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Energy and Indoor Air Quality Impacts of Compartmentalization and Different Ventilation Strategies in California Multifamily Buildings

Author

Adler, Scott William

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Energy and Indoor Air Quality Impacts of Compartmentalization and Different Ventilation Strategies in California Multifamily Buildings

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SCOTT ADLER
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APPROVED:

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Mark Modera, Chair

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Deborah H. Bennett

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Kelly Kissock

Committee in Charge

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Abstract

Compartmentalization has been proposed as a strategy to improve indoor air quality (IAQ) and energy efficiency in multifamily buildings. California's 2022 Building Energy Efficiency Standards requires multifamily buildings to either meet a unit airtightness requirement of 0.3 cfm_{50}/ft^2 or provide balanced ventilation. While there is consensus that compartmentalization enhances building performance, not enough studies exist to accurately quantify the impacts of different compartmentalization levels on pollutant exposure and energy usage. Furthermore, builders have raised concerns over the difficulty of meeting the airtightness requirement. Such discussion has called into question whether the IAQ benefits and energy savings achieved from compartmentalization justify the current requirement or support a stricter or more lenient requirement. Regulators need this primary data to develop well-informed building codes that promote safety, affordability, and energy efficiency. The study found that new-construction multifamily buildings are meeting the compartmentalization requirement with an average unit leakage of 0.16 cfm_{50}/ft^2. Ventilation flow testing suggested that adjusting flow rates down to the minimum ventilation requirement for each unit and installing air filters on dedicated outdoor air intakes could improve IAQ and save energy. Inter-unit transfer of secondhand was modeled to reduce significantly for tighter units, resulting in concentrations below hazardous exposure limits in non-smoking units. Annual energy savings from compartmentalization were estimated to be as much as 6% and GHG savings as much as 10%, however results were highly sensitive to climate zone and ventilation strategy.

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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 (CARB, 2022). California responded by establishing tailpipe emission standards, which led to the development of the catalytic converter in the 1970s (CARB, 2022). 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 (Chen, Salam, Eckel, Breton, & Gilliland, 2015). 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.

Awareness of Indoor air quality (IAQ) has been growing for decades with COVID-19 alerting the general public to the need for fresh and filtered air. Air quality is also an environmental justice issue, as disadvantaged communities are generally located near pollution sources, such as highways and power plants (Adamkiewicz, et al., 2011). Elevated levels of outdoor pollutants can also deteriorate IAQ when outdoor air enters units either intentionally (supply ventilation) or unintentionally (infiltration). 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 heating, ventilating, and air conditioning (HVAC) equipment (Lozinsky & Touchie, 2020).

Improving IAQ in multifamily buildings is important since these predominantly low-income residents are often located near external pollution sources and subject to internal transfers of pollutants through common walls separating units (Hewett M. J., Sandell, Anderson, & Niebuhr, 2007).

Today's energy policy is continuing to change the built environment. California's climate goals call for greenhouse gas (GHG) emission reductions in all sectors of the economy (CARB, 2022). Buildings account for roughly 25% of the state's emissions and are proposed to be decarbonized through increased efficiency and electrification (CARB, 2022). With increasing work-from-home jobs and rising electricity and gas prices, measures that both improve indoor environmental quality and save energy are essential.

This thesis examines how California multifamily buildings are performing in terms of IAQ and energy usage, and whether compartmentalization requirements are warranted. The first section examines existing literature on this topic. The second section presents field testing methods and findings from three new-construction multifamily buildings. The third section generalizes these results through CONTAM and EnergyPlus modeling. The fourth section discusses findings and lessons learned. The final section recommends changes to building codes and areas for future research.

Background

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, such as hotels, are generally ten or more stores. 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 (U.S. Census Bureau, 2020). Since they differ substantially in construction and operation from single-family homes, multifamily buildings follow their own set of codes and standards. An important difference to consider is inadvertent airflow “leakage” between zones in multifamily buildings, which are potentially problematic for IAQ and energy efficiency.

Construction Practices

Structures are typically built from wood, concrete, and steel and must follow the International Building Code based on function and height (ICC, 2018). Today, the construction landscape is being reimagined with labor shortages propelling innovation in construction practices (Hossain , Zhumabekova, Paul , & Kim , 2020). Construction 3-D printing has generated a lot of attention in the past decade but is yet to penetrate the market (Wu, Wang, & Wang, 2016). Prefabrication, offsite construction of building components that are later assembled onsite, is on the rise and could be the future norm (Li, Shena, & Xue, 2014). 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. The major advantages of prefabrication are increased construction speed and decreased construction costs (Kamali & Hewage, 2016).

Along with economic incentives, 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.

Ventilation

Ventilation is the circulation of 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. This is achieved by bringing in some outdoor air, heating or cooling outdoor and recirculated air, and using air filters. Most new-construction multifamily buildings use supply and/or exhaust ventilation, heat pumps (at least in California which is moving towards all-electric buildings), and air sealing to achieve a pleasant indoor environment.

Imbalanced ventilation systems supply and exhaust air at different rates. 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. Balancing flows 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 (Ueno, Lstiburek, & Bergey, 2012). 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 American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) minimum ventilation requirement (ASHRAE, 2019). 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 heath and comfort perspective (Guyot, Sherman, & Walker, 2018).

Supply ventilation systems are common in commercial buildings but seldom seen in residential 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 (Jokisalo, Kurnitski, Vuolle, & Torkki, 2016). 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 IAQ. Nevertheless, 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 (Lubliner & Walker, 2020). Additionally, balanced systems become unbalanced when intermittent kitchen or bathroom exhaust fans are in operation. Thus, the higher cost and of balanced ventilation may not be worth the benefit if leakage pathways persist between units.

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 (Lozinsky & Touchie, 2020). 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” (Lovatt & Wilson, 1994). 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 (Diamond, Feustel, & Dickerhoff, 1996; Palmiter, Francisco, & Bond, 1996).

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 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 (Diamond, Feustel, & Dickerhoff, 1996; Palmiter, Francisco, & Bond, 1996). 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 ventilation 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 (Lozinsky & Touchie, 2020).

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:

$$P + \frac{1}{2}pv^2 + pgh = constant \tag{1}$$

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

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

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

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

$$h = height\ [m]$$

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

$$assuming\ no\ change\ in\ height:$$

$$P_1 + \frac{1}{2}pv_1{}^2 = P_2 + \frac{1}{2}pv_2{}^2 \tag{2}$$

$$Continuity\ equation:$$

$$A_1v_1 = A_2v_2 \tag{3}$$

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

$$v_2 = \sqrt{\frac{2(P_2-P_1)}{p(\frac{A_2}{A_1}^2-1)}} \tag{4}$$

$$A_2 v_2 = A_2 \sqrt{\frac{2}{p(\frac{A_1}{A_2}^2 - 1)}} \sqrt{\Delta P} \quad (5)$$

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

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

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

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:

$$Q = C\Delta P^n \quad (7)$$

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

$$C = flow\ constant,$$

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

$$n = flow\ exponent$$

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 (Walker, Sherman, Joh, & Chan, 2013).

Envelope Leakage

Air barriers and air sealing help prevent leakage, which can save over 30% of a building's heating and cooling costs (DOE, 2022). 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 generated indoors.

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 (DOE, 2022).

Building airtightness is measured by performing a blower door test (ASTM, 2019). 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 or surface area to determine a relative leakage metric (DOE, 2022).

A recent comprehensive study used semi-automated pressurization fan testing to quantify air leakage in multifamily buildings (Bohac & Sweeney, 2020). 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.

Unit Leakage

In general, while the exterior surfaces of new-construction multifamily buildings appear to be becoming relatively airtight, interior walls are often left leaky (Bohac & Sweeney, 2020). When Bohac & Sweeney (2020) 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}. These results suggest that builders have made progress in sealing the exterior envelope of multifamily buildings, however, there remains work to be done on tightening the interior.

The 2012 International Energy Conservation Code (IECC) includes a requirement that air leakage may not exceed 3 ACH_{50} in DOE Climate Zones 3 through 8 (IECC, 2012). NREL has conducted studies investigating the feasibility of achieving this airtightness requirement in US multifamily buildings. One study performed fan pressurization tests to measure air leakage in three projects in upstate New York (Klocke, Faakye, & Puttagunta, 2014). 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 fan pressurization tests to determine total leakage, leakage to the outdoors, and inter-unit leakage for five three-story townhouse buildings in Washington, D.C. (Ueno & Lstiburek, 2015). Unguarded testing refers to a single-zone blower door test, 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 it. The difference in airflow between the guarded and unguarded tests equals the 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 (Klocke, Faakye, & Puttagunta, 2014).

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 (Palmiter, Francisco, & Bond, 1996). 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 (Harrje, Bohac, & Feuerman, 1988).

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 (Bohac & Sweeney, 2020). Yet, individual multifamily units remain about twice as leaky as single-family homes (Price, Shehabi, Chan, & Gadgil, 2006). It is important to consider that leaky buildings increase the ventilation rate, which can decrease the concentration of harmful pollutants. Therefore, an energy-centric sealing approach could be misguided, especially during retrofits, if energy savings are achieved at the cost of increasing inter-unit transfer of "dirty" air that could adversely affect the health of occupants. Instead, a wholistic approach is required to improve all building performance metrics, including IAQ, energy efficiency, and occupant comfort.

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 (CEC, 2019). Title 24-2019 has a requirement that all new-construction multifamily units must either:

a) meet a compartmentalization requirement of 0.3 cubic feet per minute at 50 Pa per square foot (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 (ASHRAE, 2019). 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 Title 24 requirement for ventilation and IAQ is potentially insufficient for the following two reasons. 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}. 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 a lower cost (Harrington & Modera, 2013).

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 (EPA, 1989; Klepeis, et al., 2001). 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 (Jones, 1999).

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 (Weschler, 2009). Unlike single-family homes that only exchange air with the outdoors, multifamily buildings have another 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 multifamily 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 (U.S. Department of Health Services, 2006). 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 (CARB, 2005; EPA, 1992; EPA, 2002; Cal EPA, 1997; U.S. Department of Health Services, 2006).

Questionnaire 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 5 or more units reporting drift more often relative to those living in buildings with fewer units (Holmes, Llamas, & Ling, 2020). 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 (Hewett M. J., Sandell, Anderson, & Niebuhr, 2007).

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 (King, Babb, Tynan, & Gerzoff, 2013). Using data from the 2009 American Community Survey, the study estimated that 26%, or 79 million people live in multifamily housing in the US. In California, 32%, or 12 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 63 million nationwide and 11 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% 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 27-29 million people nationwide have experienced secondhand smoke infiltration, with 4-5 million affected 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 (Wilson, Klein, Blumkin, Gottlieb, & Winickoff, 2011). Furthermore, the study found that children living in multifamily buildings 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 (Bohac, Hewett, Hammond, & Grimsrud, 2011). 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%, ranging from 2% in a new building to 35% 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 that 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 particulate matter (PM) levels (King, Travers, Cummings, Mahoney, & Hyland, 2010). $PM_{2.5}$ 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 μg/m^3, compared to the smoke-free units which had a median concentration of 8.3 μg/m^3, while the common hallways had a median concentration of 16.6 μg/m^3. The median $PM_{2.5}$ concentration on the outdoor patios was 8.6 μg/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 (NIST, 2021). 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 (Emmerich, Howard-Reed, & Gupte, 2005). 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 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, whole-building continuous exhaust ventilation, and whole-building balanced ventilation (Underhill, Dols, Lee, Fabian, & Levy, 2020). 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 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 fans were able to mitigate the increased concentrations stemming from the sealing and insulation interventions, reaching in fact a lower concentration than the baseline scenario for the balanced system.

Poor IAQ continues to expose residents in multifamily buildings to unhealthy levels of pollutants. 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 (Weschler, 2009). Gaseous pollutants were found to be the primary concern for inter-unit transfer, as very little PM was detected to transfer between units (Bohac, Hewett, Hammond, & Grimsrud, 2011). 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 (Coombs, et al., 2016). While increased ventilation with filtration are known to dilute and remove indoor pollutant concentrations, few studies exist on how different airtightness levels affect pollutant concentrations and inter-unit transfers. Understanding this interaction between leakage levels and ventilation strategies is necessary to ensure the benefits of energy efficiency and IAQ are maximized.

Energy Usage & GHG Emissions

In the US, buildings account for approximately 40% of primary energy consumption (Rastogi, Choi, Hong, & Lee, 2017; EIA, 2022). 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 heat (EPA, 2022). Building codes and certification programs, like LEED, promote energy efficient buildings that save energy and reduce GHG emissions.

Each household in California uses roughly 60 million British thermal units (MMBTU) of energy per year (EIA, 2009). While this number is about one third less than the US average, the average California household pays more for their monthly energy bill than the national average due to significantly higher energy prices in California (EIA, 2020). Therefore, energy savings can directly benefit residents by lowering their energy bills and can more broadly benefit society by reducing GHG emissions and help to mitigate climate change.

The average California family uses about 30% of their energy for heating and cooling (EIA, 2009). This number too is less than the US average (approximately 40%) due to California's "mild" climate (Rastogi, Choi, Hong, & Lee, 2017; EIA, 2022). 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) 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 (Otis & Maxwell, 2012; Ueno & Lstiburek, 2015). The stack effect induces uncontrolled airflows, creating uneven demands for space conditioning among units (Jo, Lim, Song, Yeo, & Kim, 2007). 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 (Diamond, Feustel, & Dickerhoff, 1996). This effect is amplified in leaky buildings 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 (Carlsson, Touchie, & Richman, 2017). 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 (DOE, 2022). 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 (Carlsson, Touchie, & Richman, 2017). The study modeled compartmentalized units with balanced ventilation and heat recovery systems. It found a 51% (48 kWh/m^2) reduction in total annual heating energy, which corresponded to a 29% (20 tCO_2e) annual carbon footprint decrease. 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 (Torvestad & Stone, 2018). Proposed ventilation code changes were predicted to result in annual savings of 1.7 MMBTUs and 7,800 MWh, with annual GHG reductions of 2,700 tCO_2e. 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 CO_2 mitigation strategies in office buildings (Mata, Kalagasidis, & Johnsson, 2013). 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%.

Most of the energy saving measures were predicted to be cost-effective. The most impactful measure was predicted to be heat recovery systems with an energy saving of 22%. Lowering the indoor temperature to 68 F, a reduction of 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 TRNSYS, a detailed multi-zone building energy modeling program, to evaluate potential savings from tightening units (Emmerich, McDowell, & Anis, 2005). 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 (Bohac & Sweeney, 2020). 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 energy savings from compartmentalization is understudied.

Study Objectives

A limited understanding of how compartmentalization impacts energy and IAQ stands out as an important data gap. In the literature, there are no experimental data available that quantify IAQ or health impacts from this measure alone. Research in this area is necessary to address this lack of data and provide information on how compartmentalization requirements affect 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 aims of the study were to:

- Measure the distribution of total air leakage for units in multifamily buildings
- Measure the distribution of ventilation flows for units in multifamily buildings
- Measure overall air exchange rates in units with different leakage levels
- Measure inter-unit pollutant transfer rates in units with different leakage levels
- Model air and pollutant transfer for different leakage levels and ventilation strategies
- Model energy and GHG emissions for different leakage levels and ventilation strategies

Field Testing

Primary data were gathered by performing extensive field testing on three new-construction multifamily buildings. Testing included one-time measurements focused on leakage levels and ventilation system flows, and short-term monitoring focused on air exchange rates, inter-unit air flows, and inter-unit gaseous pollutant transfer. This data was collected to evaluate how new multifamily buildings are performing under current California building codes and investigate the potential IAQ and energy improvements of compartmentalization.

Building Recruitment

Three new-construction mid-rise multifamily buildings in the San Francisco Bay Area were selected for field testing (summarized in Table 1). While all three were six-story residential buildings that met Title 24, each had distinct designs, unit sizes, mechanical equipment, and intended occupants. Two buildings targeted compartmentalization while the other installed balanced ventilation to comply with the ventilation and IAQ requirement in Title 24 (Section 120.1).

Table 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
Airtightness Target	0.3 cfm_{50}/ft^2	N/A	0.3 cfm_{50}/ft^2
Ventilation System	Exhaust	Balanced	Exhaust

Building A

The first building is a six-story, rectangular multifamily apartment complex located in Oakland, CA (pictured in Figure 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 homeless. The building consists of 59 units: 11 one-bedrooms, 28 two-bedrooms, and 20 three-bedrooms. It was designed to meet Section 120.1 of Title 24 through the compartmentalization requirement. 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.

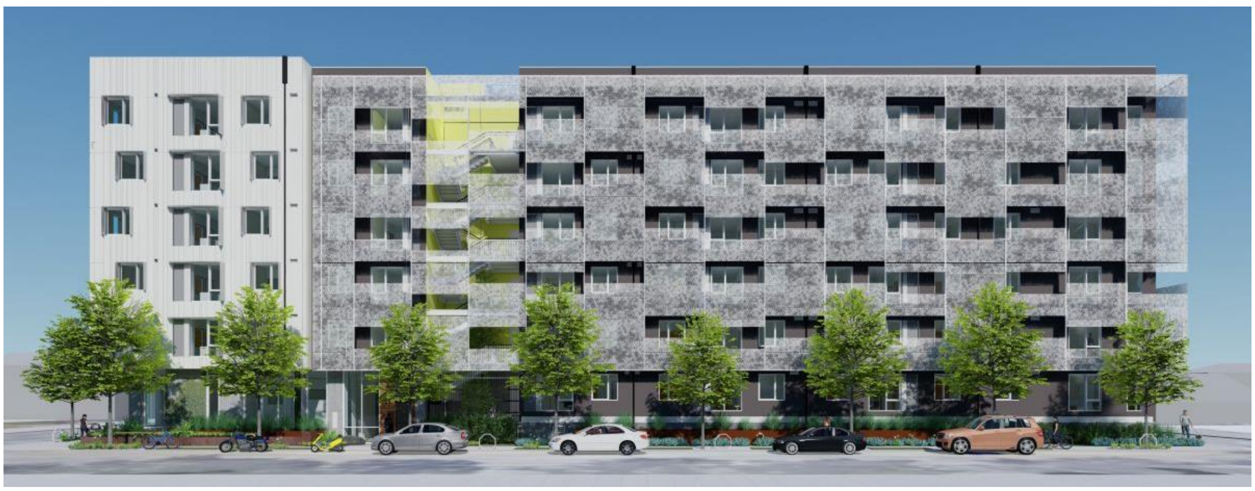

Figure 1. Computer generated architecture drawing of Building A.

Building B

The second building is a six-story, U-shaped multifamily apartment complex located in El Cerrito, CA (pictured in Figure 2). 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 studios, 106 one-bedrooms, and 25 two-bedrooms. 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. 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 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 had electric Packaged Terminal Heat Pump (PTHP) units and electric stoves. This is an affordable housing development. The building consists of 135 units: 118 studios, 16 one-bedrooms, and 1 two-bedroom. It was designed to meet Section 120.1 of Title 24 through the compartmentalization requirement. 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 PTHPs, which have 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 3. Computer generated architecture drawing of Building C.

Field Testing Methods

Field testing was performed to gather primary data on newly constructed multifamily buildings in California (see Table 2 for a summary of tests). One-time testing was conducted to measure: total unit leakage, ventilation flows (including continuous supply and exhaust grilles, and intermittent kitchen and bathroom fans), and unit-to-unit leakage. Short-term monitoring was conducted to measure: air change rates and gaseous pollutant transfer between units. The specification (range, resolution, and accuracy) for field-testing equipment is reported in Table 3.

Table 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
Ventilation flows	3	10-13	35	Powered flow-capture hood
Inter-unit leakage	2	3-6	9	Guarded blower door test
Air exchange rate	2	2-3	10	CO_2 decay
Gaseous transfer	2	2-3	10	CO_2 constant concentration

Table 3. Specifications (Range, Resolution, and Accuracy) for Field Testing Equipment

Equipment	Range	Resolution	Accuracy
Model 3 Blower Door Fan (TEC, 2017)	11-6,300 cfm	1 cfm	+/- 3%
Series B Duct Blaster Fan (TEC, 2016)	10-1,550 cfm	1 cfm	+/- 3%
DG-1000 (TEC, 2016)	-2,500-2,500 Pa	0.1 Pa	+/- 0.9%
DG-700 (TEC, 2016)	-1,250-1,250 Pa	0.1 Pa	+/- 1%
Alicat MFC (Alicat Scientific, 2022)	0-10 SLPM	0.01 SLPM	+/- 0.6%
Telaire T6713 (Amphenol, 2022)	0-5,000 ppm	1 ppm	+/- 30 ppm +/- 3%
HOBO Max 1102A (Onset, 2022)	0-2,000 ppm	1 ppm	+/- 50 ppm +/- 5%

Unit Leakage Testing

Total unit air leakage (compartmentalization) was measured by performing single-zone blower door tests on individual units (see diagram and picture in Figure 4). 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 in accordance with the "Standard Test Method for Determining Air Leakage Rate by Fan Pressurization: ASTM E779-19" (ASTM, 2019). 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 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 (TEC, 2022). 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.

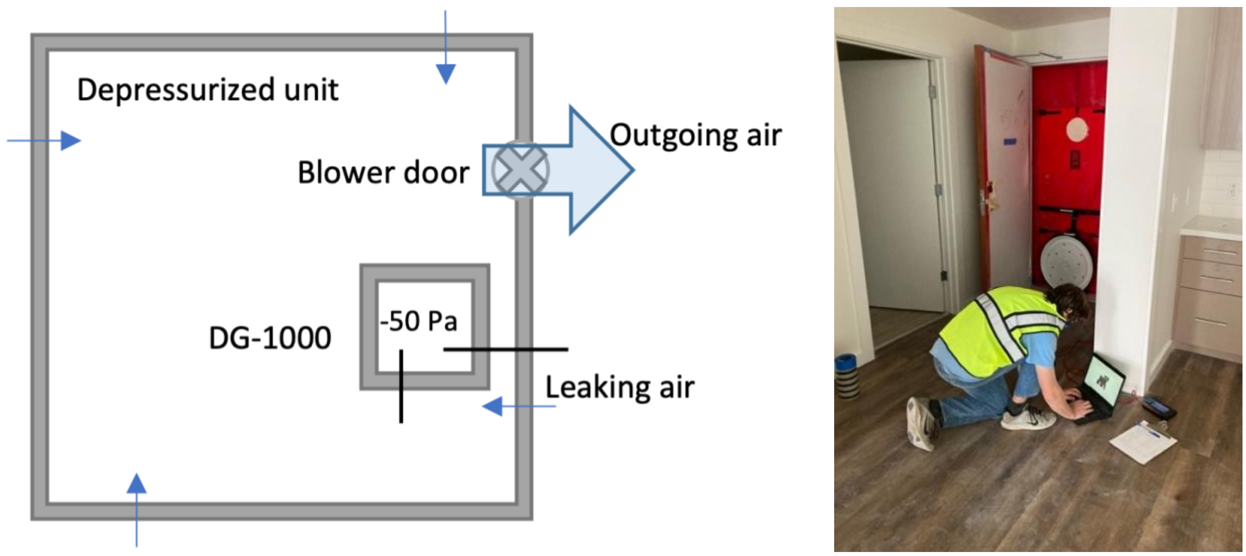

Figure 4. Blower door testing: diagram of the test (left); photo during field testing (right).

Ventilation Testing

Ventilation grille flow rates were determined by performing powered flow-capture hood tests (see diagram and picture in Figure 5). 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 the air current 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 pliable 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 (TEC, 2022). 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.

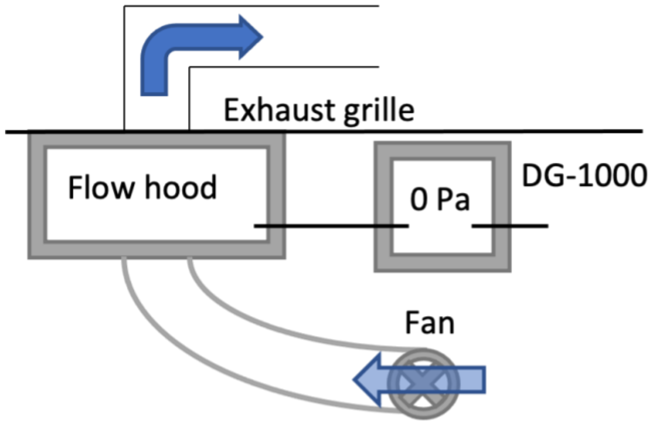

Figure 5. Ventilation grille testing: diagram of the test (left); photo during field testing (right).

AIR SEALING

Three identical units in two buildings were used to analyze 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 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 6 shows a diagram and blower door test demonstrating how leaks are sealed and the units becomes "tighter" over time). 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 (Aeroseal, 2022). 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, "tight", and 0.1 cfm_{50}/ft^2, "very tight" (see sealing reports for Building A in appendix Figure A-1 and Figure A-2).

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 interior finishes were complete). Second, blower door testing found other units were tighter than the expected "as-found" condition. Third, one building that was sealed was unable to participate in the follow-up testing, so units with naturally different leakage values from the third building (that did not receive any sealing) were selected. Nevertheless, similar units at different leakage levels were identified for further testing.

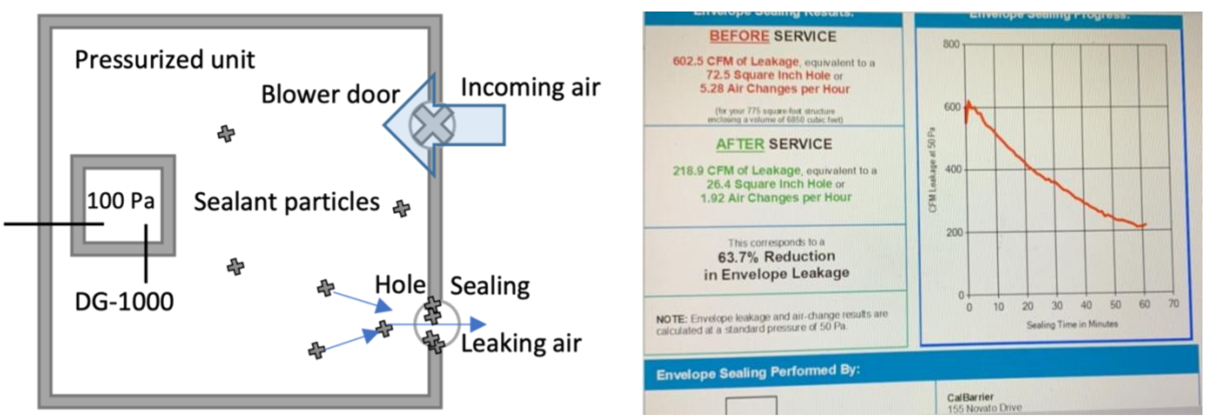

Figure 6. Aerosol-based Air sealing: diagram of the sealing process (left); graph of unit's leakage throughout the one-hour sealing process (right).

Inter-Unit Leakage Testing

Inter-unit air leakage was determined by performing guarded blower door tests (see diagram and picture in Figure 7). All the units that were sealed and some units that were not sealed were tested to measure how much air was flowing between units (both horizontally and vertically adjacent). These tests were also used to measure the reduction in inter-unit leakage from sealing units to tighter levels.

A guarded blower door test differs from a “standard” blower door test by using a second blower door to maintain the same pressure in an adjacent unit as the unit being tested. No air flows between two zones that are equally pressurized or depressurized, thereby guarded testing eliminates any air flow to the adjacent unit using the second blower door. Leakage to adjacent units can be calculated by subtracting the guarded test result from the unguarded 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.

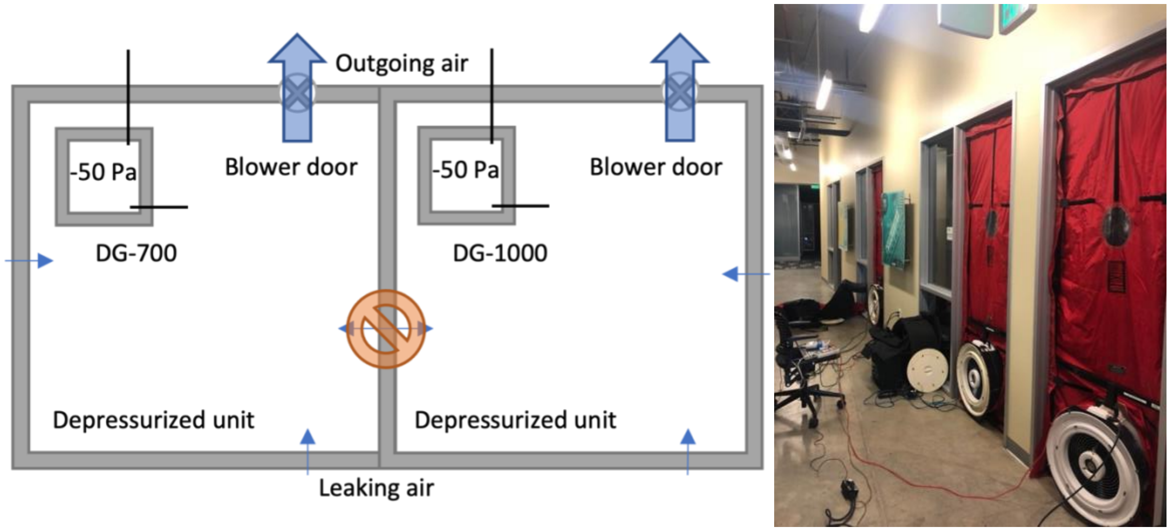

Figure 7. Guarded blower door test: diagram of the test (left); photo of field testing (right).

AIRFLOW TESTING

Carbon dioxide was used as a tracer gas to determine gaseous transfer between units, as well as overall unit air exchange rates (see diagram and picture in Figure 8). Tests were performed in the three "test" units (each at different leakage levels) in two buildings. 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 PID control loop in the source unit for 1-2 hours, after which the CO_2 injection was stopped, and the concentration allowed to decay for 2-3 hours. The air change rate was calculated from the slope of the decay:

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

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

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

$$C = indoor\ CO_2\ concentration\ [ppm], and$$

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

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

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

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

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

$$where\ {}^{Q}/_{V} = N = air\ change\ rate\ per\ unit\ time\ (t)$$

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 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 calibration to 400 ppm. After the calibration was complete, sensors were within 20 ppm (5%) of one another (see Figure 9).

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:

$$V\frac{dC}{dt} = C_sQ_s - Q(C_t - C_{out}) \quad (13)$$

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

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

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

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

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

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

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

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 ventilation rate (measured previously with ventilation flow testing):

$$f = \frac{Q_s}{Q} \quad (15)$$

$$where\ f = fraction\ of\ air\ in\ adjacent\ unit\ from\ source\ unit\ [\%]$$

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. 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.

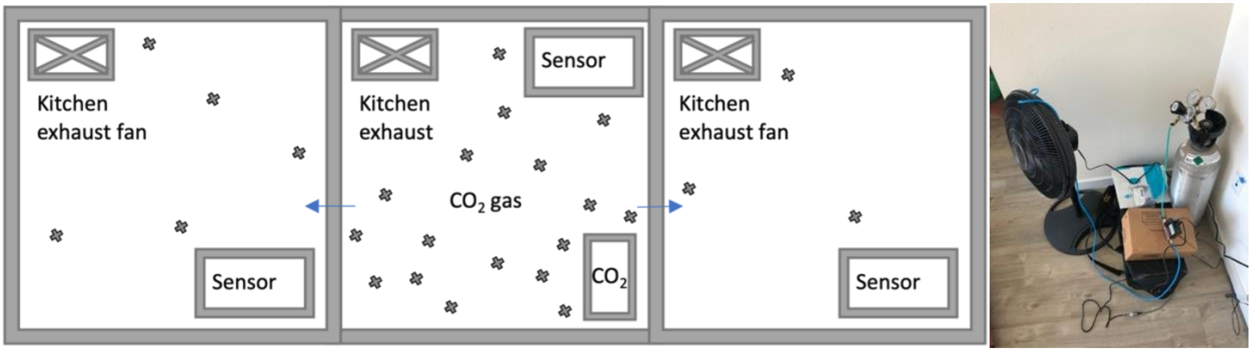

Figure 8. Gaseous pollutant transfer testing: diagram of the test with adjacent kitchen exhaust fans on (left); photo of field-testing setup showing Alicat, CO_2 tank, and fan (right).

Figure 9. Post-calibration photo of HOBO CO_2 sensors showing they are within +/- 20 ppm (5%) of each other.

Field Testing Results

Field testing data were used to assess the IAQ and energy performance of three new-construction multifamily buildings in California. The parameters analyzed were 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 (reported in Table 4) with all tests performed prior to occupancy.

Table 4. 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

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 5). 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). Therefore, new-construction units appear to be about half as leaky as the current airtightness requirement with only modest variation in leakage.

Table 5. Total Unit Leakage Comparison Between Buildings Normalized by Surface Area and Volume

Building	[cfm_{50}/ft^2]	SD [%]	ACH_{50} [/hr]	SD [%]	# Units
A	0.17	15%	3.9	16%	14
B	0.14	14%	3.2	14%	10
C	0.16	10%	4.3	11%	12

Blower door test results from the three buildings showed unit leakage was consistent among buildings (see Figure 10). 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 11).

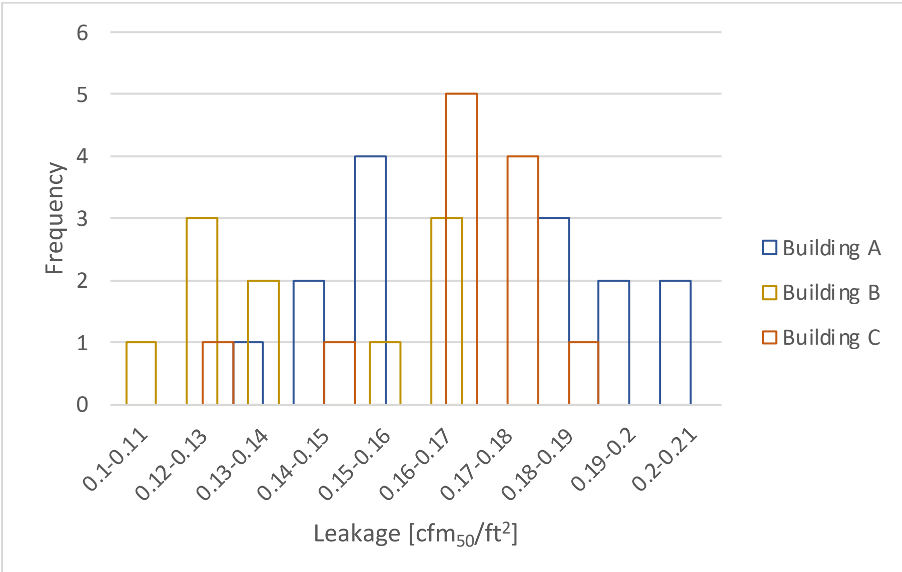

Figure 10. Total unit leakage distributions for each building normalized by surface area [cfm_{50}/ft^2].

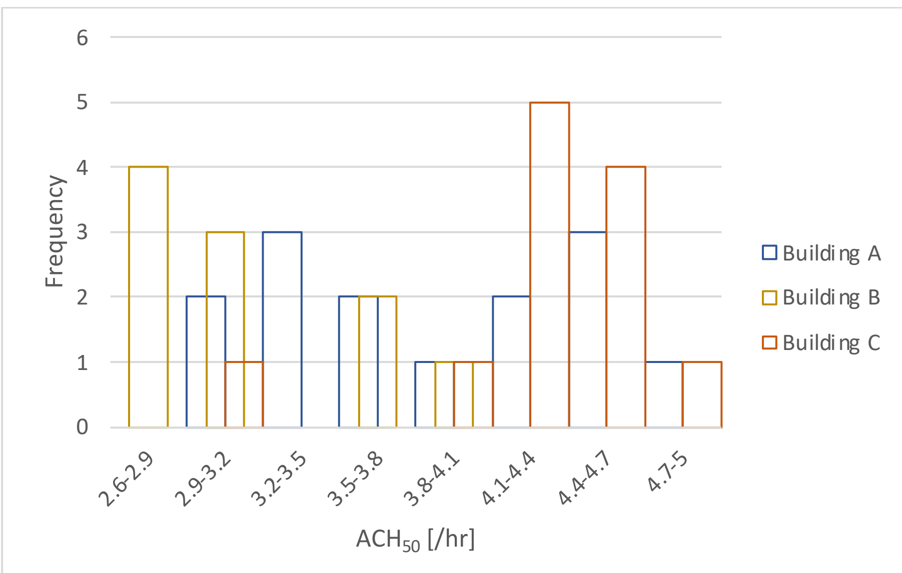

Figure 11. Total unit leakage distributions for each building normalized by volume [ACH_{50}].

Ventilation Flows

Each building was designed with a different ventilation strategy, resulting in different ventilation flows for each of the buildings (see Table 6). Units in Building B were designed with supply and exhaust ventilation and to be balanced (see Figure 12). Units in Buildings A and C were designed with exhaust-only ventilation and to be unbalanced (see Figure 12). Building A had in-unit HRVs. Building C had in-unit PTHPs open to the outside to supply air. It was unclear whether further commissioning and adjusting of flow rates would take place in these buildings.

Table 6. Field Testing Continuous Ventilation Flow Summary Statistics (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

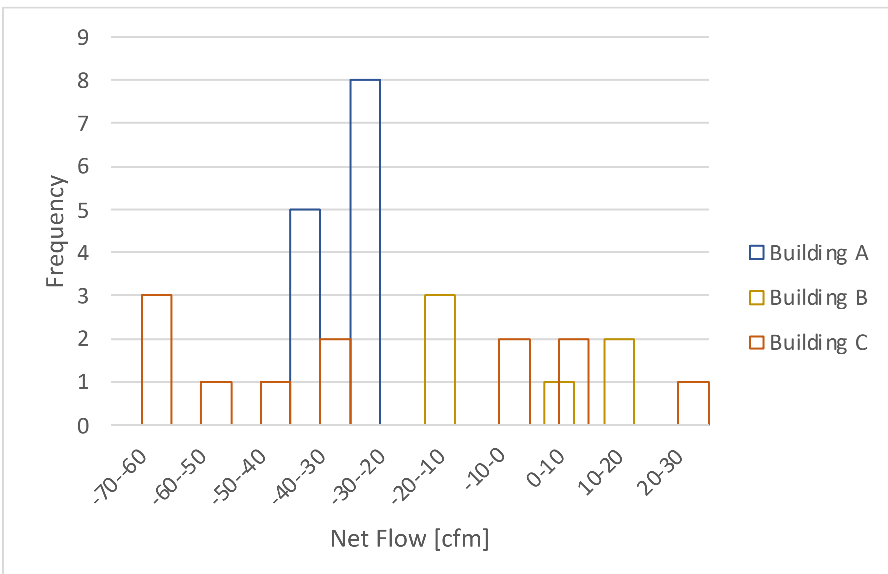

Figure 12. The net continuous ventilation flow distribution [cfm] shows that most units are negatively pressurized and there is significant variation in ventilation flows for some buildings.

The continuous ventilation systems in Building A were performing as expected. 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 (see Figure 13). Failing to adjust ventilation flows between different units resulted in overventilation compared to Title 24 and larger pressure differences between units.

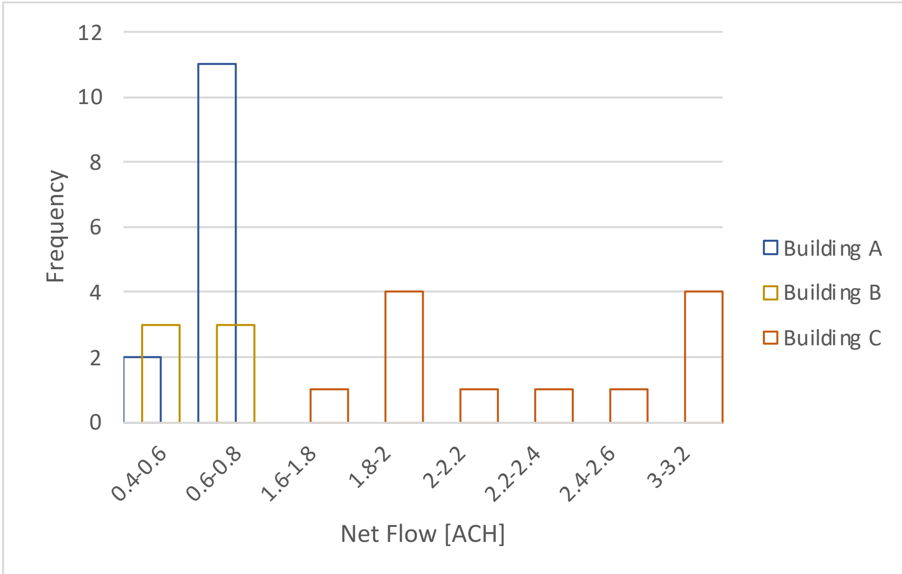

Figure 13. The net continuous ventilation flow distribution [ACH] shows that Building C has far more air changes than buildings A and B.

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. Common corridor supply 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, flows were imbalanced by about 10 cfm, which was 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 continuously removed, on average, 150 cfm of air from the small (1,500 square foot) studios. The corridors also had continuous exhaust fans. Supply air was delivered 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 through each PTHP were constant between units since the whole building was depressurized by about 30 Pa and the same model PTHP was installed in each unit.

As a result, each unit experienced the same pressure difference and the same leakage area, which resulted in similar supply air flows through each PTHP. These units were simultaneously severely overventilated and poorly ventilated, stemming from a poor design decision to provide makeup air through unfiltered outdoor air intakes on PTHP units in a building located next to a major highway.

Kitchen exhaust fan flow results showed that when in operation, kitchen fans generally dominate the ventilation flows in a unit (see Figure 14). 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 fans had not yet been commissioned and needed additional work. 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.

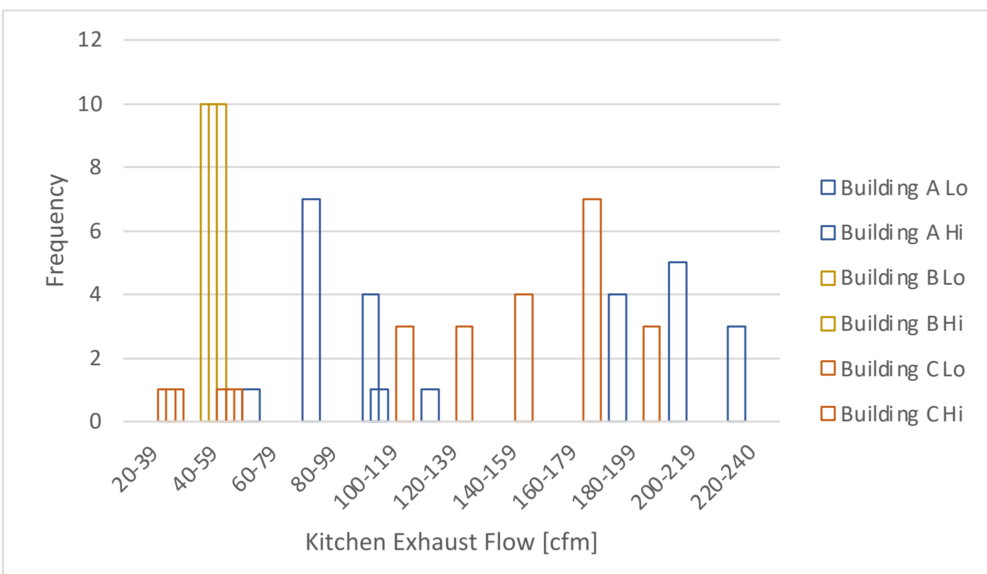

Figure 14. Kitchen exhaust flow distribution for each building with the fan speed is indicated by “Hi” high or “Lo” low.

INTER-UNIT LEAKAGE

Inter-unit leakage results varied between buildings since different building designs produce 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 7). Total unit leakage slightly increased from 0.13 cfm_{50}/ft^2 and 0.15 cfm_{50}/ft^2 for the "sealed" units to 0.16 cfm_{50}/ft^2 for the "unsealed" unit. Unit 609 was slightly tighter than the other "unsealed" units in this building 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 of wall leakage.

Table 7. Inter-unit Leakage Results in Building A as Both Direct cfm Measurements and a Percentage of Total Leakage

Building A	Leakage	Q left		Q right		Q down		Q up	
[unit]	[CFM_{50}/ft^2]	[cfm]	[%]	[cfm]	[%]	[cfm]	[%]	[cfm]	[%]
409	0.13	42	12%	46	14%	NA	NA	NA	NA
509	0.15	40	10%	32	8%	NA	NA	NA	NA
609	0.16	49	13%	66	17%	26	7%	NA	NA

In Building B, significant inter-unit leakage was found through floors/ceilings but not between side-by-side common walls. Total unit leakage slightly increased from 0.13 cfm_{50}/ft^2 for the "sealed" units to 0.16 cfm_{50}/ft^2 for the unsealed unit (see Table 8). Virtually no air was measured to transfer between units horizontally. This is probably a consequence of modular construction. It is likely that air still leaks through the first wall but then travels elsewhere instead of leaking through the second wall and into the adjacent unit. Vertical leakage results in Building B were similar to those measured in Building A as both a percentage of total leakage (7-11%) and when normalized by surface area.

Table 8. Inter-unit Leakage Results in Building B as Both Direct cfm Measurements and a Percentage of Total Unit Leakage

Building B	Leakage	Q left		Q right		Q down		Q up	
[unit]	[CFM_{50}/ft^2]	[cfm]	[%]	[cfm]	[%]	[cfm]	[%]	[cfm]	[%]
305	0.13	5	2%	4	1%	NA	NA	NA	NA
405	0.13	0	0%	0	0%	21	7%	22	7%
505	0.16	9	2%	2	0%	NA	NA	44	11%

In Building C, inter-unit leakage was a significant source of airflow. Leakage through shared walls was measured to be between 12-20% (see Table 9). 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 that found in 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 PTHP (which are effectively large holes in the exterior envelope) were sealed during leakage testing.

Table 9. Inter-unit Leakage Results in Building C Both as Direct cfm Measurements and a Percentage of Total Unit Leakage

Building C	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

Unit Air Changes

Tracer gas tests were conducted for 2-3 units in Buildings A and C. These tests were compared with mechanical ventilation rates previously measured during ventilation flow testing.

The tracer gas decay was used to calculate the total unit ventilation flow from which the mechanical ventilation rate could be subtracted to calculate the natural ventilation rate (or infiltration rate).

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:

$$n = n_{mech} + n_{nat} \qquad (16)$$

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

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

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

In Building A, the total air change rate increased as the total unit leakage increased (see Table 10). 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 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 10. Tracer Gas Results Showing Total ACH in Building A Units when Adjacent Kitchen Exhaust Fans are On and Off

Building A	Leakage [cfm_{50}/ft^2]	Tot ACH (adj fans off)	Tot ACH (adj fans on)	Mech ACH
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 11). In Building C, the natural air change rates appeared to be highly dependent on weather conditions (see Table 12). 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 simple supply and exhaust systems, 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 unit 531 is situated 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 time duration for each test and time required for units to stabilize after testing caused these tests to be performed on different days).

Table 11. Tracer Gas Results Showing Total ACH in Building C Units when Adjacent Kitchen Exhaust Fans are On and Off

Building C	Leakage [cfm_{50}/ft^2]	Tot ACH (adj fans off)	Tot ACH (adj fans on)	Mech ACH
531	0.18	2.54	3.12	1.93
534	0.12	3.12	2.93	2.29

Table 12. Tracer Gas Results Showing Natural ACH in Building C Units when Adjacent Kitchen Exhaust Fans are On and Off

Building C	Leakage [cfm_{50}/ft^2]	Nat ACH (adj fans off)	Nat ACH (adj fans on)	Mech ACH
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 (since this hole in the wall would likely dominate unit leakages). 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 tests occurred on different days and may have experienced different weather conditions that could have impacted results.

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 (see Figure 15). The graphs show a time lag between the CO_2 levels observed in the source and adjacent units. While the source unit responded almost immediately to the injection of CO_2, the adjacent units had a delayed respond to the high levels of CO_2 in the source 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 2 hours). When intermittent fans were turned off and pressure differences between units were nominally zero, there was virtually no measured transfer of CO_2 between units (Figure 16).

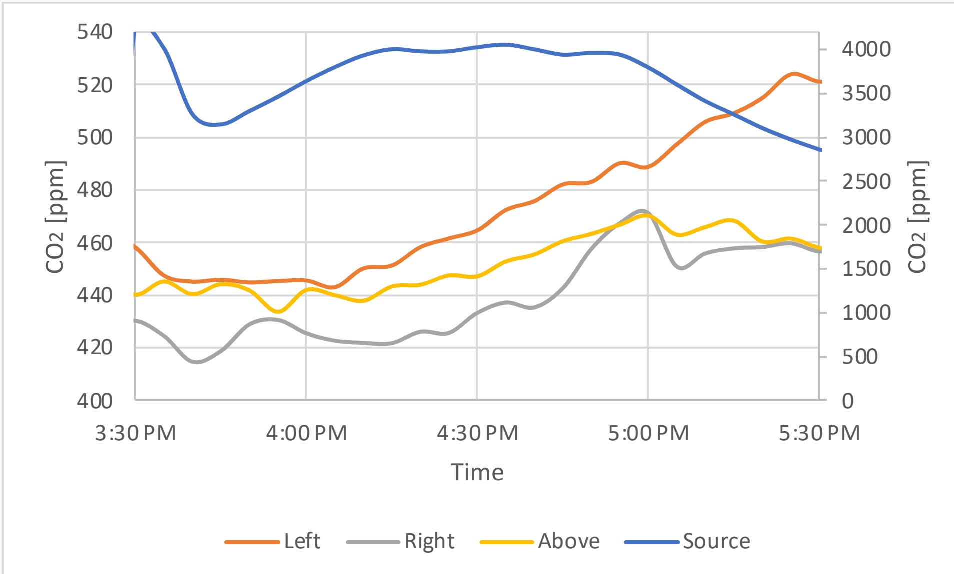

Figure 15. Tracer gas results showing source CO_2 concentration (right y-axis) and CO_2 concentrations in adjacent units (left y-axis) with kitchen exhaust fans on in Building A.

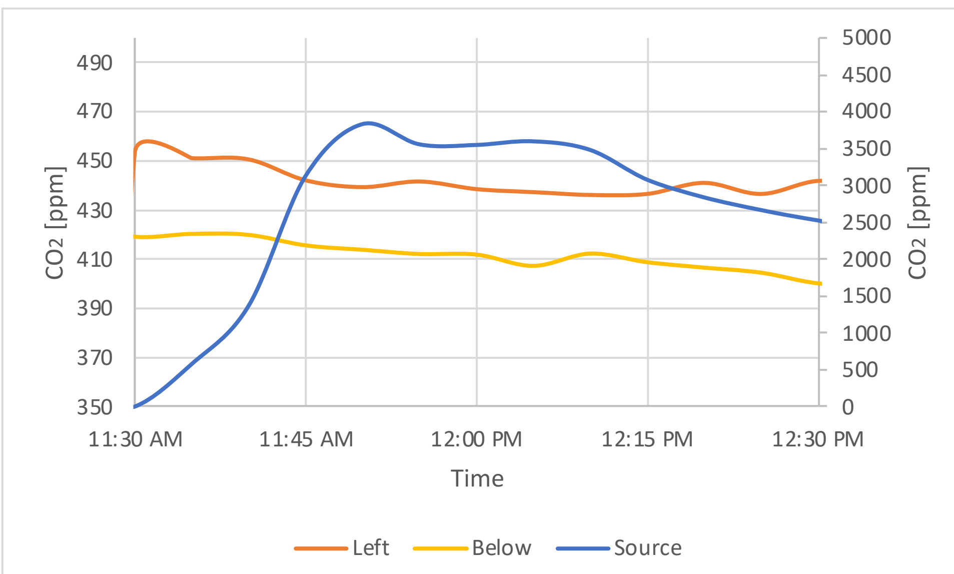

Figure 16 Tracer gas results showing source CO_2 concentration (right y-axis) and CO_2 concentrations in adjacent units (left y-axis) with kitchen exhaust fans off in Building A.

In Building A, measurements of inter-unit transfer of CO_2 indicated that only a very small fraction of the receiving units' air flows comes from the source unit when the receiving units' intermittent (i.e., kitchen exhaust) fans were off (see Table 13). This is not surprising when you consider that inter-unit airflows are driven by pressure differences between units, which Table 13 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. On the other hand, pressure differences of about 10 Pa were created by turning on kitchen exhaust fans in the receiving units (see Table 14). 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.

Table 13. Tracer Gas Results Showing Gaseous Pollutant Transfer in Building A with Adjacent Kitchen Exhaust Fans Turned Off

Building A	Leakage	Left			Right			Above/Below		
[unit]	[cfm_{50}/ft^2]	[Pa]	[cfm]	[%]	[Pa]	[cfm]	[%]	[Pa]	[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 14. Tracer Gas Results Showing Gaseous Pollutant Transfer in Building A with Adjacent Kitchen Exhaust Fans Turned on (Unit 607 had a Broken Kitchen Exhaust Fan)

Building A	Leakage	Left			Right			Above/Below		
[unit]	[cfm_{50}/ft^2]	[Pa]	[cfm]	[%]	[Pa]	[cfm]	[%]	[Pa]	[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	NA	NA	4	1%

In Building C, inter-unit transfer of CO_2 again only results in a very 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 15). Between 1-4 cfm was calculated to transfer to adjacent units when kitchen exhaust fans were turned on in these units (see Table 16). 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 Building A (refer to appendix Figure A-3 through Figure A-12 for all of the tracer gas test results).

Table 15. Tracer Gas Results Showing Gaseous Pollutant Transfer in Building C with Adjacent Kitchen Exhaust Fans Turned Off

Building C	Leakage	Left	Right/Below	Above

[unit]	[cfm$_{50}$/ft^2]	[Pa]	[cfm]	[%]	[Pa]	[cfm]	[%]	[Pa]	[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 16. Tracer Gas Results Showing Gaseous Pollutant Transfer in Building C with Adjacent Kitchen Exhaust Fans Turned On

Building C	Leakage	Left			Right/Below			Above		
[unit]	[cfm$_{50}$/ft^2]	[Pa]	[cfm]	[%]	[Pa]	[cfm]	[%]	[Pa]	[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 17). 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).

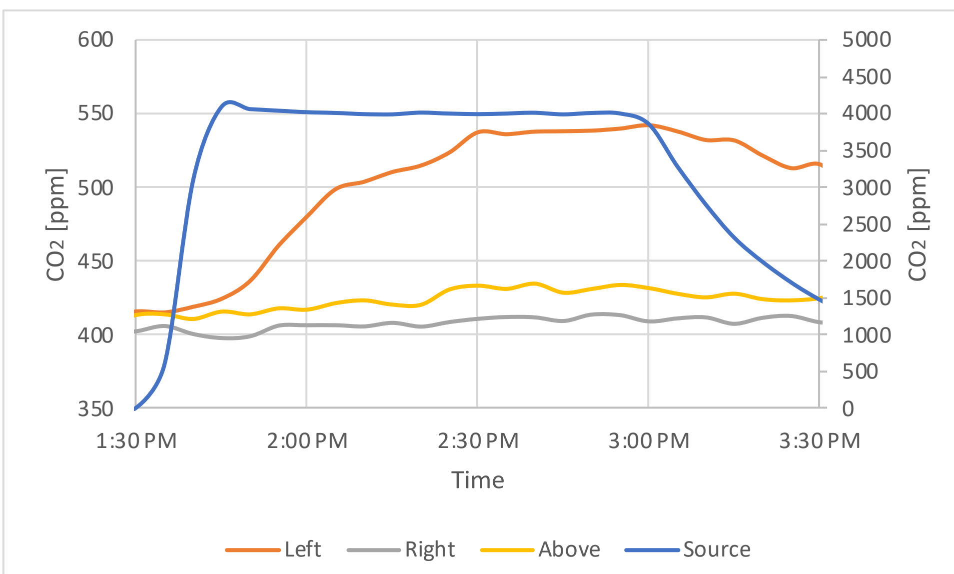

Figure 17. Tracer gas results showing source CO_2 concentration (right y-axis) and CO_2 concentrations in adjacent units (left y-axis) with kitchen exhaust fans on in Building C.

Overall, in both buildings, the transfer of CO_2 (which is a surrogate for the transfer of gaseous pollutants) 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.

Modeling

A mid-rise multifamily residential building model was developed to simulate air and pollutant transfer, occupant exposure, and energy savings associated with different levels of compartmentalization and different ventilation strategies. This model also allows sensitivity analyses to be performed, which are not practically possible using limited field data. Running multiple simulation scenarios that vary parameters incrementally from the same base case allows for the advantages and disadvantages of different measures/strategies to be independently assessed. In this manner, the impacts of different code changes can be quantified and used to inform code updates.

Modeling Methods

Models were developed in CONTAM and EnergyPlus to investigate airflows, pollutant transfer, and energy savings. CONTAM is a multizone air-flow-network model that is used to analyze IAQ and ventilation and calculate airflows, contaminant concentrations, and personal exposure based upon inputted leakage site distributions (NIST, 2021). 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 (DOE, 2022). EnergyPlus outputs hourly infiltration rates, 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 ventilation system delivery rates (Dols, Emmerich, & Polidoro , 2016).

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 (TRC, 2022). 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 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 18). The building has balanced central ventilation and PTHPs in each unit.

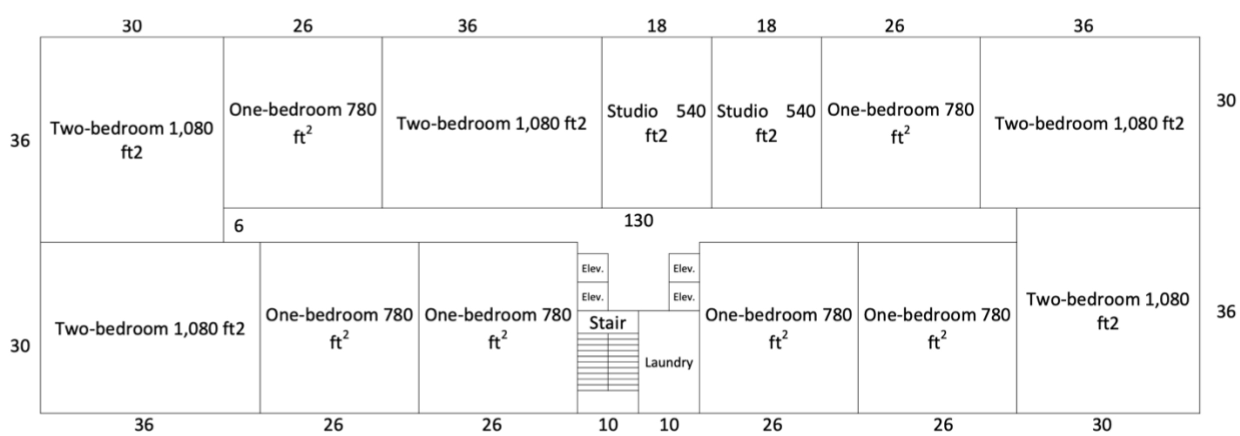

Figure 18. Building floorplan (identical for all five stories) used for energy and air quality modeling.

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: ventilation flows were defined using the minimum ventilation requirement (ASHRAE, 2019), the corridors on each floor were supplied 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 (CEC, 2019), 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 setpoint 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 17).

Table 17. 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 (Bohac & Sweeney, 2020; Lozinsky & Touchie, 2020).

Door leakage was modeled using CONTAM's crack description equation (NIST, 2021). 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 (Miller & Beasley, 2009). 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 the flow exponent. Leaks through walls were assumed to have a constant flow exponent of 0.65 (Walker, Sherman, Joh, & Chan, 2013).
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 19 showing leakage element on every surface).

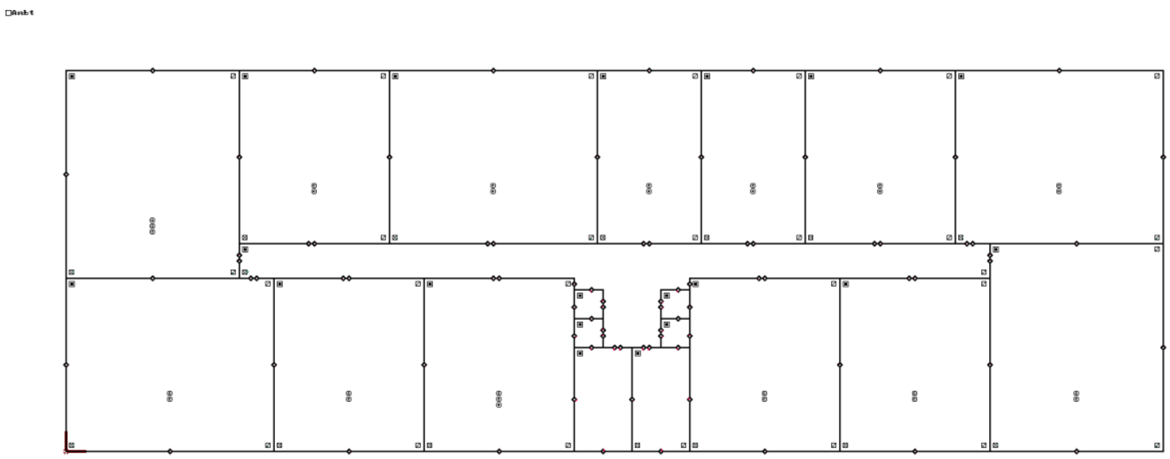

Figure 19. CONTAM floorplan showing leakage elements and pollutant generation sources.

Ventilation Flows

Unit ventilation flows were defined according to the minimum ventilation requirement for multifamily attached dwelling units (CEC, 2019):

$$Q_{tot} = 0.03A_{floor} + 7.5(N_{br} + 1) \tag{17}$$

$$where\ Q_{tot} = ventilation\ rate\ [cfm],$$

$$A_{floor} = \ floor\ area\ [ft^2],$$

$$N_{br} = number\ of\ bedrooms$$

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 studios. 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 through cracks in the walls. The laundry room was exhausted at 0.15 cfm/ft^2, according to the CEC ventilation requirement (CEC, 2019). 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 adjacent units cooking or not cooking with exhaust fans on or off. The kitchen range hood capture efficiency was assumed to be 50% (Chan, Kim, Less, Singer, & Walker, 2019).

Cooking schedules were determined by random sampling from normal distributions generated from questionnaire data on cooking times (Logue, Klepeis, Lobscheid, & Singer, 2014). 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 18). Thus, every unit in the building had unique cooking and kitchen fan schedules.

Table 18. 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. 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. Outdoor NO_2 levels were assumed to be 10 ppb (Alexeeff, et al., 2018). NO_2 generation was scheduled according to cooking schedules. An average NO_2 generation rate of 1.1 mg/min per burner was used (Singer, et al., 2009). Occupants were assumed to use one burner to cook breakfast and lunch and two burners to cook dinner. There is variability in outdoor concentrations throughout California, but since there is no decay rate assigned to NO_2, the indoor concentration resulting from outdoors is constant, and thus increasing the outdoor concentrations by a given amount would result in the same increase indoors. By holding the outdoor NO_2 concentration constant, the analysis focused on how changes in leakage levels, ventilation strategies, and climate zones affected exposure.

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 µg/h-m^2 and a standard deviation of 17 µg/h-m^2. These numbers are from a study that was conducted in buildings built with low-emitting materials (Hult, et al., 2014; Li, et al., 2019). 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 (Nazaroff & Singer, 2004). Each cigarette was estimated to generate 430 µg of Benzene and take 9 minutes to smoke, yielding a generation rate of 48 µg/min (Charles, Batterman, & Jia, 2007). 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 19).

Table 19. 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 (the first week in July) 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 (DOE, 2022). EnergyPlus EPW weather files were converted into WTH CONTAM weather files using the online CONTAM Weather File Creator (NIST, 2022).

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 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 the first week in July to calculate pollutant concentrations, occupant exposure, and inter-unit transfer. 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.

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 indoor 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 (CEC, 2019). Building infiltration was modeled using a simplified infiltration equation:

(18)

$$I = I_{design} \times C \times v_{wind}$$

$$where\ I = infiltation\ [m^3/s],$$

$$I_{design} = design\ infiltration\ [m^3/s],$$

$$C = 0.224, and$$

$$v_{wind} = wind\ speed\ [m/s]$$

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

The EnergyPlus model was used to simulate a base case for annual energy usage. 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 base case most closely resembles the CONTAM simulation with balanced ventilation but was much leakier.

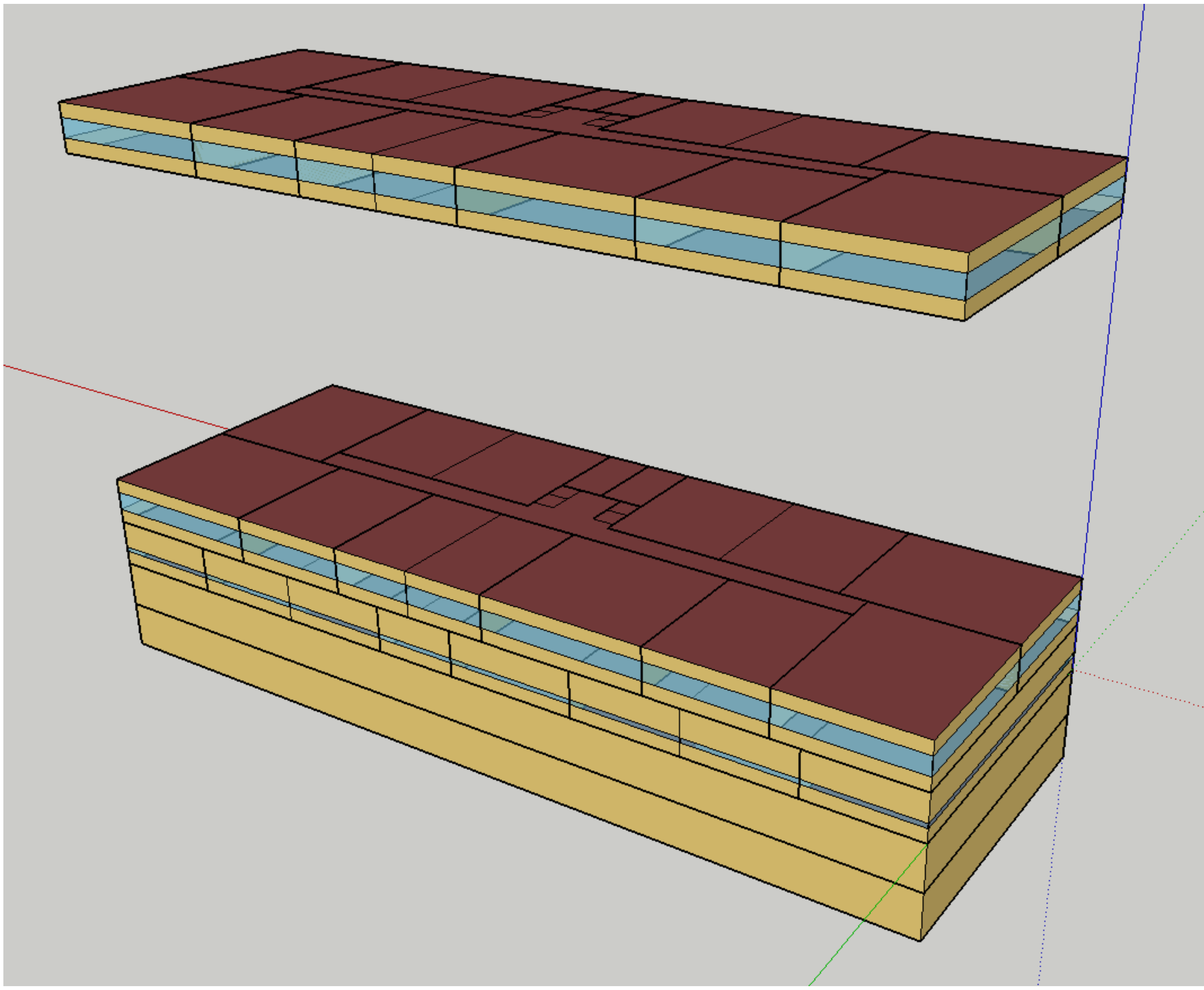

Figure 20. EnergyPlus building schematic showing floors and zones (floors 3-9 are not showed but are copies of floor 2).

ENERGY OUTPUTS

Outputs were exported from both CONTAM and EnergyPlus to determine the energy implications of different simulations. Only energy data related to HVAC systems were 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 COP were exported from EnergyPlus. EnergyPlus was run once for each climate zone to determine the baseline energy use. Then 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 associated with different modeling scenarios. For each scenario, outdoor air (infiltration plus supply ventilation) entering the CONTAM building each hour was subtracted from 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:

$$\Delta E_{OA} = \Delta I_{OA} \times p \times (h_{IA} - h_{OA}) \tag{19}$$

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

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

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

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

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

The increase or decrease in airflow only triggered additional energy usage to condition that 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):

(20) $$\Delta E_{fan} = E_{fan} \times (\frac{Q_{sim}}{Q_{base}})^3$$

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

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

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

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

GHG Calculation

GHG emissions were calculated by summing the total HVAC energy use (central fans and unit PTHPs) for each hour in the year and multiplying that energy use by the respective marginal emission factors. Time Dependent Valuation (TDV) electricity GHG emission factors were averaged over California's 16 climate zones to create annual hourly marginal GHG emissions data for the state (E3, 2020). 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.

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 the results below was a balanced building at 0.15 cfm_{50}/ft^2 in Sacramento. Results are generally presented in relation to this “base case” (i.e., one factor is varied while the other factors in the base case are held constant).

Airflow Analysis

As expected, unit air change rates increased as unit leakage increased (see Figure 21). 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 5^{th} through 95^{th} percentiles. As expected, leakier buildings allowed more air to infiltrate and exfiltrate through the building shell, leading to higher ACH levels for leakier buildings. The average unit at a leakage level of 0.3 cfm_{50}/ft^2 increased ACH by 5-15% (depending on the ventilation strategy and climate zone) compared to the average unit at a leakage level of 0.15 cfm_{50}/ft^2. The average unit at a leakage level of 0.45 cfm_{50}/ft^2 increased in ACH by 15-30% (depending on the ventilation strategy and climate zone) compared to the average unit at a leakage level of 0.15 cfm_{50}/ft^2. 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 little wind had less infiltration due to smaller pressures created by stack effect and wind (see Figure 22).

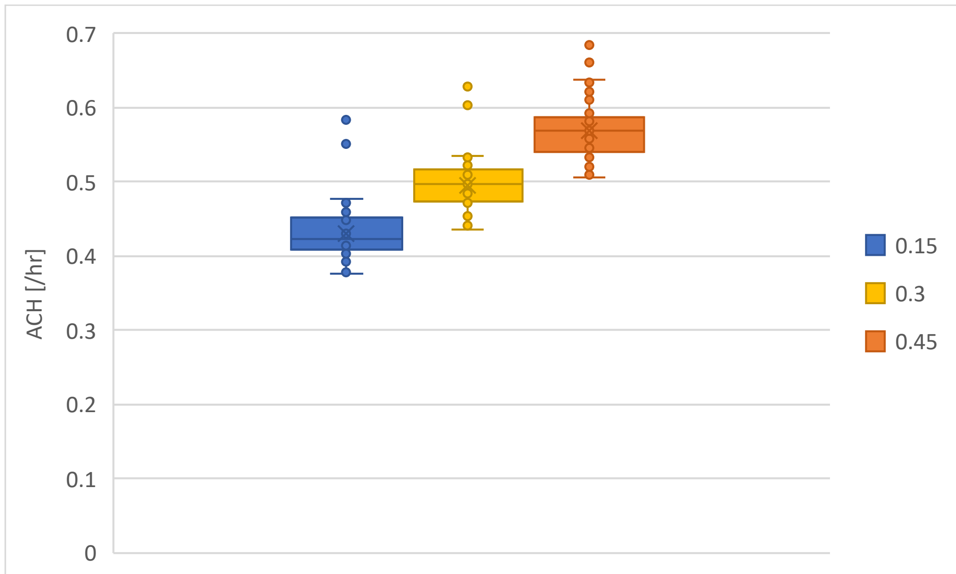

Figure 21. ACH for 55 modeled units at three different leakage levels: 0.15 cfm$_{50}$/ft^2, 0.3 cfm$_{50}$/ft^2, and 0.45 cfm$_{50}$/ft^2 for a balanced building using Sacramento weather data.

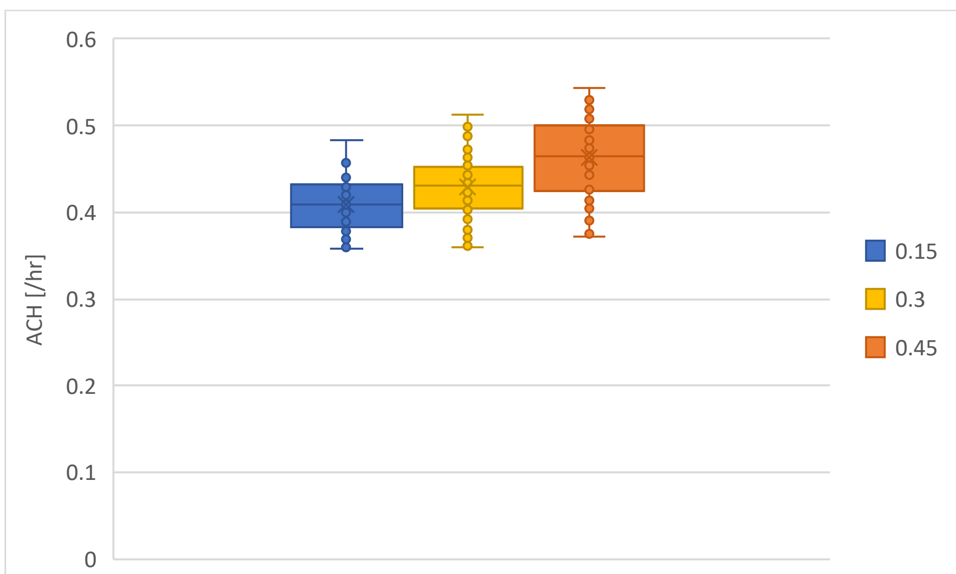

Figure 22. ACH for 55 modeled units at three different leakage levels: 0.15 cfm$_{50}$/ft^2, 0.3 cfm$_{50}$/ft^2, and 0.45 cfm$_{50}$/ft^2 for a supply-only building using Los Angeles weather data.

Unit air change rates were greater in balanced and supply buildings than exhaust-only buildings (see Figure 23). Although the unit ventilation rates were identical among simulations (regardless of ventilation strategy), the common corridor was supplied in all simulations. Thus, in the exhaust-only building, corridor supply air was pulled 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.

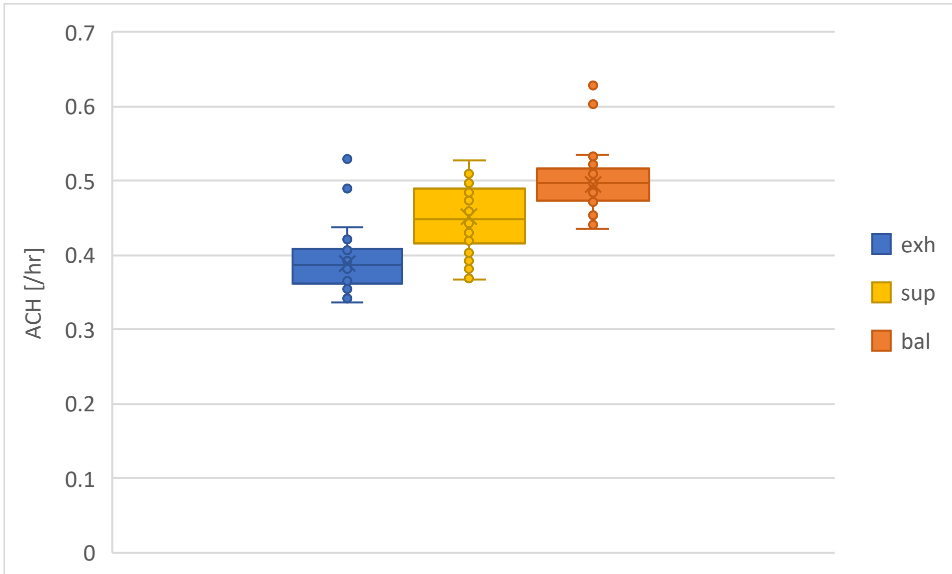

Figure 23. ACH for 55 modeled units with three different ventilation systems: exhaust-only, supply-only, and balanced for a building at 0.15 cfm_{50}/ft^2 using Sacramento weather data.

Unit air change rates were slightly impacted by climate zone (see Figure 24). 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.

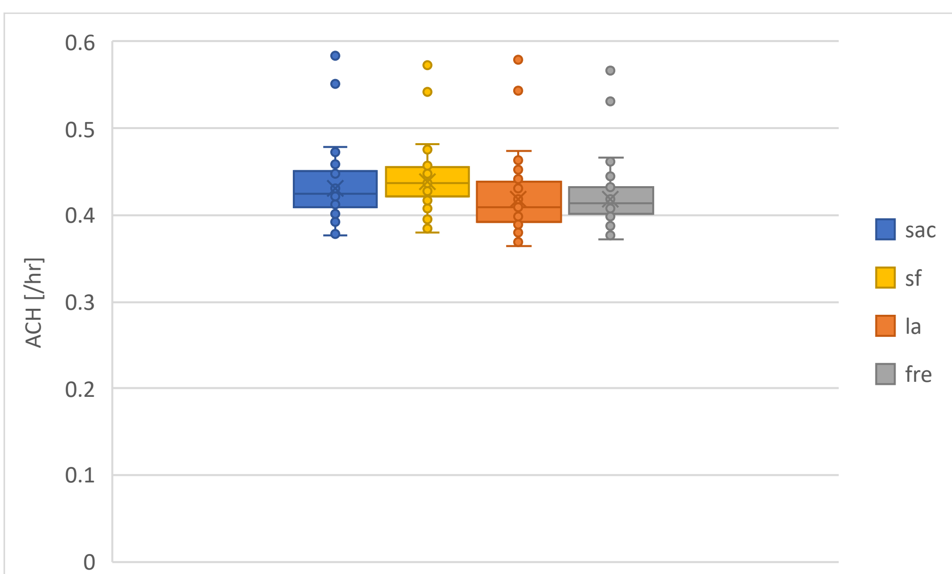

Figure 24. ACH for 55 modeled units in four different climate zones: Sacramento, San Francisco, Los Angeles, and Fresno for a building at 0.15 cfm_{50}/ft^2 with balanced ventilation.

The unit ventilation flow rate similarly increased as unit leakage increased (see Figure 25). The ventilation flow rate was defined as air coming directly from either the mechanical supply system or outdoors. The ventilation flow rate increased by about 1-10% when moving from 0.15 cfm_{50}/ft^2 to 0.3 cfm_{50}/ft^2 and by about 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 ACH, since air that is passed between units could be contaminated, and therefore was not counted towards fresh, outdoor ventilation air.

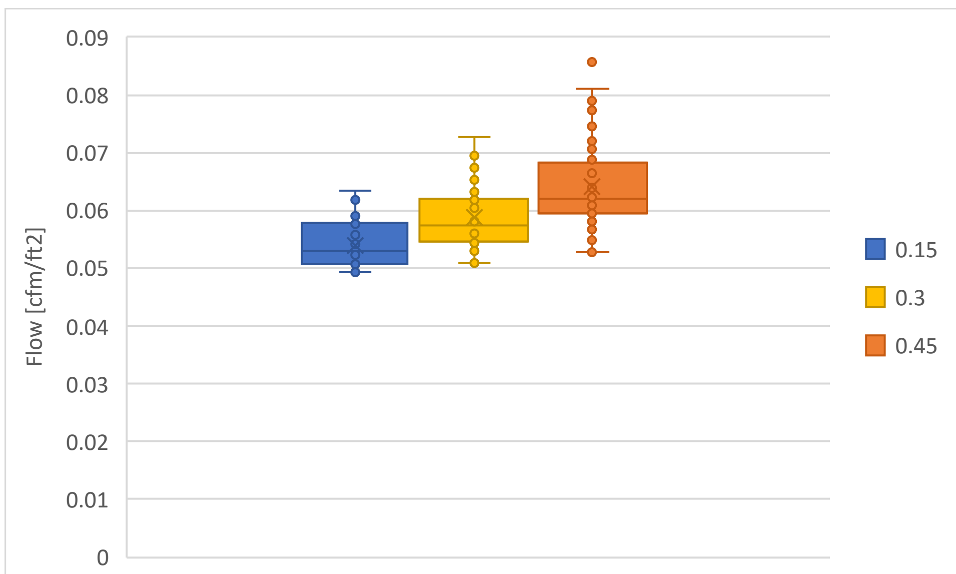

Figure 25. Ventilation flow rates for 55 modeled units at three different leakage levels: 0.15 cfm_{50}/ft^2, 0.3 cfm_{50}/ft^2, and 0.45 cfm_{50}/ft^2 for a balanced building using Sacramento weather data.

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 26). Corner units have more exterior surface area than interior units, allowing more air to infiltrate/exfiltrate through the exterior walls of corner units 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 27). 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 28).

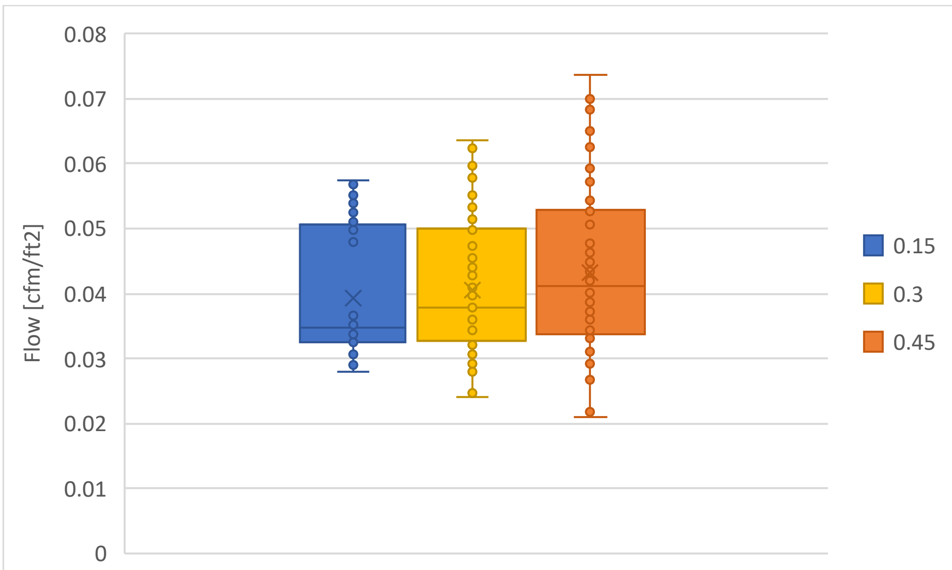

Figure 26. Ventilation flow rates for 55 modeled units at three different leakage levels: 0.15 cfm_{50}/ft^2, 0.3 cfm_{50}/ft^2, and 0.45 cfm_{50}/ft^2 for an exhaust-only building using Sacramento weather data.

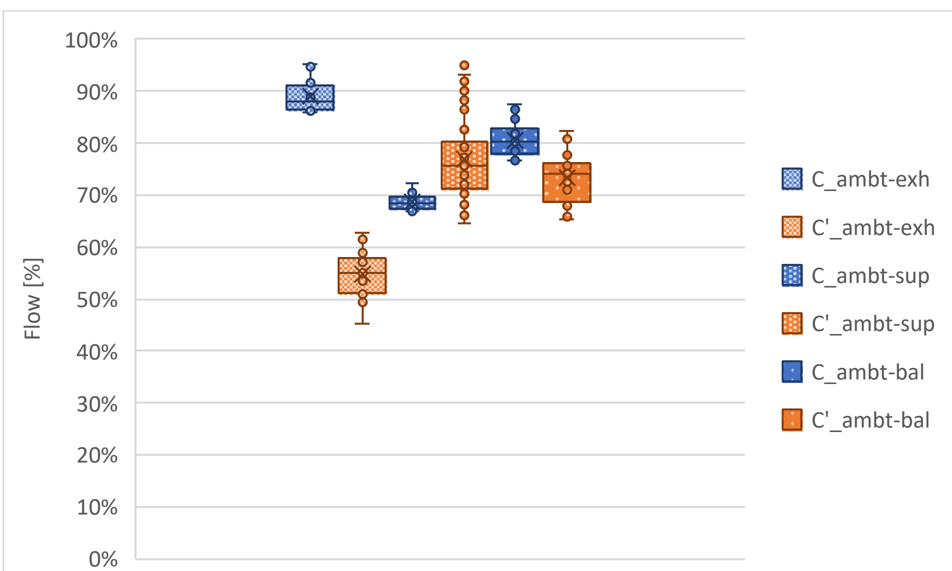

Figure 27. Outdoor air entering 55 modeled units differentiated by corner ("C") and interior ("C'") units with three different ventilation strategies: exhaust-only, supply-only, and balanced for a building at 0.15 cfm_{50}/ft^2 using Sacramento weather data.

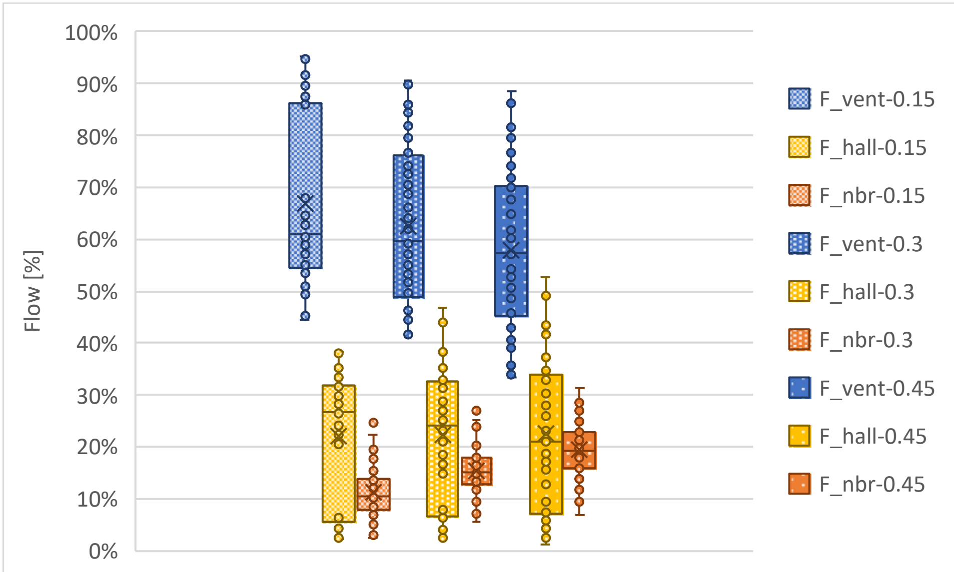

Figure 28. Source of air flowing into 55 modeled units differentiated by ventilation air ("vent"), corridor air ("hall"), and neighboring air ("nbr") at three leakage levels: 0.15 cfm_{50}/ft^2, 0.3 cfm_{50}/ft^2, and 0.45 cfm_{50}/ft^2 for an exhaust-only building using Sacramento weather data.

Unit ventilation flow rates were greater for balanced and supply buildings than exhaust-only buildings (see Figure 29). 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 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 30).

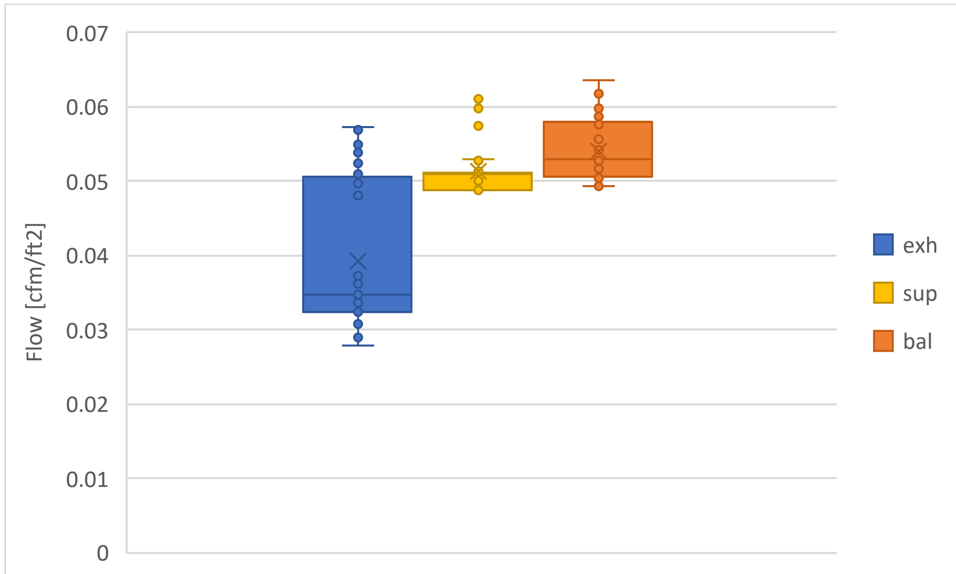

Figure 29. Ventilation flow rates for 55 modeled units with three different ventilation strategies: exhaust-only, supply-only, and balanced for a building at 0.15 cfm$_{50}$/ft^2 using Sacramento weather data.

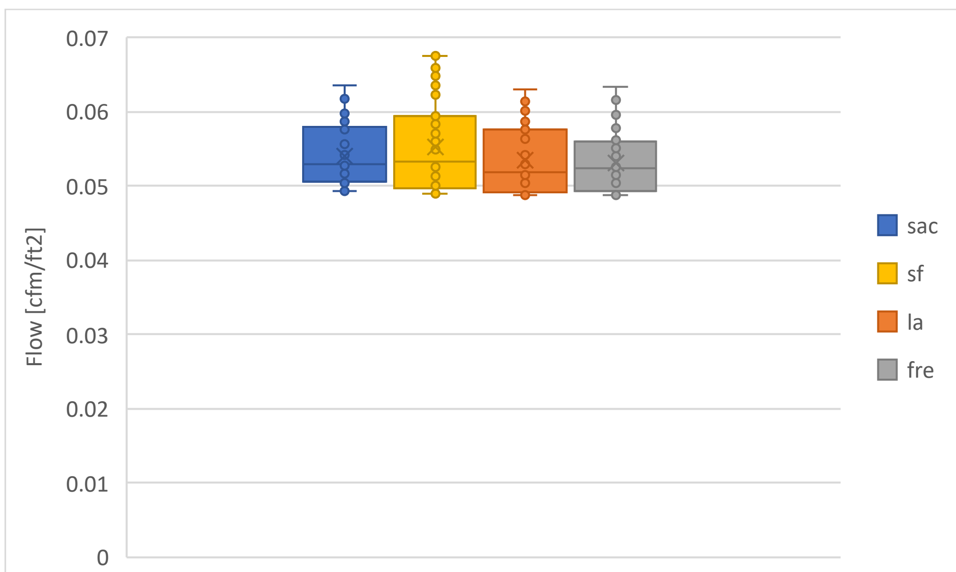

Figure 30. Ventilation flow rates for 55 modeled units differentiated by supply air ("sup"), outdoor air ("ambt"), corridor air ("hall"), and neighboring air ("nbr") in four different climate zones: Sacramento, San Francisco, Los Angeles, and Fresno for a building at 0.15 cfm$_{50}$/ft^2 with balanced ventilation.

Building infiltration was highly dependent on the ventilation strategy (see Figure 31). 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) but was much lower than the design unit infiltration values in the EnergyPlus model (between 25-80 cfm). The design unit infiltration values in the balanced EnergyPlus model best aligned with the exhaust only CONTAM unit infiltration values. The disagreement in infiltration between models suggests that design unit infiltration values in EnergyPlus are overestimated.

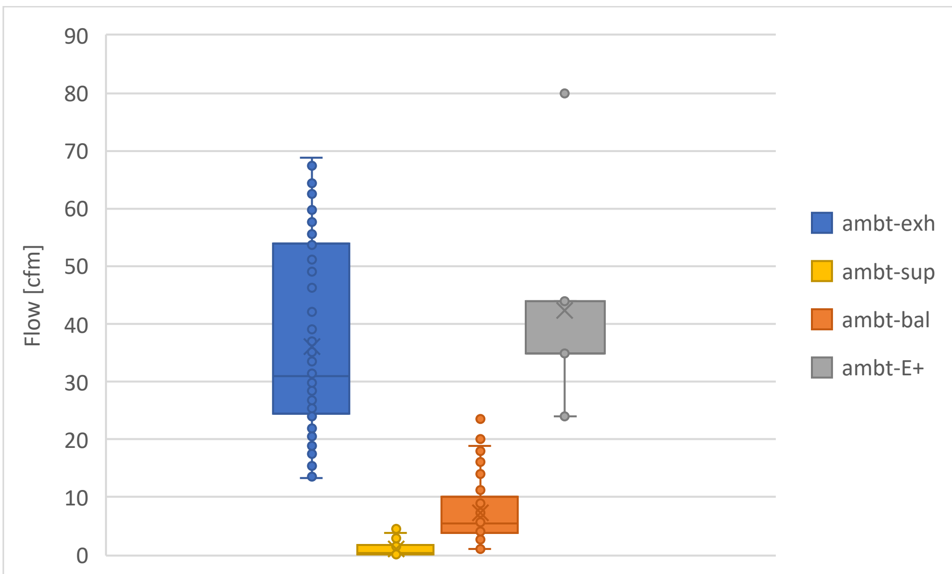

Figure 31. Infiltrations flows for 55 modeled units with three different ventilation strategies: exhaust-only, supply-only, and balanced for a building at 0.3 cfm$_{50}$/ft^2 using Sacramento weather data compared to EnergyPlus design infiltration values (also for a balanced ventilation system using Sacramento weather data).

Transfer of air from neighboring units increased in the leakier models (see Figure 32). This trend occurred for all ventilation scenarios: balanced, exhaust-only, and supply-only (see Figure 33 and Figure 34). 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).

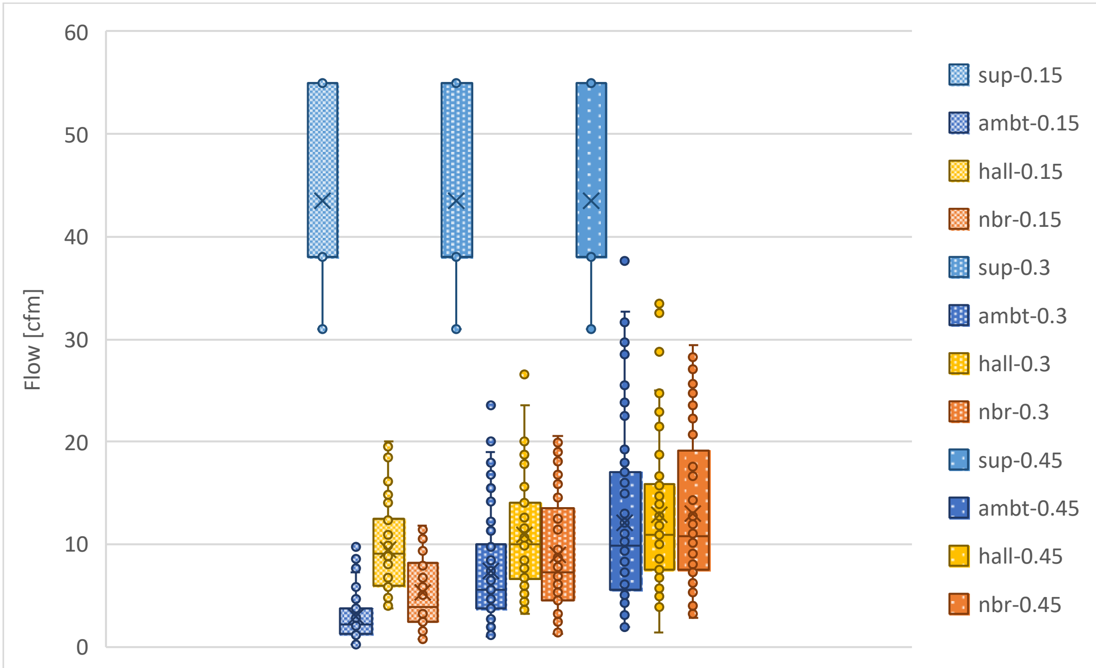

Figure 32. Source of air for 55 modeled units at three difference leakage levels: 0.15 cfm_{50}/ft^2, 0.3 cfm_{50}/ft^2, and 0.45 cfm_{50}/ft^2 for a balanced building using Sacramento weather data.

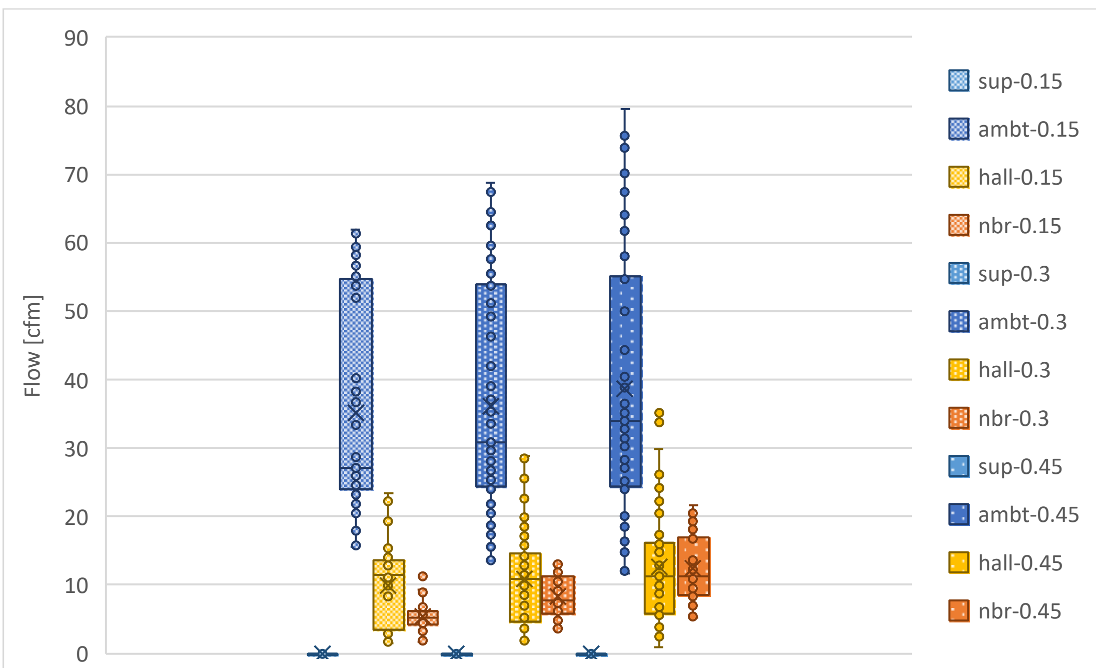

Figure 33. Source of air for 55 modeled units at three different leakage levels: 0.15 cfm_{50}/ft^2, 0.3 cfm_{50}/ft^2, and 0.45 cfm_{50}/ft^2 for an exhaust-only building using Sacramento weather data.

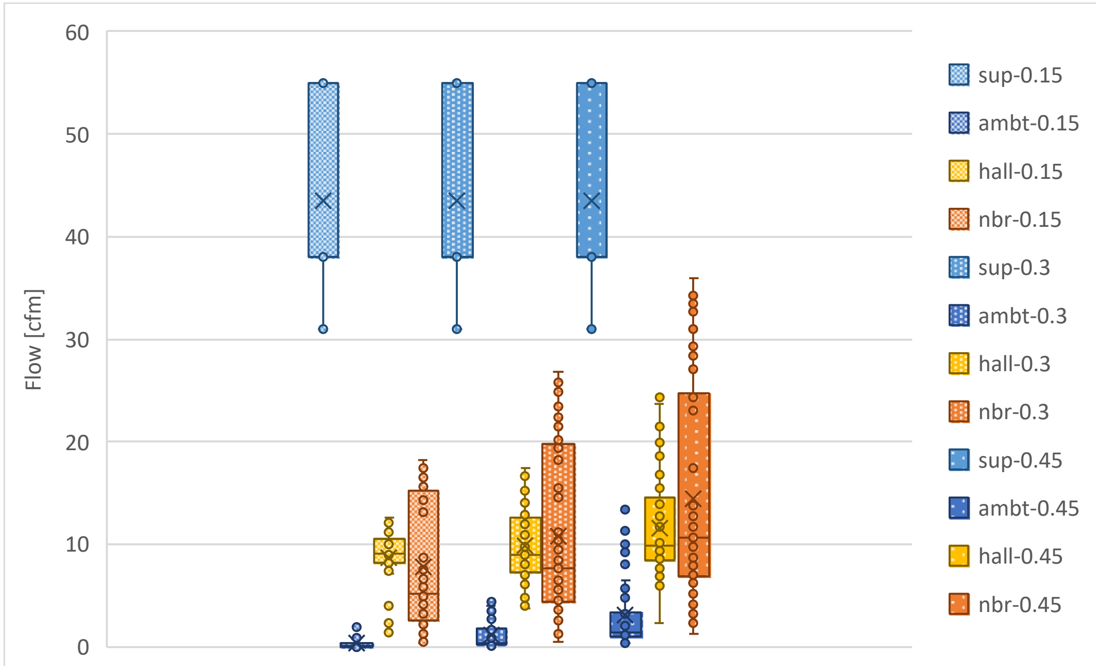

Figure 34. Source of air for 55 modeled units at three different leakage levels: 0.15 cfm_{50}/ft^2, 0.3 cfm_{50}/ft^2, and 0.45 cfm_{50}/ft^2 for a supply-only building using Sacramento weather data.

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 and compare pollutant concentrations in units to health guidelines.

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 35). 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 decrease in 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 35).

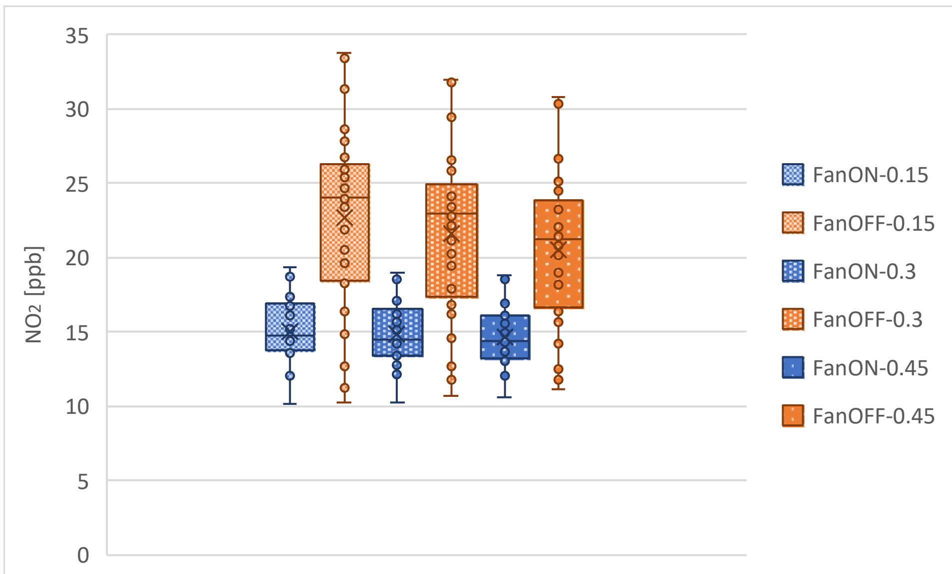

Figure 35. Nitrogen Dioxide (NO_2) concentrations in units that turn on their kitchen exhaust fans while cooking ("FanON") and those that never turn on their kitchen exhaust fans ("FanOFF") at three different leakage levels: 0.15 cfm_{50}/ft^2, 0.3 cfm_{50}/ft^2, and 0.45 cfm_{50}/ft^2 for a balanced building using Sacramento weather data.

The average concentration distributions for CH_2O (see Figure 36), decrease, 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.

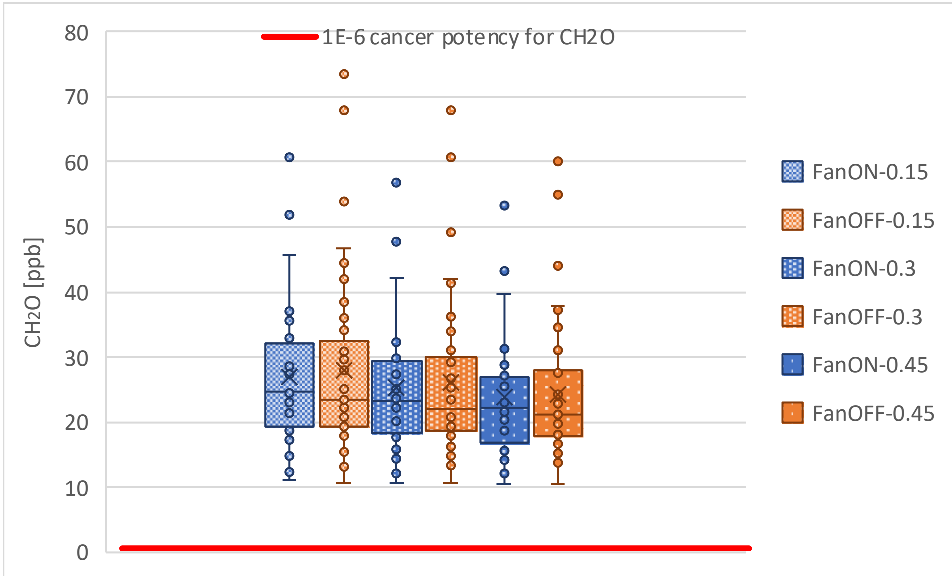

Figure 36. Formaldehyde (CH_2O) concentrations in units that turn on their kitchen exhaust fans while cooking ("FanON") and those that never turn on their kitchen exhaust fans ("FanOFF") at three different leakage levels: 0.15 cfm_{50}/ft^2, 0.3 cfm_{50}/ft^2, and 0.45 cfm_{50}/ft^2 for a balanced building using Sacramento weather data.

For C_6H_6, only a portion of the units had a smoker (see Figure 37). 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.

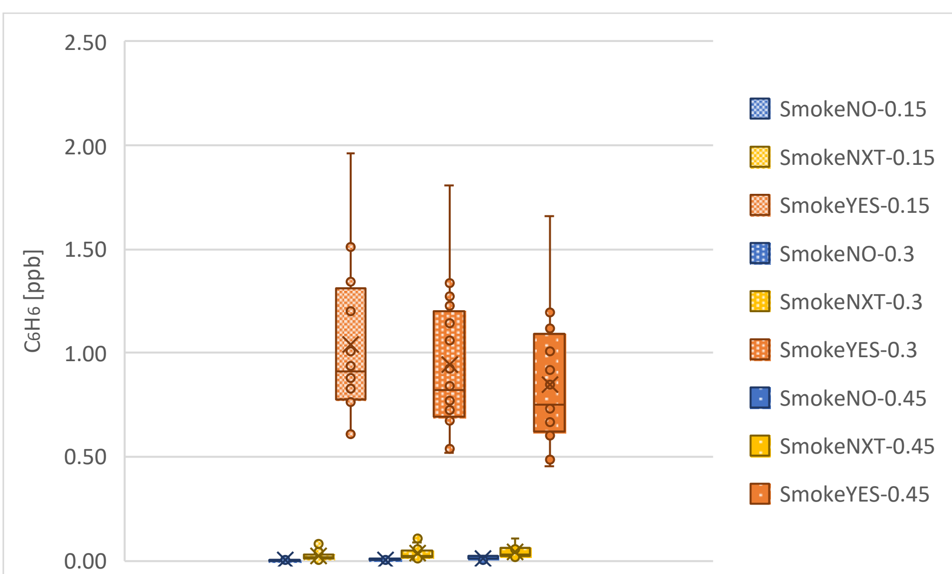

Figure 37. Benzene (C_6H_6) concentrations in units with a smoker ("SmokeYES"), next to a smoker ("SmokeNXT"), and without a smoker and not next to a smoker ("SmokeNO") at three different leakage levels: 0.15 cfm_{50}/ft^2, 0.3 cfm_{50}/ft^2, and 0.45 cfm_{50}/ft^2 for a balanced building using Sacramento weather data.

While increasing unit leakage levels, on average, decreased average unit pollutant concentrations due to increased outdoor air infiltration, it also increased the concentration of pollutants transferred from adjacent units (see Figure 38 and Figure 39). 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.

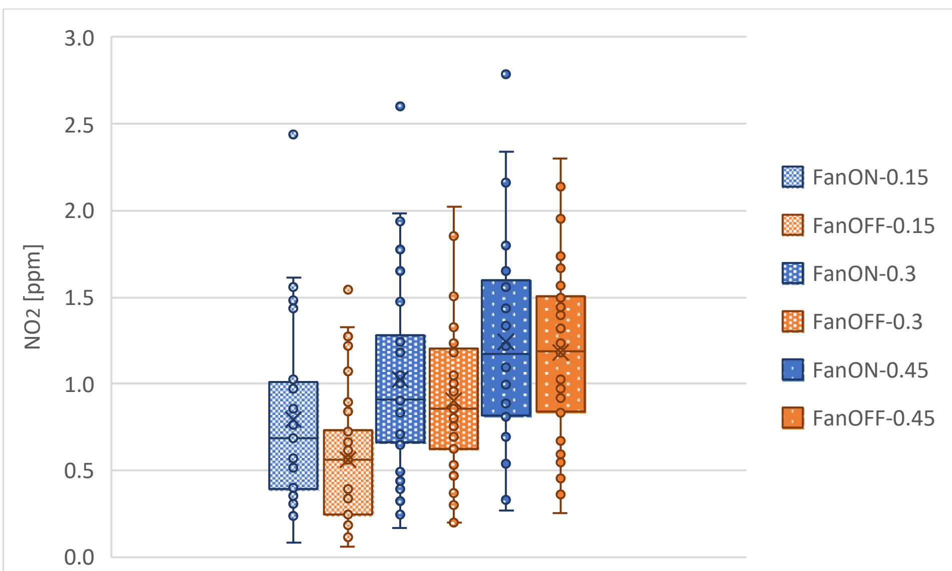

Figure 38. Concentration of NO_2 transferred from other units differentiated by units that turn on their kitchen exhaust fans while cooking ("FanON") and those that never turn on their kitchen exhaust fans ("FanOFF") at three different leakage levels: 0.15 cfm_{50}/ft^2, 0.3 cfm_{50}/ft^2, and 0.45 cfm_{50}/ft^2 for a balanced building using Sacramento weather data.

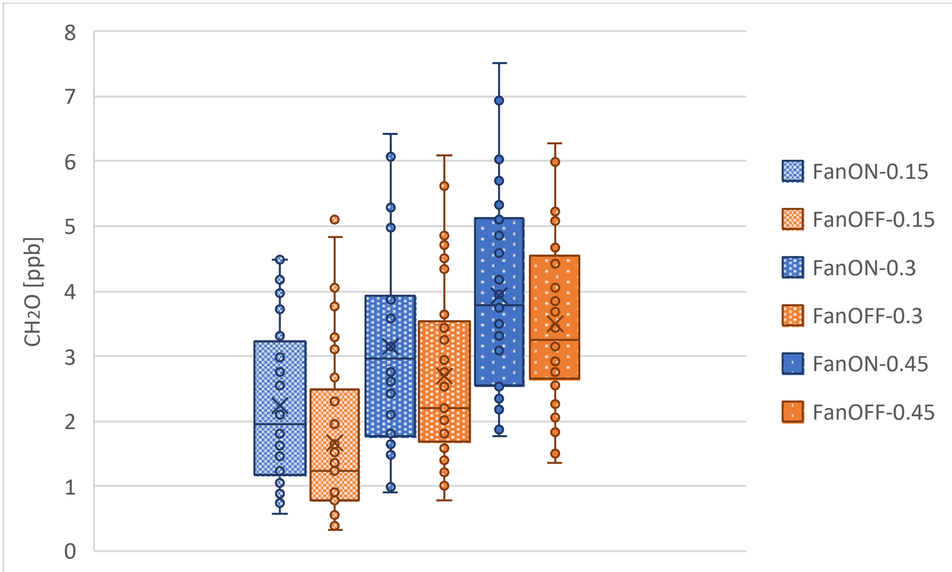

Figure 39. Concentration of CH_2O transferred from other units differentiated by units that turn on their kitchen exhaust fans while cooking ("FanON") and those that never turn on their kitchen exhaust fans ("FanOFF") at three different leakage levels: 0.15 cfm_{50}/ft^2, 0.3 cfm_{50}/ft^2, and 0.45 cfm_{50}/ft^2 for a balanced building using Sacramento weather data.

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 40). Smokers also have additional C_6H_6 transferred into their units, and 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. As for the other pollutants, concentrations in units adjacent to smoker units increase as leakage increases, but in this case the overall exposure increases in leakier non-smoker units, as their entire exposure is due to transfer from the smoker unit. 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 allowed 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 data includes units with smokers next door, and no smoker next door.

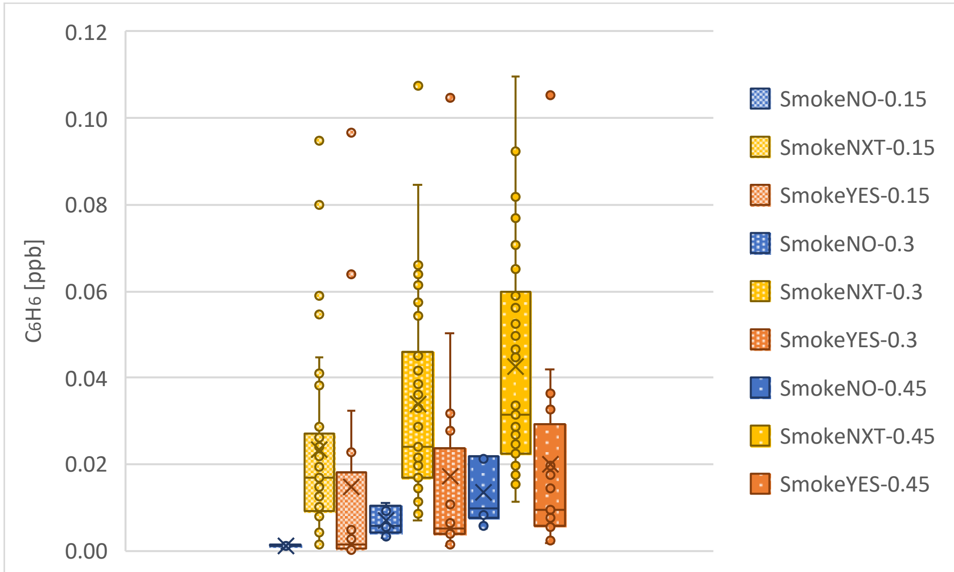

Figure 40. Concentration of C_6H_6 transferred from other units differentiated by units with a smoker ("SmokeYES"), next to a smoker ("SmokeNXT"), and without a smoker and not next to a smoker ("SmokeNO") at three different leakage levels: 0.15 cfm_{50}/ft^2, 0.3 cfm_{50}/ft^2, and 0.45 cfm_{50}/ft^2 for a balanced building using Sacramento weather data.

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 Figure 41 for an example of NO_2 concentrations). 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 42). 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.

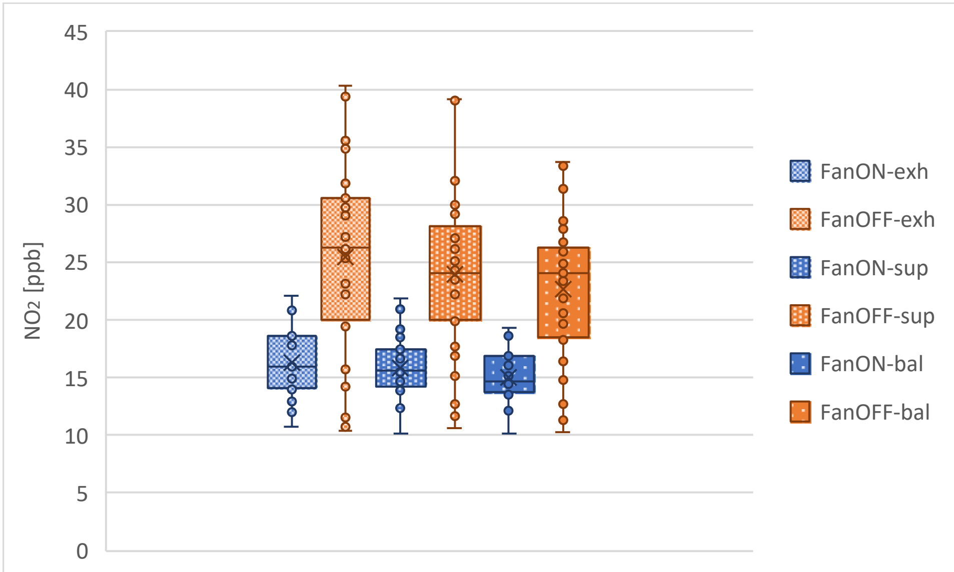

Figure 41. Nitrogen Dioxide (NO_2) concentrations in units that turn on their kitchen exhaust fans while cooking ("FanON") and those that never turn on their kitchen exhaust fans ("FanOFF") for three different ventilation strategies: exhaust-only, supply-only, and balanced for a building at 0.15 cfm_{50}/ft^2 using Sacramento weather data.

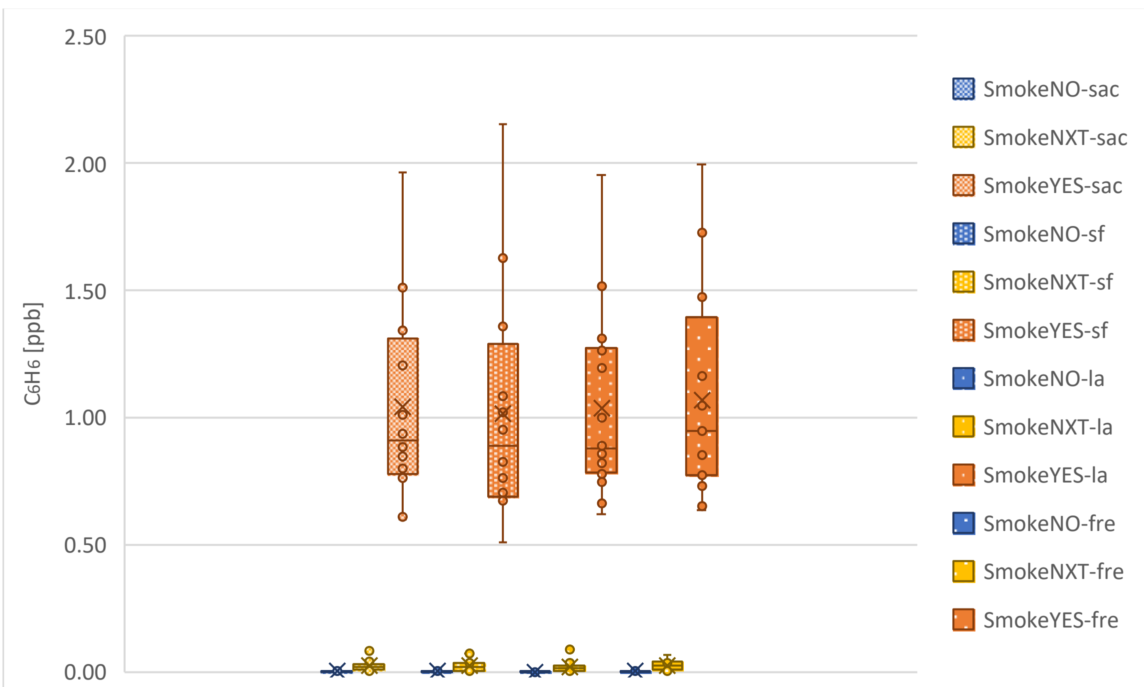

Figure 42. Benzene (C_6H_6) concentrations in units with a smoker ("SmokeYES"), next to a smoker ("SmokeNXT"), and without a smoker and not next to a smoker ("SmokeNO") for four different climate zones: Sacramento ("sac"), San Francisco ("sf"), Los Angeles ("la"), and Fresno ("fre") for a balanced building at 0.15 cfm_{50}/ft^2.

One-hour peak concentrations for the first week of July, not surprisingly, resulted in much higher concentrations for all pollutants relative to the average concentrations. For NO_2, the biggest determinant of the peak concentration is whether the fan was on or off. Operation of kitchen exhaust fans while cooking on a natural gas stove was found to be necessary to maintain unit NO_2 concentrations below the outdoor 1-hour standard of 100 ppb (see Figure 43) (EPA, 2022). All-electric buildings do not have to worry about NO_2 emissions; however, operation of kitchen exhaust fans is still recommended while cooking to minimize PM 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.

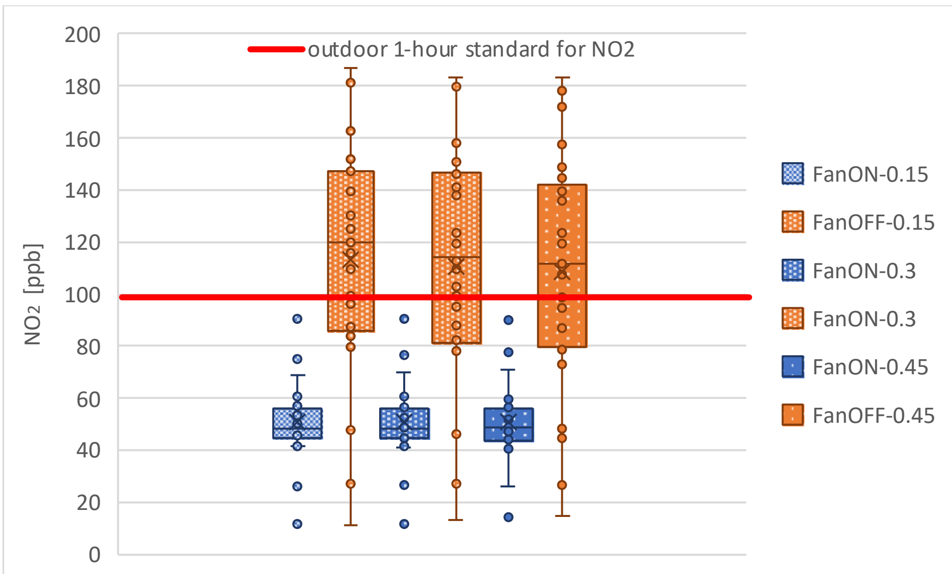

Figure 43. Maximum hourly NO_2 concentrations compared to the exposure standard of 100 ppm for units that that turn on their kitchen exhaust fans while cooking ("FanON") and those that never turn on their kitchen exhaust fans ("FanOFF") at three different leakage levels: 0.15 cfm_{50}/ft^2, 0.3 cfm_{50}/ft^2, and 0.45 cfm_{50}/ft^2 for a balanced building using Sacramento weather data.

CH_2O concentrations in units were found to be considerably above the cancer potency levels of 0.13 ppm (one-in-a-million risk) and 1.3 ppm (one-in-a-hundred-thousand risk) (OEHHA, 2022). Total unit CH_2O average concentrations were more than two orders of magnitude above the one-in-a-million cancer potency risk (see Figure 44). Inter-unit transfer of CH_2O, which account for around 10% of the total unit concentration, was above the one-in-a-hundred-thousand cancer potency risk (see Figure 45). Although these numbers seem high, they are consistent with similar studies that measured CH_2O in buildings (Hult, et al., 2014; Li, et al., 2019).

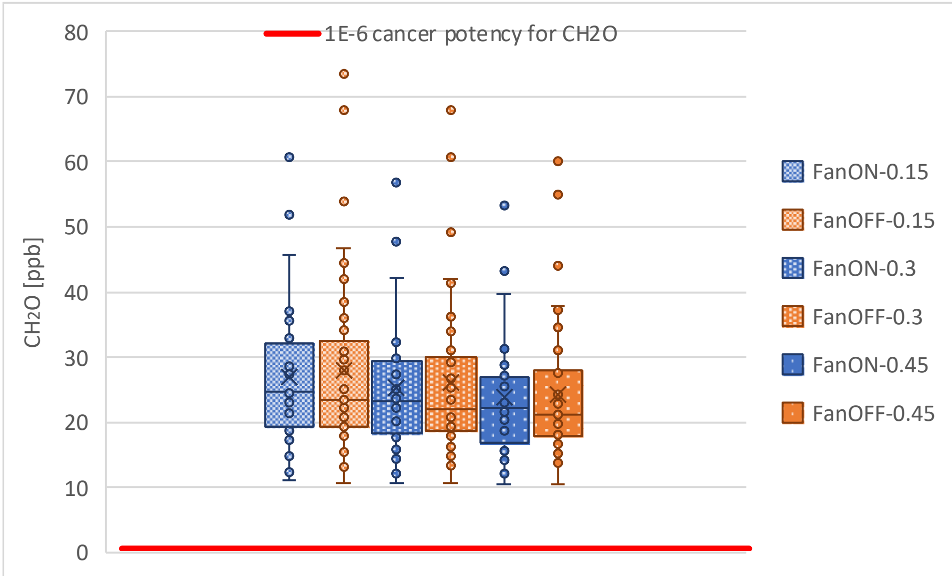

Figure 44. Total CH_2O concentrations compared to the exposure cancer potency (one in a million) of 0.13 ppm for units that that turn on their kitchen exhaust fans while cooking ("FanON") and those that never turn on their kitchen exhaust fans ("FanOFF") at three different leakage levels: 0.15 cfm_{50}/ft^2, 0.3 cfm_{50}/ft^2, and 0.45 cfm_{50}/ft^2 for a balanced building using Sacramento weather data.

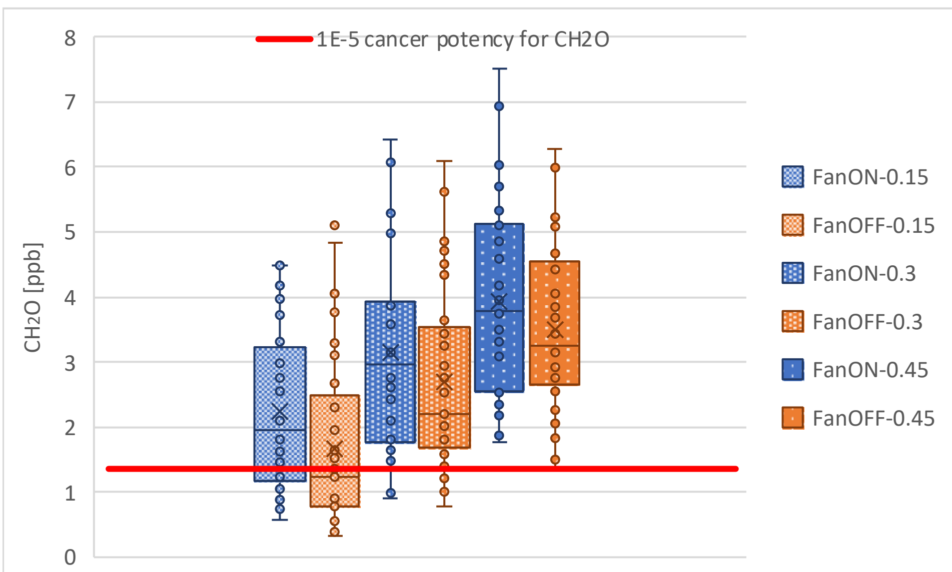

Figure 45. CH_2O concentrations due to inter-unit transfer compared to the exposure cancer potency (1 E-5) of 1.3 ppm for units that that turn on their kitchen exhaust fans while cooking ("FanON") and those that never turn on their kitchen exhaust fans ("FanOFF") at three different leakage levels: 0.15 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.

C_6H_6 concentrations in units next to smokers were found to be elevated above the cancer potency level of 0.04 ppm (EPA, 2003). 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 cancer potency 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 cancer potency risk level (see Figure 46). Therefore, compartmentalization can protect occupants from secondhand smoke transferring between units.

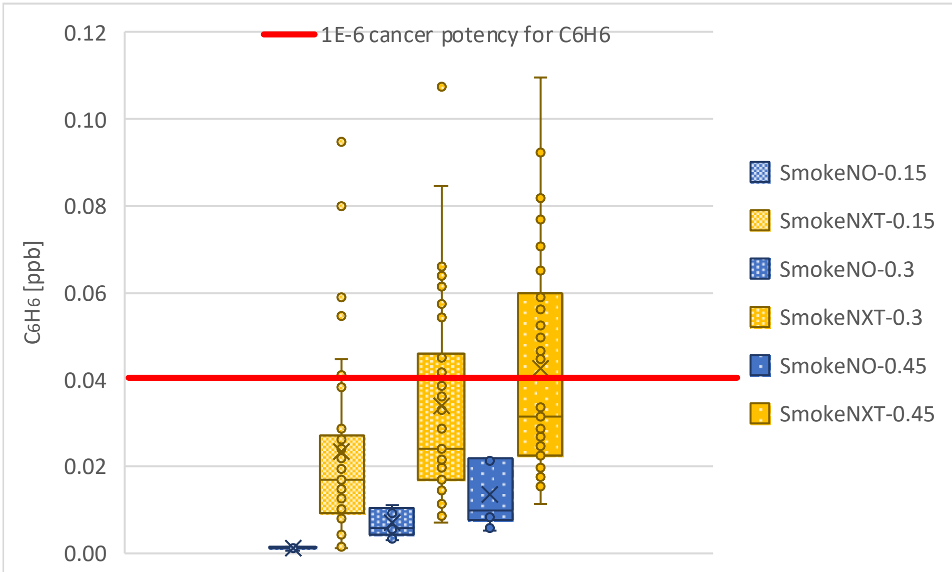

Figure 46. C_6H_6 concentrations compared to the exposure cancer potency (1 E-6) of 0.04 ppm for units next to a smoker ("SmokeNXT") and without a smoker and not next to a smoker ("SmokeNO") at three different leakage levels: 0.15 cfm_{50}/ft^2, 0.3 cfm_{50}/ft^2, and 0.45 cfm_{50}/ft^2 for a balanced building using Sacramento weather data.

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. This finding is particularly important to consider for secondhand smoke transfer, which was found to transfer at unhealthy levels to neighboring units at a leakage level of 0.45 cfm_{50}/ft^2. Kitchen exhaust fans were found to be necessary during cooking times to maintain NO_2 concentrations from natural gas stoves at acceptable levels.

Energy Analysis

Running the EnergyPlus model for four different climate zones indicated that HVAC energy usage was highest in Sacramento and Fresno and lowest in San Francisco and Los Angeles (see Figure 47). 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.

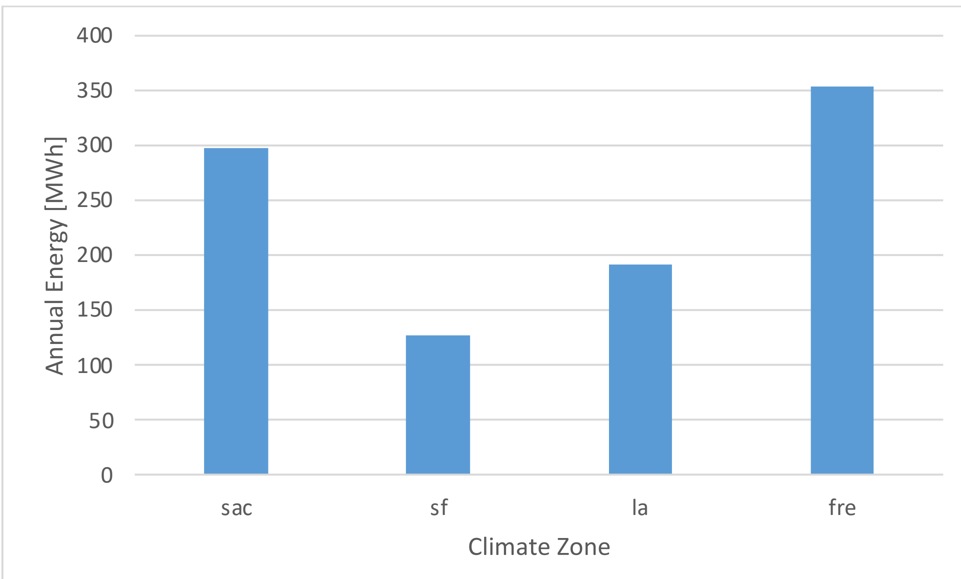

Figure 47. Annual energy simulated in EnergyPlus for the four different climate zones: Sacramento ("sac"), San Francisco ("sf"), Los Angeles ("la"), and Fresno ("fre").

A representative day in the winter (January 15th) shows that infiltration flows in CONTAM responded to kitchen fan schedules and outdoor wind speed (see Figure 48). 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. The infiltration flow rate was proportional to wind speed, and 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.

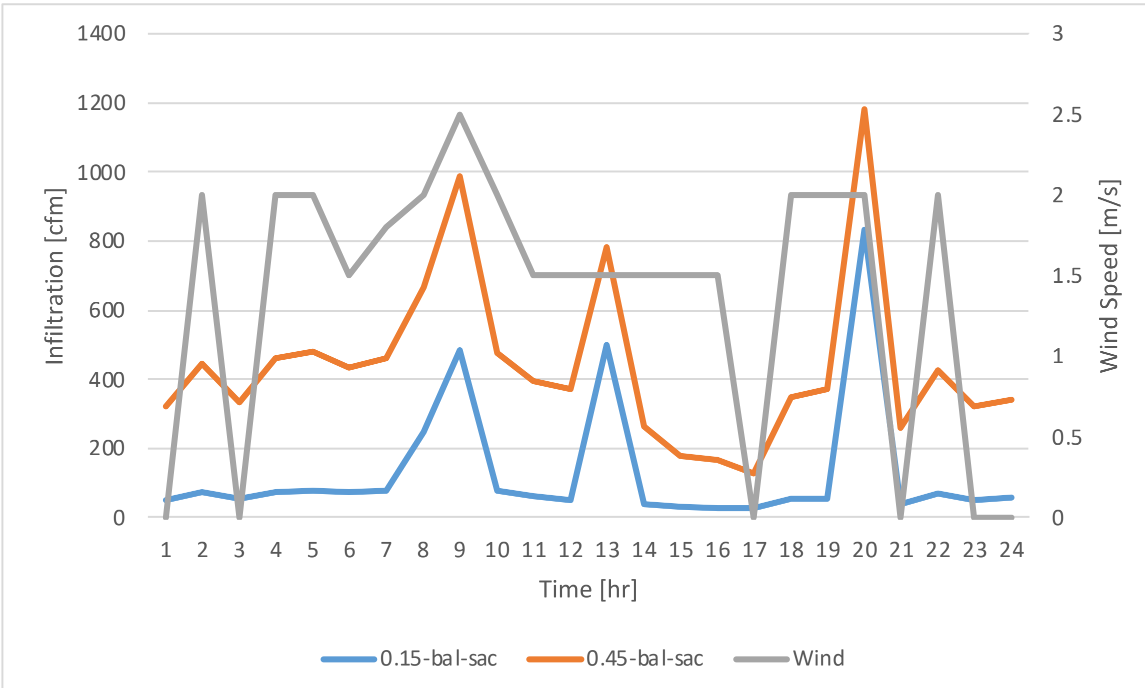

Figure 48. January 15th hourly building infiltration comparison between 0.15 cfm_{50}/ft^2 and 0.45 cfm_{50}/ft^2 (left y-axis) graphed alongside outdoor wind speed (right y-axis) for a balanced building using Sacramento weather data.

Annual HVAC energy was dominated by the cooling load in all simulated California climate zones (see Figure 49). Fan energy required to ventilate the building (with supply and/or exhaust air) was responsible for about 5-20% of building HVAC energy. Fan energy doubled from about 10 MWh/yr to 20 MWh/yr between the single-fan supply- and exhaust-only simulations and 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.

Tightening units resulted in only a very small HVAC energy saving in most climate zones when building was simulated with inoperable windows. The HVAC energy savings from compartmentalization in supply- and exhaust-only buildings was only a fraction of a percentage. Balanced buildings had annual HVAC energy savings of 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. In Los Angeles, HVAC energy increased when the building was tightened. This is because in Los Angeles there are many times when infiltration provides "free cooling". This result is unrealistic, as in practice residents open windows for cooling. Moreover, the result that buildings in San Francisco rarely require more cooling than heating is incorrect (again because EnergyPlus does not model operable windows).

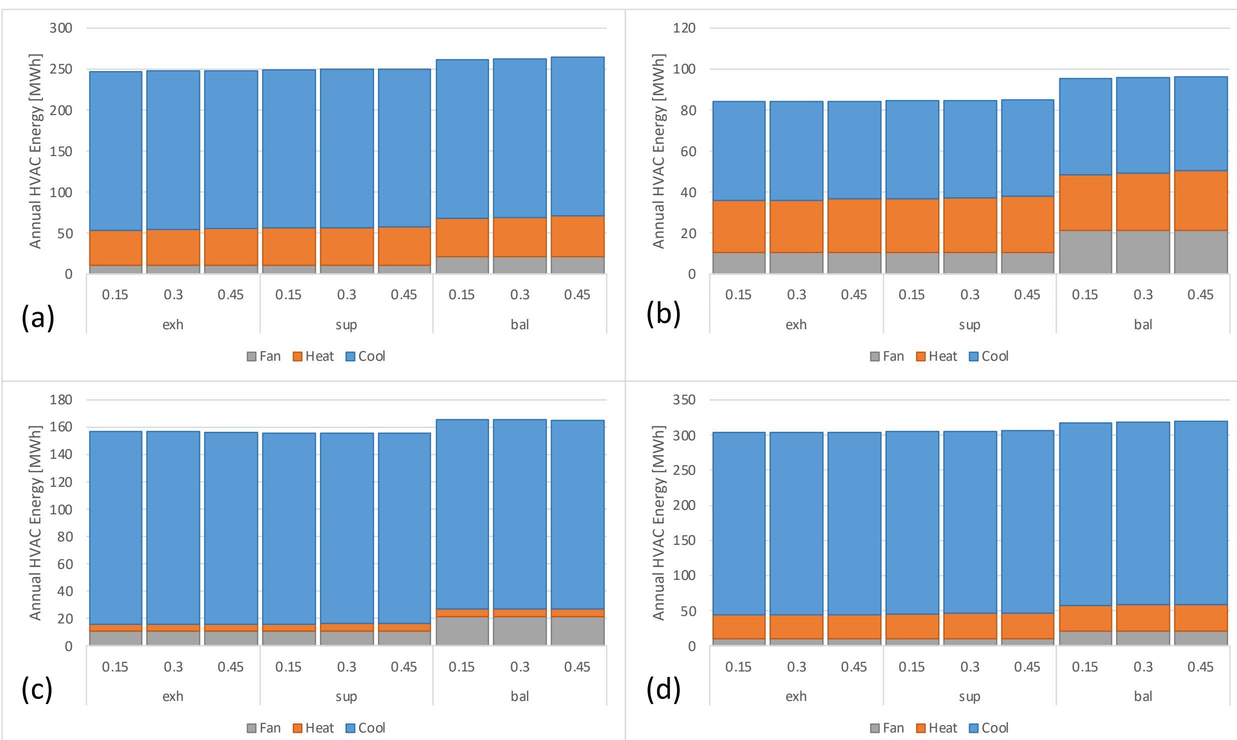

Figure 49. Annual HVAC energy usage split into central ventilation fan energy ("Fan"), heat pump heating energy ("Heat"), and heat pump cooling energy ("Cool") displayed for four climate zones: (a) Sacramento, (b) San Francisco, (c) Los Angeles, and (d) Fresno (scales are different for each climate zone).

Adding a 70% efficient heat exchanger to the balanced building saved about 5% of HVAC energy, which approximately offset the additional energy needed for the second fan by the energy savings from pre-conditioning (heating/cooling) supply air in most climates (see Figure 50). However, the usefulness of the heat exchanger was highly climate dependent. The absolute energy savings in Sacramento and Fresno (just over 10 MWh/yr) were more than double the absolute energy savings in San Francisco (around 5 MWh/yr) since a building in the Central Valley requires more than double the space conditioning as compared to a building located in San Francisco. In Los Angeles, the heat exchanger resulted in increased annual energy usage due to the "free cooling" effect. However, in practice, occupants opening windows or demand-control ventilation with a bypass around the heat exchanger should results in much greater heat exchangers savings energy in all climate zones.

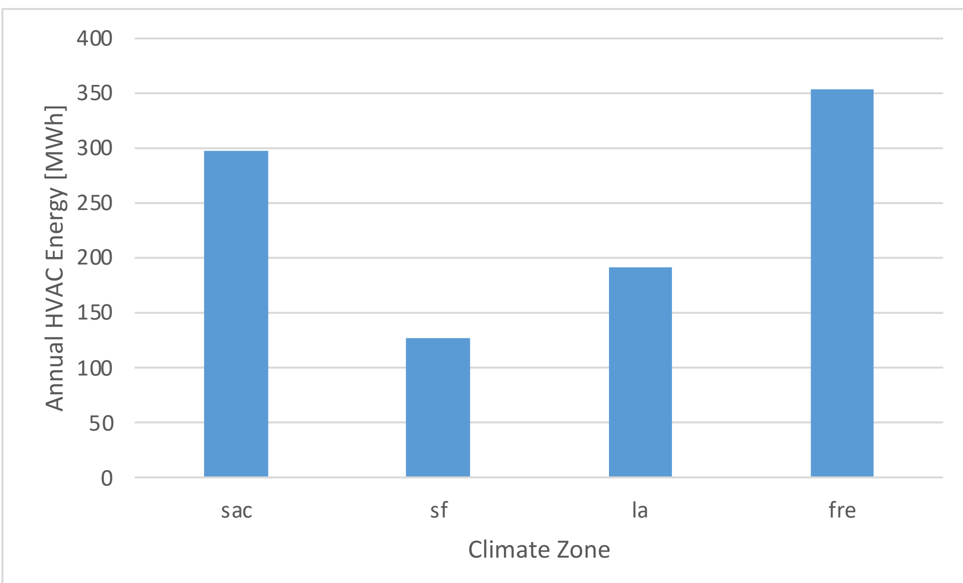

Figure 50. Annual HVAC energy usage comparison between different ventilation strategies: exhaust-only ("exh"), supply-only ("sup), balanced ("bal"), and balanced with a heat exchanger ("bal-hx") for a 0.15 cfm_{50}/ft^2 building using Sacramento weather data.

The cooling loads in all climate zones are likely overestimated, because the EnergyPlus and CONTAM models assume no operable windows, preventing occupants from opening windows to cool interior spaces. For example, many buildings in the San Francisco Bay Area do not have air conditioning, suggesting the HVAC energy usage would be more representative if the simulated cooling energy was removed (see Figure 51). Without cooling, a building in San Francisco would save almost 5% of annual HVAC energy when tightening from 0.45 cfm_{50}/ft^2 to 0.15 cfm_{50}/ft^2. Including a heat exchanger would reduce the heating load by about 35% and save close to 20% of annual HVAC energy usage.

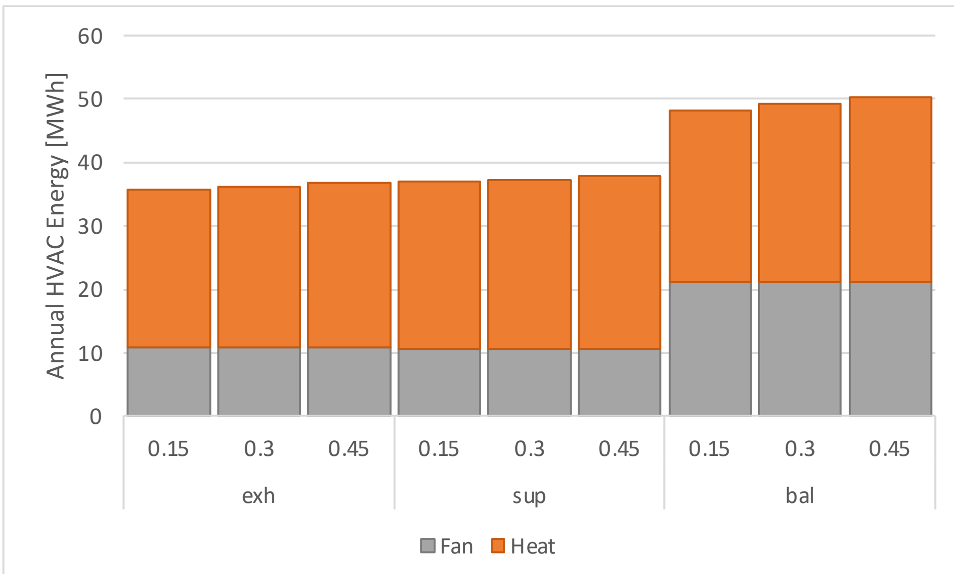

Figure 51. Annual HVAC energy usage split into central ventilation fan energy ("Fan") and heat pump heating energy ("Heat") for a building using San Francisco weather data.

The complication of modeling free cooling was 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. This calculation assumes operable windows that residents open to take advantage of pleasant outdoor conditions or the use of economizers (however economizer energy itself is not modeled). Ignoring "free cooling" resulted in the energy response to leakage levels being what was expected expected – tightening the building resulted in less energy consumption in all climate zones.

Energy and GHG savings were calculated relative to the balanced scenario at a leakage level of 0.15 cfm_{50}/ft^2 in each climate zone (see Table 20). Moving from a two-fan balanced system to a one-fan supply- or exhaust-only system was estimated to save about 5-15% of HVAC energy and 10-20% of HVAC GHG emissions. 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 energy consumption by around 20-80 MWh/yr (20-25%) and GHG emissions by around 100-500 tCO_2e/30 yrs (30-40%). 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. Tightening units in a balanced building from 0.45 cfm_{50}/ft^2 to 0.15 cfm_{50}/ft^2 saved between 4-6% of HVAC energy and between 5-10% of HVAC GHG emissions depending on the climate zones.

Table 20. 30-year Building HVAC GHG Emission and Savings After Correcting for "Free-Cooling" (Relative to the Balanced Building at 0.15 cfm_{50}/ft^2 for each Climate) Displayed for Four Climates: Sacramento ("Sac"), San Francisco ("SF"), Los Angeles ("LA"), and Fresno ("Fre"), Three Ventilation Strategies: Balanced ("bal"), Balanced with a Heat Exchanger ("bal-hx"), and Exhaust-Only ("exh"), and Two Leakage Levels: 0.15 cfm_{50}/ft^2 and 0.45 cfm_{50}/ft^2

Climate	Ventilation	Leakage [cfm_{50}/ft^2]	GHG Emissions [tCO_2e/30 yrs]	GHG Savings [%]
Sac	bal	0.15	882	0%
Sac	bal	0.45	963	-9%
Sac	bal-hx	0.15	515	42%
Sac	exh	0.15	748	15%
SF	bal	0.15	353	0%
SF	bal	0.45	391	-11%
SF	bal-hx	0.15	226	36%
SF	exh	0.15	280	21%
LA	bal	0.15	482	0%
LA	bal	0.45	501	-4%
LA	bal-hx	0.15	350	27%
LA	exh	0.15	388	20%
Fre	bal	0.15	1,072	0%
Fre	bal	0.45	1,167	-9%
Fre	bal-hx	0.15	575	46%
Fre	exh	0.15	915	15%

Overall, energy modeling results suggest that compartmentalization can save a significant fraction of building HVAC energy and GHG emissions in a balanced building (approximately 4-6% and 5-10%, respectively). The largest HVAC energy and GHG savings opportunities were attributed to installing a heat exchanger. However, the magnitude of savings was highly dependent on climate zones and ventilation strategies. Heat exchangers were particularly effective in the Central Valley climate zones (saving as much as 25% on HVAC energy). 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 exchangers may require bypass valves in some climate zones to work most effectively.

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 designs 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 operation strategies compare to one another.

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. These buildings were deemed representative based upon information from a firm that runs multifamily utility programs throughout California. 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.

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 (ASHRAE, 2019). 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 volume translates to more air changes and larger pressure differences across walls). Finally, the practice of supplying air through unfiltered PTHP units allowed outdoor pollutants to transfer directly indoors. This is especially concerning for low-income multifamily building, which are often located in areas with poorer outdoor air quality, such as next to highways.

Inter-unit pollutant transfer was measured to be minimal during field testing. 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 ventilation rates. Furthermore, results from CONTAM modeling suggest that most indoor pollutant sources originate within the same unit. Therefore, maintaining healthy pollutant concentrations and reducing exposure could best be achieved by implementing smart ventilation systems that monitor pollutant concentrations or installing smart kitchen range hoods that automatically turn on when they detect moisture or heat.

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 could be desirable by the developer and 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 (Mitchell & Smith, 2016). Cooking mackerel generates C_3H_9NO at concentrations measured directly over the stove of 160 ppb for raw fish, 265 ppb for cooked fish, and 465 ppb for overcooked fish (Ahn, Szulejko, Kim, Kim, & Kim, 2014). The modeled average maximum hourly concentration of NO_2 in units cooking without a fan was between 100 and 125 ppb with the concentrations directly over the stove expected to be even higher. Based on the studies reporting C_3H_9NO concentrations over the stove during cooking events, the average concentration of C_3H_9NO over an hour is assumed to be on the same order of magnitude as the modeled NO_2 concentrations. The maximum hourly concentration in a unit with someone cooking in an adjacent unit is 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. This approach likely overestimates the typical fish smell, as maceral is a variety of fish associated with a particularly strong fishy odor. Therefore, it is possible that good sealing could prevent transfer of detectable levels of odor.

Modeling results also suggest that the location of units within a building influences the ventilation 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. Alternatively, installing passive vents in units could ensure that most of the infiltrating air comes from the outdoors.

It is also worth noting that the EnergyPlus building prototype 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. 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, on average, about 10 cfm in each unit. 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 5-10% of 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 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 practicality and magnitude of savings from economizers are predicated to be climate dependent with the largest savings obviously occurring in cooling dominated climates. Similarly, the usefulness of heat exchangers was found to be highly climate-zone dependent.

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 could 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 the original cooling loads simulated in EnergyPlus may be required.

Conclusion

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, and 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 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.

Ventilation flow testing found some ventilation flows were inconsistent between design and measured flows and sometimes insufficient to ensure good IAQ. Variations between units is problematic, as it suggests some units are either being overventilated (which is wasteful from an energy perspective) or under ventilated (which is potentially harmful from an IAQ perspective). Furthermore, units with unfiltered outdoor air intakes appeared to be pose a threat to IAQ, especially if the building was located nearby an outdoor pollutant source, such as a highway.

While inter-unit transfer of pollutants appeared to be small, compartmentalization did significantly reduce modeled exposure to gaseous secondhand smoke transfer between units. Furthermore, tightening units was estimated to significantly reduce the transfer of odors possible below the detection limits of the human nose for most smells. Minimizing the transfer of sound, odors, and pests between units might provide the greatest incentive for occupants and developers to pursue compartmentalization.

HVAC Energy and GHG savings from compartmentalization were simulated to be around 4-6% and 5-10%, respectively. The largest energy savings were associated with installing heat exchangers, which could save up to 40% of HVAC energy in the Central Valley climate zones. While not modeled, economizers appear useful in California's cooling-dominated climates, especially in Los Angeles. The reported energy and GHG savings ignore the free-cooling penalty (i.e., assume occupants open windows or use economizers to increase outdoor air intake during pleasant outdoor conditions).

Code Recommendations

Data from this study demonstrate that new-construction multifamily buildings appear to be consistently meeting the compartmentalization requirement of 0.3 cfm_{50}/ft^2. Therefore, the 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 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.

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. Passive vents or other equipment (e.g., PTHP units) could be an effective means to control where makeup air infiltrates. All intentional supply/makeup airflow paths should include air filters (with regularly cleaning or replacement) to remove harmful PM from entering units. This measure could improve IAQ in exhaust-only building, which were simulated to have slightly worse air quality than supply or balanced ventilation alternatives.

Future Research

There may be more effective ways to control indoor concentrations of pollutants than constant ventilation rates. 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 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 the most 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 adopted in future building codes.

Finally, it should be noted that this research did not evaluate cost effectiveness, which would obviously need to be examined before code changes can be proposed.

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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:	**BUILDING TYPE:**
6/16/2021	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)

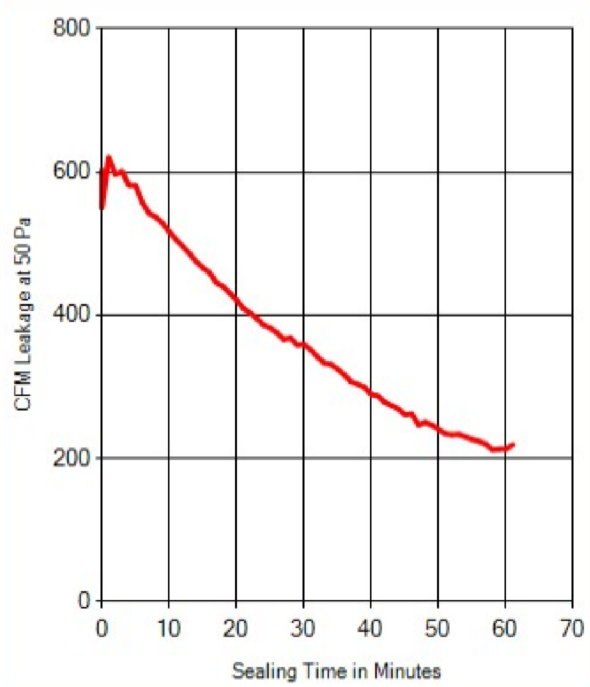
AFTER SERVICE

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 A-1. 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

AEROBARRIER CASE ID: 8052

HARDWARE: AeroBarrier

DATE:
6/17/2021

BUILDING TYPE:
Apartment

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)

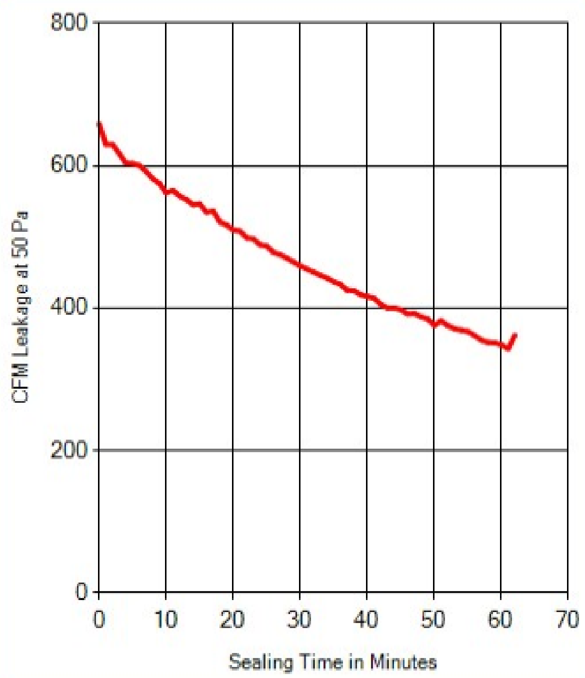
AFTER SERVICE

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 A-2. Air sealing report for unit 509 in Building A.

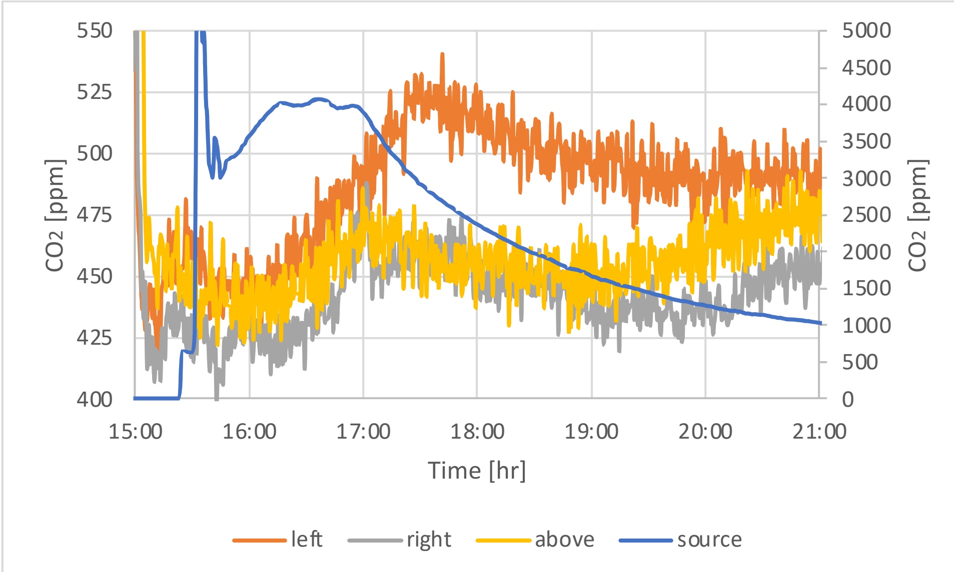


Figure A-3. Tracer gas results showing source CO_2 concentration (right y-axis) and CO_2 concentrations in adjacent units (left y-axis) with kitchen exhaust fans on in unit 409 of Building A.

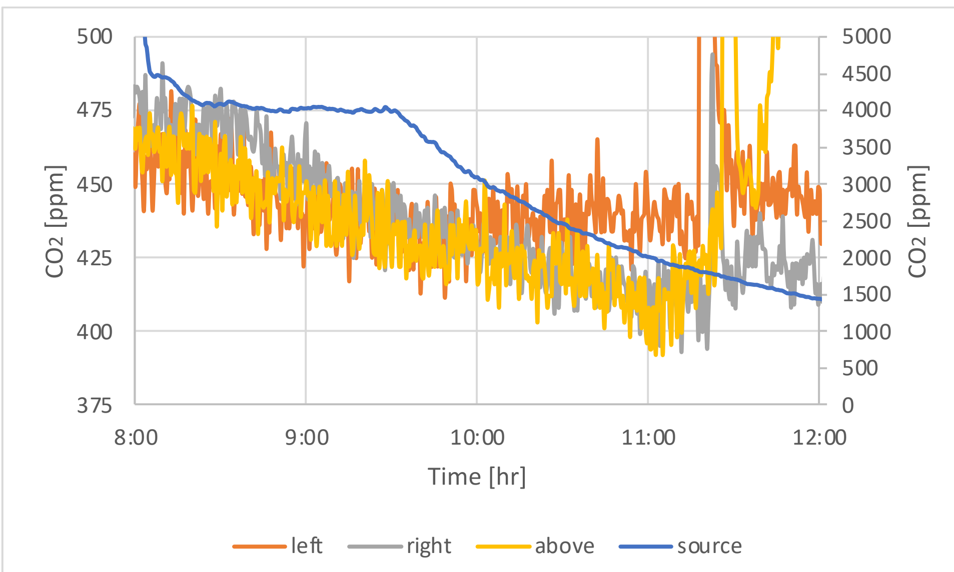


Figure A-4. Tracer gas results showing source CO_2 concentration (right y-axis) and CO_2 concentrations in adjacent units (left y-axis) with kitchen exhaust fans off in unit 409 of Building A.

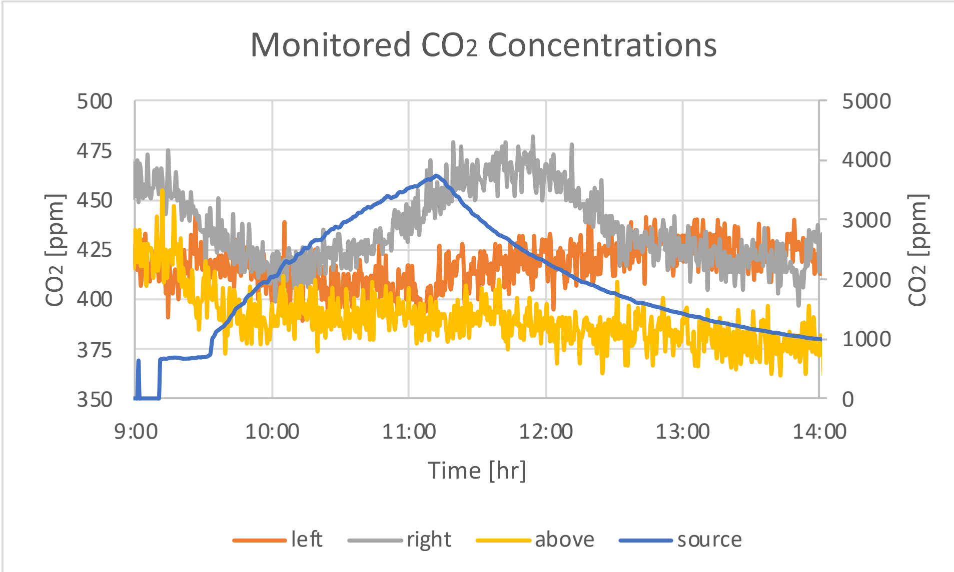


Figure A-5. Tracer gas results showing source CO_2 concentration (right y-axis) and CO_2 concentrations in adjacent units (left y-axis) with kitchen exhaust fans on in unit 509 of Building A.

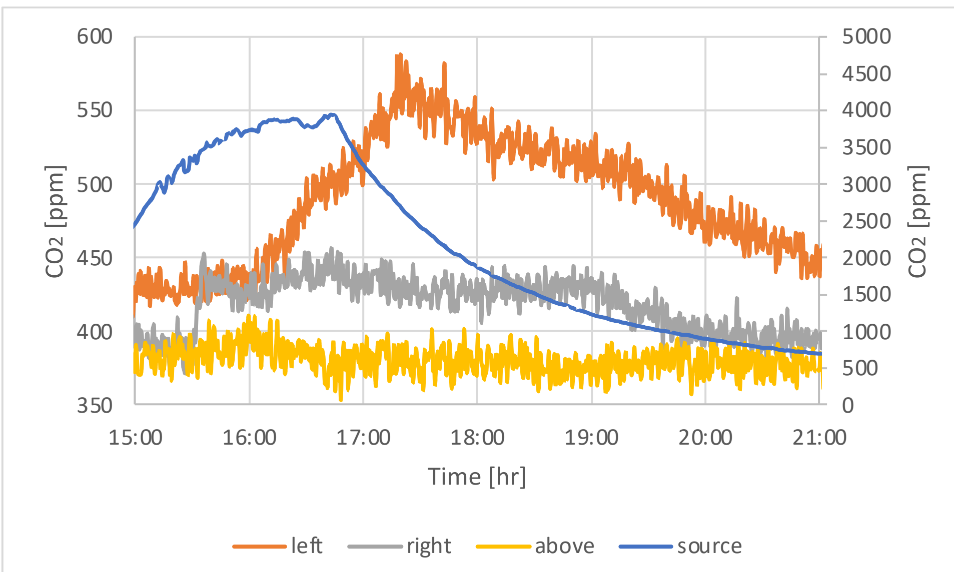


Figure A-6. Tracer gas results showing source CO_2 concentration (right y-axis) and CO_2 concentrations in adjacent units (left y-axis) with kitchen exhaust fans off in unit 509 of Building A.

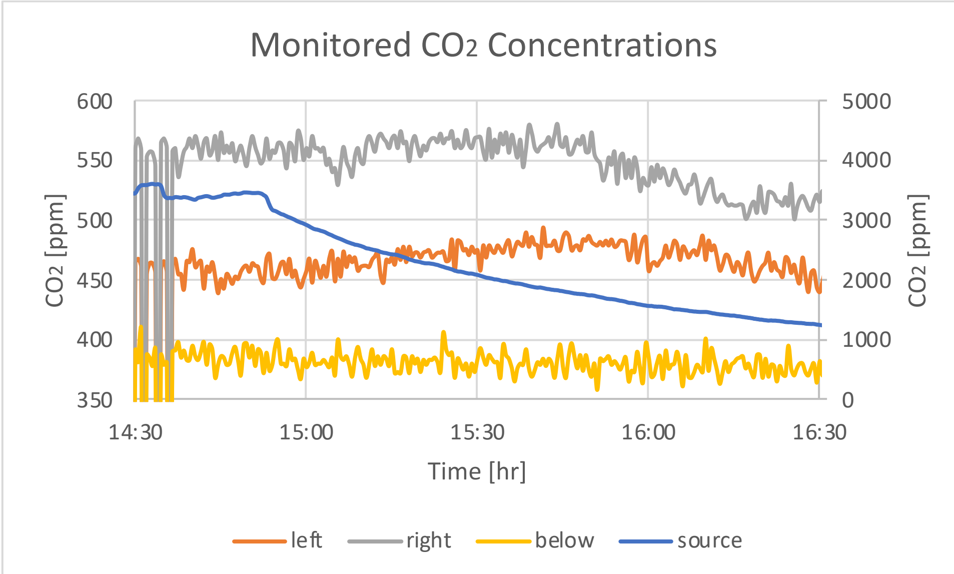


Figure A-7. Tracer gas results showing source CO_2 concentration (right y-axis) and CO_2 concentrations in adjacent units (left y-axis) with kitchen exhaust fans on in unit 609 of Building A.

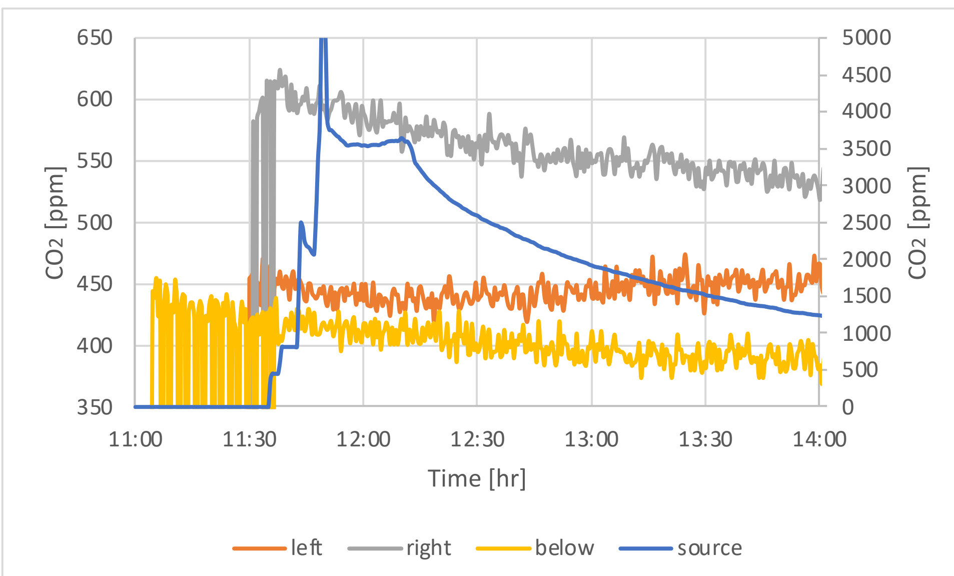


Figure A-8. Tracer gas results showing source CO_2 concentration (right y-axis) and CO_2 concentrations in adjacent units (left y-axis) with kitchen exhaust fans off in unit 609 of Building A.

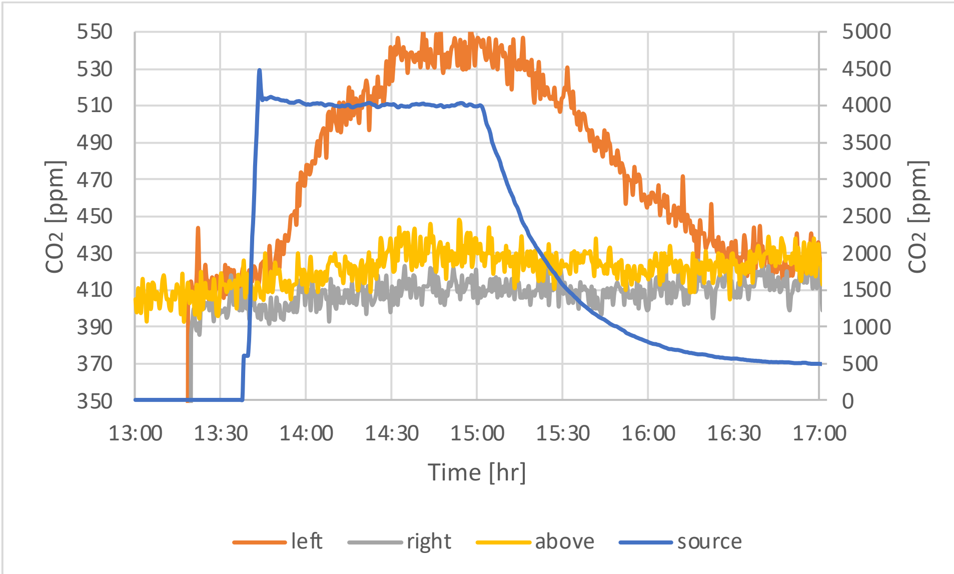


Figure A-9. Tracer gas results showing source CO_2 concentration (right y-axis) and CO_2 concentrations in adjacent units (left y-axis) with kitchen exhaust fans on in unit 531 of Building C.

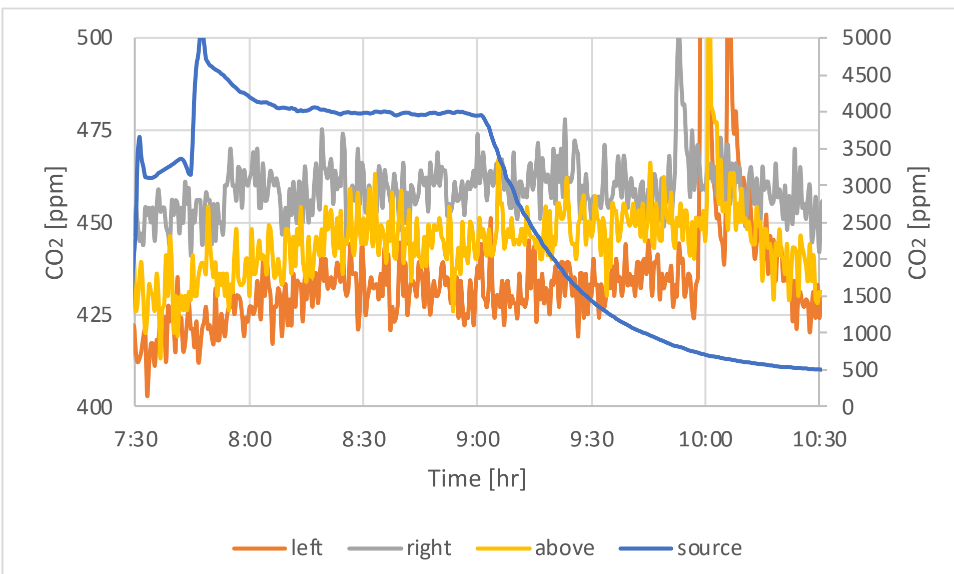


Figure A-10. Tracer gas results showing source CO_2 concentration (right y-axis) and CO_2 concentrations in adjacent units (left y-axis) with kitchen exhaust fans off in unit 531 of Building C.

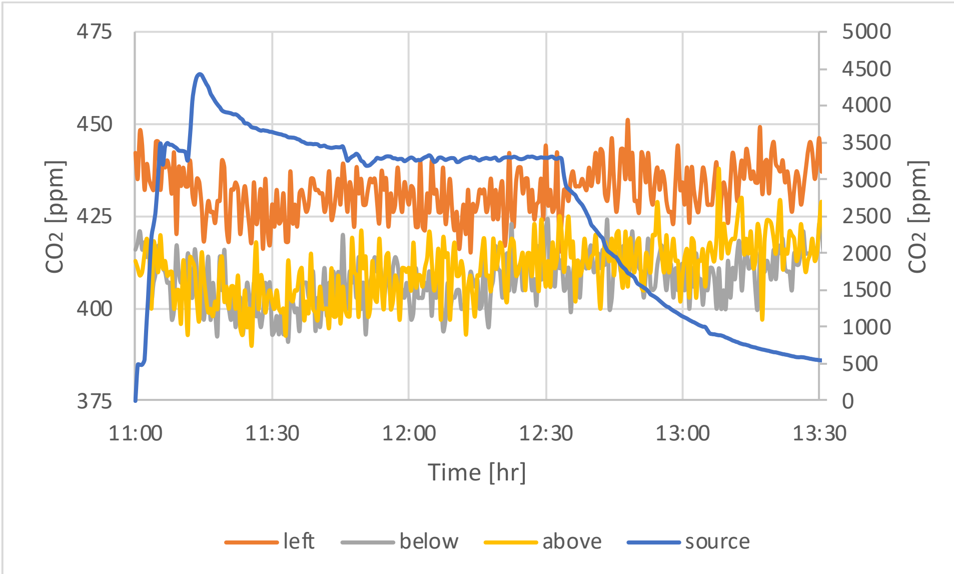


Figure A-11. Tracer gas results showing source CO_2 concentration (right y-axis) and CO_2 concentrations in adjacent units (left y-axis) with kitchen exhaust fans on in unit 534 of Building C.

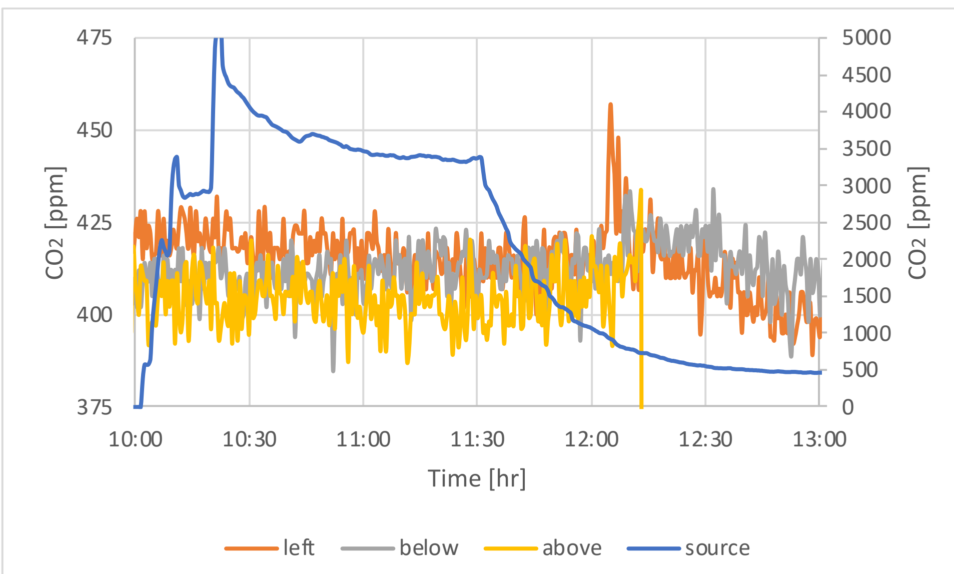


Figure A-12. Tracer gas results showing source CO_2 concentration (right y-axis) and CO_2 concentrations in adjacent units (left y-axis) with kitchen exhaust fans off in unit 534 of Building C.