooking.

Figure 2.2.3 Computer generated architecture drawing of Building C

2.3 Field Testing

Primary data were gathered by performing extensive field testing on three new-construction multifamily buildings. Testing included one-time measurements of total unit air leakage levels and mechanical ventilation flow rates in 10 – 14 units of each building, and short-term monitoring of air change rates, inter-unit air flows, and inter-unit gaseous pollutant transfer in a subset of units of these building. Table 2.3.1 lists the tests conducted in each building. The equipment used for testing is listed in Table 2.3.2.

Table 2.3.1 Field Tests: Parameters of Interest, Number of Tests, and Methodology

Parameter	Buildings	Units/building	Methodology
Total unit leakage	3	10-14	Single-zone blower-door test
Mechanical Ventilation flows	3	10-13	Powered flow-capture hood
Inter-unit leakage	2	3-6	Guarded blower-door test
	2	2-3	CO_2 decay
Gas and PM transfer	2	2-3	CO_2 and PM elevation

Table 2.3.2 Specifications (Detailing Range, Resolution, and Accuracy) for Field Testing Equipment

Equipment	Measurement	Range	Resolution	Accuracy
Model 3 Blower Door Fan [64]	Unit leakage	11-6,300 cfm	1 cfm	+/- 3%
Series B Duct Blaster Fan [65]	Ventilation testing	10-1,550 cfm	1 cfm	+/- 3%
DG-1000 [66]	Pressure difference	-2,500-2,500 Pa	0.1 Pa	+/- 0.9%
DG-700 [67]	Pressure difference	-1,250-1,250 Pa	0.1 Pa	+/- 1%
Alicat MFC [68]	CO_2 flow controller	0-10 SLPM*	0.01 SLPM*	+/- 0.6%
Telaire T6713 [69]	CO_2	0-5,000 ppm	1 ppm	+/- 30 ppm +/- 3%
HOBO Max 1102A [70]	CO_2	0-2,000 ppm	1 ppm	+/- 50 ppm +/- 5%
TSI DustTrak DRX (Models 8533 and 8534)	$PM_{2.5}$	0.1-15 µm	0.001 mg/m^3	+/-0.1%
TSI DustTrak II (model 8530)	$PM_{2.5}$	0.1-10 µm	(same as above)	--

**Standard Liter per Minute (SLPM)*

2.3.1 Unit Leakage Testing

Total unit air leakage (compartmentalization) was measured by performing single-zone blower-door tests on individual units (see Table 2.3.2 for specification of equipment, diagram and picture in Figure 2.3.1). A blower-door is a calibrated fan used to measure the airtightness of buildings. The calibrated fan mounts onto an exterior door and pressurizes the zone by either pushing air into or pulling air out of the building to pressurize or depressurize the space relative to its surroundings. This pressure differential causes air to flow through leaks in all surfaces of the unit (except interior partitions). Common leakage pathways include windows, plumbing and electrical chases, sill plates, and HVAC equipment. This test measures the inverse of the flow resistance of the unit to all external spaces (i.e., inter-unit walls and exterior surfaces).

Tests were performed following directions from the "Standard Test Method for Determining Air Leakage Rate by Fan Pressurization: ASTM E779-19" [23]. A fan pressurization test is generally referred to as a blower door test. Units were prepared by closing all windows within the unit, opening all interior doors within the unit, opening all doors and windows in adjacent units and the hallway, turning off and taping over mechanical ventilation equipment, and filling plumbing drain traps with water. The blower door was mounted in the hallway and configured to depressurize the unit. A multipoint test was performed at five pressure levels (generally 10 Pa, 20 Pa, 30 Pa, 40 Pa, and 50 Pa), averaging over 10-second periods once instrumentation had stabilized. A 60-second baseline pressure reading (between the test unit and hallway) was taken pre- and post-testing.

The Energy Conservatory's TECLOG4 software was used to control blower-door tests, as well as to store and visualize results [71]. For each pressure level, a digital manometer (DG-1000) was used to measure the pressure difference between inside and outside the unit, and the pressure difference across the calibrated fan, which is automatically converted to a flow by the TECLOG4 program. Using a power law fit, the program runs a linear regression in log space to determine the flow constant and flow exponent for each unit.

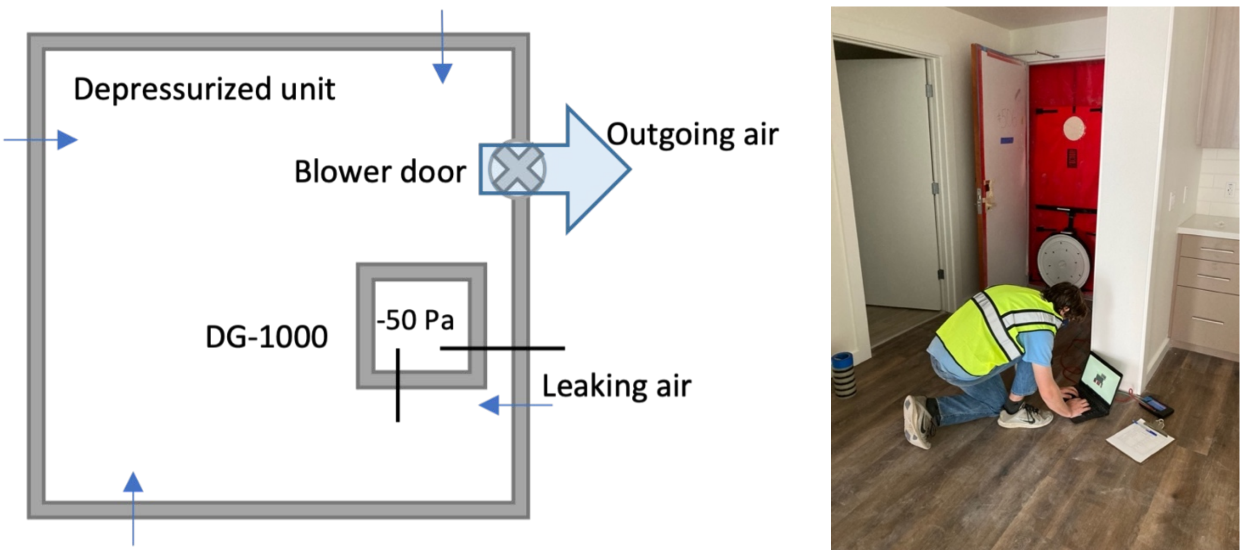


Figure 2.3.1 Blower-door testing: diagram of the test (left); photo during field testing (right).

2.3.2 Ventilation Testing

Ventilation flow rates through the grille were determined by performing powered flow-capture hood tests (see diagram and picture in Figure 2.3.2). A powered flow-capture hood is a flow hood connected to a calibrated fan that is used to measure the rate of air flowing through ventilation grilles while eliminating any back pressure associated with the hood. Flow-capture hoods cover the air inlet/outlet and collect all air entering/exiting the air terminal, guiding air flow over the instrument. Powered flow-capture hoods use a fan to maintain a neutral pressure between the hood and the room, thus eliminating any resistance from the measuring device. The fan is calibrated to measure the flow rate, using an elevated pressure drop across a flow resistance to measure the flow more accurately.

All ventilation flows were measured, including continuous exhaust grilles, continuous supply grilles, and intermittent kitchen and bathroom exhaust grilles. Units were prepared by closing all exterior doors and windows within the unit, opening all interior doors within the unit, and turning off all ventilation systems apart from the one being measured. Unique flow hoods were built to tightly fit around different grille openings and connected via a flexible duct to the calibrated fan. The flow hood was pushed firmly onto the surface around the grilles to eliminate any air leakage (which is in fact minimal due to the zero-pressure difference across the hood created by the fan). The flow rate was calculated as an average over a 30 second measurement period once the instrumentation had stabilized.

The Energy Conservatory's TECLOG4 software was used to control the calibrated fan, as well as to store and visualize results [71]. For an exhaust grille, the fan blew air into the hood. The fan speed was increased until the pressure difference between inside and outside the flow hood was zero. A DG-1000 also measured the pressure difference across the calibrated fan, which is automatically converted to a flow by the software. This flow equaled the flow rate of air through the ventilation grille. The setup was reversed for supply grilles, with the calibrated fan sucking air out of the hood at a rate equal to the supply grille blowing air into the hood.

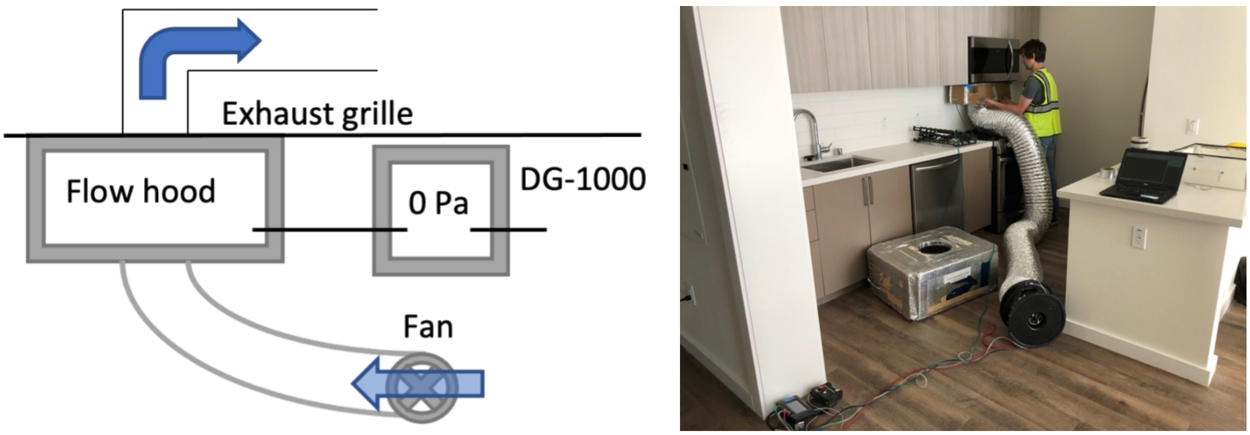


Figure 2.3.2 Ventilation grille testing: diagram of the test (left); photo during field testing (right).

2.3.3 Air Sealing

Three identical units in two buildings (Buildings A and B) were used to analyze the impacts of different leakage levels. Buildings had the same floor plan on each level, so three units in a vertical column of each building were selected for testing. This resulted in units being essentially identical to one another with the only differences being the airtightness level and the floor on which they were located. All other variables were held constant to see what impact compartmentalization alone had on outdoor and inter-unit air flows and pollutant transfer.

Two of the three units in each of buildings A and B were sealed using an aerosol-based sealing method, implemented by a commercial contractor. This process uses a blower door to pressurize a unit while injecting an aerosolized sealant material into the units. The induced pressure difference causes air to flow to all the leaks between the unit and outside/adjacent units. This air flow carries the aerosolized sealant particles to leakage sites where they accumulate and seal the leaks. The particles are flung into the sides of the leaks due to their momentum as the air turns to exit through the leaks. Figure 2.3.3 shows a diagram and blower-door test demonstrating how leaks are sealed and the units becomes "tighter" over time. The sealing results for Building A are shown in Figures A1 and A2. The computer-monitored process adjusts the fan flow to maintain a target pressure differential across the leaks (i.e., 100 Pa), allowing for precise tracking of the airtightness level throughout the sealing process [72]. This process allowed units to be sealed until a predetermined target leakage level was reached.

At the outset of the project, it was assumed that undisturbed unit leakage would be about 0.3 cfm_{50}/ft^2 in the "as-found" condition. As a result, sealing targets were set at 0.2 cfm_{50}/ft^2 for the "tight" condition, and 0.1 cfm_{50}/ft^2 for the "very tight" condition during the planning process. Although these sealing targets were initially achieved by the sealing process, the final spread was not as precise as intended for a variety of reasons. First, sealed units got leakier during the remaining construction work (units were sealed before construction on the buildings was completely finished, e.g., all electrical box covers and plumbing enclosures not installed). Second, blower-door testing of other units found that they were tighter than expected in the "as-found" condition. Third, one building (Building B) that was sealed was unable to participate in the follow-up testing for air change rates and inter-unit air pollutant transfers, so units with naturally different leakage values from the third building (Building C, which did not receive any sealing) were selected for the follow-up testing. Nevertheless, similar units at different leakage levels were identified for further testing.

For the testing and analyses described below, the unit receiving the most aerosol sealing is referred to as the sealed unit, and the unit that was sealed with aerosols to an intermediate target is referred to as partially sealed.

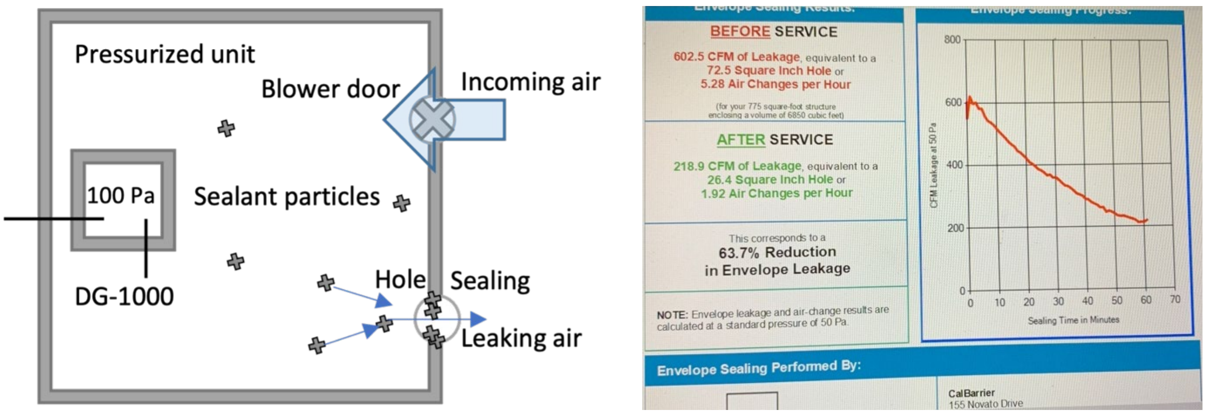


Figure 2.3.3 Aerosol-based air sealing: diagram of the sealing process (left); graph of unit's leakage throughout the one-hour sealing process in Building C (right)

2.3.4 Inter-Unit Leakage Testing

Inter-unit air leakage levels were determined by performing guarded blower-door tests (see diagram and picture in Figure 2.3.4). The three "test" units in the two buildings that received aerosol sealing were tested to measure how much air was flowing to adjacent units (both horizontally and vertically adjacent). These tests were also used to measure the reduction in inter-unit leakage from aerosol sealing units to tighter levels. In addition, in Building C, leakage to an adjacent unit was tested via guarding with a second blower door for six different interfaces (i.e. walls) between units.

A guarded blower-door test differs from a "standard" blower door by using a second blower door to maintain the pressure in an adjacent unit at the same pressure as the unit being tested, thereby eliminating any air flow to the adjacent unit. There are not air flows between two zones that are equally pressurized or depressurized. Thus, the leakage to an adjacent unit can be determined by subtracting the guarded test result from the standard blower-door test results.

Guarded blower-door tests were performed by setting up two single-zone blower-door tests in adjacent units. First, the target unit was pressurized to 50 Pa and the corresponding airflow was recorded. Next, the blower door in the adjacent unit was turned on and set to the same pressure. The blower door in the target unit continued to run and the new airflow with the adjacent zone pressurized was recorded. The difference in airflows between tests corresponds to the amount of air moving between these two units at a pressure difference of 50 Pa.

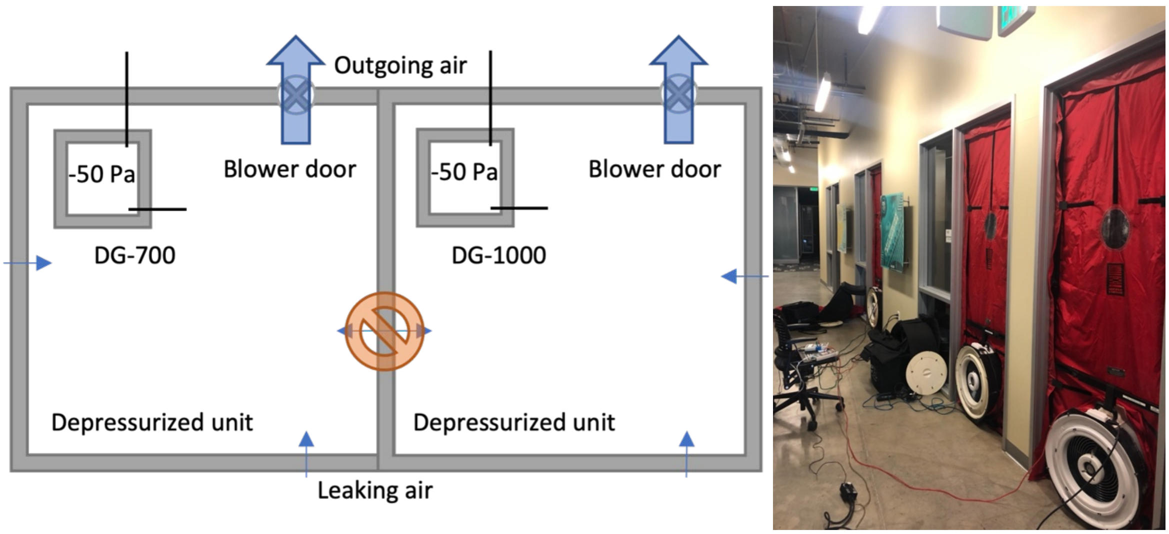


Figure 2.3.4 Guarded blower-door test: diagram of the test (left); photo of field testing (right).

2.3.5 Airflow Testing

Carbon dioxide was used as a tracer gas to determine gaseous transfer between units, as well as overall unit air change rates (see equipment in Table 2.3.2, diagram and picture in Figure 2.3.5). Tests were performed in the three "test" units (one "as-is" and two sealed to different leakage levels) in one building (building A). For the second building (Building B) that had sealing completed, since it did not have the ventilation system commissioned and all operational by the end of the project period, tracer gas and particulate testing was performed in Building C instead. As no sealing had been performed in that building, units that were at naturally different leakage levels were selected for these tests to best fulfill the goals of the project. CO_2 was maintained at a constant concentration in the test (source) unit of 4,000 ppm (well above background levels) using a mass flow controller, CO_2 sensor, and a proportional–integral–derivative (PID) control loop in the "source unit" for 1-2 hours, after which the CO_2 injection was stopped, and the concentration was allowed to decay for 2-3 hours. The air change rate was calculated from the slope of the decay:

(8) $$\boldsymbol{V\frac{dC}{dt} = -Q(C(t) - C_{out})}$$

$$where \;\; V = volume,$$

$$Q = air\,flow\,rate\;[m^3/s],$$

$$C(t) = indoor\;CO_2\;concentration\;[ppm], and$$

$$C_{out} = background\;CO_2\;concentration\;[ppm]$$

(9) $$\boldsymbol{\frac{dC}{C_t - C_{out}} = -\frac{Q}{V}dt}$$

(10) $$\boldsymbol{\int_{C_0}^{C_t}\frac{dC}{C_t - C_{out}} = -\frac{Q}{V}\int_0^t dt}$$

(11) $$\boldsymbol{ln(C_t - C_{out}) - ln\,(C_0 - C_{out}) = -\frac{Q}{V}t}$$

(12) $$\boldsymbol{\frac{Q}{V} = \frac{ln(C_0 - C_{out}) - ln\,(C_t - C_{out})}{t}}$$

$$where\;\boldsymbol{\frac{Q}{V}} = N = air\;change\;rate\;per\;unit\;time\;(t)$$

The concentration in the source unit was monitored using a Telaire T6713 CO_2 sensor that can measure CO_2 concentrations up to 5,000 ppm. HOBO Max 1102A sensors were placed in neighboring units, the hallway, and outside. These CO_2 sensors were used to detect transfer of CO_2 from the source unit to its adjacent units.

The HOBO sensors were manually calibrated prior to testing in each building. The sensors were brought outside the building to an open outdoor space with fresh air. The “calibrate” button was pressed and the five sensors were left for five minutes while being calibrated to 400 ppm. After the calibration was complete, sensors were within 20 ppm (5%) or one another. Note, this process ensured consistency between sensors in detecting CO_2 concentrations rather than absolute accuracy of the measurement.

The CO_2 injection was controlled using LabVIEW code and an Alicat mass flow controller. A fan was used to mix injected CO_2 throughout the unit. Constant concentration was achieved by continuously reading the CO_2 concentration in the unit and adjusting the Alicat’s flow rate to maintain 4,000 ppm. Pressure differences between the source unit and adjacent units were recorded with a DG-700. LabVIEW recorded the CO_2 concentration within the unit and mass flow rate of CO_2 every 15 seconds, and TECLOG4 recorded the pressure differences between the source and neighboring units every second.

Air transfer between units was calculated by measuring the transfer of tracer gas from the source to the adjacent units. The absolute air flow between units was calculated from a mass balance equation:

(13)
$$\boldsymbol{V\frac{dC}{dt} = C_s Q_s - Q(C_t - C_{out})}$$

$$where\ V = volume\ [m^3],$$

$$C_t = adjacent\ unit\ CO_2\ concentration\ [ppm]$$

$$C_s = source\ CO_2\ concentration\ [ppm],$$

$$Q_s = interunit\ airflow\ [m^3/s],$$

$$Q = ventilation\ rate\ of\ adjacent\ unit\ [m^3/s], and$$

$$C_{out} = background\ CO_2\ concentration\ [ppm]$$

(14)
$$\boldsymbol{Q_s = \frac{V\frac{dC}{dt} + Q(C_t - C_{out})}{C_s}}$$

The fraction of air in the adjacent unit coming from the source units was calculated by dividing the inter-unit air flow rate by the unit total air change rate (measured previously with air change rate testing):

(15)
$$\boldsymbol{f_s = \frac{Q_s}{Q}}$$

$$where\ f_s = fraction\ of\ air\ from\ one\ neighboring\ unit\ [\%]$$

Each of the test units in each building were tested twice. The first test occurred under normal operating conditions where all intermittent ventilation systems were turned off. The second test occurred under maximum transfer conditions where the kitchen exhaust fans in neighboring units were turned on high and the fan in the source unit was left off. During ventilation flow testing, kitchen exhaust fans were found to create the largest pressure differences between units. Therefore, running kitchen exhaust fans in adjacent units was assumed to result in the greatest inter-unit transfer.

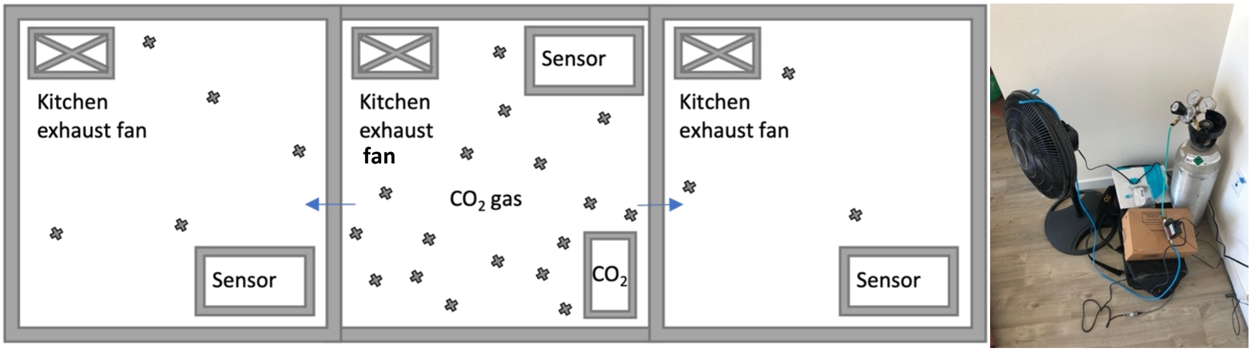


Figure 2.3.5 Gaseous pollutant transfer testing: diagram of the test (left); photo of field-testing setup showing Alicat, CO_2 tank, and fan (right).

2.3.6 PM Outdoor to Indoor Testing

Originally, the plan to measure the indoor/outdoor (I/O) ratios was to use 48-hour integrated filter samples. Upon arriving at our first test site, it became apparent that contractors from various trades were constantly going in and out of the units, and that it would not be feasible to keep people out of them for multiple 48-hour periods. Therefore, the plan shifted to measure indoor and outdoor mass concentrations of $PM_{2.5}$ overnight using real-time TSI DustTrak samplers (Table 2.3.2) when the units were empty. Measurements of $PM_{2.5}$ concentrations in the test units and outdoors for each building were measured simultaneously. The indoor/outdoor (I/O) ratio was calculated by taking the ratio of indoor PM concentrations to outdoor PM concentrations, focusing on time periods where there was a relatively stable outdoor concentration. The original plan also was to include tests with the HVAC and filter running, but these ended up being very limited due to logistical reasons. Specifically, in order to conduct the testing of PM transfer from unit to unit, the HVAC system needed to be turned off. However, if the research staff went into the unit in the morning to turn off the HVAC system, particles were resuspended, causing a spike in the PM level that then was decreasing while the transfer test was going on, Therefore, when possible, the research staff set up the units so there was no need to enter them in the morning. Samplers were co-located as a QA/QC check three times, when the equipment was received and prior to each sampling campaign.

2.3.7 Pollutant Transfer Testing

Particle pollutant testing was performed concurrently with gaseous pollutant testing described in section 2.3.4 (see Figure 2.3.6 for diagram and picture). Cat litter was used as a PM source to determine particle transfer and the deposition rate. Simultaneously with CO_2 injection, $PM_{2.5}$ was maintained initially at roughly 1.5 mg/m^3 (well above background levels) in the source unit for 1-2 hours followed by a decay for 2-3 hours. Later tests maintained a concentration of 3 mg/m^3 or in some cases, 5 mg/m^3 in an attempt to have levels high enough that an increase could be detected in the adjoining units. In all tests, there were four stations for source generation, distributed throughout the unit. Levels were initially brought to the desired level by transferring the cat litter from one bowl to the other, rotating from one source generation station to the next. Then, after the concentrations had experienced some decay, the litter was transferred from one bowl to the other in all four stations. The frequency of conducting the transfers was adjusted over time to result in the most consistent measured concentrations. This process was repeated for the duration of the time period with concentrations held at steady levels. Floors around the transfer stations as well as any carpeted surfaces were protected with paper. At the beginning of the decay period, the researchers left the unit. TSI DustTrak samplers were placed in the source unit, neighboring units, the hallway, and outside to detect transfer of PM_1, $PM_{2.5}$, and PM_{10} from the source unit to its surroundings. The decay was likewise monitored and the difference in decay rates between gaseous and particle pollutants was used to calculate the deposition velocity in the source unit. This value would be needed to determine the transfer rate to other units if there was measurable transfer to account for deposition within the unit.

Particle transfer tests were performed twice for each source unit: once with and once without the adjacent-unit kitchen exhaust fans running, as running the exhaust fans in the adjacent units creates pressure differentials that drive pollutants from the source unit to the adjacent units. The penetration ratio was determined by comparing the amount of PM that transferred from the source to the adjacent units to the amount of CO_2 that transferred from the source to the adjacent units.

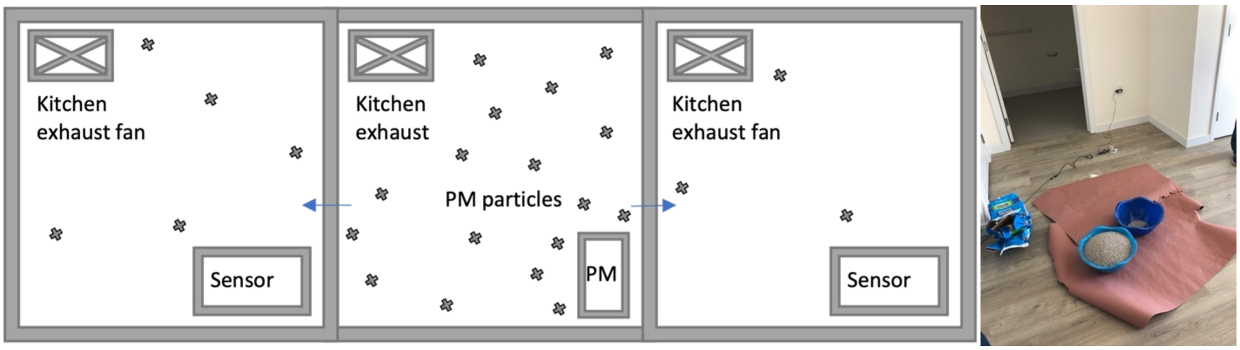


Figure 2.3.6 Particle transfer testing: diagram of the test (left); photo of field-testing setup showing a cat litter pouring station.

2.4 Modeling

Models were developed in CONTAM and EnergyPlus to investigate airflows, pollutant transfer, and energy savings for different compartmentalization levels, ventilation strategies and climate zones. CONTAM is a multizone air-flow-network model that is used to analyze IAQ and ventilation, calculating airflows, contaminant concentrations, and personal exposure based upon an inputted leakage site distribution [48]. CONTAM outputs time series of airflow and pollutant concentration that can be analyzed to determine ACH, ventilation flows, standard deviations in flows, spatial variation of flows, the sources of air entering units, average and hourly maximum pollutant concentrations, pollutant transfer between units, and occupant exposure levels. Only gaseous pollutants were simulated, as field testing data found no discernable transfer of PM between units. EnergyPlus is a whole-building energy simulation program used to calculate heating, cooling, ventilation, lighting, and plug/process loads [60]. EnergyPlus outputs hourly infiltration rates, mechanical ventilation rates, fan energy, HVAC energy, and heat pump COP, which can be used to calculate energy savings and GHG emissions from different measures and in different climate zones. While it is possible to run a coupled simulation between CONTAM and EnergyPlus, separate simulations were run to reduce unnecessary coding in EnergyPlus, since the only changes in energy usage relate to increased infiltration or mechanical ventilation system delivery rates [73].

2.4.1 Building Prototype

The prototype building used for the analyses described herein is a modified version of the high-rise prototype used by the Statewide Codes and Standards Enhancement (CASE) Teams in modeling 2022-Title 24 Part 6 code changes, including in the Multifamily IAQ CASE report [74]. The building was modified to have only five stories, to be only residential (no commercial first floor), and to be slab-on-grade (no underground parking garage). The energy analysis was focused on the changes in energy use associated with different total leakage levels and ventilation strategies. Although the baseline energy use should change somewhat due to the inclusion of a garage, the relative changes due to compartmentalization and ventilation were not expected to change. The only minor change could be that the height of the prototype building is changed by adding a garage, and the first-floor units may have a little extra leakage into the garage. But the impacts should be minimal. The floor area of each level is 12,540 ft^2. Units were modeled with a ceiling height of 9 ft and the distance between floors was assumed to be 10 ft. Each floor contains 13 units: five two-bedroom (with floor areas of 1,080 ft^2), six one-bedroom (with floor areas of 780 ft^2), and two studios (with floor areas of 540 ft^2); along with a laundry room, stairwell, elevators, and enclosed corridor (see Figure 2.4.1). The building has balanced central ventilation and PTHPs in each unit.

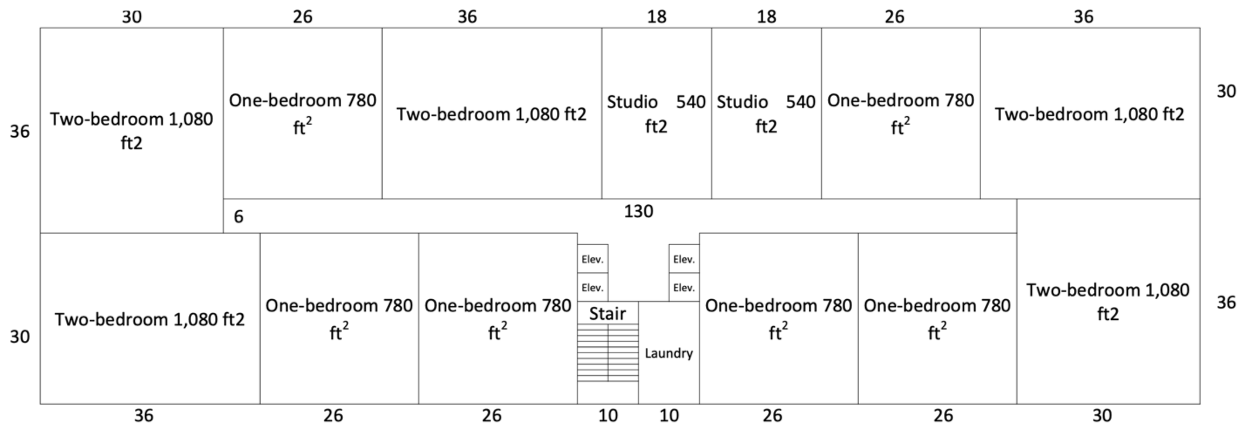


Figure 2.4.1 Building floorplan (identical for all five stories) used for energy and air quality modeling.

2.4.2 CONTAM

A CONTAM model was developed to investigate air flows and pollutant exposure for different combinations of leakage levels, ventilation strategies, and climate zones. The program calculates building airflow rates and relative pressure differences between zones, making it widely used for evaluating the impacts of ventilation design decisions on IAQ. In the CONTAM model, infiltration is calculated for each timestep using pressures and leakage areas between zones. The prototype building was built in CONTAM with the following alterations: mechanical ventilation flows were defined using the minimum ventilation requirement [31], the corridors on each floor were supplied with mechanical ventilation according to the minimum ventilation requirement of 0.15 cfm/ft^2 that is equal to a continuous supply flow of 138 cfm per floor [30], unit supply systems were deleted in the exhaust-only scenario and unit exhaust systems were deleted in the supply-only scenario (both supply and exhaust systems were present in the balanced scenario), total unit leakage was varied between 0.15 cfm_{50}/ft^2 (field testing average), 0.3 cfm_{50}/ft^2 (California code requirement), and 0.45 cfm_{50}/ft^2 (possible "leaky" building), the thermostat set point was fixed at 70 F for all zones year round.

Leakage Distribution

Flow paths were created at every interface with outdoors, between units, and with corridors (i.e., for all six surfaces of each unit, noting that some units have more than one flow path on a given surface). No partitions flow paths (i.e., in-unit resistances) were modeled, essentially assuming that all doors within a unit were open or were adequately undercut, or in other words, that each unit is a single zone with a single pressure. Leakage elements for each flow path were defined using normalized surface leakage ratios (i.e., cfm_{50}/ft^2) based on field testing data and data from other recent studies (see Table 2.4.1).

Table 2.4.1 Fraction of Air Leakage through each Wall in a Unit within Multifamily Buildings

	Corridor	Adjoining	Outside
Field Testing	28-43%*	14-44%	28-43%*
Latest Literature**	36-45%	25-34%	30%
Model	35%	35%	30%

*Guarded blower-door field testing only measured the air transfer to adjoining units. The fraction to the corridor and outside is estimated by dividing the remaining leakage evenly.
**Latest literature refers to recent comprehensive multifamily air leakage studies [25, 4]

Door leakage was modeled using CONTAM's crack description equation [48]. Three doors were defined: apartment doors, laundry and stairwell doors, and elevator doors with crack lengths and widths of 3 ft, 1/16 inch; 3.5 ft, 1/4 inch; and 22 ft, 1/4 inch; respectively [75]. Air flow was assumed to be effectively resistance-free in the vertical direction for stairwells and elevator shafts.

Surface leakage ratios were determined by distributing unit leakage among each surface type (door, corridor, outside, horizontally adjacent, vertically adjacent). The relative leakiness of each surface was calculated by summing the total leakage through each surface type and dividing by the total surface area for each surface type. The corridor walls and exterior walls were assumed to have approximately equal normalized leakage (i.e., leakage per unit of surface area) and to have the highest normalized leakage. Shared walls were assumed to have half the normalized leakage of corridor and exterior walls. Ceilings and floors were assumed to be only about 10% as leaky as the corridor and exterior walls per unit of surface area.

Leakage coefficients for each surface of each unit were assigned according to the following steps:

1. Assume a total unit leakage (e.g., 0.3 cfm_{50}/ft^2).
2. Calculate the unit leakage coefficient using the volumetric flow power law: multiply by the unit's surface area and then divide by 50 Pa raised to the power of flow exponent. Leaks through walls were assumed to have a constant flow exponent of 0.65 [21].
3. Subtract the door leakage (after converting it to a leakage coefficient) from the total leakage coefficient.
4. Calculate the nominal total surface leakage of each unit (excluding door leakage) by summing each surface leakage area multiplied by its leakage ratio.
5. For each unit surface, calculate the fraction of leakage through this surface relative to the rest of the unit (i.e., multiply the nominal surface leakage ratio for that type of surface by the surface area, then divide this value by the nominal total surface leakage).
6. If the leakage path is between two units, then average the inter-unit leakage results from each unit.
7. Multiply the total leakage coefficient (Step 3) by the leakage fraction (Step 5).
8. Assign the resulting leakage coefficient and a flow exponent of 0.65 to the flow path.
9. Repeat steps 4-8 until all unit surfaces have been assigned flow paths (see Figure 2.2.2 showing leakage element on every surface for a single floor).

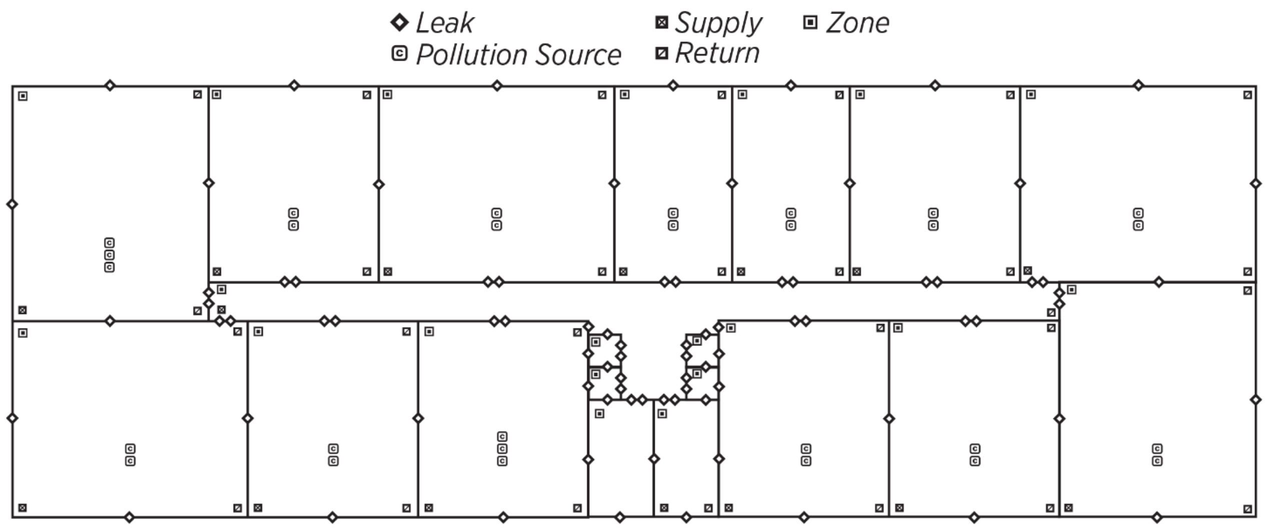


Figure 2.4.2 CONTAM floorplan showing leakage elements and pollutant generation sources. There are three pollutants generated, NO_2 and formaldehyde in all units represented as two circles, and benzene in units with smokers, indicated by a third circle. Leakage elements are on each surface, and pollutants sources are shown in the middle of each unit (treated as a single zone).

VENTILATION FLOWS

Unit mechanical ventilation flows were defined according to the minimum ventilation requirement for multifamily attached dwelling units [30]:

$$\boldsymbol{Q_{tot} = 0.03A_{floor} + 7.5(N_{br} + 1)} \quad (16)$$

$$where\ Q_{tot} = ventilation\ rate\ [cfm],$$
$$A_{floor} = floor\ area\ [ft^2],$$
$$N_{br} = number\ of\ bedrooms$$

The ventilation requirements for the three types of units were 55 cfm for two-bedroom units, 38 cfm for one-bedroom units, and 31 cfm for studio units. Each unit was fitted with an exhaust and supply grille. Whether air flowed through one or both grilles at the minimum ventilation rate was determined by the ventilation strategy. For example, for balanced ventilation, the flow through both grilles was equal, whereas for exhaust-only ventilation, the flow through the supply grille was set to zero, and make-up air enters cracks in the walls. The laundry room was exhausted at 0.15 cfm/ft^2, according to the CEC ventilation requirement [30]. All other interior spaces (stairwell and elevators) were not ventilated.

COOKING & KITCHEN-FAN SCHEDULING

Cooking and kitchen range hood operation were scheduled based on typical residential usage. Half of the units were assumed to always run their kitchen fans when they cooked while the other half were assumed to never run their kitchen fans, providing the opportunity to evaluate multiple combinations of kitchen exhaust fan operation for neighboring units while pollutants were being generated. The kitchen range hood capture efficiency was assumed to be 50% [76].

Cooking schedules were determined by random sampling from normal distributions generated from questionnaire data on cooking times [77]. Weekday and weekend schedules were defined separately. Three times a day, a cooking activity was assigned a probability of whether the stove is used or not for a meal, a random start time within a representative window, and the cooking time based on an average and standard deviation (see Table 2.4.2). Thus, every unit in the building had unique cooking and kitchen fan schedules.

Table 2.4.2 Cooking Distribution Parameters Used to Randomize Cooking Schedules for each Unit

	Breakfast		Lunch		Dinner	
	Weekday	Weekend	Weekday	Weekend	Weekday	Weekend
Probability	25%	75%	25%	50%	75%	50%
Earliest	6:30 AM	7:00 AM	12:00 PM	12:00 PM	6:00 PM	6:00 PM
Latest	7:30 AM	9:00 AM	1:00 PM	1:00 PM	8:00 PM	8:00 PM
AVG [min]	11	11	15	15	27	27
SD [min]	2	2	2	2	2	2

POLLUTANT DISTRIBUTION

Release of gaseous pollutants were simulated to calculate inter-unit transfer and occupant exposure. Exposure was calculated both for pollutants released within a unit, as well as for pollutants transferred in from other units. Particles were not modeled, because field testing found no discernable transfer of PM at the tightness levels in these tested building so PM transfer rates were not available for the modeling. The three gaseous pollutants that were modelled were: nitrogen dioxide (NO_2) from natural gas burners (intermittent source), formaldehyde (CH_2O) from the contents of each unit (constant source), and benzene (C_6H_6) from cigarette smoke (intermittent source only coming from some units). For each pollutant, a unique signature by unit number was assigned so that the total concentration of each pollutant within each unit could be traced to either originate within the same unit or transfer from other units.

Nitrogen Dioxide (NO_2)

All units were modeled to have natural gas burners. Indoor NO_2 generation was scheduled according to cooking schedules. Occupants were assumed to use one burner to cook breakfast and lunch and two burners to cook dinner. An average NO_2 generation rate of 1.1 mg/min per burner was used [78].

Outdoor NO_2 levels were assumed to be 10 ppb in all modeling scenarios [79]. While there is variability in outdoor NO_2 concentrations throughout California, much of the variability is on a local scale, and thus outdoor concentrations should be considered for the exact building location [80] [81]. Since there is no decay rate assigned to NO_2, increasing the outdoor concentrations by a given amount would result in the same increase indoors. One can add the differential between the NO_2 concentration at the location of the building and 10 ppb to the modeled indoor results. By holding the outdoor NO_2 concentration constant, the analysis focused on indoor generated NO_2 and how changes in leakage levels, ventilation strategies, and climate zones affected NO_2 exposure within the modeled buildings.

Formaldehyde (CH_2O)

Buildings were assumed to be built with materials having low formaldehyde emission rates, making the largest source of formaldehyde be occupant possessions, such as furniture. This serves to maximize the component of formaldehyde being transferred between units, providing a more interesting case study. Outdoor CH_2O levels were assumed to be 0 ppb. Each unit's formaldehyde emission rate was determined by random sampling from a log normal distribution with an average of 38 $\mu g/h\text{-}m^2$ and a standard deviation of 17 $\mu g/h\text{-}m^2$. These numbers are from a study that was conducted in buildings built with low-emitting materials [82]. The unit formaldehyde emission rates were re-randomized until the formaldehyde distributions for units operating and not operating kitchen exhaust fans were similar.

Benzene (C_6H_6)

Smokers were simulated to be living in 25% of the units, distributed throughout the building. This number was selected to provide enough smokers to examine the issue of non-smokers living next to smokers. Outdoor C_6H_6 levels were assumed to be 0 ppb, allowing the exposure from inter-unit transfer of smoke to be isolated. The number of cigarettes smoked per day was determined by random sampling from a normal distribution with an average of 17 cigs/day and a standard deviation of 2 cigs/day [83]. Each cigarette was estimated to generate 430 µg of Benzene and take 9 minutes to smoke, yielding a generation rate of 48 µg/min [84]. To simplify the source rate modeling, smoking schedules were made for weekdays and weekends with five "smoking windows" (morning, midday, afternoon, evening, and night) each day in which the smokers smoked a number of cigarettes in a row (see Table 2.4.3).

Table 2.4.3 Smoking Distribution Parameters Used to Randomize Smoking Schedules (Benzene Generation) for each Smoker's Unit

	Morning		Midday		Afternoon		Evening		Night	
	Week-day	Week-end	Week-day	Week-end	Week-day	Week-end	Week-day	Week-end	Week-day	Week-end
Earliest	6:30 AM	7:00 AM	9:00 AM	10:00 AM	1:00 PM	1:00 PM	6:00 PM	6:00 PM	9:00 PM	9:00 PM
Latest	8:00 AM	9:00 AM	12:00 PM	12:00 PM	5:00 PM	5:00 PM	8:00 PM	8:00 PM	10:30 PM	11:00 PM
AVG [cigs/day]	5	4	2	2	2	2	4	4	4	5
SD [cigs/day]	2	2	1	1	1	1	1	1	2	2

SIMULATION CONFIGURATIONS

CONTAM was configured to run a transient simulation for both airflows and pollutants. Airflows were simulated over one year at 1-hour timesteps, and pollutants were simulated over one week at 1-minute timesteps. The default solver, Implicit Euler, is a fixed time step solver and was selected for the transient integration method. California climate zone weather data was downloaded from EnergyPlus [85]. EnergyPlus EPW weather files were converted into WTH CONTAM weather files using the online CONTAM Weather File Creator [86].

VARIED PARAMETERS

Parameters were varied incrementally to understand how different scenarios impact airflows, pollutant concentrations, and inter-unit transfers. The parameters that were varied were: airtightness level, ventilation strategy, and climate zone.

- **Airtightness Level.** Three leakage levels were simulated: 0.15 cfm_{50}/ft^2 (average from the field testing), 0.3 cfm_{50}/ft^2 (California code requirement), and 0.45 cfm_{50}/ft^2 (representing what might happen without code requirements).
- **Ventilation System.** Three ventilation systems were simulated: exhaust-only, supply-only, and balanced.
- **Climate Zone.** Four climate zones were simulated: CZ12 (Sacramento), CZ3 (San Francisco), CZ9 (Los Angeles), and CZ13 (Fresno).

AIRFLOW & POLLUTANT OUTPUTS

After running a scenario, outputs were exported for analysis. The annual average airflows between zones were exported to determine air change rates, ventilation rates, and the sources of air entering units. Transient pollutant concentrations for each zone were exported for both the first week in January and the first week in July to calculate pollutant concentrations, occupant exposure, and inter-unit transfer. The winter and summer week had very similar results and only the results for July are presented for simplicity. Transient air changes for the building were exported to calculate the change in outdoor air entering the building at every hour and the associated energy (and GHG intensity) required to condition the air at that time.

2.4.3 EnergyPlus

An EnergyPlus model was used to investigate energy consumption from different combinations of leakage levels, ventilation strategies, and climate zones. EnergyPlus accurately models building HVAC energy by considering fenestration, heat transfer, thermal mass, equipment efficiency, etc. Unit thermostats have heating and cooling setpoints that are triggered any day of the year when the temperature goes below the heating setpoint or above the cooling setpoint. The heating setpoint is 68 F during the day (6 AM – 10 PM) and 60 F during the night (10 PM – 6 AM), and the cooling setpoint is always 78 F. Design ventilation flow rates were consistent with California's minimum ventilation requirement at 31 cfm for studios, 38 cfm for one-bedrooms, 55 cfm for two bedrooms, and 126 cfm for the corridor [30]. Building infiltration rates were modeled using a simplified infiltration equation:

(17)
$$\boldsymbol{I = I_{design} \times C \times v_{wind}}$$
$$where\ I = infiltration\ [m^3/s],$$
$$I_{design} = design\ infiltration\ [m^3/s],$$
$$C = 0.224\ [1/(m/s)], and$$
$$v_{wind} = wind\ speed\ [m/s]$$

The design infiltration values were 24 cfm for studios, 35 cfm for one-bedroom units, 44 cfm (interior) and 80 cfm (corner) for two-bedroom units, 13 cfm for the stairwell, and 0 cfm for corridors and elevators (since they have no exterior walls).

ENERGY BASELINE

An existing EnergyPlus modeled building, the same Multifamily IAQ CASE report building (TRC 2022), as was used for the CONTAM modeling, was simulated to determine a base case for annual energy usage (Figure 2.4.3). Total Building outputs were halved to conform with the modification of the prototype building being cut in half (from ten to five stories). The direct outdoor air system (DOAS) central supply air pre-heating/cooling coils were deleted, so that the entire space conditioning load was met by in-unit PTHPs (to simplify the energy comparison between different ventilation systems). Each zone was assigned a predefined infiltration rate, which varied during the simulation based upon wind direction and speed. The EnergyPlus base case most closely resembles the CONTAM simulation at a leakage level of 0.3 cfm_{50}/ft^2, with balanced ventilation, and with no variation in leakage or ventilation flows between units.

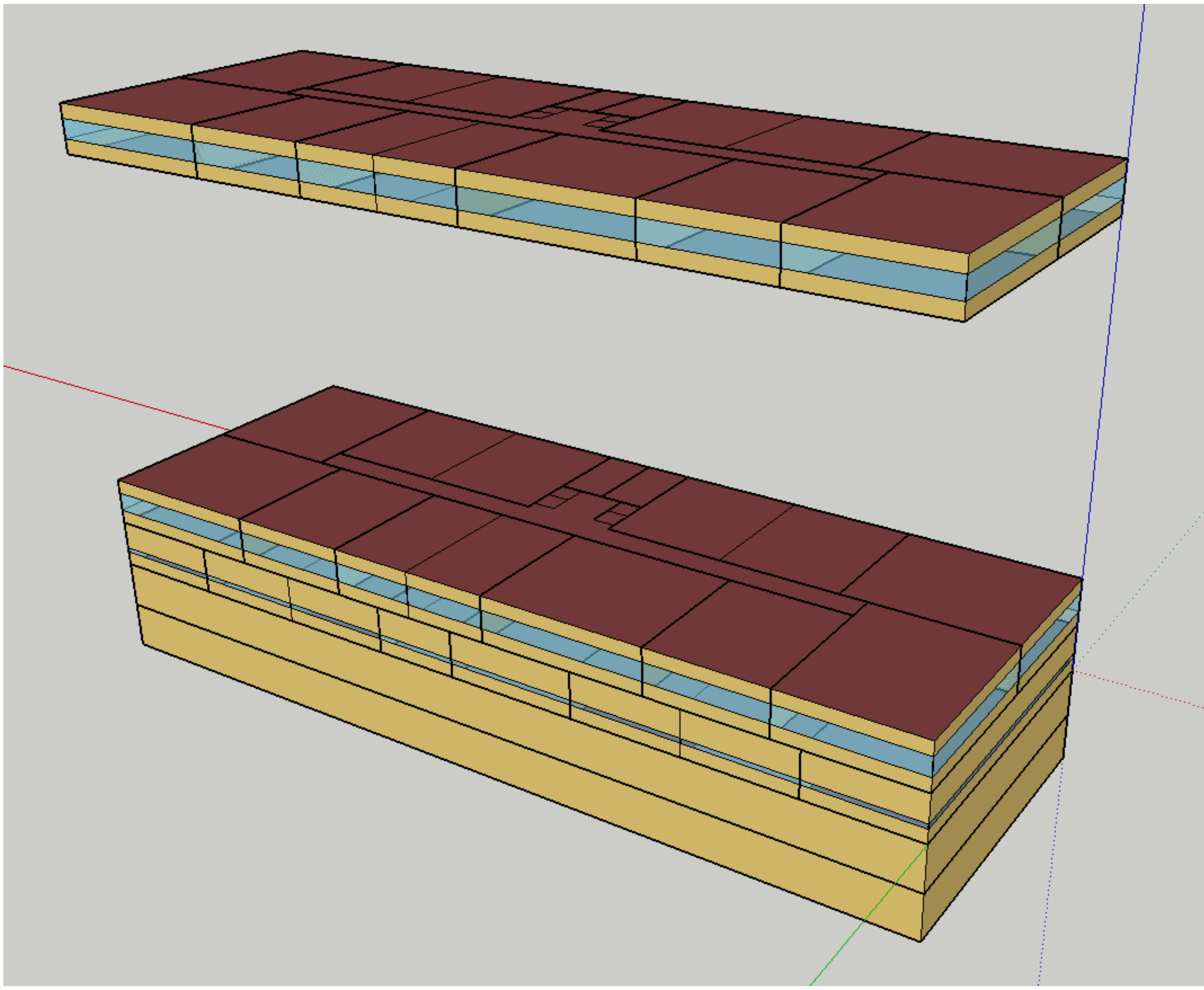


Figure 2.4.3. EnergyPlus building schematic showing floors and zones (floors 3-9 are not showed but are copies of floor 2).

Energy Outputs

Outputs were exported from both CONTAM and EnergyPlus to determine the energy implications of different simulations. Only energy related to HVAC systems was analyzed, since other energy end uses (e.g., lighting, plug loads, etc.) are unaffected by the modeled scenarios. Annual hourly time series for infiltration rate and ventilation rate were exported from CONTAM and converted to energy use. Annual hourly time series for infiltration rate, ventilation rate, fan energy, HVAC energy, and Coefficient of Performance (COP) were exported from EnergyPlus. EnergyPlus was run once for each climate zone to determine the baseline energy use. Multiple CONTAM simulations were run for each climate zone to determine the relative advantages/disadvantages from an energy perspective of different leakage levels and ventilation strategies.

Energy Calculation

An energy spreadsheet calculation was performed in Excel to quantify the increase or decrease in annual energy consumption between different modeling scenarios. For each scenario, outdoor air (infiltration plus supply ventilation) entering the CONTAM building each hour was subtracted from the base case which was the outdoor air (infiltration plus supply ventilation) entering the EnergyPlus building. This marginal change in outdoor air entering the building was used in conjunction with TMY weather data to calculate the additional load (as a product of change in airflow and enthalpy) on the building at each timestep:

(18) $$\Delta \boldsymbol{E_{OA}} = \Delta \boldsymbol{I_{OA}} \times \boldsymbol{p} \times (\boldsymbol{h_{IA}} - \boldsymbol{h_{OA}})$$

$$where\ \Delta E_{OA} = change\ in\ heating\ or\ cooling\ energy\ [kJ],$$

$$\Delta I_{OA} = change\ in\ outdoor\ air\ entering\ the\ building\ [m^3/s],$$

$$p = density\ of\ air\ [kg/m^3],$$

$$h_{IA} = specific\ enthalpy\ of\ indoor\ air\ [kJ/kg], and$$

$$h_{OA} = specific\ enthalpy\ of\ outdoor\ air [kJ/kg]$$

The increase or decrease in airflow only triggered additional energy usage to condition the extra air if the EnergyPlus simulation required heating or cooling during the same timestep, since there is a dead-band that EnergyPlus models. Performance parameters for HVAC systems (assuming the same size ductwork) were used to calculate the total increase/decrease in energy associated with scenarios that increased or decreased space conditioning (COP) and fan airflow rates (using the Cube Law):

(19) $$\Delta \boldsymbol{E_{fan}} = \boldsymbol{E_{fan}} \times \left(\frac{\boldsymbol{Q_{sim}}}{\boldsymbol{Q_{base}}}\right)^{\boldsymbol{3}}$$

$$where\ \Delta E_{fan} = change\ in\ fan\ energy\ [kJ],$$

$$E_{fan} = EnergyPlus\ fan\ energy\ [kJ],$$

$$Q_{sim} = CONTAM\ fan\ air\ flow\ [m^3/s], and$$

$$Q_{base} = EnergyPlus\ fan\ air\ flow\ [m^3/s]$$

GHG CALCULATION

GHG emissions were calculated by summing the total HVAC energy (central fans and unit PTHPs) for each hour in the year and multiplying by the respective marginal emission factors. Time Dependent Valuation (TDV) electricity GHG emission factors were averaged over California's 16 climate zones for each hour to create annual hourly marginal GHG emissions data for the state [87]. Annual GHG emissions for each simulation were calculated by summing hourly emissions for one year. Annual GHG emissions were multiplied by a 30-year time horizon to correspond with the TDV data, which is forecast over the next 30 years.

Chapter 3: Results

3.1 Field Testing

Field testing measurements were used to assess the IAQ and energy performance of three new-construction multifamily buildings in California. The parameters analyzed were total unit leakage, ventilation flows, inter-unit leakage, unit air changes, and gaseous pollutant transfer. Field testing results were additionally used to inform assumptions in the subsequent modeling section. In total, 38 units were tested (listed by building in Table 3.1.1) with all tests performed prior to occupancy. The total number of tests completed are listed in Table 3.1.2.

Table 3.1.1 Breakdown of the Quantity and Size of Units Tested in Each Building

Building	Studio	One-bed	Two-bed	Three-bed	Total
A	0	0	12	2	14
B	4	8	0	0	12
C	12	0	0	0	12

Table 3.1.2 Overview of Field Tests Summarizing Parameter of Interest, Number of Tests, and Methodology

Parameter	Buildings	Units/building	Total Tests	Methodology
Total unit leakage	3	10-14	36	Single-zone blower-door test
Mechanical Ventilation flows	3	10-13	35	Powered flow-capture hood
Inter-unit leakage	2	3-6	9	Guarded blower-door test
Air change rate	2	2-3	10	CO_2 decay
Gas and PM transfer	2	2-3	10	CO_2 and PM elevation

3.1.1 Unit Leakage

Blower-door test results from the three buildings found all units were tighter than the 0.3 cfm_{50}/ft^2 compartmentalization requirement (see summary results in Table 3.1.3). The average leakage level was 0.16 cfm_{50}/ft^2 with a standard deviation of 0.02 cfm_{50}/ft^2 (about 15% of the mean). Based on these measurements, new-construction units appear to be about half as leaky as the current airtightness requirement with only modest variation in leakage.

Table 3.1.3 Total Unit Leakage Comparison Between Buildings Normalized by Surface Area and Volume

Building	[cfm_{50}/ft^2]	SD [%]	ACH_{50} [/h]	SD [%]	# Units
A	0.17	15%	3.88	16%	14
B	0.14	14%	3.16	14%	10
C	0.16	10%	4.26	11%	12

Blower-door test results from the three buildings showed unit leakage was fairly consistent among buildings (see Figure 3.1.1). Building B, which was not targeting compartmentalization, had the tightest units with an average unit leakage of 0.14 cfm_{50}/ft^2, while Building A and C, which were targeting compartmentalization, were slightly leakier (but still well below the requirement) with average unit leakages of 0.17 cfm_{50}/ft^2 and 0.16 cfm_{50}/ft^2, respectively. Units in Building C were relatively leakier when normalized by volume than surface area since their footprint was rectangular rather than square like the units in Building A and B (see Figure 3.1.2).

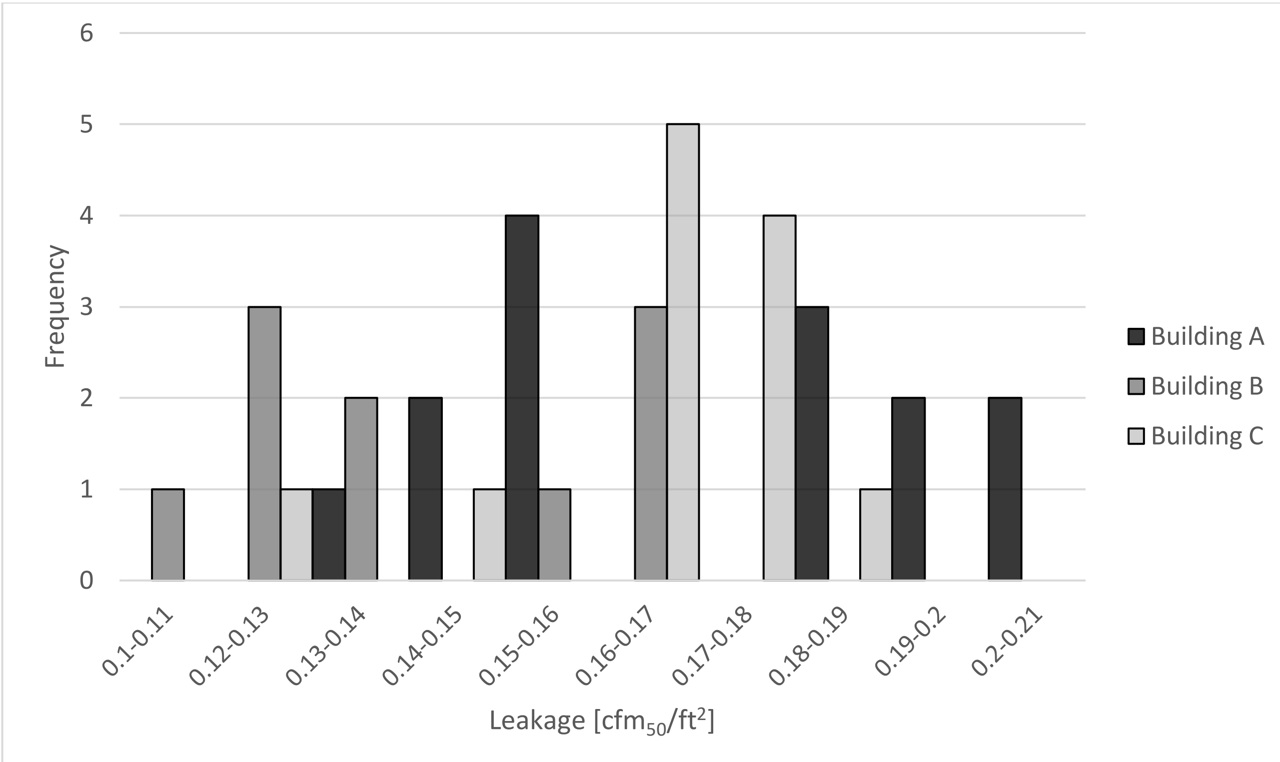


Figure 3.1.1 Total unit leakage distributions for each building normalized by surface area [cfm_{50}/ft^2].

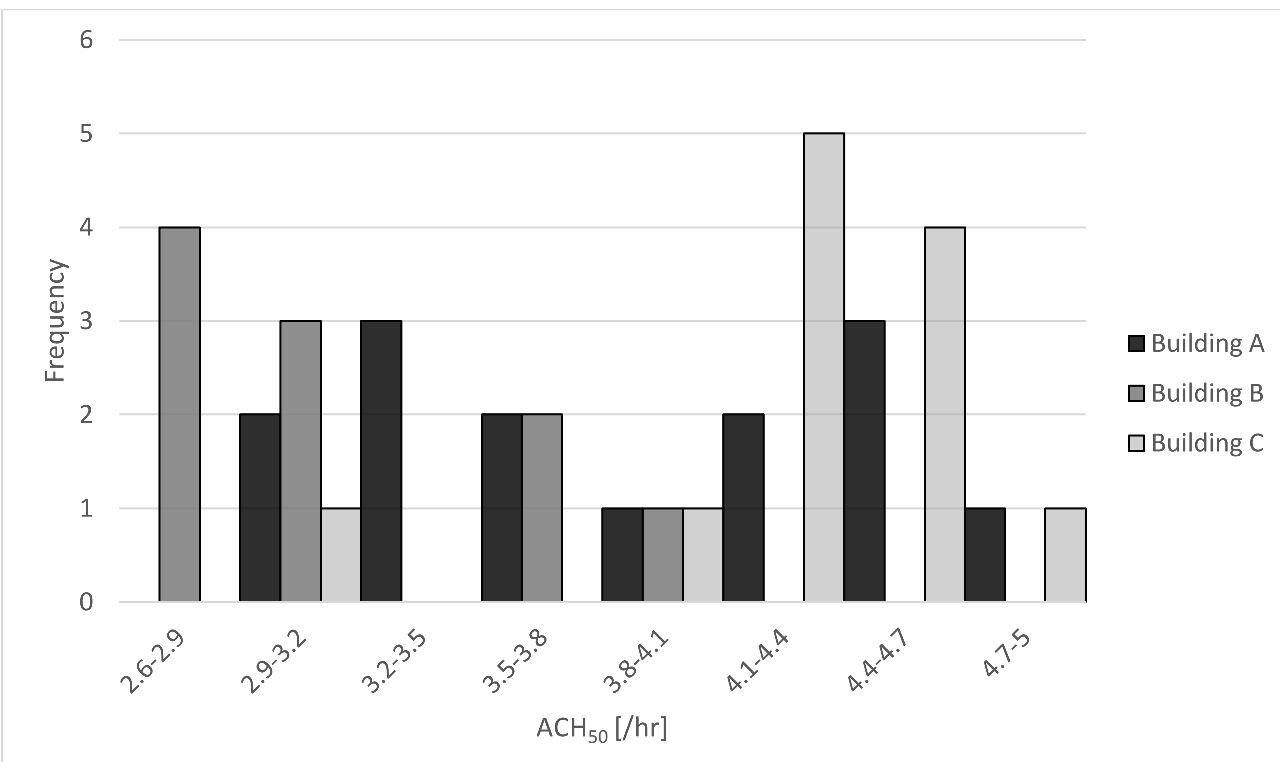


Figure 3.1.2 Total unit leakage distributions for each building normalized by volume [ACH_{50}].

3.1.2 Ventilation Flows

Each building was designed with a different ventilation strategy, resulting in different ventilation flows for each of the buildings (see Table 3.1.4). Units in Building A were designed to be balanced with heat recovery (HRV) between supply and exhaust; however, the HRV systems were set with higher exhaust flow relative to supply. Units in Building B were designed with supply and exhaust ventilation systems that were to operate together as a balanced system. Units in Building C were designed with exhaust-only ventilation and relied on makeup air through the PTHP units with an opening to outside. The summary of ventilation flow measurements is shown in Figure 3.1.3, which shows that most units are negatively pressurized and there is significant variation in ventilation flows for some buildings. Interestingly, Building A was clearly unbalanced, despite the design intent apparently being for balanced supply and exhaust flows. It was unclear whether further commissioning and adjusting of flow rates would take place in these buildings.

Table 3.1.4 Field Testing Continuous Mechanical Ventilation Flow Summary (Values are Rounded)

Building	Supply [cfm]	SD [%]	Exhaust [cfm]	SD [%]	Net [cfm]	Net [ACH]	# Units
A	52	8%	81	5%	-30	0.7	13
B	53	33%	53	14%	-1	0.6	10
C	114	6%	142	25%	-29	2.4	12

Note: Supply and exhaust flows in this table were the average flows for all units within each building, and Net flows were the average of the difference between supply and exhaust flow rates for each unit within each building.

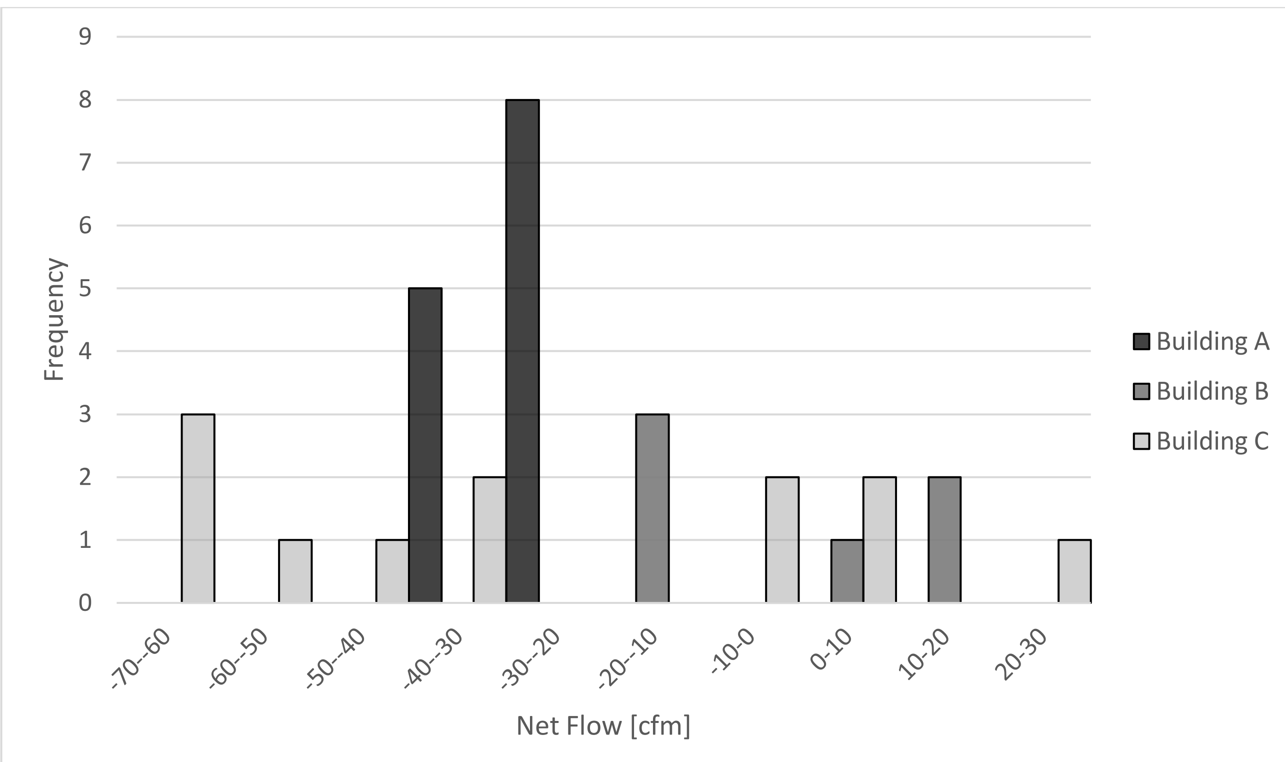


Figure 3.1.3 The net continuous mechanical ventilation flow distribution [cfm] shows that most units are negatively pressurized and there is significant variation in ventilation flows for some buildings.

The continuous ventilation systems in Building A were consistently different from the stated design intent (i.e. balanced supply and exhaust). Units were depressurized by an HRV that was set to supply 50 cfm and exhaust 100 cfm. These settings were unchanged between different sized units (one-bedroom, two-bedroom, and three-bedroom), causing the smaller units to be more negatively pressurized and have more air changes than the larger units (i.e. moving the same air flow through a smaller hole results in a larger pressure differential). Failing to adjust ventilation flows based upon unit size resulted in overventilation of some units compared to Title-24 code requirements and unintended pressure differences between units.

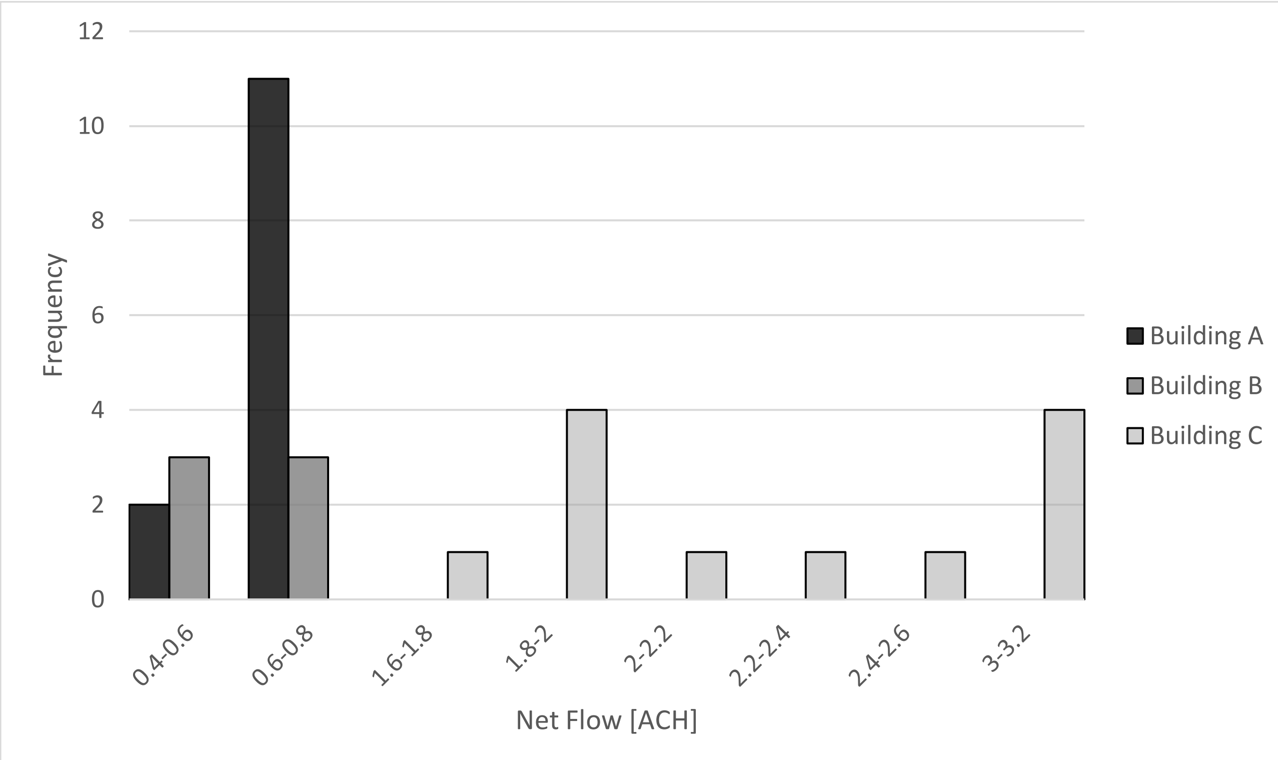


Figure 3.1.4 The net continuous ventilation flow distribution [ACH] shows that Building C has far more air changes than buildings A and B.

The continuous ventilation system in Building B was balanced at the building level, but slightly imbalanced for individual units. Continuous supply and exhaust flows were close to their respective design flow rates of 40-55 cfm to bedrooms and 40 cfm from bathrooms. Supply ventilation was not flowing into four units during field testing, suggesting further commissioning still had to be completed in Building B. However, for the units where both supply and exhaust flows were measured, although the average net flow was small (-1 in Table 3.1.4), the flows in individual units were in general imbalanced by about 10 cfm, with some units being depressurized by 10 cfm more exhaust, and others being pressurized by 10 more supply. These 10-cfm flow differentials represent roughly 20% of the total continuous ventilation flow to each unit.

The continuous ventilation system in Building C significantly depressurized the entire building relative to the outdoors. Continuous exhaust systems in the kitchen and bathroom removed, on average, 150 cfm of air from the small (1,500 square foot) studios. The corridors also had continuous exhaust fans. Supply air came from the outdoor through PTHP units, which were effectively holes in the walls. Exhaust flows varied between units due to some fans working better than others. Supply flows were constant between units since the whole building was depressurized by about 30 Pa and the same PTHP was installed in each unit – the same pressure difference and the same open area between units resulted in similar air flows through each PTHP. These units were simultaneously severely overventilated and may have IAQ problems, because makeup air was provided through unfiltered outdoor air intakes on PTAC units in a building located next to a major highway. Note that this project was constructed under Title 24-2016, which did not require filtration of ventilation air for this system type (because it does not have ductwork). Beginning in the 2019 version of Title 24, Part 6, filtration would have been required for ventilation air, which would reduce particulate matter infiltration from the outdoors.

Kitchen exhaust fan flow results showed that when in operation, kitchen fans generally dominate the ventilation flows in a unit (see Figure 3.1.5). Kitchen exhaust fans in Building A and C had flows of roughly 100 cfm at "low" speed and 200 cfm at "high" speed. Kitchen exhaust fans in Building B had a flow of roughly 50 cfm that did not change between "low" and "high". The design flow rate of kitchen fans in Building B was 125 cfm, which suggests that the kitchen exhaust fan ducting may have been too restrictive. One fan in Building A and two fans in Building C were identified to be faulty, since they were outlier values, with very low flows.

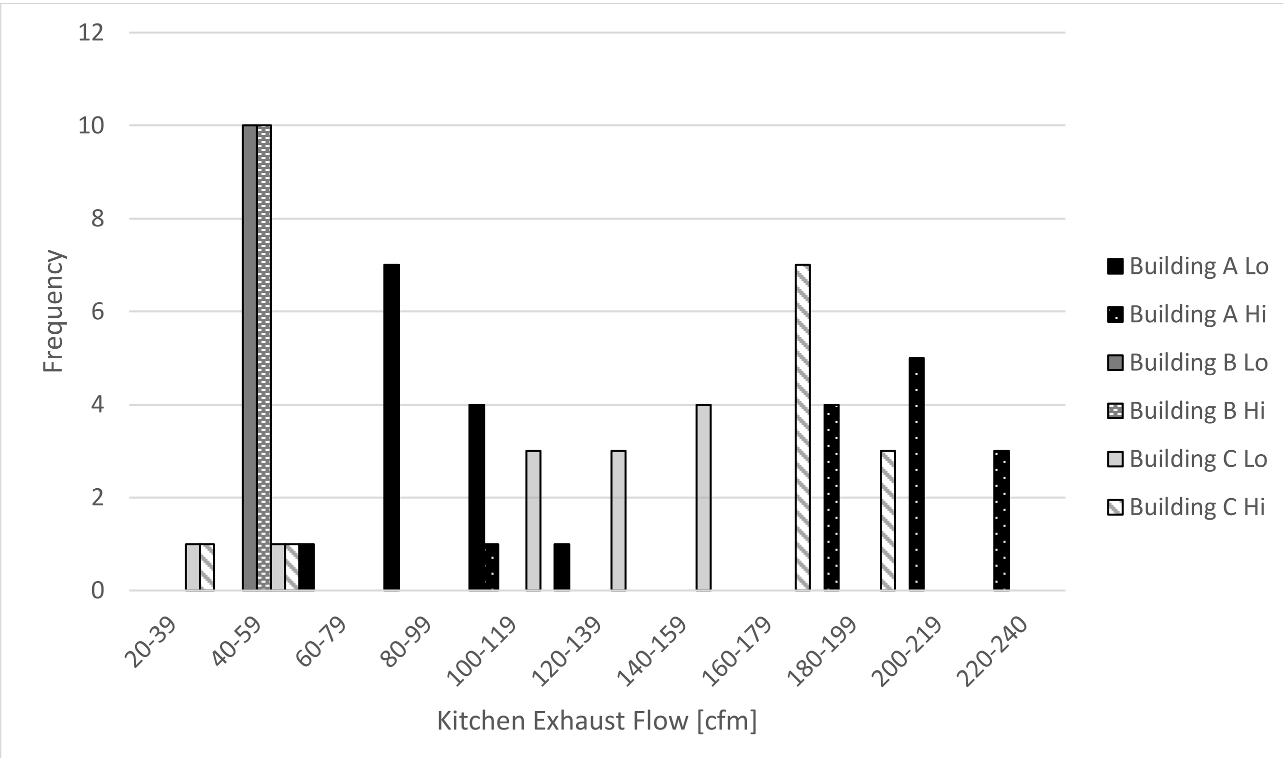


Figure 3.1.5 Kitchen exhaust flow distribution for each building with the fan speed indicated by "H" high or "L" low.

3.1.3 Inter-Unit Leakage

Inter-unit leakage results varied between buildings as a result of different designs producing different leakage pathways. Each adjoining surface between units was responsible for about 10-20% of total unit leakage. However, this value was highly dependent on construction practices, ducts and plumbing, and unit geometry (ratio of floor/wall area to total surface area).

In Building A, inter-unit leakage did not change significantly among the units selected for further testing (see Table 3.1.5). Total unit leakage was only slightly higher for the "unsealed" unit compared to the "sealed" units. Unit 609 was tighter than the other "unsealed" units because it was on the top floor and the roof minimized leakage through the ceiling. These total leakage levels were not far enough apart to observe a trend in inter-unit leakage. Side-to-side leakage was between 8-17% of total leakage for each wall. The one above-below guarded leakage test found that 7% of total leakage was across a vertical surface. When normalized by surface area, floor/ceiling leakage was only about 15% of wall leakage and the area-normalized value for corridor/outside leakage was roughly double that or wall leakage.

Table 3.1.5 Inter-unit Leakage Results in Building A as Both Direct cfm Measurements and a Percentage of Total Leakage

Building A	Total Unit Leakage	Inter-unit Leakage							
		Q_Left		Q_Right		Q_Down		Q_Up	
[unit]	[cfm_{50}/ft^2]	[cfm]	[%]	[cfm]	[%]	[cfm]	[%]	[cfm]	[%]
409 (Sealed)	0.13	42	12%	46	14%	NA	NA	NA	NA
509 (Partially Sealed)	0.15	40	10%	32	8%	NA	NA	NA	NA
609(Unsealed)	0.16	49	13%	66	17%	26	7%	NA	NA

In Building B, a higher fraction of inter-unit leakage was found through floors/ceilings than between side-by-side common walls. Total unit leakage was slightly higher for the "unsealed" unit compared to the "sealed" units (see Table 3.1.6). Surprisingly, virtually no air was measured to transfer between units horizontally. This is probably a consequence of modular construction which uses a double-wall between units. It is likely that air still leaks through the first wall but then travels elsewhere instead of leaking through the second wall into the neighboring unit. Vertical leakage was similar to that measured for Building A as both a percentage of total leakage (7-11%) and when normalized by surface area.

Table 3.1.6 Inter-unit Leakage Results in Building B as Both Direct cfm Measurements and a Percentage of Total Unit Leakage

Building B	Total Unit Leakage	Inter-unit Leakage							
		Q_Left		Q_Right		Q_Down		Q_Up	
[unit]	[cfm_{50}/ft^2]	[cfm]	[%]	[cfm]	[%]	[cfm]	[%]	[cfm]	[%]
305(Sealed)	0.13	5	2%	4	1%	NA	NA	NA	NA
405(Partially Sealed)	0.13	0	0%	0	0%	21	7%	22	7%
505(Unsealed)	0.16	9	2%	2	0%	NA	NA	44	11%

In Building C, inter-unit leakage was found to be significant. Leakage through a single shared wall was measured to be between 12-20% of the total leakage (see Table 3.1.7). Only side-to-side measurements were taken in this building. While these measurements suggest that more than 50% of air leakage is between units (assuming vertical leakage is similar to Building A and B at around 7-11%), actual air flow between units during normal operation is likely much less than would be predicted from these leakage measurements, due to the fact that the PTHPs (which are effectively large holes in the exterior envelope) were sealed during leakage testing.

Table 3.1.7 Inter-unit Leakage Results in Building C Both as Direct cfm Measurements and a Percentage of Total Unit Leakage

Building C	Total Unit Leakage	Inter-unit Leakage			
		Q_Left		Q_Right	
[unit]	[cfm_{50}/ft^2]	[cfm]	[%]	[cfm]	[%]
231	0.17	42	17%	NA	NA
234	0.17	42	16%	NA	NA
531	0.18	53	20%	NA	NA
532	0.17	NA	NA	31	12%
631	0.15	34	15%	NA	NA
634	0.19	37	18%	NA	NA

3.1.4 Unit Air Changes

Tracer gas tests were conducted for 2-3 units in Buildings A and C. These test results were compared with mechanical ventilation rates previously measured during mechanical ventilation flow testing. The tracer gas decay was used to calculate the total air change rate (and therefore total air flow) from which the mechanical ventilation rate could be subtracted to calculate the natural ventilation rate (infiltration rate plus flow from other units). The total ventilation rate should always be greater than the measured mechanical ventilation rate, as it is the sum of mechanical ventilation and natural ventilation:

(20)
$$\boldsymbol{n} = \boldsymbol{n_{mech}} + \boldsymbol{n_{nat}}$$

$$where\ n = total\ air\ changes\ per\ hour\ [/hr],$$

$$n_{mech} = mechanical\ air\ changes\ per\ hour\ [/hr],$$

$$n_{nat} = natural\ air\ changes\ per\ hour\ [/hr]$$

In Building A, the total air change rate increased as the total unit leakage increased (see Table 3.1.8). Turning on kitchen exhaust fans in adjacent units was observed to further increase air change rates, having a greater impact on the leakier units. The natural ventilation rate could not be calculated for this building, as the total air change rate was less than the measured mechanical ventilation air change rate. Possible explanations for this unexpected result include (1) that the CO_2 may not have been thoroughly mixed throughout the source unit, (2) possible CO_2 contamination from the hallway, and (3) possible leakage within the HRVs.

Table 3.1.8 Tracer Gas Results Showing Total ACH in Building A Units when Adjacent Kitchen Exhaust Fans are On and Off

Building A	Total Unit Leakage [cfm_{50}/ft^2]	Total ACH (adj fans off, h^{-1})	Total ACH (adj fans on, h^{-1})	Mechanical ACH (h^{-1})
409	0.13	0.49	0.49	0.74
509	0.15	0.54	0.60	0.74
609	0.16	0.60	0.71	0.68

The measured total air change rate was much higher in Building C than Building A (see Table 3.1.9). In Building C, the expected increase in natural air change rates with turning on fans in adjacent units is not consistent, potentially due to changes in weather conditions, although once again, the tighter units are less impacted by kitchen fan use in adjacent units (see Table 3.1.10). Complications potentially impacting the tracer gas decay in Building A were not an issue in Building C, because the units were small (basically one zone), had a simple exhaust system, and the corridor was depressurized relative to outside. Natural ventilation accounted for between 20-40% of total unit ventilation. It is suspected that this large variation is due to geometry and weather. Unit 534 is on the corner while 531 is sandwiched between two other units. The corner unit (534) has more exterior surface area and shows larger natural ventilation when adjacent exhaust fans are off. The interior unit (531) shows a stronger response to adjacent kitchen fan operation, likely because it experiences pressure differences on both sides and is leakier than 534. The decrease in natural ventilation for unit 534 when the adjacent unit fans are turned on is likely due to changing weather conditions between tests, such as changing wind direction or speed (the tests were performed on different days).

Table 3.1.9 Tracer Gas Results Showing Total ACH in Building C Units when Adjacent Kitchen Exhaust Fans are On and Off

Building C	Total Unit Leakage [cfm_{50}/ft^2]	Total ACH (adj fans off, h^{-1})	Total ACH (adj fans on, h^{-1})	Mechanical ACH (h^{-1})
531	0.18	2.54	3.12	1.93
534	0.12	3.12	2.93	2.29

Table 3.1.10 Tracer Gas Results Showing Natural ACH in Building C Units when Adjacent Kitchen Exhaust Fans are On and Off

Building C	Total Unit Leakage [cfm_{50}/ft^2]	Natural ACH (adj fans off, h^{-1})	Natural ACH (adj fans on, h^{-1})	Mechanical ACH (h^{-1})
531	0.18	0.61	1.19	1.93
534	0.12	0.83	0.64	2.29

Tracer gas results indicated that the air change rate increased more for leakier units than tighter units when adjacent kitchen exhaust fans were turned on. All the unit leakage levels in Building C were likely very similar when including the PTHP leakage. Yet, unit 531 had leakier walls than unit 534. As a result, further depressurizing the adjacent zones forced more infiltration into the "leaky" unit 531 than the "tight" unit 534. However, this theory cannot be conclusively backed up by field data, since the tests occurred on different days and may have experienced different weather conditions that could have impacted results.

3.1.5 Inter-Unit Gaseous Pollutant Transfer

Inter-unit pollutant transfer tests were conducted for 2-3 units in Buildings A and C. During the constant concentration generation period, the CO_2 concentration in adjacent units increased if the unit was receiving air from the source unit. The quantity of air flowing between units was a function of airtightness and pressure differences. Operation of kitchen exhaust fans induced pressure differences that drove detectable transfer of CO_2 between units (for example, see Figure 3.1.6). There was a time lag between the source and adjacent units. While the source unit responded almost immediately to the injection of CO_2, the adjacent unit was slower to respond to the high levels of CO_2 in the neighboring unit. This is because only a small fraction of air was transferred between units, causing the concentration in the adjacent unit to slowly increase (even continuing to increase after the CO_2 injection stopped, after approximately 2 hours). In tests where intermittent fans were off and pressure differences between units were nominally zero, there was no measurable transfer of CO_2 between units (see for example Figure 3.1.7). Figures for all of the other CO_2 tests are in Appendix A, Figures A3-A12. It should be noted that the data for all real time figures were smoothed.

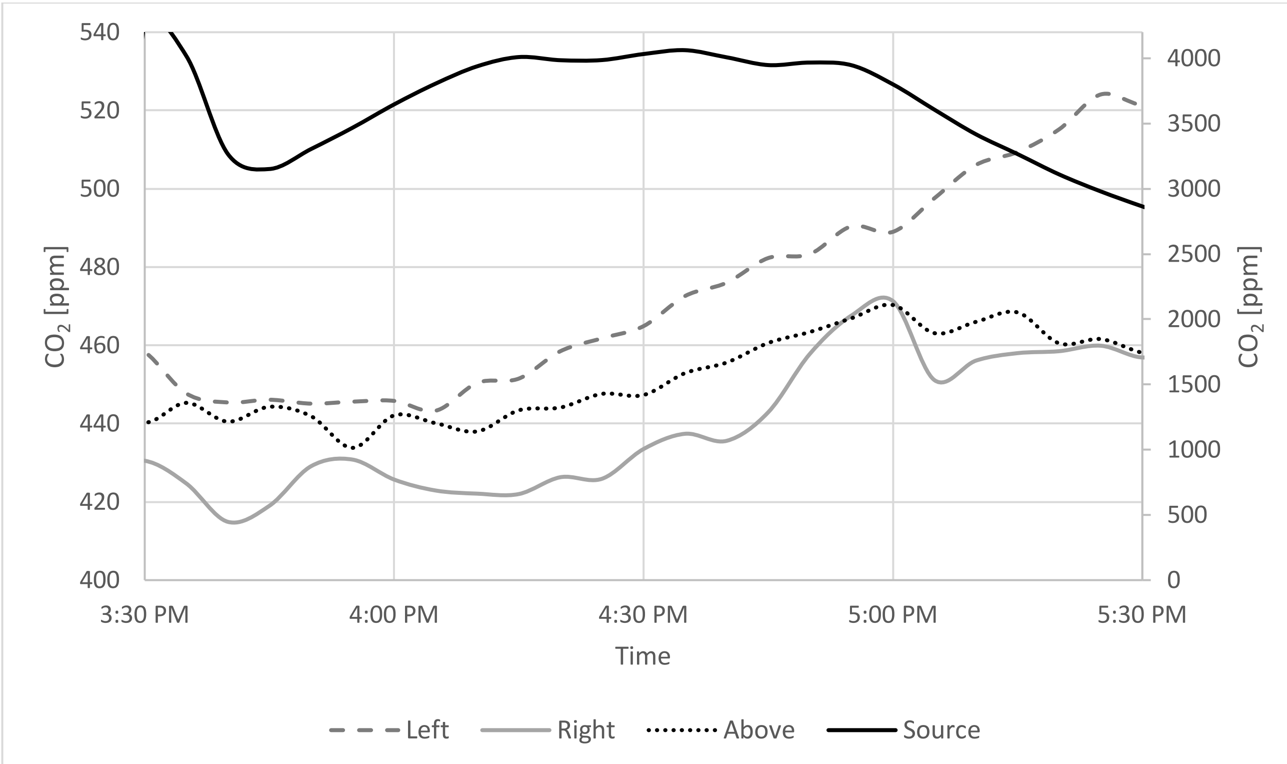


Figure 3.1.6 CO_2 concentrations in the source unit on the 4th floor in Building A and in adjacent units with kitchen exhaust fans on. (Source line is referenced to the right-side Y axis)

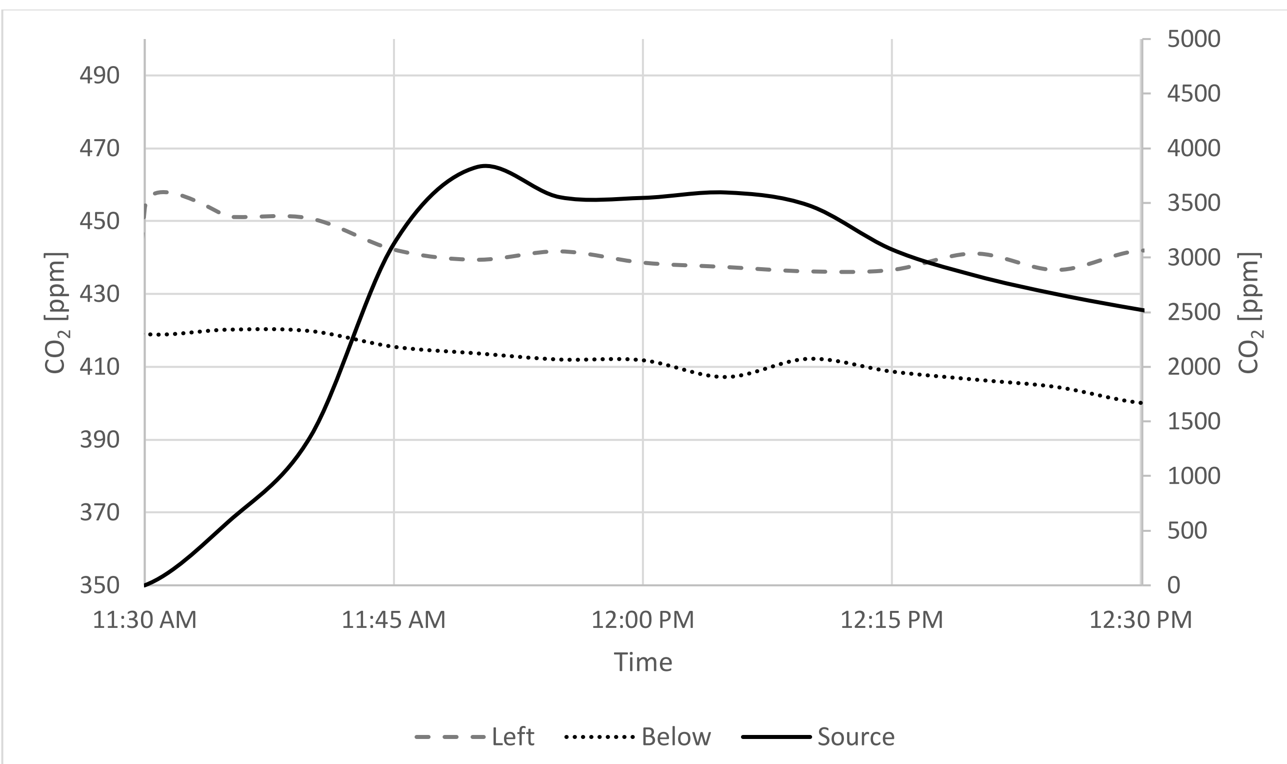


Figure 3.1.7 CO_2 concentrations in the source unit on the 6th floor in Building A and in adjacent units with kitchen exhaust fans off. (Source line is referenced to the right-side Y axis)

In Building A, measurements of inter-unit transfer of CO_2 only indicated a very small fraction of the receiving units' air flows coming from the source unit when the receiving units' intermittent (i.e., kitchen exhaust) fans were off (see Table 3.1.11). This is not surprising when you consider that inter-unit airflows are driven by pressure differences between units, which Table 3.1.11 shows to be rather small. These small pressure differences are not unexpected when only continuous ventilation systems are acting on units, leading to little or no CO_2 transfer between units. On the other hand, pressure differences of about 10 Pa were created by turning on kitchen exhaust fans in the receiving units (Table 3.1.12). This increased the amount of air moving between units, however failed to dramatically increase the concentrations in the receiving units, since increased airflow from the kitchen fan simultaneously increased outdoor air infiltration, thereby diluting concentrations in the receiving units (see Table 3.1.12).

Table 3.1.11. Pressure Differences and Inter-unit Air Transfer Flow Rates in Building A with Adjacent Kitchen Exhaust **Fans Off**

		Left Unit			Right Unit			Above/Below Unit		
Source unit	Total Unit Leakage [cfm_{50}/ft^2]	Pressure Difference [Pa]	Inter-unit Air Transfer [cfm]	[%]	Pressure Difference [Pa]	Inter-unit Air Transfer [cfm]	[%]	Pressure Difference [Pa]	Inter-unit Air Transfer [cfm]	[%]
409	0.13	-1	0	0%	0	0	0%	NA	0	0%
509	0.15	-3	3	3%	2	0	0%	NA	0	0%
609	0.16	-4	0	0%	3	1	2%	NA	0	0%

Table 3.1.12 Pressure Differences and Inter-unit Air Transfer Flow Rates in Building A with Adjacent Kitchen Exhaust **Fans On**

		Left Unit			Right Unit			Above/Below Unit		
Source unit	Total Unit Leakage [cfm_{50}/ft^2]	Pressure Difference [Pa]	Inter-unit Air Transfer [cfm]	[%]	Pressure Difference [Pa]	Inter-unit Air Transfer [cfm]	[%]	Pressure Difference [Pa]	Inter-unit Air Transfer [cfm]	[%]
409	0.13	-10	8	3%	-8	5	2%	NA	6	2%
509	0.15	-2	2	1%	-10	7	2%	NA	2	1%
609	0.16	-14	7	3%	NA*			NA	4	1%

*Unit 607, the unit on the right of Unit 609, had a Broken Kitchen Exhaust Fan so there is no data available.

In Building C, inter-unit transfer of CO_2 again only results in a small fraction of the receiving unit's air coming from the source unit. No transfer of CO_2 was measured in this building when adjacent kitchen exhaust fans were off (see Table 3.1.13). Between 1-4 cfm was calculated to transfer to adjacent units when kitchen exhaust fans were turned on in these units (see Table 3.1.14). Transfer was found to be greater horizontally than vertically. However, the total inter-unit flow as a percentage of a unit's total flow was never greater than 3%, consistent with results from Building A.

Table 3.1.13 Pressure Differences and Inter-unit Air Transfer Flow Rates in Building C with Adjacent Kitchen Exhaust **Fans Off**

		Left Unit			Right Unit			Above/Below Unit		
Source unit	Total Unit Leakage [cfm_{50}/ft^2]	Pressure Difference [Pa]	Inter-unit Air Transfer [cfm]	[%]	Pressure Difference [Pa]	Inter-unit Air Transfer [cfm]	[%]	Pressure Difference [Pa]	Inter-unit Air Transfer [cfm]	[%]
531	0.18	-5	0	0%	1	0	0%	NA	0	0%
534	0.12	0	0	0%	NA	0	0%	NA	0	0%

Table 3.1.14 Pressure Differences and Inter-unit Air Transfer Flow Rates in Building C with Adjacent Kitchen Exhaust **Fans On**

		Left Unit			Right Unit			Above/Below Unit		
Source unit	Total Unit Leakage [cfm_{50}/ft^2]	Pressure Difference [Pa]	Inter-unit Air Transfer [cfm]	[%]	Pressure Difference [Pa]	Inter-unit Air Transfer [cfm]	[%]	Pressure Difference [Pa]	Inter-unit Air Transfer [cfm]	[%]
531	0.18	-12	4	2%	-7	0	0%	NA	0	0%
534	0.12	-6	3	1%	NA	1	0%	NA	1	0%

Occasionally, only one neighboring unit would respond to CO_2 generation in the source unit (e.g., Figure 3.1.8, additional Figures A9-A12). In Building C, gaseous transfer occurred more prominently between units where the bathrooms were located on the adjoining walls, versus when the adjoining walls were between living rooms. One could speculate that air may be flowing through cracks around plumbing pipes or through common return ducts that serve both bathrooms (if the pressure difference between units was significant enough to cause some flow to occur between bathrooms rather than all moving up the return shaft).

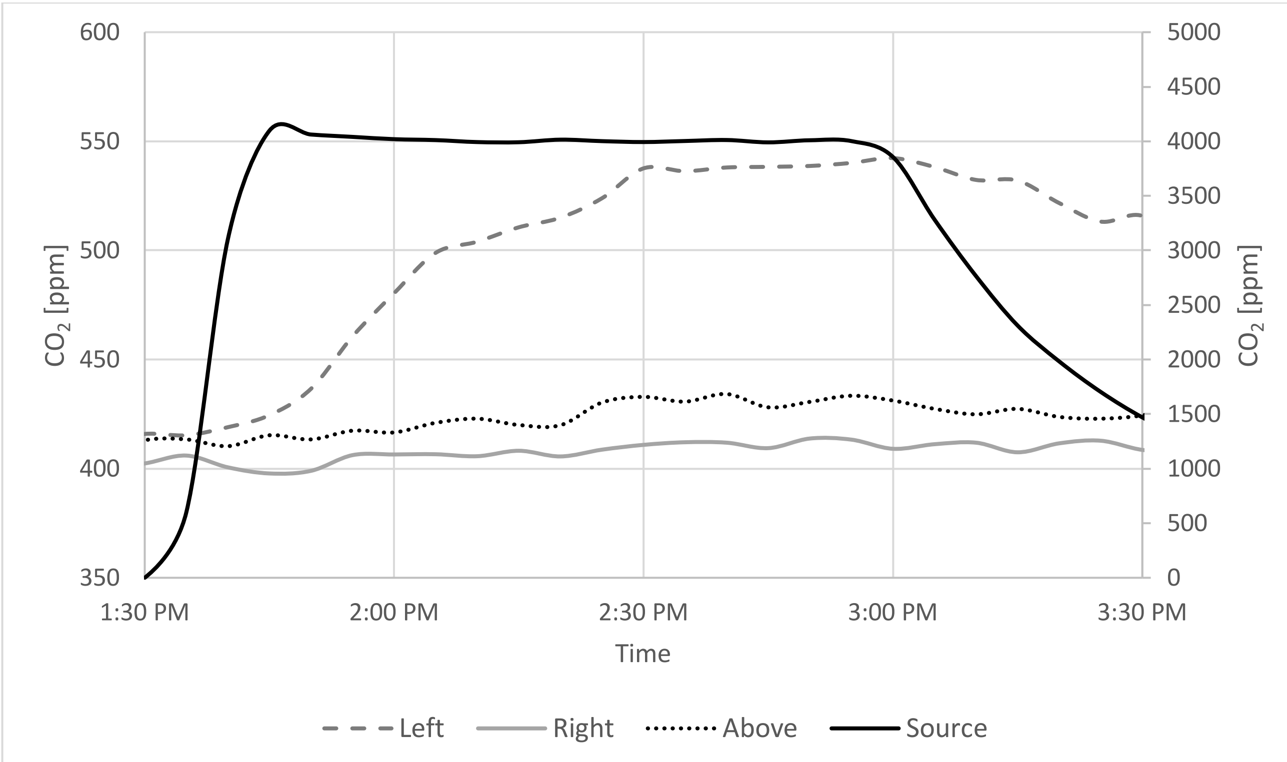


Figure 3.1.8 Tracer gas results showing response in adjacent units with kitchen exhaust fans on from CO_2 constant concentration in Building C. (Source line is referenced to the right-side Y axis)

Overall, in both buildings, the transfer of CO_2 (which is a surrogate for the transfer of gaseous pollutants) concentrations between units was modest at best. Minimal absolute transfer occurred under normal operating conditions where only continuous ventilation systems were running. The air flow rate between units was increased when adjacent kitchen exhaust fans were turned on, however greater dilution from increased outdoor-air ventilation negated most of the increase in inter-unit flow under that operation condition.

3.1.6 I/O Ratios

Indoor and outdoor concentrations were measured using real-time instruments, with concentrations recorded outside and at each indoor location every 2 minutes. The ten-minute moving average was then calculated at each location and the I/O ratio calculated every 2 minutes. The I/O ratio when there are no indoor sources is a measure of the impact of both PM infiltration and deposition. The indoor and outdoor data was visually inspected to determine the point in time the impact of any day-time sources had subsided, and for which there was a relatively constant outdoor concentration, and the average I/O ratio was calculated over this time period. In all but one case where the outdoor concentration dropped significantly in the middle of the night, and the indoor levels started to slowly decline, the whole night-time period was used. Figure 3.1.9 shows an example of the outdoor and indoor concentrations in multiple units during a night from Building A. In this example, indoor concentrations were measured in two unsealed units, which had the highest indoor concentrations, in the partially sealed unit, which had a slightly lower concentration, and in an unsealed unit with the HVAC fan running throughout the night, resulting in the lowest concentrations. It is anticipated that during the night while there are no sources in the units, concentrations would be lower in sealed than unsealed units because more of the particles would be removed from the air entering the unit.

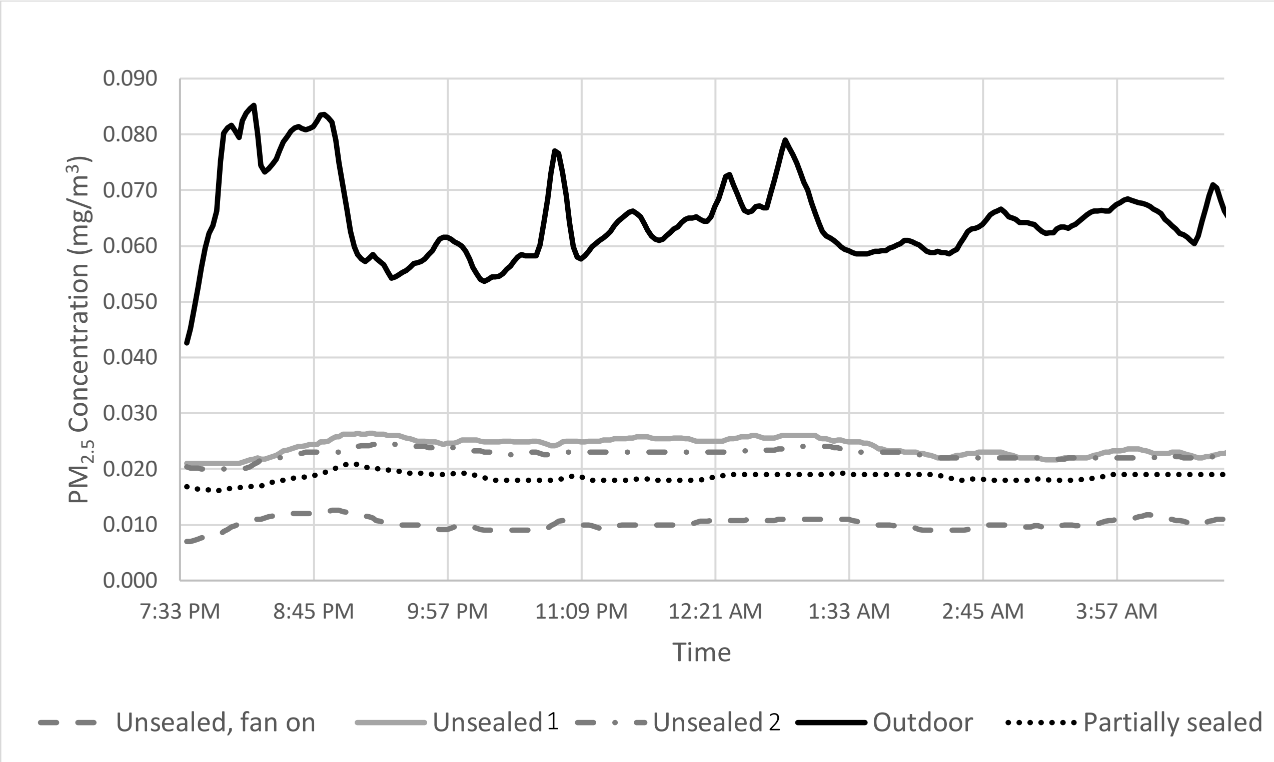


Figure 3.1.9 Overnight measurements of $PM_{2.5}$ concentration in four units at Building A and outdoors.

Overall, I/O testing was conducted for 5 overnight periods at Building A. Data for 3 of the nights is presented in Table 3.1.15. For the 2 nights not shown, the weather had intermittent periods of drizzle, and the outdoor concentrations were so low that reliable I/O concentrations could not be calculated. The HVAC fan was operated in one of the units, and for much of the night, the concentration recorded as 0, indicating that the HVAC filter was eliminating what little PM was in the air. Reviewing the results in Table 3.1.15, there is more variability in the I/O measurements between nights than between the unsealed units on any given night. There are consistently lower values for the partially sealed and sealed values than for the unsealed units as well.

Table 3.1.15 I/O Ratios of $PM_{2.5}$ at Building A. Up to three unsealed units were tested each night.

	Night 1	Night 2	Night 3
Unsealed	0.43	0.53	0.37
Unsealed	0.37	0.52	0.35
Unsealed , fan on			0.17
Partial Seal	0.35	0.48	0.29
Sealed		0.45	

Only one night of data was collected at Building C as the research staff only had access to the building for two days. The graph of the outdoor concentrations and indoor concentrations in four units is in Figure 3.1.10, with the average values in Table 3.1.16. As is visually apparent, the indoor concentrations quickly respond to changes in the outdoor concentrations. This building had a significant amount of air being brought in from the outdoor with limited filtration for the PTHP. The I/O Ratio values were much higher at Building C than at Building A.

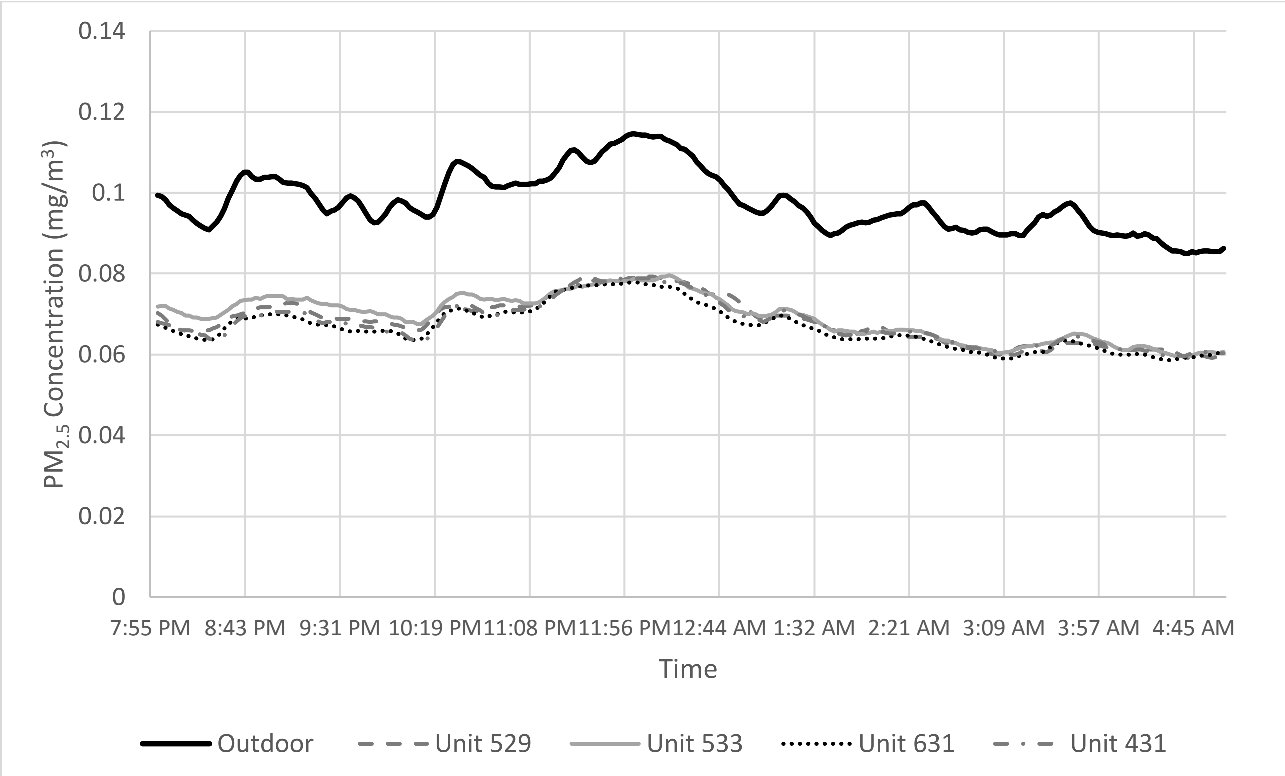


Figure 3.1.10 Overnight Measurements of $PM_{2.5}$ concentrations in four units at Building C and outdoors

Table 3.1.16 I/O Ratios of $PM_{2.5}$ at Building C

	Night 1
Unit 529	0.70
Unit 533	0.71
Unit 631	0.68
Unit 431	0.69

3.1.7 PM Transfer

For Building A, tests were done for units of all sealing levels with the kitchen fans in the receiving units either on or off, and in some cases, repeat testing under the same conditions were conducted. Figure 3.1.11 displays results for the source being in the sealed units, with the kitchen fans on in the adjacent units. The black solid line presents the concentration in the source unit, with the scale on the right axis. There had been some activity in the unit above prior to the test, apparent from the black dotted line decreasing prior to the test. One can also see a slight increase in the adjacent unit, the gray dashed line, when field staff entered the unit to turn the kitchen fan on. Looking at the lines after the source started, it is apparent that there was no increase in the concentrations in the receiving unit, a clear indication there was no transfer of particles through the walls. Results were similar for testing on the 4th floor with the fans off (Appendix A, Figure A13). The indoor concentrations appear to mirror the outdoor concentrations, without a signal from the source unit.

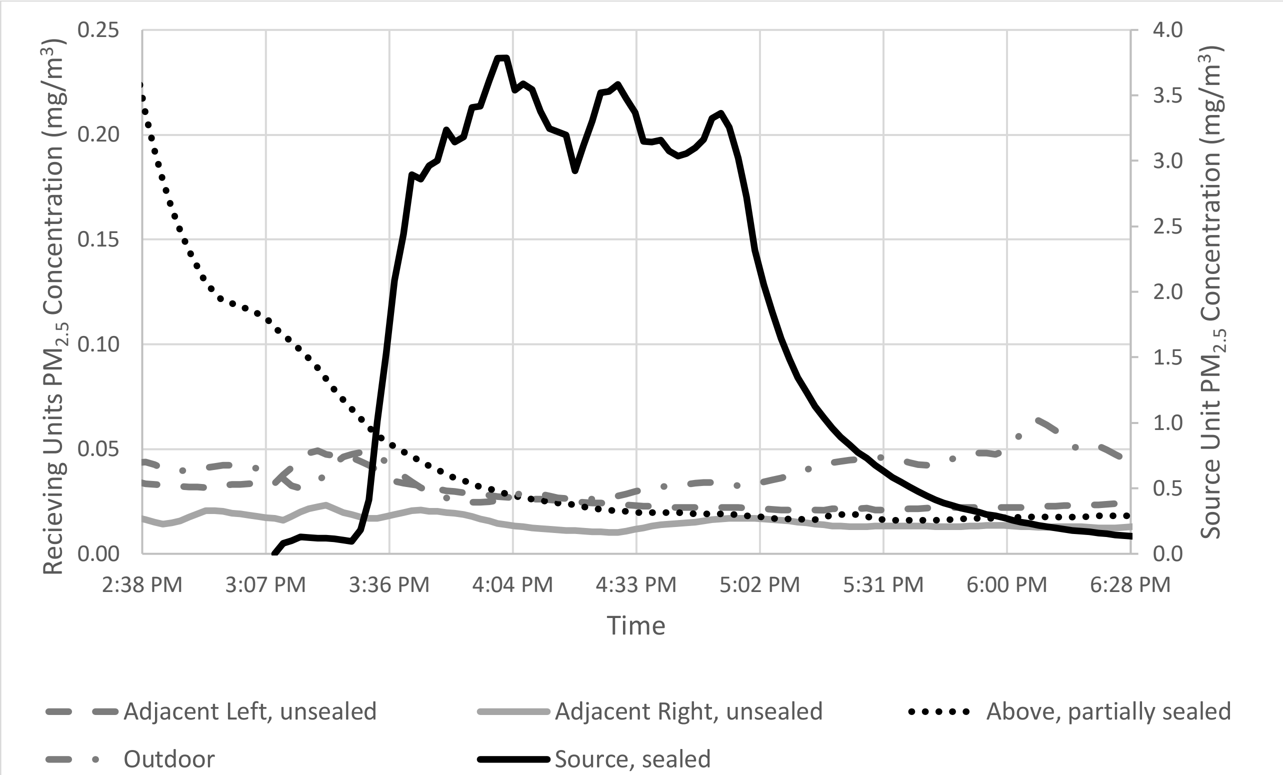


Figure 3.1.11 Inter-unit PM2.5 transfer test with the source unit on the 4th floor at Building A and kitchen fans on in adjacent units**.** (Source line is referenced to the right-side Y axis)

Testing was also done in the partially sealed unit with the kitchen fan on in the receiving units and the results were more difficult to interpret (Figure 3.1.12). There was a clear increase of the concentration in the adjacent units during the time of the source emission. However, upon closer examination, the concentrations actually started to increase before the source was released in response to an increase in the outdoor concentration, and continued to increase after the source ends. The unit adjacent to the right (grey) most clearly reflects the signal from the outdoors. This test was done twice, and the other time there was no indication of increased concentrations in the receiving units (Appendix A, Figure A14). The test results with the kitchen fan off in the receiving unit had no indication of an increase in concentration in the receiving units (Appendix A, Figure A15).

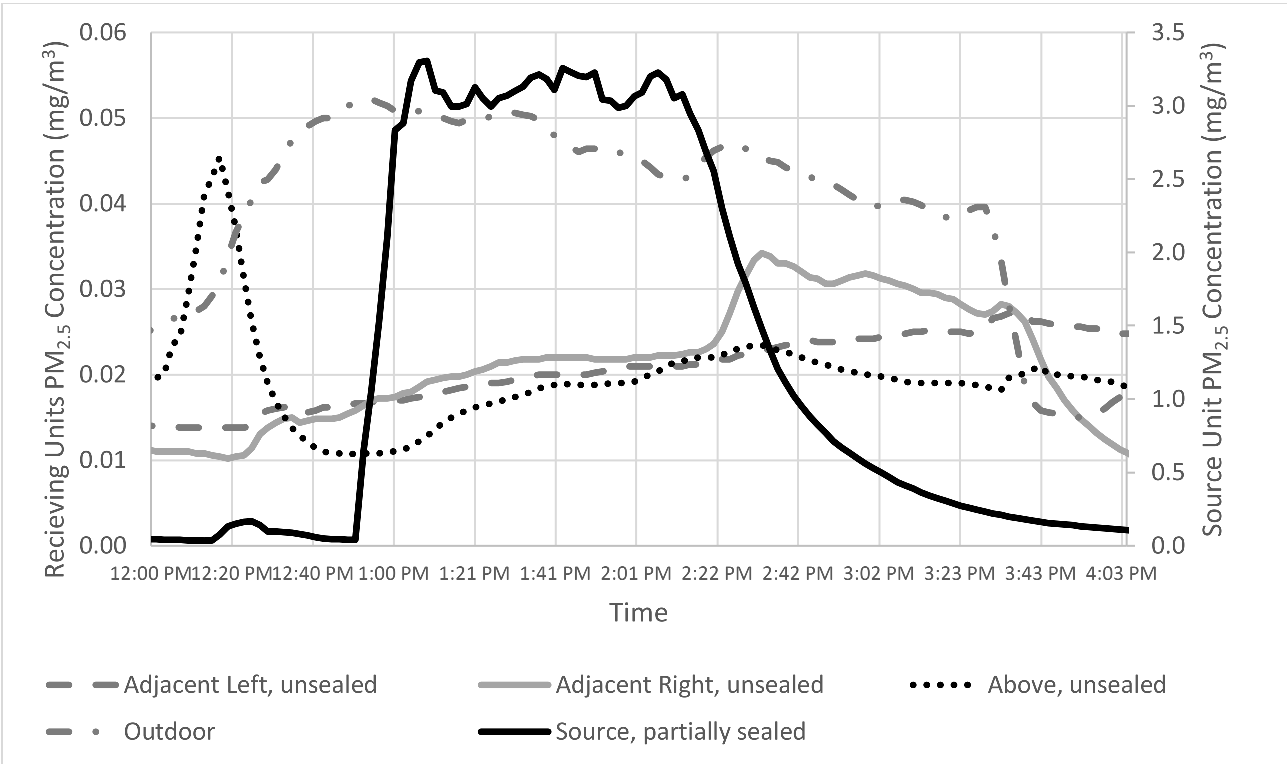


Figure 3.1.12 Inter-unit PM2.5 transfer test with the source unit on the 5th floor at Building A and kitchen fans on in adjacent units. (Source line is referenced to the right-side Y axis)

Next, tests were conducted in the unsealed unit, with the kitchen fans on in the receiving units. In the first test, an attempt was made to raise the source level higher than previous attempts in order to hopefully have some response in the receiving units. This was a poor decision, as the smoke detectors were activated in the source unit. The door to the hallway was immediately opened to turn the smoke alarms off. Interestingly, the research staff did not see anything in the receiving units while the doors were closed, but once the doors to the hallway were opened, there was a clear increase in both the adjacent units, indicating the PM transferred through hallway (Figure 3.1.13). The research staff repeated this test after levels subsided from the fire alarm incident and saw no sign of transfer (Appendix A, Figure A16). The test was also conducted with the fans off (Appendix A, Figure A17). There was an increase and subsequent decrease in the middle of the testing period. This increase in the middle of the sampling period would not be reflective of a steady transfer from the other unit as can be seen for the CO_2, but rather there was likely some sort of disturbance, such as a workman that entered the room.

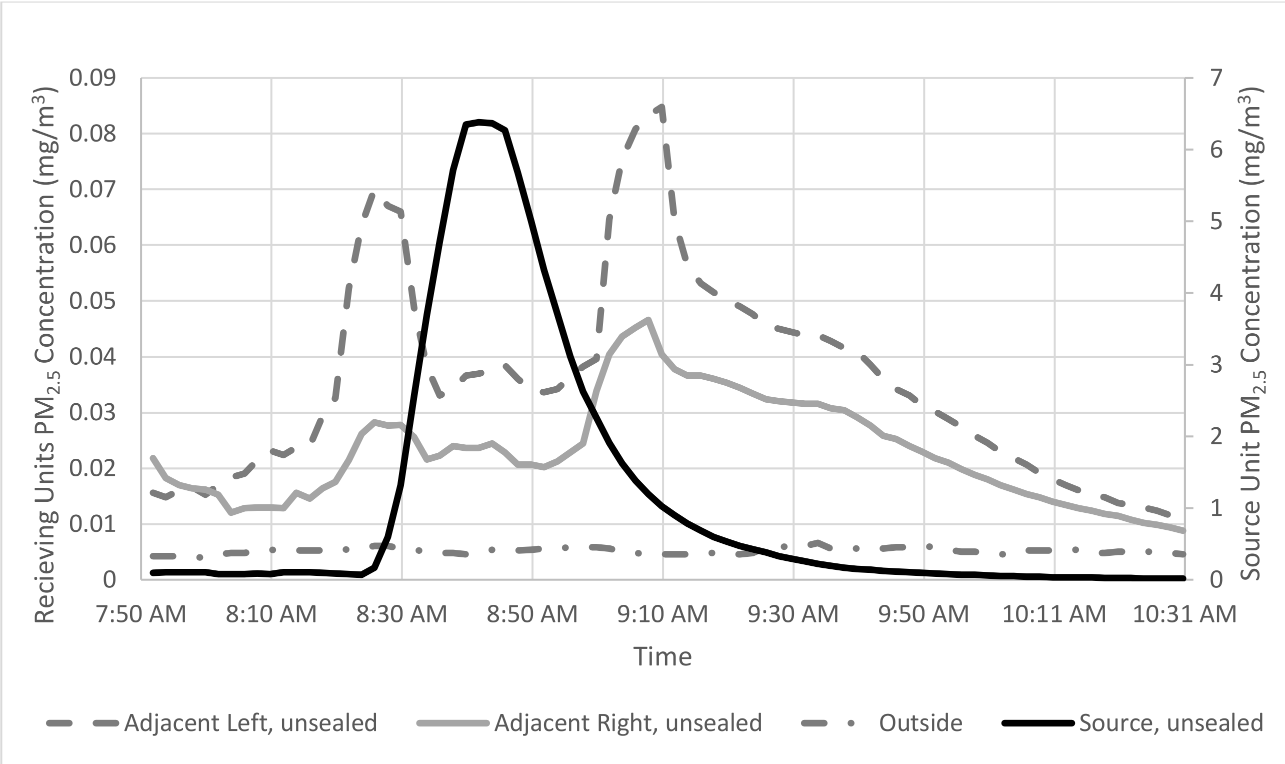


Figure 3.1.13 Inter-unit PM2.5 transfer test with the source unit on the 6th floor at Building A, kitchen fans on in adjacent units, and the source unit door opened at approximately 8:45am. (Source line is referenced to the right-side Y axis)

Tests were also conducted at Building C, with the goal to conduct testing in a unit that had significant natural leakage as well as one that did not have significant natural leakage, both with and without kitchen fans on in the adjacent units. Recalling from the I/O Ratio results that the indoor concentrations rapidly responded to outdoor concentrations. This same phenomenon is observed in the test results for the PM transfer results. For example, in Figure 3.1.14, showing the test results from the leakier unit with fans on, the concentrations do go up; however, they mirror the outdoor concentrations, and thus it was concluded there is no actual transfer of PM. Figure 3.1.15 displays the results for the same unit, but with fans off, and again, the indoor concentrations mirror the outdoor concentrations. Tests were also conducted on a unit that had a lower leakage level, and the results again showed no indication of transfer between the units (Appendix A, Figures A18-A19).

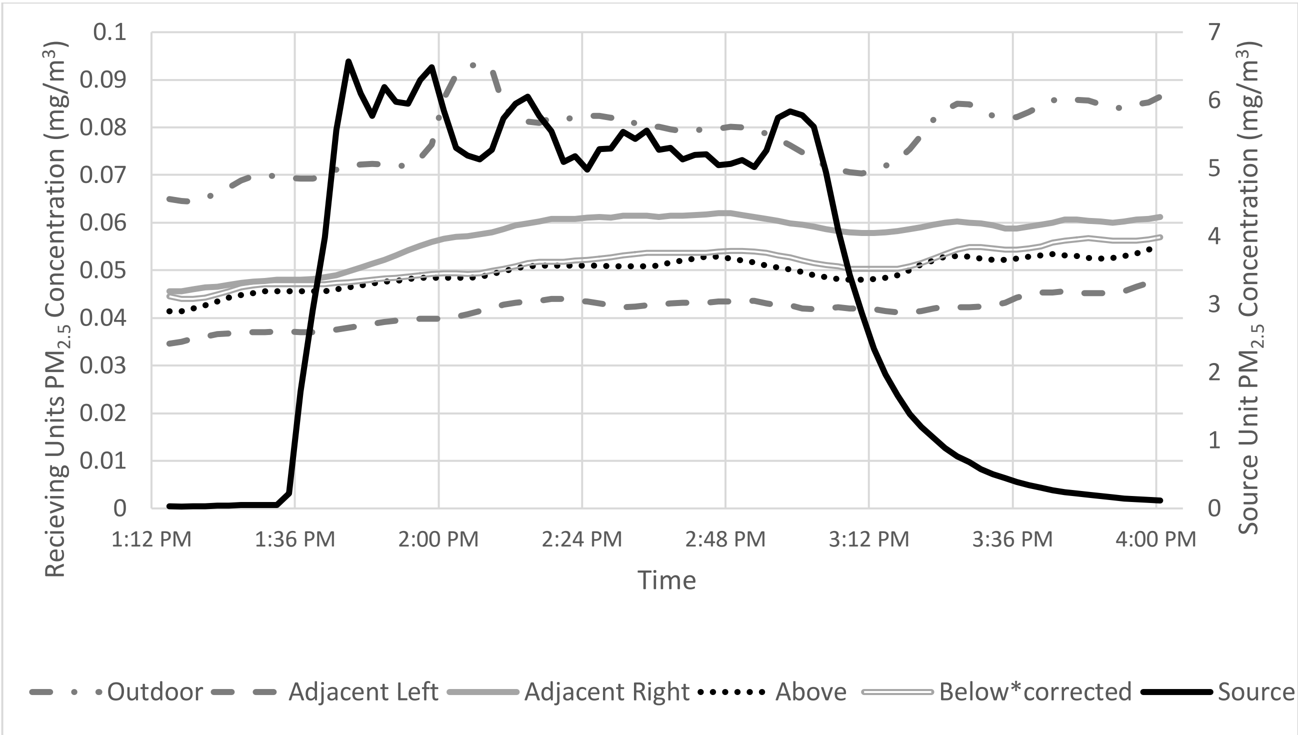


Figure 3.1.14 Inter-unit PM2.5 transfer test with the source unit (Unit 531, a looser unit) on the 5th floor at Building C and kitchen fans on in adjacent units. (Source line is referenced to the right-side Y axis). *Based on colocation results just prior to the test, the data in the unit below was corrected to align with other samplers.

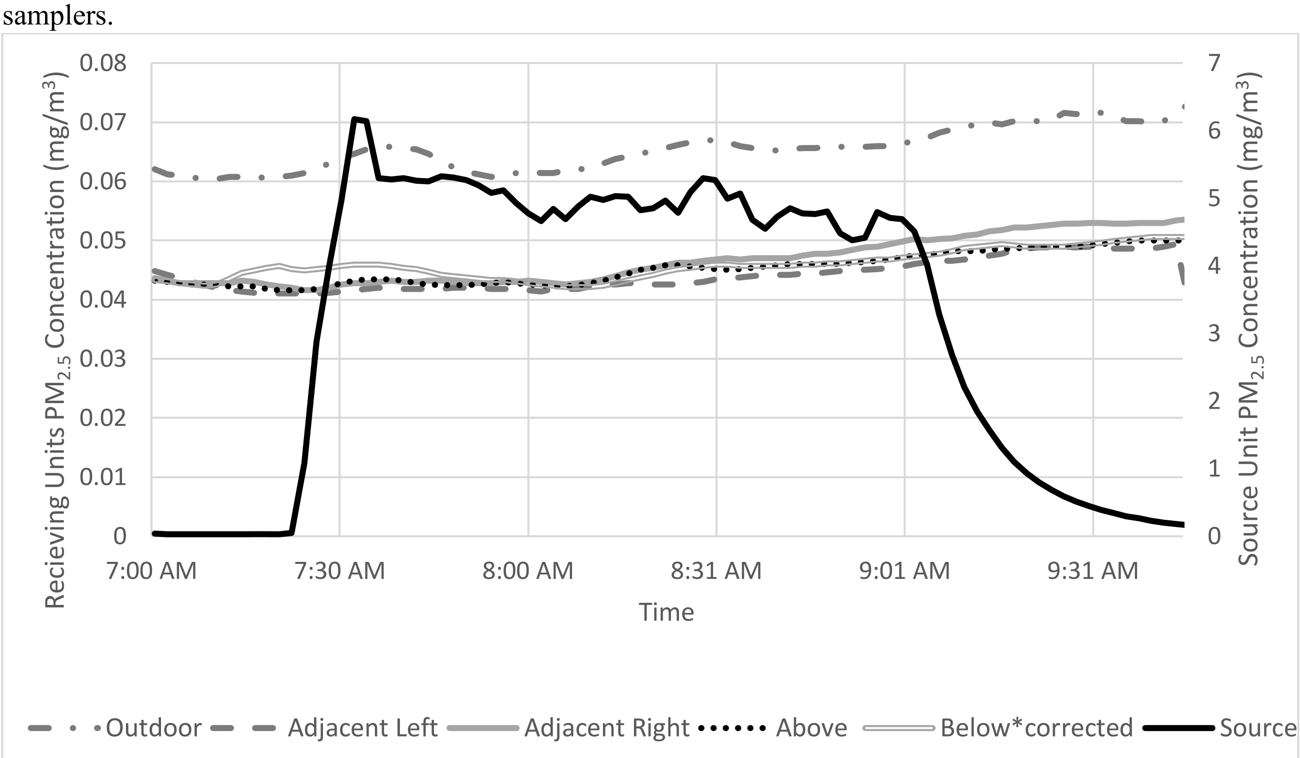


Figure 3.1.15 Inter-unit PM2.5 transfer test with the source unit (Unit 531, a looser unit) on the 5th floor at Building C and kitchen fans off in adjacent units. (Source line is referenced to the right-side Y axis). *Based on colocation results just prior to the test, the data in the unit below was corrected to align with other samplers.

The original data analysis plan was to utilize the particle decay rates when determining the transfer of $PM_{2.5}$ to the other units. They were calculated and are in Appendix A, Figure A32 and Table A1. However, as there was no discernable increase in PM values, the PM decay rates were not needed and PM2.5 transfer between units was not modeled in this study. Concentration profiles for PM_1 likewise show no apparent transfer, and all PM_1 results are in Appendix A, Figure A20 – A31. PM equipment was co-located for a certain period for comparison purposes, the results of which are in Appendix A.

3.2 Modeling Results

Modeling was used to simulate IAQ, energy usage, and GHG emissions in multifamily buildings with different leakage levels and ventilation strategies for different climate zones in California. The parameters analyzed were unit air changes, unit ventilation flows, source of air entering units, gaseous pollutant exposure (from both generation within the same unit and inter-unit transfer), energy savings/penalties related to space conditioning and fan energy, and GHG emissions. The modeling analysis focused on understanding how different combinations of unit leakage levels and ventilation strategies impact IAQ and energy usage, and how climate zones affect these metrics. The baseline model used for most of the results below was a balanced building at 0.15 cfm_{50}/ft^2 total leakage in Sacramento, although the energy savings and GHG impacts are relative to a balanced building in each climate zone at 0.45 cfm_{50}/ft^2 total leakage. Results are generally presented in relation to the "base case" (i.e., one factor is varied while the other factors in the base case are held constant).

3.2.1 CONTAM Airflow Analysis

3.2.1.1 Unit Air Change Rate

As expected, unit air change rates increased as unit leakage increased (see Figure 3.2.1). Box and whiskers plots were generated using data from all 55 units in the building. The box shows the middle 50% of data and the whiskers bound the 5th through 95th percentiles. As expected, leakier buildings allowed more air to infiltrate and exfiltrate through the building shell, leading to higher ACH levels for leakier buildings. Compared to a leakage level of 0.15 cfm_{50}/ft^2, the average ACH increased by 5-15% for a leakage level of 0.3 cfm_{50}/ft^2 and by 15-30% for a leakage level of 0.45 cfm_{50}/ft^2, depending on the ventilation strategy and climate zone. Natural infiltration was greater in the simulations for balanced buildings than exhaust- or supply-only buildings. This is because the exhaust- and supply-only buildings are approximately 10 Pa positively or negatively pressurized relative to the outdoors, while the balanced building is at a neutral pressure. When the building envelope experiences static pressure (e.g., wind), the extra air infiltration that occurs with a pressure change from 0 to 5 Pa (balanced building with a static pressure of 5 Pa on a wall) is greater than the extra air infiltrations that occurs when going from 10 to 15 Pa (exhaust- or supply-only building with the same static pressure of 5 Pa on a wall) due to the nonlinearity of the pressure/flow relationship.

Furthermore, buildings in temperate climates with less wind and smaller indoor-outdoor temperature differences (e.g., Los Angeles) had less natural infiltration due to smaller pressures created by stack effect and wind. This came be seen by comparing Figure 3.2.1 (Sacramento) with Figure 3.2.2 (Los Angeles). The impact of increasing leakage is much more pronounced in Sacramento, where going from 0.15 cfm_{50}/ft^2 to 0.45 cfm_{50}/ft^2 increases the average ventilation rate by 36%, versus only a 24% increase for the same modification in Los Angeles.

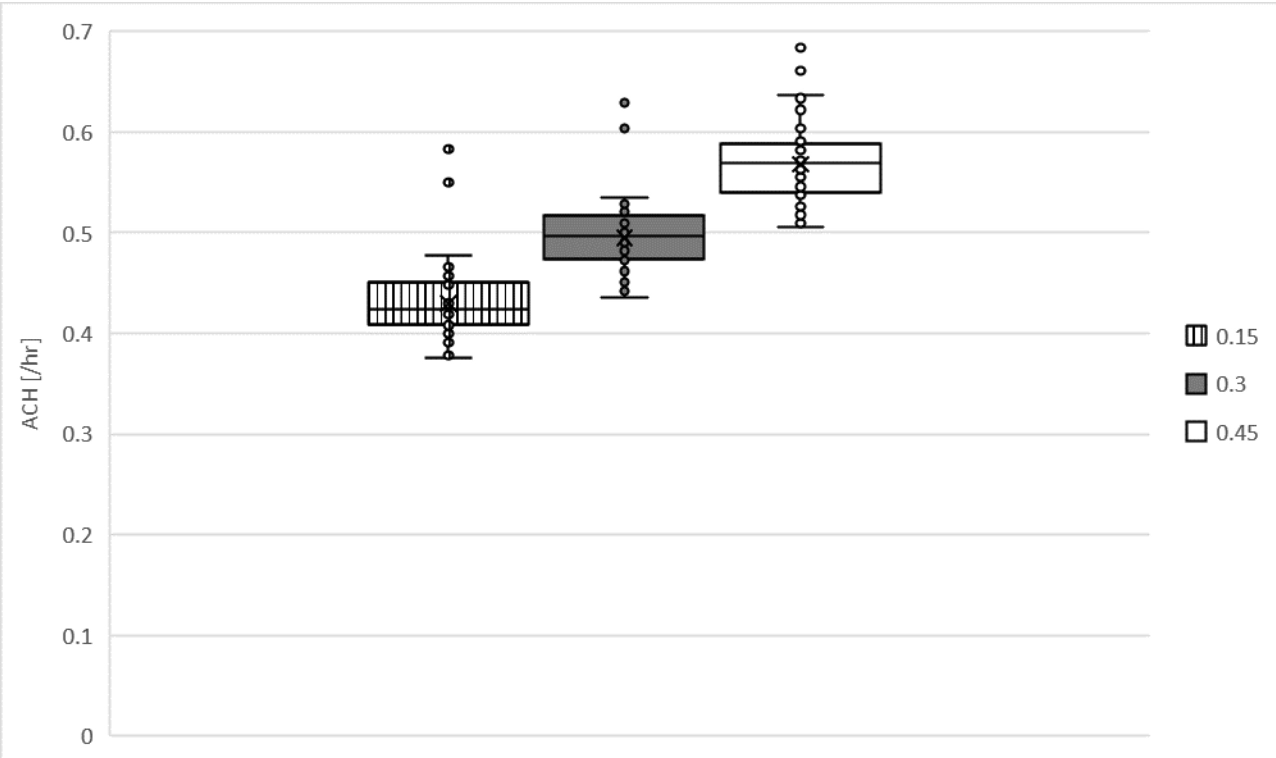


Figure 3.2.1 Overall ACH for 55 modeled units at three different leakage levels: 0.15 cfm_{50}/ft^2, 0.3 cfm_{50}/ft^2, and 0.45 cfm_{50}/ft^2 for a balanced building using Sacramento weather data.

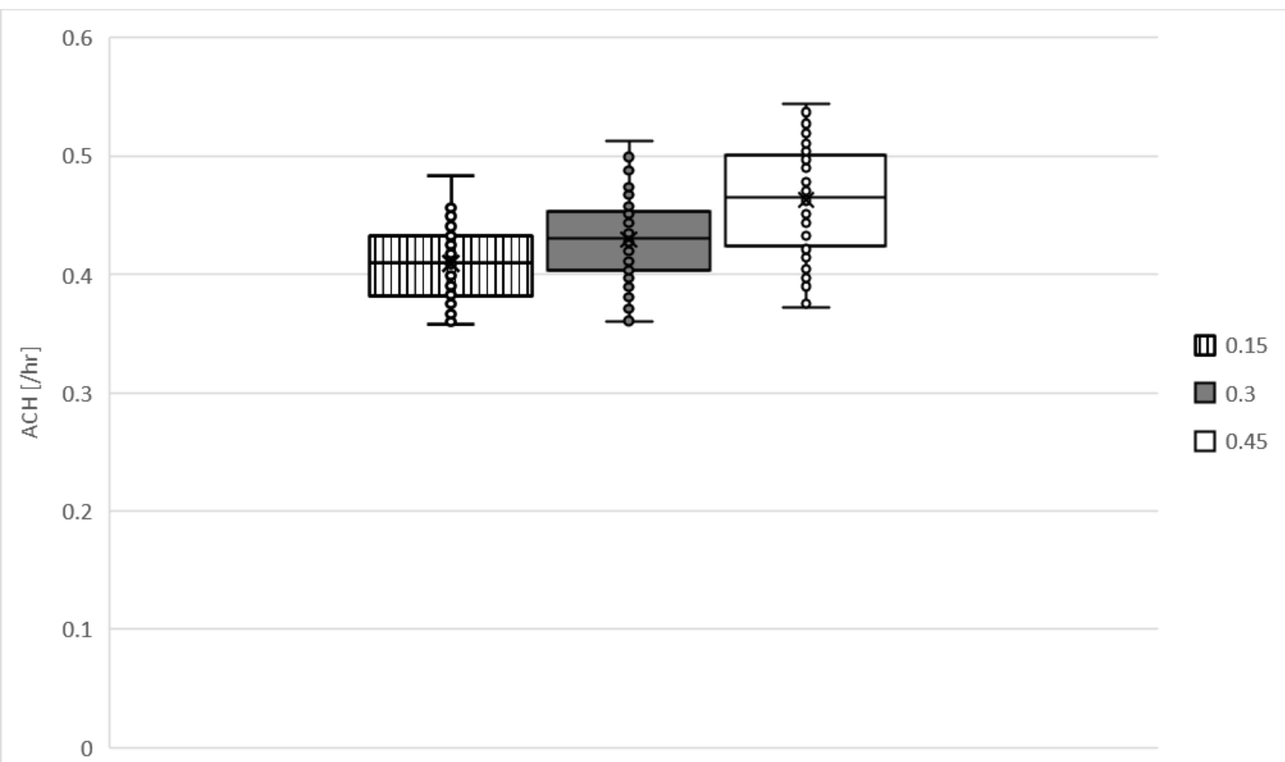


Figure 3.2.2 Overall ACH for 55 modeled units at three different leakage levels: 0.15 cfm_{50}/ft^2, 0.3 cfm_{50}/ft^2, and 0.45 cfm_{50}/ft^2 for a balanced building using Los Angeles weather data.

At the whole-building level, although the unit mechanical ventilation rates were identical among simulations (regardless of ventilation strategy), the common corridor was supplied with air in all simulations. Thus, in the exhaust-only building, corridor supply air was drawn into units, decreasing the total amount of makeup air to the units from outdoors. Therefore, the exhaust-only building had a building air change rate about 25% less than in the supply and balanced buildings due to some ventilation air to the units coming from the corridor. In other words, the total air exchange of the building goes down when the supply air for the corridor is being used for the ventilation requirement of exhaust-only units, whereas the corridor supply air flow is added on top of the unit supply air for the supply and balanced buildings. These results are consistent with the total corridor ventilation flow being 25% of total unit ventilation flow.

At the individual unit level, the same trend was found in overall unit air change rates, which were greater in balanced and supply buildings than exhaust-only buildings (see Figure 3.2.3). To understand this better, it needs to be realized that the corridors were pressurized by their supply-only ventilation for all three unit-ventilation strategies. Because the corridors were rather tight, the pressurization is enough to push air into the units for all unit ventilation strategies. However, for unit-exhaust ventilation this flow does not change the unit air exchange rate, whereas it is an additional flow for the other two types of unit ventilation.

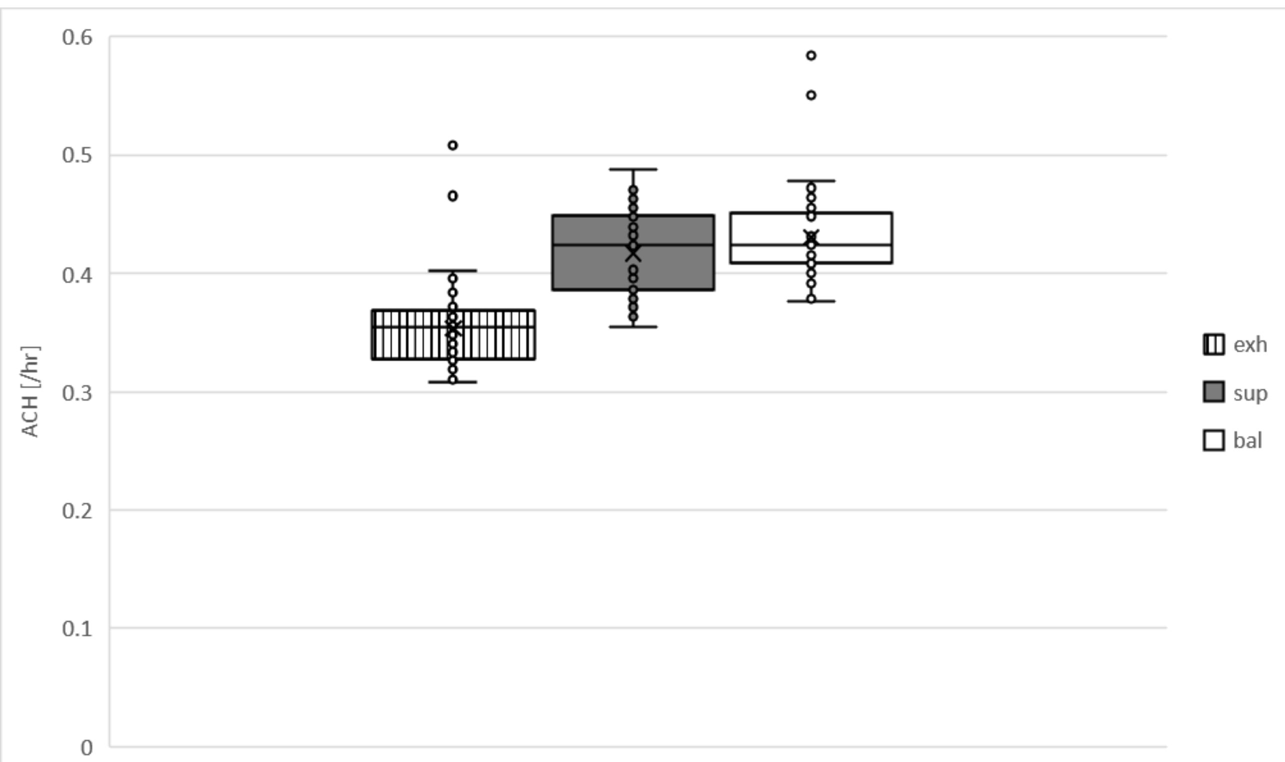


Figure 3.2.3 Overall ACH for 55 modeled units with three different ventilation systems: exhaust-only, supply-only, and balanced for a building at 0.15 cfm_{50}/ft^2 using Sacramento weather data.

Unit air change rates for the base-case building configuration were slightly impacted by climate zone (see Figure 3.2.4). Weather conditions cause wind and stack effect to drive infiltration and exfiltration in buildings. The climates in Sacramento and San Francisco resulted in slightly more infiltration than the climates in Los Angeles and Fresno.

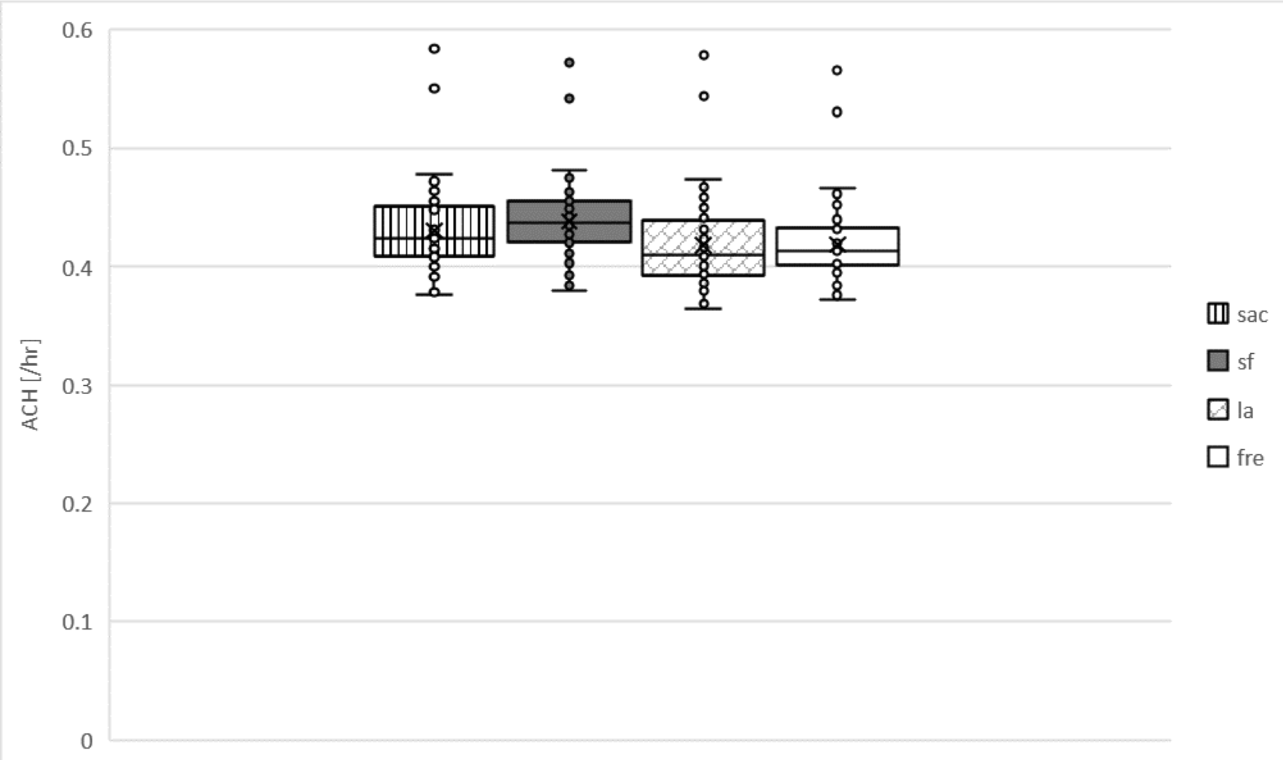


Figure 3.2.4 ACH for 55 modeled units in four different climate zones: Sacramento, San Francisco, Los Angeles, and Fresno for a building at 0.15 cfm_{50}/ft^2 with balanced ventilation.

3.2.1.2 Unit Ventilation Flow Rate

The unit ventilation flow rate similarly increased as unit leakage increased (see Figure 3.2.5). The ventilation flow rate was defined as outdoor air coming directly into the unit either from the mechanical supply system or infiltration from outdoors. Ventilation rate differs from overall air change rate in that it does not include flows from the hallway or neighboring units. The ventilation flow rate increased by 1-10% when moving from 0.15 cfm_{50}/ft^2 to 0.3 cfm_{50}/ft^2, and by 5-20% when moving from 0.15 cfm_{50}/ft^2 to 0.45 cfm_{50}/ft^2. These increases are slightly less than the increases in overall ACH, since air that is passed between units could be contaminated, and therefore was not counted towards fresh, outdoor ventilation air.

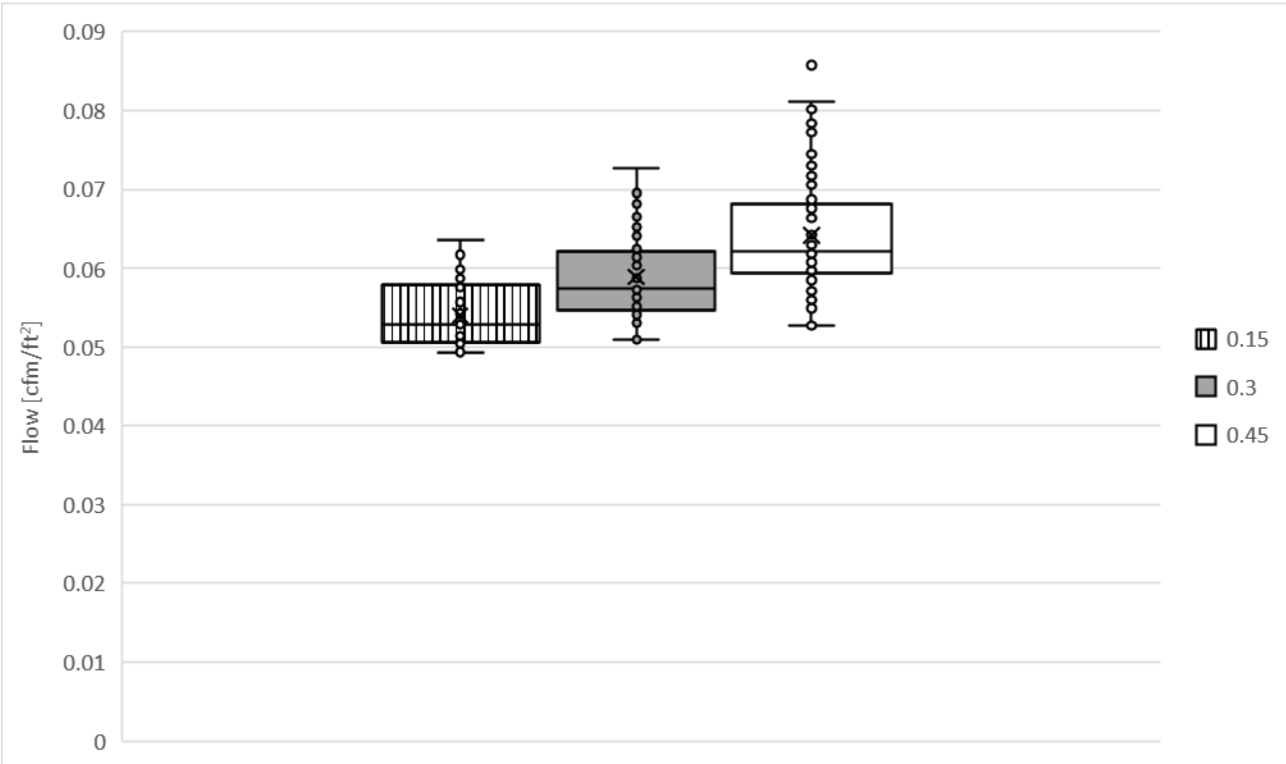


Figure 3.2.5 Ventilation flow rates (normalized by floor area) for 55 modeled units at three different leakage levels: 0.15 cfm_{50}/ft^2, 0.3 cfm_{50}/ft^2, and 0.45 cfm_{50}/ft^2 for a balanced building using Sacramento weather data.

In an exhaust-only building, increasing the leakage level increased the ventilation flow rate for some units and decreased the ventilation flow rate for other units (see Figure 3.2.6). Corner units have more exterior surface area than interior units, allowing more air to exchange with outside than interior units. In the exhaust-only simulation, more air infiltrated into corner units than was required to meet the exhaust flow rate (see Figure 3.2.7). The extra air was passed on to neighboring units to satisfy their exhaust flow rates. For units with a higher leakage level, the effect of corner units infiltrating extra air to share with neighbors was magnified, causing the ventilation flow rate to increase in some (primarily corner) units due to increased outdoor air, while the ventilation flow rate decreased in other (primarily interior) units due to increased air from neighbors (see Figure 3.2.8). Note that for Figure 3.2.8 the ventilation rate is equal to the infiltration of air from outdoors, as it is an exhaust only building. Thus, as the units are made leakier, the average fraction of air flow coming from other units and the corridor steadily increases.

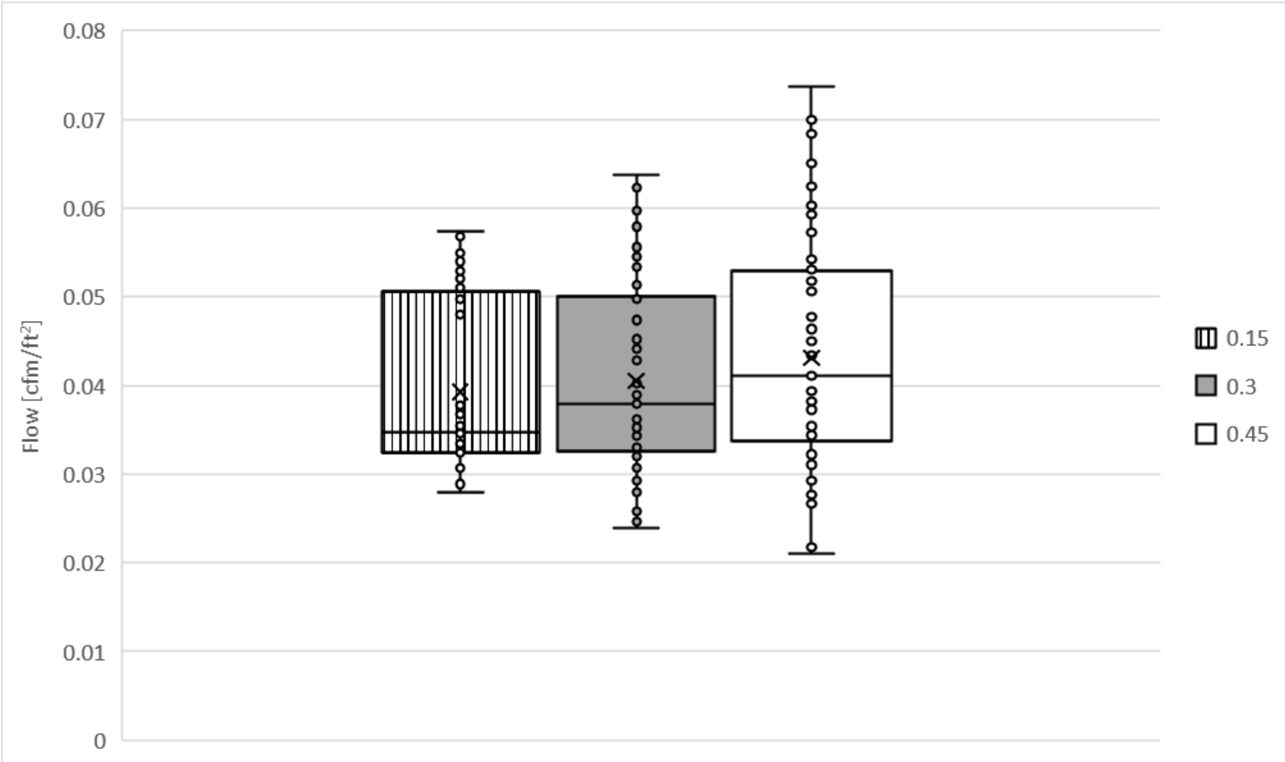


Figure 3.2.6 Ventilation flow rates for 55 modeled units at three different leakage levels: 0.15 cfm_{50}/ft^2, 0.3 cfm_{50}/ft^2, and 0.45 cfm_{50}/ft^2 for an exhaust-only building using Sacramento weather data.

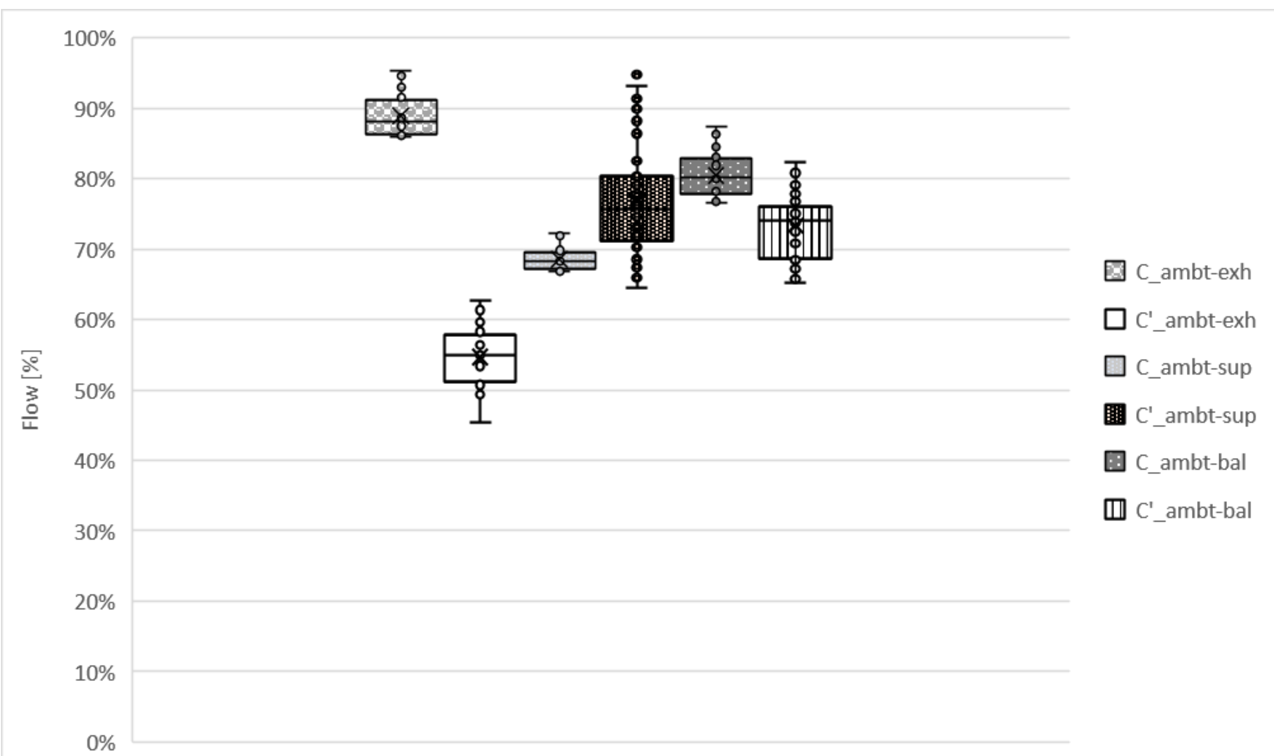


Figure 3.2.7 Outdoor air entering 55 modeled units differentiated by corner ("C") and interior ("C'") units with three different ventilation strategies: exhaust-only, supply-only, and balanced for a building at 0.15 cfm_{50}/ft^2 using Sacramento weather data. Flow % is the fraction of total air flow through a unit that is coming from outdoors (either through supply ventilation or directly from outdoors).

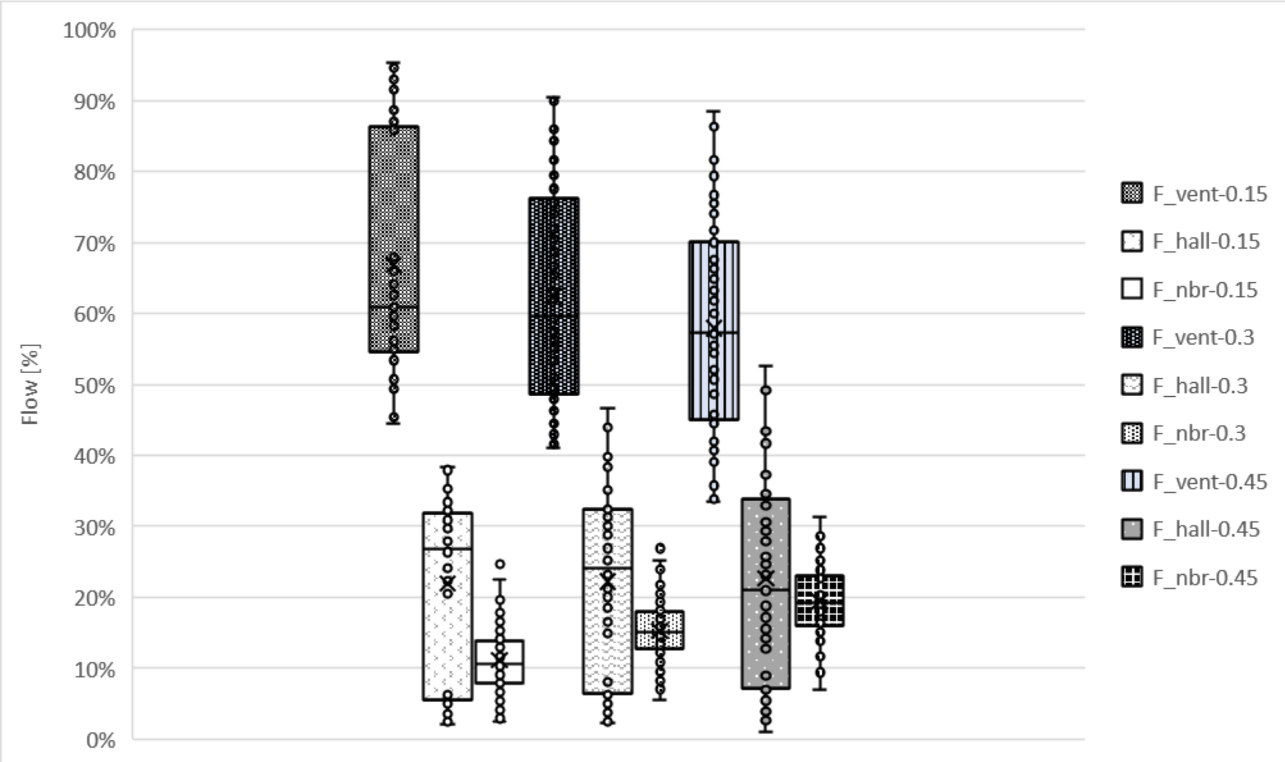


Figure 3.2.8 Source of air flowing into 55 modeled units differentiated by outdoor (ventilation) air ("vent"), corridor air ("hall"), and neighboring air ("nbr") at three leakage levels: 0.15 cfm_{50}/ft^2, 0.3 cfm_{50}/ft^2, and 0.45 cfm_{50}/ft^2 for an exhaust-only building using Sacramento weather data.

Unit ventilation flow rates (outdoor air plus supply air) were greater for balanced and supply buildings than exhaust-only buildings (see Figure 3.2.9). The balanced building had the highest ventilation flow rate. In the balanced building, units were mechanically supplied with outdoor air and the neutral pressure across the building envelope allowed extra outdoor air to infiltrate more easily than for the supply-only building. The exhaust-only building had the lowest ventilation flow rate. In the exhaust-only building, makeup air infiltrates through the building shell. Corner units generally have high ventilation rates, as outdoor air infiltrates into these units more readily as they have a large exterior surface area. Interior units generally have low ventilation rates (about 30% less than corner units), as only a small amount of outdoor air infiltrates through the relatively small exterior wall area while the rest of the air entering those units comes from other interior zones within the building. Unit ventilation flow rates followed the same climate zone relationship as unit air change rates. Sacramento and San Francisco had slightly higher ventilation flow rates than Los Angeles and Fresno (see Figure 3.2.10).

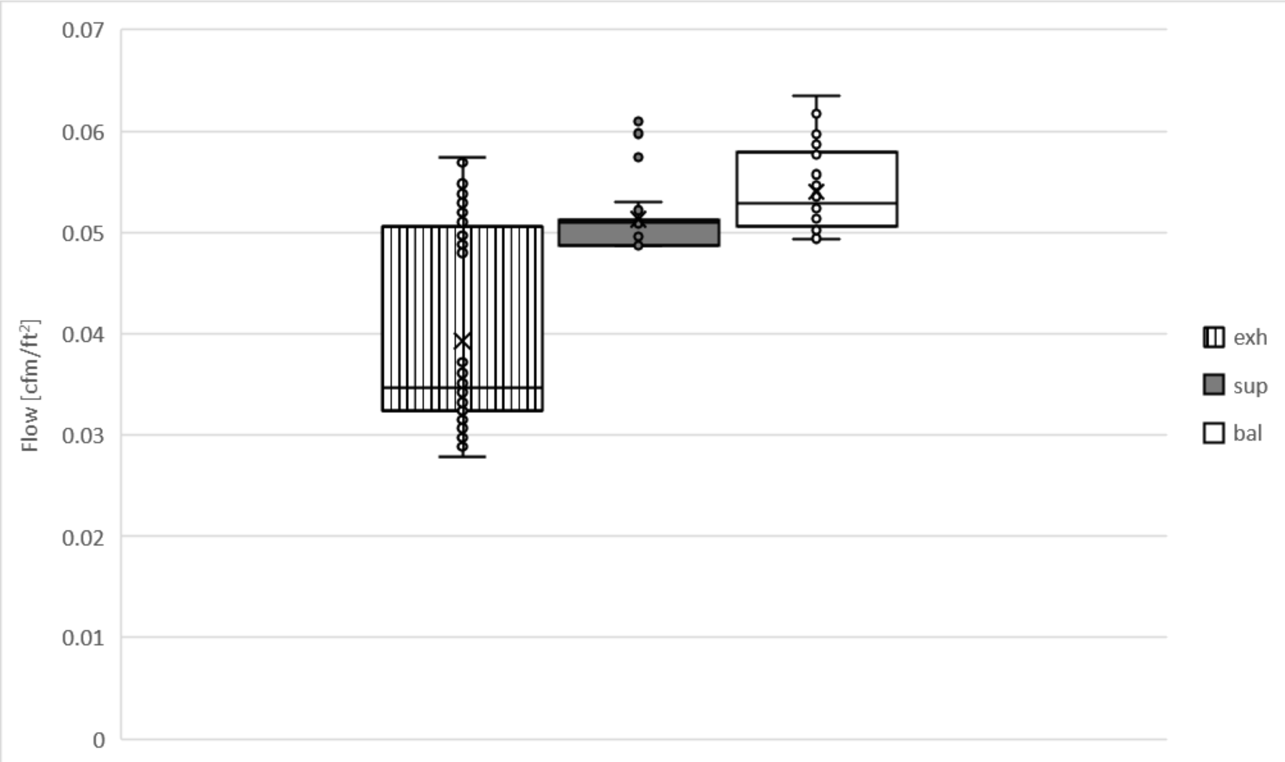


Figure 3.2.9 Ventilation flow rates (normalized by floor area) for 55 modeled units with three different ventilation strategies: exhaust-only, supply-only, and balanced for a building at 0.15 cfm_{50}/ft^2 using Sacramento weather data.

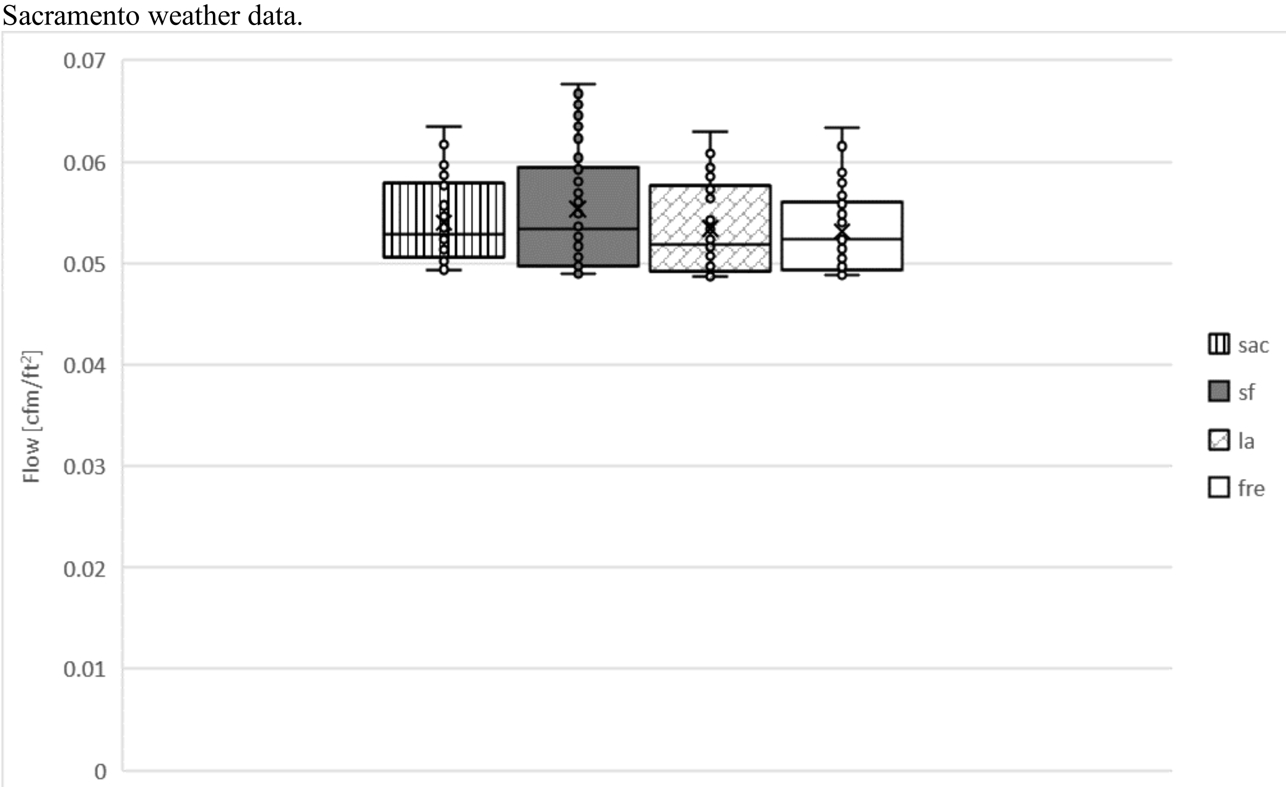


Figure 3.2.10 Ventilation flow rates (normalized by floor area) for 55 modeled units in four different climate zones: Sacramento, San Francisco, Los Angeles, and Fresno for a building at 0.15 cfm_{50}/ft^2 with balanced ventilation.

3.2.1.3 Infiltration

Building infiltration was highly dependent on the ventilation strategy (see Figure 3.2.11). The exhaust-only building had the greatest unit infiltration (about 15-70 cfm), as makeup air is intended to infiltrate through the building envelope. The supply-only building had minimal unit infiltration (about 0-5 cfm), as this building was positively pressurized relative to the outdoors. The balanced building at 0.3 cfm_{50}/ft^2 had some unit infiltration (about 5-20 cfm) which is significantly lower than the unit infiltration values (between 25-80 cfm) in the EnergyPlus model with balanced ventilation. The unit infiltration values in the balanced EnergyPlus model best aligned with the exhaust only CONTAM unit infiltration values. This disagreement in infiltration between models suggests that unit infiltration values in EnergyPlus are significantly overestimated for a building with balanced or supply ventilation.

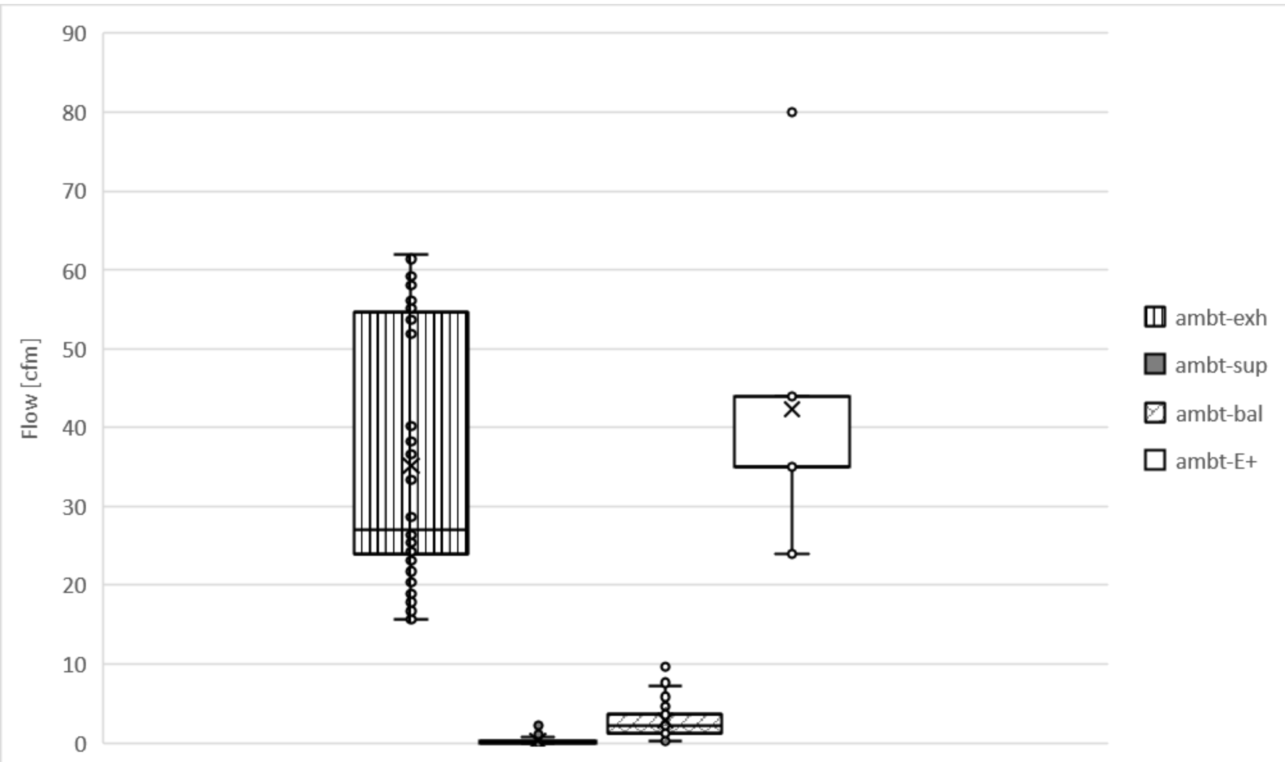


Figure 3.2.11 Unit infiltration flow rates for 55 modeled units with three different ventilation strategies: exhaust-only, supply-only, and balanced for a building at 0.3 cfm_{50}/ft^2 using Sacramento weather data, compared to EnergyPlus unit infiltration values (also for a balanced system using Sacramento weather data).

Transfer of air from neighboring units increased in the leakier scenarios (see Figure 3.2.12). This trend occurred for all ventilation types: balanced, exhaust-only, and supply-only (see Figure 3.2.13 and Figure 3.2.14). The variation in ventilation flows also increased for leakier units, indicating some units received a higher percentage of outdoor air while others received a higher percentage of air from neighboring units. This trend suggests that as buildings get leakier, flows into units becomes more uneven with some units being over ventilated while others are under ventilated (with insufficient fresh, outdoor air).

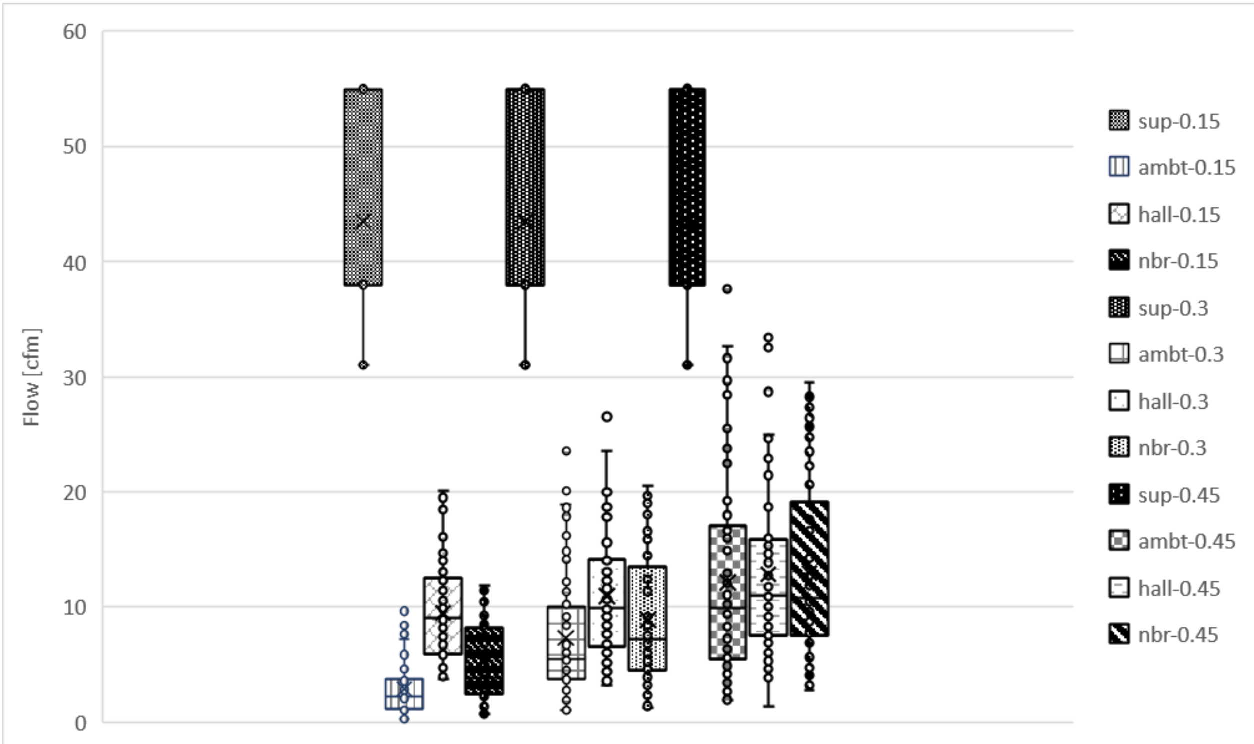


Figure 3.2.12 Source of air for 55 modeled units differentiated by supply ventilation air ("sup"), direct outdoor air ("ambt"), corridor air ("hall"), and neighboring air ("nbr") at three difference leakage levels: 0.15 cfm_{50}/ft^2, 0.3 cfm_{50}/ft^2, and 0.45 cfm_{50}/ft^2 for a balanced building using Sacramento weather data. Median values for supply-only ventilation are equal to the 25th percentile value, due to there being only three flow choices.

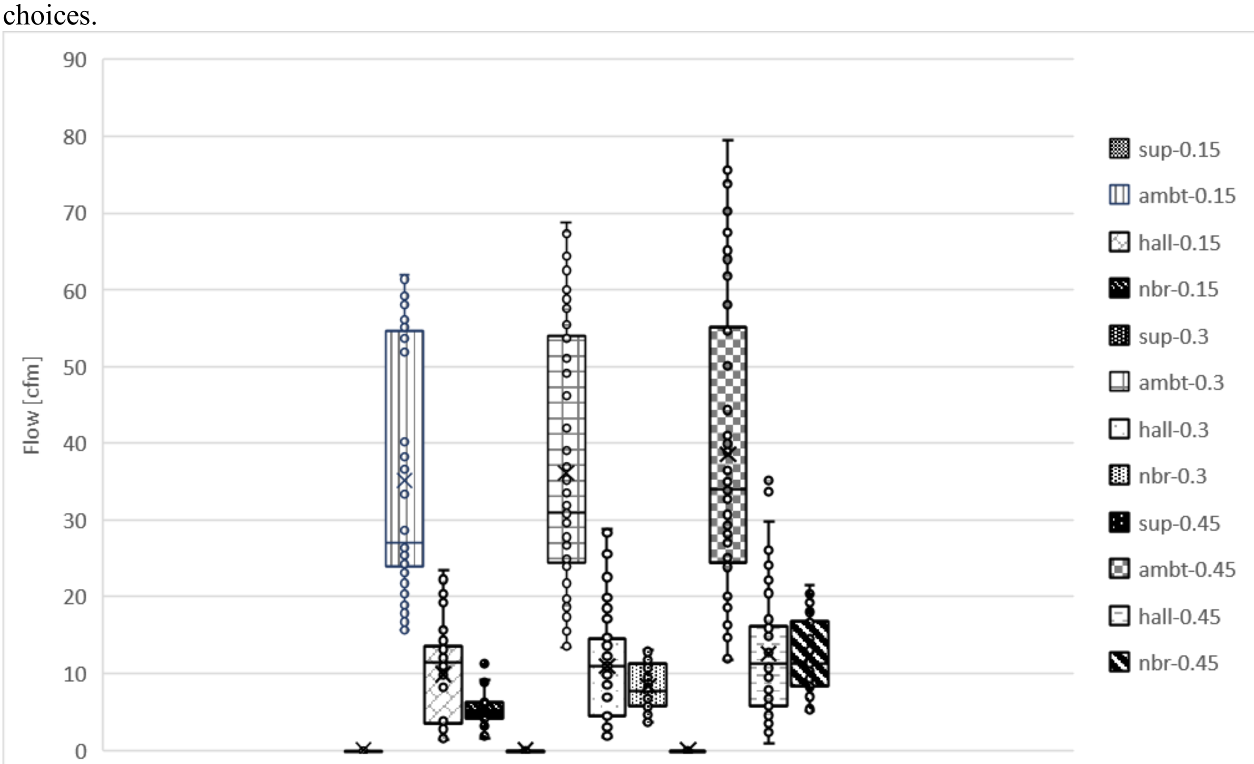


Figure 3.2.13 Source of air for 55 modeled units differentiated by supply ventilation air ("sup"), direct outdoor air ("ambt"), corridor air ("hall"), and neighboring air ("nbr") at three different leakage levels: 0.15 cfm_{50}/ft^2, 0.3 cfm_{50}/ft^2, and 0.45 cfm_{50}/ft^2 for an exhaust-only building using Sacramento weather data.

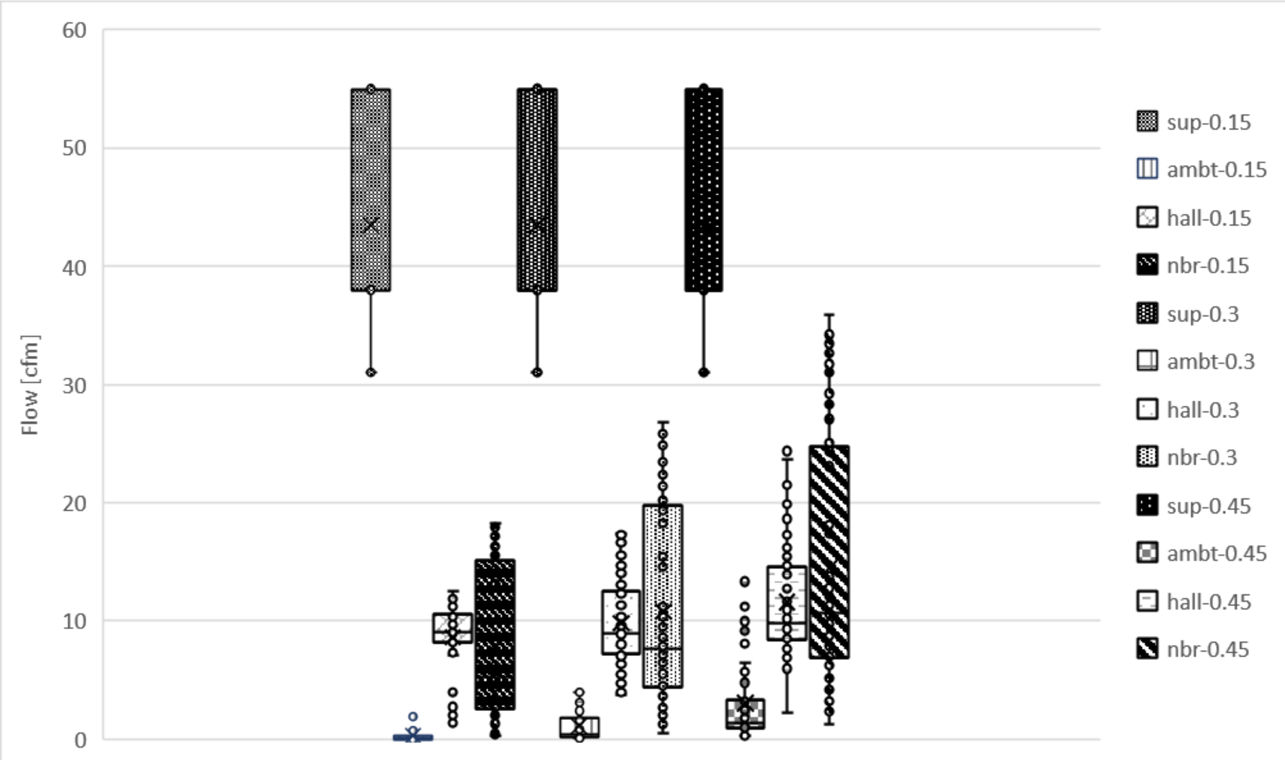


Figure 3.2.14 Source of air for 55 modeled units differentiated by supply ventilation air ("sup"), direct outdoor air ("ambt"), corridor air ("hall"), and neighboring air ("nbr") at three different leakage levels: 0.15 cfm_{50}/ft^2, 0.3 cfm_{50}/ft^2, and 0.45 cfm_{50}/ft^2 for a supply-only building using Sacramento weather data. Median values for supply-only ventilation are equal to the 25th percentile value, due to there being only three flow choices.

3.2.2 Pollutant Analysis

Average pollutant concentrations (over 24 hours) in units were calculated, considering both concentrations resulting from sources within the unit as well as concentrations resulting from pollutants transferred to the unit from sources in other units. Additionally, hourly peak concentrations in units were calculated for concentrations originating within the unit and concentrations transferred from other units. These two metrics were selected to evaluate both intermittent and constant pollutant sources. The rate of transfer of gaseous pollutants was consistent, but the various source profiles (i.e. steady vs. intermittent sources, all vs. some units having a source) result in the differences in results between pollutants.

For NO_2, which has sources in units from cooking activities as well as contributions from outdoors, average concentrations decreased when the unit leakage level was increased (see Figure 3.2.15). This decrease in pollutant concentrations from higher leakage levels is associated with increases in natural ventilation or infiltration. It was most noticeable at times when a unit had a low ventilation rate. For example, the impact of leakage levels on NO_2 concentrations is greater for units that do not run their kitchen exhaust fans, in which case the dilution of NO_2 generated within the unit is heavily influenced by natural ventilation or infiltration. On the other hand, for units that run their kitchen exhaust fans, the dilution is dominated by the exhaust fan flow, and is thus essentially unaffected by the leakiness of the unit (see Figure 3.2.15). It was noted that these simulations were conducted using an outdoor concentration of 10 ppb. To consider levels in areas with concentrations greater than 10 ppb, the difference between the outdoor concentration in the location of the building and 10 ppb can be added to the modeled concentrations to reflect the indoor concentration.

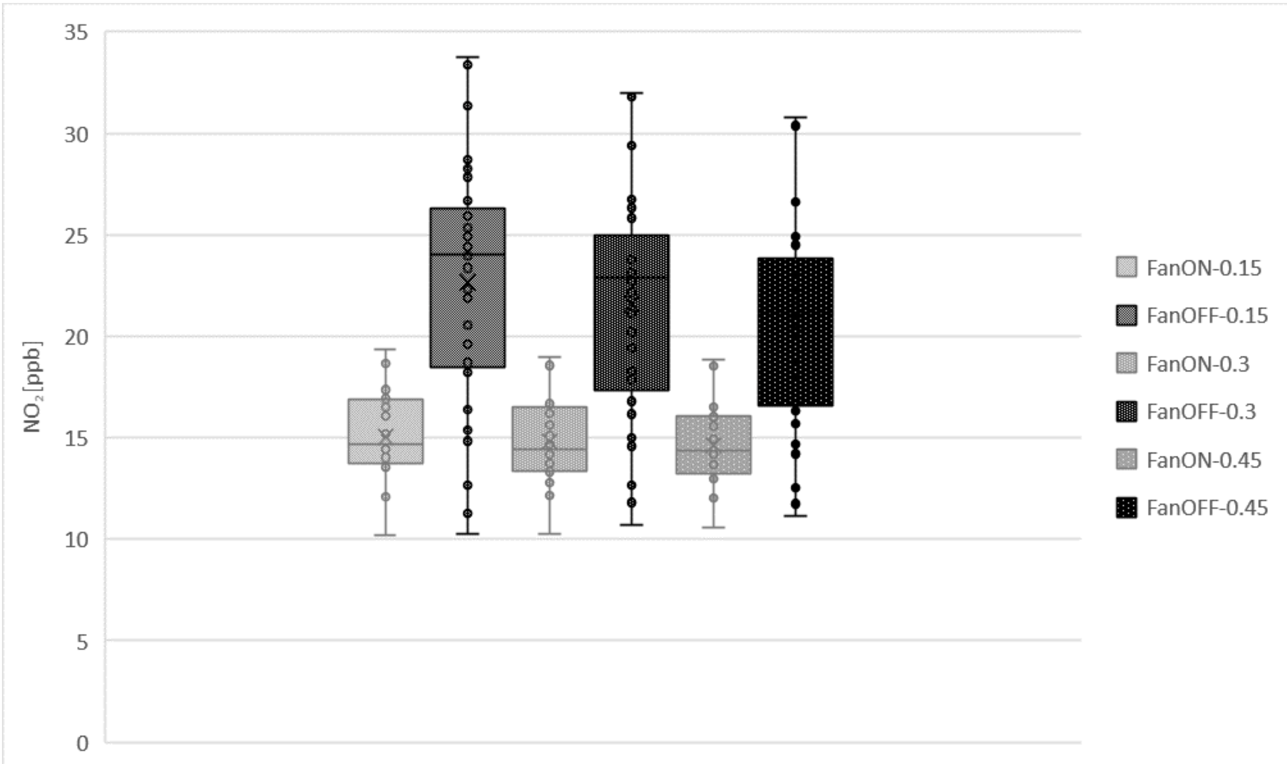


Figure 3.2.15 Nitrogen Dioxide (NO_2) average concentrations in units that turn on their kitchen exhaust fans while cooking ("FanON") and those that never turn on their kitchen exhaust fans ("FanOFF") at three different leakage levels: 0.15 cfm_{50}/ft^2, 0.3 cfm_{50}/ft^2, and 0.45 cfm_{50}/ft^2 for a balanced building using Sacramento weather data.

As NO_2 is intermittently emitted, the peak one-hour concentrations for the first week of July were also determined (Figure 3.2.16). For NO_2, the biggest determinant of the peak one-hour concentration is whether the fan was on or off. Operation of kitchen exhaust fans while cooking on a natural gas stove was found to greatly lower concentration. To put the modeled concentrations in context, concentrations were compared to health-relevant levels. The US EPA NAAQS for 1-hour NO_2 is 100 ppb [88]. As shown in Figure 3.2.16, for those units that do not use their kitchen fan during cooking, they consistently have NO_2 concentrations above the standard. All-electric buildings do not have significant indoor sources of NO_2 emissions; however, operation of kitchen exhaust fans is still recommended while cooking to minimize other air pollutants generated from cooking activities such as PM.

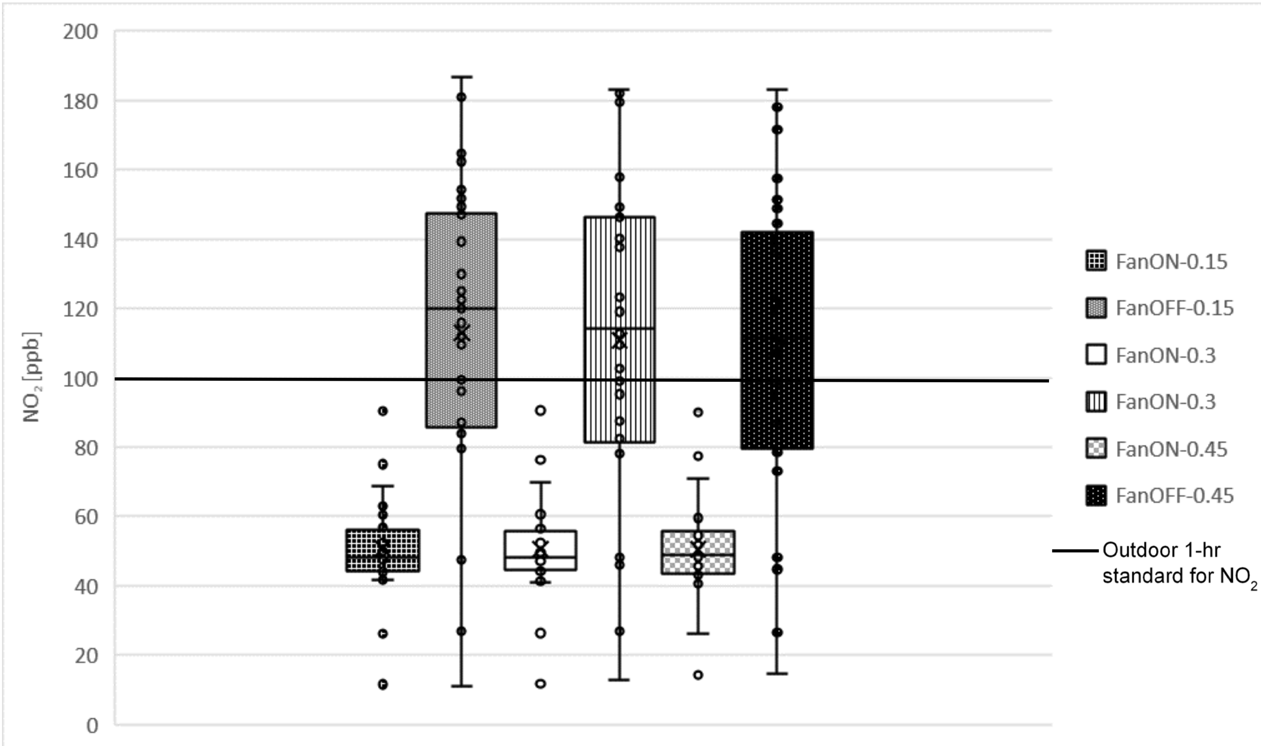


Figure 3.2.16 Peak one-hour NO_2 concentrations compared to the level of the National Ambient Air Quality Standard (NAAQS) for one-hour NO_2 (100 ppb) for units that that turn on their kitchen exhaust fans while cooking ("FanON") and those that never turn on their kitchen exhaust fans ("FanOFF") at three different leakage levels: 0.15 cfm_{50}/ft^2, 0.3 cfm_{50}/ft^2, and 0.45 cfm_{50}/ft^2 for a balanced building using Sacramento weather data.

While increasing unit leakage levels, on average, decreased average unit pollutant concentrations generated in the same unit due to increased outdoor air infiltration, it also increased the concentration of pollutants transferred from adjacent units (see Figure 3.2.17). The operation of kitchen exhaust fans while cooking also increased inter-unit transfer of pollutants. While the transfer of pollutants increased significantly (often doubling) between 0.15 cfm_{50}/ft^2 and 0.45 cfm_{50}/ft^2, the total unit pollutant concentrations steadily decreased. This is because inter-unit transfer of pollutants only made up a small fraction of the total unit pollutant concentrations, and they were more than offset by the dilution by essentially pollutant-free outdoor air that infiltrated at higher rates for the leakier buildings.

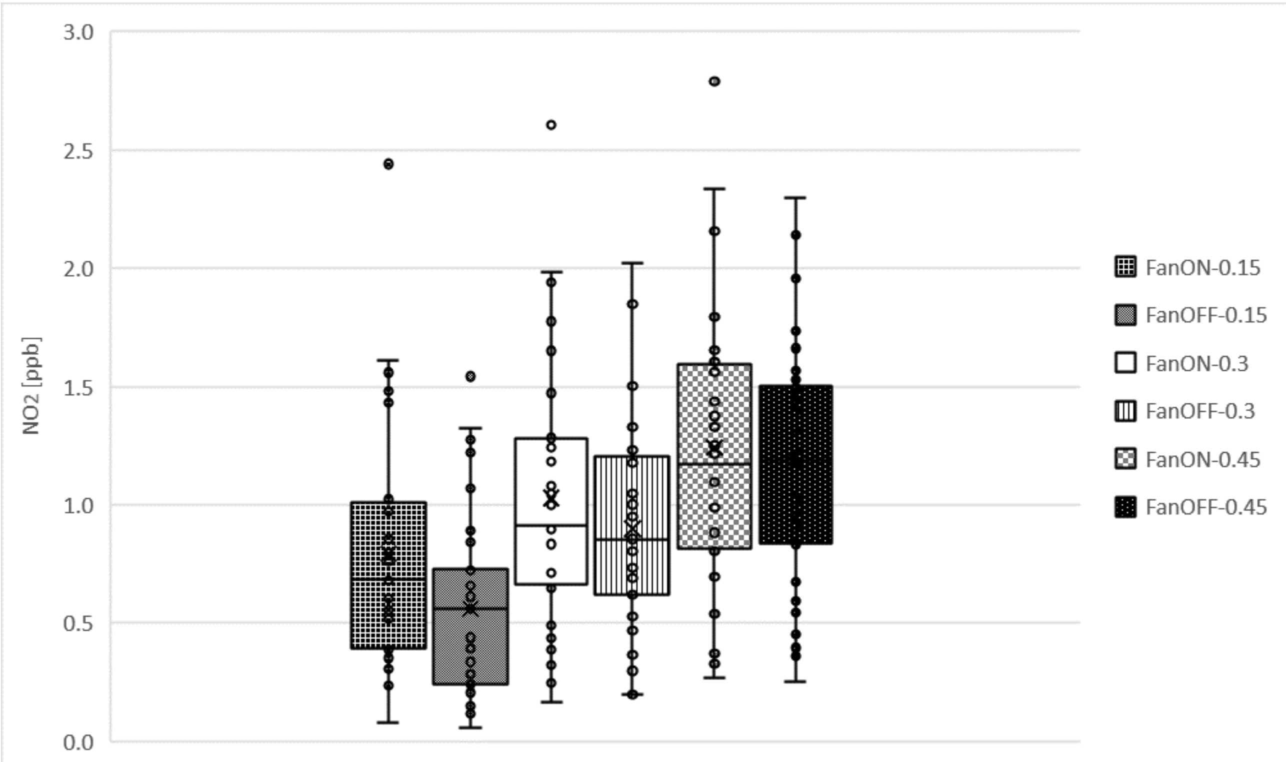


Figure 3.2.17 Concentration of NO_2 from cooking activity in other units. Units are differentiated by whether it had its kitchen fan on or off, at three different leakage levels: 0.15 cfm_{50}/ft^2, 0.3 cfm_{50}/ft^2, and 0.45 cfm_{50}/ft^2 for a balanced building using Sacramento weather data.

The average concentration distributions for formaldehyde, CH_2O (see Figure 3.2.18), decreased, on average, by about 5%, when the unit leakage level increased from 0.15 cfm_{50}/ft^2 to 0.3 cfm_{50}/ft^2; and by 10% when the unit leakage level increased from 0.15 cfm_{50}/ft^2 to 0.45 cfm_{50}/ft^2. Units run their kitchen exhaust fans while cooking have slightly higher average ventilation rates than those that do not, thereby diluting and lowering CH_2O concentrations. As CH_2O is emitted continually from the units, as opposed to just while cooking occurs, there is not as much of a difference in the distribution of concentrations between units that use their kitchen fan while cooking as opposed to those that do not use their fan while cooking. Only a small amount of CH_2O is transferred from other units (Figure 3.2.19), with the mass transferred being slightly higher with the fan on. CH_2O concentrations in units were found to be considerably above both the one-in-a-million cancer risk level of 0.13 ppm and the one-in-a-hundred-thousand cancer risk level of 1.3 ppm [89].

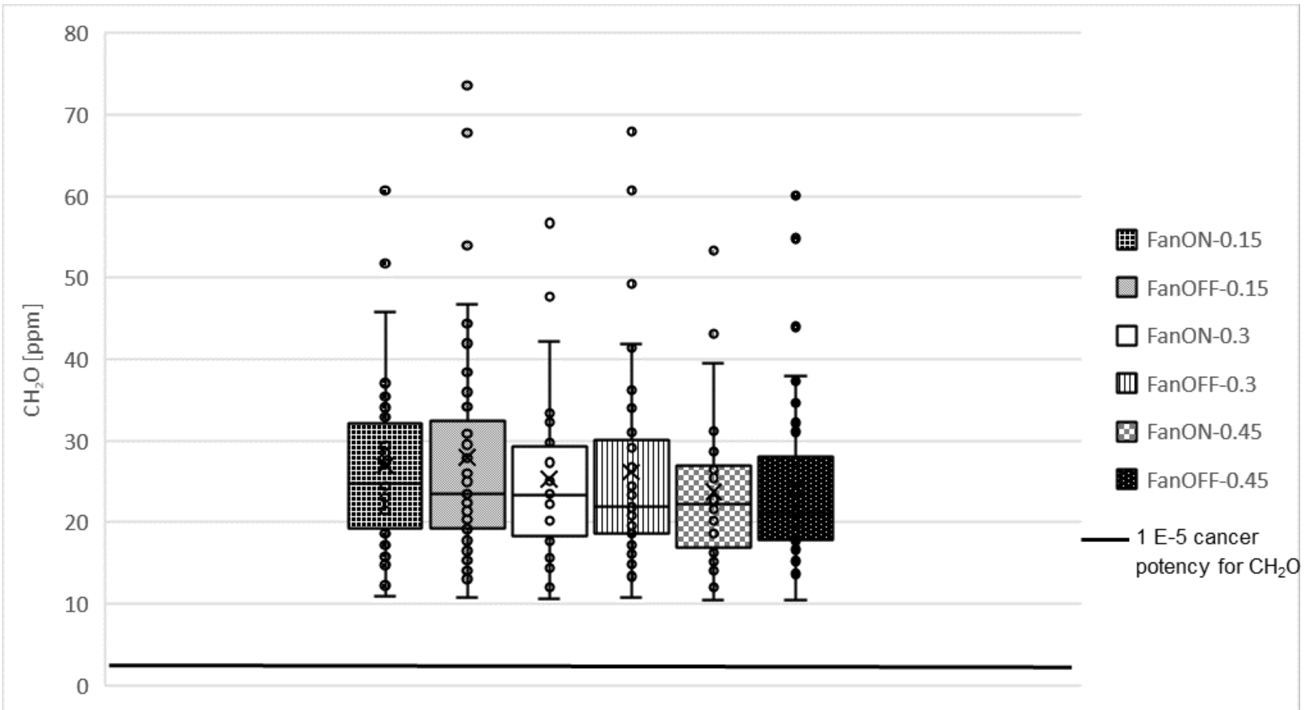


Figure 3.2.18 Formaldehyde (CH_2O) concentrations in units that turn on their kitchen exhaust fans while cooking (“FanON”) and those that never turn on their kitchen exhaust fans (“FanOFF”) at three different leakage levels: 0.15 cfm_{50}/ft^2, 0.3 cfm_{50}/ft^2, and 0.45 cfm_{50}/ft^2 for a balanced building using Sacramento weather data. CH_2O concentrations due to inter-unit transfer compared to the exposure cancer potency (1 x 10^{-5}) of 1.3 ppm.

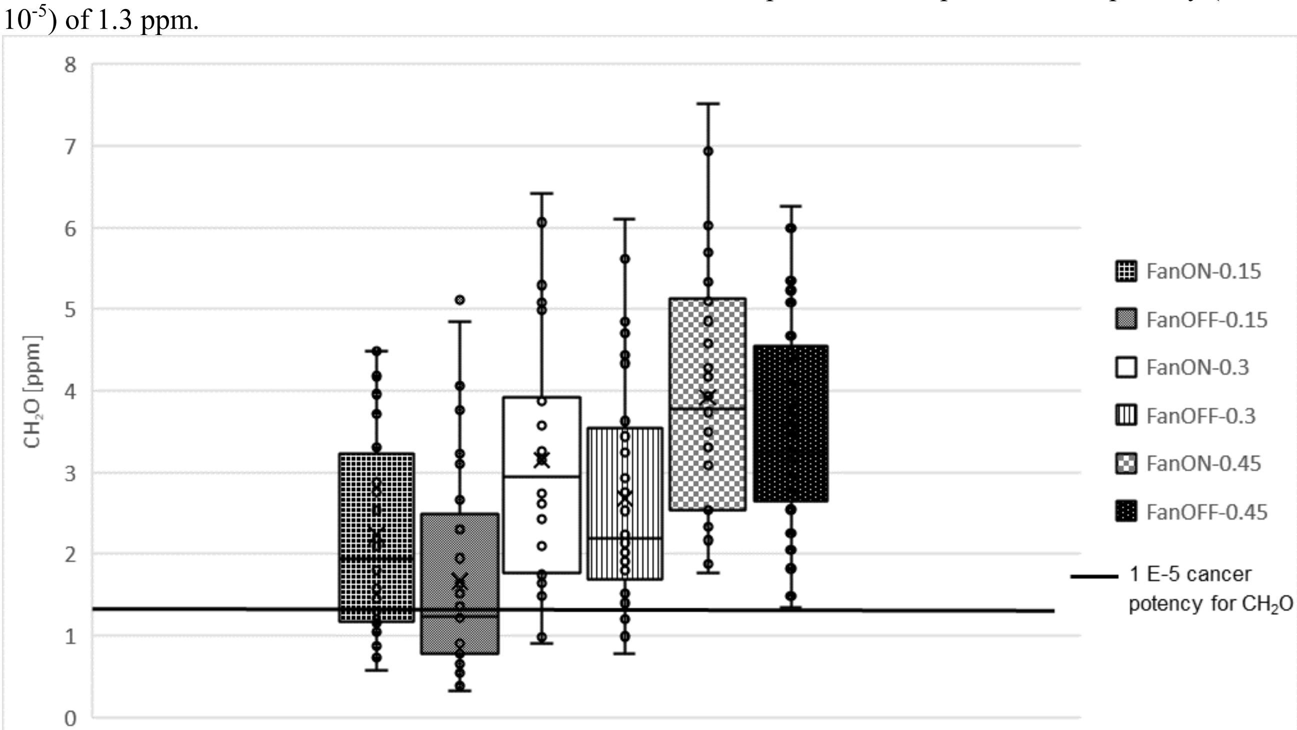


Figure 3.2.19 Concentration of CH_2O transferred from other units differentiated by units that turn on their kitchen exhaust fans while cooking (“FanON”) and those that never turn on their kitchen exhaust fans (“FanOFF”) at three different leakage levels: 0.15 cfm_{50}/ft^2, 0.3 cfm_{50}/ft^2, and 0.45 cfm_{50}/ft^2 for a balanced building using Sacramento weather data. CH_2O concentrations due to inter-unit transfer compared to the exposure cancer potency (1 x 10^{-5}) of 1.3 ppm.

For benzene, C_6H_6, only a portion of the units had a smoker (see Figure 3.2.20). Average concentrations in units with smokers decreased by about 10% when the unit leakage level increased from 0.15 cfm_{50}/ft^2 to 0.3 cfm_{50}/ft^2; and by 20% when the unit leakage level increased from 0.15 cfm_{50}/ft^2 to 0.45 cfm_{50}/ft^2. Concentrations for C_6H_6 transferred to units without smokers are much lower than for units with smokers, as expected (Figure 3.2.20 and Figure 3.2.21).

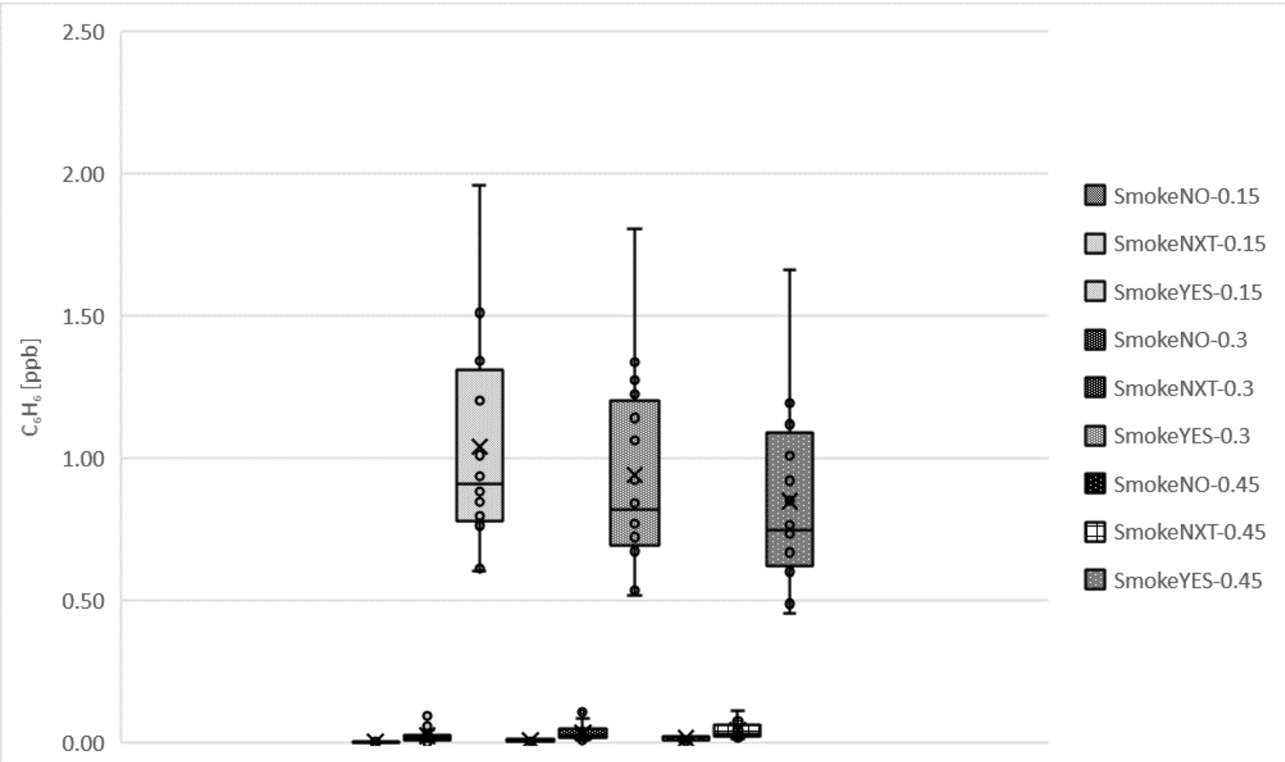


Figure 3.2.20 Benzene (C_6H_6) concentrations in units with a smoker ("SmokeYES"), next to a smoker ("SmokeNXT"), and without a smoker and not next to a smoker ("SmokeNO") at three different leakage levels: 0.15 cfm_{50}/ft^2, 0.3 cfm_{50}/ft^2, and 0.45 cfm_{50}/ft^2 for a balanced building using Sacramento weather data.

For transfers of C_6H_6 from other units, whether you live next door to a smoker or not results in the greatest difference in the distribution of concentrations (see Figure 3.2.21). Smokers also have additional C_6H_6 transferred into their units from other units with smokers, however whether they lived next to a smoker is not differentiated as the concentrations in the smoker units are driven by the source in the smoker unit. Concentrations in units adjacent to smoker units that do not have smokers in them increase as leakage increases. As there is no source benzene in these non-smoking units, the overall exposure is higher in leakier non-smoker units, as their entire exposure is due to transfer from the smoker unit. In other words, there is no internal source of smoke in a non-smoker unit that gets diluted by the added ventilation in leakier buildings. Secondhand smoke transfer was reduced by 20% when moving from 0.45 cfm_{50}/ft^2 to 0.30 cfm_{50}/ft^2, and an additional 33% when moving from 0.30 cfm_{50}/ft^2 to 0.15 cfm_{50}/ft^2. There is a very small amount of transfer to units with no smoker next door, because a smoker could be located above or below the unit. Leakage elements in the model were set up to allow for more horizontal than vertical air transfer. Thus, the "smoker next door" group was constrained to be horizontally adjacent to observe the maximum transfer. It is also worth noting that the concentration in smoking units due to transfer from other units falls between that for no smoking and smoker-next-door, which is because the smoker units sometimes have a smoker next door, and sometimes have no smoker next door. C_6H_6 concentrations in units next to smokers were compared to a concentration of 0.04 ppm, the concentration associated with a cancer risk of one-in-a-million, (Figure 3.2.21) [90]. At a unit leakage level of 0.15 cfm_{50}/ft^2 about 90% of units neighboring a smoker had C_6H_6 levels below the one-in-a-million cancer risk level, whereas at a leakage level of 0.45 cfm_{50}/ft^2 only about 50% of units neighboring a smoker had C_6H_6 levels below the one-in-a-million cancer risk level.

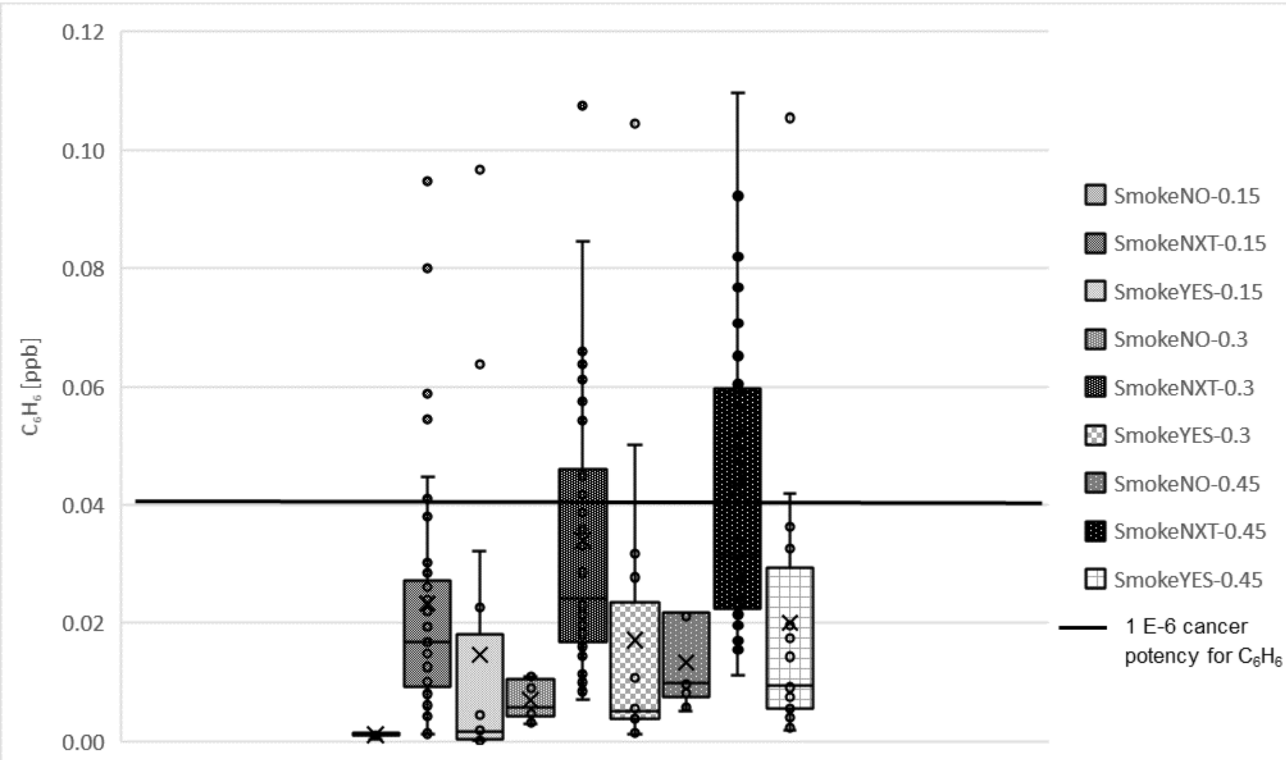


Figure 3.2.21 Concentration of C_6H_6 transferred from other units differentiated by units with a smoker ("SmokeYES"), next to a smoker ("SmokeNXT"), and without a smoker and not next to a smoker ("SmokeNO") at three different leakage levels: 0.15 cfm_{50}/ft^2, 0.3 cfm_{50}/ft^2, and 0.45 cfm_{50}/ft^2 for a balanced building using Sacramento weather data. C_6H_6 concentrations are also compared to the exposure cancer potency (1×10^{-6}) of 0.04 ppm.

The unit concentrations of all three pollutants were roughly the same for all ventilation strategies, but were marginally lowest in the balanced scenario and marginally highest in the exhaust-only scenario (see results for NO_2 in Figure 3.2.22, other compounds not shown). This follows from the ventilation rates being highest in the balanced building and lowest in the exhaust-only building. Changing climate zone had a minimal impact on pollutant concentrations (see Figure 3.2.23). Sacramento and San Francisco appear to have slightly lower concentrations than Los Angeles and Fresno due to the induced natural ventilation rates of each climate.

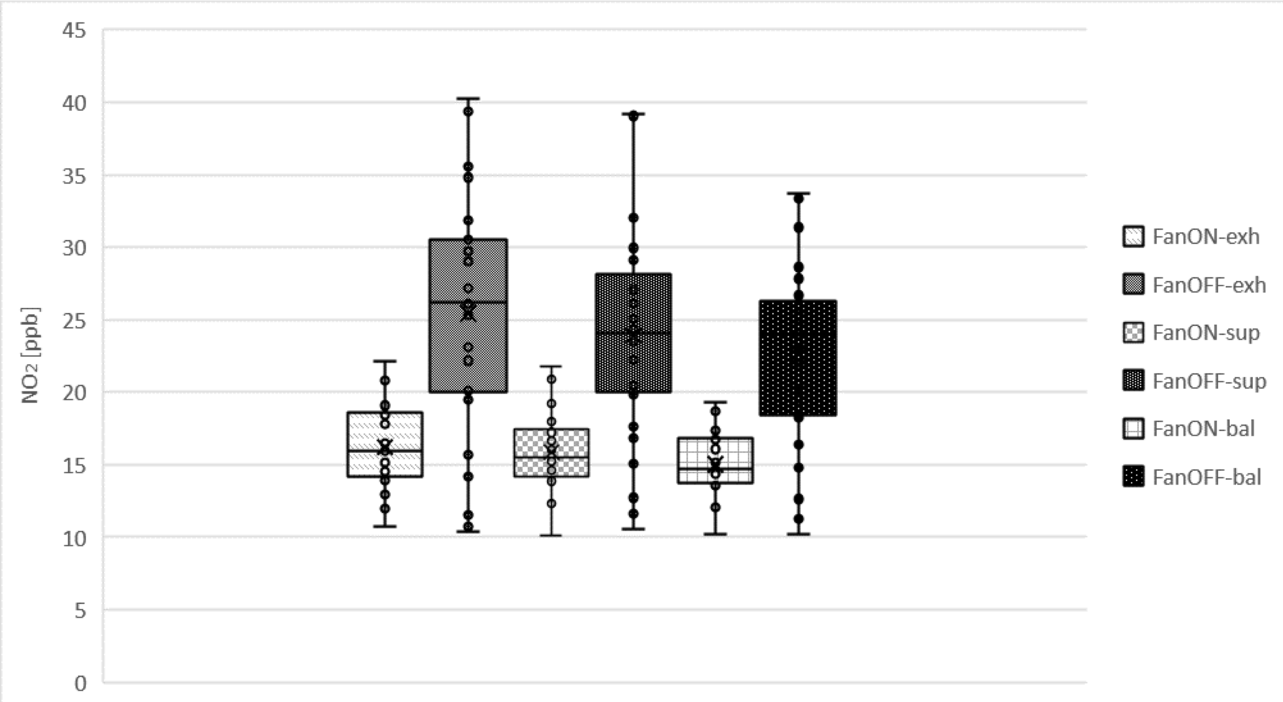


Figure 3.2.22 Nitrogen Dioxide (NO_2) concentrations in units that turn on their kitchen exhaust fans while cooking ("FanON") and those that never turn on their kitchen exhaust fans ("FanOFF") for three different ventilation strategies: exhaust-only, supply-only, and balanced for a building at 0.15 cfm_{50}/ft^2 using Sacramento weather data.

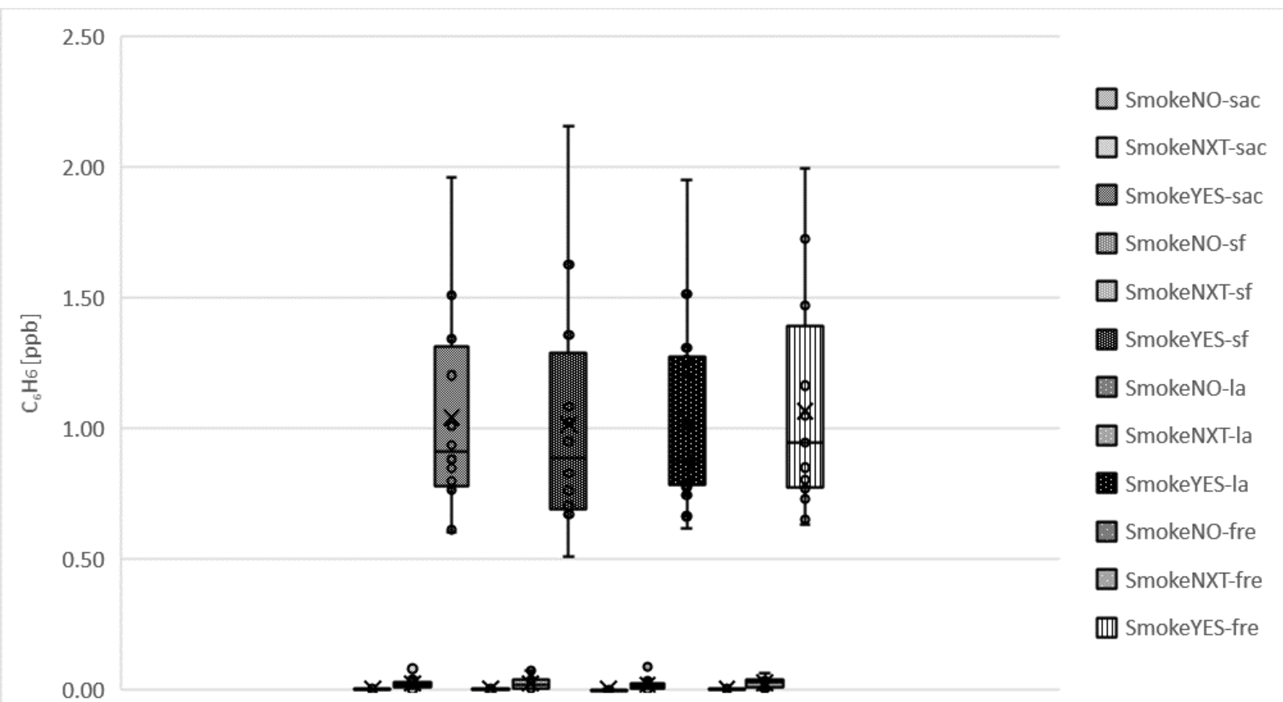


Figure 3.2.23. Benzene (C_6H_6) concentrations in units with a smoker ("SmokeYES"), next to a smoker ("SmokeNXT"), and without a smoker and not next to a smoker ("SmokeNO") for four different climate zones: Sacramento ("sac"), San Francisco ("sf"), Los Angeles ("la"), and Fresno ("fre") for a balanced building at 0.15 cfm_{50}/ft^2.

3.2.3 EnergyPlus Energy Analysis

Running the EnergyPlus model for four different climate zones indicated that HVAC energy usage was higher in Sacramento and Fresno and lower in San Francisco and Los Angeles (see Figure 3.2.24). This result was expected, as Sacramento and Fresno are in the Central Valley and experience much hotter summers than the relatively temperate, coastal cities of San Francisco and Los Angeles. Annual HVAC energy usage for the five-story, 55-unit multifamily building with balanced ventilation ranged between 130 and 350 MWh/yr. These numbers are likely lower bounds since most people heat their homes above the CEC (and DOE) recommended setpoint of 68 F and cool their homes below the recommended setpoint of 78 F.

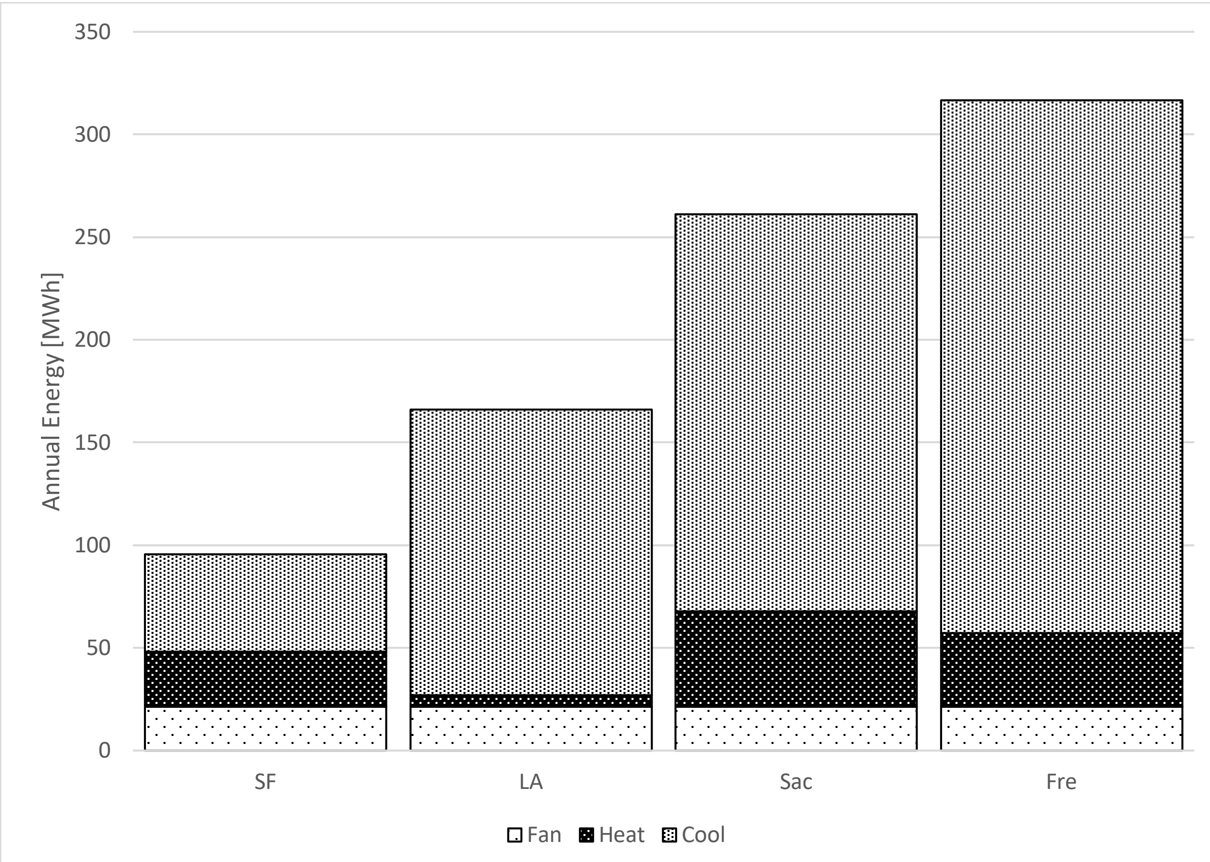


Figure 3.2.24 Annual energy use simulated in EnergyPlus for the four different climate zones: Sacramento (“sac”), San Francisco (“sf”), Los Angeles (“la”), and Fresno (“fre”). (No window opening)

Although the focus of the analysis is on annual energy results, a representative day in the winter (January 15th) was examined to assure that the CONTAM simulations provide appropriate results at short time scales. The simulation results show that infiltration flows in CONTAM responded to kitchen fan schedules and outdoor wind speed (see Figure 3.2.25). The three spikes in infiltration flow rates in the morning, noon, and evening correspond to occupants using their kitchen exhaust fans during breakfast, lunch, and dinner. Use of the kitchen exhaust fan in a balanced building depressurizes units relative to the outdoors, driving infiltration. Figure 3.3.25 also shows that the infiltration flow rate is proportional to wind speed, and that the leakier units (0.45 cfm_{50}/ft^2) always had higher infiltration rates than the tighter units (0.15 cfm_{50}/ft^2), as expected.

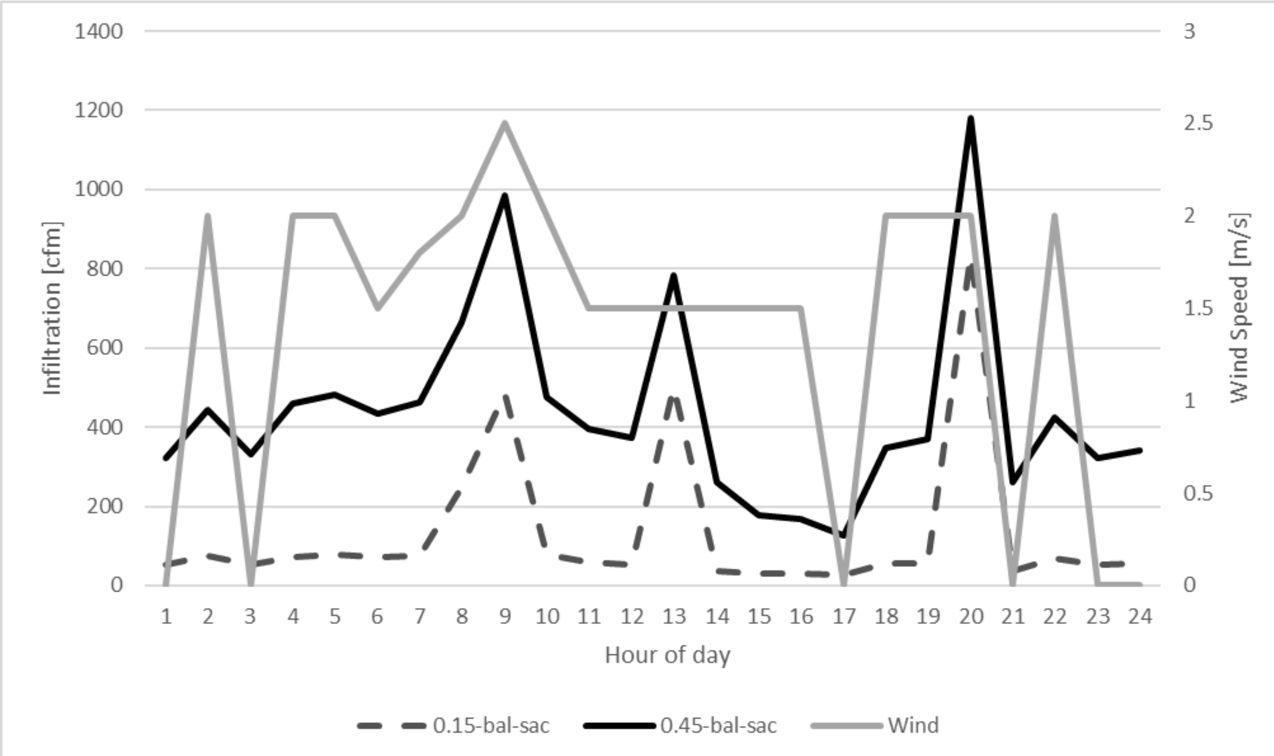


Figure 3.2.25 January 15th hourly building infiltration comparison between 0.15 cfm_{50}/ft^2 and 0.45 cfm_{50}/ft^2 (left y-axis) graphed alongside outdoor wind speed (right y-axis) for a balanced building using Sacramento weather data.

Annual HVAC energy was dominated by the cooling load in all simulated California climate zones (see Figure 3.2.24). Fan energy required to ventilate the building (with supply and/or exhaust air) was responsible for 5-20% of building HVAC energy. Fan energy doubled from about 10 MWh/yr to 20 MWh/yr between the single-fan supply-only and exhaust-only simulations versus the double-fan balanced simulations. In Sacramento, about 20% of HVAC energy was used for heating and 75% of HVAC energy was used for cooling. In San Francisco, about 30% of HVAC energy was used for heating and about 50% of HVAC energy was used for cooling. In Los Angeles, about 5% of HVAC energy was used for heating and 90% of HVAC energy was used for cooling. In Fresno, about 10% of HVAC energy was used for heating and 85% of HVAC energy was used for cooling. The fact that the cooling loads are consistently higher than the heating loads are rather surprising, particularly in San Francisco (many buildings in the San Francisco Bay Area do not have air conditioning). This is mostly due to the fact that EnergyPlus does not consider the use of window openings to provide free cooling and thereby reduce cooling loads. This is a limitation of EnergyPlus. However, as EnergyPlus has been used for modeling air infiltration for a long time and by many CASE projects to inform CA building code updates, it was chosen for this project to provide comparable results.

The impact of unit leakage on energy use was simulated for all four climate zones and ventilation types. The results are shown in Figures 3.2.26 and 3.2.27. The fan energy is not plotted, as it is not impacted by climate or unit leakage. These figures show that tightening decreases heating energy uniformly, but that tightening only decreases cooling energy use in Fresno and Sacramento, and increases cooling energy use San Francisco and Los Angeles.

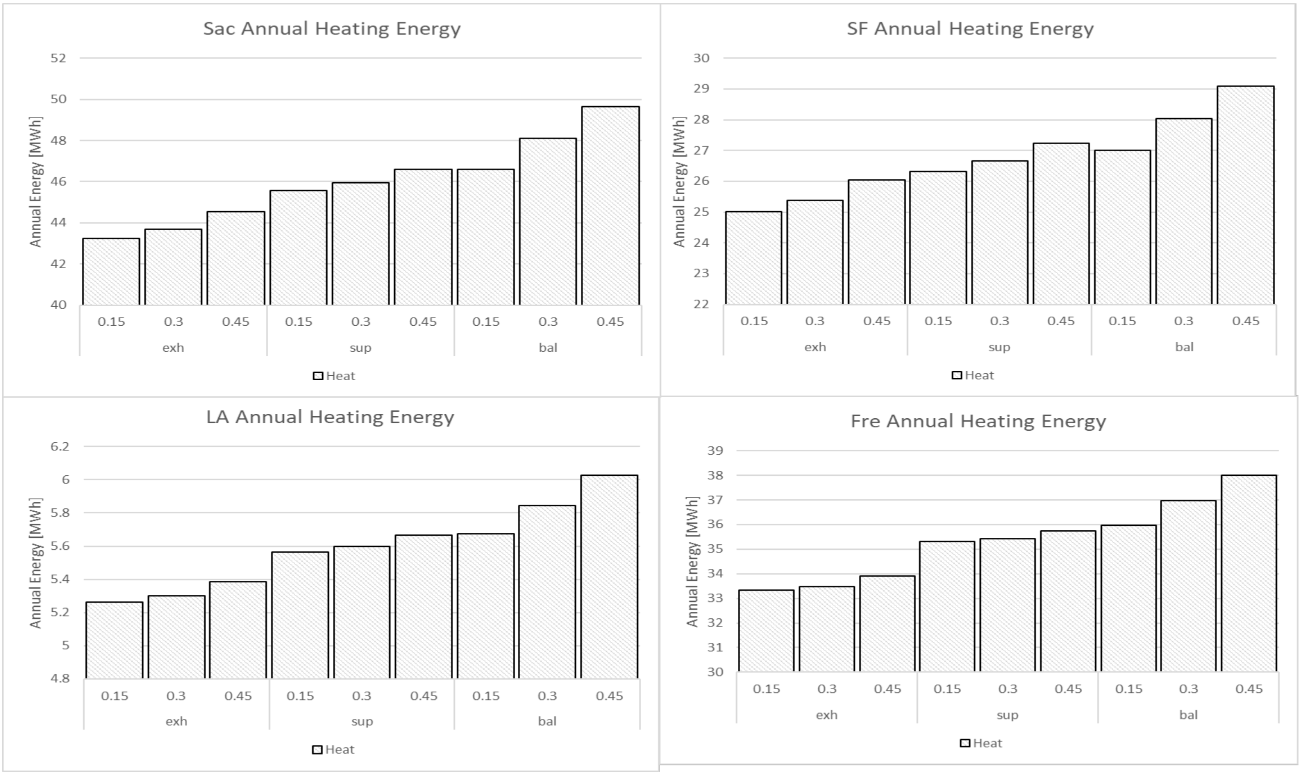


Figure 3.2.26 Heat pump heating energy for different leakage levels and ventilation strategies for four climate zones: Sacramento, San Francisco, Los Angeles, and Fresno (scales are different for each climate zone).

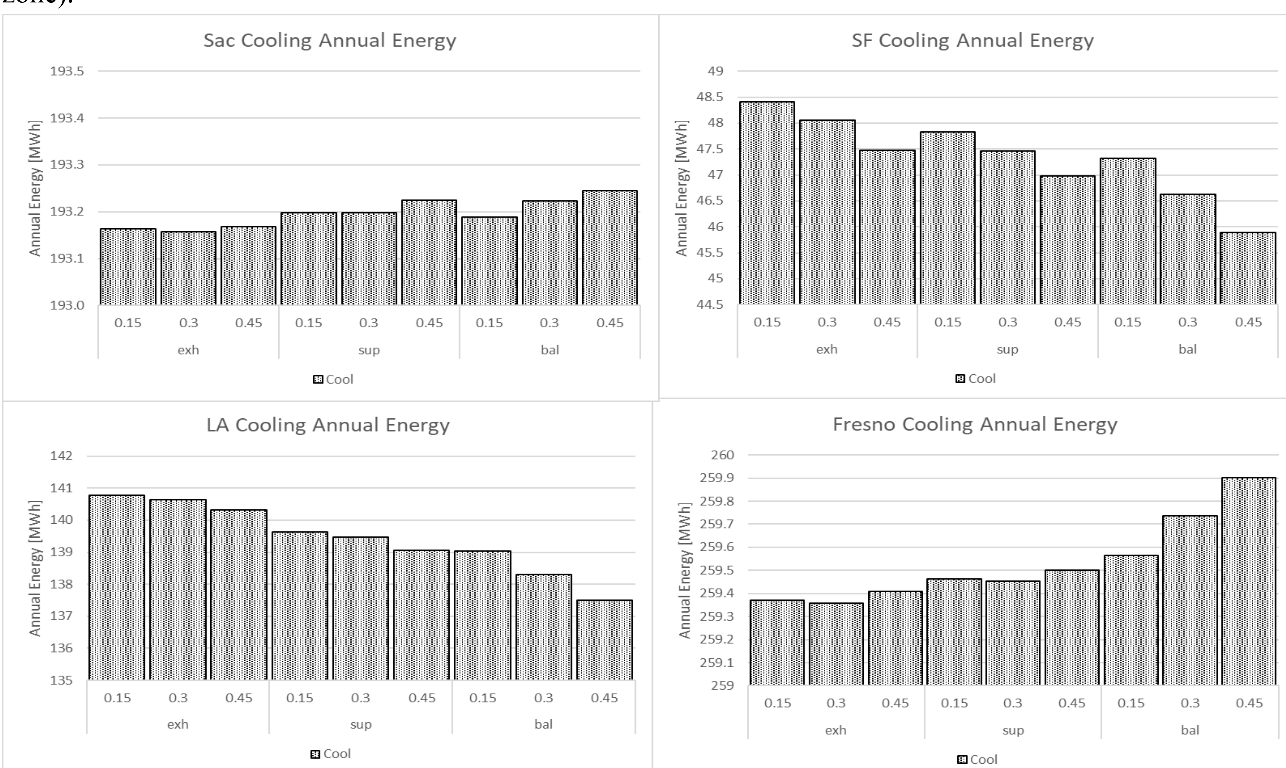


Figure 3.2.27: Heat pump cooling energy for different leakage levels and ventilation strategies for four climate zones: Sacramento, San Francisco, Los Angeles, and Fresno (scales are different for each climate zone, no window opening).

Combining the results in Figures 3.2.26 and 3.2.27, by assuming no window openings (or some form of economizer) to provide free cooling when available, the predicted HVAC energy saving from tightening units (compartmentalization) in most climate zones is very small. The HVAC energy savings from compartmentalization in supply-only and exhaust-only buildings was only a fraction of a percentage point. Balanced buildings had the highest annual HVAC energy savings, which was about 1% when moving from 0.45 cfm_{50}/ft^2 to 0.15 cfm_{50}/ft^2, since the change in infiltration between leakage levels was greatest for the balanced building (see Figure 3.2.28). In Los Angeles, HVAC energy actually increased when the building was tightened. This is because in Los Angeles there are many times when excess infiltration provides "free cooling".

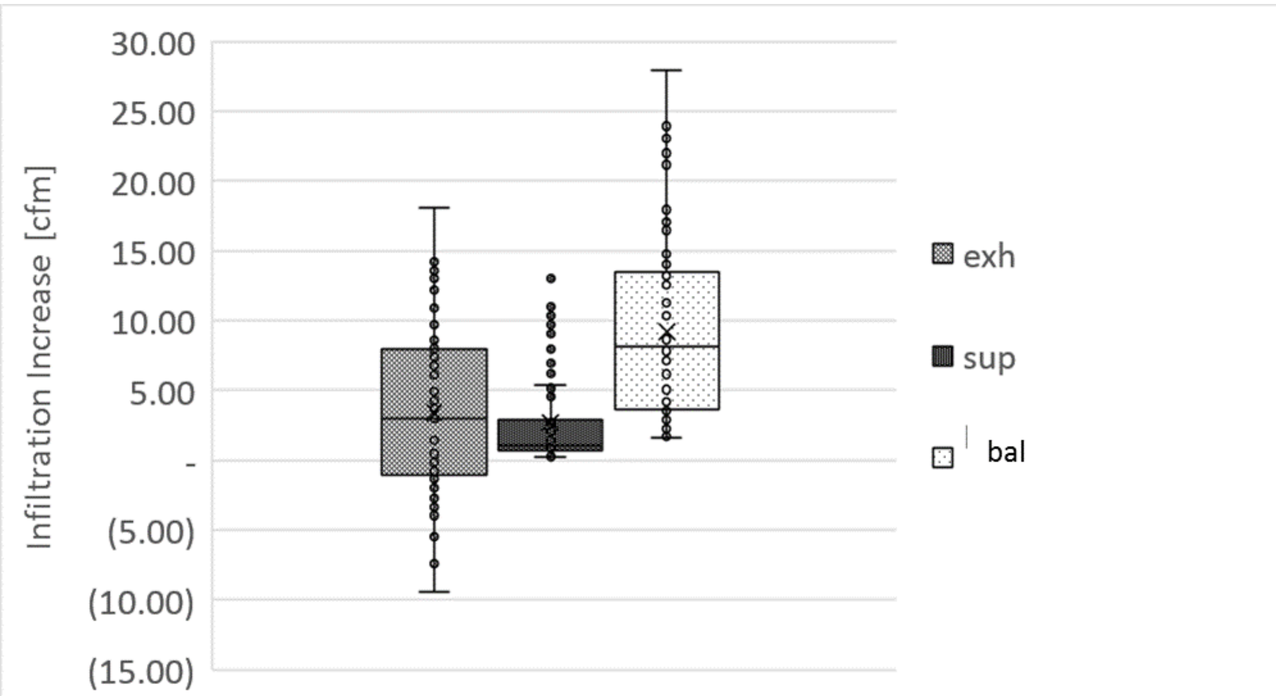


Figure 3.2.28 Impact of unit leakage level (0.45 cfm50/ft^2 versus 0.15 cfm50/ft^2) on unit infiltration for three types of ventilation system using Sacramento weather data. Mean infiltration values at 0.15 cfm50/ft^2 were 2.9, 0.6 and 35.1 cfm for balanced, supply-only and exhaust-only ventilation, respectively.

The complications associated with precise modeling of free cooling were avoided by calculating the relative savings in heating energy, which are not impacted by free cooling, and assuming similar energy savings (by percentage) for cooling energy. The assumption regarding energy savings from heating and cooling due to infiltration is a very simplified one; precise verification will take some additional work. However, the assumption is based on the understanding that 1. the percentage increase in load due to extra infiltration from extra leakage area when the air conditioner is running should be roughly the same as the increase in load due to extra infiltration from extra leakage area when the heat pump is running; 2. load due to infiltration is only a small fraction of the total load. This calculation assumes that residents open windows to take advantage of pleasant outdoor conditions, or use economizers (however economizer energy itself is not modeled). In addition, so as to apply the percentage savings to an appropriate amount of cooling (i.e. to the reduced cooling load seen by the equipment when free cooling by window opening is accounted for), the EnergyPlus cooling loads for each climate zone were recalculated. The methodology was to calculate the indoor and outdoor enthalpies for all hours in which there was a cooling load calculated by EnergyPlus, and then assume that the windows would be open if the outdoor enthalpy was lower than the indoor enthalpy. The magnitude of free cooling provided by the window opening was calculated by assuming that opening windows produced a 200-cfm flow of outdoor air through the units that were cooling during that hour. For each such hour, the free cooling provided was calculated as product of that hour's enthalpy difference and the mass flow associated with 200 cfm. The sum of free cooling for all hours in the year was then compared to the total cooling load for the year for each climate zone to calculate a fractional reduction in cooling loads for each climate zone. The resulting reductions in cooling loads were: 63% for San Francisco, 46% for Los Angeles, and 15% for both Sacramento and Fresno, all of which seem reasonable, considering the climates (e.g. San Francisco now has more heating than cooling). Figure 3.2.29 shows the new resulting breakdown of energy use for each climate. Moreover, this treatment of "free cooling" resulted in the energy response to leakage levels being what was expected – tightening the building resulted in less energy consumption in all climate zones.

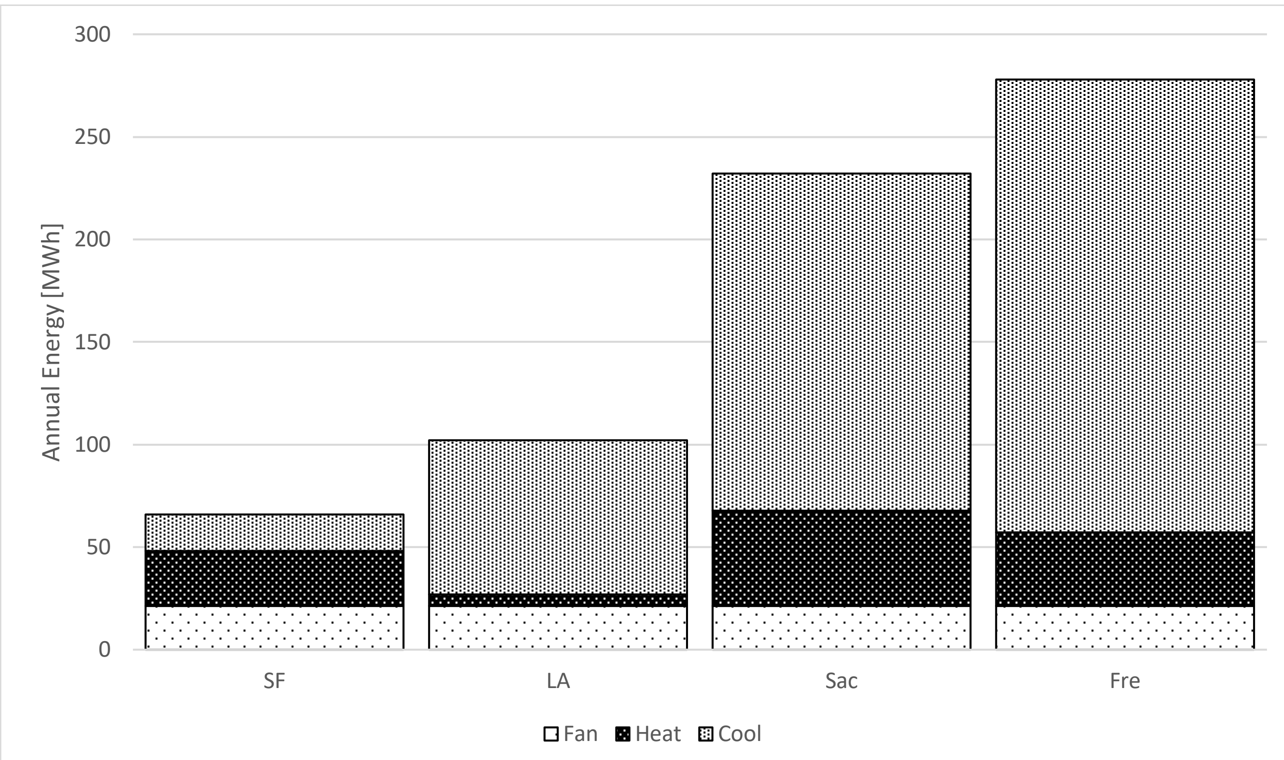


Figure 3.2.29 Annual energy use simulated in EnergyPlus for the four different climate zones: Sacramento ("sac"), San Francisco ("sf"), Los Angeles ("la"), and Fresno ("fre") assuming window openings for free cooling.

The CONTAM balanced building simulations were also used to investigate the impact of adding a 70% efficient heat exchanger to perform heat recovery ventilation in the balanced-ventilation building (see Figure 3.2.30). However, Table 3.2.1 shows that the value of the heat exchanger was highly dependent on climate.

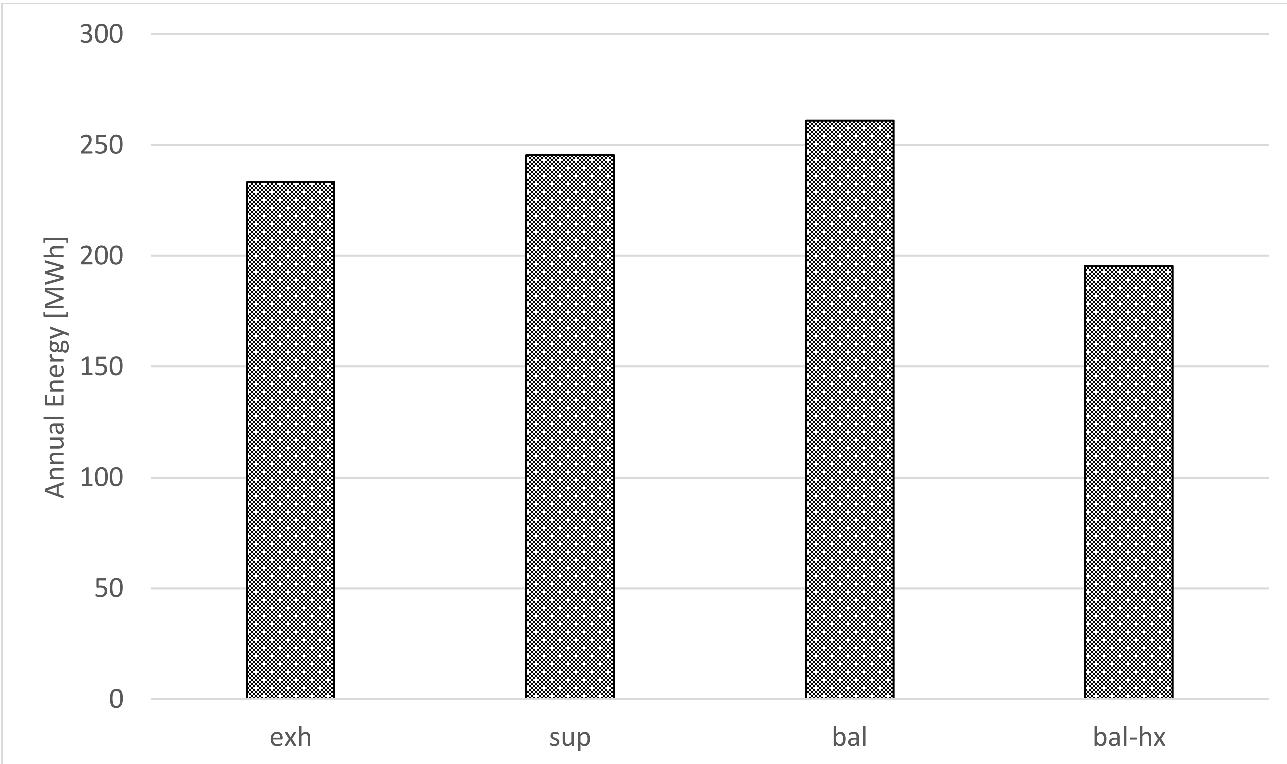


Figure 3.2.30 Annual HVAC energy usage by ventilation strategy, including impact of adding heat recovery to the balanced system ("bal-hx") for a 0.15 cfm_{50}/ft^2 building using Sacramento weather data, with window-opening correction of cooling.

Energy and GHG savings were calculated relative to the balanced ventilation scenario with 0.45 $cfm50/ft^2$ leakage in four climates: Sacramento ("Sac"), San Francisco ("SF"), Los Angeles ("LA"), and Fresno ("Fre"), for four ventilation strategies: balanced ("bal"), balanced with a heat exchanger ("bal-hx"), supply-only and exhaust-only ("exh"), and three leakage levels: 0.15 $cfm50/ft^2$, 0.30 $cfm50/ft^2$ and 0.45 $cfm50/ft^2$ (see Table 3.2.1). Looking first at the impact of compartmentalization, going from 0.45 $cfm50/ft^2$ to 0.15 $cfm50/ft^2$ produces 4-6% savings of HVAC energy and HVAC GHG emissions, producing GHG savings of 10-48 tonnes CO_2e/30 yrs, depending on the climate zone. Moving from a two-fan balanced system to a one-fan supply- or exhaust-only system is shown to save an additional 5-20% of HVAC energy and GHG emissions, producing GHG savings of 35-98 tonnes CO_2e/30 yrs. The largest percentage savings are in the mild climates (LA and SF), and the larger absolute savings are in the harsher climates (Sacramento and Fresno). Finally, including a heat exchanger between the supply and exhaust air in a balanced system was found to save the most HVAC energy and GHG emissions, reducing HVAC energy consumption by 16-26% when applied to a balanced system with 0.15 $cfm50/ft^2$ unit leakage level. GHG emissions are reduced by 41-248 tonnes CO2e/30 yrs by adding the heat exchanger. It should be noted that this analysis does not include any additional pressure losses and associated fan energy increases associated with the heat exchangers. The largest savings occurred in the Central Valley climate zones (Sacramento and Fresno), while the smallest savings occurred in San Francisco, as this climate zone requires very little space conditioning.

Table 3.2.1 Building HVAC Energy Use, 30-yr GHG Emissions and Savings After Correcting for "Free-Cooling" (Relative to Balanced Ventilation Building at 0.45 cfm50/ft²)

Climate	Ventilation	Leakage [cfm50/ft²]	Annual HVAC Energy Use [MWh]	HVAC-Energy (GHG) Savings [%]	GHG Emission Savings [t CO_2e/30 yrs]
Sac	bal	0.15	222	6%	45
Sac	bal	0.3	228	3%	23
Sac	**bal**	**0.45**	**235**		
Sac	bal-hx	0.15	167	29%	231
Sac	exh	0.15	197	16%	130
Sac	sup	0.15	207	12%	96
SF	bal	0.15	65	4%	10
SF	bal	0.3	66	2%	5
SF	**bal**	**0.45**	**67**		
SF	bal-hx	0.15	54	20%	51
SF	exh	0.15	51	24%	60
SF	sup	0.15	53	21%	54
LA	bal	0.15	98	4%	11
LA	bal	0.3	100	2%	6
LA	**bal**	**0.45**	**102**		
LA	bal-hx	0.15	78	23%	67
LA	exh	0.15	82	19%	56
LA	sup	0.15	86	15%	46
Fre	bal	0.15	266	5%	48
Fre	bal	0.3	273	3%	25
Fre	**bal**	**0.45**	**280**		
Fre	bal-hx	0.15	193	31%	296
Fre	exh	0.15	237	15%	146
Fre	sup	0.15	251	10%	100

Operable windows or economizers were necessary to take advantage of "free cooling" conditions in all climate zones and maximize the energy benefits of compartmentalization. Similarly, the energy benefits of heat recovery ventilation are also calculated assuming window openings. Calculating the impact of heat recovery without window openings would result in low savings estimates, as heat would be exchanged during periods when it would be better to not have heat exchange (i.e. loss of free cooling).

Chapter 4: Discussion

Field testing and modeling results for multifamily buildings in California suggest some design practices could be improved to enhance building performance. Field testing of three new-construction multifamily buildings assessed design practices that were working well and those that were working poorly. Modeling of multifamily buildings throughout California was performed to further evaluate how building designs and operating strategies compare to one another.

Field testing was conducted in three multifamily buildings near the end of construction. These buildings reflected common multifamily buildings in California. All three buildings were mid-rise, meaning a building with 4 to 6 occupiable stories. Recent analysis by the Statewide Utilities Codes and Standards Enhancement (CASE) Team shows that mid-rise buildings comprise 58% of square footage in newly constructed multifamily buildings in California [91] [92]. The buildings tested in this study were also a mix of market-rate and affordable housing. The buildings included a mix of ventilation types, including balanced and exhaust-only. Both systems are common in the market. Exhaust-only has been common since mechanical ventilation was required starting in the 2008 version of Title 24, Part 6. Because the 2019 version of Title 24, Part 6 required either balanced ventilation or compartmentalization, balanced ventilation has become more common in recent years. Two of the buildings were site-based construction (traditional), and the third was modular construction. Although modular construction is still much less common than site-based, modular construction is becoming more common, with at least three modular developers active in the Bay Area[i]. In addition, two buildings were constructed targeting compartmentalization and the third used balanced ventilation, representing different compliance paths required in Title 24, Part 6.

All 36 units tested throughout three representative new-construction buildings had total unit leakage levels tighter than the current requirement of 0.3 cfm_{50}/ft^2. The fact that the mean leakage level was half of the current requirement, even though one building was not even targeting any leakage level (it opted to install balanced ventilation), suggests that builders can meet this standard. If desired, tightening the code requirement to 0.2 cfm_{50}/ft^2 should be manageable for builders, since only two (5%) of the units tested had leakage levels greater than 0.2 cfm_{50}/ft^2.

Inter-unit leakage results varied between buildings, since different building designs produce different leakage pathways. Each adjoining surface between units was generally responsible for 7-20% of total unit leakage for traditional (in-situ) construction. For modular construction, vertical inter-unit leakages were similar, ranging from 7-11%, however there was virtually no horizontal air leakage between modular units. It appears that these leakage values are highly dependent on construction practices, ducts and plumbing, and unit geometry (ratio of floor/wall area to total surface area).

Field testing results and conversations with developers suggest several opportunities to improve multifamily building ventilation. First, developers need to thoroughly understand and stay updated on building codes. There was some confusion with one developer misinterpreting the mechanical code (Title 24 – part 4) as requiring greater ventilation rates than the energy code (Title 24 – part 6), when they both reference the same ASHRAE 62.2 ventilation rates [31]. Second, field testing results suggested ventilation flow rates are sometimes not adjusted based on unit size, but rather are set using a one-size-fits-all approach. Building developers estimated that maybe one quarter of contractors opted for the one-size-fits-all approach. This practice is undesirable as it wastes energy by over ventilating some units and encourages pollutant transfer by creating pressures differences between units in unbalanced buildings, since smaller units become more negatively pressurized than larger units with the same ventilation flow rate (i.e., less surface area translates to less total leakage). However, it is understandable given constraints of discrete equipment sizing, and the simplicity of ordering the same equipment for all units, regardless of their size. Finally, the practice of supplying air through unfiltered packaged Heat Pump units allowed outdoor pollutants to transfer directly indoors. This is especially concerning for low-income multifamily buildings, which are often located in areas with poorer outdoor air quality, such as next to highways. However, this last issue should have been addressed starting with the 2019 version of Title 24, part 6, which calls for minimum efficiency reporting value (MERV) 13 filtration of outdoor air.

Inter-unit pollutant transfer was measured to be minimal at the tightness levels in these three buildings. Airflows between units were small under normal operating conditions, since units were relatively tight and pressure differences between units were relatively small. Actions that drove inter-unit transfer, such as turning on kitchen exhaust fans, increased the absolute flow of gaseous pollutants between units, but failed to substantially raise the pollutant concentrations due to dilution from increased infiltration from outdoors. This study also measured PM transfer from unit to unit with the tightness values present in those buildings, and there was no indication of PM transfer from one unit to another from the field measurements. Since all units tested were 0.2 cfm_{50}/ft^2 or tighter, it was not possible to draw conclusions about the transfer of PM in buildings that are constructed with greater leakage between the units, as it was not possible to know if higher leakage levels could translate to non-negligible PM transfer.

Modeling results also suggest that the location of units within a building influences infiltration rate and source of makeup air. In exhaust-only buildings, infiltration was greatest in corner units with relatively large exterior surface areas, and lowest in interior units with small exterior surface areas. Some of the additional air infiltrating into corner units was transferred to neighboring interior units. This effect was exacerbated in leakier buildings and is concerning because it results in some units being overventilated while others being under ventilated. Further tightening common walls between units relative to exterior walls could redirect the source of makeup air flowing into interior units back to the outdoors.

Furthermore, results from CONTAM modeling suggest that the highest indoor pollutant concentrations are due to pollutant sources within the same unit. Overall, pollutant concentrations decreased as ventilation rates increased. Balanced ventilation resulted in the lowest pollutant concentrations in units, closely followed by supply-only ventilation. Exhaust-only ventilation had the lowest unit ventilation rates and highest pollutant concentrations, although the changes due to ventilation strategy were minimal as compared to other parameters (i.e., fan use, proximity to a smoker, unit tightness). Increasing unit leakage levels generally decreased total pollutant concentration (via more dilution from outdoor air) but increased inter-unit transfer of pollutants. Stated another way, not using compartmentalization slightly decreased the concentration of pollutants generated within a unit (~10%), but significantly increased the concentrations of pollutants coming from other units by a factor of 3 to 11 times.

To put the modeled concentrations in context, concentrations were compared to health-relevant levels. The US EPA NAAQS for 1-hour NO_2 is 100 ppb [88]. As shown in Figure 3.2.16, for those units that do not use their kitchen fan during cooking, they consistently have NO_2 concentrations above the standard. All-electric buildings do not have significant indoor NO_2 emissions; however, operation of kitchen exhaust fans is still recommended while cooking to minimize PM and other air pollutants generated from cooking activities. The importance of kitchen exhaust fans to reduce NO_2 concentrations to safe levels was true for all ventilation strategies and all climate zones. Therefore, maintaining healthy pollutant concentrations and reducing exposure could best be achieved by providing sufficient ventilation during the periods when indoor sources are present.

CH_2O concentrations in units were found to be considerably above both the one-in-a-million cancer risk level of 0.13 ppm and the one-in-a-hundred-thousand cancer risk level of 1.3 ppm [89]. Total unit CH_2O average concentrations were more than an order of magnitude above the one-in-a- a-hundred-thousand cancer risk level. Inter-unit transfer of CH_2O, which account for around 10% of the total unit concentration, were above the one-in-a-hundred-thousand cancer potency risk. Although these numbers seem high, they are consistent with similar studies that measured CH_2O in buildings [82, 93].

The implication of reducing unit leakage level was relevant when comparing C6H6 concentrations transferred from units with smokers (Figure 3.2.21). At a unit leakage level of 0.15 cfm_{50}/ft^2, about 90% of units neighboring a smoker had C_6H_6 levels below the one-in-a-million cancer risk level, whereas at a leakage level of 0.45 cfm_{50}/ft^2, only about 50% of units neighboring a smoker had C_6H_6 levels below the one-in-a-million cancer risk level. Therefore, compartmentalization can protect occupants from secondhand smoke transferring between units.

A potential concern for residents might be unpleasant odors entering their unit that originate in other units. While this does not pose a health risk, eliminating odors would be seem to be desirable for the developer and the occupants, and provide another motivation for tightening units. One semi-quantifiable compound to consider is trimethylamine oxide (C_3H_9NO), which can come from cooking fish and can be detected by the human nose at relatively low concentrations, down to 0.5 ppb [94]. Cooking mackerel on a stove generates C_3H_9NO at concentrations of 160 ppb for raw fish, 265 ppb for cooked fish, and 465 ppb for overcooked fish in the vicinity of the stove in the unit doing the cooking [95]. The modeled average maximum hourly concentration of NO_2 in units cooking without a fan was between 100 and 125 ppb, and the NO_2 concentrations directly over the stove were expected to be even higher. Based on the studies reporting C_3H_9NO concentrations over the stove during cooking events [95], it is reasonable to assume the average concentration of C_3H_9NO over an hour is on the same order of magnitude as the modeled NO_2 concentrations in this study. Therefore, the maximum hourly concentration of C_3H_9NO in a unit with someone cooking in an adjacent unit could be around 2.5-7.5 ppb for the 0.15 cfm_{50}/ft^2 leakage level, 3-9 ppb for the 0.3 cfm_{50}/ft^2 leakage level, and 4-10 ppb for the 0.45 cfm_{50}/ft^2 leakage level. These are all higher than the detection limit by the human nose for C_3H_9NO, although this simplified approach likely overestimates the typical fish smell, as mackerel is a variety of fish associated with a particularly strong fishy odor. Therefore, it is possible that good sealing between units could prevent transfer of detectable levels of odor.

It is also worth noting that the EnergyPlus building prototype (balanced ventilation only) used for code change analyses in California showed a significant discrepancy in infiltration rates relative to the code-compliant infiltration simulations performed in CONTAM. The disagreement in infiltration between CONTAM and EnergyPlus suggests that design unit infiltration values in EnergyPlus are overestimated.

Trying to understand this discrepancy, the corridor ventilation assumptions were investigated. The CONTAM model assumed a building that ventilates the corridors with supply air. If corridors were instead outfitted with balanced ventilation systems, then if all the corridor supply air going into units was replaced by outdoor air infiltration, infiltration would have increased by about 10 cfm in each unit on average. However, even if this were the case, unit infiltration rates would be around 10-30 cfm, which is still significantly lower than the EnergyPlus design infiltration rates of 25-80 cfm. Ultimately, performing a co-simulation between the two programs should improve the accuracy of results.

Compartmentalization was modeled to save between 4-6% of annual HVAC energy usage and annual HVAC GHG emissions. While reducing outdoor air infiltrations generally saves energy related to space conditioning, there are many times throughout the year when outdoor infiltration helps to cool down a building, a result that was most prominent in Los Angeles. Therefore, in order to achieve the maximum savings, controlled infiltration (e.g., open windows) is needed alongside compartmentalization. Economizers, while not directly evaluated in this study, serve as a possible automated solution to control outdoor air infiltration and take advantage of favorable outdoor conditions. The biggest rationale for analyzing the performance with this assumption is that otherwise San Francisco is simulated to be a cooling dominated climate, which does not square with practical experience. The practicality and magnitude of savings from economizers are predicted to be climate dependent, with the largest savings occurring in milder climates (San

Francisco and Los Angeles). Similarly, the usefulness of heat recovery ventilation was found to be highly climate-zone dependent, with the value being highest in more extreme climates (Sacramento and Fresno)

The free-cooling energy penalty could be avoided by occupants opening windows during pleasant outdoor conditions or installing economizers (and heat exchangers with bypass valves). These actions significantly save cooling energy loads in all simulated climate zones. However, with warmer temperatures due to climate change, climates like San Francisco may need to be built with cooling equipment moving forward, meaning that the reality would shift towards the original cooling loads simulated in EnergyPlus.

Chapter 5: Summary and Conclusions

Multifamily buildings can be designed in many ways, each of which has associated advantages and disadvantages for building performance. Field testing of three new-construction multifamily buildings and subsequent modeling found opportunities to improve building ventilation, and consequently IAQ, as well as opportunities to save energy, and consequently GHG emissions. Code recommendations from the results of this study are suggested; however, further research is necessary to fully evaluate health and energy impacts in all 16 CA climate zones and ensure code changes are feasible and cost effective.

Overall, field testing found that three new-construction multifamily buildings in California were performing better than expected in terms of total unit leakage and inter-unit pollutant transfer. The average unit leakage was 0.16 cfm_{50}/ft^2, which is almost half as leaky as the compartmentalization level in California's Energy Code (Section 120.1). Also, only small amounts of inter-unit gaseous pollutant transfer were measured, and there was no indication of particulate transfer between units.

Ventilation flow testing found some ventilation flows were inconsistent between design and measured flows were sometimes insufficient to ensure good IAQ. Variations between units was problematic, as it suggested some units were either being overventilated (which is wasteful from an energy perspective) or under ventilated (which is potentially harmful from an IAQ perspective).

While inter-unit transfer of pollutants appeared to be small, compartmentalization did significantly reduce modeled exposure to potential gaseous compounds (such as the gaseous component of secondhand smoke) emitted in one unit, but not others. Furthermore, tightening units might significantly reduce the transfer of odors (e.g., fish smells) possibly below the detection limits of the human nose, which might provide greatest incentive for occupants and developers to pursue compartmentalization.

HVAC Energy and GHG savings from compartmentalization were simulated to be 4-6%. The largest energy savings were associated with installing heat exchangers, which could save up to 26% of HVAC energy in the Central Valley climate zones. While not modeled, economizers appear useful in California's milder climates, in particular San Francisco and Los Angeles. Note the reported energy and GHG savings above ignored the free-cooling penalty (i.e., results assume that occupants open windows or use economizers to increase outdoor air intake during pleasant outdoor conditions). Ignoring this penalty seems reasonable, as not ignoring it produces results indicating that San Francisco apartments are cooling dominated.

Chapter 6: Recommendations

6.1 Recommendations for Future Studies

There may be more effective ways to control indoor concentrations of pollutants than constant ventilation rates, and they warrant future research. Ventilation systems that monitor pollutant concentrations and automatically adjust ventilation rates to maintain concentrations below safe levels could improve IAQ while decreasing energy usage (by never over ventilating a space). Similarly, intermittent kitchen and bathroom exhaust fans that automatically turn on when they detect heat or moisture could be effective at preventing mold in bathrooms and removing pollutants generated from cooking. This is a common practice in many European countries. While smart ventilation systems were not evaluated in this study, they are emerging technologies that have the potential to improve IAQ and save energy in buildings.

Although not the focus of this study, heat exchangers and economizers appeared to save a significant amount of HVAC energy in certain climate zones. Heat exchangers were modeled to save a significant amount of HVAC energy in the Central Valley climate zones, while economizers appeared to be able to take advantage of "free cooling" conditions, most prominently in Los Angeles and likely San Diego. More detailed studies evaluating the appropriateness of these technologies in different CA climate zones would be useful to inform whether they should be considered in future building codes.

Finally, it should be noted that this research did not evaluate cost effectiveness, which would obviously need to be examined for proper code change proposals.

6.2 Recommendations for Future Building Codes

Data from this study suggest that new-construction multifamily buildings appear to be consistently meeting the compartmentalization requirement of 0.3 cfm_{50}/ft^2. Therefore, this current unit leakage level is achievable, and a 0.2 cfm_{50}/ft^2 requirement appears manageable, since 95% of tested units had leakage below this value. A tighter compartmentalization requirement within the building code should be considered, since modeling data suggests that further tightening could reduce inter-unit transfer of secondhand smoke and save HVAC energy and GHG emissions in multifamily buildings. The only downside of tightening the code is a small increase in the concentration of pollutants generated within a unit (~10%), which seems to be outweighed by a 3-11 times reduction in the concentration of pollutants generated in other units.

In an exhaust-only building, makeup air entering a unit can contain high pollutant concentrations if there are pollution sources inside or outside of the building. This result support recent Title 24 changes requiring all intentional supply/makeup airflow paths include air filters to remove harmful PM from entering units. This measure should improve IAQ in exhaust-only building, which were simulated to have slightly worse air quality than supply or balanced ventilation alternatives.

References

[1] CARB, "History," 2022. [Online]. Available: https://ww2.arb.ca.gov/about/history.

[2] Z. Chen, . M. T. Salam, . S. P. Eckel, . C. V. Breton and F. D. Gilliland, "Chronic Effects of Air Pollution on Respiratory Health in Southern California Children: Findings from the Southern California Children's Health Study," *Journal of Thoracic Disease,* pp. 46-58, 2015.

[3] G. Adamkiewicz, A. R. Zota, P. M. Fabian, T. Chahine, R. Julien, J. D. Spengler and J. I. Levy, "Moving Environmental Justice Indoors: Understanding Structural Influences on Residential Exposure Patterns in Low-Income Communities," *American Journal of Public Health,* pp. S238-S245, 2011.

[4] C. H. Lozinsky and M. F. Touchie, "Inter-Zonal Airflow in Multi-Unit Residential Buildings: A Review of the Magnitude and Interaction of Driving Forces, Measurement Techniques and Magnitudes, and its Impact on Building Performance," *Indoor Air,* pp. 1083-1108, 2020.

[5] M. J. Hewett, . S. D. Sandell, J. Anderson and M. Niebuhr, "Secondhand Smoke in Apartment Buildings: Renter and Owner or Manager Perspectives," *Nicotine & Tobacco Research,* p. S39–S47, 2007.

[6] CARB, "Climate Change," 2022. [Online]. Available: https://ww2.arb.ca.gov/our-work/topics/climate-change.

[7] CARB, "Building Decarbonization," 2022. [Online]. Available: https://ww2.arb.ca.gov/our-work/programs/building-decarbonization/about.

[8] U.S. Census Bureau, "Building Permits Survey," 2020. [Online]. Available: https://www.census.gov/construction/bps/stateannual.html.

[9] ICC, "International Building Code," International Code Council, Washington, D.C., USA, 2018.

[10] M. A. Hossain , A. Zhumabekova, S. C. Paul and J. R. Kim , "A Review of 3D Printing in Construction and its Impact on the Labor Market," *Sustainability,* p. 8492, 2020.

[11] Z. Li, G. Q. Shena and X. Xue, "Critical Review of the Research on the Management of Prefabricated Construction," *Habitat International,* pp. 240-249, 2014.

[12] M. Kamali and K. Hewage, "Life Cycle Performance of Modular Buildings: A Critical Review," *Renewable and Sustainable Energy Reviews,* pp. 1171-1183, 2016.

[13] K. Ueno, J. Lstiburek and D. Bergey, "Multifamily Ventilation Retrofit Strategies," U.S. Department of Energy, Oak Ridge, TN, USA, 2012.

[14] ASHRAE, "Standard 62.1, Ventilation for Acceptable Indoor Air Quality," ANSI, Atlanta, GA, USA, 2019.

[15] G. Guyot, M. H. Sherman and I. S. Walker, "Smart Ventilation Energy and Indoor Air Quality Performance in Residential Buildings: A Review," *Energy and Buildings,* pp. 416-430, 2018.

[16] J. Jokisalo, J. Kurnitski, M. Vuolle and A. Torkki, "Performance of Balanced Ventilation with Heat Recovery in Residential Buildings in a Cold Climate," *International Journal of Ventilation,* pp. 223-236, 2016.

[17] M. Lubliner and I. Walker, "Residential Ventilation Systems," *ASHRAE Journal,* pp. 70-74, 2020.

[18] J. E. Lovatt and A. G. Wilson, "Stack Effect in Tall Buildings," U.S. Department of Energy, Washington, D.C., USA, 1994.

[19] R. C. Diamond, H. E. Feustel and D. J. Dickerhoff, "Ventilation and Infiltration in High-Rise Apartment Buildings," Lawrence Berkeley Labratory, Berkeley, CA, USA, 1996.

[20] L. Palmiter, P. W. Francisco and T. Bond, "Infiltration and Ventilation Measurements on Three Electrically Heated Multifamily Buildings," U.S. Department of Energy, Office of Science and Technical Information, 1996.

[21] I. S. Walker, M. H. Sherman, J. Joh and W. R. Chan, "Applying Large Datasets toDeveloping a Better Understanding of Air Leakage Measurement in Homes, *International Journal of Ventilation,* pp. 323-338, 2013.

[22] DOE, "Air Sealing for New Home Construction," 2022. [Online]. Available: https://www.energy.gov/energysaver/air-sealing-new-home-construction.

[23] ASTM, "Standard Test Method for Determining Air Leakage Rate by Fan Pressurization," ASTM E779, West Conshohocken, PA, USA, 2019.

[24] DOE, "Blower Door Tests," 2022. [Online]. Available: https://www.energy.gov/energysaver/blower-door-tests.

[25] D. Bohac and L. Sweeney, "Energy Code Field Studies: Low-Rise Multifamily Air Leakage Testing," Center for Energy and Environment, Minneapolis, MN, USA, 2020.

[26] IECC, "2012 International Energy Conservation Code, Section 402.4 "Air Leakage"," International Code Council (ICC), Washington, D.C., USA, 2012.

[27] S. Klocke, O. Faakye and S. Puttagunta, "Challenges of Achieving 2012 IECC Air Sealing Requirements in Multifamily Dwellings," NREL, Golden, CO, USA, 2014.

[28] K. Ueno and J. W. Lstiburek, "Field Testing of Compartmentalization Methods for Multifamily Construction," National Renewable Energy Lab, Golden, CO, USA, 2015.

[29] E. T. Harrje, D. L. Bohac and D. Feuerman, "Extended Testing of a Multifamily Building Using Constant Concentration and PFT methods," *Proceedings of the 9th AIVC Conference, International Energy Acency Air Infiltration and Ventilation Center, Ghent, Belgium,* pp. 193-212, 1988.

[30] CEC, "Building Energy Efficiency Standards for Residential and Nonresidential Buildings," California Energy Comission, Sacramento, CA, USA, 2019.

[31] ASHRAE, "Standard 62.2, Ventilation and Acceptable Indoor Air Quality in Residential Buildings," ASHRAE, Atlanta, GA, USA, 2019.

[32] C. Harrington and M. Modera, "Achieving and Certifying Building Envelope Air Tightness with an Aerosol-Based Automated Sealing Process," Western Cooling Efficiency Centeer, Davis, CA, 2013.

[33] EPA, "Report to Congress on indoor air quality: Volume 2 Assessment and Control of Indoor Air Pollution," US EPA, Washington D.C., USA, 1989.

[34] N. E. Klepeis, W. C. Nelson, W. R. Ott, J. P. Robinson, A. M. Tsang, P. Switzer, J. V. Behar, S. C. Hern and W. H. Engelmann, "The National Human Activity Pattern Survey (NHAPS): a Resource for Assessing Exposure to Environmental Pollutants," *Journal of Exposure Science & Environmental Epidemiology,* p. 231–252, 2001.

[35] A. P. Jones, "Indoor Air Quality and Health," *Atmospheric Environment,* pp. 4535-4564, 1999.

[36] C. J. Weschler, "Changes in indoor pollutants since the 1950s," *Atmospheric Environment ,* pp. 153-169, 2009.

[37] U.S. Department of Health Services, "The Health Consequences of Involuntary Exposure to Tobacco Smoke: A Report of the Surgeon General," Centers for Disease Control and Prevention, Atlanta, GA, USA, 2006.

[38] CARB, "Proposed Identification of Environmental Tobacco Smoke as a Toxic Air Contaminant," State of California, Sacramento, CA, USA, 2005.

[39] EPA, "Respiratory Health Effects of Passive Smoking: Lung Cancer and Other Disorders," EPA, Washington, D.C., USA, 1992.

[40] EPA, "Health Effects of Passive Smoking: Assesment of Lung Cancer in Adults, and Respiratory Disorders in Children," U.S. Environmental Protection Agency, Washington, D.C., USA, 2002.

[41] Cal EPA, "Health Effects of Exposure to Environmental Tobacco Smoke," *Tobacco Control,* vol. 6, no. 4, pp. 346-353, 1997.

[42] L. M. Holmes, J. D. Llamas and P. M. Ling, "Drifting Tobacco Smoke Exposure Among Young Adults in Multiunit Housing," *Journal of Community Health,* vol. 45, no. 2, pp. 319-328, 2020.

[43] M. J. Hewett, S. D. Sandell, J. Anderson and M. Niebuhr, "Secondhand Smoke in Apartment Buildings: Renter and Owner or Manager Perspectives," *Nicotine & Tobacco Research,* vol. 9, no. 1, pp. 39-47, 2007.

[44] B. A. King, S. D. Babb, M. A. Tynan and R. B. Gerzoff, "National and State Estimates of Secondhand Soke Infiltration Among U.S. Multiunit Housing Residents," *Nicotine Tobacco Research,* vol. 15, no. 7, pp. 1316-1321, 2013.

[45] K. M. Wilson, J. D. Klein, A. K. Blumkin, M. Gottlieb and J. P. Winickoff, "Tobacco-Smoke Exposure in Children Who Live in Multiunit Housing," *Pediatrics,* vol. 127, no. 1, pp. 85-92, 2011.

[46] D. L. Bohac, S. K. Hewett, K. S. Hammond and D. T. Grimsrud, "Secondhand Smoke Transfer and Reductions by Air Sealing and Ventilation in Multiunit Buildings: PFT and Nicotine Verification," *Indoor Air,* vol. 21, pp. 36-44, 2011.

[47] B. A. King, M. J. Travers, K. M. Cummings, M. C. Mahoney and A. J. Hyland, "Secondhand Smoke Transfer in Multiunit Housing," *Nicotine & Tobacco Research,* vol. 12, no. 11, pp. 1133-1141, 2010.

[48] NIST, "CONTAM," 2021. [Online]. Available: https://www.nist.gov/services-resources/software/contam.

[49] S. J. Emmerich, C. Howard-Reed and A. Gupte, "Modelling the IAQ impact of HHI Interventions in Inner-City Housing," National Institute of Standards and Technology, 2005.

[50] L. J. Underhill, W. S. Dola, S. K. Lee, M. P. Fabian and J. I. Levy, "Quantifying the impact of housing interventions on indoor air quality and energy consumption using coupled simulation models," *Journal of Exposure Science Environmental Epidemiology,* vol. 30, no. 3, pp. 436-447, 2020.

[51] K. C. Coombs, G. L. Chew, C. Schaffer, P. H. Ryan, C. Brokamp, S. A. Grinshpun, G. Adamkiewicz, S. Chillrud, C. Hedman, M. Colton, J. Ross and T. Reponen, "Indoor Air Quality in Green-Renovated vs. Non-Green Low-Income Homes of Children Living in a Temperate Region of the US (Ohio)," *Science of the Total Environment,* pp. 178-185, 2016.

[52] A. Rastogi, J. K. Choi, T. Hong and M. Lee, "Impact of Different LEED Versions for Green Building Certification and Energy Efficiency Rating System: A Multifamily Midrise Case Study," *Applied Energy,* no. 205, pp. 732-740, 2017.

[53] EIA, "How Much Energy Is Consumed in U.S. Buildings," 2022. [Online]. Available: https://www.eia.gov/tools/faqs/faq.php?id=86&t=1.

[54] EPA, "Sources of Greenhouse Gas Emissions," 2022. [Online]. Available: https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions.

[55] EIA, "Household Energy Use in California: A Closer Look at Residential Energy Consumption," 2009. [Online]. Available: https://www.eia.gov/consumption/residential/reports/2009/state_briefs/pdf/ca.pdf.

[56] EIA, "2020 Average Monthly Bill- Residential," 2020. [Online]. Available: https://www.eia.gov/electricity/sales_revenue_price/pdf/table5_a.pdf.

[57] C. Otis and S. Maxwell, "Measure Guideline: Air Sealing Attics in Multifamily Buildings," U.S. Department of Energy, Oak Ridge, TN, USA, 2012.

[58] J. H. Jo, J. H. Lim, S. Y. Song, M. S. Yeo and K. W. Kim, "Characteristics of Pressure Distribution and Solution to the Problems Caused by Stack Effect in High-Rise Residential Buildings," *Building and Environment,* pp. 263-277, 2007.

[59] M. Carlsson, M. Touchie and R. Richman, "A Compartmentalization & Ventilation System Retrofit Strategy for High-Rise Residential Buildings in Cold Climates," *Energy Procedia,* no. 132, pp. 867-872, 2017.

[60] DOE, "EnergyPlus," 2022. [Online]. Available: https://energyplus.net.

[61] G. Torvestad and N. Stone, "Unique Multifamily Buildings Proposed Energy Code Measures," California Energy Commission, Folosm, CA, USA, 2018.

[62] E. Mata, A. S. Kalagasidis and F. Johnsson, "A Modelling Strategy for Energy, Carbon, and Cost Assessments of Building Stocks," *Energy and Buildings,* no. 56, pp. 100-108, 2013.

[63] S. J. Emmerich, T. P. McDowell and W. Anis, "Investigation of the Impact of Commercial Building Envelope Airtightness on HVAC Energy Use," U.S. Department of Commerce, 2005.

[64] TEC, "Model 3 Minneapolis Blower Door," 2017. [Online]. Available: http://energyconservatory.com/wp-content/uploads/2017/08/Blower-Door-Overview-Booklet.pdf.

[65] TEC, "Minneapolis Duct Blaster," 2016. [Online]. Available: https://energyconservatory.com/wp-content/uploads/2016/06/Duct-Blaster-Brochure.pdf.

[66] TEC, "DG-1000 Pressure AND Flow Gague," 2016. [Online]. Available: http://energyconservatory.com/wp-content/uploads/2016/09/DG-1000-Overview-Booklet.pdf.

[67] TEC, "DG-700 Pressure and Flow Gague DG-500 Pressure Gague TEC WiFi Link," 2016. [Online]. Available: https://energyconservatory.com/wp-content/uploads/2016/06/Gauge-and-WiFi-Link-Brochure.pdf.

[68] Alicat Scientific, "MC–Series: Gas Mass Flow Controllers," 2022. [Online]. Available: https://www.alicat.com/models/mc-gas-mass-flow-controllers/.

[69] Amphenol, "Telaire T6713 Series," 2022. [Online]. Available: https://www.amphenol-sensors.com/en/telaire/co2/525-co2-sensor-modules/3399-t6713.

[70] Onset, "MX1102A," 2022. [Online]. Available: https://www.onsetcomp.com/products/data-loggers/mx1102a/.

[71] TEC, "TECLOG4," 2022. [Online]. Available: https://energyconservatory.com/downloads/teclog3/.

[72] Aeroseal, "AeroBarrier," 2022. [Online]. Available: https://aeroseal.com/aerobarrier/.

[73] W. S. Dols, S. J. Emmerich and B. J. Polidoro , "Coupling the Multizone Airflow and Contaminant Transport Software CONTAM with EnergyPlus Using Co-Simulation," *Builidng Simulations,* p. 469–479, 2016.

[74] M. Goebes, R. Grindrod, G. McLaughlin, M. Nakajima, N. Perry, E. McCollum, D. Springer, A. German, J. Peralta, N. Dichter, C. Harrington and N. Young, "Multifamily Indoor Air Quality," Codes & Standards Enhancement (CASE) Initative 2022 California Energy Code, 2022-MF-IAQ-F, October2020.

[75] R. S. Miller and D. Beasley, "On Stairwell and Elevator Shaft Pressurization for Smoke Control in Tall Buildings," *Building and Environment,* pp. 1306-1317, 2009.

[76] W. R. Chan, Y. S. Kim, B. D. Less, B. C. Singer and I. S. Walker, "Ventilation and Indoor Air Quality in New California Homes with Gas Appliances and Mechanical Ventilation," LBNL, Berkeley, CA, USA, 2019.

[77] J. M. Logue, . N. E. Klepeis, . A. B. Lobscheid and B. C. Singer, "Pollutant Exposures from Natural Gas Cooking Burners: A Simulation-Based Assessment for Southern California," *Environmeltal Health Perspective,* p. 43–50, 2014.

[78] B. C. Singer, M. G. Apte, D. R. Black, T. Hotchi, D. Lucas, M. M. Lunden, A. G. Mirer, M. Spears and D. P. Sullivan, "Natural Gas Variability in California: Environmental Impacts and Device Performance Experimental Evaluation of Pollutant Emissions from Residential Appliances," LBNL, Berkeley, CA, USA, 2009.

[79] S. E. Alexeeff, A. Roy, J. Shan, X. Liu, K. Messier, J. S. Apte, C. Portier, S. Sidney and S. K. Van Den Eeden , "High-Resolution Mapping of Traffic Related Air Pollution with Google Street View Cars and Incidence of Cardiovascular Events within Neighborhoods in Oakland, CA," *Environmental Health,* pp. 1-13, 2018.

[80] Y. Wang, M. J. Bechle, S.-Y. Kim, P. J. Admans, S. N. Pandis, C. A. Pope, A. Robinson, L. Sheppard, A. A. Szpiro and J. D. Marshall, "Spatial decompsoition analysis of NO2 and PM2.5 air pollution in the United States," *Atmospheric Environment ,* vol. 241, 117470, 2020.

[81] E. V. Novotny, M. J. Bechle, D. B. Millet and J. D. Marshall, "National Satellite-Based Land-Use Regression: NO2 in the United States," *Environmental Science & Technology,* vol. 45, pp. 4407-4414, 2011.

[82] E. L. Hult, H. Willem, P. N. Price, T. Hotchi, M. L. Russell and B. C. Singer, "Formaldehyde and Acetaldehyde Exposure Mitigation in US Residences: In-Home Measurements of Ventilation Control and Source Control," *Indoor Air,* pp. 525-535, 2014.

[83] W. W. Nazaroff and B. C. Singer, "Inhalation of Hazardous Air Pollutants from Environmental Tobacco Smoke in US Residences," *Journal of Exposure Science & Environmental Epidemiology,* pp. S71-S77, 2004.

[84] S. M. Charles, S. A. Batterman and C. Jia, "Composition and Rmissions of VOCs in Main- and Side-Stream Smoke of Research Cigarettes," *Atmospheric Environment,* pp. 5371-5384, 2007.

[85] DOE, "Weather Data by Country," 2022. [Online]. Available: https://energyplus.net/weather-region/north_and_central_america_wmo_region_4/USA/CA-Zones.

[86] NIST, "CONTAM Weather File Creator 2.0," 2022. [Online]. Available: https://pages.nist.gov/CONTAM-apps/webapps/WeatherTool/index.htm.

[87] E3, "Time Dependent Valuation of Energy for Developing Building Efficiency Standards," Energy + Environmental Economics, San Francisco, USA, 2020.

[88] EPA, "Primary National Ambient Air Quality Standards (NAAQS) for Nitrogen Dioxide," 2022. [Online]. Available: https://www.epa.gov/no2-pollution/primary-national-ambient-air-quality-standards-naaqs-nitrogen-dioxide.

[89] OEHHA, "Formaldehyde," 2022. [Online]. Available: https://oehha.ca.gov/chemicals/formaldehyde.

[90] EPA, "Benzene," 2003. [Online]. Available: https://iris.epa.gov/ChemicalLanding/&substance_nmbr=276.

[91] WSP, "Modular Construction for Multifamily Housing," 2018.

[92] TRC Advanced Energy, "Multifamily Prototypes," Southern California Edison, Rosemead, 2019.

[93] B. Li, Z. Cheng, R. Yao, H. Wang, W. Yu, Z. Bu, J. Xiong, T. Zhang, E. Essah, Z. Luo, M. Shahrestani and H. Kipen, "An investigation of Formaldehyde Concentration in Residences and the Development of a Model for the Prediction of its Emission Rates," *Building and Environment,* pp. 540-550, 2019.

[94] S. C. Mitchell and R. L. Smith, "Trimethylamine - The Extracorporeal Envoy," *Chemical Senses,* p. 275–279, 2016.

[95] J.-H. Ahn, J. E. Szulejko, K.-H. Kim, Y.-H. Kim and B.-W. Kim, "Odor and VOC Emissions from Pan Frying of Mackerel at Three Stages: Raw, Well-Done, and Charred," *International Journal of Environmental Research and Public Health,* p. 11753–11771, 2014.

[96] P. Wu, J. Wang and X. Wang, "A Critical Review of the Use of 3-D Printing in the Construction Industry," *Automation in Construction,* pp. 21-31, 2016.

[97] P. N. Price, A. Shehabi, R. W. Chan and A. J. Gadgil, "Indoor-Outdoor Air Leakage of Apartments and Commercial Buildings," Lawrence Berkeley National Laboratory, Berkeley, CA, USA, 2006.

[98] M. P. Modera, R. C. Diamond and J. T. Brunsell, "Improving Disgnostics and Energy Analysis for Multifamily Buildings: A Case Study," Lawrence Berkeley Labratory, Berkeley, CA, USA, 1986.

[99] L. J. Underhill, W. S. Dols, S. K. Lee, M. P. Fabian and J. I. Levy, "Quantifying the Impact of Housing Interventions on Indoor Air Quality and Energy Consumption Uisng Coupled Simulation Models," *Journal of Exposure Science & Environmental Epidemiology,* vol. 30, no. 3, pp. 436-447, 2020.

Glossary

ACH	Air Changes per Hour
ARB	Air Resources Board
ASHRAE	American Society of Heating, Refrigerating, and Air Conditioning Engineers
C	Celsius
C_6H_6	Benzene
CH_2O	Formaldehyde
C_3H_9NO	Trimethylamine Oxide
CA	California
CARB	California Air Resources Board
CASE	Statewide Codes and Standards Enhancement
cfm	Cubic Feet per Minute
CO	Carbon Monoxide
CO_2	Carbon Dioxide
F	Fahrenheit
ft^2	Square Feet
GHG	Greenhouse Gas
HRV	Heat Recovery Ventilators
HVAC	Heating, Ventilating, and Air Conditioning
I/O Ratio	Indoor / Outdoor Ratio
IAQ	Indoor Air Quality
IECC	International Energy Conservation Code
LEED	Leadership in Energy and Environmental Design
MERV	Minimum Efficiency Reporting Value
MWh	Mega Watt hours
$MMTCO_2e$	Million Metric Tons of Carbon Dioxide
NAAQS	National Ambient Air Quality Standards
NHANES	National Health and Nutrition Examination
NO_2	Nitrogen Dioxide
Pa	Pascal

PFT	Perfluorocarbon Tracers
PM	Particulate Matter
ppb	Parts Per Billion
ppm	Parts Per Million
PTAC	Packaged Terminal Air Conditioning
PTHP	Packaged Terminal Heat Pump
QA/QC	Quality Assurance / Quality Control
RH	Relative Humidity
SLPM	Standard Liter per Minute
SD	Standard Deviation
T	Temperature
TDV	Time Dependent Valuation
µg	Microgram
US	United States
US EPA	United States Environmental Protection Agency

APPENDIX A

AEROBARRIER
Air Sealing Technology from Aeroseal

ENVELOPE SEALING REPORT

Envelope Sealing Performed For:

Unit 409
Oakland, CA 94621

AEROBARRIER CASE ID: 8052

HARDWARE: AeroBarrier

DATE:
6/16/2021

BUILDING TYPE:
Apartment

Envelope Sealing Results:

BEFORE SERVICE

602.5 CFM of Leakage, equivalent to a
72.5 Square Inch Hole or
5.28 Air Changes per Hour

(for your 775 square-foot structure
enclosing a volume of 6850 cubic feet)

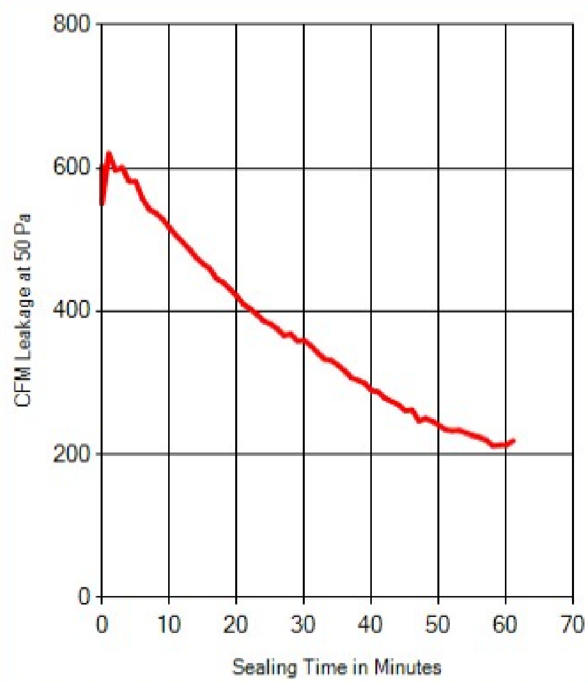
AFTER SERVICE

218.9 CFM of Leakage, equivalent to a
26.4 Square Inch Hole or
1.92 Air Changes per Hour

This corresponds to a
**63.7% Reduction
in Envelope Leakage**

NOTE: Envelope leakage and air-change results are calculated at a standard pressure of 50 Pa.

Envelope Sealing Progress:



Envelope Sealing Performed By:

CALBARRIER

CalBarrier
155 Novato Drive
Vacaville, Ca 95688
Phone: 530 545-1138

Figure A1. Air sealing report for unit 409 in Building A.

AEROBARRIER
Air Sealing Technology from Aeroseal

ENVELOPE SEALING REPORT

Envelope Sealing Performed For:

Unit 509
Oakland, CA 94621

DATE:
6/17/2021

BUILDING TYPE:
Apartment

AEROBARRIER CASE ID: 8052

HARDWARE: AeroBarrier

Envelope Sealing Results:

BEFORE SERVICE

659.1 CFM of Leakage, equivalent to a
79.4 Square Inch Hole or
5.77 Air Changes per Hour

(for your 775 square-foot structure
enclosing a volume of 6850 cubic feet)

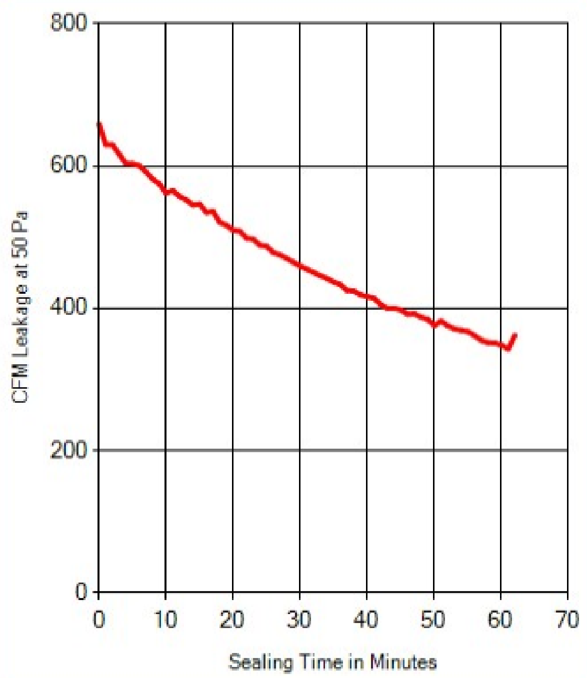
AFTER SERVICE

361.9 CFM of Leakage, equivalent to a
43.6 Square Inch Hole or
3.17 Air Changes per Hour

This corresponds to a
45.1% Reduction
in Envelope Leakage

NOTE: Envelope leakage and air-change results are calculated at a standard pressure of 50 Pa.

Envelope Sealing Progress:



Envelope Sealing Performed By:

CALBARRIER

CalBarrier
155 Novato Drive
Vacaville, Ca 95688
Phone: 530 545-1138

Figure A2. Air sealing report for unit 509 in Building A.

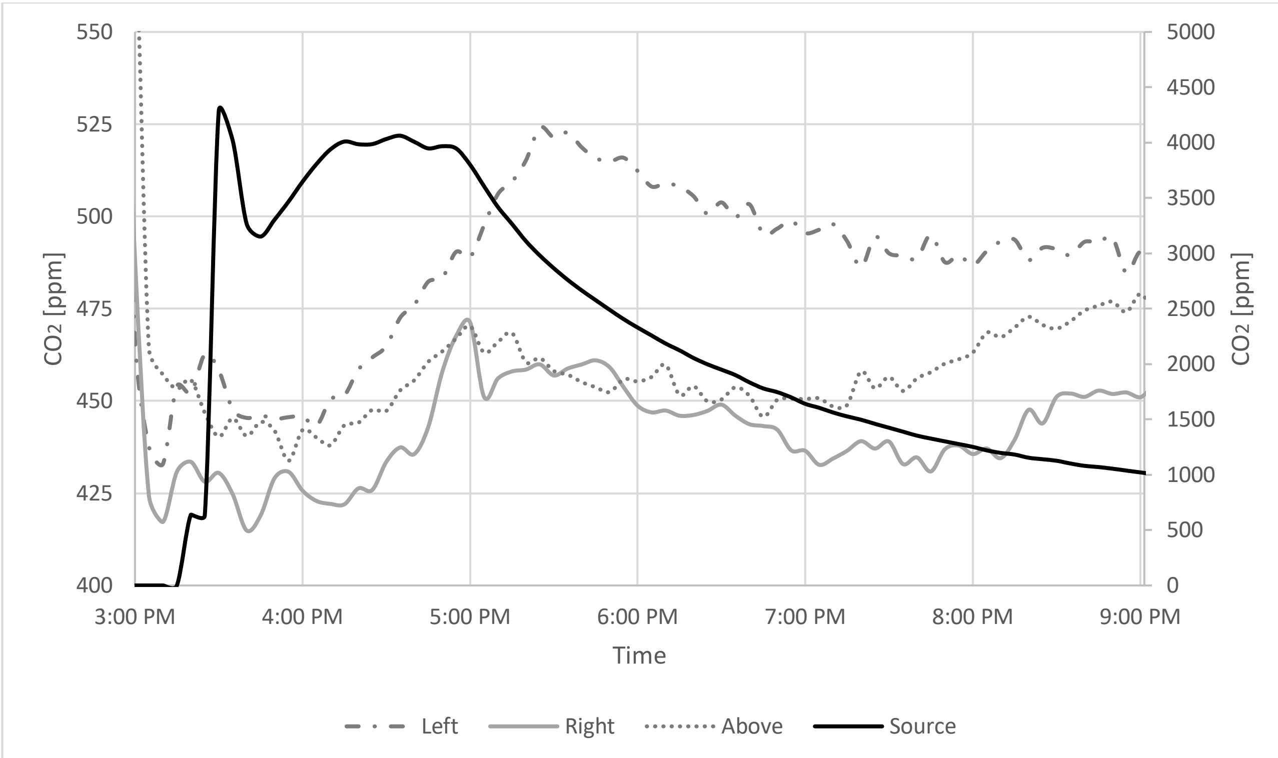


Figure A3. CO_2 concentrations in the source unit on the 4th floor in Building A and in adjacent units with kitchen exhaust fans on. (Source line is referenced to the right-side Y axis)

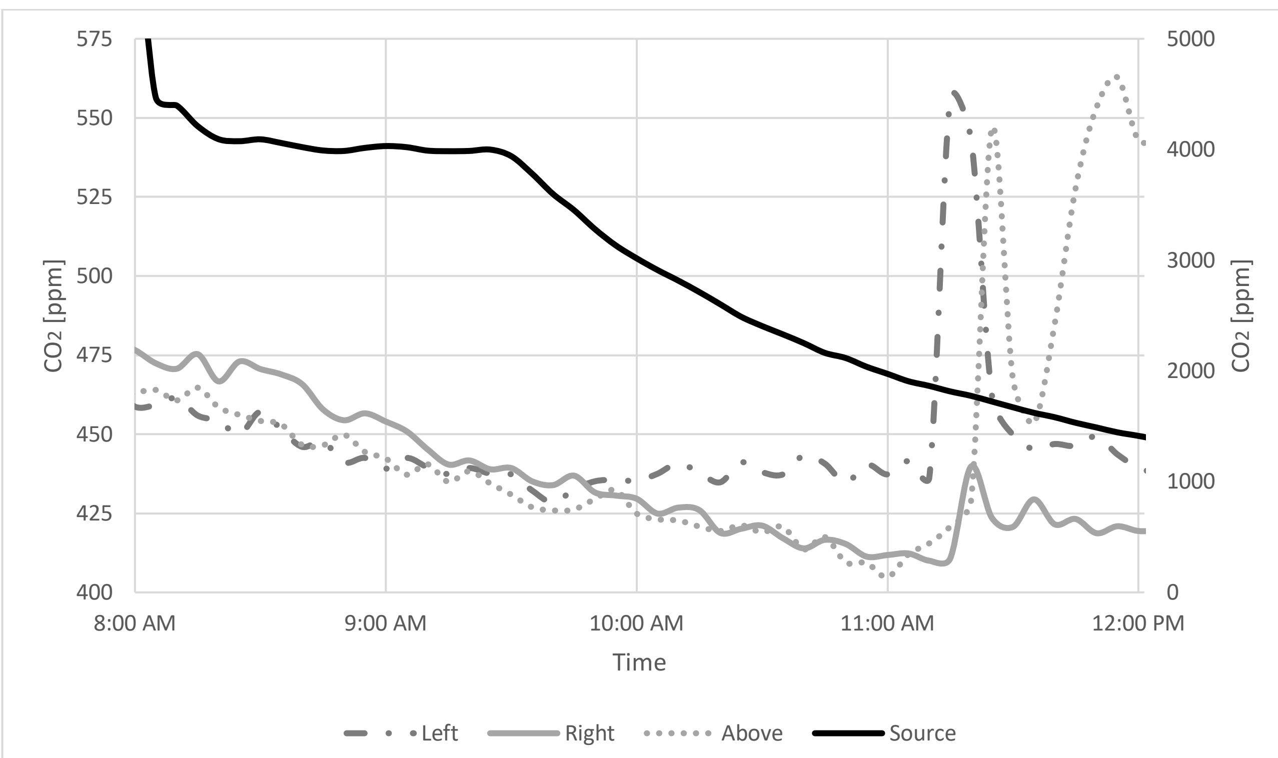


Figure A4. CO2 concentrations in the source unit on the 4th floor in Building A and in adjacent units with kitchen exhaust fans off. (Source line is referenced to the right-side Y axis)

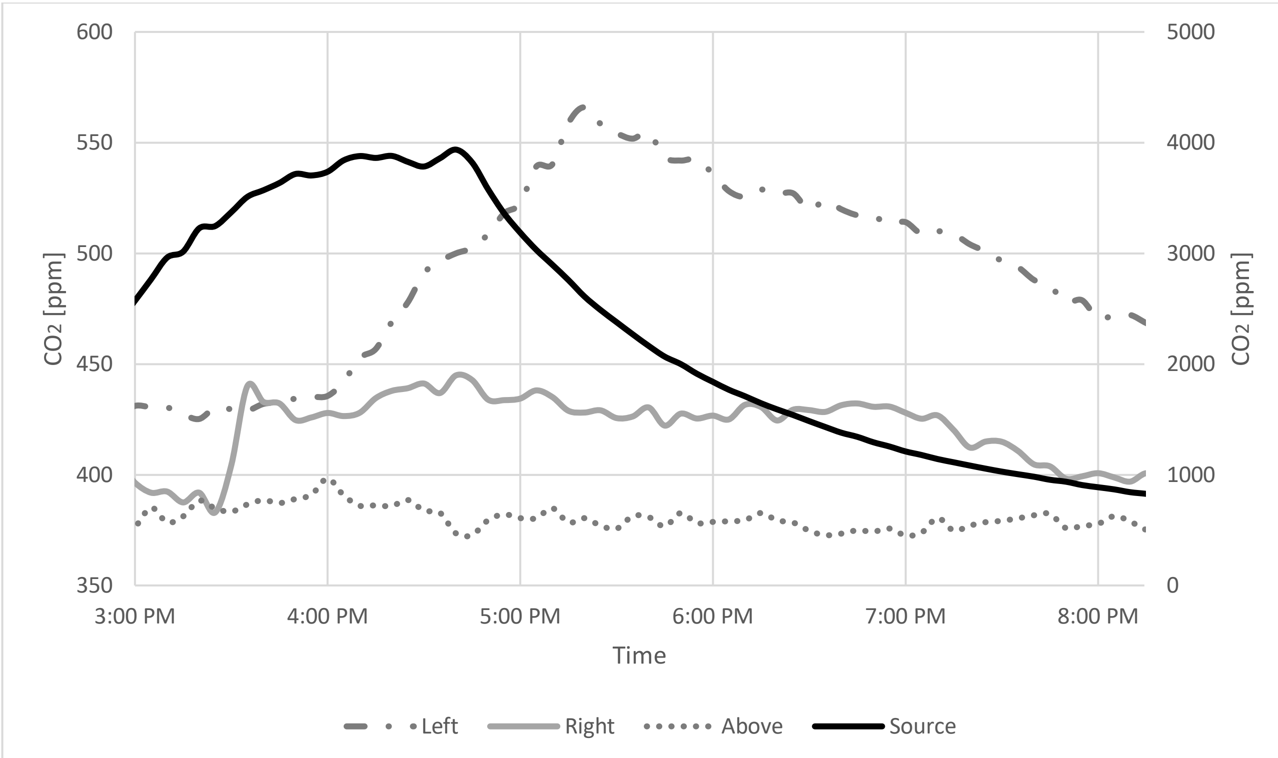


Figure A5. CO2 concentrations in the source unit on the 5th floor in Building A and in adjacent units with kitchen exhaust fans off. (Source line is referenced to the right-side Y axis)

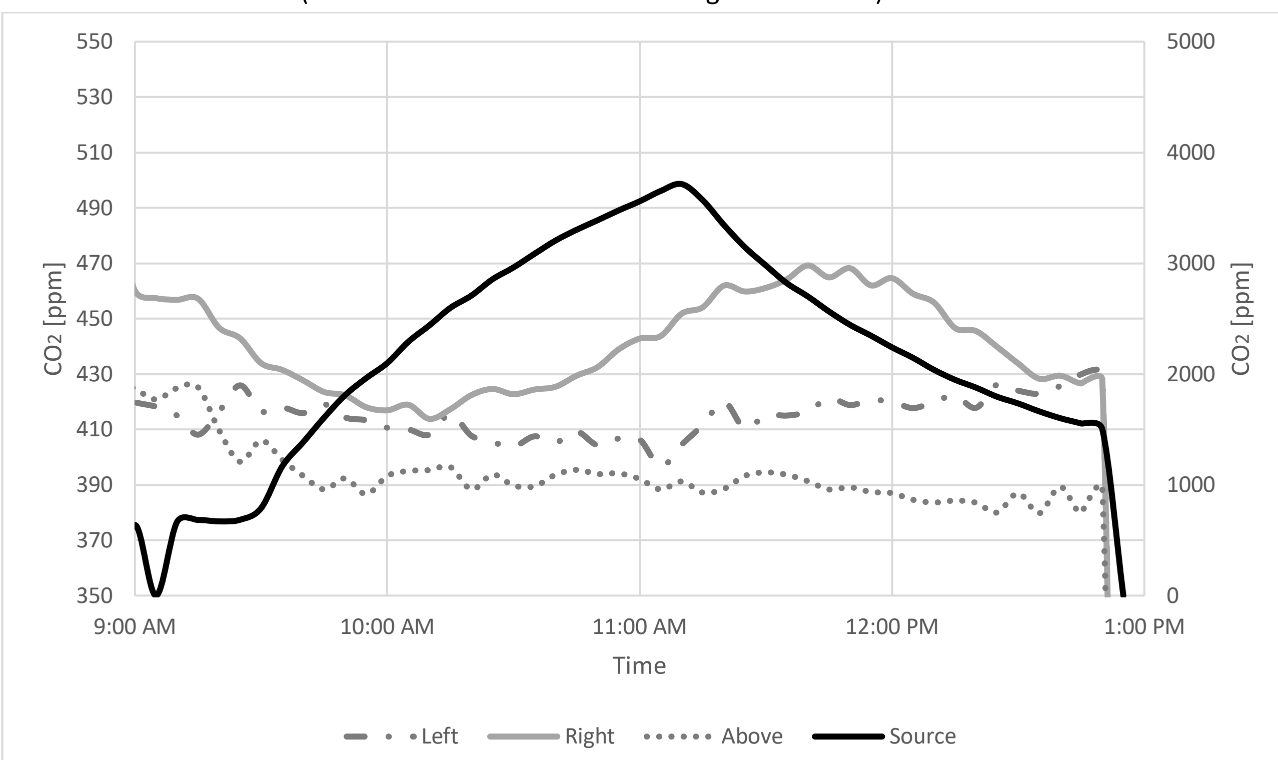


Figure A6. CO2 concentrations in the source unit on the 5th floor in Building A and in adjacent units with kitchen exhaust fans on. (Source line is referenced to the right-side Y axis)

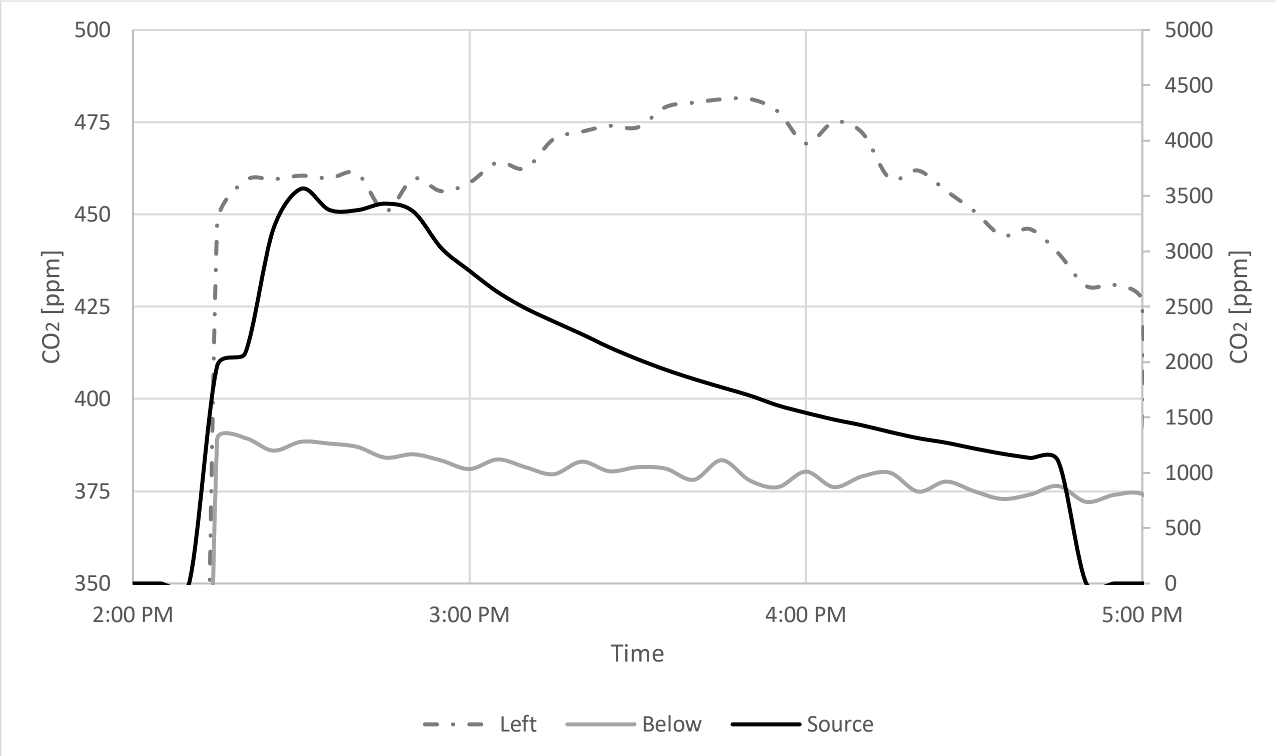


Figure A7. CO_2 concentrations in the source unit on the 6th floor in Building A and in adjacent units with kitchen exhaust fans on. (Source line is referenced to the right-side Y axis)

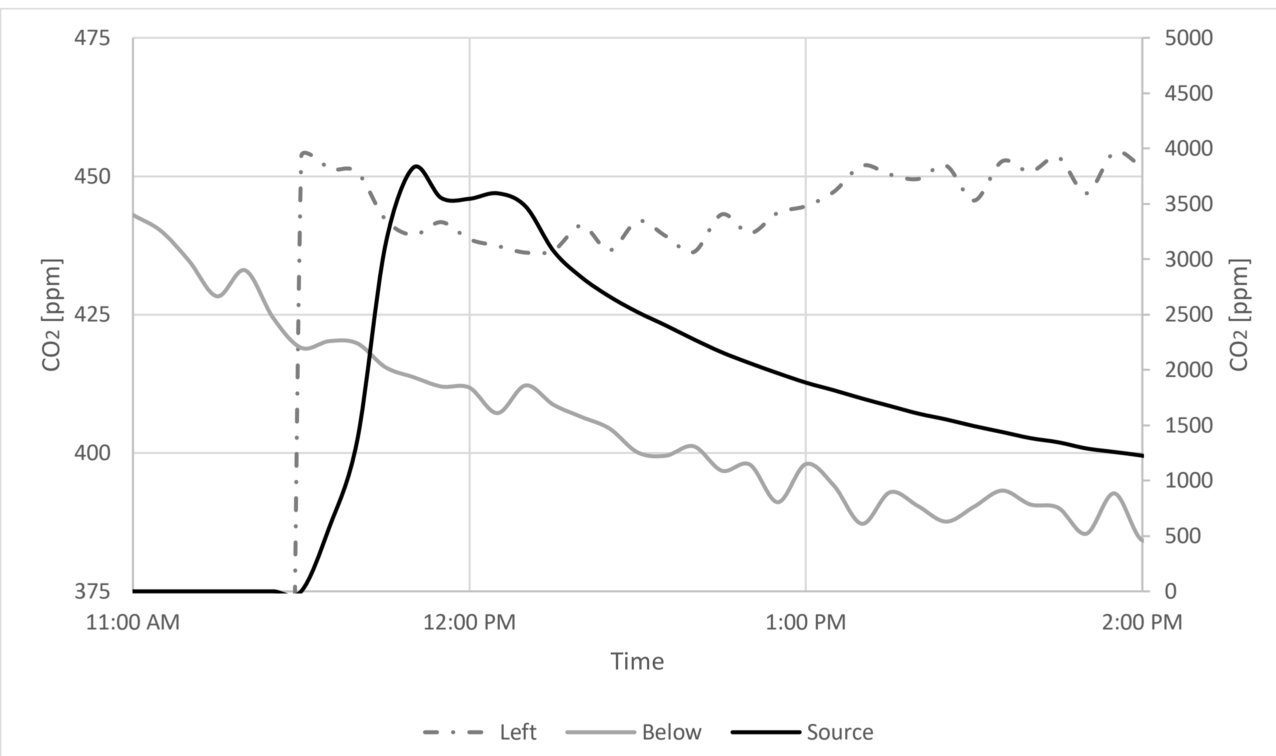


Figure A8. CO2 concentrations in the source unit on the 6th floor in Building A and in adjacent units with kitchen exhaust fans off. (Source line is referenced to the right-side Y axis)

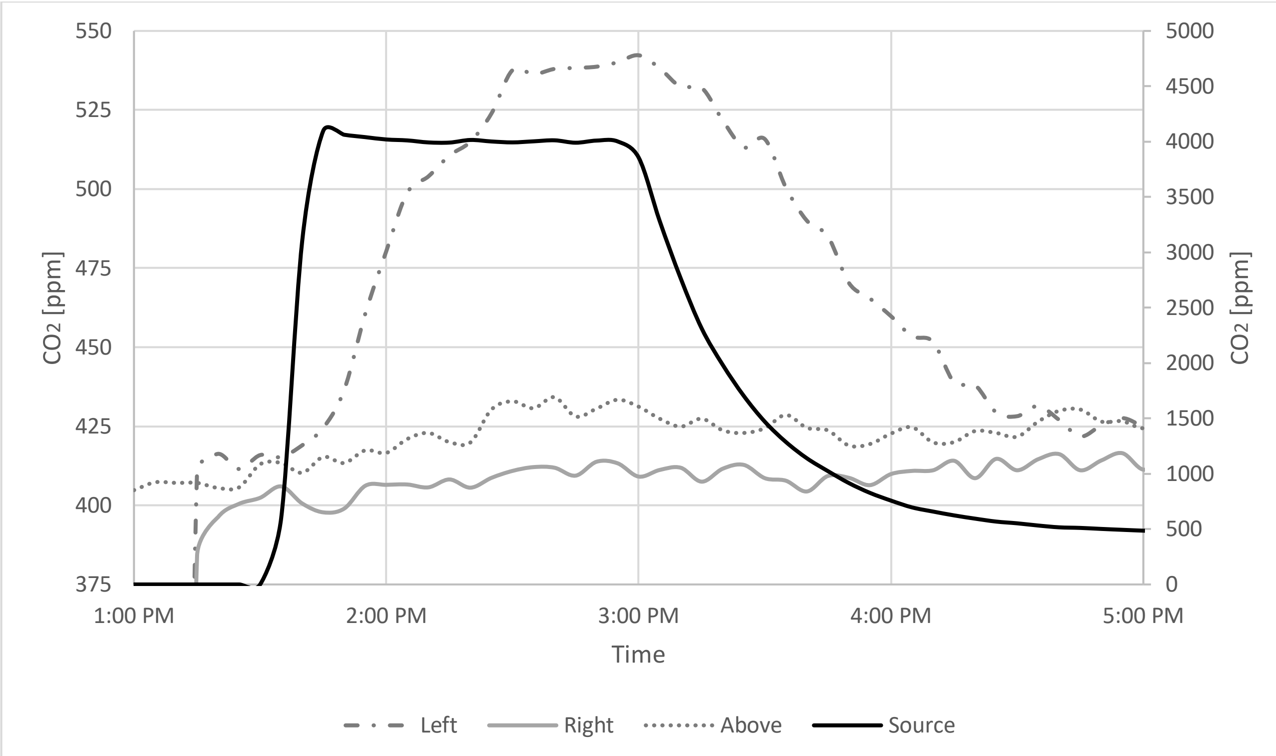


Figure A9. CO_2 concentrations in source unit 531, on the 5th floor in Building C and in adjacent units with kitchen exhaust fans on. (Source line is referenced to the right-side Y axis)

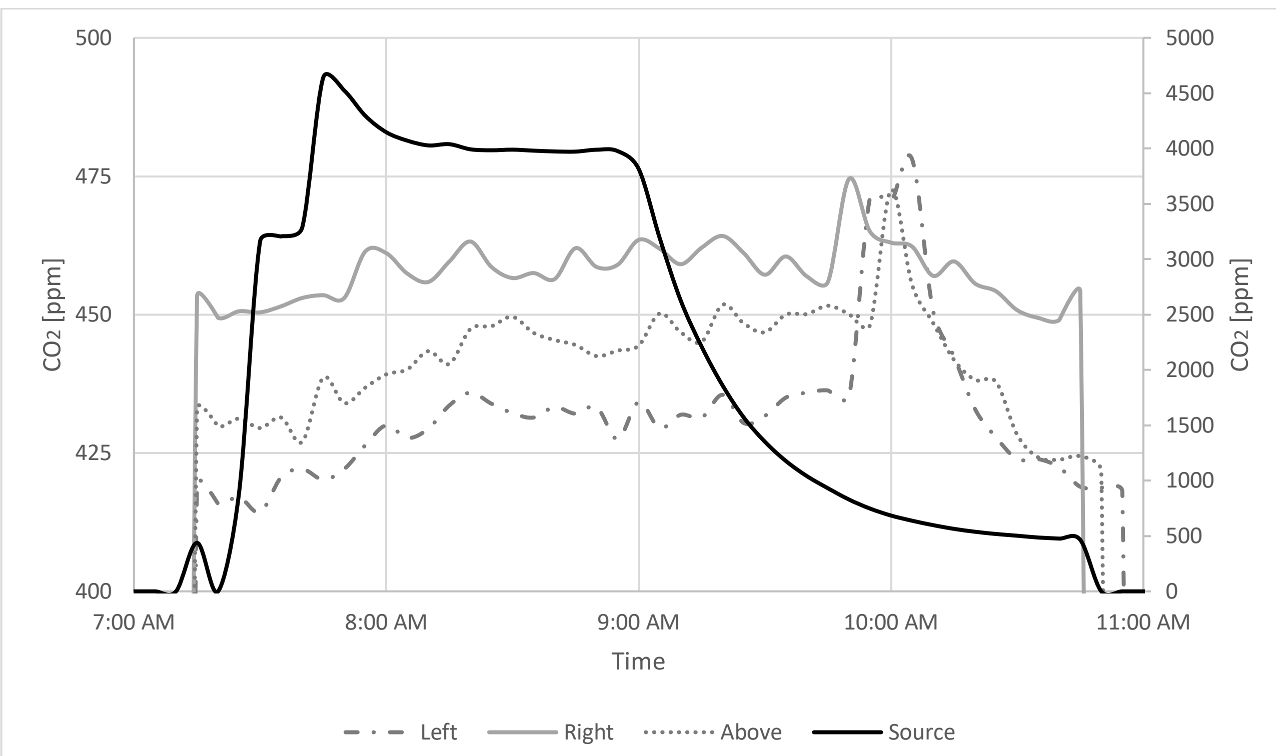


Figure A10. CO2 concentrations in source unit 531 on the 5th floor in Building C and in adjacent units with kitchen exhaust fans off. (Source line is referenced to the right-side Y axis)

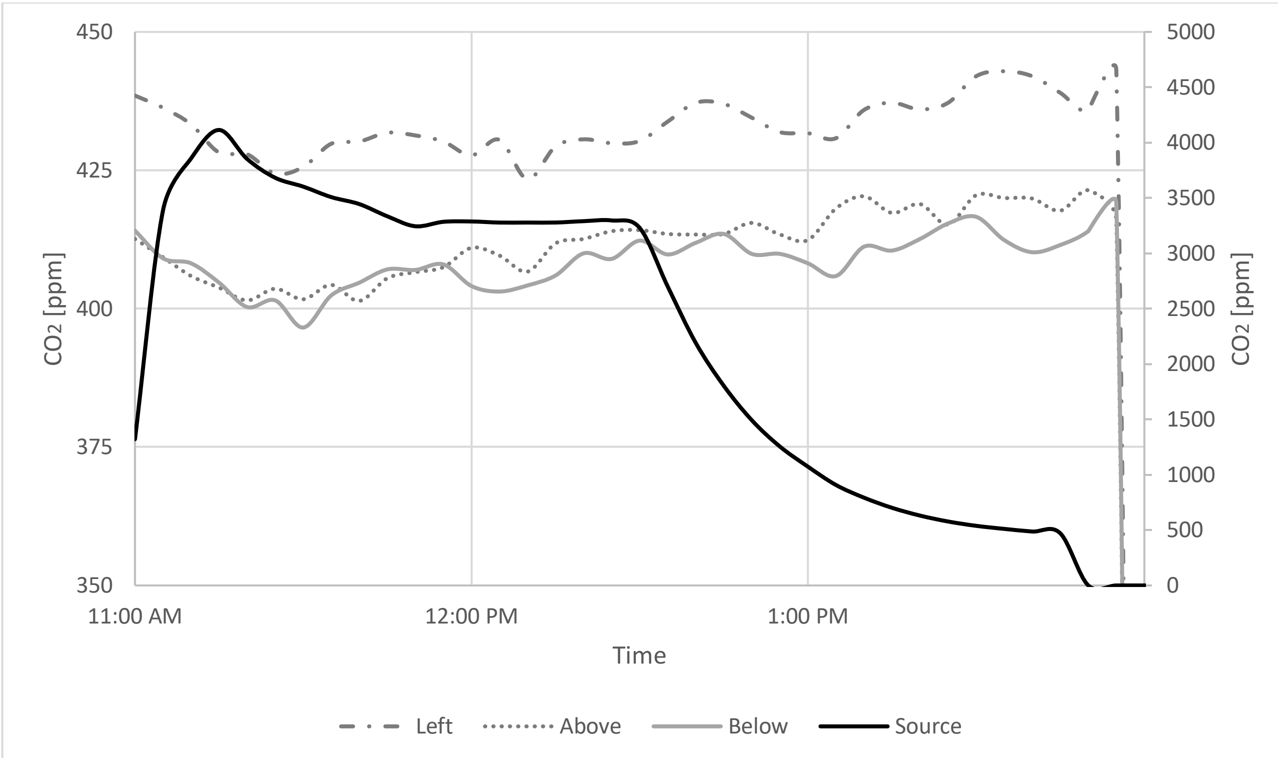


Figure A11. CO_2 concentrations in source unit 534 on the 5th floor in Building C and in adjacent units with kitchen exhaust fans on. (Source line is referenced to the right-side Y axis)

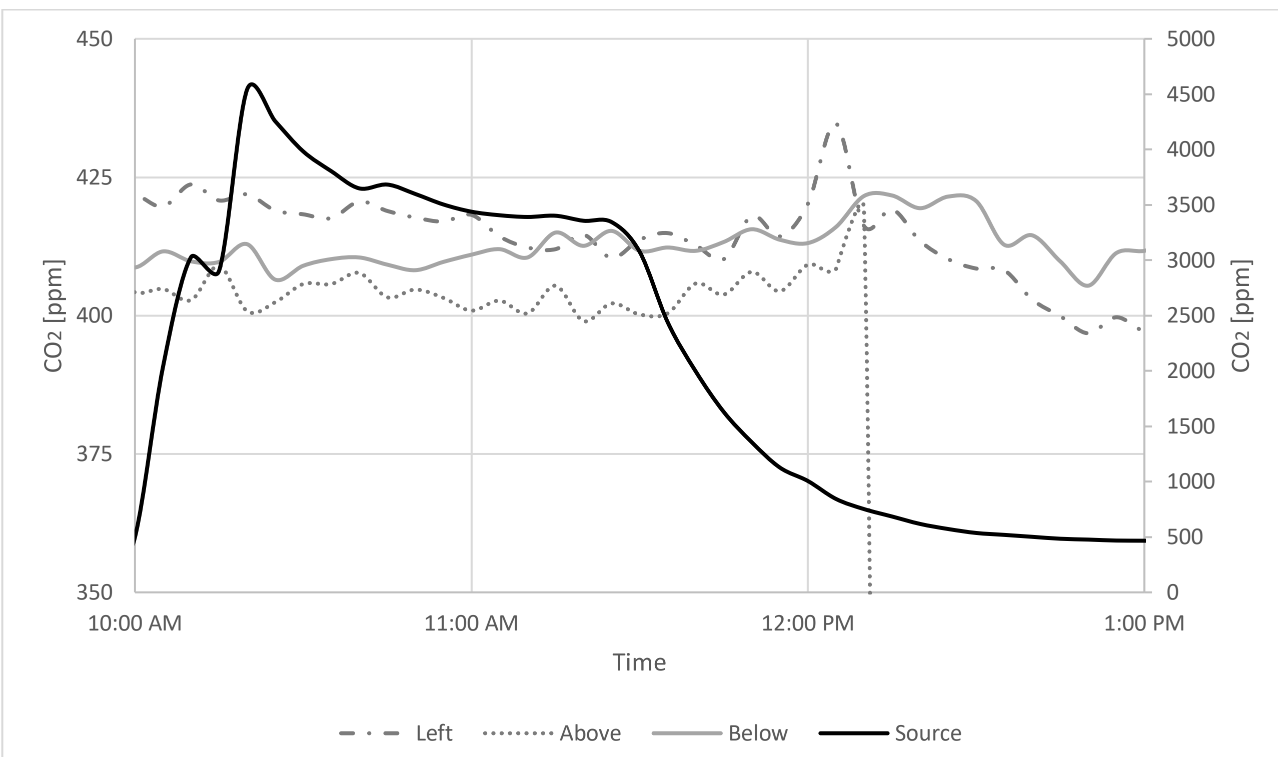


Figure A12. CO2 concentrations in source unit 534 on the 5th floor in Building C and in adjacent units with kitchen exhaust fans off. (Source line is referenced to the right-side Y axis)

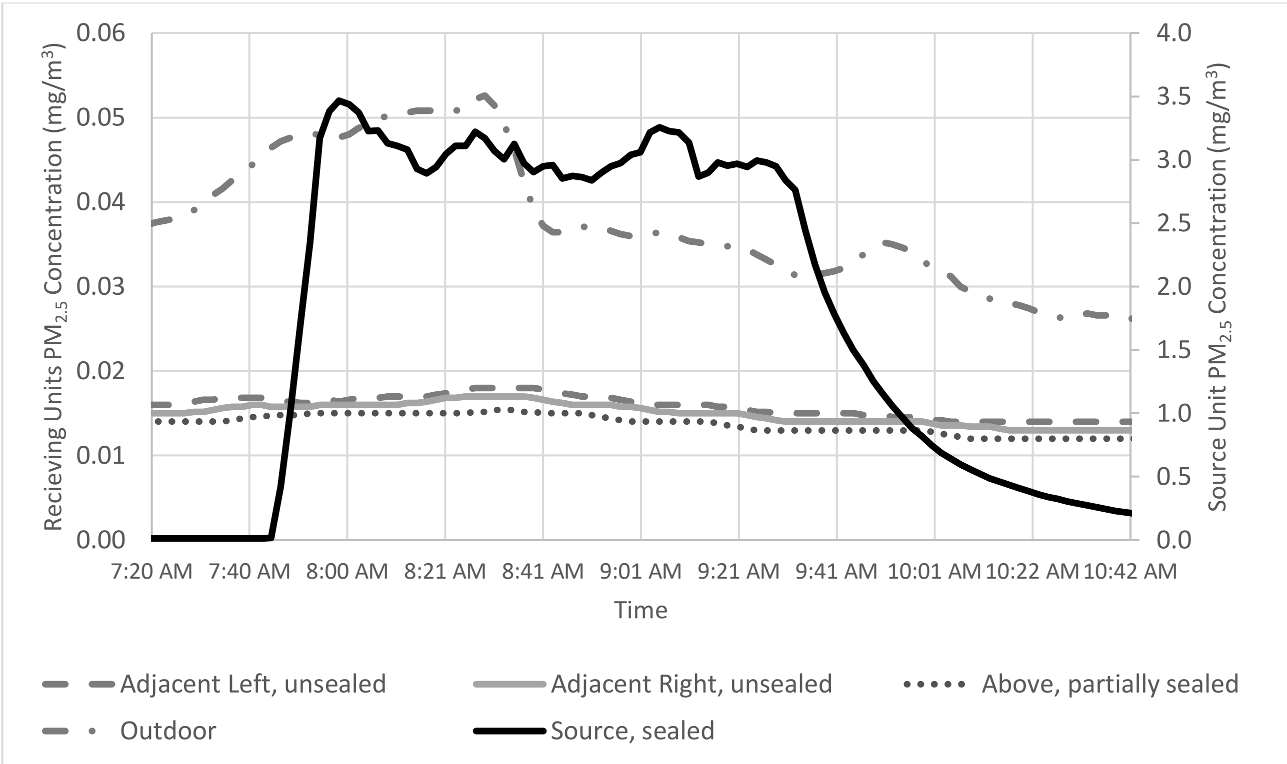


Figure A13. Inter-unit $PM_{2.5}$ transfer test with source unit on the 4th floor at Building A and kitchen exhaust fans off in adjacent units. (Source line is referenced to the right-side Y axis)

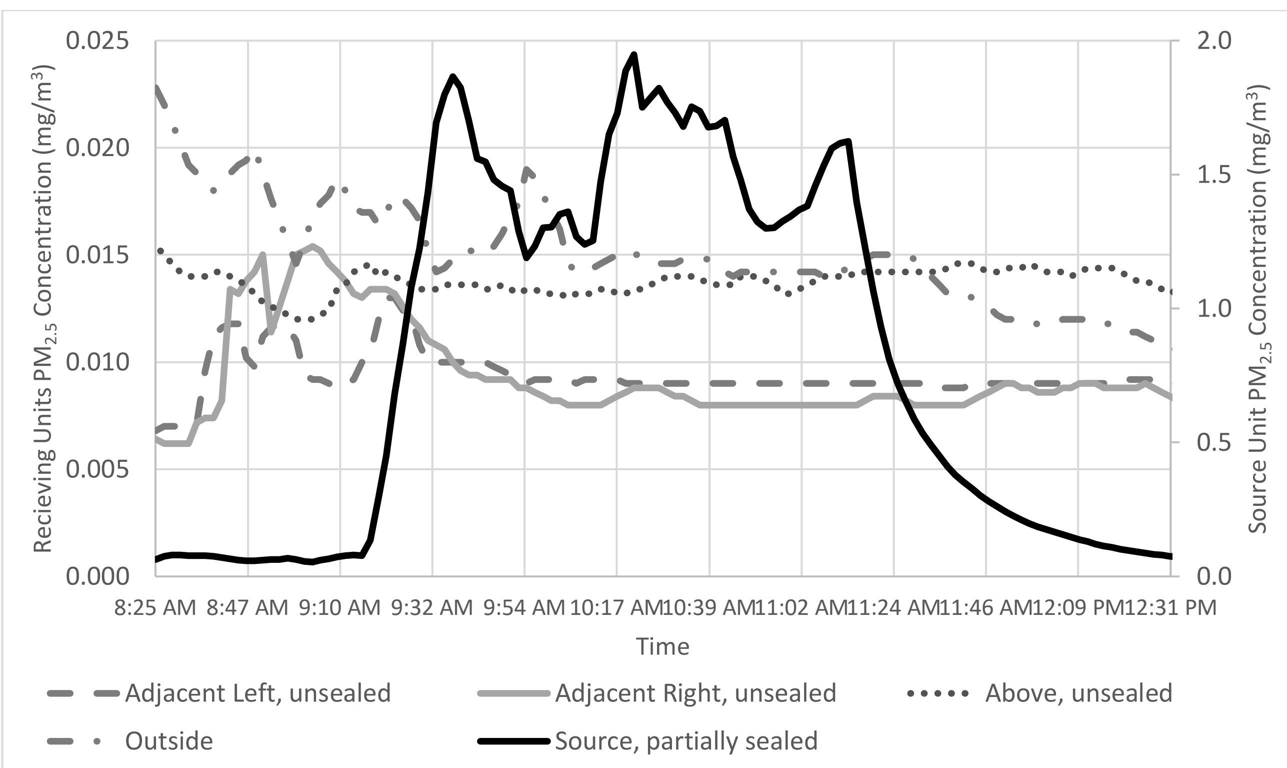


Figure A14. Inter-unit $PM_{2.5}$ transfer test with source unit on the 5th floor at Building A and kitchen exhaust fans on in adjacent units. (Source line is referenced to the right-side Y axis)

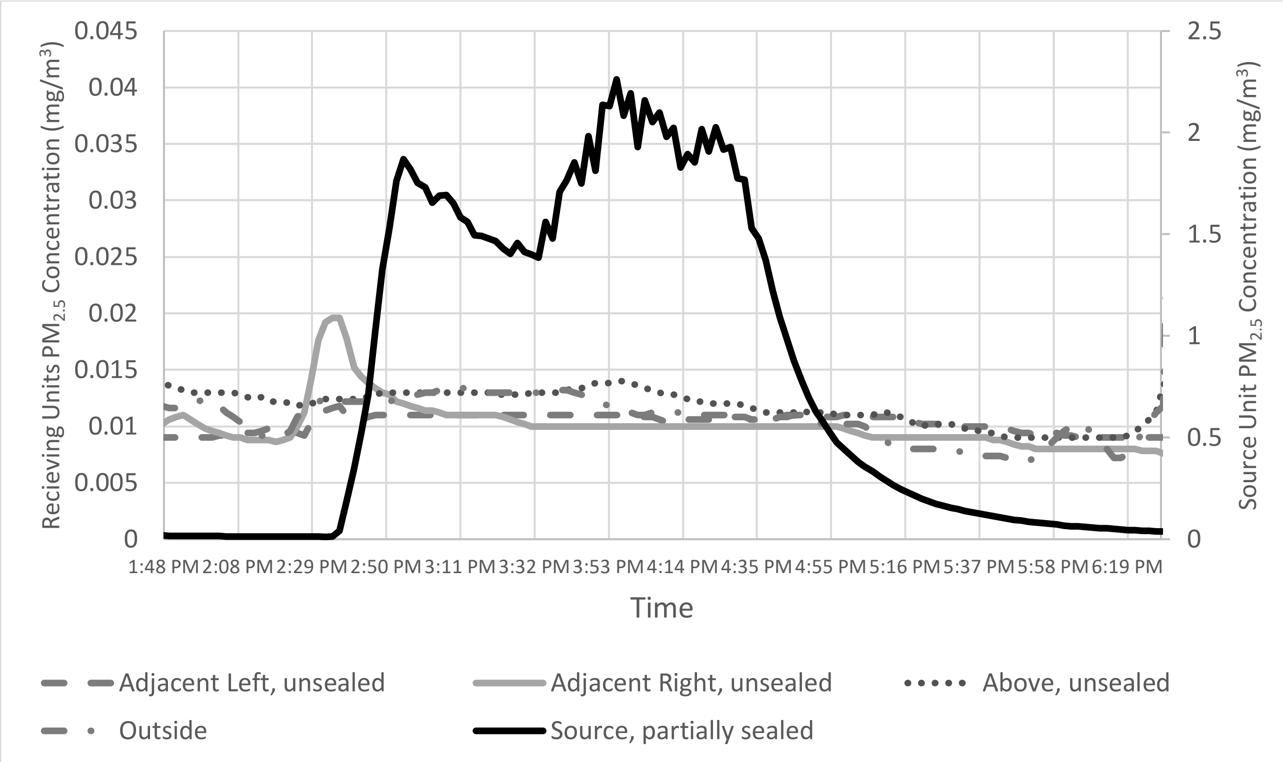


Figure A15. Inter-unit $PM_{2.5}$ transfer test with source unit on the 5th floor at Building A and kitchen exhaust fans off in adjacent units. (Source line is referenced to the right-side Y axis)

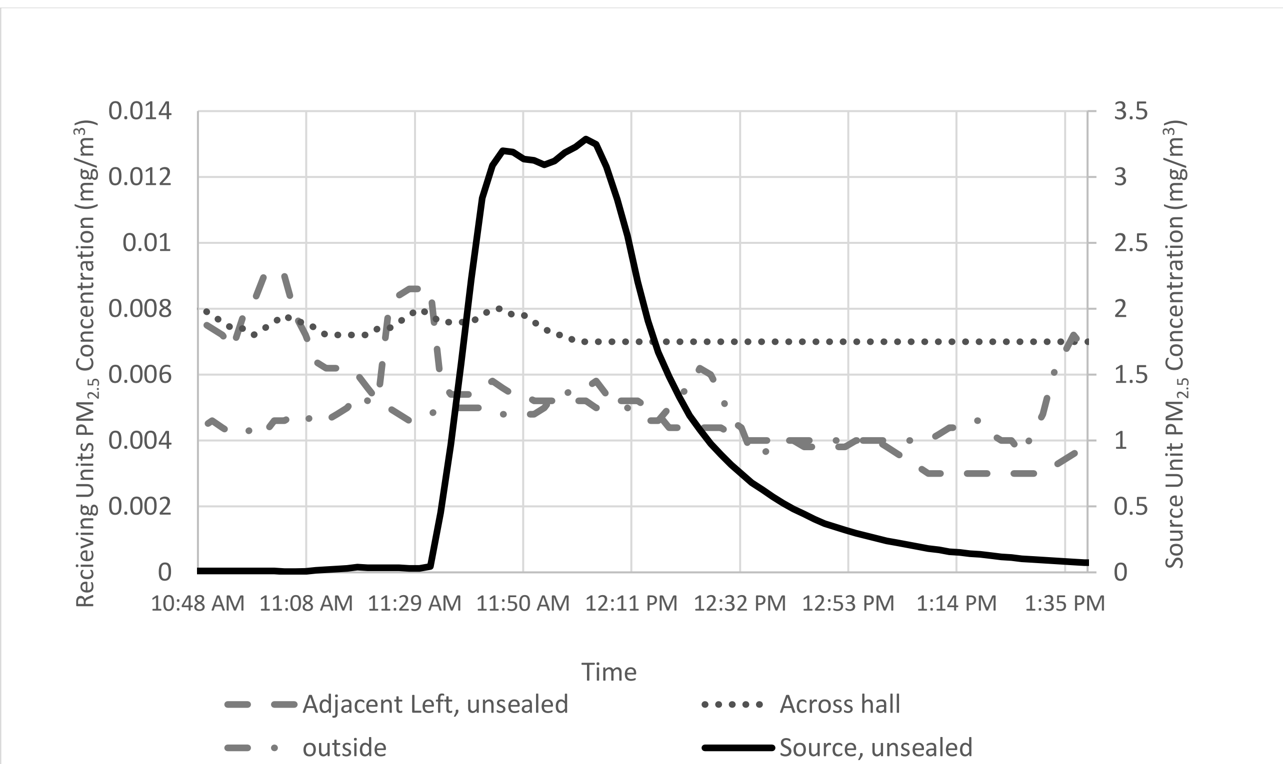


Figure A16. Repeat of inter-unit $PM_{2.5}$ transfer test with source unit on the 6th floor at Building A and kitchen exhaust fans on in adjacent units. (Source line is referenced to the right-side Y axis)

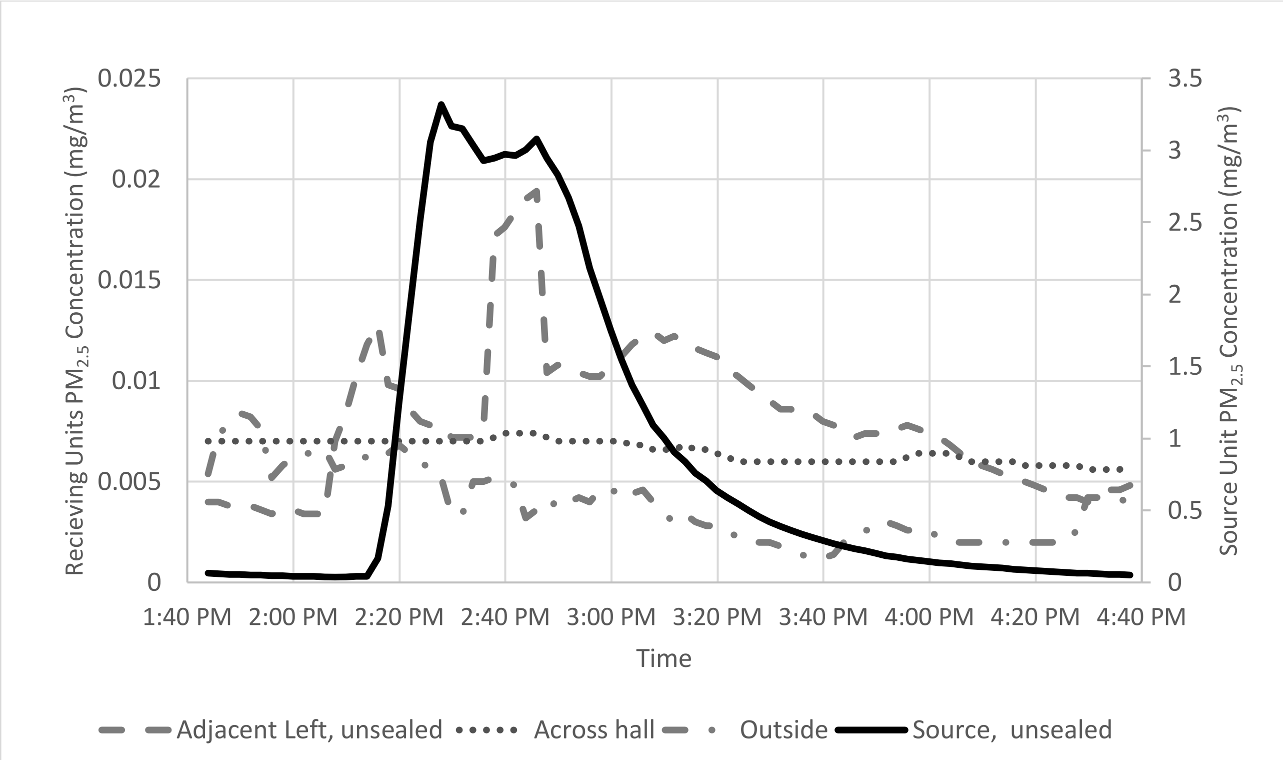


Figure A17. Inter-unit $PM_{2.5}$ transfer test with source unit on the 6th floor at Building A and kitchen exhaust fans off in adjacent units. (Source line is referenced to the right-side Y axis)

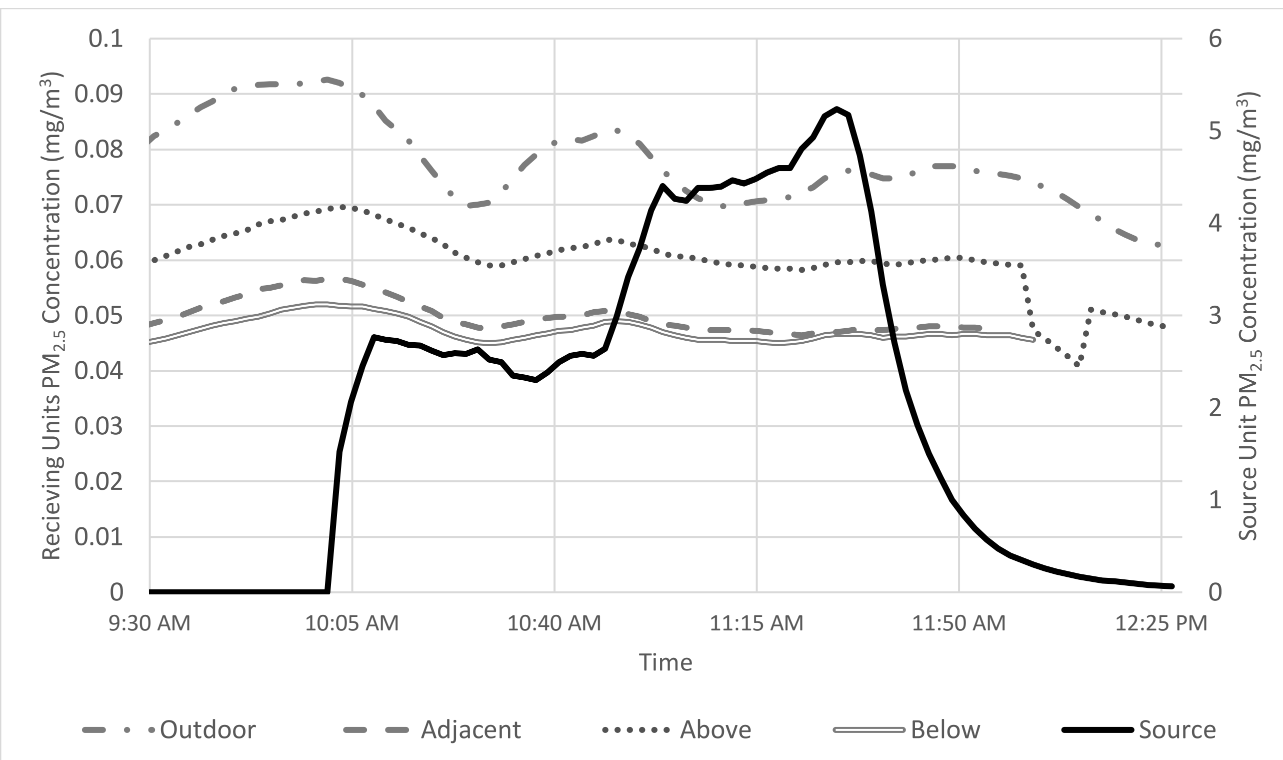


Figure A18. Inter-unit $PM_{2.5}$ transfer test with source unit in 534 on the 5th floor at Building C and kitchen exhaust fans off in adjacent units. (Source line is referenced to the right-side Y axis)

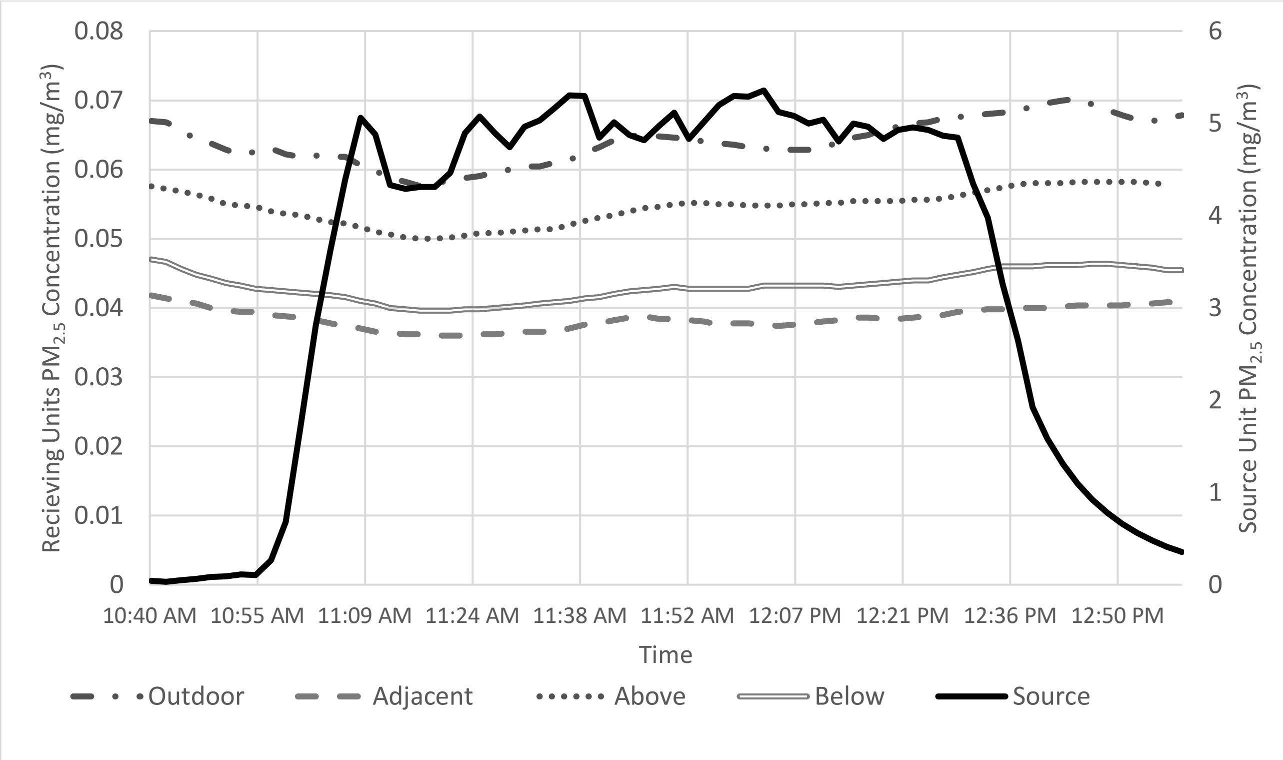


Figure A19. Inter-unit $PM_{2.5}$ transfer test with source unit 534 on the 5th floor at Building C and kitchen exhaust fans on in adjacent units. (Source line is referenced to the right-side Y axis)

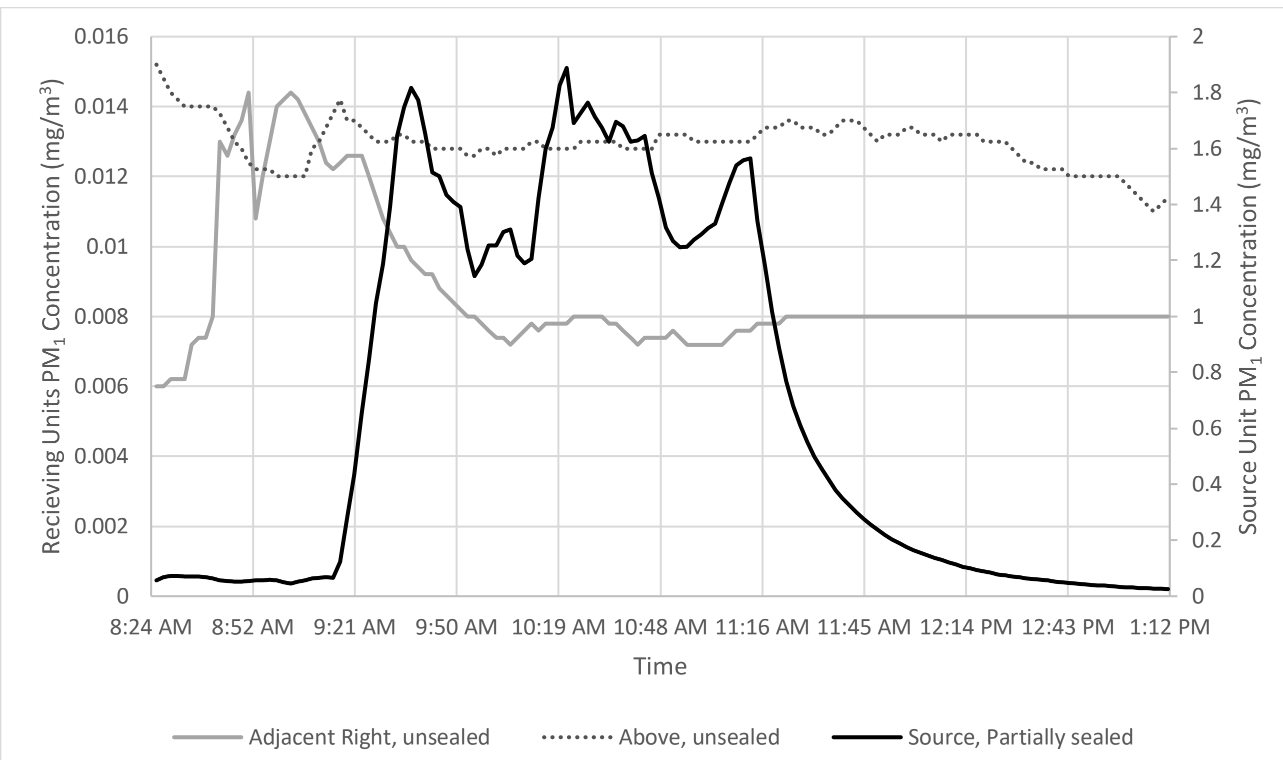


Figure A20. Inter-unit PM_1 transfer test with source unit on the 5^{th} floor at Building A and kitchen exhaust fans on in adjacent units. (Source line is referenced to the right-side Y axis)

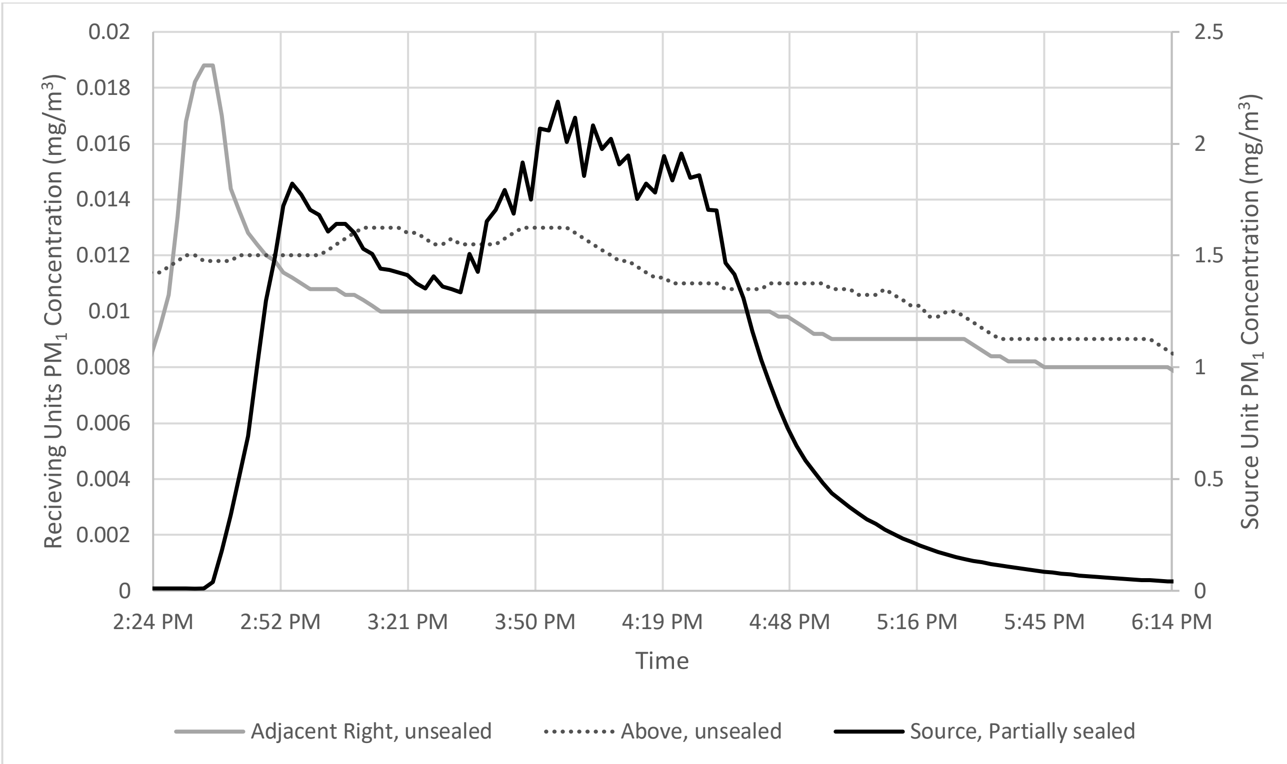


Figure A21. Inter-unit PM_1 transfer test with source unit on the 5th floor at Building A and kitchen exhaust fans off in adjacent units. (Source line is referenced to the right-side Y axis)

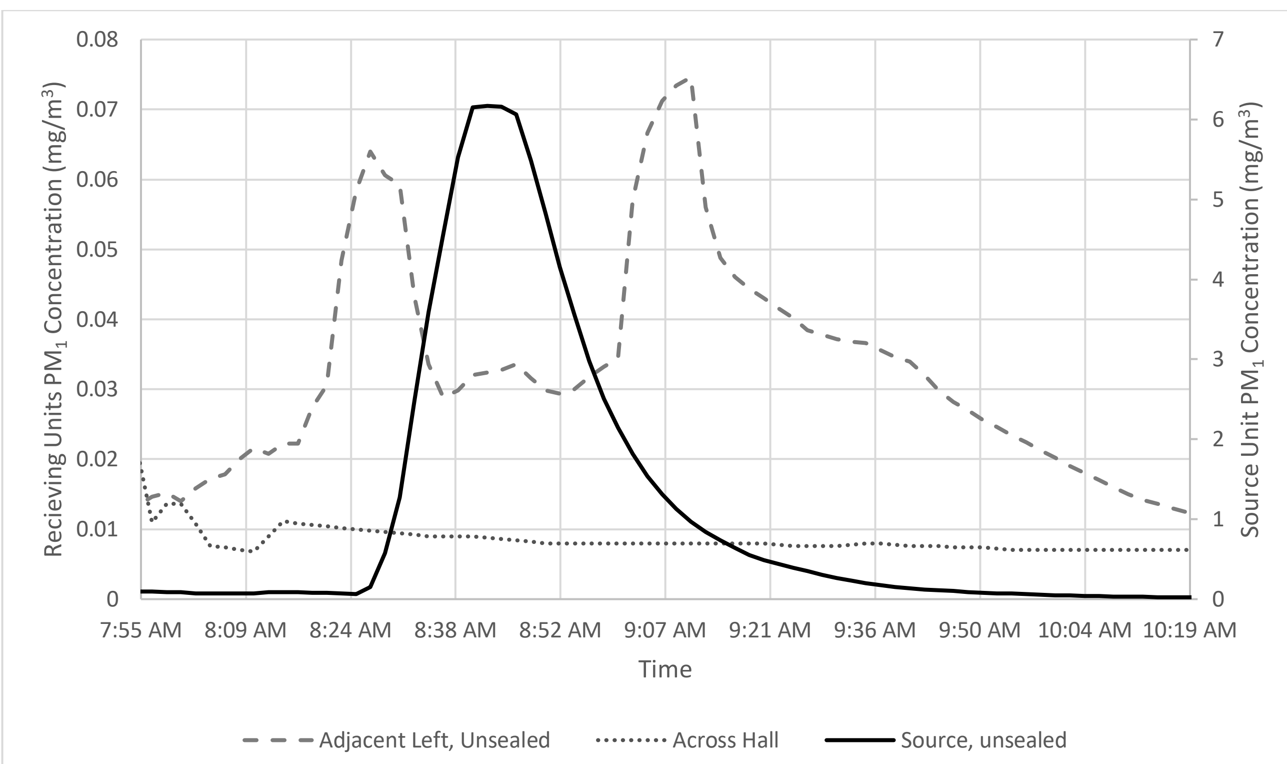


Figure A22. Inter-unit PM_1 transfer test with source unit on the 6th floor at Building A and kitchen exhaust fans on in adjacent units. (Source line is referenced to the right-side Y axis). Note that smoke alarm went off in source unit and door was opened at approximately 8:45am.

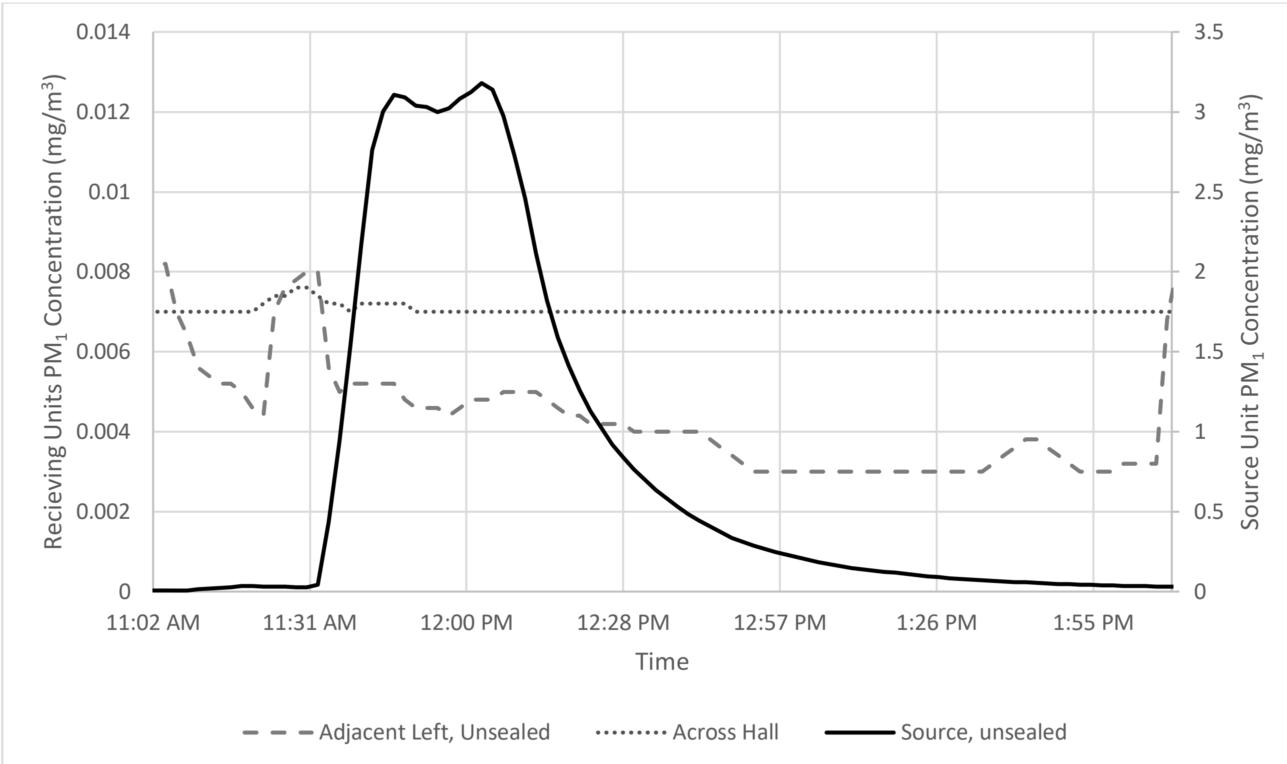


Figure A23. Inter-unit PM_1 transfer test with source unit on the 6th floor at Building A and kitchen exhaust fans on in adjacent units. (Source line is referenced to the right-side Y axis)

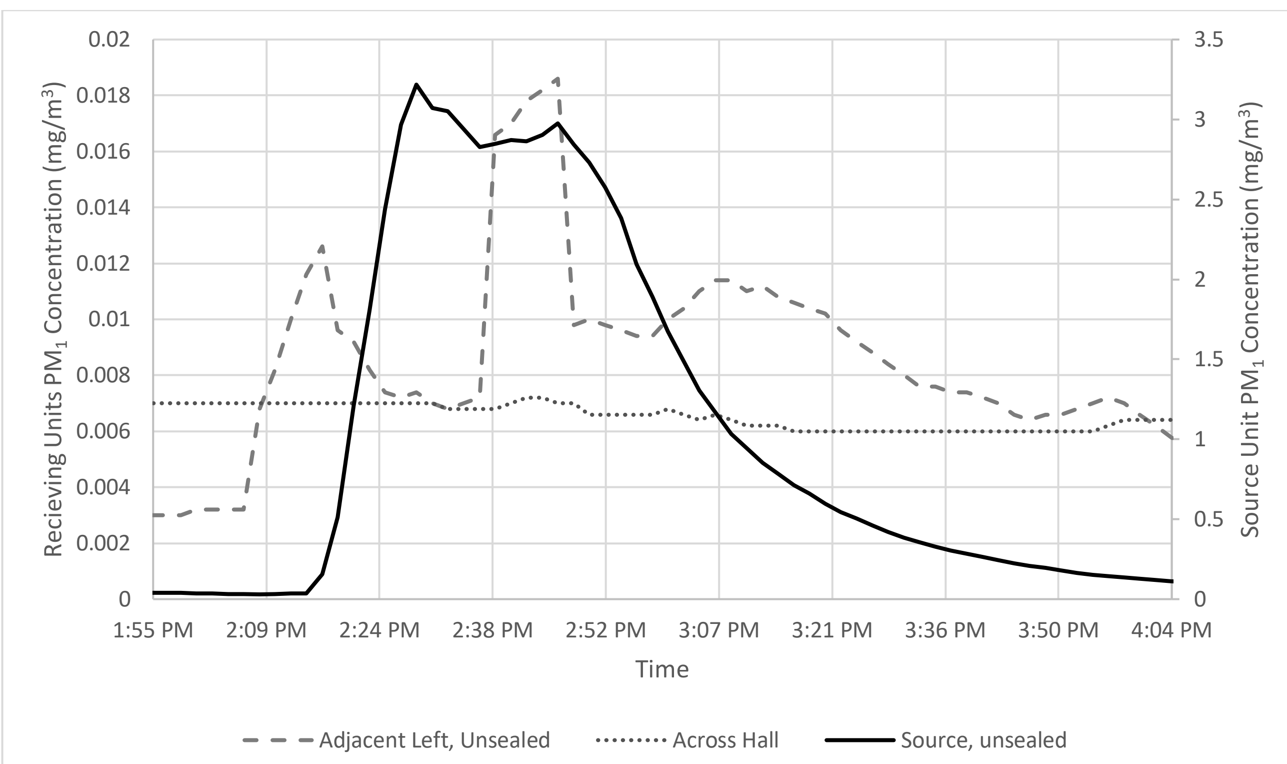


Figure A24. Inter-unit PM_1 transfer test with source unit on the 6th floor at Building A and kitchen exhaust fans off in adjacent units. (Source line is referenced to the right-side Y axis)

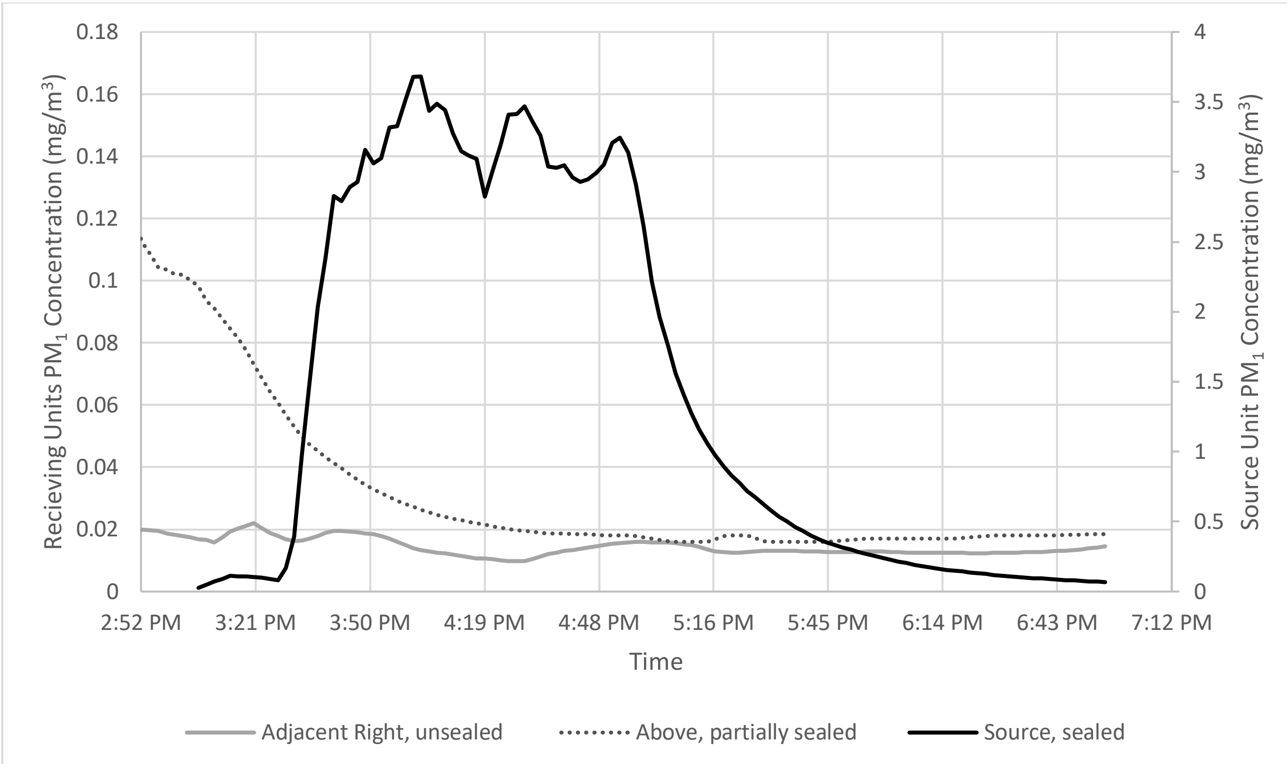


Figure A25. Inter-unit PM_1 transfer test with source unit on the 4th floor at Building A and kitchen exhaust fans on in adjacent units. (Source line is referenced to the right-side Y axis)

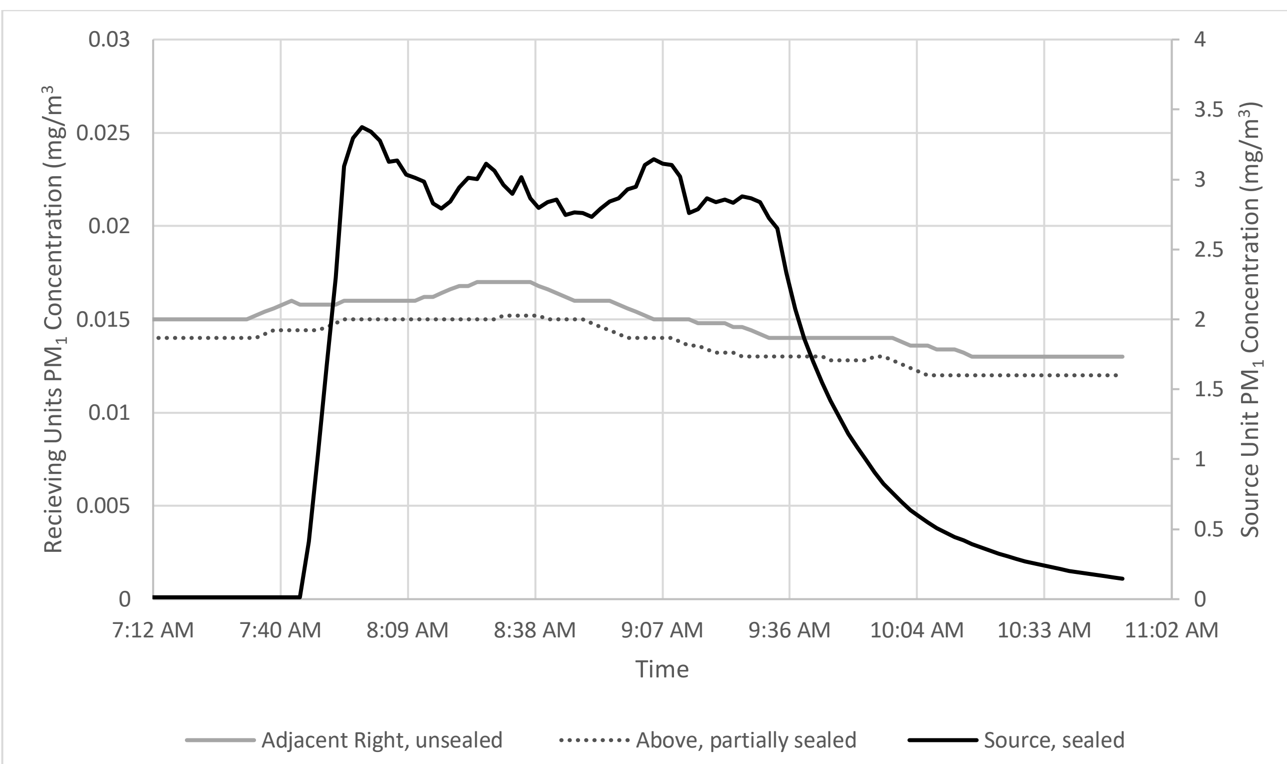


Figure A26. Inter-unit PM_1 transfer test with source unit on the 4th floor at Building A and kitchen exhaust fans off in adjacent units. (Source line is referenced to the right-side Y axis)

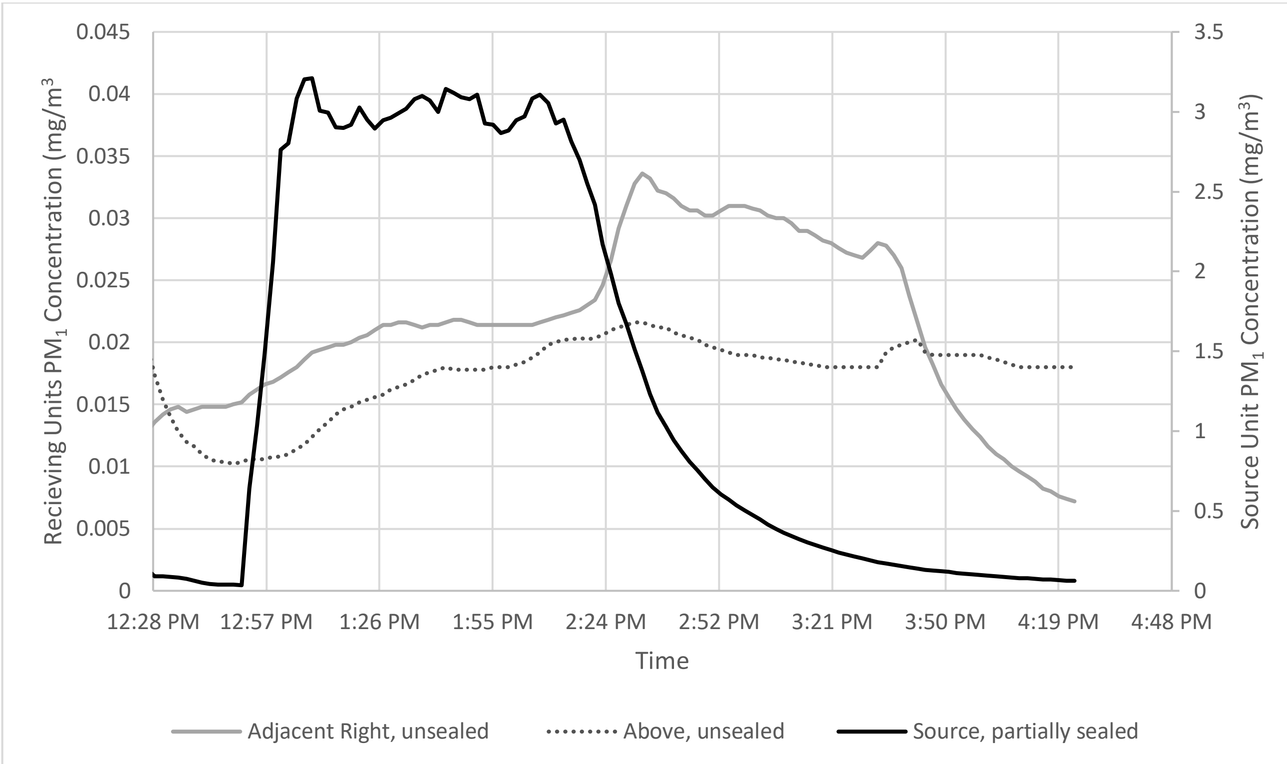


Figure A27. Repeat of inter-unit PM_1 transfer test with source unit on the 5th floor at Building A and kitchen exhaust fans on in adjacent units. (Source line is referenced to the right-side Y axis)

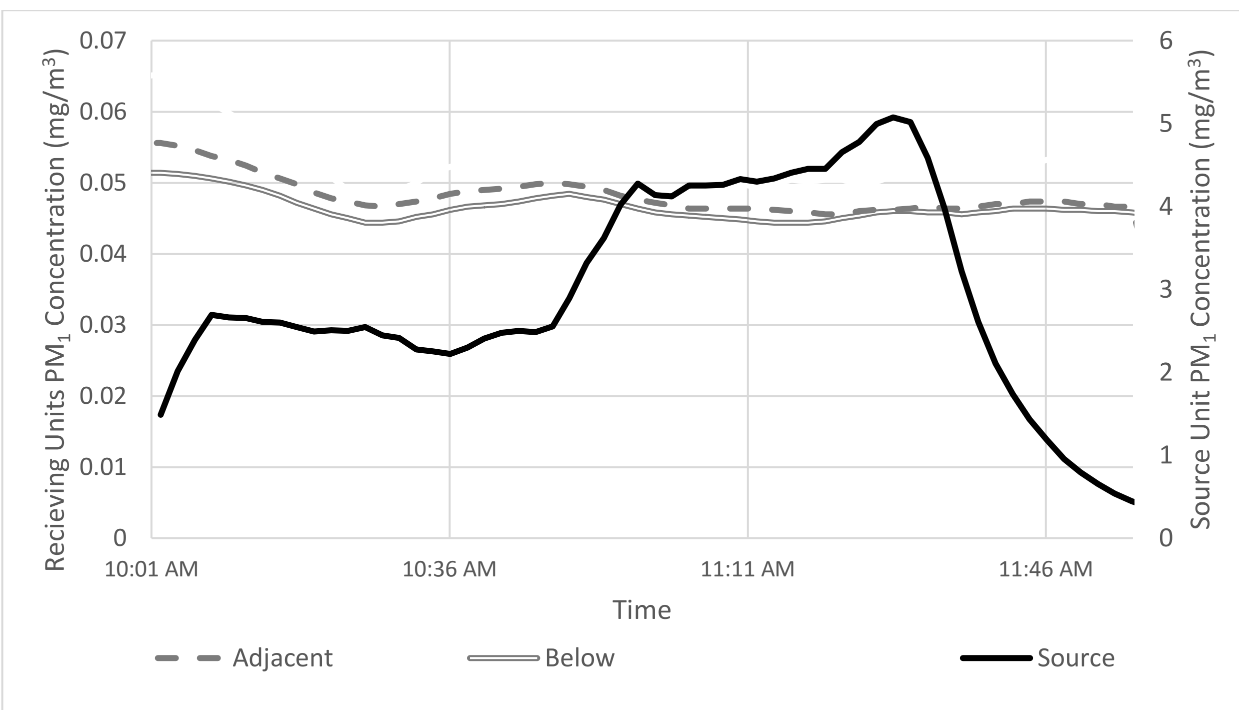


Figure A28. Inter-unit PM_1 transfer test with source unit 534 on the 5th floor at Building C and kitchen exhaust fans off in adjacent units. (Source line is referenced to the right-side Y axis)

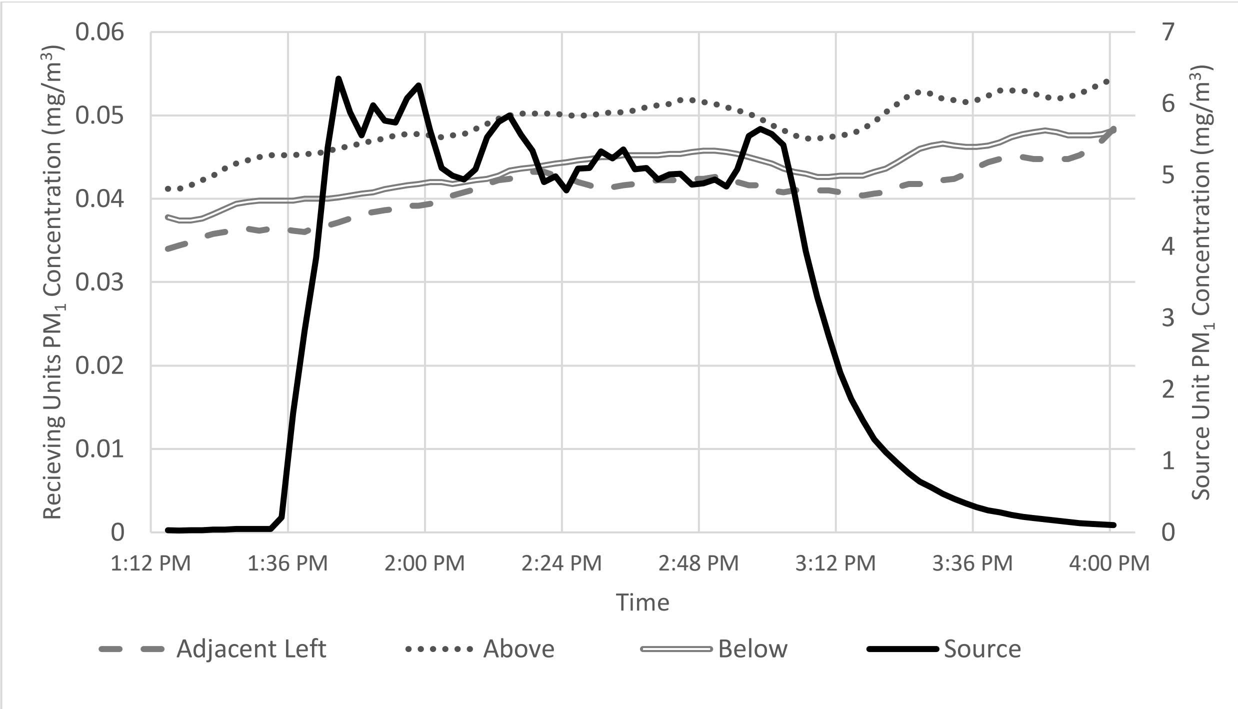


Figure A29. Inter-unit PM_1 transfer test with source unit 531 on the 5th floor at Building C and kitchen exhaust fans on in adjacent units. (Source line is referenced to the right-side Y axis)

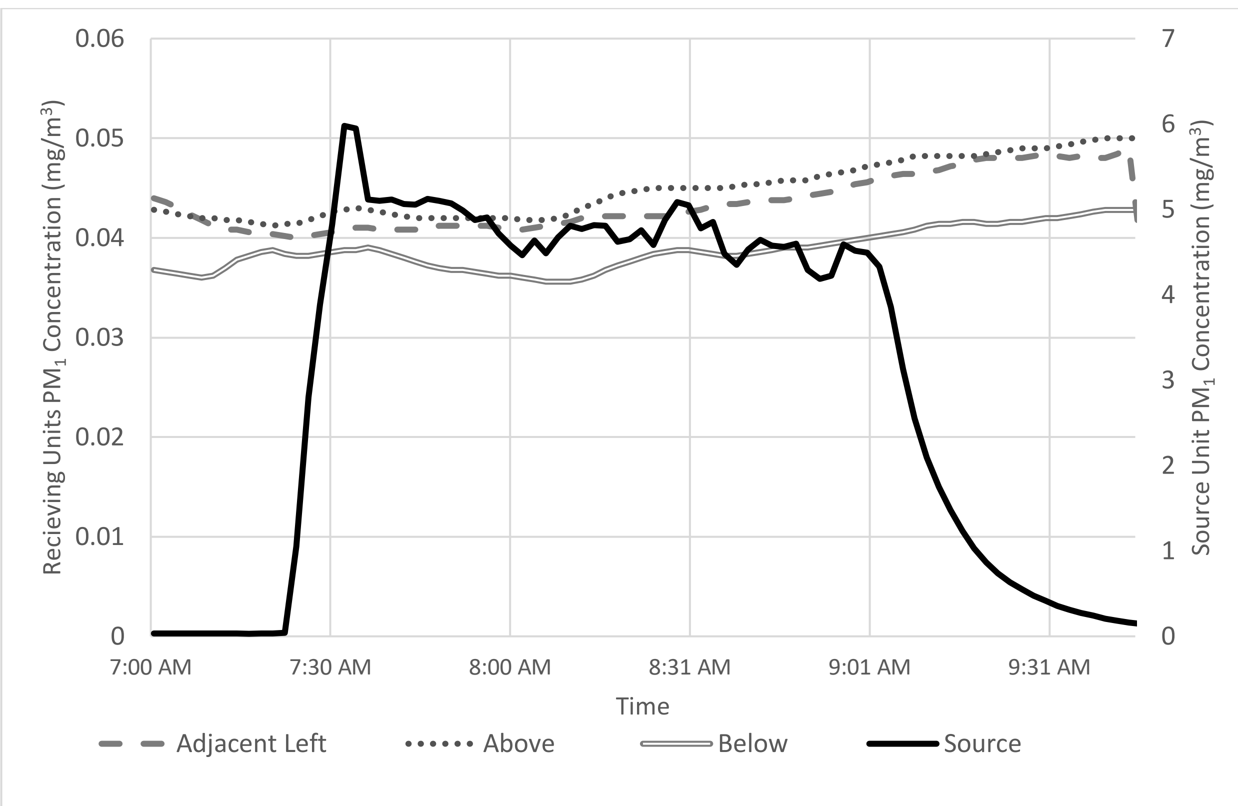


Figure A30. Inter-unit PM_1 transfer test with source unit 531 on the 5th floor at Building C and kitchen exhaust fans off in adjacent units. (Source line is referenced to the right-side Y axis)

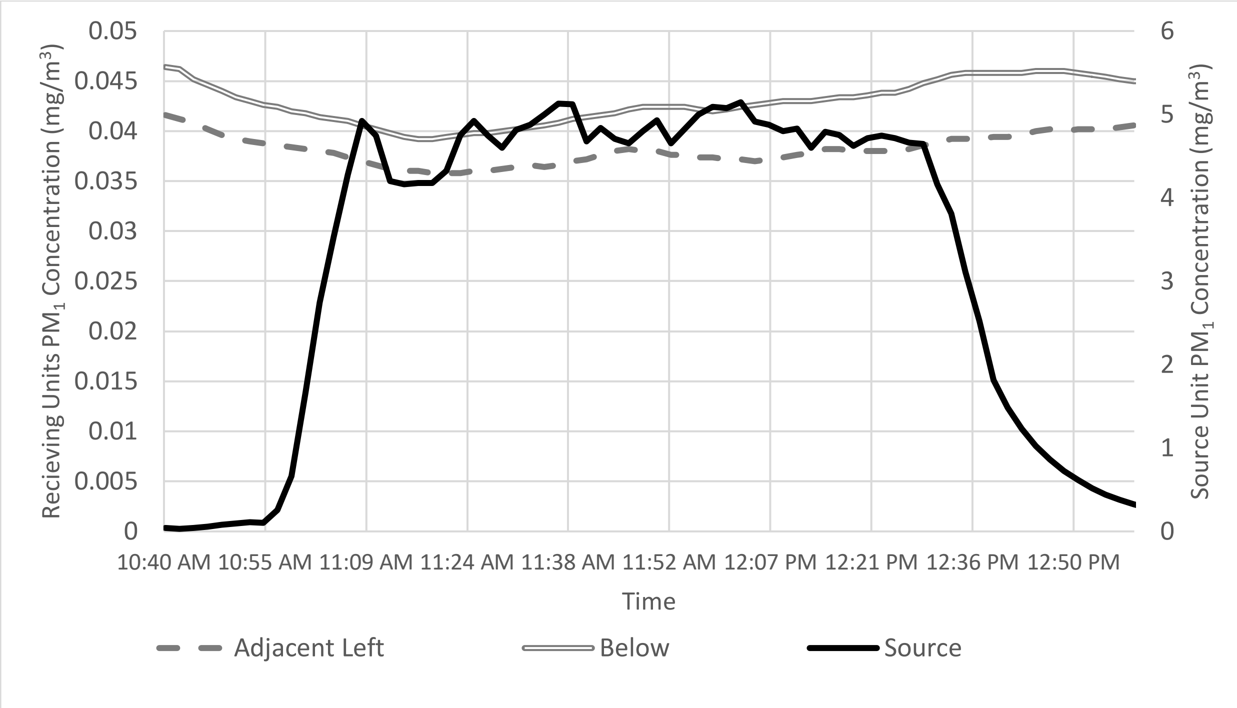


Figure A31. Inter-unit PM_1 transfer test with source unit 534 on the 5th floor at Building C and kitchen exhaust fans on in adjacent units. (Source line is referenced to the right-side Y axis)

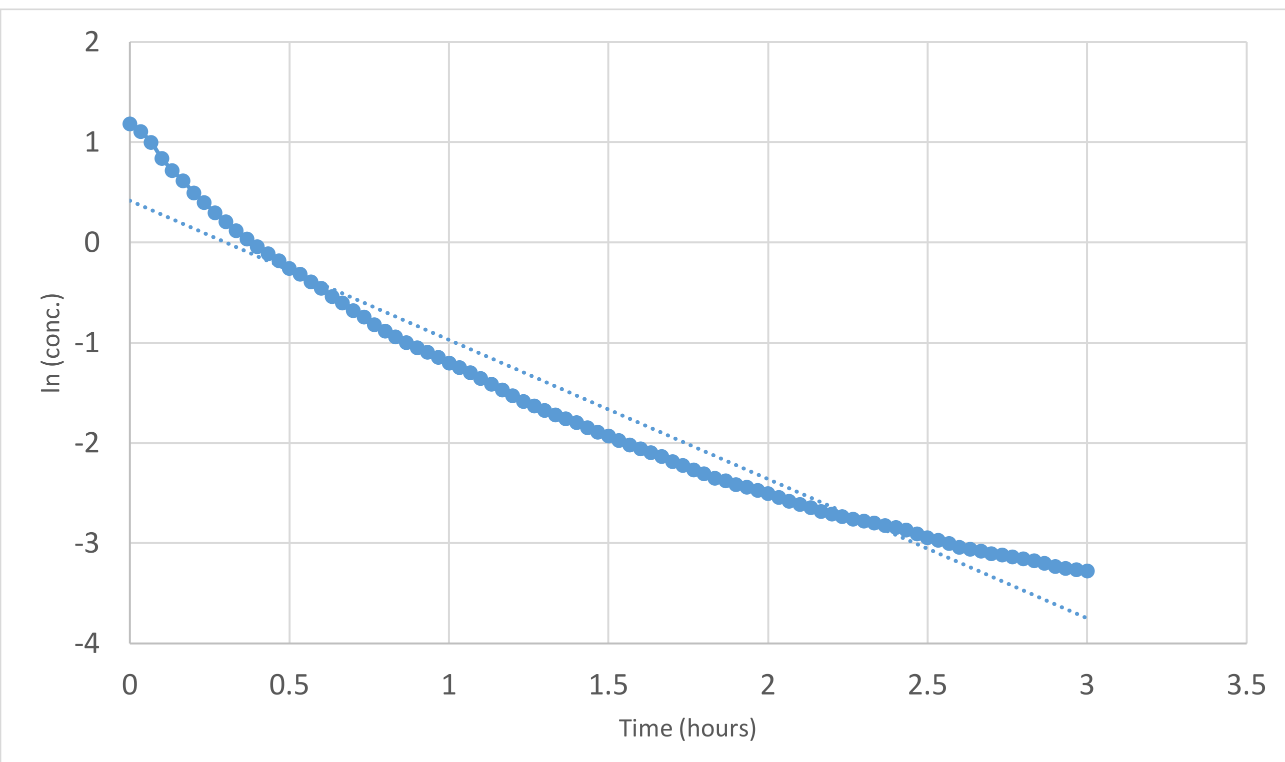


Figure A32. Example of $PM_{2.5}$ Decay. From measurements taken at Building A on the 4th floor, in a sealed unit, with fans on in adjoining units.

Table A1. Decay rates for PM in tests

	Slope	Slope, last hour
Building A, 4th floor, sealed, fans on	-1.39	-0.77
Building A, 4th floor, sealed, fans off	-1.58	-1.05
Building A, 5th floor, partially sealed, fans on	-1.46	-0.91
Building A, 5th floor, partially sealed, fans off	-1.62	-0.97
Building A, 6th floor, unsealed, fans on	-2.13	-1.58
Building A, 6th floor, unsealed, fans off	-2.31	-1.945
Building C, 5th floor, 531-"looser", fans on	-2.85	-1.60
Building C, 5th floor, 531-"looser", fans off	-3.16	-2.22
Building C, 5th floor, 534-"tighter", fans on	-4.13	-3.76
Building C, 5th floor, 534-"tighter", fans off	-3.01	-1.51

QA/QC Results for DustTraks

All of the DustTraks were collocated at the beginning of the project (July 2021), prior to sampling in Building A (October 2021), and prior to sampling in Building C (February 2022). While the various DustTraks do not give consistent absolute values, with some reading high and some reading low, they track very well together to record increases and decreases in the PM values over relatively stable concentration ranges, which was the key quality measure to determine transfers between units. The absolute value is important for evaluating I/O ratios, and only those monitors with consistent values were utilized for that activity. To assess the consistency between samplers for each co-location period, the following steps were taken:

1. The 10-minute moving average was calculated for the whole sampling period.
2. The ratio of the concentration from each sampler relative to the reference sampler was calculated. The reference sampler was the newest sampler.
3. The 5th, 25th, 50th, 75th, and 95th percentiles were calculated.

The testing results are presented below.

Table A2: 48-hour co-location test conducted outdoors in July 2021. Percentiles are of the calculated ratio between the listed DustTraK and the reference DustTrak.

Model	DustTrak II	DustTrak II	DustTrak DRX	DustTrak DRX	DustTrak DRX	DustTrak DRX	DustTrak DRX
Calibration Date	2/19/2020	7/17/2017	3/28/2019	2/3/2021	4/16/2019	4/4/2019	4/4/2019
Owner	UC Davis	UC Davis	UC Davis	UC Davis	ARB	ARB	ARB
Percentile	Sampler 1	Sampler 2	Sampler 3	reference	Sampler 4	Sampler 5	Sampler 6
5th	0.80	0.86	1.05	1.00	1.49	1.40	0.39
25th	0.83	0.89	1.11	1.00	1.53	1.46	0.53
50th	0.85	0.92	1.13	1.00	1.66	1.68	0.57
75th	0.92	0.99	1.15	1.00	1.74	1.81	0.61
95th	0.97	1.04	1.17	1.00	1.82	1.95	0.67

Table A3: 4-hour co-location test conducted indoors in July 2021 during a source generation event. Percentiles are of the calculated ratio between the listed DustTraK and the reference DustTrak.

Model	DustTrak II	DustTrak II	DustTrak DRX	DustTrak DRX	DustTrak DRX	DustTrak DRX	DustTrak DRX
Calibration Date	2/19/2020	7/17/2017	3/28/2019	2/3/2021	4/16/2019	4/4/2019	4/4/2019
Owner	UC Davis	UC Davis	UC Davis	UC Davis	ARB	ARB	ARB
	Sampler 1	Sampler 2	Sampler 3	reference	Sampler 4	Sampler 5	Sampler 6
5th	1.27	1.43	1.12	1.00	0.81	0.91	0.78
25th	1.33	1.50	1.13	1.00	0.88	0.91	0.85
50th	1.38	1.51	1.13	1.00	0.88	0.92	0.87
75th	1.41	1.53	1.13	1.00	0.89	0.95	0.89
95th	1.43	1.54	1.18	1.00	0.91	1.20	0.91

Table A4: 48-hour co-location test conducted outdoors in February 2022 during a source generation event. Percentiles are of the calculated ratio between the listed DustTraK and the reference DustTrak. The value for Sampler 4 was adjusted to the references samples for the testing in Building C as it was consistently lower. The sampler was only used in some of the tests in Building C.

Model	DustTrak II	DustTrak II	DustTrak DRX	DustTrak DRX	DustTrak DRX	DustTrak DRX	DustTrak DRX
Calibration Date	2/19/2020	7/17/2017	3/28/2019	2/3/2021	4/16/2019	4/4/2019	4/4/2019
Owner	UC Davis	UC Davis	UC Davis	UC Davis	ARB	ARB	ARB
Percentile	Sampler 1	Sampler 2	Sampler 3	reference	Sampler 4	Sampler 5	Sampler 6
5th	0.31	0.37	1.00	1.00	0.45	0.40	0.79
25th	0.50	0.58	1.09	1.00	0.58	0.56	0.94
50th	0.65	0.72	1.16	1.00	0.74	0.87	1.31
75th	0.75	0.88	1.22	1.00	0.87	1.05	1.82
95th	0.93	1.00	1.35	1.00	1.00	1.24	2.16

Table A5: 48-hour co-location test conducted outdoors in February 2022 during a source generation event. Percentiles are of the calculated ratio between the listed DustTraK and the reference DustTrak.

Model	DustTrak II	DustTrak II	DustTrak DRX	DustTrak DRX	DustTrak DRX	DustTrak DRX	DustTrak DRX
Calibration Date	2/19/2020	7/17/2017	3/28/2019	1/21/2022	4/16/2019	4/4/2019	4/4/2019
Owner	UC Davis	UC Davis	UC Davis	UC Davis	ARB	ARB	ARB
Percentile	Sampler 1	Sampler 2	Sampler 3	reference	Sampler 4	Sampler 5	Sampler 6
5th	0.69	0.92	0.63	1.00	0.00	Out of Service	0.23
25th	1.05	1.10	0.90	1.00	0.29	Out of Service	0.61
50th	1.13	1.14	0.95	1.00	0.68	Out of Service	0.90
75th	1.21	1.18	1.00	1.00	0.79	Out of Service	1.00
95th	1.80	1.31	1.39	1.00	1.13	Out of Service	1.36