Final Report

Energy Code Field Studies: Low-Rise Multifamily Air Leakage Testing

Prepared for:

Jeremiah Williams

U.S. Department of Energy

Office of Energy Efficiency & Renewable Energy

Prepared by:

CEE: David Bohac and Lauren Sweeney

Ecotope: Robert Davis

The Energy Conservatory: Collin Olson and Gary Nelson

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EXECUTIVE SUMMARY

Over the past fifteen years, there has been increased interest in quantifying the amount of unintentional air leakage found in both residential and commercial buildings. This leakage results in increased conditioning energy requirements despite providing benefit to occupants as ventilation air. As energy codes have become increasingly stringent, there is even more interest in the contribution of air leakage to overall building energy usage. During this period, testing techniques and tools have also evolved, and this combination of interest and improved analytical ability has facilitated various research efforts.

The work described in this report uses semi-automated pressurization fan testing to quantify low-rise multifamily (up to three stories above grade) air leakage in 25 buildings. Results are presented in both volume-normalized (ACH_{50}) and surface-area normalized format (CFM_{50}/ft^2 (where ft^2 is the total surface area of the tested volume) which has been used for about 10 years by the U.S. Army Corps of Engineers (USACE) on commercial and high-rise residential buildings). Some states now require air tightness testing, and the infrastructure to perform air leakage tests is present in some areas. These details are found early in Section 1 of this report. This work was carried out in parallel with a study of energy-related building characteristics[1] and some of the buildings were part of both studies.

Test buildings were located in the Pacific Northwest and Midwest and two-thirds of test sites were part of a parallel study of low-rise multifamily building characteristics that was undertaken with almost 100 sites (in Minnesota, Illinois, Washington, and Oregon). Buildings had a median number of about 10 living units, with median living unit conditioned floor area of about 825 ft^2. Testing was conducted both on common-entry buildings (where all living units open into shared, interior hallways) and garden-style buildings (where all living units have doors that open directly to the outside). Results are discussed for each building type.

The analysis considered several factors that might influence air leakage, including building attic type, exterior building sealing materials, and the position of the living unit in the building (e.g., ground floor, middle floor, top floor). Further, the report quantifies and investigates the effect of leakage between living units and between living units and common areas (so-called "interior leakage") and discusses at length the difference in testing results when compartmentalization and fully guarded tests are performed on living units. (Guarded tests remove pressure differentials between adjacent units and common areas so neutralize interior leakage; however, they require more time and equipment to perform). Finally, the analysis includes a series of prototype simulations to estimate energy savings that can accrue to different levels of air tightness in different climates.

On a whole building basis, results could be tabulated for 24 buildings (as one garden-style building could not be completely tested due to time constraints) and all but one building came in below 4.0 ACH_{50}, thereby meeting most states' air tightness limit. (Note the metric here, ACH_{50}, indicates the amount of exterior leaking through the building shell at a test pressure of 50 Pascals, normalized by the building's volume. This is the most commonly used metric, although another, which normalizes leakage by overall building area (all sides) is expressed as CFM_{50}/ft^2 and is also used in this report (and in similar research.)) Overall, the leakiest buildings were in Washington and Oregon, which had the least stringent exterior leakage limits; Oregon does not require air leakage testing for this type of construction.

Also of note, 21 buildings had measured exterior leakage of below 3.0 ACH_{50}, which was the tightest state-mandated requirement (Minnesota), and within this group, the average air leakage rate was less than 1.5 ACH_{50}. A total of 83% of the buildings had a whole building surface-area-normalized leakage rate less than 0.30 CFM_{50}/ft^2, and 58% were below the USACE requirement of 0.19 CFM_{50}/ft^2.The volume-normalized results are shown in Figure 1:

[1] *Residential Building Energy Efficiency Field Studies: Low-Rise Multifamily* (Davis et al. 2020)

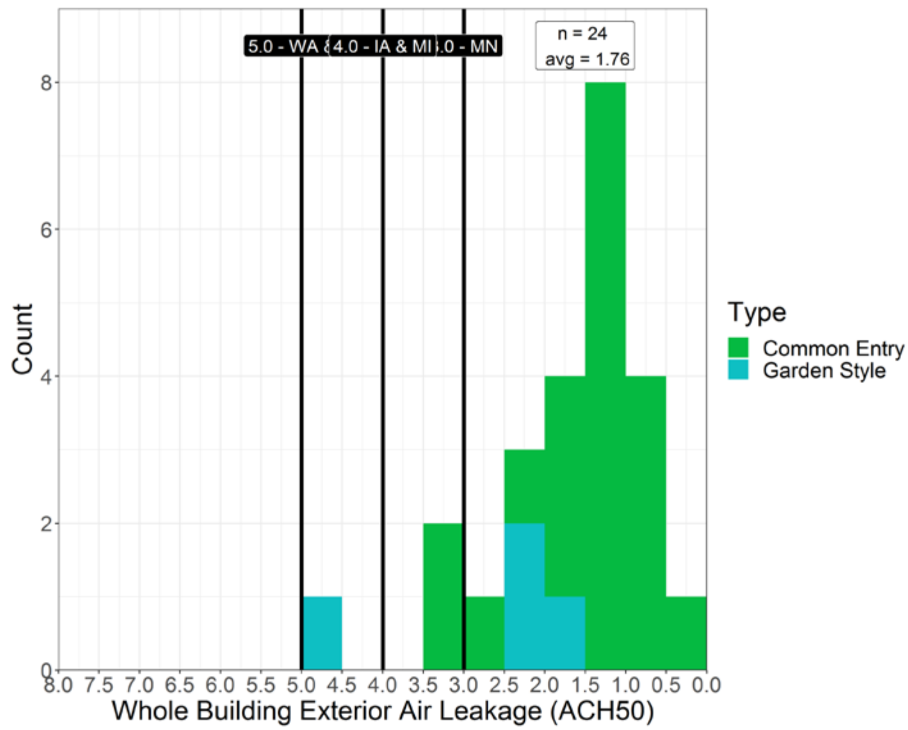


Figure 1. Whole Building Exterior Air Leakage (ACH50)

On a living unit basis, which is particularly relevant to most testing scenarios outside of a research setting (since whole-building tests, especially for garden-style buildings, are extremely labor and equipment intensive, and there is great interest in methods that could allow limited unit testing to be extrapolated to whole-building air tightness), 88% of all units (n = 274) had volume-normalized exterior leakage of less than 3.0 ACH_{50}; 95% were tighter than 4.0 ACH_{50}; and 97% were tighter than 5.0 ACH_{50}. Unit exterior leakage followed the pattern of whole building exterior leakage, with the leakiest units found in Oregon and Washington. Figure 2 shows the distribution of volume-normalized exterior leakage in individual living units:

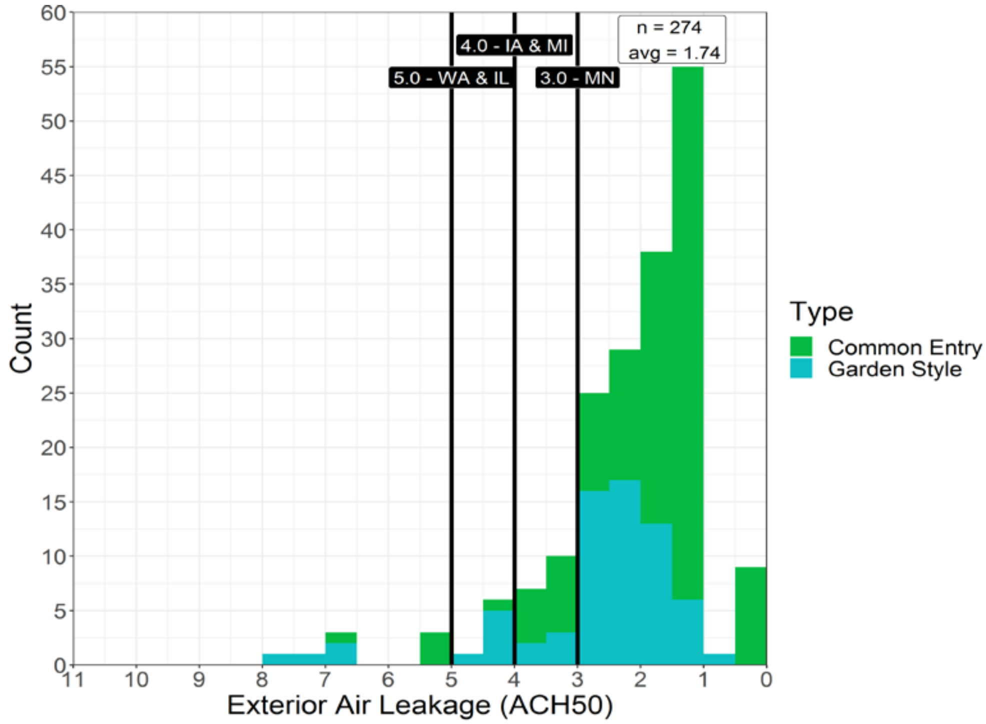


Figure 2. Exterior Air Leakage (ACH50)

A total of 49% of the living units had a total surface-area-normalized exterior leakage rate less than 0.20 CFM_{50}/ft^2; 62% had leakage less than the State of Illinois requirement of 0.25 CFM_{50}/ft^2; and 88% were below the proposed State of Washington maximum leakage of 0.40 CFM_{50}/ft^2. The average for all of the units was 0.24 CFM_{50}/ft^2.

When the more common compartmentalization test (i.e., pressurization fan set up in a single unit) was used to measure total unit volume-normalized leakage (which includes both interior and exterior leakage), 75% of the common-entry units and 54% of the garden-style units complied with a leakage requirement of 5.0 ACH_{50}. The average was 4.10 ACH_{50} for the common-entry units and 5.13 ACH_{50} for the garden-style units. The average for all of the units was 4.53 ACH_{50}. The average total leakage was 2.91 times greater than the exterior leakage for the common-entry buildings and 1.88 times greater for the garden-style buildings. Adding the interior leakage to the exterior leakage significantly reduces the rate of compliance with the leakage requirement for individual living units.

Building characteristics that were logically thought to influence air leakage were investigated. Across states and building types (e.g., common entry and garden style), buildings with vented attics were consistently leakier than those with flat roofs. An analysis was also performed for the type of exterior wall air barrier. For all four types of air barriers with two or more results, there was a relatively even distribution of positive and negative residuals. This indicates that the type of air barrier did not have a noticeable impact on the whole building exterior leakage for this sample of buildings. Similarly, the type of space below the building's lowest living space level (whether a crawlspace, garage, slab, or commercial space) did not have a significant influence on overall building tightness.

The main emphasis of the work was measuring exterior leakage, given this type of leakage has direct bearing on the added space conditioning energy needed to either heat or cool outside air. However, the interior leakage (leakage between living units and leakage between common areas and living units) is also important, given that odor and sound transfer between units is a primary concern to both occupants and building owners. It was also notable that, in this set of buildings, the surface-area-normalized leakage from the units to the common areas (e.g., hallways) is at least five times higher than the leakage from units to adjacent units. The focus of this research was to quantify leakage amounts and not to investigate building construction details, but it is now apparent that more investigation of transfer pathways should be carried out.

Considerable effort was made to extend the results of a living unit compartmentalization test (which, again, includes both exterior and interior leakage) to estimate the exterior air leakage. This has been a primary interest for this building type, since if a limited number of tests results could be reliably used to estimate whole building leakage, more buildings would likely be tested (due to less time and equipment required). One approach has been to multiply the whole unit leakage number by the ratio of the unit's exterior surface area to entire surface area. This approach yielded estimates that varied by as much as 50% above and below the measured exterior leakage for the unit. Other approaches were investigated, and a two-step process that yields a different multiplier per building level (i.e., which floor above grade) was found to improve the estimates. The discussion of results and methods for this topic should encourage others to conduct additional research and broaden the age (i.e., beyond new construction) and relative leakiness of test units.

The results from the tests conducted for this project may help inform future versions of envelope leakage test protocols on issues that are unique to multifamily buildings. For example, the compartmentalization tests conducted for this project were performed first with the adjacent units closed and then opened as necessary. This provided information as to how often keeping the adjacent units closed has a significant impact on the measurement. It also provided guidelines for adjusting the total leakage measurement when the adjacent units must remain closed.

The final topic that was investigated was the direct energy impacts of varying air leakage levels in low-rise multifamily buildings. A set of combined CONTAM/EnergyPlus™ models, based on National Institute of Standards and Technology (NIST) prototypes for low-rise multifamily buildings, were run in the four climates that apply to the test sites. These climates vary from a temperate marine climate (e.g., Seattle) to a very cold continental climate (e.g., Minneapolis). The results suggest a range of heating and cooling savings amounting to between 5 and 15% of the whole-building Energy Use Intensity (EUI). The savings analysis is based on comparison of a 50 CFM continuous exhaust system for living units with intermittent (1 hour/day) exhaust ventilation. A separate analysis was run for a balanced flow (supply and exhaust levels both 50 CFM) ventilation system; this analysis shows that additional energy savings can accrue to reducing exterior leakage to levels much below current air tightness standards, a contrast to exhaust-only ventilation systems.

The graphical methodology developed as part of the simulations provides an accessible means of estimating the savings that could be achieved by more carefully detailed buildings and infiltration-related improvements on existing buildings. As well, the analysis shows that sealing interior leaks (that is, leaks between living units and other living units or between living units and common areas), also can provide some energy savings, although this benefit is much reduced versus sealing exterior leakage.

It is important to note that the results discussed here apply only to the 20 buildings tested from six states (20 buildings provided sufficient data to be employed in summaries). While this is a moderate number of buildings and states, almost all of the buildings were from states that required envelope air leakage testing, and 16 (64%) of the buildings were being certified for an energy efficiency program. Since the project team's work for multifamily new construction has been focused on energy efficiency, the sample is biased toward buildings participating in energy efficiency certifications that include an air leakage testing requirement. As such, the buildings may be tighter than those that would be obtained from a random sample from each state. A greater number of buildings from a greater number of states is necessary to reach conclusions applicable to U.S. new construction. Nevertheless, the data and analysis presented provide a useful basis for further investigation of this building type, leakage paths, and ventilation strategies.

1. INTRODUCTION

Over the last several years, state, regional, national code agencies, and other parties have trained their eye on energy efficiency codes. Rather than the just "checking the box" for prescriptive requirements, the renewed focus concerns the actual energy impacts of these codes on a whole-building basis. Further, if the effects of noncompliance can be estimated accurately, the overall impact of the code on expected new building performance could apply to all new buildings (commercial, multifamily residential, and single-family residential).

The subject of this study is low-rise multifamily buildings. That included buildings of predominantly residential occupancy that have no more than three stories above grade (Davis et al. 2020). The main portion of the study reviewed buildings' thermal shell, mechanical systems, water heating, and lighting. Almost 100 buildings permitted between 2012 and 2015 were evaluated in four states (Illinois, Minnesota, Oregon, and Washington). Results are found in a companion report. The results are a good start to understanding the energy performance of this sector across the United States.

Envelope air leakage is another key component that impacts building performance. For example, a modeling study on multizone air flow and energy use of a prototype 36,864 ft^2, four-story multifamily building in Minneapolis, Minnesota, found annual air infiltration rates of 0.24, 0.09, and 0.05 air changes per hour for envelope leakages of 1.06, 0.18, and 0.03 CFM_{50}/ft^2, respectively (Emmerich, McDowell, and Anis 2005). The space heating annual gas use was 5,400; 3,000; and 2,600 Therms for the three envelope leakage levels, which converts to space heating saving of 44% and 52% for the reduced envelope leakages of 0.18 and 0.03 CFM_{50}/ft^2. For one- to three-story buildings, the residential International Energy Conservation Code® (IECC) requires building or dwelling-unit air leakage rates to measure below a maximum value and be verified by a performance test.[2] Since the 2012 version, IECC section R402.4 has included the following requirement for air leakage testing:

> *The building or dwelling unit shall be tested and verified as having an air leakage rate not exceeding 5 air changes per hour in Climate Zones 1 and 2, and 3 air changes per hour in Climate Zones 3 through 8.*

This test ensures a low level of envelope leakage for buildings built in compliance with this code. However, it is ambiguous on whether the leakage rate is meant to be total leakage or exterior leakage only.

For single-family homes, it is clear that the requirement applies to only the exterior envelope leakage of the home. Conversely, for multifamily units, the envelope is split between the exterior portion that borders the outdoors and the interior portion that is adjacent to other inside spaces (e.g., other units and common areas). While the exterior envelope leakage is the primary concern for energy use needed to condition uncontrolled air infiltration, it is, again, unclear whether the code-specified leakage requirement applies to only the exterior leakage or to the sum of interior and exterior leakage.

As an important side note, we offer that interior leakage might be of more concern to building occupants, since odor (and sound) transmission between units is undesirable. From a developer or building owner perspective, building units with very limited interior leakage could be as much of a selling point as offering units with very tight exterior envelopes.

[2] Appendix A provides the 2012, 2015, and 2018 versions of the IECC Residential Envelope Testing Requirement.

Further, ongoing discussions with both the building industry members and certainly within the building science community indicate that there is no consensus on what type of envelope tightness should be applied or how tightness should be measured for low-rise multifamily buildings (Davis et al. 2020).

There are two common envelope leak test methods for multifamily buildings. The first method is often referred to as the whole building test. All of the residential units and any common areas are tested simultaneously so that the test measures the exterior leakage of the entire building. (Since all units are at the same test pressure, all interior leakage is taken out of the measurement.) The second method is referred to as a compartmentalization test. Individual units are tested separately so that the measurement includes the sum of the interior and exterior envelope leakage of one unit.

The advantages and disadvantages of both test methods are listed in Table 1. From the perspective of individual dwelling and building air movement, the primary difference between the two methods is that the whole building test measures the exterior leakage, which impacts air infiltration, while the compartmentalization test includes interior leakage, which impacts air and contaminant transfer between units. Section 4 contains extensive discussion of interior and exterior leakage in this data set.

Table 1: Advantages and Disadvantages of Common Test Methods

Whole Building		Compartmentalization	
Advantages	Disadvantages	Advantages	Disadvantages
Only one test for entire building	No information for individual units	Results for individual units	Requires multiple tests. Units typically sampled – no complete survey
Includes common area leakage	Entire building envelope must be complete and need control of entire building for test	Only individual unit envelope must be complete. Can often get feedback earlier in construction cycle.	No information on common area leakage
Measures exterior leakage, which has greatest impact on energy use	No interior leakage information to address sound and odor/contaminant transfer	Includes interior leakage that impacts odor/sound and contaminant transfer	Exterior leakage estimated from algorithms (discussed extensively in this report)
	Higher level of training, experience, and equipment required (fewer firms available)	Similar to house leakage test (many firms available)	

Besides the two test methods, there are two distinct styles of low-rise multifamily buildings that are important to distinguish:

- Common entry: The building has a single entry for all units, a closed corridor, and common area. All units are connected through these common areas.
- Garden style: The building has open corridors to the outside, and each unit has an outside entry. The units are not directly connected to an interior common area.

Since common-entry buildings have an interior area that connects all of the units and garden-style buildings do not, different test procedures are required to measure exterior leakage for the two building types. Note for buildings in this study, "common areas" are made up almost completely of corridors and a few small rooms such as mechanical closets and elevator rooms. In mid- or high-rise multifamily buildings, more varied (and larger) common spaces such as lounges, exercise rooms, and site offices would be found.

1.1 Research Goals and Scope

The relative importance of air infiltration's energy impact and the current industry divergence between the two multifamily test methods necessitated a detailed evaluation of the test methods. The research goals were intended to resolve some of the divergence. The primary project goals were to:

- Document compliance with envelope leakage standards. Evaluate the relationship between testing requirements, design approach, and building characteristics on envelope leakage.
- Determine whether a relationship between these tests exists for the two building types, and, if so, how strong it is and what variables affect its predictive power for energy use.
- Assess the impact of exterior and total envelope leakage on building energy use.
- Provide an envelope air leakage test protocol(s) that would be practical and appropriate for determining energy code compliance for multifamily buildings.
- Provide guidance for the development of code language to address envelope tightness in model energy codes aimed at the low-rise multifamily sector.

The research was successful in delving into the first four subjects, and the results are presented in great detail in the following sections. The authors do not feel that the data and analysis are conclusive enough to provide clear guidance on new code language, with the exception of suggesting that it would be best to stress exterior leakage as the metric that should be focused on in low rise multifamily buildings, and further, that it would be advisable for other testing agencies to continue to perform whole building tests as much as possible to assist in development of the codes for this building type.

The project team conducted three types of envelope leakage tests on each building. First, the exterior leakage of the entire building was measured with a whole building test. Second, the total leakage of a sample of up to 12 units was measured with compartmentalization tests. Third, guarded tests were conducted on the same subset of units to measure the exterior leakage of each unit. The guarded tests were added to provide a direct comparison between the exterior and total envelope leakage for a sample of units. The difference between the whole building and individual unit exterior leakages was used to estimate the exterior leakage of any common space.

In late 2017, the project team conducted two trial tests to identify opportunities to improve the protocol, provide additional staff training, and generate data for preliminary analysis. The experience of performing the tests resulted in numerous minor modifications to the protocol to improve data quality and streamline the process. No changes were made to the type of tests conducted. After the protocol was updated, the project team conducted tests on 23 buildings from August 2018 to October 2019. Including the two trial test buildings, the tests measured the envelope leakage of 211 units in 20 common-entry buildings located in 6 states. (Two additional buildings, one each in Michigan and Iowa, were added to the final dataset when recruiting in other areas was exhausted.)

A total of 68 units were tested in 5 garden-style buildings located in Minnesota, Oregon, and Washington. Air flow rate and pressure difference data was collected using The Energy Conservatory's (TEC's) TECLOG3 testing software. The data was exported to customized Microsoft® Excel® tabs to compute air leakage values and R software (R Foundation for Statistical Computing 2019) was used to produce summary statistics and charts.

1.2 Code and Energy Program Air Leakage Testing Requirements

The state-to-state differences in energy code testing requirements, inconsistent code enforcement, and wide-ranging energy program requirements produced significant variation in the air leakage requirements for tested buildings. Since almost all of the tests were conducted over a 14-month period when builders were near the end of construction, the buildings within each state were permitted under the same code cycle or air leakage testing code requirement. Table 2 shows the requirement enforced at the time of the testing by state. The details of the amended codes (which cover items other than just air tightness testing) are included in Appendix A. Oregon was the only state that did not have an air leakage test requirement in its residential code (which applies to most of the conditioned area of these buildings). Minnesota had the lowest leakage requirement of 3.0 air changes per hour for a pressure difference of 50 Pascals (ACH_{50}), two states had a requirement of 4.0 ACH_{50} (Iowa and Michigan), and two had a requirement of 5.0 ACH_{50} (Illinois and Washington).

Table 2: Energy Code Required Air Leakage Testing

State	IECC Version	Amendments	Max. Leakage (ACH_{50})
Illinois	2015	Yes	5.0
Iowa	2012	Yes	4.0
Michigan	2015	Yes	4.0
Minnesota	2012	No	3.0
Oregon	2009	n/a	Not Required
Washington	2015	Yes	5.0

Seventeen of the buildings tested were in the process of being certified for an energy efficiency program. Fourteen of the buildings were being certified for ENERGY STAR Certified Homes; one was being certified for the Passive House Institute U.S. (PHIUS) standard; one was being certified for Earth Advantage; and the units in another building needed a Home Energy Rating System (HERS) score of no greater than 62. ENERGY STAR Certified Homes v3.1 (ENERGY STAR 2015) requires an envelope air leakage test performed by a rater using a RESNET-approved testing protocol. Typically, the envelope leakage is measured using a compartmentalization test. The Reference Design specifies that the leakage shall be less than or equal to 4.0 ACH_{50} for climate zones 1– 2, and 3.0 ACH_{50} or less for climate zones 3–7. For multifamily buildings using the Performance Path, the Reference Design leakage rate is the value used to determine the HERS Index Target — the highest numerical HERS Index value that each rated dwelling unit may achieve. Consequently, there can be trade-offs with other energy features that allow the envelope leakage to be higher or lower than the Reference Design value. The builder is typically aware of the target leakage level that they must meet in order to obtain an acceptable score.

The PHIUS certification for multifamily buildings includes an envelope air leakage requirement for the whole building and individual dwelling units (PHIUS 2018). For buildings up to four stories, the whole building envelope exterior leakage must not exceed 0.06[3] CFM_{50}/ft^2 of envelope surface area. There is an exception for taping off leakage that can be proven to be due to a non-assembly-threatening element. The un-taped leakage result must be used for energy

[3] The PHIUS certified building in the study was built under the 2015 version that a required whole building leakage rate of 0.05 CFM_{50}/ft^2.

modeling purposes. Individual dwelling units must have air leakage no greater than 0.30 CFM_{50}/ft^2 of dwelling unit shell as measured by a compartmentalization test.

At the start of the study, none of the states had an air leakage requirement specifically targeted at low-rise multifamily buildings. However, there have been recent efforts to include an exception that specifies a leakage rate and test type for multifamily buildings. As of July 1, 2019, the State of Illinois energy code requires that low-rise multifamily building dwelling units should have a leakage rate not to exceed 0.25 cubic feet per minute at a pressure difference of 50 Pascals divided by the total envelope surface area (CFM_{50}/ft^2) as measured by a compartmentalization test. The code also includes a sampling protocol. (Complete text is included in Appendix A.) In addition, there is a proposal to amend the State of Washington code to include an exception for dwelling units that are accessed directly from the outdoors to have a leakage rate not to exceed 0.40 CFM_{50}/ft^2 as measured by a compartmentalization test. The earliest this requirement would be enacted would be late 2020. Finally, the U.S. Army Corps of Engineers (USACE) requires whole building leakage no greater than 0.25 CFM/ft^2 for a reference (test) pressure of 75 Pa (USACE & ABAA 2012).

1.3 State-by-State Approach

The project was structured to represent a healthy national cross section of climate zones, energy codes, building designers, and builders. The sampling frame represented a distribution of climate zones encompassing the milder and colder parts of the Pacific Northwest (Zones 4 and 5), a typical Midwest continental climate (Illinois, Zone 5), and much colder continental climates (Minnesota, Zones 6 and 7). The IECC code requirements are calibrated to the severity of the climate, and the compliance and energy analyses in this report follow these requirements.

However, the use of the term “sample” above, implies that the number of buildings tested was sufficient to draw statistically significant conclusions about air tightness (at least for the whole group, if not for individual states). This was not possible within the time constraints of the project, since there was a limited number of this type of building available at the right stage of construction and occupancy in the four sub-regions addressed by the study.

State-by-state compliance is documented in separate sections of this report, allowing readers to compare state results easily. A now-familiar graphic format developed by the Pacific Northwest National Laboratory (PNNL) is used to describe compliance with state codes. The energy impacts of noncompliance for each climate zone are summarized in Chapters 3 and 4, as well. In fact, the energy impact analysis shows the “bottom line” in terms of what resources could be conserved if different building components were brought up to code in each state and climate zone. This approach, combined with other recent research efforts across the United Sates, allows policymakers to aggregate remaining conservation opportunities using a consistent format.

2. METHODOLOGY

2.1 Sampling

The primary goal for the envelope air leakage testing portion of the project was to evaluate different methods for code requirement testing and provide recommendations. The sample of buildings tested was not expected to be of a size statistically significant enough to evaluate the level of code compliance by state. The intent was to obtain a representative sample of buildings so that the recommendations would be applicable to many low-rise multifamily buildings in the United States.

As stated above, the project was constrained by the total number of buildings available in each testing sub-region that met both low-rise multifamily building type requirements and that were of the right stage of construction and occupancy. The ideal test site would be very nearly complete (with all air barriers installed) but not be occupied (to facilitate the invasive testing process, especially in garden-style buildings, where a large number of units would be tested simultaneously). Alignment of all of these factors was very difficult — therefore, the final testing frame was not sufficient to allow statistically significant conclusions about testing methods or results. Still, there is a very rich trove of data and analysis that follows that provides several new insights into this sector.

2.2 Recruitment

The goal was to test 30 low-rise multifamily buildings with the following regional distribution: Minnesota, 14; Illinois, 5; and Oregon and Washington, 11. It was expected that the buildings in Minnesota would be predominantly common entry, that those in Oregon and Washington would be garden style, and that those in Illinois would be a mixture.

A variety of recruiting methods was used, and many of the buildings that ended up in the testing group were also part of the broader building characteristic assessment (Davis et al. 2020) that was conducted in parallel with the air tightness testing. Recruiting buildings for envelope air leakage testing was coordinated with the recruiting for the building characteristic research. Obviously, it was most convenient to recruit for both studies through the same process, but this approach did not ensure success, mostly because of the stage of construction that buildings were in relative to the ideal testing stage. (That is, a building that was finished or mostly finished but not yet occupied provided the ideal testing scenario.)

Consequently, the buildings were a convenience sample. Since the project team's work for multifamily new construction has been focused on energy efficiency, the sample is biased toward buildings participating in energy efficiency certifications that include an air leakage testing requirement. As such, the buildings may be tighter than those that would be obtained from a random sample from each state.

Recruiting began in October 2018 with the intention of completing testing by February 2019. The testing was extended through September 2019, and the Midwest region was expanded to include Iowa and Michigan to get closer to the target of 30 buildings. In the end, the total number of Midwest buildings tested (20) was one greater than the original goal of 19 for Minnesota and Illinois. Five buildings were tested in Oregon and Washington — six fewer than the goal. Consequently, there are fewer garden-style buildings in the data set than was expected.

Table 3 provides a summary of the types of contacts used to recruit the tested buildings. About three-quarters of the buildings were obtained from industry contacts familiar to the project team. Another 16% (4 of 25) of the buildings were working with the project team for another reason (i.e., direct contact). Only 8% of the buildings (2 of 25) came through information from Dodge Reports, and no buildings were recruited from lists obtained from municipal jurisdictions (e.g., cities and counties).

Table 3: Type of Contact Used to Recruit Participants

State	Industry	Direct	Dodge Data	Jurisdiction	Total
Illinois	4	0	0	0	4
Iowa	3	0	0	0	3
Michigan	1	0	0	0	1
Minnesota	6	4	2	0	12
Oregon	2	0	0	0	2
Washington	3	0	0	0	3
Total	19	4	2	0	25

2.3 Air Leakage Test Methods

The project team conducted three types of envelope air leakage tests on each building. The first two types are often used for energy code or efficiency program compliance purposes to measure whole building exterior leakage and individual unit total leakage. The procedure for the third test is more complex and not commonly used by practitioners and measures the exterior leakage of individual units. This test was added to the protocol so that the project team could directly compare the exterior and total leakage of individual units for a sample of units in each building. The test procedures vary for common-entry and garden-style buildings. All tests were performed as single-point depressurization measurements with pre- or post-baseline adjustment. The single-point measurement was conducted to achieve an induced pressure difference of 50 +/- 1.0 Pascals (Pa).

Nine subject-matter experts (see Acknowledgements) provided feedback on the Research Plan. The project team incorporated that feedback into the detailed test procedures included in Appendix B and summarized below. Trial tests were conducted on a garden-style building in Oregon and a common entry building in Illinois in November and December of 2017, respectively. The purpose of the trial was to identify opportunities to improve the protocol, provide field staff training, and generate data for preliminary analysis. The trial resulted in numerous minor modifications to the protocol to improve data quality and streamline the process. No changes were made to the type of tests conducted or number of units to be tested. It was expected that 2–3 field staff could conduct the tests on a building in 8–12 hours. That proved to be an accurate time estimate with the exception of the larger garden-style buildings, which required extra time.

After testing began on the remaining 23 buildings, no additional changes were made to the test protocol that caused any differences in the envelope air leakage measurements. Two changes were made to simplify the testing process and generate additional leakage measurements for individual units. First, the compartmentalization test protocol was changed to conduct continuous pressure measurements in all units throughout the testing period, instead of monitoring only the units adjacent to the test unit.

That adjustment eliminated the need to move pressure gauges after each unit was tested, and it provided pressure measurements for units further away from the test unit. Second, another measurement was added to the guarded test method for common-entry buildings — the sum of the unit leakage to the exterior and adjacent units. That measurement allowed the interior leakage of a unit to be split between leakage to adjacent units and leakage to common areas.

2.3.1 Building Setup

A list of 30 building setup items was specified in the detailed protocol provided to the project testing staff. Appendix B includes a description of the items and how they were addressed for the tests. They were grouped into four categories: (1) Building Envelope; (2) Heating/Cooling System Setup; (3) Ventilation Penetrations Between the Conditioned Space and Exterior or Unconditioned Space; and (4) Other. The list was generated by first using the guidance provided by the six items in the *During testing* subsection of IECC 2012/15/18 (R402.4.1.2 Testing) that describe the building setup for air leakage testing. (See Appendix A.) When an issue was not addressed by these six items, Section 3.2 *Procedure to Prepare the Building for Testing* of ANSI/RESNET/ICC 380-2016 was used for guidance (RESNET 2016). Finally, when an issue was not addressed by either of those references (particularly issues regarding large building testing), the project team consulted the Operation Envelope column of *Table 1. Building Preparation for Test Boundary* of ASTM E3158-18 *(Standard Test Method for Measuring the Air Leakage Rate of a Large or Multizone Building)* for guidance.

2.3.2 Whole Building Exterior Leakage

This test measures only the exterior portion of the building envelope leakage. It includes the exterior leakage for all of the units and any common space. One significant advantage of this approach is that the exterior leakage has the greatest impact on building energy use. As such, the measurement from this test corresponds most closely with the impact of envelope leakage on energy use due to air infiltration. For both garden-style and common-entry buildings, the test requires a higher level of operator training and experience. All the units must be complete and accessible.

For garden-style buildings, blower doors are operated in every one of the units simultaneously. (See Figure 3 - red lines indicate walls included in the leakage measurement). This is sometimes referred to as a fully guarded test. The air flow through each fan measures the exterior leakage for the individual unit, and the flows are added together to determine the leakage of the entire building. (Note all test schematics in this section created by Paul Morin of The Energy Conservatory and used with his permission.)

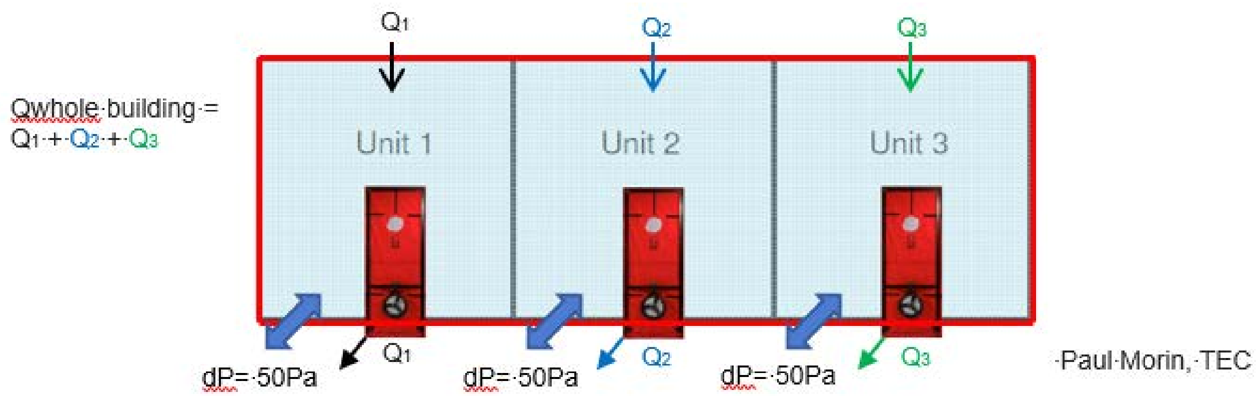


Figure 3. Whole building test for garden-style building with three units

For common-entry buildings, one or more blower door fans are installed in one or more exterior doors to the common area. Interior doors (e.g., hallway doors) are opened so that the entire building acts as a single zone. As shown in Figure 4 the flow rate of the three blower door fans at the building entrance are added together to measure the whole building exterior leakage. There is no indication of the leakage of individual units. The measurement includes the exterior leakage of all of the individual units and the common space.[4]

[4] There is an important note regarding the living unit doors. Current code requires that hallway doors be sealed. For example, the 2012 International Residential Code (IRC- Appendix K (sound transmission)) specifies: “Dwelling unit entrance doors, which share a common space, shall be tight fitting to the frame and sill.” While hall door undercuts used to be standard practice for the transfer of hall air into units, that is no longer allowed. All of the living units tested in this study had door sweeps on the hallway doors.

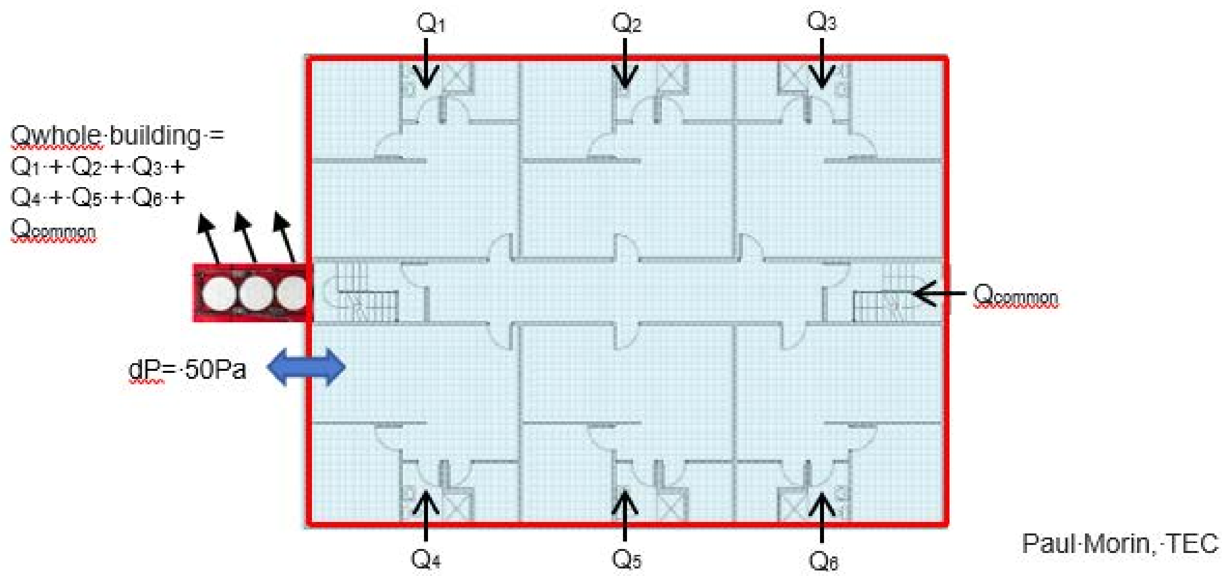


Figure 4. Whole building test for a single-story common-entry building with six units

2.3.3 Unit Compartmentalization Total Leakage

This test measures the total, or sum, of the exterior and interior envelope leakage of an individual unit. This test cannot distinguish between the exterior and interior leakage. Consequently, the result has an uncertain relationship to the building's energy use. The test is the same for garden-style (See Figure 5) and common-entry buildings (See Figure 6). Both figures show that a single blower door measures the total leakage of each unit. The total is the sum of the exterior (solid red lines) and interior (dashed red lines). The test can be performed by anyone trained to conduct single-family leakage tests and does not require all units in the building to be finished.

Adjacent units should be open to the outdoors or hallway during the leakage test so that the pressure difference across the interior portion of the envelope is the same as that for the exterior envelope. However, the units were first tested with adjacent units closed. One objective was to evaluate whether the pressure difference between closed units during the compartmentalization test could be used to help compute the fraction of total leakage that was to the exterior. A second objective was to determine the typical bias in leaving adjacent units closed and establish criteria for when they should be opened.

At the start of each test, all exterior doors and windows as well as any hallway doors of adjacent units were closed. The first portion of the test measured the total leakage with the adjacent units closed. The inside-to-outside pressure differences of all vertically and horizontally adjacent units were monitored during the test. After the first total leakage measurement, the induced pressure differences of the adjacent units were computed. When the induced pressure was more than 5 Pa, the hallway door or exterior door of that unit was opened. The single-point depressurization test was then repeated. Finally, the test fan was sealed and the baseline pressure difference recorded with the hallway and exterior doors in the same configuration (i.e., opened as necessary).

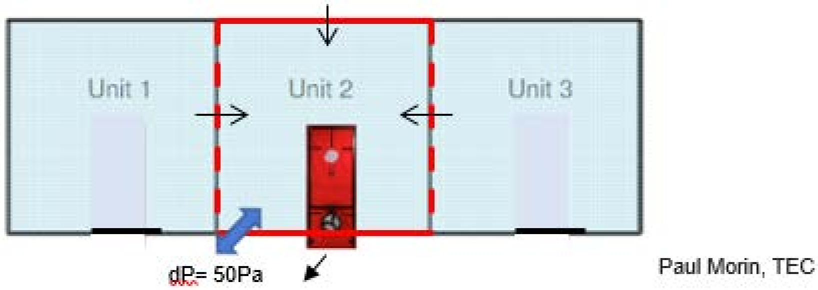


Figure 5. Compartmentalization test of single unit in a garden-style building

Figure 6. Compartmentalization test of single unit in a common-entry building

2.3.4 Unit Guarded Exterior Leakage

This test measures the exterior leakage of an individual unit. For garden-style buildings, it is simply each unit's measurement from the whole building test. As shown in Figure 7, each of the three fans is operated to produce an induced pressure difference of -50 Pa between the unit interior and exterior and zero difference between units. The exterior leakage of each unit is equal to the flow rate of the fan located in that unit. This is the same configuration as the whole building test for garden-style buildings. For common-entry buildings, an additional fan is installed in an individual unit while the whole building test is conducted. For the configuration shown in Figure 8, the fans in the building entrance are adjusted to achieve an induced pressure difference of -50 Pa. The fan in the hallway door of the test unit is adjusted to achieve an induced pressure of 0 Pa between the test unit and the building interior. The flow through that fan (Q2, green arrow) is equal to the exterior leakage of the test unit. The results from the single-unit exterior test and the compartmentalization test provide a direct accounting of the exterior and total leakage for individual units.

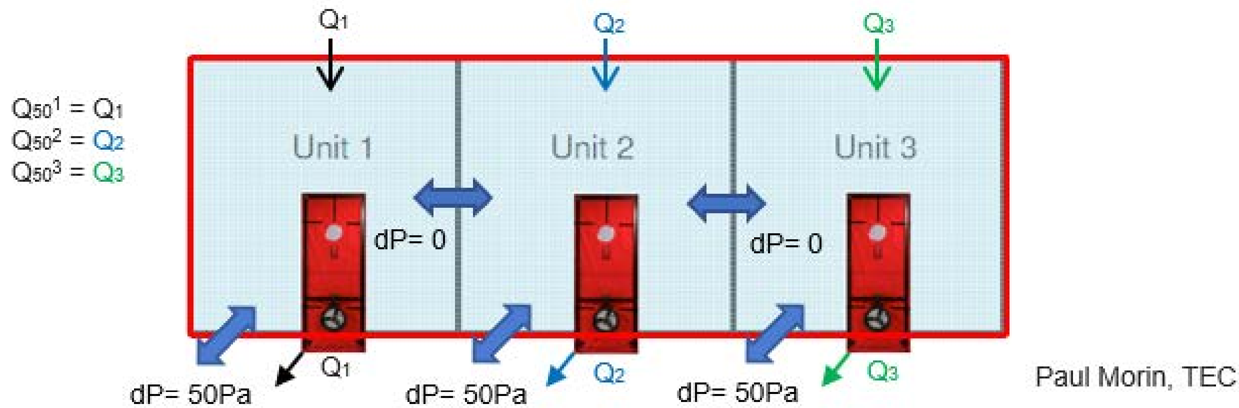


Figure 7. Single-unit exterior test for three units in a single-story garden-style building

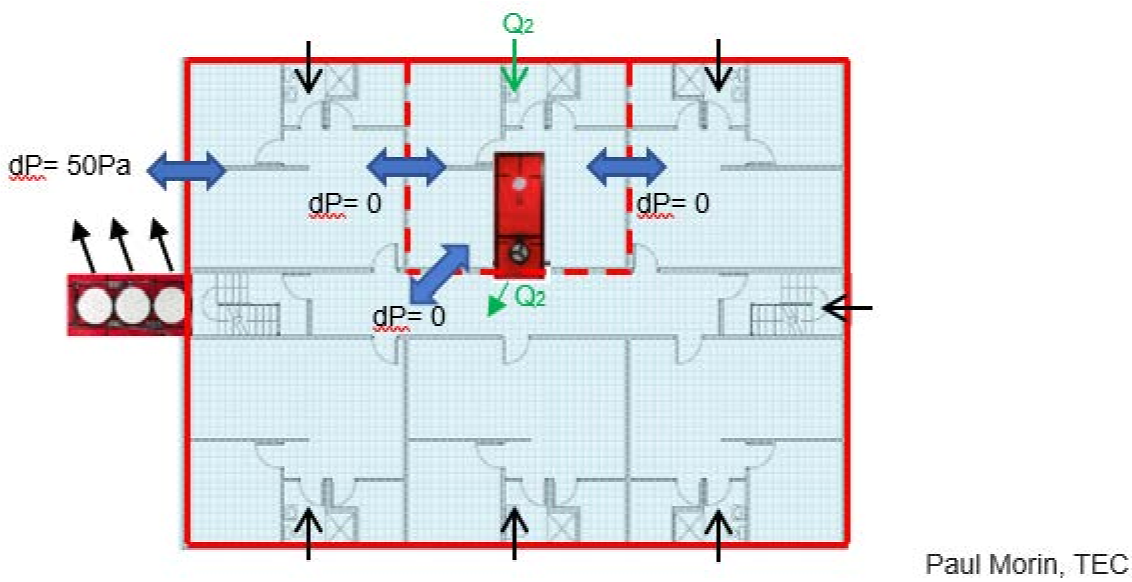


Figure 8. Single-unit exterior test for a single-story common-entry building with six units

For common-entry buildings, a second step was added to the guarded test to measure the sum of the leakage to the exterior and adjacent units. (See Figure 9.) After the initial test, the adjacent units (shaded yellow) were opened to the outside and closed to the hallway. With this configuration, the pressure difference between the test unit and adjacent units was equal to approximately -50 Pa, while the induced pressure difference between the test unit and the common areas was 0 Pa. The flow rate through the test fan (Q2) was approximately equal to the sum of the leakage to the exterior and adjacent units. The exterior leakage measured in the first step was subtracted from the measurement of the second step to compute the leakage to adjacent units. In addition, the leakage from the second step was subtracted from the total leakage to compute the leakage to the common areas.

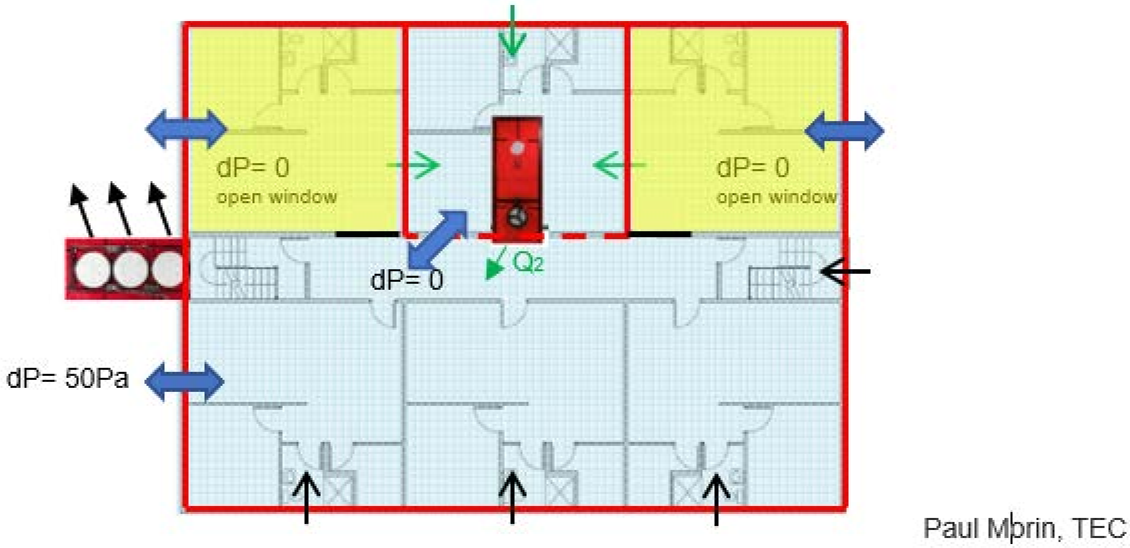


Figure 9. Second portion of single-unit guarded test for a single story common-entry building with six units

2.3.5 Air Leakage Calculations and Quality Control

Air flow rate and pressure difference data were collected using The Energy Conservatory (TEC) TECLOG3 testing software. Values were recorded at one-second intervals. For the whole building and individual unit guarded tests, the baseline and depressurization measurements were conducted for at least 30 seconds. The measurement periods were at least 60 seconds for the compartmentalization tests. The data were exported to customized Microsoft® Excel® tabs to compute air leakage values. The envelope leakage at a reference pressure of 50 Pa was computed using the algorithms specified in Section 9.3 Single-Point Method of ASTM E 1827-11 (2017).

The air leakage rates are reported as the air flow rate of the unit or building for a pressure difference of -50 Pa (CFM_{50}) for standard air density conditions. Building plans (and field verification) were used to determine the floor area, volume, and envelope surface area for tested units and for the whole building. The building dimensions were used to convert the leakage rates to values normalized for volume and envelope surface area. The leakage rate divided by the interior volume (ft^3) was used to compute the volume-normalized leakage of air changes per hour at a pressure difference of 50 Pa (ACH_{50}). The leakage rate was divided by envelope surface area (ft^2) to compute the surface-area-normalized leakage rate (CFM_{50}/ft^2). R and Microsoft® Excel® software were used to produce summary statistics and charts.

Air leakage tests were conducted by three organizations: Ecotope (Oregon and Washington), EcoAchievers (Illinois and Michigan), and CEE (Iowa and Minnesota). The field-testing staff played a critical role in ensuring that the tests were conducted according to the protocol and that the quality of the measurements was acceptable. The protocol specified the criteria for acceptable data quality, field staff were instructed regarding the key results to review, and forms were established for them to document those results. Data had to be reviewed on-site as it was recorded, since for most buildings it was not possible to return to repeat the measurements.

All air leakage test data were processed by a single staff person (CEE's project manager) to help assure high data quality and a consistent calculation procedure. The process also provided field staff feedback on adherence to the test protocol. Field staff submitted TECLOG3 data files and field forms to CEE after a building test was complete. The first step in the quality control process was to review the data files. One advantage of TECLOG3 is that the one-second measurements and defined averaging periods can be easily reviewed. Figure 10 shows the one-second flow and pressure data displayed in TECLOG3 for a typical two-step, guarded unit depressurization test (Green line = building in/out dP; light blue = unit/hall dP; red lines = building blower door flows; blue line = test unit fan flow; green rectangles = averaging periods). A visual scan of the graph confirmed that flows and pressures were steady prior to each measurement period and there were no erroneous data spikes during the measurement periods. If necessary, averaging periods were modified to eliminate atypical measurements due to short-term wind gusts, door or window opening, or hose steps.

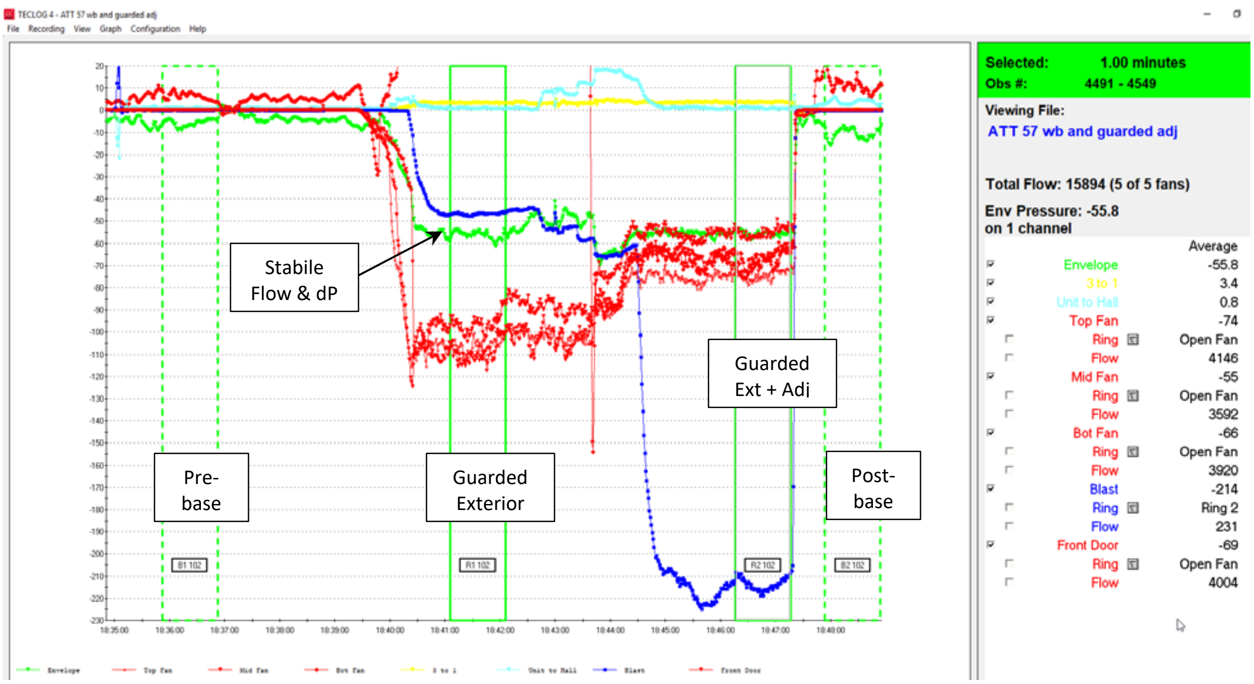


Figure 10. Air flow and pressure time history for a guarded unit depressurization test

The average values from the measurement periods were transferred from TECLOG3 to a Microsoft® Excel®Excel sheet after the visual review of the time history data was complete. A structured labeling process was used to identify measurement periods in TECLOG3 so that Excel lookup functions could be used to extract baseline and depressurization values for each type of test for each unit — this helped minimize data translation errors. Indoor and outdoor air temperature values were entered manually from information recorded on the field data sheets. A CEE staff person used a Microsoft® Office Excel sheet template to compute the floor area, volume, and envelope surface areas for the tested units and whole building from architectural plans. A second staff person reviewed the values. A customized Excel tab was developed to calculate air leakage values for the three test methods and display leakage values in multiple charts. Intermediate values (such as induced pressure differences) were tabulated, and custom formatting was used to identify any values that were outside of the expected range (e.g., 50 +/- 1 Pa for building's induced depressurization). The result tabs were separated into two files based on building type. For each file there was a tab for individual unit leakage results and a second tab for the whole building results.

2.4 Data Analysis

All data analysis in the study was performed by CEE and is presented in Sections 3 through 5 of this report. Section 3 identifies compliance trends within each state based on the whole building and individual unit envelope air leakage measurements. Section 4 analyzes trends in the measured

envelope leakage, as well as identifies building characteristics and leakage standards that impact those trends. Section 5 uses linked building simulations (CONTAM and EnergyPlus™) to determine variations in annual air infiltration and space conditioning energy use for a range of interior and exterior envelope air leakage. The range of above and below-code leakage values were selected based on the analysis of measured values. The following sections provide an overview of the analysis methods applied to the field study data.

2.4.1 Statistical Analysis by State

The first stage of analysis involved examination of the data set and distribution of the measured envelope air leakage. For each state, the air leakage distribution was plotted by building type (e.g., common-entry or garden-style) to understand the range of the data. Distributions portraying the individual values also facilitated comparison to code requirements, an understanding of trends in the surveyed buildings, and exploration of areas where there may be potential for improved code compliance. Figure 11 below shows a sample distribution.

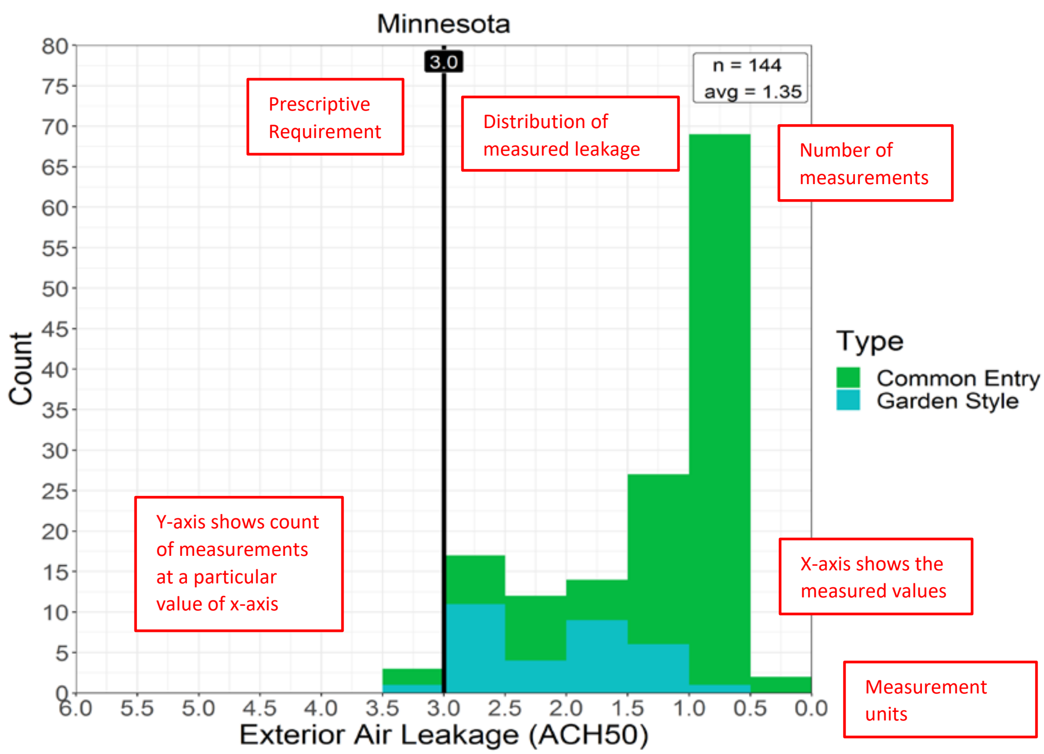


Figure 11. Sample Distribution Graph

Each graph is set up in a similar fashion — identifying the state, building type, and leakage measurement type. The total sample size (n) is displayed in the top left or right corner of the graph, along with the distribution average. The leakage value associated with the item is displayed along the horizontal axis (e.g., exterior leakage for individual units measured in ACH_{50}), and a count of the number of measurements for each x-axis value is plotted along the vertical axis. The vertical line imposed on the graph represents the code required leakage for the state (e.g., the requirement for Minnesota is 3.0 ACH_{50}) — lower values (those to the right-hand side of this line) are better than the code requirement. Values to the left-hand side represent areas for improvement.

Since the code-required air leakage can be applied to the whole building or to individual units, the distributions were plotted for the whole building exterior leakage, individual unit exterior leakage, and individual unit total leakage. The plots were generated for both the volume-normalized leakage (ACH_{50}) and the unit's six-sided surface-area-normalized leakage (CFM_{50}/ft^2). Both measurements were included because the most recent versions of the IECC specify the requirement for ACH_{50}, while some program requirements and proposed updates to the code specify the leakage requirement for CFM_{50}/ft^2.

2.4.2 Statistical Analysis by Building Type

The second stage of analysis evaluated trends in measured envelope leakage, as well as identified building characteristics and leakage standards that impacted those trends. This included an analysis of whole building leakage, individual unit total and exterior leakage, methods to estimate unit exterior leakage, and implications for test protocols. It was anticipated that the hallways and other common areas of the common-entry buildings could result in significant differences in air leakage results between the common-entry and garden-style buildings. Consequently, the analyses of leakage trends were performed separately for those building types.

The leakage distributions are presented for whole buildings and individual units. Similar to the Section 3 analysis, the leakage measurements are reported for both the volume-normalized leakage (ACH_{50}) and the surface-area-normalized leakage (CFM_{50}/ft^2). For whole building leakage, least square regressions were conducted for the following characteristics that were expected to impact leakage: (1) state code leakage requirement; (2) type of attic (i.e., vented or flat/unvented); and (3) participation in an energy program. A residual analysis assessed the correlation between leakage and the type of space under the bottom floor as well as type of exterior wall air barrier. Finally, the contribution of common space leakage to whole building exterior leakage was documented.

The volume- and surface-area-normalized leakage distributions are also presented for individual units. The leakage is presented for both exterior and interior measurements. For the common-entry buildings, the interior leakage is split between that from the unit to the common space and that from the unit to adjacent units. The magnitudes of the different leakages are compared, and building level trends are established (e.g., bottom, middle, and top). For common-entry buildings, the analysis is further split into buildings with vented attics and those with flat roofs.

Methods for estimating the exterior leakage from measurements of total leakage were examined. The exterior portion of envelope leakage is the primary concern regarding energy use for conditioning uncontrolled air infiltration, and there are a number of challenges for measuring the exterior leakage of units. Researchers also evaluated the reliability of using the ratio of the exterior portion of the envelope surface area divided by the envelope surface area of the entire unit with the total leakage of the unit. They also documented the improvement of including a multiplier that varies by building level and attic type. For garden-style buildings, algorithms were developed that use the total leakage measurement and the pressures in the adjacent units to compute the exterior leakage. The difference between the computed and measured exterior leakages were documented and compared to the surface-area-ratio methods.

The results from the tests conducted for this project may help inform future versions of envelope leakage test protocols on issues that are unique to multifamily buildings. For example, the compartmentalization tests conducted for this project were performed first with the adjacent units closed and then opened as necessary. This provided information as to how often keeping the adjacent units closed has a significant impact on the measurement. It also provided guidelines for adjusting the total leakage measurement when the adjacent units must remain closed. In addition, the results from the whole building leakage tests of the common-entry buildings were evaluated to determine the distribution of the number of blower doors that were needed to test the buildings. Finally, tables presenting the variation of leakage measurements of tests performed for units on the same floor or in the same building may be useful for refining sampling methods.

2.4.3 Energy Use Analysis

The third stage of analysis used coupled airflow and building energy models to evaluate the impact of varying levels of envelope leakage on annual air infiltration and space conditioning energy use. The primary goals of the energy use analysis were to:

- Evaluate the separate effect of the exterior envelope leakage and total (i.e., exterior and interior) envelope leakage to provide guidance on the type of testing required to determine whether buildings meet energy use targets.
- Estimate potential savings from bringing buildings that do not meet state code tightness requirements to the required level and, further, to evaluate additional savings that would accrue due to reduced leakage. This evaluation was done for both exhaust-only and balanced ventilation systems, since these systems (literally) provide different pathways for air tightening and effective unit ventilation.

The sample of buildings tested was not expected to be large enough (i.e., statistically significant) to evaluate the level of code compliance by state or the overall impact of noncompliance on energy use. As such, models were not constructed for each building tested. The intent was to develop models for a prototype building with leakage values that spanned the range of measured envelope leakage from the project buildings. This was to help assure that testing recommendations and performance maps would be applicable to many low-rise multifamily buildings in the United States. A similar approach was used to estimate added energy conservation benefits from upgrading building components in the parallel building characteristics study (Davis et al. 2020).

3. AIR LEAKAGE RESULTS BY STATE

This section summarizes the whole building and individual unit envelope air leakage measurements by state and type of building. Air leakage tests were conducted on five garden-style and 20 common-entry buildings in six states. Table 4 displays the distribution of the number of buildings and units tested by each state and building type. There were fewer garden-style buildings in the sample than initially expected because the recruiting was less successful in the Pacific Northwest, where the buildings are predominantly garden-style. The five garden-style buildings were located in Minnesota, Oregon, and Washington, with each state having either one or two buildings. There was at least one common-entry building in each of the six states. About half of the common-entry buildings and units were located in Minnesota. Illinois and Iowa had the next largest number of buildings (four and three, respectively).

Table 4: Distribution of Buildings and Units Tested by State and Type

	Garden-Style		Common Entry		Total	
State	Units	Buildings	Units	Buildings	Units	Buildings
Illinois	0	0	31	4	31	4
Iowa	0	0	30	3	30	3
Michigan	0	0	12	1	12	1
Minnesota	32	2	112	10	144	12
Oregon	12	1	11	1	23	2
Washington	24	2	10	1	34	3
Total	68	5	206	20	274	25

There were three two-story buildings, and the rest were three-story. Out of all the buildings, 23 were entirely residential, while two common-entry buildings had two floors of residential units above first-floor commercial space. The number of units per building ranged from six to 60 and averaged 28. For common-entry buildings with more than 12 units, a sample of 10 to 12 units were tested. The floor area for individual units ranged from 405 to 1,500 ft^2 and averaged 929 ft^2. The total floor area of the buildings ranged from 8,155 to 72,721 ft^2 and averaged 29,864 ft^2. The number of units per building and the total floor area of the common-entry buildings were greater than that for the garden-style buildings, but the average floor area of the individual garden-style units was greater. Since the exterior air leakage requirement can be applied to the whole building or to individual units, the results are presented for both the whole building (Section 3.1) and the individual units (Section 3.2).

3.1 All Buildings

This section contains air leakage results for all of the buildings tested.[5] This includes the whole building exterior, individual unit exterior, and individual unit total leakages. The leakages have been normalized by volume (ACH_{50}) and six-sided envelope surface area (CFM_{50}/ft^2). The summary tables break out the compliance rate by state. For volume-normalized leakage, the compliance rates are shown for 3.0, 4.0, and 5.0 ACH_{50}. The highlighted cells indicate the compliance rate for the leakage level required in the specific state. Minnesota, where 12 of the buildings were located, has a leakage requirement of 3.0 ACH_{50}; four buildings were in either Iowa or Michigan, which both require 4.0 ACH_{50}; six buildings were in either Washington or Illinois, which both require 5.0 $ACH_{50;}$ and two buildings were in Oregon, which does not have a testing requirement. In addition to the state code leakage requirements, 17 of the buildings were being certified by an energy efficiency program that required air leakage testing and performance to a stated maximum leakage. Note again that the histograms are set up to display tighter statistics to the right of the diagram. A summary and interpretation section of key findings is included after each set of charts and tables. The compliance rates and averages are computed for garden-style and common-entry buildings combined. Results by building type and more extensive interpretation of results are included in Section 4.

The 2012, 2015, and 2018 versions of the IECC do not include a specification for maximum surface-area-normalized leakage (e.g., CFM_{50}/ft^2) and the conversion between ACH_{50} and CFM_{50}/ft^2 is not the same for every building since the conversion depends on the relationship between the building volume and surface area. For the whole building areas, the average multiplier was 0.130 to convert ACH_{50} and CFM_{50}/ft^2 (standard deviation = 0.021, range = 0.088 to 0.157). However, as of July 1, 2019, the State of Illinois energy code requires that the leakage rate for low-rise multifamily dwelling units does not exceed 0.25 CFM_{50}/ft^2, and there is a proposal for the State of Washington code to include an exception for garden-style dwelling units to have a leakage that does not exceed 0.40 CFM_{50}/ft^2. In addition, for buildings up to four stories, the 2018 version of PHIUS requires a whole building leakage no greater than 0.06 CFM_{50}/ft^2 of envelope surface area and individual dwelling unit leakage no greater than 0.30 CFM_{50}/ft^2. Finally, the USACE requires whole building leakage no greater than 0.25 CFM_{75}/ft^2, (USACE & ABAA 2012) which is approximately equal to 0.19 CFM_{50}/ft^2.

The relationship between ACH_{50} and CFM_{50}/ft^2 is discussed in detail in section 4.2.1 for whole buildings. The analysis there does not show full scatterplots of unit exterior and total leakage, but Figures 60 and 62 do show cumulative distributions of unit exterior and unit total – which provide a richer picture of the comparison.

[5] The whole building leakage for one of the Washington garden-style buildings is not included because not all of the units in the building were measured for the whole building test due to time constraints.

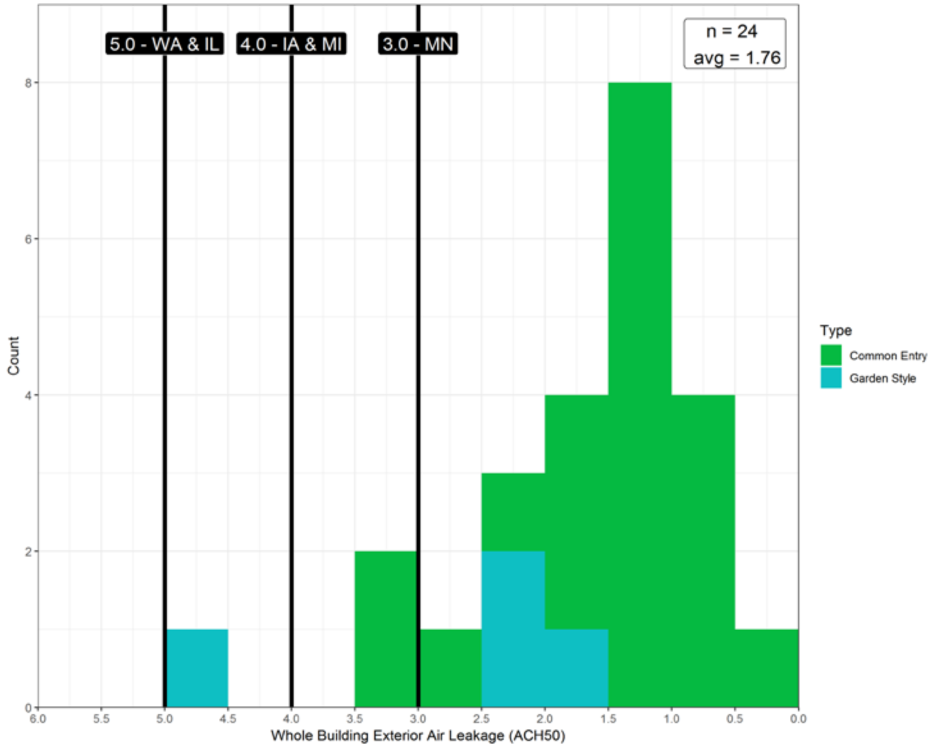


Figure 12. All Buildings: Whole Building Exterior Leakage

Table 5. Whole Building Exterior Leakage (ACH_{50})

					Compliance Rate vs ACH_{50}		
State	# Bldgs	Min	Max	Avg	3.0	4.0	5.0
Illinois	4	0.41	2.88	1.47	100%	100%	100%
Iowa	3	1.29	2.28	1.63	100%	100%	100%
Michigan	1	1.89	1.89	1.89	100%	100%	100%
Minnesota	12	0.95	2.23	1.34	100%	100%	100%
Oregon*	2	2.38	3.25	2.81	50%	100%	100%
Washington**	2	3.06	4.72	3.89	0%	50%	100%
Total	24	0.41	4.72	1.61	92%	96%	100%

*Oregon code does not require an air leakage test.

**One Washington building was tested before it had been issued a Certificate of Occupancy; it was the leakiest building in the study.

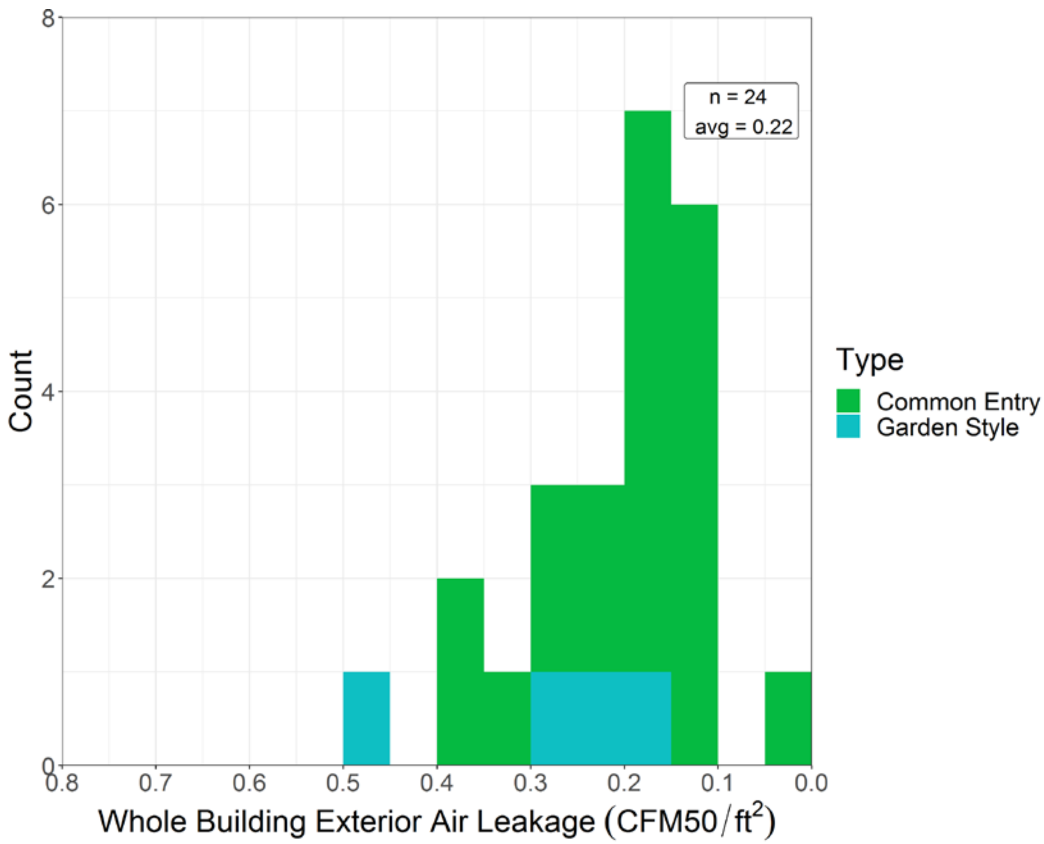


Figure 13. All Buildings: Whole Building Exterior Leakage

Table 6. Whole Building Exterior Leakage (CFM_{50}/ft^2)

					% of cases below shown CFM_{50}/ft^2			
State	# Bldgs	Min	Max	Avg	0.20	0.25	0.30	0.40
Illinois	4	0.05	0.38	0.18	75%	75%	75%	100%
Iowa	3	0.19	0.34	0.24	67%	67%	67%	100%
Michigan	1	0.28	0.28	0.28	0%	0%	100%	100%
Minnesota	12	0.13	0.24	0.18	75%	100%	100%	100%
Oregon	2	0.28	0.37	0.33	0%	0%	50%	100%
Washington	2	0.27	0.47	0.37	0%	0%	50%	50%
Total	24	0.05	0.47	0.23	58%	71%	83%	96%

Summary and interpretation:

- There was a 100% compliance rate for whole building volume-normalized exterior leakage. Only three of the buildings had a leakage rate greater than 3.0 ACH_{50}, and the overall average was 1.61 ACH_{50}.

- The highest state-average volume-normalized leakages of 2.81 and 3.89 ACH_{50} occurred for Oregon and Washington, respectively. There was no leakage testing required by code in Oregon, and Washington had the highest allowable leakage rate of 5.0 ACH_{50}.
- A total of 83% of the buildings had a whole building surface-area-normalized leakage rate less than 0.30 CFM_{50}/ft^2, and 58% were below the USACE requirement of 0.19 CFM_{50}/ft^2.

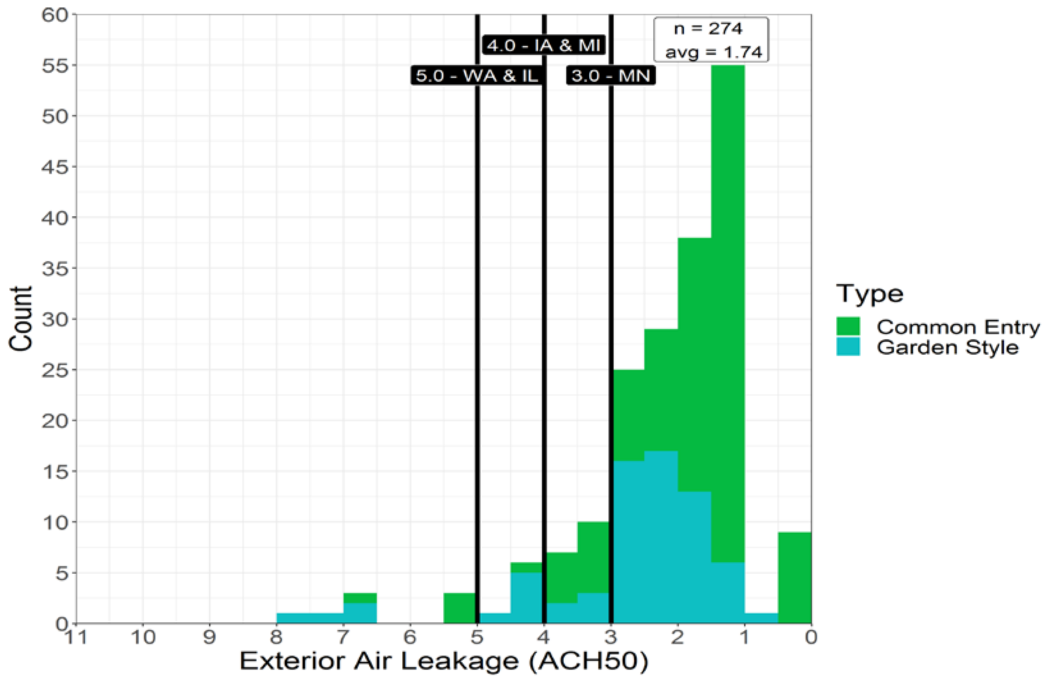


Figure 14 All Units: Unit Exterior Leakage

Table 7. Unit Exterior Leakage (ACH_{50})

					Compliance Rate vs ACH_{50}		
State	# Units	Min	Max	Avg	3.0	4.0	5.0
Illinois	31	0.25	3.79	1.33	90%	100%	100%
Iowa	30	0.78	2.18	1.37	100%	100%	100%
Michigan	12	0.60	3.10	1.41	92%	100%	100%
Minnesota	144	0.35	3.25	1.35	98%	100%	100%
Oregon	23	1.07	6.76	2.62	74%	96%	96%
Washington	34	1.33	7.81	3.58	44%	59%	79%
Total	274	0.25	7.81	1.74	88%	95%	97%

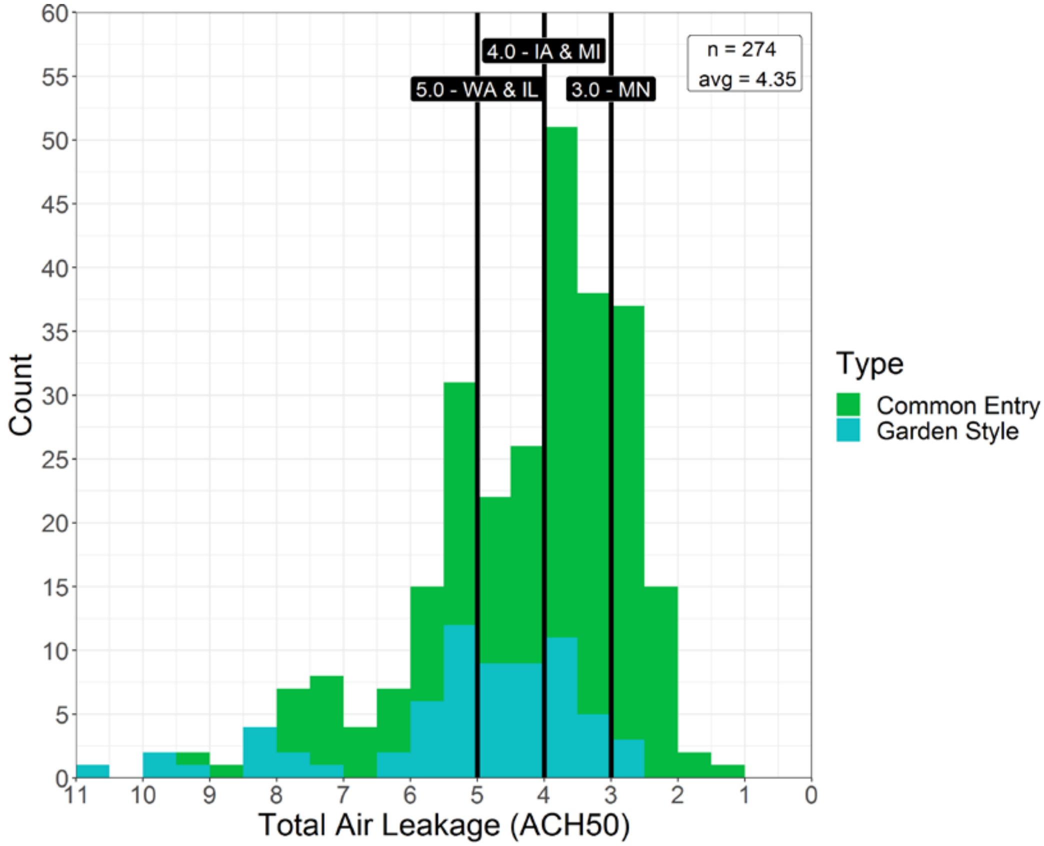


Figure 15. All Units: Unit Total Leakage (ACH_{50})

Table 8. Unit Total Leakage (ACH_{50})

					Compliance Rate vs ACH_{50}		
State	# Units	Min	Max	Avg	3.0	4.0	5.0
Illinois	31	1.45	6.48	4.32	10%	35%	61%
Iowa	30	3.82	9.32	5.81	0%	7%	37%
Michigan	12	2.54	3.89	3.15	50%	100%	100%
Minnesota	144	1.79	6.02	3.60	29%	74%	90%
Oregon	23	2.42	8.50	4.67	17%	43%	61%
Washington	34	3.02	10.71	6.50	0%	6%	21%
Total	274	1.45	10.71	4.35	20%	53%	70%

Summary and interpretation:

- The average exterior envelope volume-normalized leakage for all 274 units was 1.74 ACH_{50}. The state average values were very similar for Illinois, Iowa, Michigan, and Minnesota (range = 1.33 to 1.41 ACH_{50}). Similar to the whole building results, the average exterior leakage for units was much higher for Oregon (2.62 ACH_{50}) and Washington (3.58 ACH_{50}). The average exterior leakage for the units in Oregon and Washington were 2.3 times greater than the average for the four Midwest states.

- There was a 96% compliance rate for exterior volume-normalized leakage for the 251 units tested in the five states with an air leakage code requirement. There was a 100% compliance rate for the units in three of the states (Illinois, Iowa, and Michigan) and a 98% rate for Minnesota. The compliance rate would have been 90% or greater for Illinois, Iowa, and Michigan even if the requirement was 3.0 ACH_{50} in those states. The compliance rate for Washington was 79% even though the State's requirement was 5.0 ACH_{50}.
- The average total envelope volume-normalized leakage for all 274 units was 4.35 ACH_{50}. The total leakage is higher than the exterior leakage because the total includes both exterior and interior leakage. There was greater variability in the average total leakage by state, and the overall average for the units in Oregon and Washington was only 1.3 times greater than the average for the four Midwest states. As will be discussed in Section 4, the units in garden-style buildings had lower levels of interior leakage than did common-entry buildings, and the garden-style buildings are more prevalent in Oregon and Washington.
- There was a 33% compliance rate for total volume-normalized leakage for the 251 units tested in the five states with an air leakage code requirement. There was a 100% compliance rate for the 12 units in the one Michigan building. Illinois was the only other state that had a compliance rate greater than 50%. Minnesota, Washington, and Iowa had rates of 29%, 21%, and 7%, respectively. This demonstrates that is it significantly more challenging to meet the code required leakage values for individual units when the required level is applied to total leakage instead of only exterior leakage.

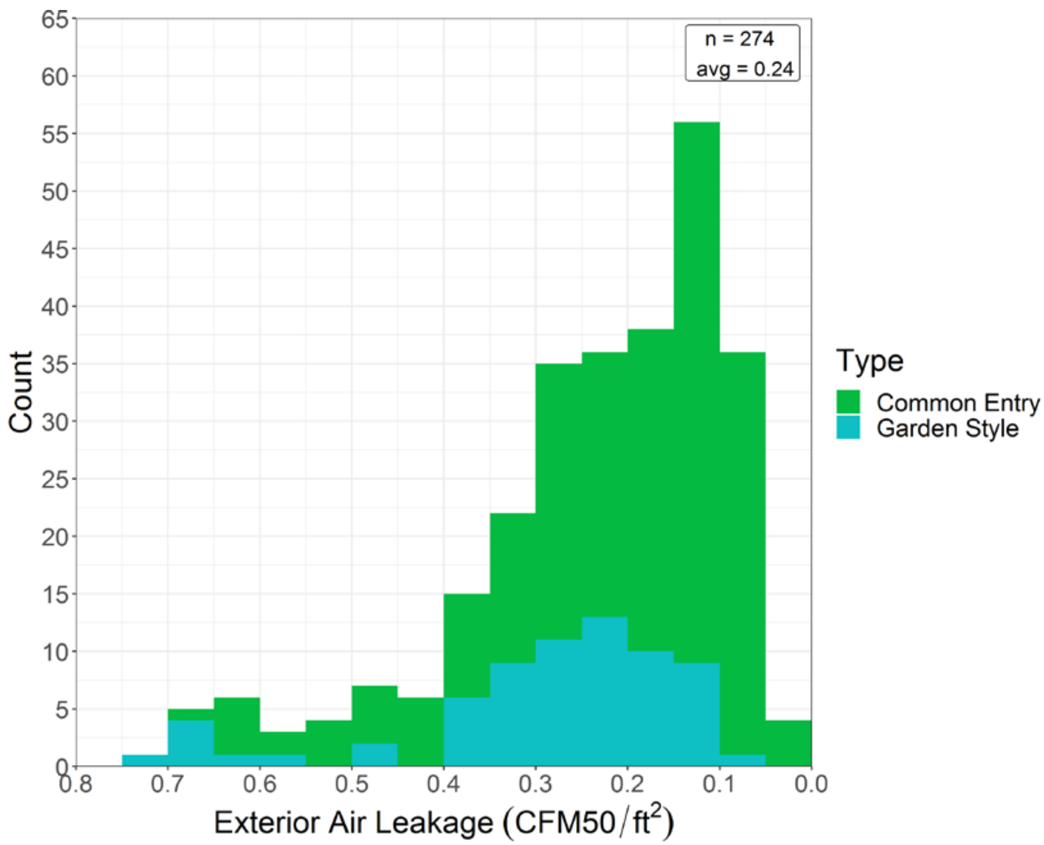


Figure 16. All Units: Unit Exterior Leakage (CFM_{50}/ft^2)

Table 9. Unit Exterior Leakage (CFM_{50}/ft^2)

					Compliance Rate vs CFM_{50}/ft^2			
State	# Units	Min	Max	Avg	0.20	0.25	0.30	0.40
Illinois	31	0.04	0.63	0.19	68%	74%	77%	87%
Iowa	30	0.09	0.65	0.25	57%	63%	73%	87%
Michigan	12	0.08	0.34	0.22	33%	42%	83%	100%
Minnesota	144	0.06	0.60	0.20	57%	71%	83%	94%
Oregon	23	0.11	0.67	0.36	9%	43%	61%	70%
Washington	34	0.11	0.75	0.34	24%	32%	47%	74%
Total	274	0.04	0.75	0.24	49%	62%	75%	88%

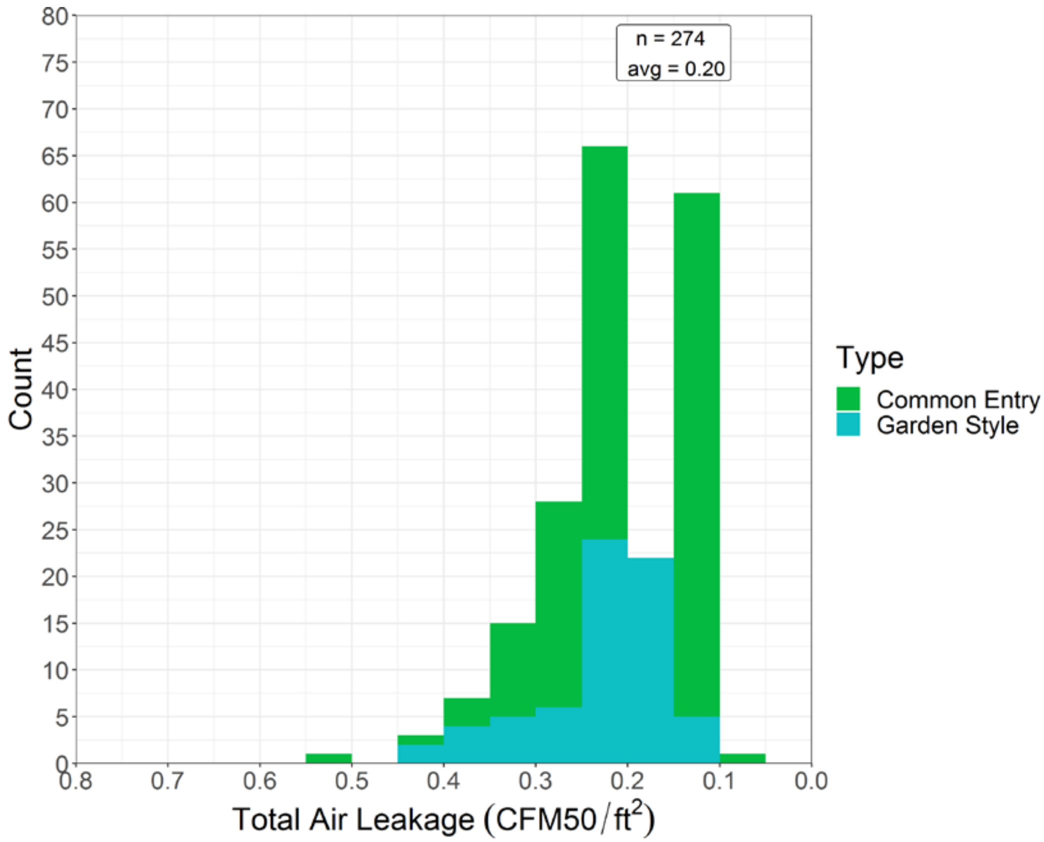


Figure 17. All Units: Unit Total Leakage (CFM_{50}/ft^2)

Table 10. Unit Total Leakage (CFM_{50}/ft^2)

					Compliance Rate vs CFM_{50}/ft^2			
State	# Units	Min	Max	Avg	0.20	0.25	0.30	0.40
Illinois	31	0.07	0.28	0.21	32%	84%	100%	100%
Iowa	30	0.17	0.52	0.29	3%	30%	63%	93%
Michigan	12	0.12	0.18	0.15	100%	100%	100%	100%
Minnesota	144	0.10	0.29	0.17	78%	97%	100%	100%
Oregon	23	0.13	0.33	0.21	57%	78%	87%	100%
Washington	34	0.13	0.44	0.28	15%	44%	65%	94%
Total	274	0.07	0.52	0.24	56%	80%	91%	99%

Summary and interpretation:

- A total of 56% of the units had a total (interior and exterior) surface-area-normalized leakage rate less than 0.20 CFM_{50}/ft^2, 80% had a leakage less than the State of Illinois requirement of 0.25 CFM_{50}/ft^2, and 99% were below the proposed State of Washington leakage of 0.40 CFM_{50}/ft^2. The compliance for a leakage of 0.25 CFM_{50}/ft^2 was greatest for Michigan (100%), Minnesota (97%), Illinois (84%), and Oregon (78%). The average for all of the units was 0.24 CFM_{50}/ft^2.
- A total of 49% of the units had an exterior surface-area-normalized leakage rate less than 0.20 CFM_{50}/ft^2, 62% had a leakage less than the State of Illinois requirement of 0.25 cfm_{50}/ft^2, and 88% were below the proposed State of Washington leakage of 0.40 CFM_{50}/ft^2. The compliance for a leakage of 0.25 CFM_{50}/ft^2 was greatest for Illinois (74%), Minnesota (71%), and Iowa (63%). The average for all of the units was 0.24 CFM_{50}/ft^2. The compliance rates were somewhat lower for exterior than total leakage because there are some units (e.g., the ones in Michigan) that had a higher surface-area-normalized leakage for the exterior portion of the envelope than the interior portion.

3.2 State Results

This section contains results for each of the six states. The organization of the charts, tables, and description of the results is the same as that used for the previous section for all 25 buildings.

3.2.1 Illinois

In Illinois, 31 units were tested in four common-entry buildings. There were no garden-style buildings. The number of units per building ranged from six to 25 and averaged 12. The floor area of individual units that were tested ranged from 552 to 1,500 ft^2 and averaged 1,013 ft^2. The whole building floor area ranged from 8,155 to 22,636 ft^2 and averaged 12,384 ft^2. On average, the common areas were 13% of the building's floor area and 15% of the exterior envelope area. The southern portion of Illinois is in IECC Climate Zone 4 and the northern portion is in Zone 5. For the buildings tested for this project, the State of Illinois code required leakage was 5.0 ACH_{50}. However, as of July 1, 2019, the State of Illinois energy code requires that the leakage rate for low-rise multifamily dwelling units not exceed 0.25 CFM_{50}/ft^2. Three of the four buildings were being certified by an energy program that required air leakage testing. Two were going through ENERGY STAR® certification, and one was going through PHIUS certification.

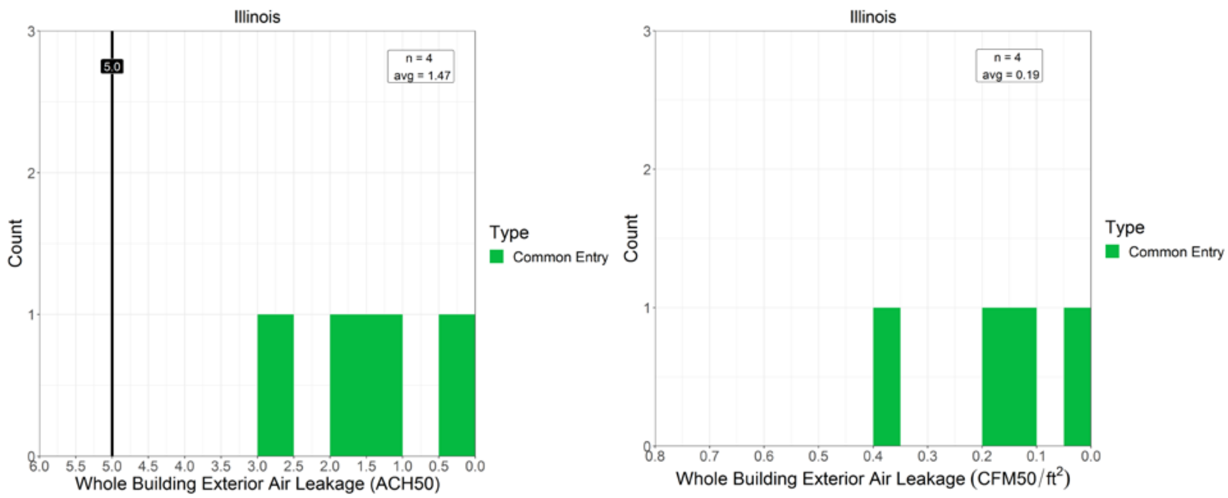


Figure 18. Illinois Whole Building Exterior Leakage

Table 11. Illinois Whole Building Exterior Leakage

Leakage	**(ACH_{50})**		**(CFM_{50}/ft^2)**
Number	4	*Number*	4
Range	0.41 to 2.88	*Range*	0.05 to 0.38
Average	1.47	*Average*	0.18
Compliance Rate (3.0)	4 of 4 (100%)	*Compliance Rate (0.20)*	3 of 4 (75%)
Compliance Rate (4.0)	4 of 4 (100%)	*Compliance Rate (0.25)*	3 of 4 (75%)
Compliance Rate (5.0)	**4 of 4 (100%)**	*Compliance Rate (0.30)*	3 of 4 (75%)
		Compliance Rate (0.40)	4 of 4 (100%)

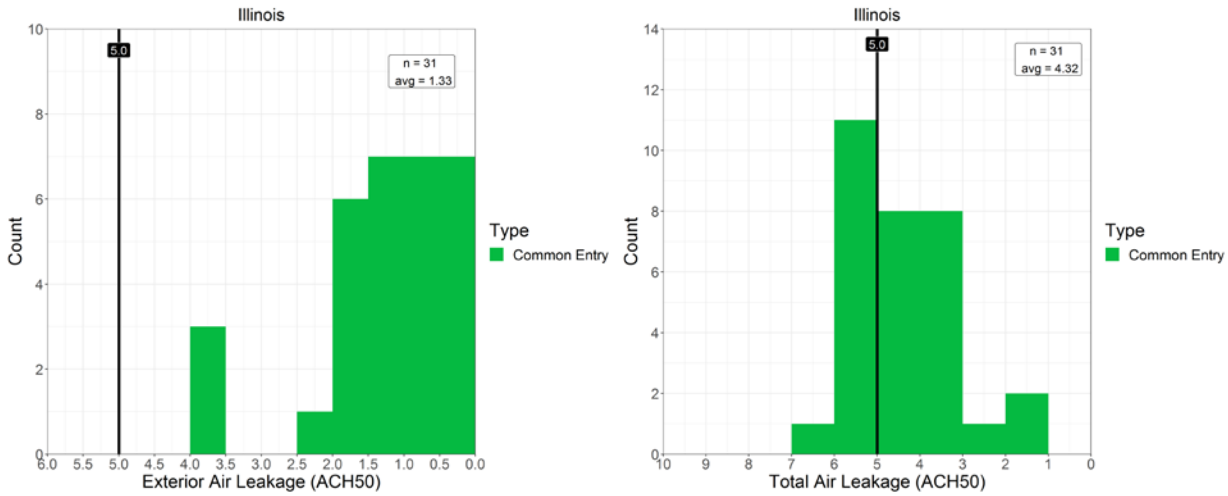


Figure 19. Illinois Unit Leakage (ACH_{50}): Exterior (left) and Total (right)

Table 12. Illinois Unit Leakage (ACH_{50})

Building Type	Exterior	Total
Number	31	31
Range	0.25 to 3.79	1.45 to 6.48
Average	1.33	4.32
Compliance Rate (3.0)	28 of 31 (90%)	3 of 31 (10%)
Compliance Rate (4.0)	31 of 31 (100%)	11 of 31 (35%)
Compliance Rate (5.0)	**31 of 31 (100%)**	**19 of 31 (61%)**

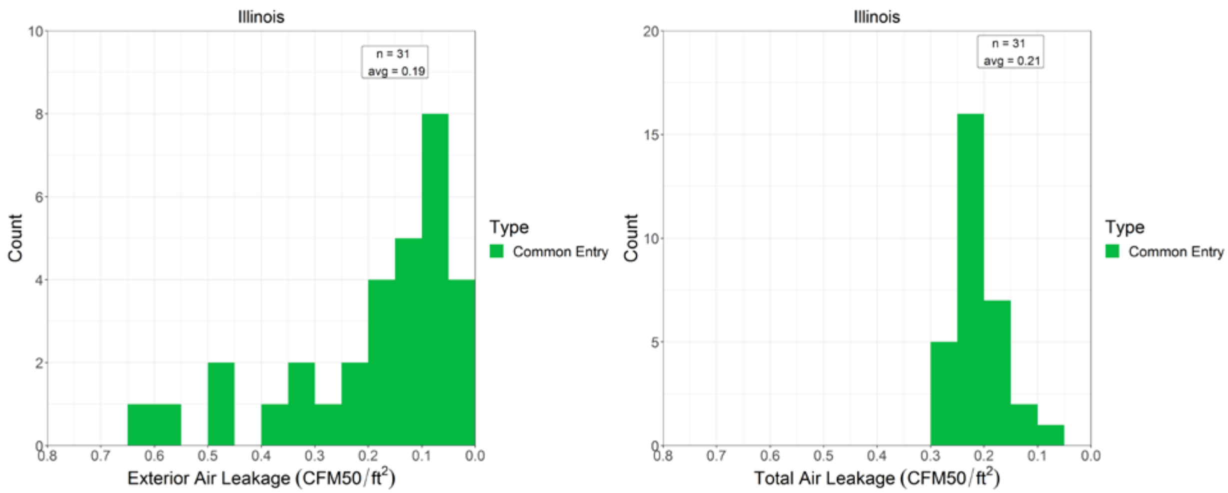


Figure 20. Illinois Unit Leakage (CFM_{50}/ft^2). Exterior (left) and Total (right)

Table 13. Illinois Unit Leakage (CFM_{50}/ft^2)

Building Type	Exterior	Total
Number	31	31
Range	0.04 to 0.63	0.07 to 0.28
Average	0.19	0.21
Compliance Rate (0.20)	21 of 31 (68%)	10 of 31 (32%)
Compliance Rate (0.25)	23 of 31 (74%)	26 of 31 (84%)
Compliance Rate (0.30)	24 of 31 (77%)	31 of 31 (100%)
Compliance Rate (0.40)	27 of 31 (87%)	31 of 31 (100%)

Summary and interpretation:

- All four buildings had a whole building exterior volume-normalized leakage rate below the requirement of 5.0 ACH_{50} that was in effect in Illinois when these buildings were constructed. In addition, all four buildings had a whole building leakage less than 3.0 ACH_{50}, and the average was 1.47 ACH_{50}.
- Three of the four buildings had a whole building surface-area-normalized leakage rate less than the USACE requirement of 0.19 CFM_{50}/ft^2. The leakage for the fourth building was 0.38 CFM_{50}/ft^2, and the overall average was 0.19 CFM_{50}/ft^2.
- When a guarded test was used to measure the exterior leakage of the units, 100% of the units complied with the volume-normalized leakage requirement of 5.0 ACH_{50}, 90% were less than 3.0 ACH_{50}, and the average was 1.33 ACH_{50}.
- When the more common compartmentalization test was used to measure total unit leakage, 19 of the 31 units (61%) complied with the volume-normalized leakage requirement of 5.0 ACH_{50}, only 10% were below 3.0 ACH_{50}, and the average leakage was 4.32 ACH_{50} — 3.2 times greater than the average for the exterior

leakage. Adding the interior leakage to the exterior significantly reduces the rate of compliance with the leakage requirement for individual units.

- A total of 74% of the units had an exterior surface-area-normalized leakage rate less than the new State of Illinois requirement of 0.25 CFM_{50}/ft^2, 77% had a leakage less than 0.30 CFM_{50}/ft^2, and 87% were below 0.40 CFM_{50}/ft^2.
- A total of 84% had a total surface-area-normalized leakage less than the new State of Illinois requirement of 0.25 CFM_{50}/ft^2, and 100% were below 0.30 CFM_{50}/ft^2. The average for all of the units was 0.21 CFM_{50}/ft^2. The compliance rates were somewhat higher for total leakage because some of the units had a lower surface-area-normalized leakage of the interior portion of the envelope.

3.2.2 Iowa

In Iowa, 30 units in three common-entry buildings were tested. There were no garden-style buildings. The number of units per building ranged from 30 to 36 and averaged 32. The floor area of individual units that were tested ranged from 721 to 1,142 ft^2 and averaged 901 ft^2. The whole building floor area ranged from 25,072 to 41,510 ft^2 and averaged 33,265 ft^2. On average, the common areas were 18% of the building's floor area and 15% of the exterior envelope area. All test sites were in the southern portion of Iowa, which is IECC Climate Zone 5. For the buildings tested for this project, the State of Iowa code required leakage was 4.0 ACH50. All three buildings were being certified by a program that required air leakage testing. Two were going through ENERGY STAR certification, and one was going through an Iowa Finance Authority program.

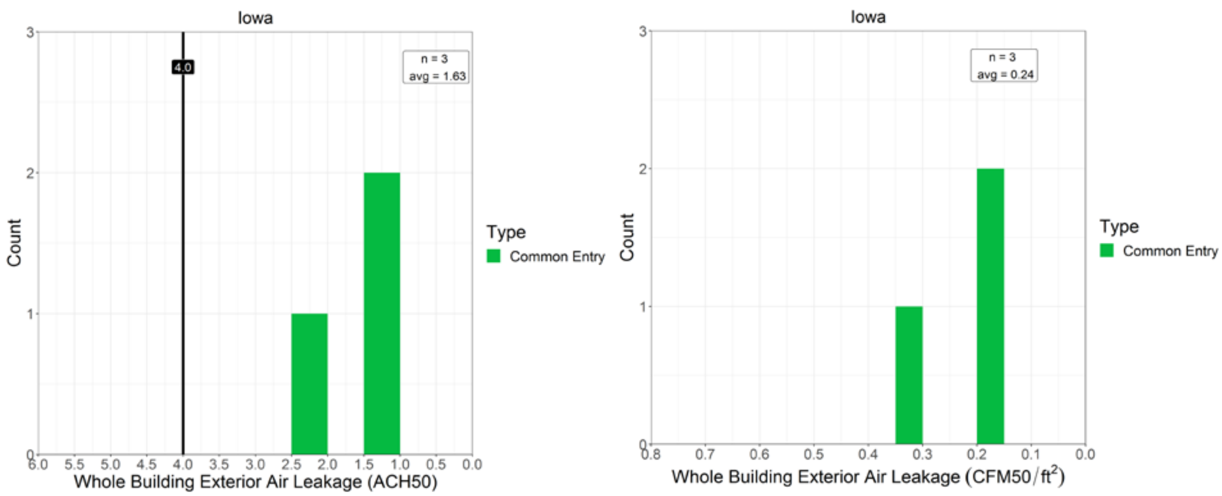


Figure 21. Iowa Whole Building Exterior Leakage

Table 14. Iowa Whole Building Exterior Leakage

Leakage Type	**(ACH_{50})**		**(CFM_{50}/ft^2)**
Number	3	*Number*	3
Range	1.29 to 2.28	*Range*	0.19 to 0.34
Average	1.63	*Average*	0.24
Compliance Rate (3.0)	3 of 3 (100%)	*Compliance Rate (0.20)*	2 of 3 (67%)
Compliance Rate (4.0)	**3 of 3 (100%)**	*Compliance Rate (0.25)*	2 of 3 (67%)
Compliance Rate (5.0)	3 of 3 (100%)	*Compliance Rate (0.30)*	2 of 3 (67%)
		Compliance Rate (0.40)	3 of 3 (100%)

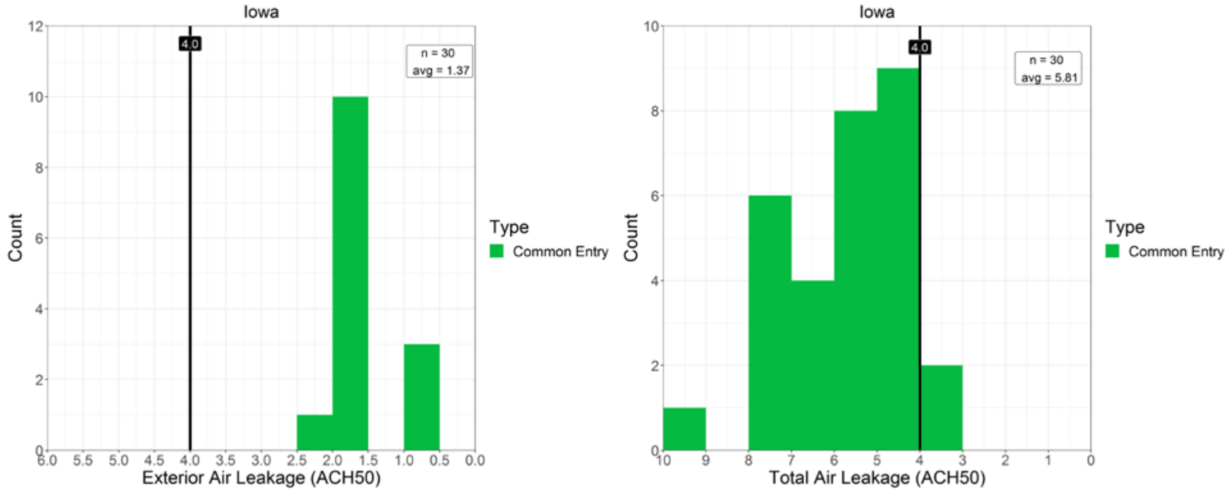


Figure 22. Iowa Unit Leakage (ACH_{50})

Table 15. Iowa Unit Leakage (ACH_{50})

Building Type	Exterior	Total
Number	30	30
Range	0.78 to 2.18	3.82 to 9.32
Average	1.37	5.81
Compliance Rate (3.0)	30 of 30 (100%)	0 of 30 (0%)
Compliance Rate (4.0)	**30 of 30 (100%)**	**2 of 30 (7%)**
Compliance Rate (5.0)	30 of 30 (100%)	11 of 30 (37%)

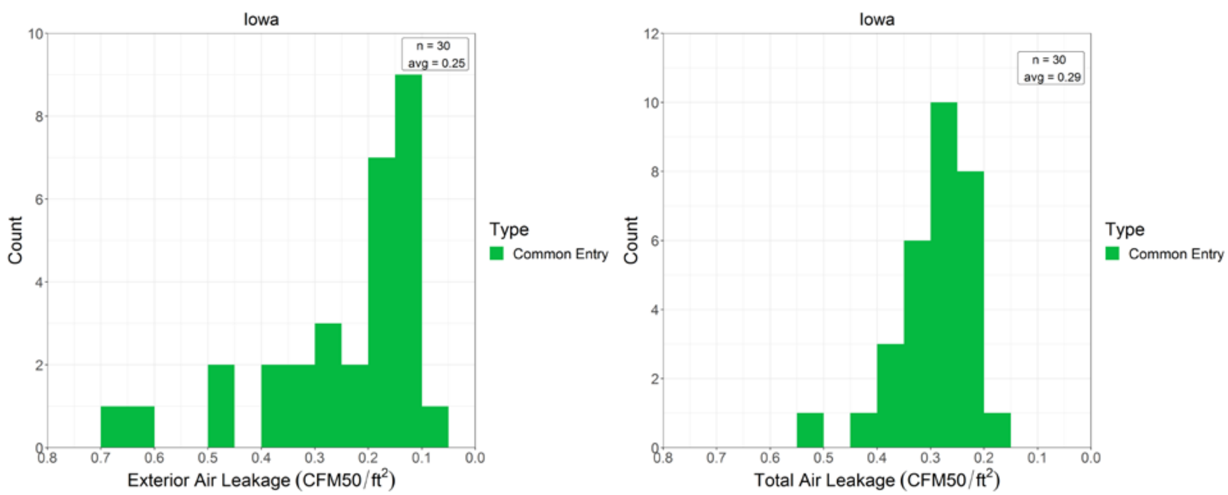


Figure 23. Iowa Unit Leakage (CFM_{50}/ft^2)

Table 16. Iowa Unit Leakage (CFM_{50}/ft^2)

Building Type	Exterior	Total
Number	30	30
Range	0.09 to 0.65	0.17 to 0.52
Average	0.25	0.29
Compliance Rate (0.20)	17 of 30 (57%)	1 of 30 (3%)
Compliance Rate (0.25)	19 of 30 (63%)	9 of 30 (30%)
Compliance Rate (0.30)	22 of 30 (73%)	19 of 30 (63%)
Compliance Rate (0.40)	26 of 30 (87%)	28 of 30 (93%)

Summary and interpretation:

- All three buildings had a whole building exterior volume-normalized leakage rate below the requirement of 4.0 ACH_{50}. In addition, all three buildings had a whole building leakage less than 3.0 ACH_{50}, and the average was 1.63 ACH_{50}.
- Two of the three buildings had a whole building surface-area-normalized leakage rate equal to the USACE requirement of 0.19 CFM_{50}/ft^2. The leakage for the third building was 0.34 CFM_{50}/ft^2, and the overall average was 0.24 CFM_{50}/ft^2.
- When a guarded test was used to measure the exterior leakage of the units, 100% of the units complied with the volume-normalized leakage requirement of 4.0 ACH_{50}, 100% were less than 3.0 ACH_{50}, and the average was 1.37 ACH_{50}.
- When the more common compartmentalization test was used to measure total unit volume-normalized leakage, two of the 30 units (7%) complied with the leakage requirement of 4.0 ACH_{50}, none were below 3.0 ACH_{50}, and the average leakage was 5.81 ACH_{50} — 4.3 times greater than the average for the exterior leakage. Adding the interior leakage to the exterior significantly reduces the rate of compliance with the leakage requirement for individual units.
- A total of 63% of the units had an exterior surface-area-normalized leakage rate less than 0.25 CFM_{50}/ft^2, 73% had a leakage less than 0.30 CFM_{50}/ft^2, and 87% were below 0.40 CFM_{50}/ft^2. The average for all of the units was 0.25 CFM_{50}/ft^2.
- A total of 30% had a total surface-area-normalized leakage less than 0.25 CFM_{50}/ft^2, and 63% were below 0.30 CFM_{50}/ft^2. The average for all of the units was 0.29 CFM_{50}/ft^2. The compliance rates were somewhat lower for total leakage because some of the units had a higher surface-area-normalized leakage of the interior portion of the envelope.

3.2.3 Michigan

In Michigan, 12 units in one 48-unit, common-entry building were tested. The floor area of individual units that were tested ranged from 726 to 971 ft^2 and averaged 843 ft^2. The whole building floor area was 54,208 ft^2. The common area was 26% of the building's floor area and 29% of the exterior envelope area. This building was located in Climate Zone 5.

For the building tested for this project the State of Michigan code required leakage was 4.0 ACH_{50}. The building was going through ENERGY STAR certification.

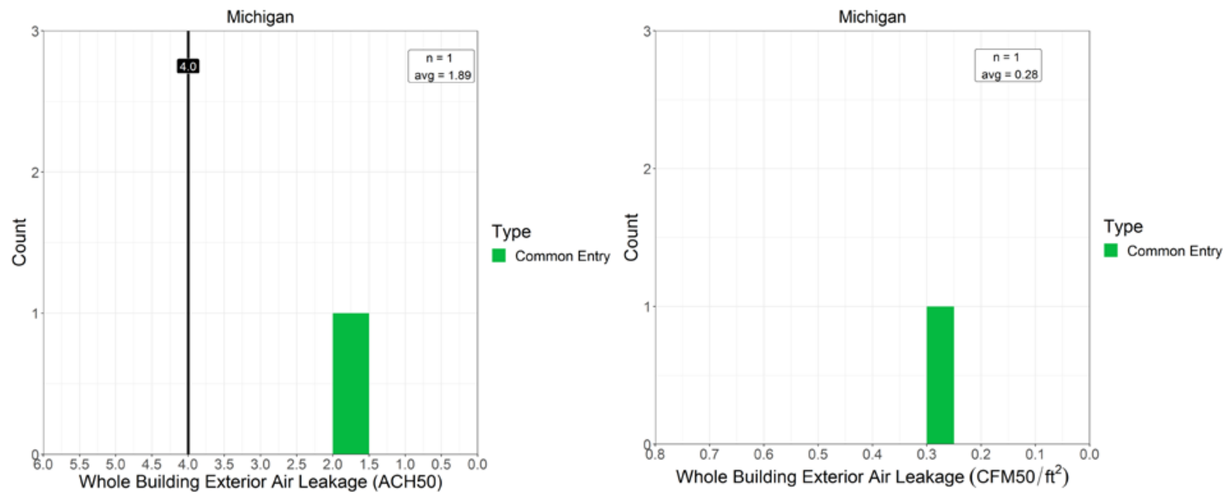


Figure 24. Michigan Whole Building Exterior Leakage

Table 17. Michigan Whole Building Exterior Leakage

Leakage Type	**(ACH_{50})**		**(CFM_{50}/ft^2)**
Number	1	*Number*	1
Range	1.89	*Range*	0.28
Average	1.89	*Average*	0.28
Compliance Rate (3.0)	1 of 1 (100%)	*Compliance Rate (0.20)*	0 of 1 (0%)
Compliance Rate (4.0)	**1 of 1 (100%)**	*Compliance Rate (0.25)*	0 of 1 (0%)
Compliance Rate (5.0)	1 of 3 (33%)	*Compliance Rate (0.30)*	1 of 1 (100%)
		Compliance Rate (0.40)	1 of 1 (100%)

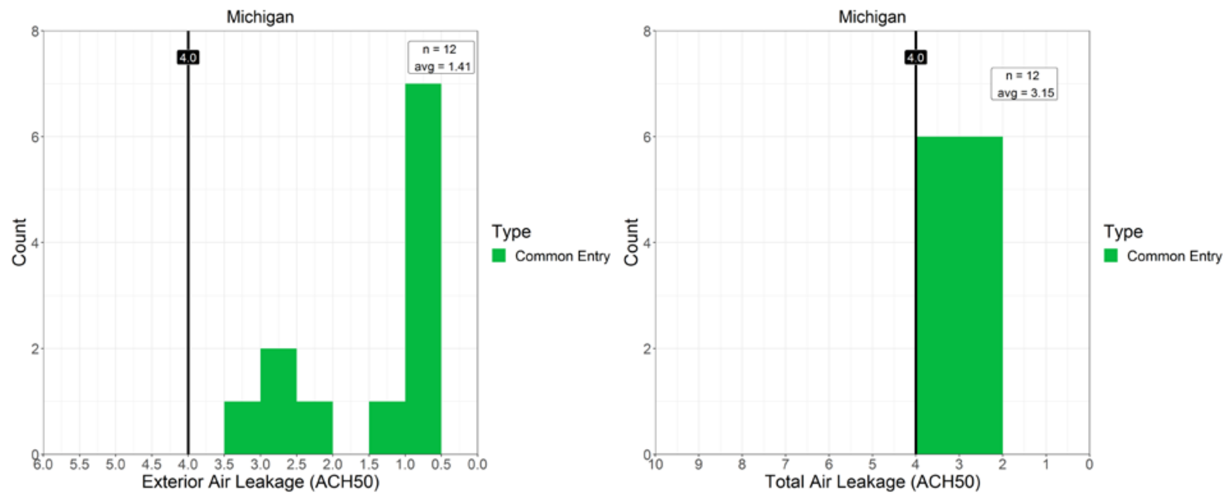


Figure 25. Michigan Unit Leakage (ACH_{50})

Table 18. Michigan Unit Leakage (ACH_{50}): Exterior (left) and Total (right)

Building Type	**Exterior**	**Total**
Number	12	12
Range	0.60 to 3.10	2.54 to 3.89
Average	1.41	3.15
Compliance Rate (3.0)	11 of 12 (92%)	6 of 12 (50%)
Compliance Rate (4.0)	**12 of 12 (100%)**	**12 of 12 (100%)**
Compliance Rate (5.0)	12 of 12 (100%)	12 of 12 (100%)

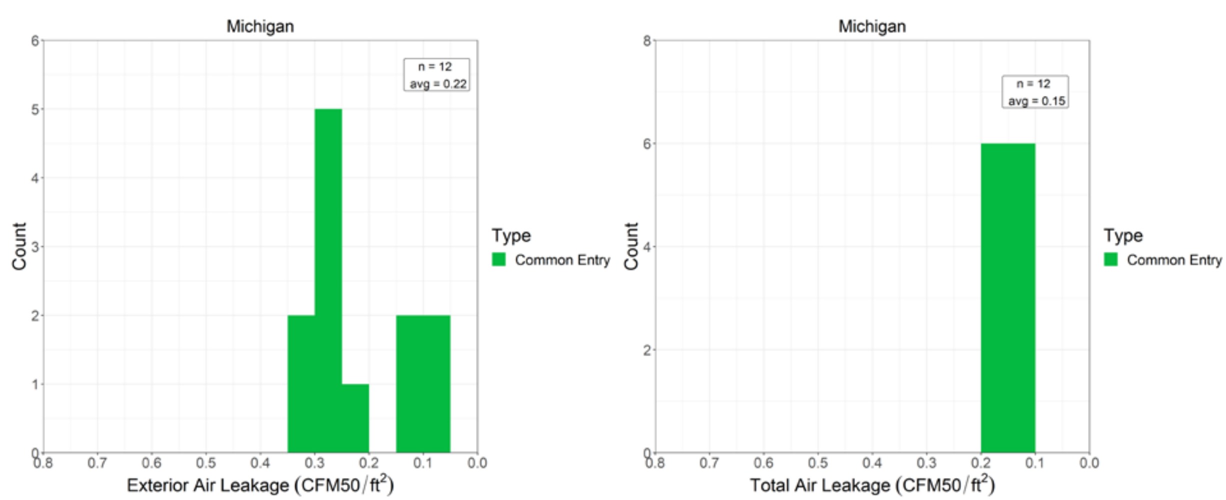


Figure 26. Michigan Unit Leakage (CFM_{50}/ft^2)

Table 19. Michigan Unit Leakage (CFM_{50}/ft^2)

Building Type	Exterior	Total
Number	12	12
Range	0.08 to 0.34	0.12 to 0.18
Average	0.22	0.15
Compliance Rate (0.20)	4 of 12 (33%)	12 of 12 (100%)
Compliance Rate (0.25)	5 of 12 (42%)	12 of 12 (100%)
Compliance Rate (0.30)	10 of 12 (83%)	12 of 12 (100%)
Compliance Rate (0.40)	12 of 12 (100%)	12 of 12 (100%)

Summary and interpretation:

- The building had a whole building exterior volume-normalized leakage rate of 1.89 ACH_{50}., which is 53% below the code requirement of 4.0 ACH_{50}.
- The building had a whole building surface-area-normalized leakage rate of 0.28 CFM_{50}/ft^2, which is 48% greater than the USACE requirement of 0.19 CFM_{50}/ft^2.
- When a guarded test was used to measure the exterior volume-normalized leakage of the units, 100% of the units complied with the leakage requirement of 4.0 ACH_{50}, 92% were less than 3.0 ACH_{50}, and the average was 1.41 ACH_{50}.
- When the more common compartmentalization test was used to measure total unit leakage, all of the units complied with the volume-normalized leakage requirement of 4.0 ACH_{50}, 50% were below 3.0 ACH_{50}, and the average leakage was 3.15 ACH_{50} — 2.2 times greater than the average for the exterior leakage. Adding the interior leakage to the exterior did not impact the rate of compliance for the individual units.
- A total of 42% of the units had an exterior surface-area-normalized leakage rate less than 0.25 CFM_{50}/ft^2, 83% had a leakage less than 0.30 CFM_{50}/ft^2, and 100% were below 0.40 CFM_{50}/ft^2. The average for all of the units was 0.22 CFM_{50}/ft^2.
- All of the units had a total surface-area-normalized leakage less than 0.25 CFM_{50}/ft^2 and the average for all of the units was 0.15 CFM_{50}/ft^2. The compliance rates were somewhat higher for total leakage because some of the units had a lower surface-area-normalized leakage of the interior portion of the envelope.

3.2.4 Minnesota

A total of 32 units in two garden-style buildings and 112 units in 10 common-entry buildings were tested. The two garden-style buildings each had 12 units. For common-entry buildings, the number of units per building ranged from 10 to 60 and averaged 40. The floor area of individual units that were tested ranged from 405 to 1,489 ft^2 and averaged 972 ft^2. The whole building floor areas ranged from 9,056 to 72,721 ft^2 and averaged 40,463 ft^2. For the common-entry buildings, the common areas were 25% of the building's floor area and 26% of the exterior envelope area on average. The southern portion of Minnesota is in Climate Zone 6 (Cold) and the northern portion is in Zone 7 (Very cold). Only one of the tested buildings was in Zone 7. For the buildings tested for this project, the State of Minnesota code required leakage was 3.0 ACH_{50}. Nine of the twelve buildings were going through ENERGY STAR certification.

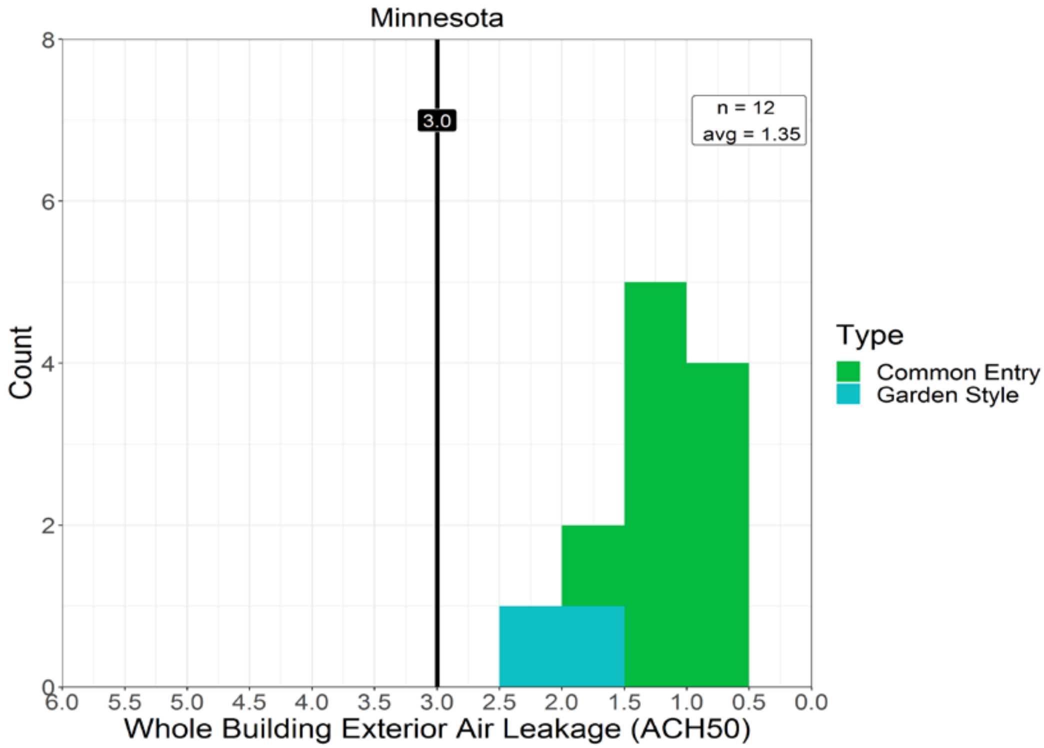


Figure 27. Minnesota Whole Building Exterior Leakage (ACH_{50})

Table 20. Minnesota Whole Building Exterior Leakage (ACH_{50})

Building Type	Common Entry	Garden-Style	Statewide
Number	10	2	12
Range	0.95 to 1.61	1.97 to 2.23	0.95 to 2.23
Average	1.19	2.10	1.35
Compliance Rate (3.0)	**10 of 10 (100%)**	**2 of 2 (100%)**	**12 of 12 (100%)**
Compliance Rate (4.0)	10 of 10 (100%)	2 of 2 (100%)	12 of 12 (100%)
Compliance Rate (5.0)	10 of 10 (100%)	2 of 2 (100%)	12 of 12 (100%)

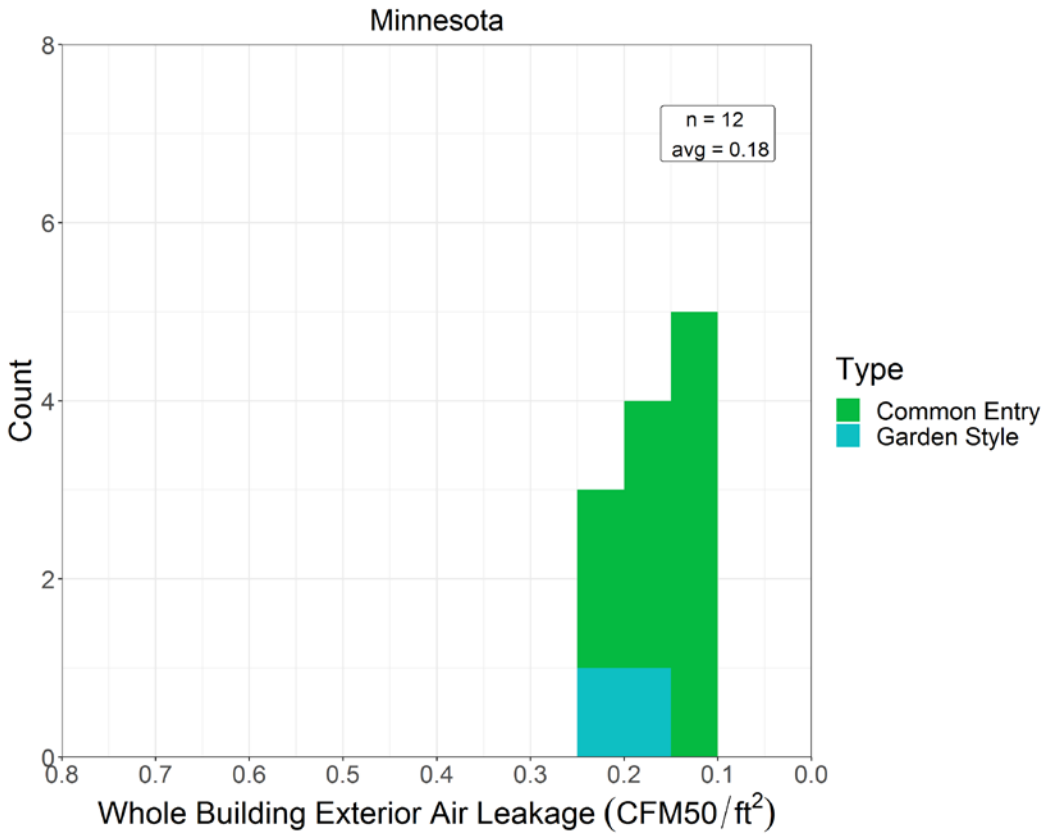


Figure 28. Minnesota Whole Building Exterior Leakage (CFM_{50}/ft^2)

Table 21. Minnesota Whole Building Exterior Leakage (CFM_{50}/ft^2)

Building Type	Common Entry	Garden-Style	Statewide
Number	10	2	12
Range	0.13 to 0.24	0.20 to 0.22	0.13 to 0.24
Average	0.17	0.21	0.18
Compliance Rate (0.20)	8 of 10 (80%)	1 of 2 (50%)	9 of 12 (75%)
Compliance Rate (0.25)	10 of 10 (100%)	2 of 2 (100%)	12 of 12 (100%)
Compliance Rate (0.30)	10 of 10 (100%)	2 of 2 (100%)	12 of 12 (100%)
Compliance Rate (0.40)	10 of 10 (100%)	2 of 2 (100%)	12 of 12 (100%)

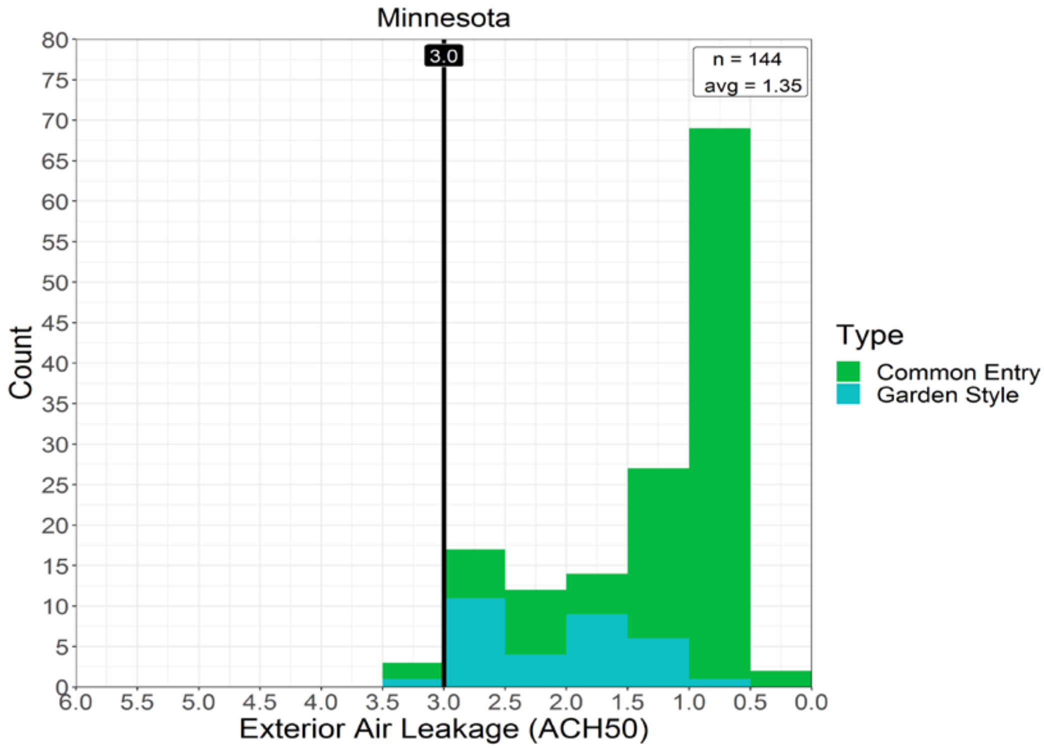


Figure 29. Minnesota Unit Exterior Leakage (ACH_{50}).

Table 22. Minnesota Unit Exterior Leakage (ACH_{50})

Building Type	**Common Entry**	**Garden-Style**	**Statewide**
Number	112	32	144
Range	0.35 to 3.25	0.91 to 3.05	0.35 to 3.25
Average	1.14	2.08	1.35
Compliance Rate (3.0)	**100 of 112 (98%)**	**31 of 32 (97%)**	**12 of 144 (100%)**
Compliance Rate (4.0)	112 of 112 (100%)	32 of 32 (100%)	114 of 114 (100%)
Compliance Rate (5.0)	112 of 112 (100%)	32 of 32 (100%)	114 of 114 (100%)

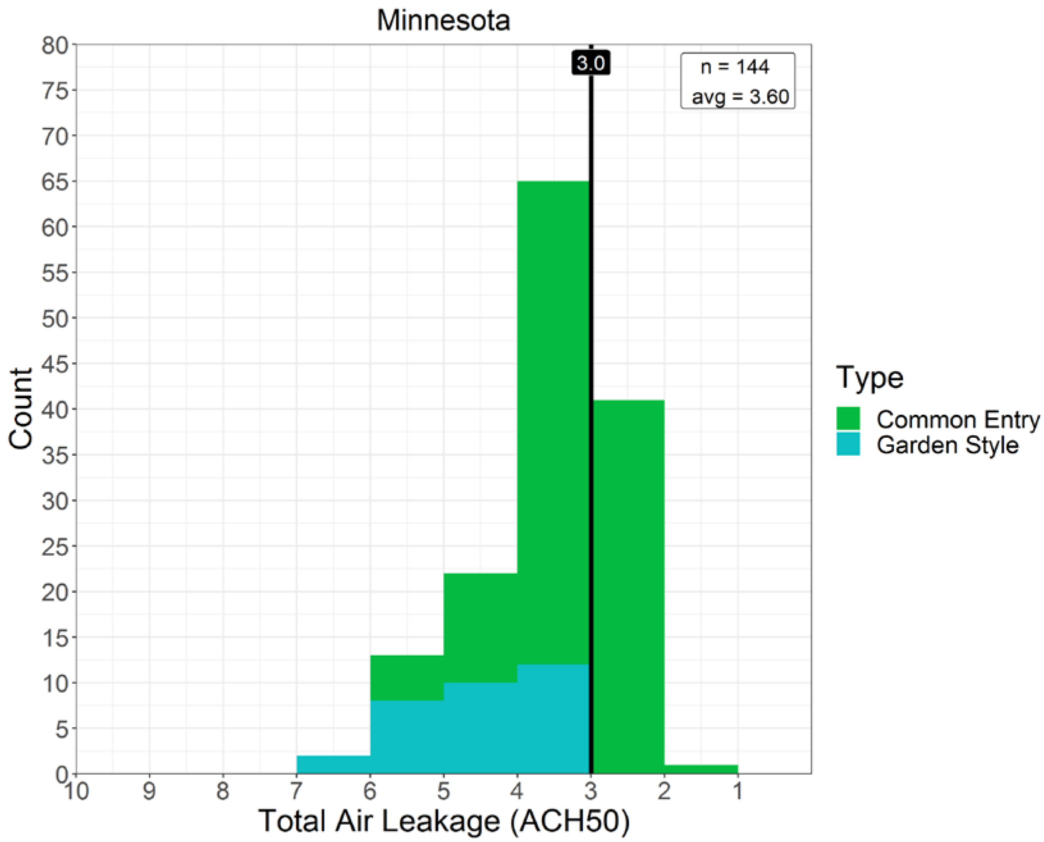


Figure 30. Minnesota Unit Total Leakage (ACH_{50})

Table 23. Minnesota Unit Total Leakage (ACH_{50})

Building Type	Common Entry	Garden-Style	Statewide
Number	112	32	144
Range	1.79 to 5.81	3.08 to 6.02	1.79 to 6.02
Average	3.35	4.47	3.60
Compliance Rate (3.0)	**42 of 112 (38%)**	**0 of 32 (0%)**	**42 of 144 (29%)**
Compliance Rate (4.0)	95 of 112 (85%)	12 of 32 (38%)	107 of 114 (74%)
Compliance Rate (5.0)	107 of 112 (96%)	22 of 32 (69%)	129 of 114 (90%)

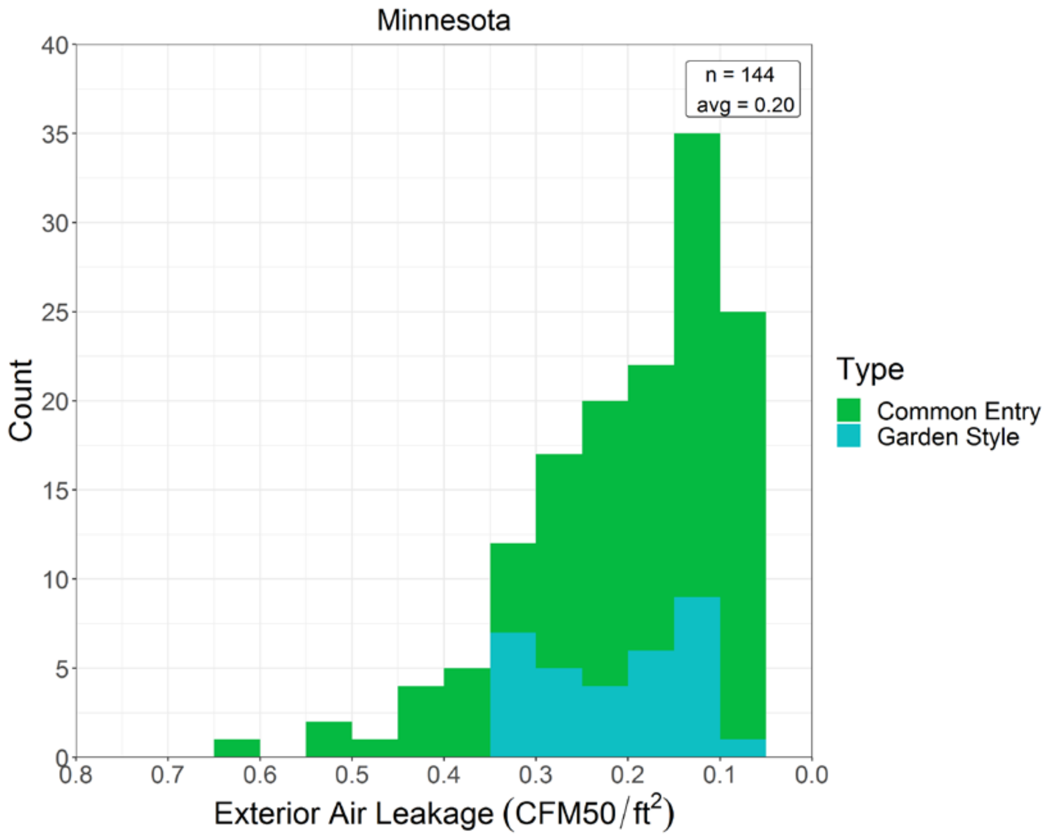


Figure 31. Minnesota Unit Exterior Leakage (CFM_{50}/ft^2)

Table 24. Minnesota Unit Exterior Leakage (CFM_{50}/ft^2)

Building Type	Common Entry	Garden-Style	Statewide
Number	112	32	144
Range	0.06 to 0.60	0.09 to 0.33	0.06 to 0.60
Average	0.20	0.21	0.20
Compliance Rate (0.20)	66 of 112 (59%)	16 of 32 (50%)	82 of 144 (57%)
Compliance Rate (0.25)	82 of 112 (73%)	20 of 32 (63%)	102 of 144 (71%)
Compliance Rate (0.30)	94 of 112 (84%)	25 of 32 (78%)	119 of 144 (83%)
Compliance Rate (0.40)	104 of 112 (93%)	32 of 32 (100%)	136 of 144 (94%)

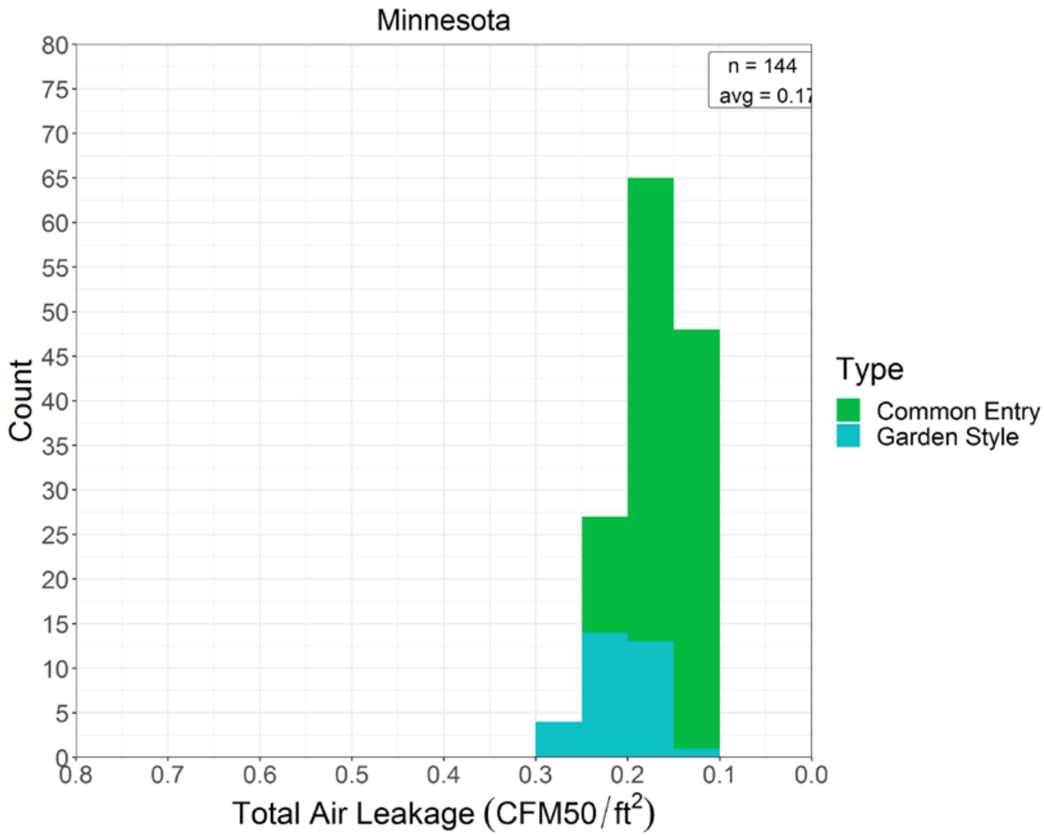


Figure 32. Minnesota Unit Total Leakage (CFM_{50}/ft^2)

Table 25. Minnesota Unit Total Leakage (CFM_{50}/ft^2)

Building Type	Common Entry	Garden-Style	Statewide
Number	112	32	144
Range	0.10 to 0.24	0.14 to 0.29	0.10 to 0.29
Average	0.16	0.21	0.17
Compliance Rate (0.20)	99 of 112 (88%)	14 of 32 (44%)	113 of 144 (78%)
Compliance Rate (0.25)	112 of 112 (100%)	28 of 32 (88%)	140 of 144 (97%)
Compliance Rate (0.30)	112 of 112 (100%)	32 of 32 (100%)	144 of 144 (100%)
Compliance Rate (0.40)	112 of 112 (100%)	32 of 32 (100%)	144 of 144 (100%)

Summary and interpretation:

- All 12 buildings (garden-style and common entry) had a whole building exterior volume-normalized leakage rate below the requirement of 3.0 ACH_{50} that was in effect in Minnesota when these buildings were constructed. The average leakage was 1.35 ACH_{50}. The two garden-style buildings had greater leakage than each of the 10 common-entry buildings. The average for the garden-style buildings was 2.10 ACH_{50} and the average for the common-entry buildings was 1.19 ACH_{50} (43% tighter).

- Seven of the 10 common-entry buildings and none of the garden-style buildings had a whole building surface-area-normalized leakage rate less than the USACE requirement of 0.19 CFM_{50}/ft^2. However, all of the buildings had a leakage less than 0.25 CFM_{50}/ft^2 and the overall average was 0.18 CFM_{50}/ft^2.
- When a guarded test was used to measure the exterior volume-normalized leakage of the units, 98% of the common-entry units and 97% of the garden-style units complied with the leakage requirement of 3.0 ACH_{50}. The average was 1.14 ACH_{50} for the common-entry units and 2.08 ACH_{50} for the garden-style units. The average for all of the units was 1.35 ACH_{50}.
- When the more common compartmentalization test was used to measure total unit volume-normalized leakage, 38% of the common-entry units and none of the garden-style units complied with the leakage requirement of 3.0 ACH_{50}. The average was 3.35 ACH_{50} for the common-entry units and 4.47 ACH_{50} for the garden-style units. The average for all of the units was 3.60 ACH_{50}. The total leakage was 2.9 times greater than the exterior for the common-entry building and 2.2 times greater for the garden-style buildings. Adding the interior leakage to the exterior significantly reduces the rate of compliance with the leakage requirement for individual units.
- The exterior surface-area-normalized leakage was similar for the units in the common-entry and garden-style buildings. A total of 71% of the units had an exterior leakage rate less than 0.25 CFM_{50}/ft^2, 83% had a leakage less than 0.30 CFM_{50}/ft^2, and 94% were below 0.40 CFM_{50}/ft^2.
- The total surface-area-normalized leakage was somewhat lower for units in common-entry buildings than for those in garden-style buildings. All of the units in the common-entry buildings had a total leakage less than 0.25 CFM_{50}/ft^2, and the average was 0.16 CFM_{50}/ft^2. A total of 88% of the garden-style building units had a total leakage less than 0.25 CFM_{50}/ft^2 and the average was 0.21 CFM_{50}/ft^2. The compliance rates were somewhat higher for total leakage because some of the units had a lower surface-area-normalized leakage of the interior portion of the envelope than that for the exterior portion.

3.2.5 Oregon

All 12 units of one garden-style building and 11 units[6] of a 12-unit common-entry building were tested. The floor area of individual units that were tested ranged from 601 to 1,121 ft^2 and averaged 877 ft^2. The whole building floor areas were 11,073 ft^2 for the garden-style building and 11,785 ft^2 for the common-entry building. For the common-entry building, the common area was 17% of the building's floor area and 12% of the exterior envelope area. The western portion of Oregon is in Climate Zone 4 (Marine) and the eastern portion is in Zone 5 (Dry). There were no test sites in Zone 5. There is no code requirement for envelope leakage testing in Oregon. The garden-style building was going through an Earth Advantage program and had a target leakage of 5.0 ACH_{50}. The common-entry building was not involved with an energy efficiency program that required envelope leakage testing.

[6] The exterior leakage test of one of the 12 units was not valid.

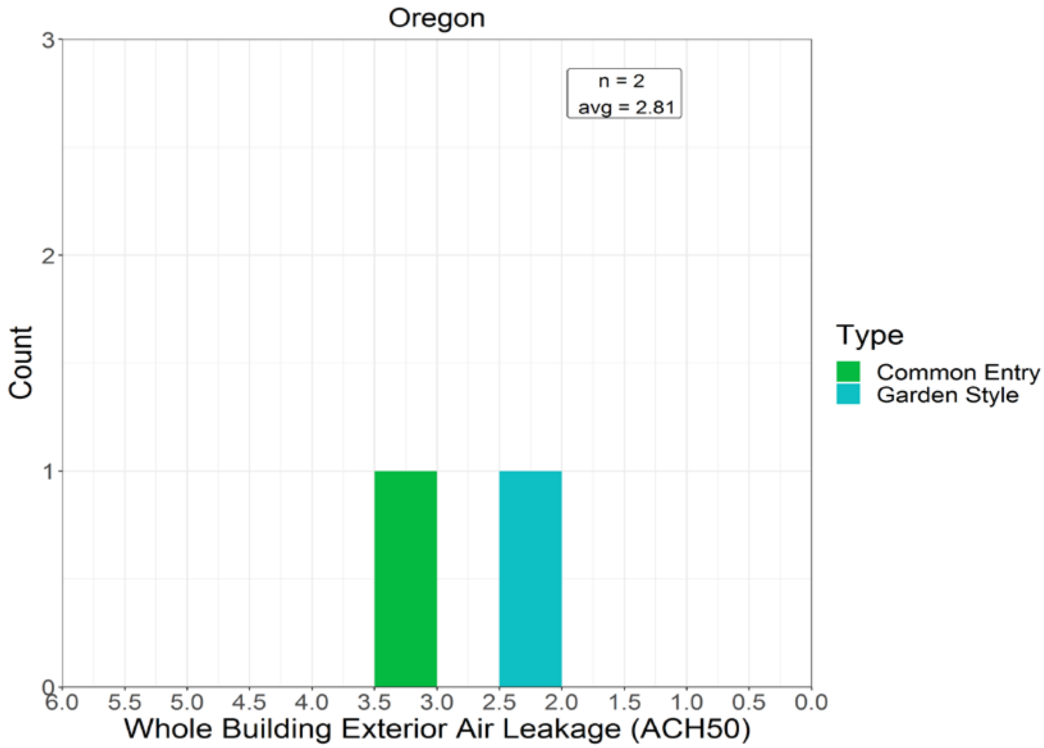


Figure 33. Oregon Whole Building Exterior Leakage (ACH_{50})

Table 26. Oregon Whole Building Exterior Leakage (ACH_{50})

Building Type	**Common Entry**	**Garden-Style**	**Statewide**
Number	1	1	2
Range	3.25	2.38	2.38 to 3.25
Average	3.25	2.38	2.81
Compliance Rate (3.0)	0 of 1 (0%)	1 of 1 (100%)	1 of 2 (50%)
Compliance Rate (4.0)	1 of 1 (100%)	1 of 1 (100%)	2 of 2 (100%)
Compliance Rate (5.0)	1 of 1 (100%)	1 of 1 (100%)	2 of 2 (100%)

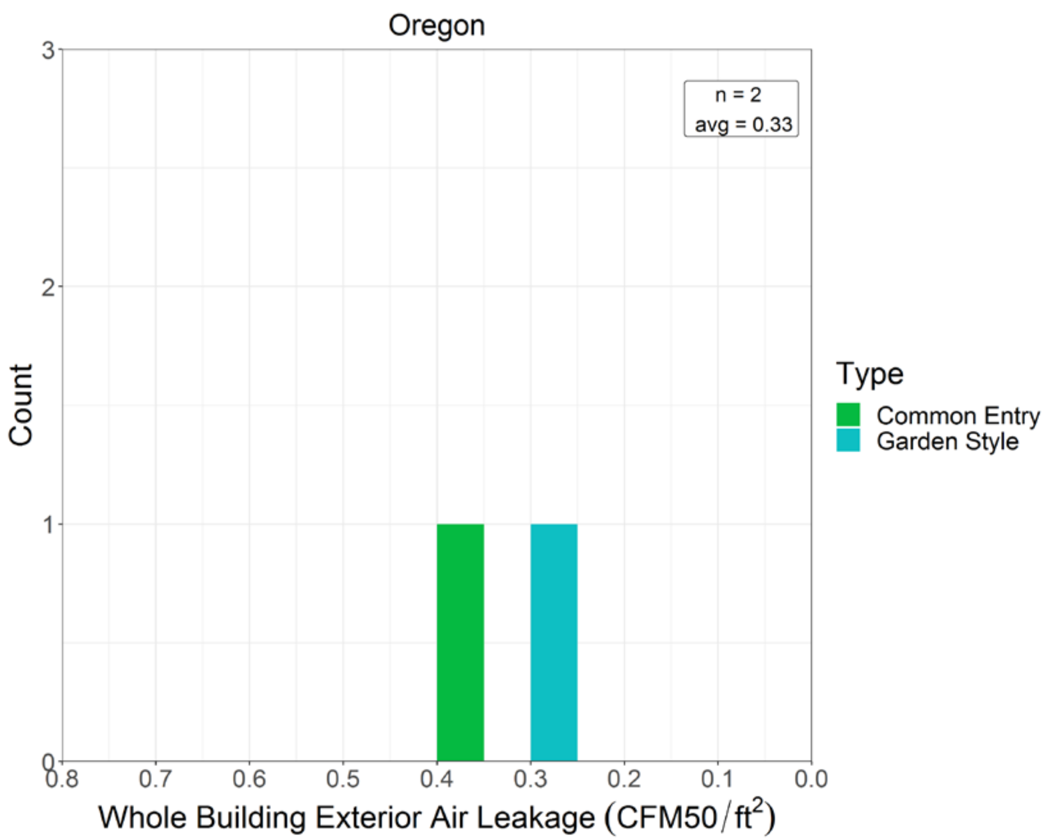


Figure 34. Oregon Whole Building Exterior Leakage (CFM_{50}/ft^2)

Table 27. Oregon Whole Building Exterior Leakage (CFM_{50}/ft^2)

Building Type	Common Entry	Garden-Style	Statewide
Number	1	1	2
Range	0.37	0.28	0.28 to 0.37
Average	0.37	0.28	0.33
Compliance Rate (0.20)	0 of 1 (0%)	0 of 1 (0%)	0 of 2 (0%)
Compliance Rate (0.25)	0 of 1 (0%)	0 of 1 (0%)	0 of 2 (0%)
Compliance Rate (0.30)	0 of 1 (0%)	1 of 1 (100%)	1 of 2 (50%)
Compliance Rate (0.40)	1 of 1 (100%)	1 of 1 (100%)	2 of 2 (100%)

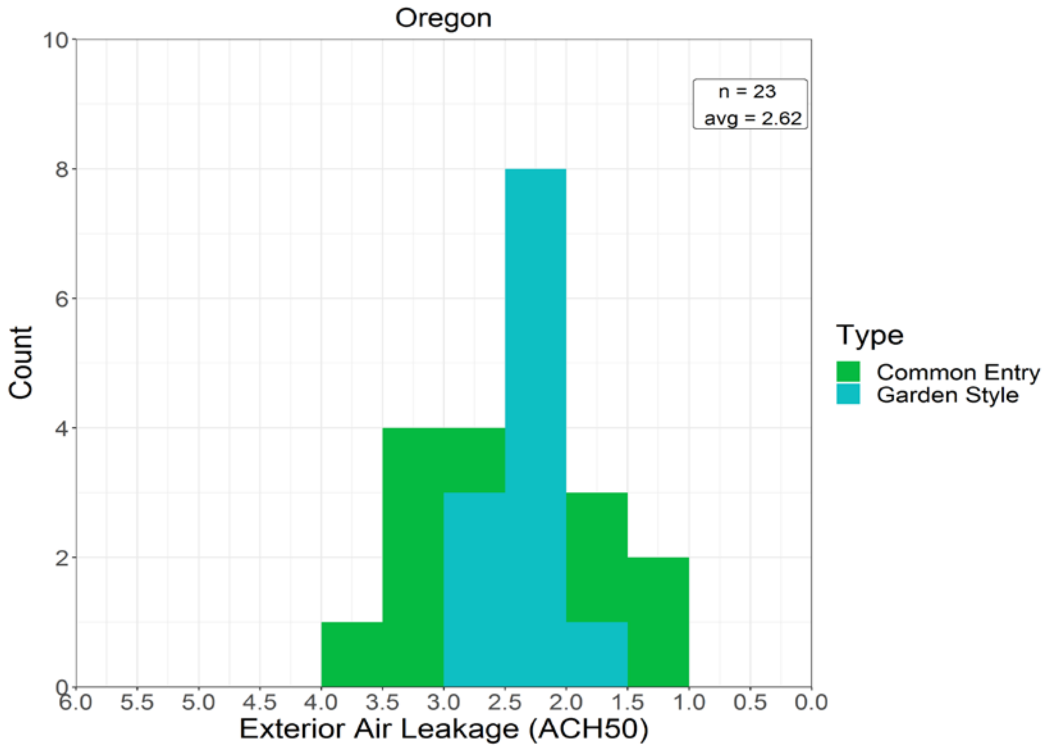


Figure 35. Oregon Unit Exterior Leakage (ACH_{50})

Table 28. Oregon Unit Exterior Leakage (ACH_{50})

Building Type	**Common Entry**	**Garden-Style**	**Statewide**
Number	11	12	23
Range	1.07 to 6.76	1.98 to 2.82	1.07 to 6.76
Average	2.88	2.38	2.62
Compliance Rate (3.0)	5 of 11 (45%)	12 of 12 (100%)	17 of 23 (74%)
Compliance Rate (4.0)	10 of 11 (91%)	12 of 12 (100%)	22 of 23 (96%)
Compliance Rate (5.0)	10 of 11 (91%)	12 of 12 (100%)	22 of 23 (96%)

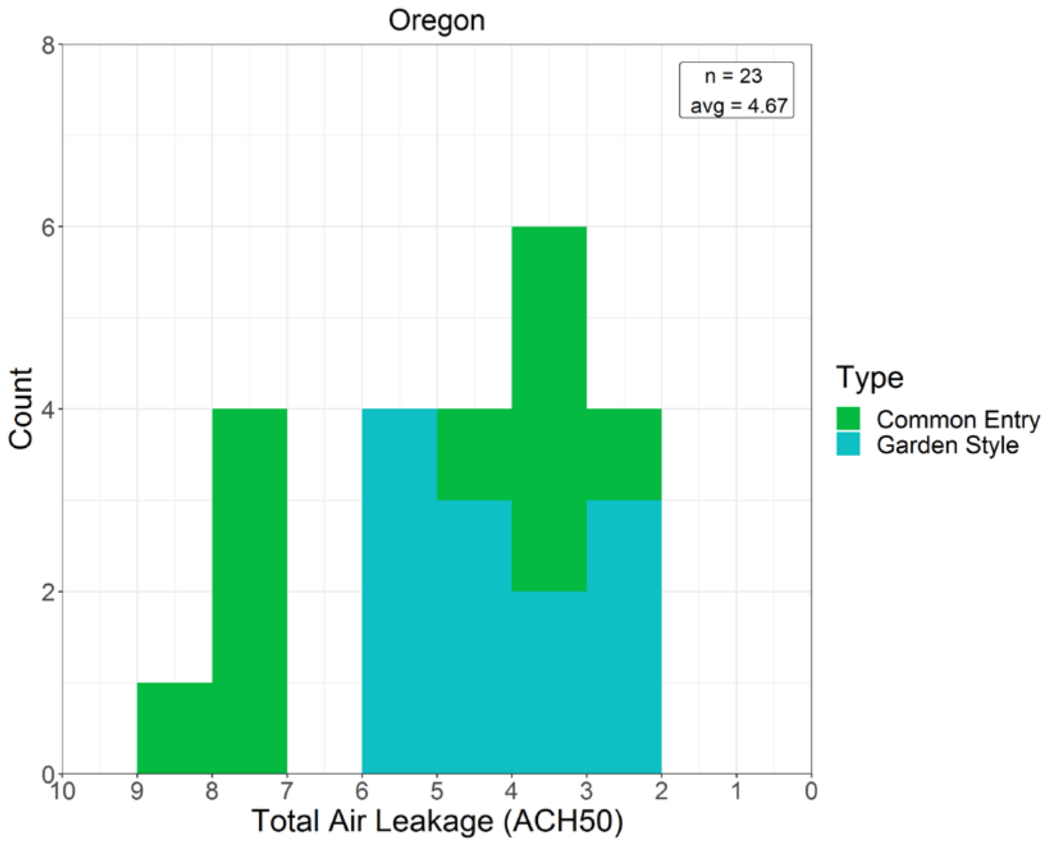


Figure 36. Oregon Unit Total Leakage (ACH_{50})

Table 29. Oregon Unit Total Leakage (ACH_{50})

Building Type	Common Entry	Garden-Style	Statewide
Number	11	12	23
Range	2.42 to 8.50	2.86 to 5.30	2.42 to 8.50
Average	5.26	4.12	4.67
Compliance Rate (3.0)	1 of 11 (9%)	3 of 12 (25%)	4 of 23 (17%)
Compliance Rate (4.0)	5 of 11 (45%)	5 of 12 (42%)	10 of 23 (43%)
Compliance Rate (5.0)	6 of 11 (55%)	8 of 12 (67%)	14 of 23 (61%)

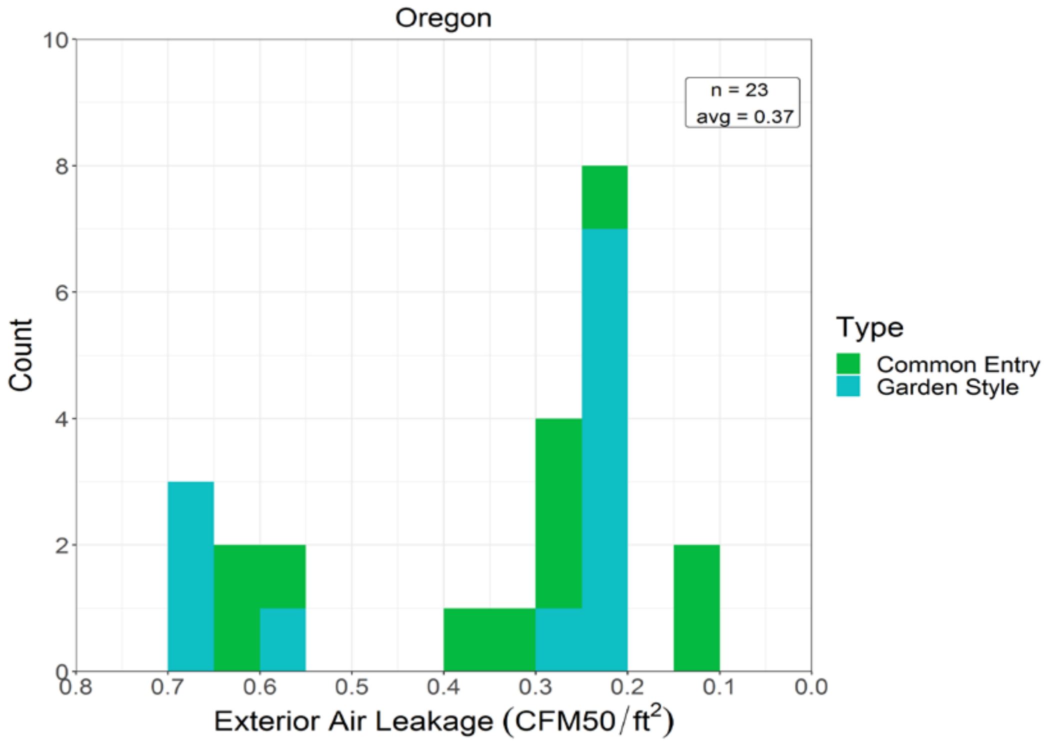


Figure 37. Oregon Unit Exterior Leakage (CFM_{50}/ft^2)

Table 30. Oregon Unit Exterior Leakage (CFM_{50}/ft^2)

Building Type	Common Entry	Garden-Style	Statewide
Number	11	12	23
Range	0.11 to 0.63	0.21 to 0.67	0.11 to 0.67
Average	0.35	0.37	0.36
Compliance Rate (0.20)	2 of 11 (18%)	0 of 12 (0%)	2 of 23 (9%)
Compliance Rate (0.25)	3 of 11 (27%)	7 of 12 (58%)	10 of 23 (43%)
Compliance Rate (0.30)	6 of 11 (55%)	8 of 12 (67%)	14 of 23 (61%)
Compliance Rate (0.40)	8 of 11 (73%)	8 of 12 (67%)	16 of 23 (70%)

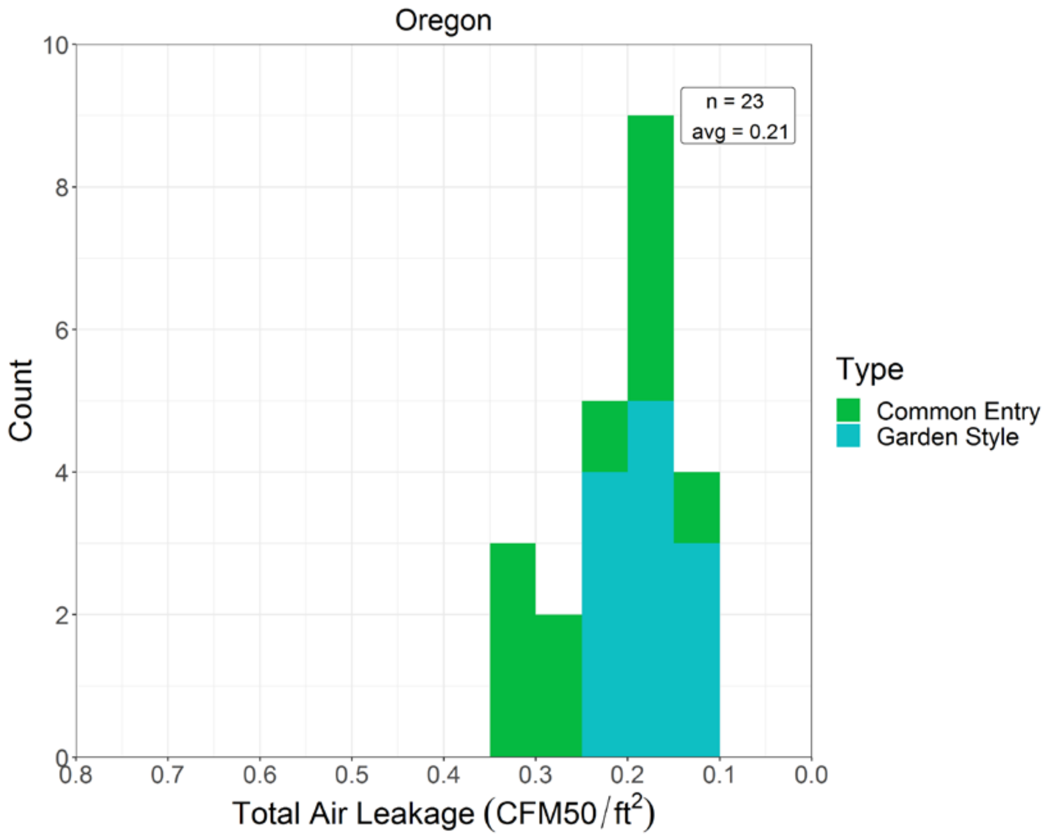


Figure 38. Oregon Unit Total Leakage (CFM_{50}/ft^2)

Table 31. Oregon Unit Total Leakage (CFM_{50}/ft^2)

Building Type	Common Entry	Garden-Style	Statewide
Number	11	12	23
Range	0.14 to 0.33	0.13 to 0.24	0.13 to 0.33
Average	0.23	0.19	0.21
Compliance Rate (0.20)	5 of 11 (45%)	8 of 12 (67%)	13 of 23 (57%)
Compliance Rate (0.25)	6 of 11 (55%)	12 of 12 (100%)	18 of 23 (78%)
Compliance Rate (0.30)	8 of 11 (73%)	12 of 12 (100%)	20 of 23 (87%)
Compliance Rate (0.40)	11 of 11 (100%)	12 of 12 (100%)	23 of 23 (100%)

Summary and interpretation:

- The whole building exterior volume-normalized leakage of the common-entry building (3.25 ACH_{50}) was 8% greater than 3.0 ACH_{50} and the leakage for the garden-style building (2.38 ACH_{50}) was 21% below 3.0 ACH_{50}. The average for the two buildings was 2.81 ACH_{50}.
- The whole building surface-area-normalized leakage of the two buildings was between 0.25 and 0.40 CFM_{50}/ft^2 and averaged 0.33 CFM_{50}/ft^2.

- When a guarded test was used to measure the exterior volume-normalized leakage of the units, 91% of the common-entry units and all of the garden-style units had a leakage less than 5.0 ACH_{50}. The average was 2.88 ACH_{50} for the common-entry units and 2.38 ACH_{50} for the garden-style units. The average for all of the units was 2.62 ACH_{50}.
- When the more common compartmentalization test was used to measure total unit volume-normalized leakage, 55% of the common-entry units and 67% of the garden-style units had a leakage less than 5.0 ACH_{50}. The average was 5.26 ACH_{50} for the common-entry units and 4.12 ACH_{50} for the garden-style units. The average for all of the units was 4.67 ACH_{50}. The total leakage was two times greater than the exterior for the common-entry building and 1.75 times greater for the garden-style buildings. Adding the interior leakage to the exterior significantly reduces the rate of compliance with the leakage requirement for individual units. As will be discussed more extensively in Section 4, the relative amount of interior leakage is greater for common-entry buildings than it is for garden-style buildings.
- The distribution of surface-area-normalized exterior leakage was similar for the units in the common-entry and garden-style buildings. A total of 43% of the units had an exterior leakage rate less than 0.25 CFM_{50}/ft^2, 61% had a leakage less than 0.30 CFM_{50}/ft^2, and 70% were below 0.40 CFM_{50}/ft^2.
- The surface-area-normalized total leakage was somewhat higher for units in common-entry buildings than for those in garden-style buildings. All of the units in the garden-style building had a total leakage less than 0.25 CFM_{50}/ft^2 and the average was 0.19 CFM_{50}/ft^2. A total of 55% of the common-entry building units had a total leakage less than 0.25 CFM_{50}/ft^2, and the average was 0.23 CFM_{50}/ft^2. The compliance rates were somewhat higher for total leakage because some of the units had a lower surface-area-normalized leakage for the interior portion of the envelope than that for the exterior portion.

3.2.6 Washington

Two garden-style buildings and one common-entry building were tested in Washington. The large number of units in the two garden-style buildings did not allow a whole building guarded test to be conducted simultaneously on all of the units. The 25-unit garden-style building had nine units on the first floor and eight units on the second and third floors. It was only possible to test the units on all three floors of one end of the building. The results are reported for 12 units.[7] The 18-unit garden-style building had six units on each of the three floors. A total of 12 blower doors were used to test the first- and second-floor units together. Then the blower doors were moved to test the second- and third-floor units together. The test procedure provided exterior and total unit leakage measurements for the six first-floor and the six third-floor units. The results are reported for individual units for the building, but not for the whole building.[8] All 10 units of the common-entry building were tested. The floor area of individual units that were tested ranged from 522 to 1,068 ft^2 and averaged 756 ft^2. The total floor area for the portion of the building that was tested was 11,723 ft^2 and 16,242 ft^2 for the two garden-style buildings and 6,676 ft^2 for the common-entry building. For the common-entry building, the common area was 18% of the building's floor area and 29% of the exterior envelope area. The western portion of Washington is in Climate Zone 4 (Marine) and the eastern portion is in Zone 5 (Cold). All test sites were in Zone 4. For the buildings tested for this project the State of Washington code required leakage was 5.0 ACH_{50}. There is a proposal for the

[7] For the whole building guarded tests, the leakage results are only included for units that were guarded on both sides of the unit. Consequently, 15 units were depressurized for the whole building test, but the results are included for only the 12 guarded units.

[8] Measurements on other buildings indicated that there are often significant differences in leakage between the middle and top floor units. An average from bottom and top floor units may not accurately represent the average results for all three floors.

State of Washington code to include an exception for garden-style dwelling units to have a leakage rate that does not exceed 0.40 CFM_{50}/ft^2. None of the three buildings were involved with an energy efficiency program that required envelope leakage testing. Two of the buildings were attempting to receive an extra tight envelope credit for the state energy code.

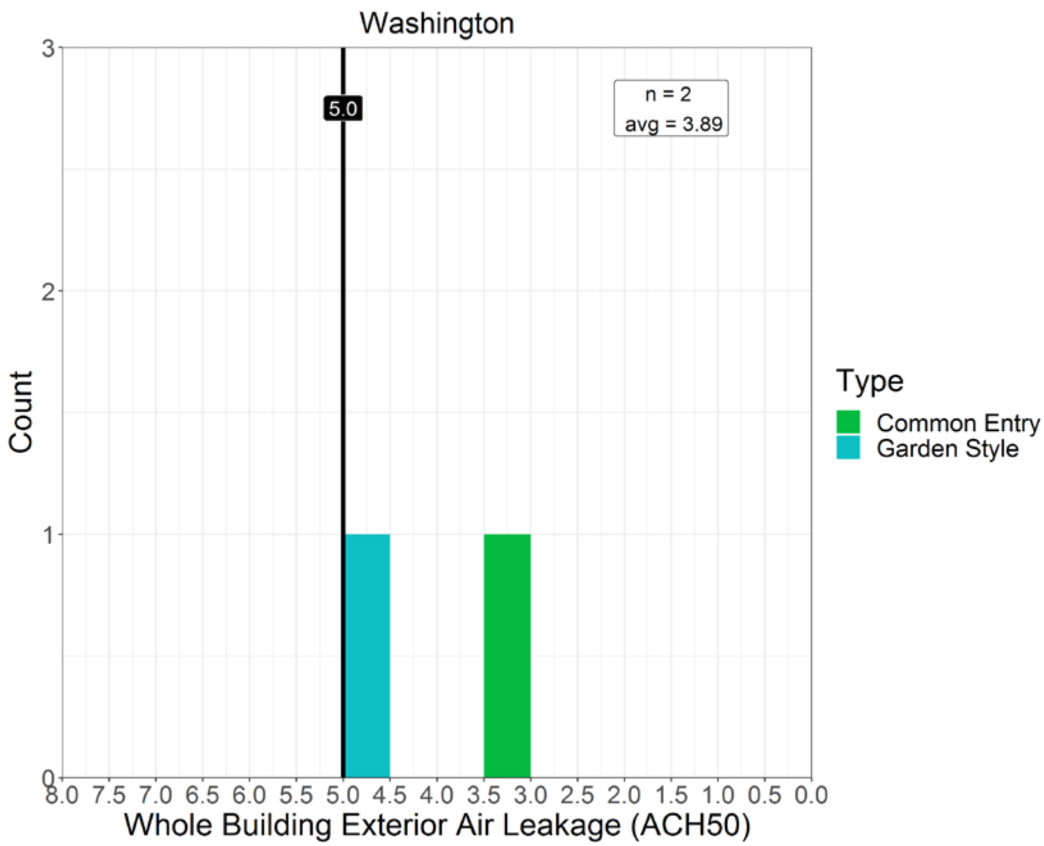


Figure 39. Washington Whole Building Exterior Leakage (ACH_{50})

Table 32. Washington Whole Building Exterior Leakage (ACH_{50})

Building Type	Common Entry	Garden-Style	Statewide
Number	1	1	2
Range	3.06	4.72	3.06 to 4.72
Average	3.06	4.72	3.89
Compliance Rate (3.0)	0 of 1 (0%)	0 of 1 (0%)	0 of 2 (0%)
Compliance Rate (4.0)	1 of 1 (100%)	0 of 1 (0%)	1 of 2 (50%)
Compliance Rate (5.0)	**1 of 1 (100%)**	**1 of 1 (100%)**	**2 of 2 (100%)**

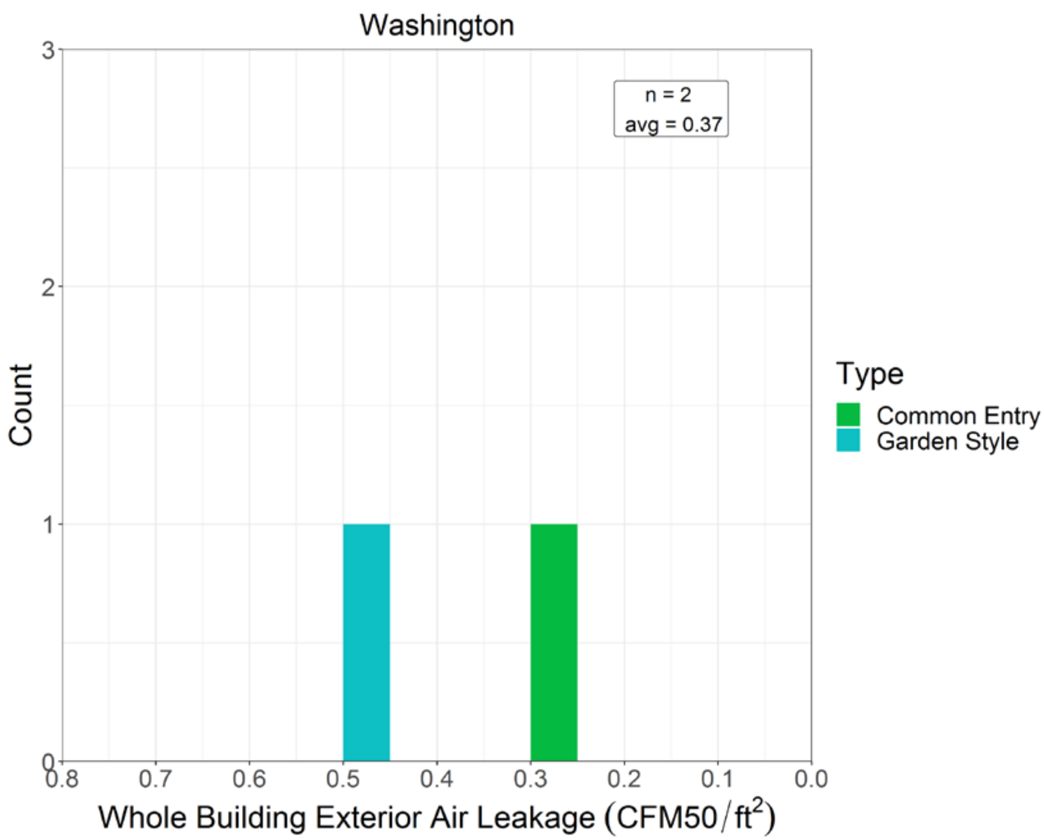


Figure 40. Washington Whole Building Exterior Leakage (CFM_{50}/ft^2)

Table 33. Washington Whole Building Exterior Leakage (CFM_{50}/ft^2)

Building Type	Common Entry	Garden-Style	Statewide
Number	1	1	2
Range	0.27	0.47	0.27 to 0.47
Average	0.27	0.47	0.37
Compliance Rate (0.20)	0 of 1 (0%)	0 of 1 (0%)	0 of 2 (0%)
Compliance Rate (0.25)	0 of 1 (0%)	0 of 1 (0%)	0 of 2 (0%)
Compliance Rate (0.30)	1 of 1 (100%)	0 of 1 (0%)	1 of 2 (50%)
Compliance Rate (0.40)	1 of 1 (100%)	0 of 1 (0%)	1 of 2 (50%)

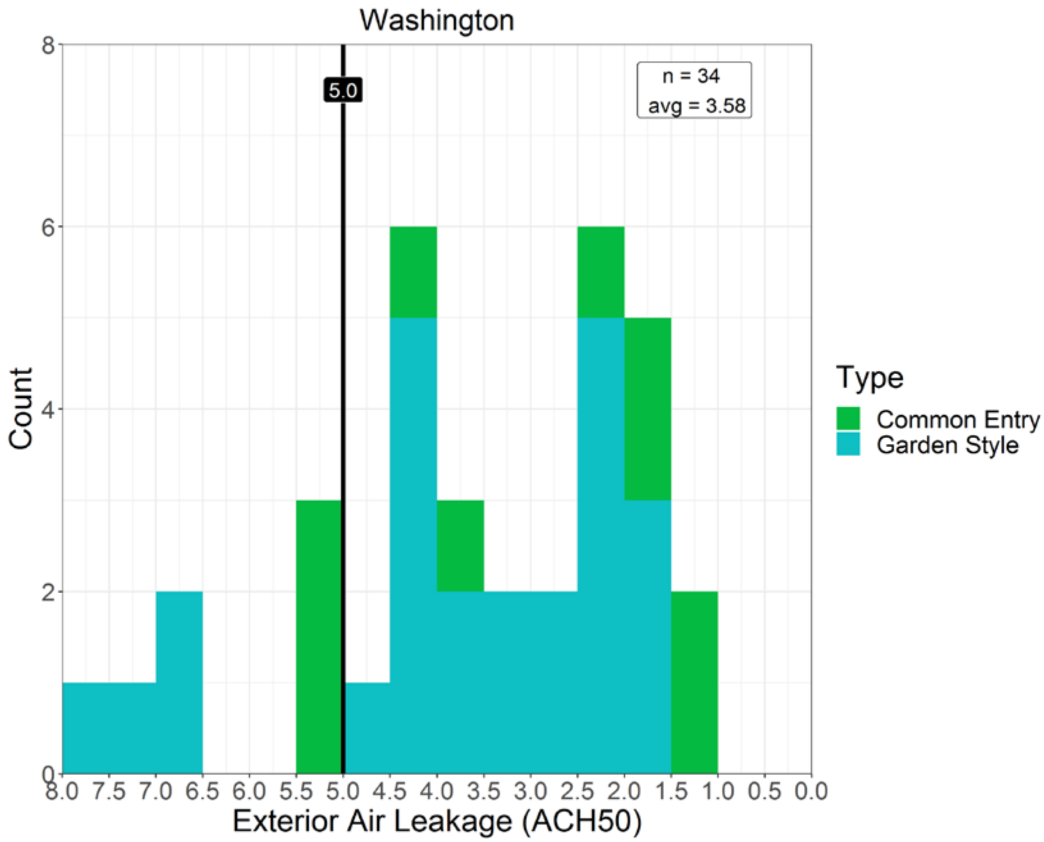


Figure 41. Washington Unit Exterior Leakage (ACH_{50})

Table 34. Washington Unit Exterior Leakage (ACH_{50})

Building Type	Common Entry	Garden-Style	Statewide
Number	10	24	34
Range	1.33 to 5.34	1.80 to 7.81	1.33 to 7.81
Average	3.22	3.73	3.58
Compliance Rate (3.0)	5 of 10 (50%)	10 of 24 (42%)	15 of 34 (44%)
Compliance Rate (4.0)	6 of 10 (60%)	14 of 24 (58%)	20 of 34 (59%)
Compliance Rate (5.0)	**7 of 10 (70%)**	**20 of 24 (83%)**	**27 of 34 (79%)**

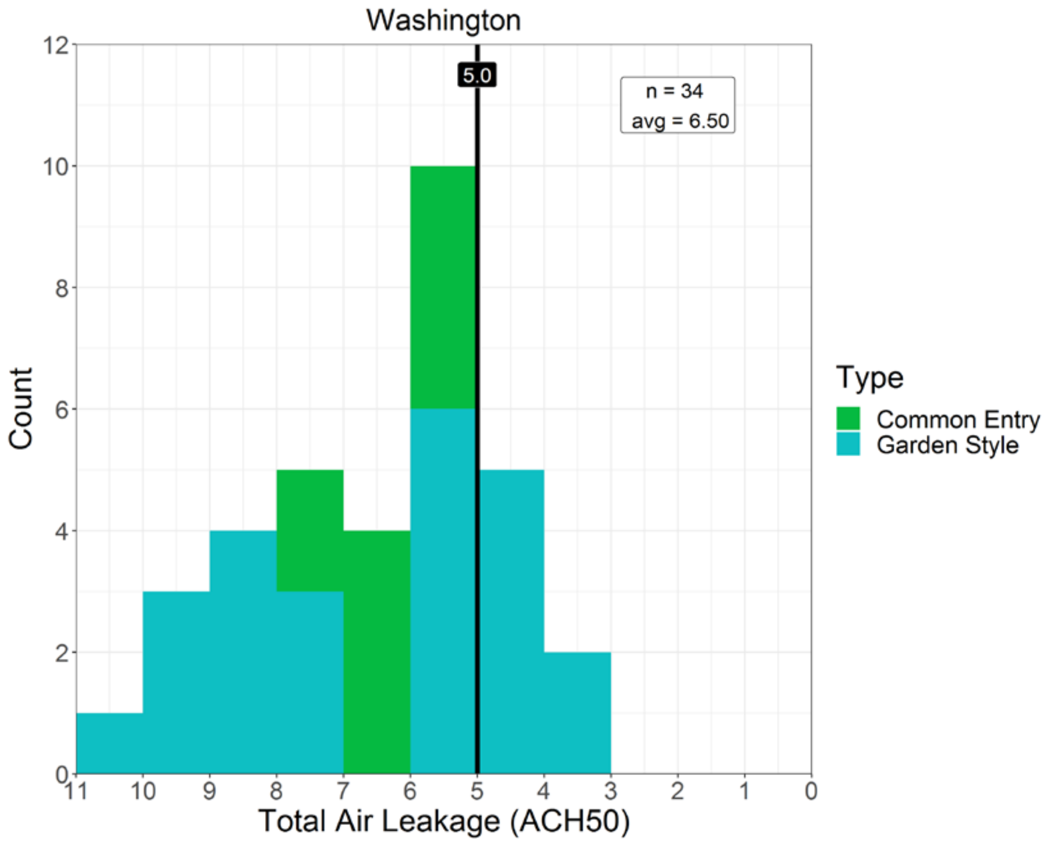


Figure 42. Washington Unit Total Leakage (ACH_{50})

Table 35. Washington Unit Total Leakage (ACH_{50})

Building Type	Common Entry	Garden-Style	Statewide
Number	10	24	34
Range	5.02 to 7.57	3.02 to 10.71	3.02 to 10.71
Average	6.43	6.53	6.50
Compliance Rate (3.0)	0 of 10 (0%)	0of 24 (0%)	0 of 34 (0%)
Compliance Rate (4.0)	0 of 10 (0%)	2 of 24 (8%)	2 of 34 (6%)
Compliance Rate (5.0)	**0 of 10 (0%)**	**7 of 24 (29%)**	**7 of 34 (21%)**

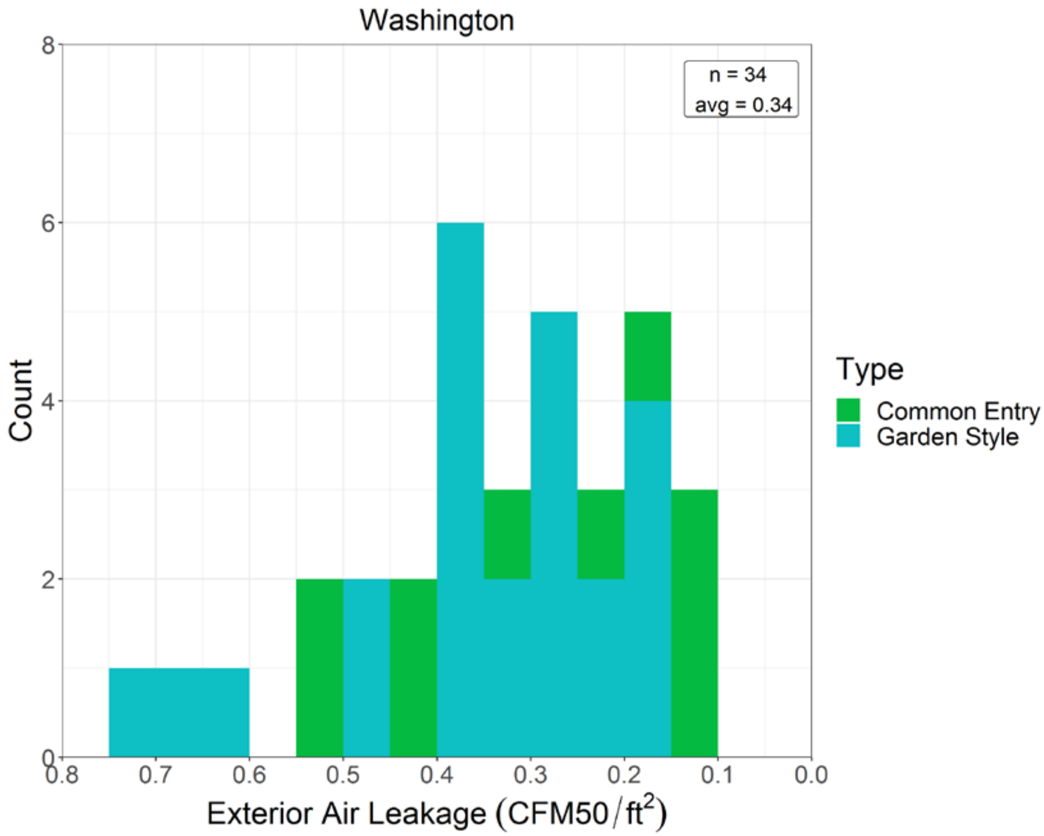


Figure 43. Washington Unit Exterior Leakage (CFM_{50}/ft^2)

Table 36. Washington Unit Exterior Leakage (CFM_{50}/ft^2)

Building Type	Common Entry	Garden-Style	Statewide
Number	10	24	34
Range	0.11 to 0.54	0.17 to 0.75	0.11 to 0.75
Average	0.30	0.36	0.34
Compliance Rate (0.20)	4 of 10 (40%)	4 of 24 (17%)	8 of 34 (24%)
Compliance Rate (0.25)	5 of 10 (50%)	6 of 24 (25%)	11 of 34 (32%)
Compliance Rate (0.30)	5 of 10 (50%)	11 of 24 (46%)	16 of 34 (47%)
Compliance Rate (0.40)	6 of 10 (60%)	19 of 24 (79%)	25 of 34 (74%)

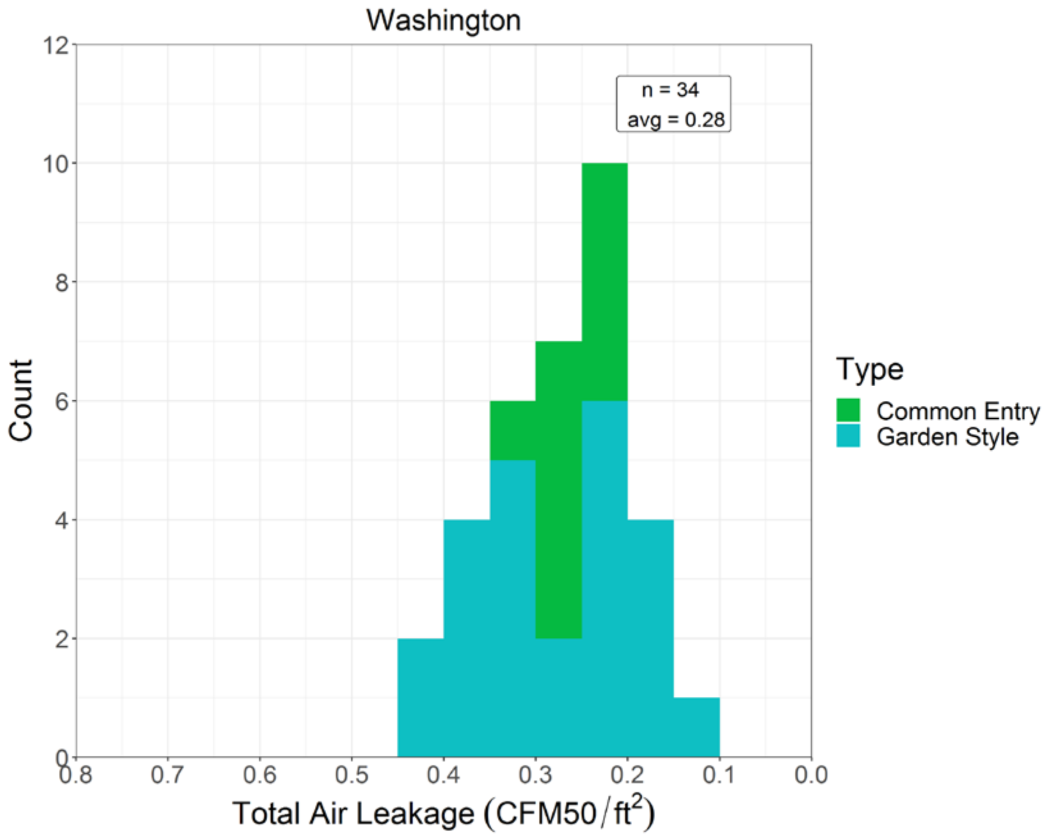


Figure 44. Washington Unit Total Leakage (CFM_{50}/ft^2)

Table 37. Washington Unit Total Leakage (CFM_{50}/ft^2)

Building Type	Common Entry	Garden-Style	Statewide
Number	10	24	34
Range	0.21 to 0.32	0.13 to 0.44	0.13 to 0.44
Average	0.26	0.28	0.28
Compliance Rate (0.20)	0 of 10 (0%)	5 of 24 (21%)	5 of 34 (15%)
Compliance Rate (0.25)	4 of 10 (40%)	11 of 24 (46%)	15 of 34 (44%)
Compliance Rate (0.30)	9 of 10 (90%)	13 of 24 (54%)	22 of 34 (65%)
Compliance Rate (0.40)	10 of 10 (100%)	22 of 24 (92%)	32 of 34 (94%)

Summary and interpretation:

- The two buildings had a whole building exterior volume-normalized leakage rate below the requirement of 5.0 ACH_{50} that was in effect in Washington when these buildings were constructed. The leakage was 3.06 ACH_{50} for the common-entry building and 4.72 ACH_{50} for the garden-style building.

- The whole building exterior surface-area-normalized leakage was 0.27 CFM_{50}/ft^2 for the common-entry building. That is 42% greater than the USACE requirement of 0.19 CFM_{50}/ft^2, but it is less than the proposed Washington code requirement of 0.40 CFM_{50}/ft^2 for individual units.
- When a guarded test was used to measure the exterior volume-normalized leakage of the units, 70% of the common-entry units and 83% of the garden-style units complied with the leakage requirement of 5.0 ACH_{50}. The average was 3.22 ACH_{50} for the common-entry units and 3.73 ACH_{50} for the garden-style units. The average for all of the units was 3.58 ACH_{50}.
- When the more common compartmentalization test was used to measure total unit volume-normalized leakage, none of the common-entry units and 29% of the garden-style units complied with the leakage requirement of 5.0 ACH_{50}. The average was 6.43 ACH_{50} for the common-entry units and 6.53 ACH_{50} for the garden-style units. The average for all of the units was 6.5 ACH_{50}. The total leakage was two times greater than the exterior for the common-entry building and 1.75 times greater for the garden-style buildings. Adding the interior leakage to the exterior significantly reduces the rate of compliance with the leakage requirement for individual units. As will be discussed more extensively in Section 4, the relative amount of interior leakage is greater for common-entry buildings than it is for garden-style buildings.
- The exterior surface-area-normalized leakage was somewhat higher for units in garden-style buildings than for those in common-entry buildings. A total of 25% of the units in the garden-style buildings had an exterior leakage less than 0.25 CFM_{50}/ft^2, and the average was 0.36 CFM_{50}/ft^2. A total of 50% of the common-entry building units had a total leakage less than 0.25 CFM_{50}/ft^2, and the average was 0.30 CFM_{50}/ft^2. The compliance rates for the proposed code requirement of 0.40 CFM_{50}/ft^2 were 79% for units in garden-style buildings and 60% for the units in the common-entry building. However, that requirement applies to the total and not exterior leakage.
- The average total surface-area-normalized leakage was about the same for the garden-style (0.28 CFM_{50}/ft^2) and common-entry (0.26 CFM_{50}/ft^2) buildings. A total of 46% of the units in the garden-style building had a total leakage less than 0.25 CFM_{50}/ft^2, and 40% of the common-entry building units had a total leakage less than 0.25 CFM_{50}/ft^2. Almost all of the units complied with the proposed code requirement of 0.40 CFM_{50}/ft^2. A total of 92% of the units in the garden-style building had a total leakage less than 0.40 CFM_{50}/ft^2, and all of the common-entry building units had a total leakage less than 0.25 CFM_{50}/ft^2.

4. AIR LEAKAGE RESULTS BY BUILDING TYPE

This section analyzes trends in the measured envelope leakage and identifies building characteristics and leakage standards that impact those trends. This includes an analysis of whole building leakage, individual unit total and exterior leakage, methods to estimate unit exterior leakage, and implications for test protocols. Air leakage tests were conducted on 5 garden-style and 20 common-entry buildings in six states. There were one or two garden-style buildings in three states: Minnesota, Oregon, and Washington. The common-entry buildings were located in six states: 10 in Minnesota, four in Illinois, three in Iowa, and one each in Michigan, Oregon, and Washington. Since this was not a random sample of buildings from all regions of the United States, it is not expected that the results represent trends for all low-rise multifamily new construction across the country. For example, there was a code required leakage test for five of the six states, and that requirement applied to 23 of the 25 buildings. In contrast, 25 states have adopted the 2012, 2015, or 2018 versions of IECC that require an air leakage test or otherwise have an air leakage test requirement in their code. In addition, about two-thirds of the buildings were being certified for an energy efficiency program, which is likely to be a higher fraction than occurs for most regions of the country. However, some of the results are consistent within the sample and are expected to extend to a large portion of U.S. new construction.

4.1 Building Characteristics

The five garden-style buildings were located in three states: two in Minnesota, one in Oregon, and two in Washington. The common-entry buildings were located in six states: ten in Minnesota, four in Illinois, three in Iowa, and one each in Michigan, Oregon, and Washington. It was anticipated that the hallways and other common areas of the common-entry buildings could result in significant differences in air leakage results between the common-entry and garden-style buildings. Consequently, the analyses of leakage trends were performed separately for common-entry and garden-style buildings.

As noted above, all states in the study required air tightness testing but Oregon; the maximum exterior leakage requirement was 3.0 ACH_{50} for Minnesota; 4.0 ACH_{50} for Iowa and Michigan; and 5.0 ACH_{50} for Illinois and Washington. At least of 16 (64%) of the buildings were being certified for an energy efficiency program: 14 for ENERGY STAR Certified Homes, one for PHIUS, and one for an Iowa financing program that required a maximum HERS score. PHIUS 2015 certification required a whole building leakage no greater than 0.05 CFM_{50}/ft^2 and individual unit total leakage no greater than 0.3 CFM_{50}/ft^2.

There was not a specific leakage requirement for ENERGY STAR certification, but the leakage impacts the overall score, and builders typically determine the maximum leakage needed to achieve the required HERS score. In total, 11 builders or their ENERGY STAR raters provided information on their air leakage target (see Table 39 and Table 41). There was no specific target for two Minnesota buildings, but the rater encouraged the builder to achieve a leakage of 3.0 to 4.0 ACH_{50}. The nine other builders that reported their leakage target indicated that it was either 5.0 or 6.0 ACH_{50}. Two of the buildings in Oregon and Washington were being certified for a green building program.

The common-entry buildings were predominantly three-story buildings with 10 or more units and only residential space (e.g., not mixed use). Overall, 18 of the buildings had only residential space (i.e., no mixed use). One of the buildings had two stories and the rest had three stories. Two of the buildings in Minnesota had two residential floors over a floor of commercial space. The commercial space was "guarded" for the exterior leakage measurements of the two Minnesota buildings so that the whole building test did not include leakage between the residential units and the first-floor commercial space.

The number of units per building ranged from six to 60 and averaged 31 (See Table 38). All of the units in a building were tested for the seven buildings that had six to 12 units. For the other 13 buildings, a representative sample of 10 or 12 units was tested.[9] The total floor area of the buildings ranged from 6,676 to 72,721 ft^2 and averaged 33,043 ft^2. The exterior envelope of the buildings ranged from 11,266 to 76,884 ft^2 and averaged 37,611 ft^2. There was over a 3-to-1 range in the average floor area of the units tested in each building. The lowest average was 431 ft^2, the highest was 1,490 ft^2 and the overall average was 860 ft^2. The percentage of whole building floor area that was taken up by the residential units varied from 60% to 95% and averaged 79%.

[9] The test units were clustered in a section of the building so that there was approximately the same number of units tested on each floor, the units were adjacent to each other, and the cluster included a variety of floor plans.

Table 38. Common Entry Building Dimensions

		# Units		Whole Building			Residential Floor Area		
ID	*Resid. Stories*	*Total*	*Tested*	*Floor Area (ft^2)*	*Volume (ft^3)*	*Ext. Env. Area (ft^2)*	*Total*	*Average Per Unit*	*% of Building*
IL 41	3	25	10	22,636	212,088	26,632	15,120	605	67%
IL 42	3	9	9	8,155	92,708	14,907	7,313	813	90%
IL 43	3	6	6	9,373	97,489	13,558	8,941	1,490	95%
IL 44	3	6	6	9,373	97,489	13,558	8,941	1,490	95%
IA 61	3	30	12	33,213	336,637	38,383	28,130	938	85%
IA 62	3	30	12	25,072	254,217	29,413	20,574	686	82%
IA 63	3	36	10	41,510	415,003	46,710	32,745	910	79%
MI 81	3	48	12	54,208	534,360	59,657	40,063	835	74%
MN 51	3	10	10	11,145	110,489	14,391	6,741	674	60%
MN 54	3	60	12	71,193	673,205	74,819	58,665	978	82%
MN 55	2*	24	10	19,521	191,659	21,735	15,370	640	79%
MN 56	2*	10	10	9,056	88,913	11,266	7,104	710	78%
MN 57	3	57	12	71,055	672,656	76,314	58,585	1,028	82%
MN 58	3	60	12	72,721	688,584	76,884	59,579	993	82%
MN 59	3	42	10	52,214	513,649	57,256	35,335	841	68%
MN 71	3	59	12	59,178	620,416	65,826	45,442	770	77%
MN 72	3	44	12	29,034	303,910	34,532	18,946	431	65%
MN 73	3	35	12	43,749	414,741	47,127	35,065	1,002	80%
OR 2	3	12	12	11,785	113,399	16,543	9,729	811	83%
WA 1	2	10	10	6,676	66,881	12,704	5,499	550	82%
Avg.	2.9	31	10.6	33,043	324,925	37,611	25,894	860	79%
Median	3	30	11	27,053	279,063	31,972	19,760	824	81%
Min.	2	6	6	6,676	66,881	11,266	5,499	431	60%
Max.	3	60	12	72,721	688,584	76,884	59,579	1,490	95%

* - two floors of residential units over one floor of commercial space

Information was gathered for key construction characteristics that may impact envelope leakage (See Table 39). The buildings had five types of space below the bottom floor: garages (8); slab-on-grade (7); basements (2); commercial space (2); and crawlspace (1). Above the top floor, 11 of the buildings had vented attics and nine had flat roofs. A total of 17 of the buildings had batt insulation in the exterior walls, two had blown cellulose, and one had structural insulated panels (SIP). A variety of approaches was used for the exterior wall air barrier: airtight drywall (4); house wrap (3); taped sheathing (2); airtight drywall and house wrap (2); interior poly sheeting (1); interior poly sheeting and house wrap (1); and SIP (1). One building had a portion of the exterior sealed with taped sheathing and a portion with house wrap. The air barrier design was not determined for four of the buildings. While the type of ventilation does not impact envelope leakage, it is interesting to note that 18 buildings had continuous general mechanical ventilation. In total, 13 buildings had balanced systems with separate exhaust and supply, two had balanced energy recovery ventilation, two had exhaust-only, and one had supply-only.

It is worth nothing that all garages were unheated (or heated to prevent freezing) and they were not included in the testing The commercial spaces were “guarded” so leakage between the residential space and commercial space was not included as exterior leakage. The crawlspace was not included in the test at that site. The basements were heated and included in the whole building test.

Table 39. Common Entry Building Construction Characteristics

	Energy Program		Space Under Bottom Floor	Exterior Wall		Space Above Top Floor	General Ventilation
ID	*Type*	*Target Leakage*		*Insulation*	*Air Barrier*		
IL 41	E Star	5.0 ACH_{50}	Slab-on-grade	Batt	Airtight drywall	Vented attic	Balanced
IL 42	None		Crawlspace	Batt	House wrap or taped sheathing*	Flat roof	Spot Only
IL 43	PHIUS	0.3 CFM_{50}/ft^2	Slab-on-grade	Batt	Liquid applied	Flat roof	ERV
IL 44	E Star	5.0 ACH_{50}	Slab-on-grade	Batt	House wrap	Flat roof	ERV
IA 61	E Star	6.0 ACH_{50}	Slab-on-grade	Batt	Taped sheathing	Flat roof	Balanced
IA 62	E Star	6.0 ACH_{50}	Slab-on-grade	Batt	Taped sheathing	Flat roof	Balanced
IA 63	Other		Garage	Blown cellulose	Inter. poly sheeting	Vented attic	Exhaust
MI 81	E Star	6.0 ACH_{50}	Slab-on-grade	Blown cellulose	House wrap	Vented attic	Supply
MN 51	None		Basement	SIP	SIP	Vented attic	Balanced
MN 54	E Star	6.0 ACH_{50}	Garage	Batt	Airtight drywall	Vented attic	Balanced
MN 55	E Star	None	Commercial	Batt	Airtight drywall & house wrap	Flat roof	Balanced
MN 56	E Star	None	Commercial	Batt	Airtight drywall & house wrap	Flat roof	Balanced
MN 57	None		Garage	Batt	Airtight drywall	Vented attic	Balanced
MN 58	None		Garage	Batt	Airtight drywall	Vented attic	Balanced
MN 59	E Star		Garage	Batt	DK	Vented attic	Balanced
MN 71	E Star		Garage	Batt	Interior poly & house wrap	Flat roof	Balanced
MN 72	E Star		Slab-on-grade	Batt	DK	Flat roof	Balanced
MN 73	E Star	6.0 ACH_{50}	Garage	Batt	House wrap	Vented attic	Balanced
OR 2	None		Garage	Batt	DK	Vented attic	DK
WA 1	None		Basement	Batt	DK	Vented attic	Exhaust

E Star = ENERGY STAR Certified Homes v3.1
* - house wrap for one section of the building and taped sheathing for the other section (not both on same section).
Balanced – separate exhaust and supply systems.

The two garden-style buildings in Minnesota had two stories, and the three buildings in Oregon and Washington had three stories (see Table 40). There were fewer garden-style buildings in the sample than initially expected because the recruiting was less successful in the Pacific Northwest where the buildings are predominantly garden-style. The number of units per building and the total floor area of the common-entry buildings were greater than that for the garden-style buildings, but the average floor area of the individual garden-style units was greater. The number of units per building ranged from 12 to 25 and averaged 17. The total floor area of the buildings ranged from 11,073 to 23,344 ft^2 and averaged 17,145 ft^2. The exterior envelope of the buildings ranged from 12,354 to 32,212 ft^2 and averaged 22,922 ft^2. There was about a 2-to-1 range in the average floor area of the units tested in each building. The lowest average was 782 ft^2, the highest was 1,459 ft^2, and the overall average was 1,105 ft^2. For the two buildings in Minnesota and the building in Oregon, all of the individual units were tested. For the 25-unit building in Washington, 12 of the units in one section of the building were tested. For the 18-unit building in Washington, six of the units on the first floor and six units on the third floor were tested.

Table 40. Garden-Style Building Characteristics

		# Units		Whole Building			Floor
ID	*Stories*	*Total*	*Tested*	*Floor Area (ft^2)*	*Volume (ft^3)*	*Ext. Env. Area (ft^2)*	*Area Per Unit (ft^2)*
MN 52	2	16	16	23,344	191,240	32,212	1,459
MN 53	2	16	16	23,344	191,240	32,212	1,459
OR 4	3	12	12	11,073	88,584	12,354	923
WA 3	3	25	12	11,723	101,222	16,790	782
WA 5	3	18	12	16,242	138,923	21,041	902
Avg.	2.6	17	14	17,145	142,242	22,922	1,105
Median	3	16	12	16,242	138,923	21,041	923
Min.	2	12	12	11,073	88,584	12,354	782
Max.	3	25	16	23,344	191,240	32,212	1,459

The key construction characteristics of the garden-style buildings are shown in Table 41. All of the buildings had slab-on-grade construction, vented attics, and used batt insulation in the exterior walls. House wrap was used for the exterior wall air barrier for the three buildings where the air barrier design was determined. All of the buildings had continuous general mechanical ventilation. The two buildings in Minnesota had balanced systems with separate exhaust and supply, and the three buildings in the Pacific Northwest had exhaust-only ventilation.

Table 41. Garden-Style Building Construction Characteristics

	Energy Program		Space Under	Exterior Wall			
ID	*Type*	*Target Leakage*	*Bottom Floor*	*Insulation*	*Air Barrier*	**Space Above Top Floor**	**General Ventilation**
MN 52	E Star	6 ACH_{50}	Slab-on-grade	Batt	House wrap	Vented attic	Balanced
MN 53	E Star	6 ACH_{50}	Slab-on-grade	Batt	House wrap	Vented attic	Balanced
OR 4	E. Adv.	5 ACH_{50}	Slab-on-grade	Batt	House wrap	Vented attic	Exhaust
WA 3	None		Slab-on-grade	Batt	DK	Vented attic	Exhaust
WA 5	None		Slab-on-grade	Batt	DK	Vented attic	Exhaust

E. Adv. – Earth Advantage program.
Balanced – separate exhaust and supply systems.

4.2 Whole Building Air Leakage

4.2.1 Common Entry Buildings

The whole building exterior leakage of the common-entry buildings ranged from 0.41 to 3.25 ACH_{50} with an average of 1.54 ACH_{50} (see Table 42, Figure 45[10], and Figure 46). All of the buildings were at least 39% below the leakage required by code for their state. On average the buildings were 61% below the code-required leakage. Only four (20%) of the buildings had a leakage greater than 2.0 ACH_{50}, and only two (10%) were above 3.0 ACH_{50}. The building with the highest leakage of 3.25 ACH_{50} was located in Oregon, which does not have a state code air leakage test requirement.

Table 42. Common-Entry Whole Building Leakage

	Total Exterior Leakage (ACH_{50})			**Total Exterior Leakage (CFM_{50}/ft^2)**			**Residential Space as Percent of Whole Building**		
ID	*Whole Building*	*Resid. Space*	*Common Space*	*Whole Building*	*Resid. Space*	*Common Space*	*% Leakage*	*% Volume*	*% Env. Area*
IL 41	2.88	2.01	4.57	0.38	0.29	0.54	46%	66%	62%
IL 42	1.08	1.04	1.43	0.11	0.11	0.13	86%	90%	88%
IL 43	0.41	0.40	0.76	0.05	0.05	0.10	92%	95%	96%
IL 44	1.51	1.40	3.77	0.18	0.17	0.50	88%	95%	96%
IA 61	1.32	1.29	1.49	0.19	0.18	0.32	83%	85%	90%
IA 62	1.29	1.41	0.71	0.19	0.19	0.14	90%	82%	87%
IA 63	2.28	1.48	5.58	0.34	0.23	0.74	52%	80%	78%
MI 81	1.89	1.29	3.46	0.28	0.20	0.49	50%	73%	71%
MN 51	1.08	1.54	0.38	0.14	0.22	0.04	86%	61%	55%
MN 54	1.61	1.50	2.13	0.24	0.21	0.42	77%	82%	86%
MN 55	0.98	0.93	1.16	0.14	0.15	0.12	75%	79%	71%
MN 56	1.00	0.75	1.89	0.13	0.11	0.17	59%	78%	68%
MN 57	1.31	1.05	2.53	0.19	0.15	0.45	66%	82%	85%
MN 58	1.23	1.07	1.96	0.18	0.16	0.32	71%	82%	83%
MN 59	1.27	1.01	1.77	0.19	0.15	0.26	53%	66%	66%
MN 71	0.95	0.78	1.50	0.15	0.12	0.25	63%	77%	78%
MN 72	0.98	0.93	1.07	0.14	0.14	0.16	60%	63%	63%
MN 73	1.49	1.42	1.80	0.22	0.20	0.29	76%	80%	82%
OR 2	3.25	2.72	6.16	0.37	0.30	0.88	71%	85%	88%
WA 1	3.06	3.21	2.64	0.27	0.29	0.21	78%	74%	71%
Avg.	1.54	1.36	2.34	0.20	0.18	0.33	71%	79%	78%
Median	1.30	1.29	1.84	0.19	0.17	0.28	73%	80%	80%
Min.	0.41	0.40	0.38	0.05	0.05	0.04	46%	61%	55%
Max.	3.25	3.21	6.16	0.38	0.30	0.88	92%	95%	96%

[10] The histograms in Section 4 place lower values to the left side of the horizontal axis with increasing values to the right. The reverse of this convention was used for the histograms in Section 3 so that they would be consistent with the PNNL graphical convention for code compliance (e.g. values to the left-hand side represent areas for improvement).

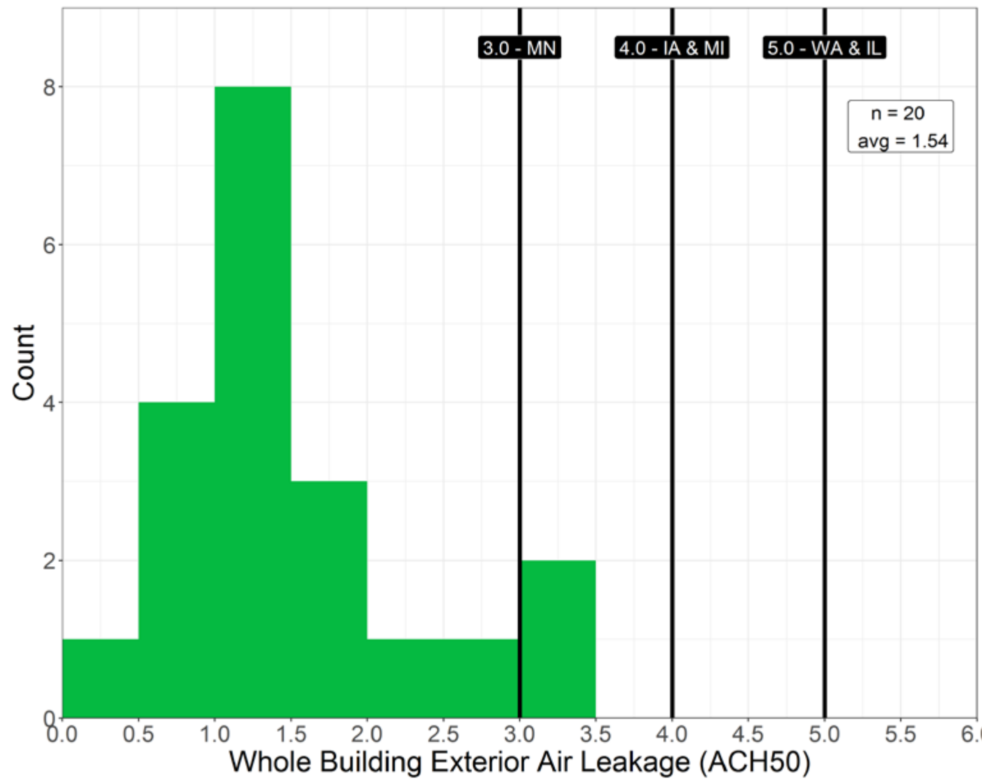


Figure 45. Histogram of Whole Building Leakage: Common Entry Buildings (ACH_{50})

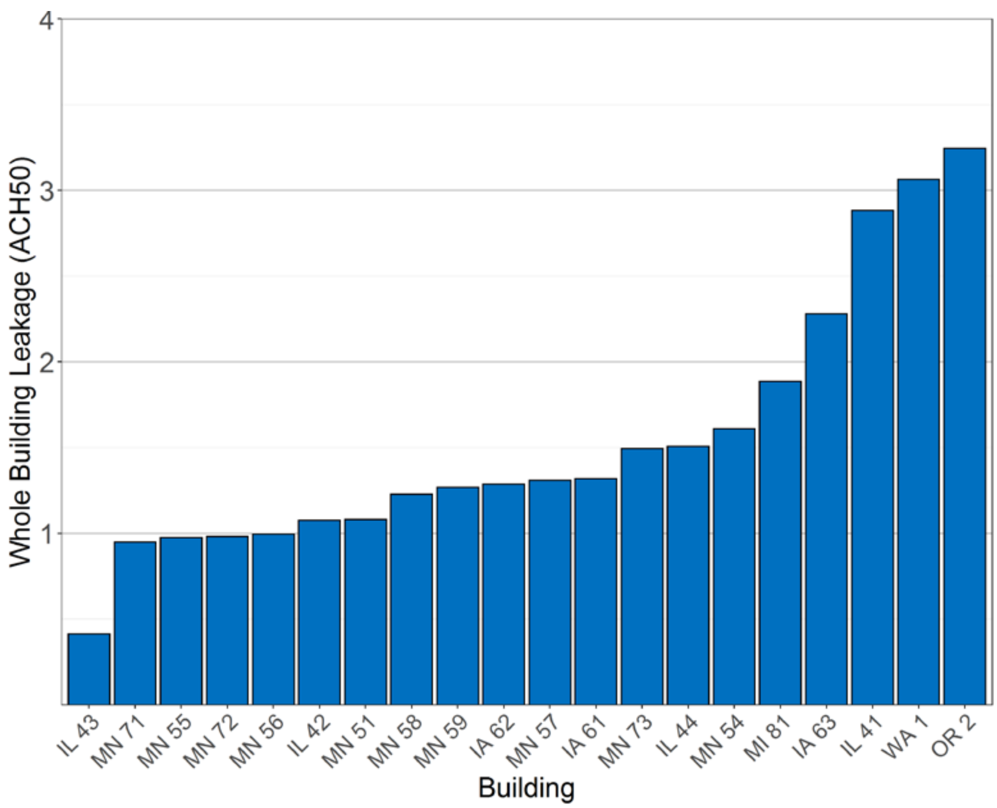


Figure 46. Distribution of Whole Building Leakage: Common Entry Buildings (ACH_{50})

Least square regressions were conducted for the whole building leakage for characteristics that were expected to impact leakage. Three single-variable regressions were conducted for: (1) state code leakage requirement (3.0, 4.0, or 5.0 ACH_{50}), (2) type of attic (flat roof = 0, vented attic = 1), and (3) participation in an energy program (no = 0, yes = 1). Table 43 displays the coefficient, standard error of the coefficient, and P-value for each of the three single-variable regressions. The results in the left portion of the table were generated using measurements from all 20 buildings. Since the leakage requirements for PHIUS certification are significantly lower than any other requirements, the regressions were repeated with the PHIUS-certified building excluded (i.e., for the remaining 19 buildings), and those results are shown in the right portion of the table.

The low P-values (< 0.01) for the first two regressions indicate that the relationship for the code-required leakage and type of attic are highly statistically significant. That was true both with and without the PHIUS-certified building. The coefficient of determination (R^2) was between 0.3 and 0.4. As expected, a positive coefficient for the code leakage indicates that measured leakage is lower for lower levels of required leakage. The positive coefficient for type of attic indicates that the buildings with vented attics have significantly higher leakage than those with flat roofs.

It is somewhat surprising that there was no statistically significant difference between the 14 buildings that participated in an energy program and the six that did not (coefficient P-values = 0.27 and 0.36, R^2 = 0.07 and 0.05 with and without the PHIUS building, respectively). A multivariable linear regression was conducted for the building measured leakage with both the code leakage level and type of attic (See Table 43). The R^2s were 0.72 and 0.83 for all of the buildings and all buildings except the PHIUS building, respectively. The coefficients were highly statistically significant (P-value < 0.001) with positive values for both variables.

Table 43. Regression of Whole Building Leakage with Other Building Characteristics

	All Buildings				**Without Illinois PHIUS Building**			
Variable	*R^2*	*Coeff.*	*Std. Err*	*P-value*	*R^2*	*Coeff.*	*Std. Err*	*P-value*
Single Variable Regressions								
Code Leakage	0.37	0.41	0.13	0.004	0.40	0.50	0.10	<0.001
Attic Type	0.35	1.06	0.21	<0.001	0.31	0.80	0.29	0.013
Energy Prgm.	0.07	-0.42	0.37	0.27	0.05	-0.34	0.36	0.36
Two Variable Regression								
Code Leakage	0.72	0.41	0.09	<0.001	0.83	0.47	0.07	<0.001
Attic Type		0.88	0.19	<0.001		0.73	0.15	<0.001

Figure 47 displays the relationship between the measured whole building leakage and the code-required leakage. The symbols are colored red for the 11 buildings with vented attics and blue for those with flat roofs. For each of the three levels of code-required leakage, the measured leakages of all of the vented-attic buildings are greater than those for the buildings with flat roofs. Figure 47 also displays the dashed least square linear regression lines for the subsets of vented-attic and flat-roof buildings[11] The coefficients for both regressions are statistically significant. The regression lines indicate that in Minnesota, the vented-attic buildings are 32% leakier than the flat-roof buildings, and the vented-attic

[11] The vented-attic building in Oregon was removed from the regression since there is no test requirement in Oregon. The symbol was plotted for a code leakage of 7.0 ACH_{50} to provide a comparison of that building to the others. Also, the Illinois PHIUS-certified building was not included in the flat roof regression due to the atypically low PHIUS leakage requirement.

buildings in Illinois and Washington (code leakage = 5.0 ACH_{50}) are 146% leakier than the flat-roof buildings. The small sample of buildings in this analysis suggests that the computed percentage differences by code-required leakage may not apply to other buildings. However, the trend for higher leakage of vented-attic buildings is consistent and is expected to hold for other buildings.

On this subject, an experienced field crew member at Center for Energy and Environment had this to say:

> For vented attics in multi-family buildings, sealing is usually done with fire caulking, which is not as good of a seal as foam or caulk. There can be large chaseways of plumbing and venting that are not sealed as well either. For flat attics … the roof is generally very air-tight due to the foamed band, plywood, foam and rubber on the roof. Overall, new construction insulators do not fully understand sealing bypasses, and they most likely are not going to air seal a penetration they see is already fire-caulked below. The person blowing the attic usually …has no real training or understanding of why to air seal, as they would assume it was done below [someone else]. With fire-caulking, we find it best practice still to foam and/or caulk from above, as the fire caulking cracks, shrinks, and moves as the building is being built and wood dries. (Anderson 2019)

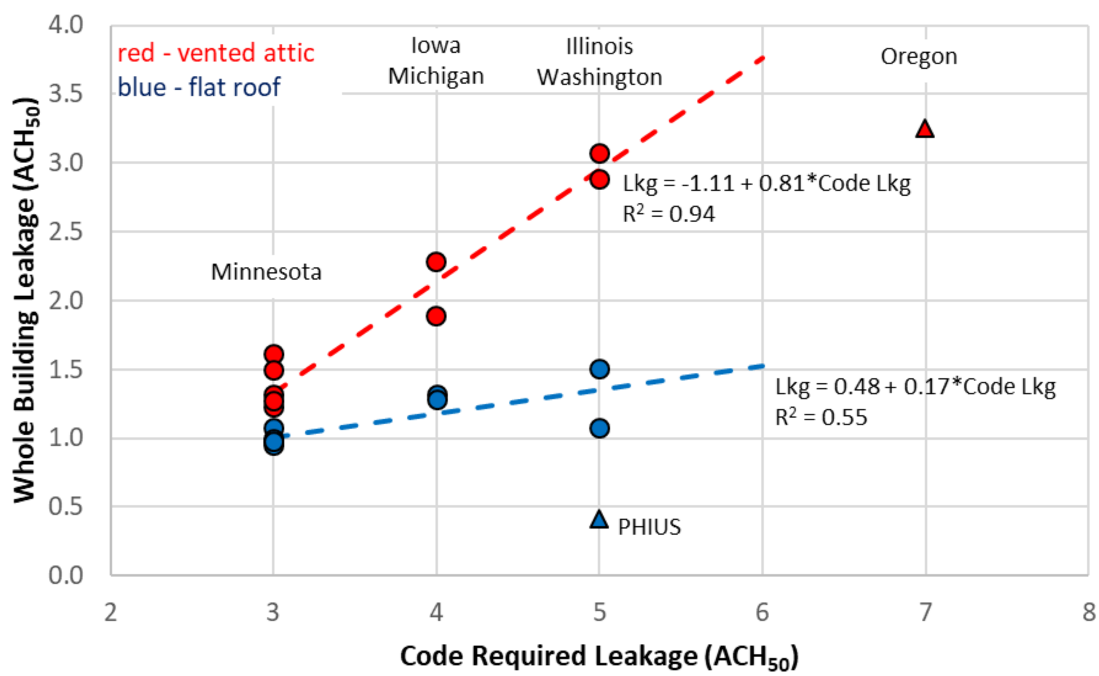


Figure 47. Impact of Code Required Leakage and Attic Type on Whole Building Leakage (ACH_{50})

It was expected that other building characteristics such as the type of space under the bottom floor and type of exterior wall air barrier could impact whole building exterior leakage. However, for each of those variables there were five or more types and a small number of buildings with each type. An evaluation of measured to regression model leakage was used to evaluate the impact of the two variables on building leakage. The two regressions of the measured leakage with code-required leakage for the vented-attic and flat-roof buildings (as shown in Figure 47) were used for the modeled values. Figure 48 displays the residuals for the five types of space under the bottom floor. Values that fall below the thick black line indicate that the measured leakage was lower or tighter than the model had estimated, and measurements above were leakier. If a type of space (e.g., garages) produces tighter buildings, it is expected that significantly more than half of the residuals (i.e., blue circles) would be below the line. However, for all four types of spaces with two or more results there was a relatively even distribution of positive and negative residuals (i.e., circles above and below the line). This indicates that the type of space under the bottom floor did not have a noticeable impact on the whole building exterior leakage for this sample of buildings.[12]

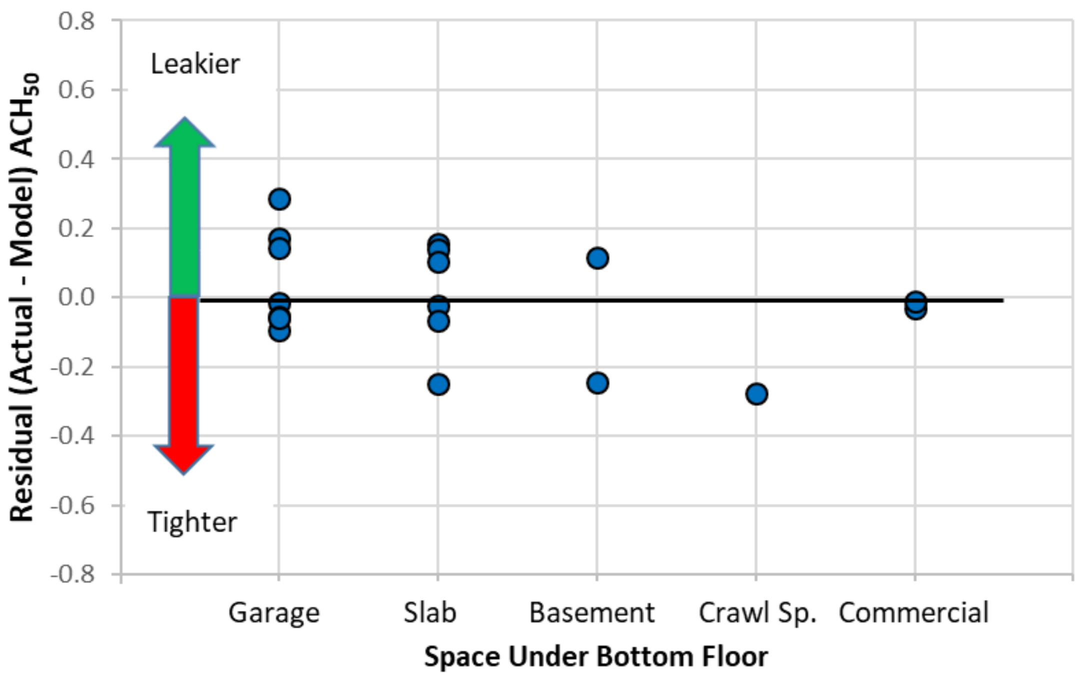


Figure 48. Whole Building Leakage Model Residual vs. Type of Space Under Bottom Floor

A residual analysis was also performed for the type of exterior wall air barrier (see Figure 49). For all four types of air barriers with two or more results there was a relatively even distribution of positive and negative residuals. This indicates that the type of air barrier did not have a noticeable impact on the whole building exterior leakage for this sample of buildings. Since the measured leakage was at least 39% below the
leakage required by code for their state for all of the buildings, this suggests that all of the air barrier designs can be successful.

It is important to note that the results from the regression and residual analysis only apply to the 20 buildings tested from the six states. While this is a moderate number of buildings and states, almost all of the buildings were from states that required envelope air leakage testing and 16 (64%) of the buildings were being certified for an energy efficiency program. This sample of buildings is not expected to be representative of all U.S. new construction low-rise multifamily buildings. A greater number of buildings from a greater number of states is necessary to reach conclusions applicable to U.S. new construction.

[12] Using a model that includes the type of attic and state code leakage requirement.

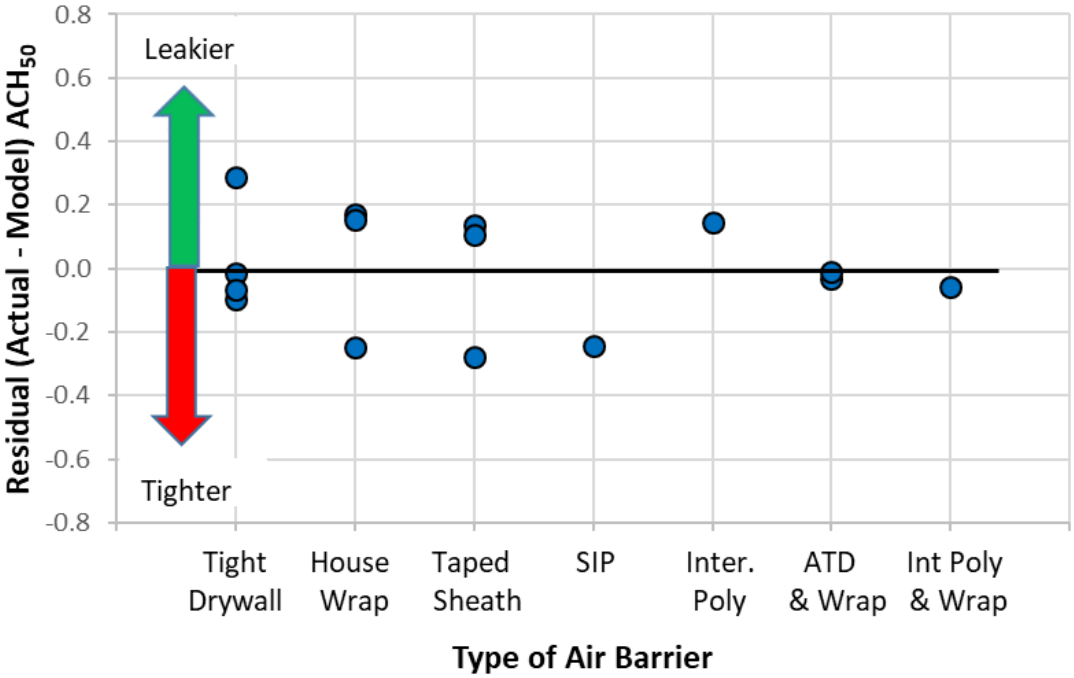


Figure 49. Whole Building Leakage Model Residual vs Type of Exterior Wall Air Barrier

The 2012, 2015, and 2018 editions of the IECC specify a volume-normalized leakage in units of ACH_{50}. However, some codes and energy programs use a surface-area-normalized (six-sided) leakage. Since the relationship between the volume and exterior surface area of a building is not consistent, the conversion between the two leakage rates is not constant. Figure 50 shows the multiplier to convert ACH_{50} to CFM_{50}/ft^2 for the common-entry buildings. The symbols are coded by color for the number of building stories (two-story = green and three-story = red) and by type for the number of units (≤ 25 = triangle and > 25 = circle). The multiplier generally increases for increasing building floor area. This is expected since the relative amount of exterior surface area needed to contain the volume of a building generally decreases for larger buildings. For the three-story buildings with more than 25 units the average multiplier was 0.150 with a range from 0.144 to 0.157 (average # units = 46).[13] For these buildings a volume-based leakage requirement of 3.0 ACH_{50} would on average convert to a surface area based requirement of 0.45 CFM_{50}/ft^2. For the smaller three-story buildings with 25 or fewer units, a volume-based leakage requirement of 3.0 ACH_{50} would on average convert to a surface area-based requirement of 0.36 CFM_{50}/ft^2. The two two-story buildings with commercial space below the bottom floor are outliers because the surface area of the bottom floor was not included in the exterior surface area. The only other two-story building had a low multiplier of 0.088.

These results demonstrate that if a surface area-based leakage requirement of 0.45 CFM_{50}/ft^2 were selected for code or program compliance, for the larger buildings the requirement would be about the same as a 3.0 ACH_{50} requirement. However, for smaller buildings, 0.45 CFM_{50}/ft^2 would be equal to about 3.8 ACH_{50}. Overall, buildings that are smaller and have a more irregular shape (e.g. bump outs) will more easily meet an exterior surface-based standard than buildings that are larger and more cubic.

[13] The units of the multiplier are ft -hr/min

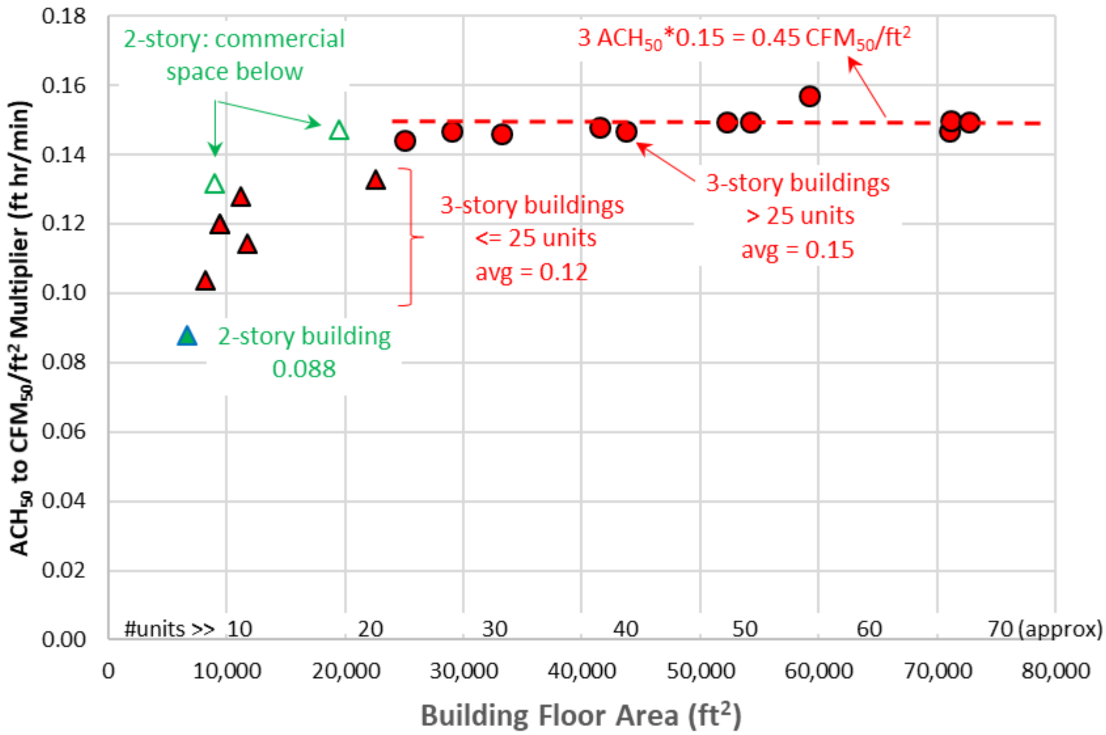


Figure 50. Multiplier to Convert Leakage from ACH_{50} to CFM_{50}/ft^2: Common Entry Buildings

The variation of the multiplier with building size and number of stories was examined by computing the multiplier for a rectangular, common entry prototype building with a variable number of units (see Figure 51). Average unit and common space dimensions of the tested common entry buildings were used to establish the configuration of the prototype building. The prototype had an 860 ft^2 (28 x 30.7 ft) unit on each side of a six-foot-wide hallway. Extra common area space was added across the width of the center portion of the building so that the residential area was 80% of the total building area[14]. Each floor had at least four units and units were added to each end of the building to increase the total floor area so that it ranged from about 5,000 to 70,000 ft^2. The multipliers were computed for one-, two-, and three-story buildings. Each story had a height of 10 ft.

[14] The sum of the residential and common space floor area was 1,075 ft^2 per unit.

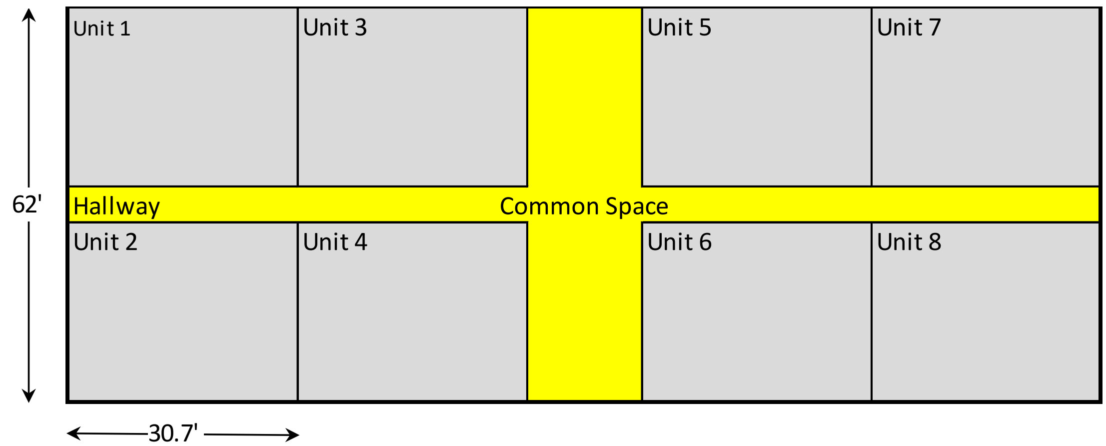


Figure 51. Rectangular Prototype Common Entry Building (Plan View)

The relationship between the multiplier and building total floor area for the prototype building and tested buildings is shown in Figure 52. As expected, the prototype building multipliers (solid lines) increased with increasing floor area and number of floors. The increase in the multiplier with increasing floor area is significant as the floor area increases from 5,000 to 20,000 ft^2 and then levels out for larger floor areas. The multiplier is about 70% greater for two-story buildings than one-story buildings with the same floor area and the multiplier is about 30% greater for three-story buildings than two-story buildings. The multipliers for the tested buildings were equal to or slightly below the values for the prototype buildings with the same number of stories. The multipliers for the tested buildings are expected to be lower than those for the prototype when it is not rectangular and there are bump outs.

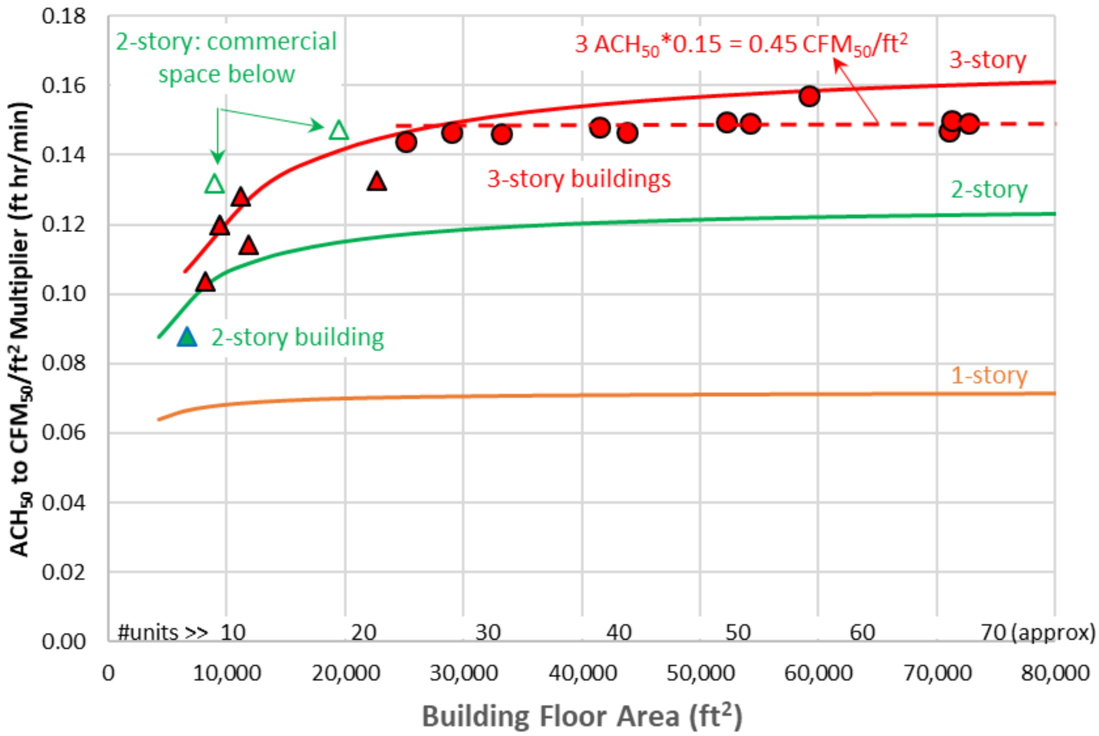


Figure 52. Multiplier to Convert Leakage from ACH_{50} to CFM_{50}/ft^2 for Common Entry Buildings

The whole building surface-area-normalized exterior leakage of the common-entry buildings ranged from 0.05 to 0.38 CFM_{50}/ft^2 with an average of 0.20 CFM_{50}/ft^2. (See Table 42, Figure 53, and Figure 54.) At the time of the testing, none of the states had a code requirement for envelope leakage that was based on exterior surface area. All of the buildings had an exterior leakage rate less than 0.40 CFM_{50}/ft^2, 85% were below 0.30 CFM_{50}/ft^2, and 55% were below the USACE requirement of 0.19 CFM_{50}/ft^2. The relationship of surface-area-normalized leakage to state code required leakage specified in ACH_{50} is not as strong as the relationship for measured volume-normalized leakage[15] (See Figure 55). It is logical that the level of code required leakage is more strongly related to the leakage value that uses the same method for normalization, but the sample size is too small to draw any significant conclusions.

[15] In addition to higher R^2 values for the measured surface-area-normalized leakage, the coefficient P-values were higher for both flat-roof and vented-attic buildings.

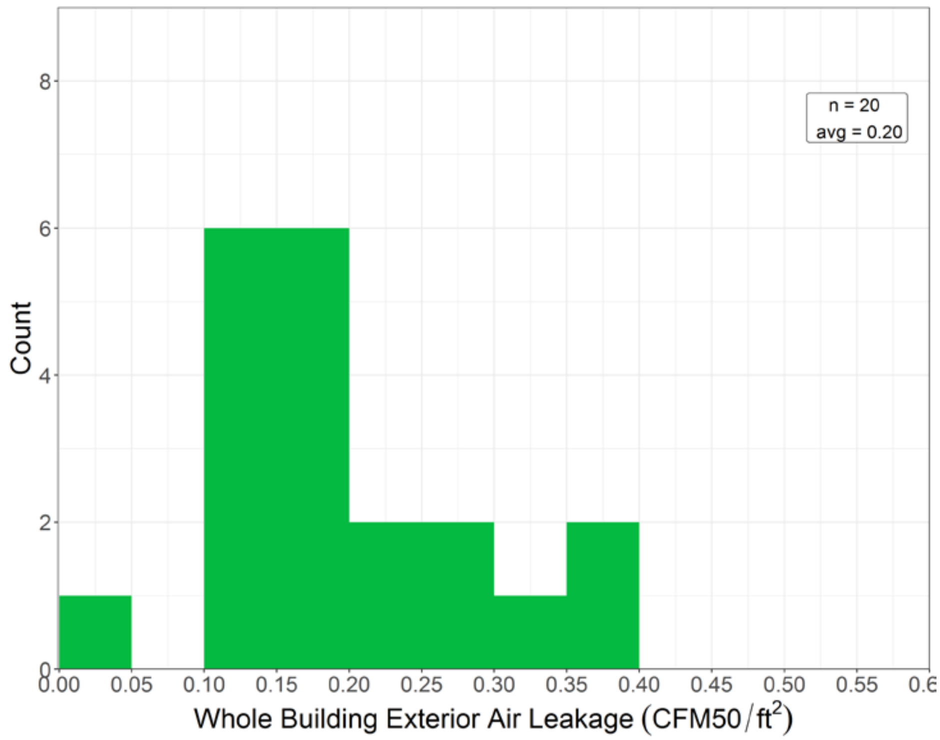


Figure 53. Histogram of Whole Building Leakage: Common Entry Buildings (CFM_{50}/ft^2)

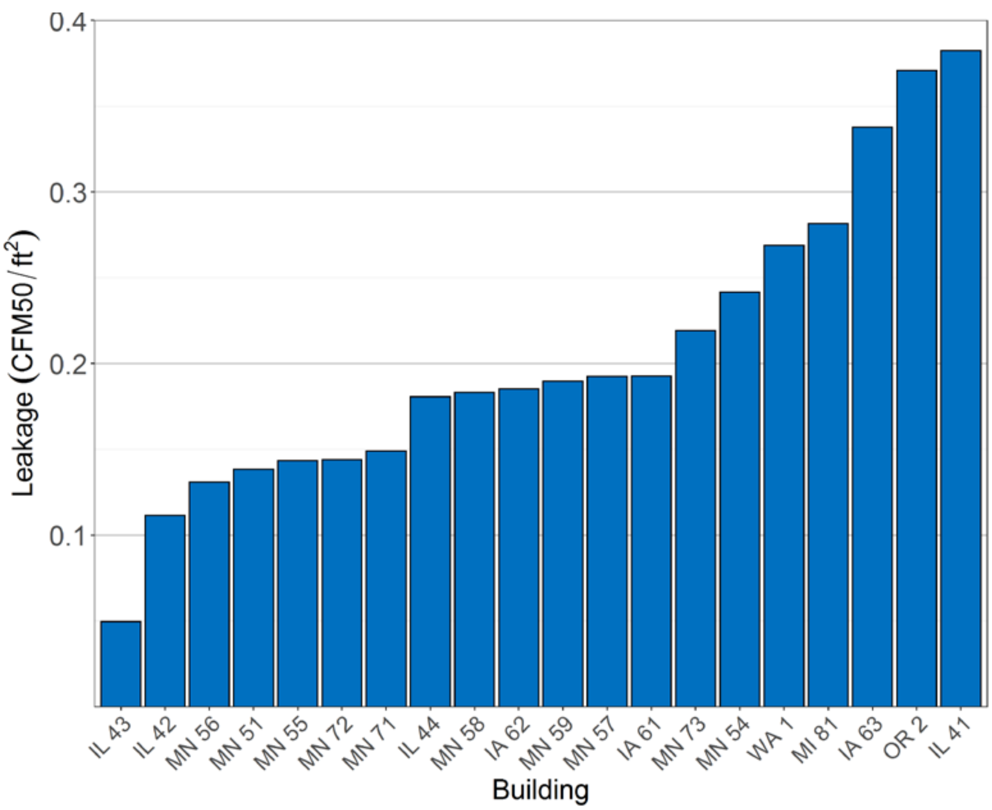


Figure 54. Distribution of Whole Building Leakage: Common Entry Buildings (CFM_{50}/ft^2)

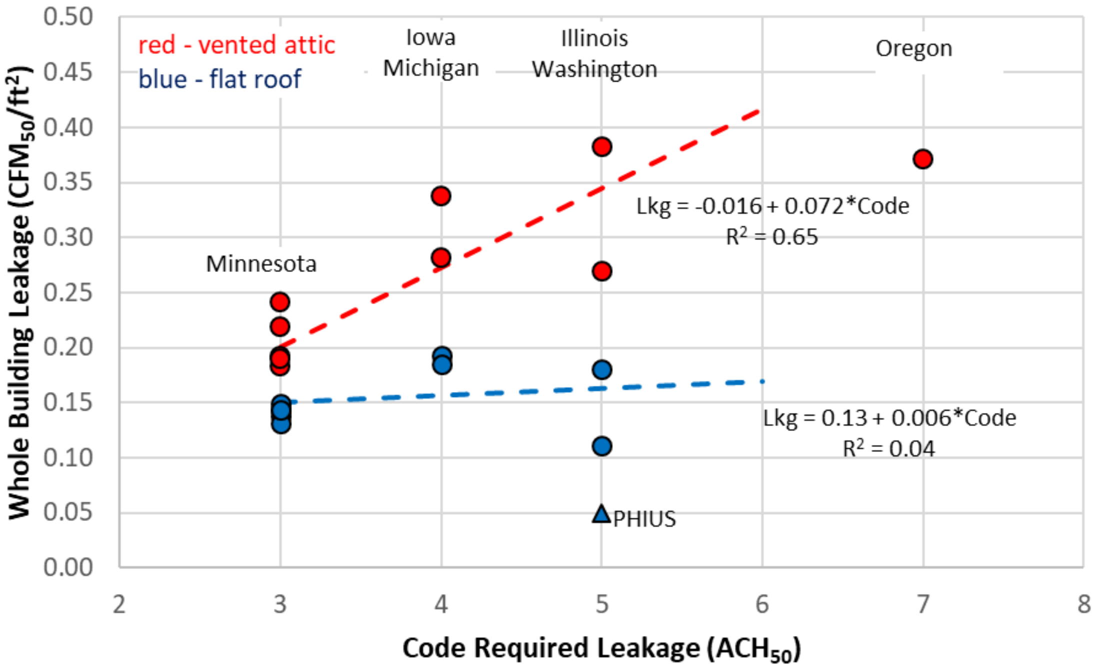


Figure 55. Impact of Code-Required Leakage and Attic Type on Whole Building Leakage (CFM_{50}/ft^2)

4.2.2 Garden-Style Buildings

Whole building exterior leakage of the four garden-style buildings ranged from 1.97 to 4.72 ACH_{50} and averaged 2.83 ACH_{50}.[16] (See Table 44, Figure 56, and Figure 57.) The leakage for three of the buildings was below 2.5 ACH_{50}. The leakage for all of the buildings was at least 6% below the leakage required by code for their state. The two buildings in Minnesota were 26% and 34% below the 3.0 ACH_{50} code requirement, and the building in Washington was 6% below the 5.0 ACH_{50} requirement. On average, the buildings were 22% below the code-required leakage. Due to the small number of buildings and consistency of the building characteristics, an exercise correlating whole building air leakage to building characteristics was not conducted.

[16] Tests were conducted on a fifth building, but exterior leakage results are only available for the first- and third-floor units. It is not possible to compute a valid estimate of the exterior leakage for the entire building.

Table 44. Whole Building Leakage: Garden-Style Buildings

	Whole Building Leakage	
ID	*(ACH_{50})*	*(CFM_{50}/ft^2)*
MN 52	1.97	0.20
MN 53	2.23	0.22
OR 4	2.38	0.28
WA 3	4.72	0.47
Average	2.83	0.29
Median	2.31	0.25
Min.	1.97	0.20
Max.	4.72	0.47

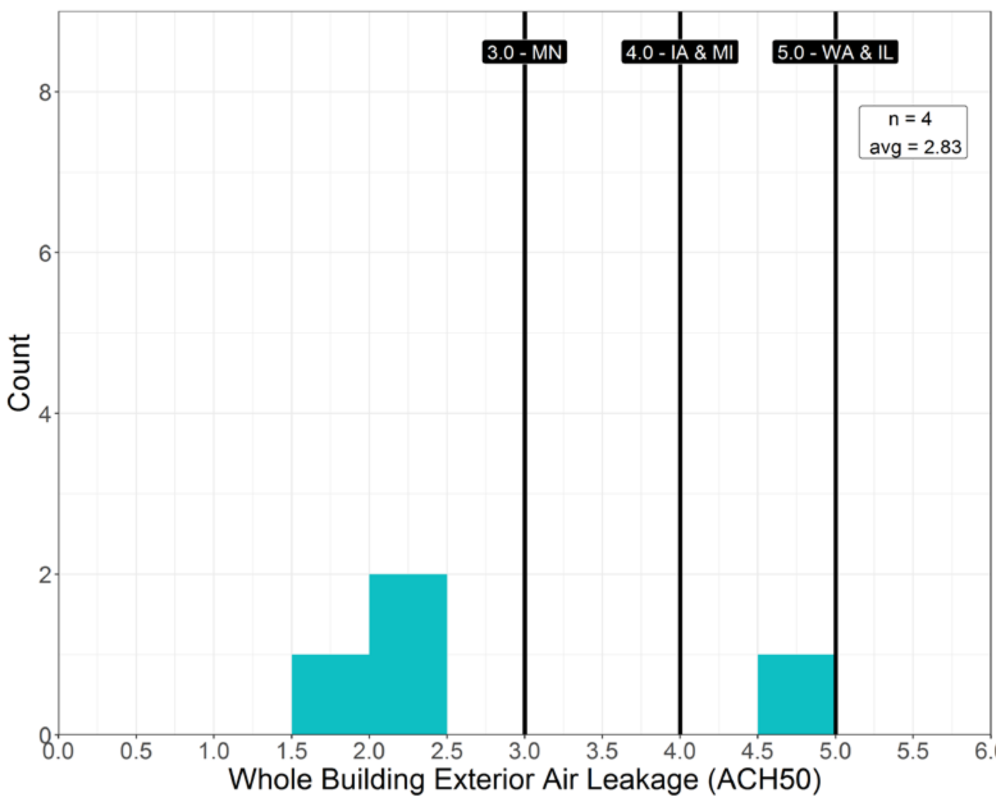


Figure 56. Histogram of Whole Building Leakage: Garden-Style Buildings (ACH_{50})

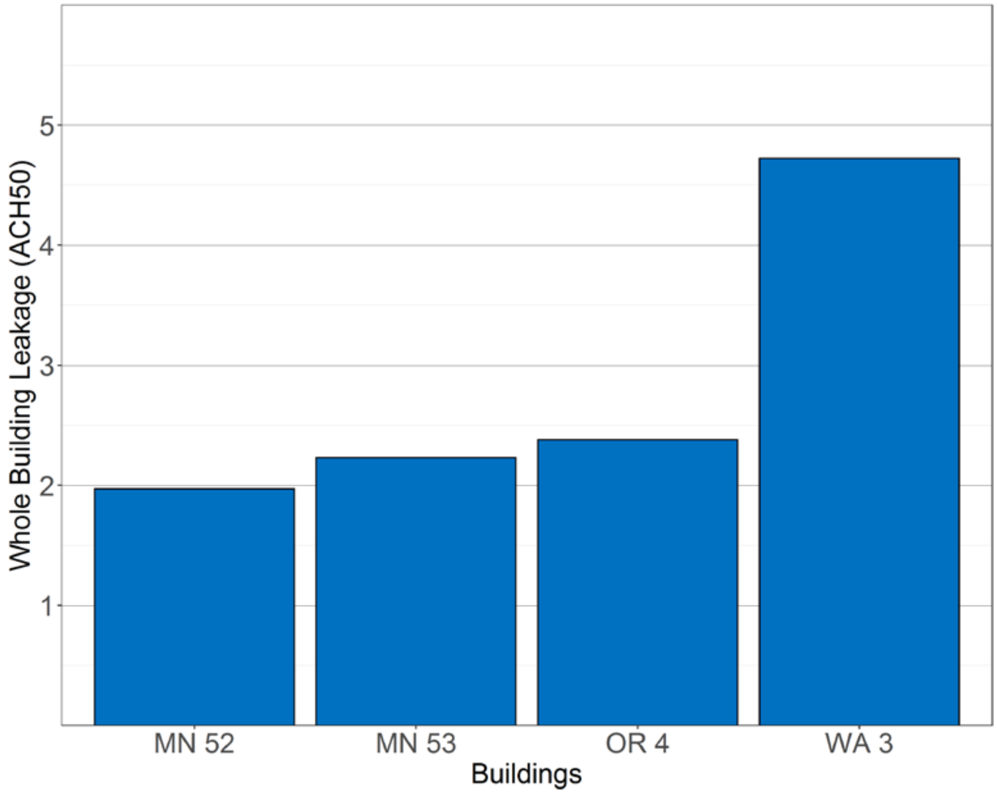


Figure 57. Distribution of Whole Building Leakage: Garden-Style Buildings (ACH_{50})

Compared to the common-entry buildings, the five garden-style buildings had a relatively narrow range in floor area, from 11,073 to 23,344 ft^2. Consequently, the multiplier to convert ACH_{50} to CFM_{50}/ft^2 only ranged from 0.099 to 0.120 ft-hr/min and averaged 0.106 ft-hr/min. The building layout had more impact on the multiplier than the size of the building. The three-story building in Oregon had the smallest floor area, but the cubic design resulted in the largest multiplier. The two largest buildings in Minnesota were long and thin, which resulted in the lowest multiplier: 0.099 ft-hr/min.

The average surface-area-normalized leakage of the garden-style buildings was 44% greater than the average for the common-entry buildings. The whole building surface-area-normalized exterior leakage of the garden-style buildings ranged from 0.20 to 0.47 CFM_{50}/ft^2 and averaged 0.29 CFM_{50}/ft^2. (See Table 44.) At the time of the testing, none of the states had a code requirement for envelope leakage that was based on exterior surface area. Three of the four buildings had a leakage rate less than 0.40 CFM_{50}/ft^2, three were below 0.30 CFM_{50}/ft^2, and none were below the USACE requirement of 0.19 CFM_{50}/ft^2.

4.2.3 Impact of Common Area on Whole Building Leakage

One advantage of a whole building test of common-entry buildings is that it includes the exterior leakage of both residential and common areas. As shown in Table 42, the residential portion of each building's exterior envelope surface area accounts for 55% to 96% of the total and averages 78%. Consequently, on average, exterior leakage tests that exclude the common area do not measure the leakage of about 20% of the exterior envelope, and for some buildings that portion is as high as 45% of the total envelope. Since the construction of the exterior envelope of the common areas is similar to that for the residential spaces, it might be expected that the surface-area-normalized leakage for the two spaces are similar. However, the measurements for the test buildings indicate that the common area portion of the buildings is typically significantly leakier than the residential portion, and the total leakage through the common area exterior envelope was sometimes greater than that through the residential exterior envelope.

For the seven buildings with 12 or fewer units, the residential portion of the exterior leakage was computed from the sum of the individual unit exterior leakages measured from the guarded tests. For the other 13 buildings, the residential exterior leakage was computed from the sum of the exterior leakage of the tested units multiplied by the total residential exterior surface area divided by the sum of the exterior surface area of the tested units. The residential exterior leakage was also computed from floor area and volume weighted averages from the tested units. Those values were typically within 2% of the surface area-weighted values. In addition, testing about the same number of units on each floor and including a variety of unit floor plans helped ensure a representative sample of unit leakages. The common area leakage was computed as the difference between the whole building measurement and the computed total for the residential units.

The exterior volume-normalized leakage of the residential portion of the buildings ranged from 0.40 to 3.21 ACH_{50} with an average of 1.36 ACH_{50}. The exterior leakage for the common areas ranged from 0.38 to 6.16 ACH_{50} with an average of 2.34 ACH_{50}. As shown in Figure 58, the common area exterior leakage was greater than that for the residential units for 17 (85%) of the buildings. For seven (35%) of the buildings, the common area leakage was more than two times greater than that for the residential units, and, on average, the common area leakage was 76% greater than that of the residential units.

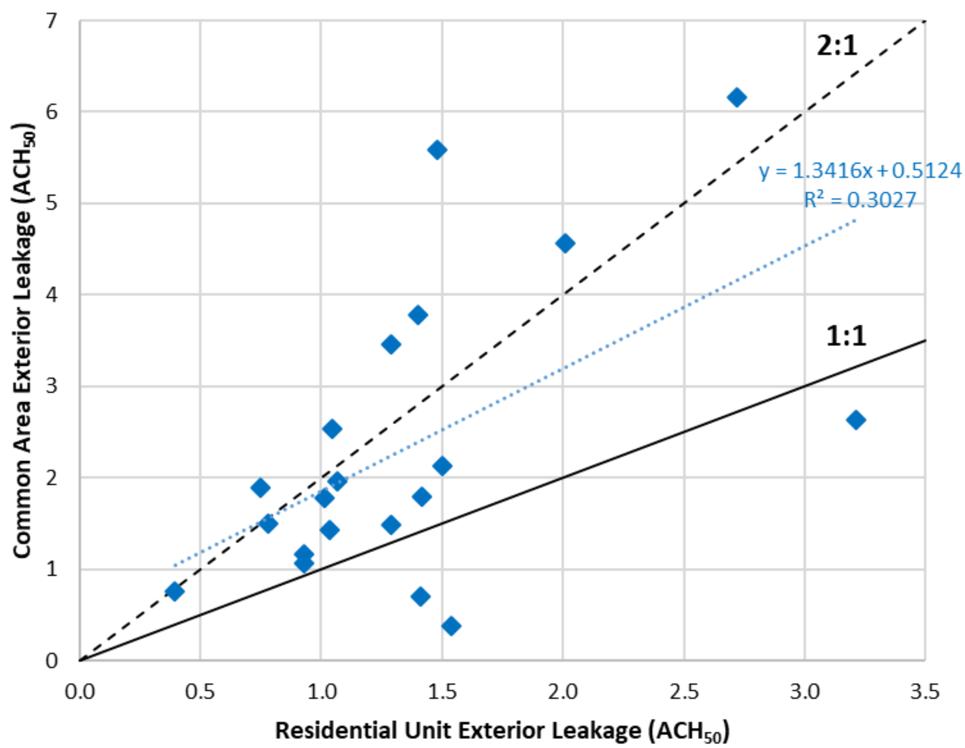


Figure 58. Comparison of Common and Residential Area Leakage (ACH_{50})

There was a similar trend for the exterior surface-area-normalized leakage. The exterior leakage of the residential portion of the buildings ranged from 0.05 to 0.30 CFM_{50}/ft^2 with an average of 0.18 CFM_{50}/ft^2. The exterior leakage for the common areas ranged from 0.04 to 0.88 CFM_{50}/ft^2 with an average of 0.33 CFM_{50}/ft^2. As shown in Figure 59, the common area exterior leakage was greater than that for the residential units for 16 (80%) of the buildings. For eight (40%) of the buildings, the common area leakage was more than two times greater than that for the residential units, and on average, the common area leakage was 80% greater than that for the residential units.

The relationship between the whole building, common area, and residential unit exterior leakage for individual buildings is shown in Figure 60. The distance that the red diamonds (residential leakage) and gray circles (common area leakage) are above or below the top of the blue bars indicate the impact that the leakage of each portion of the building has on the whole building leakage. When a large percentage of the whole building exterior surface area is from the residential units, the top of the blue bar (e.g., whole building leakage) is closer to the red diamond (i.e., residential leakage).

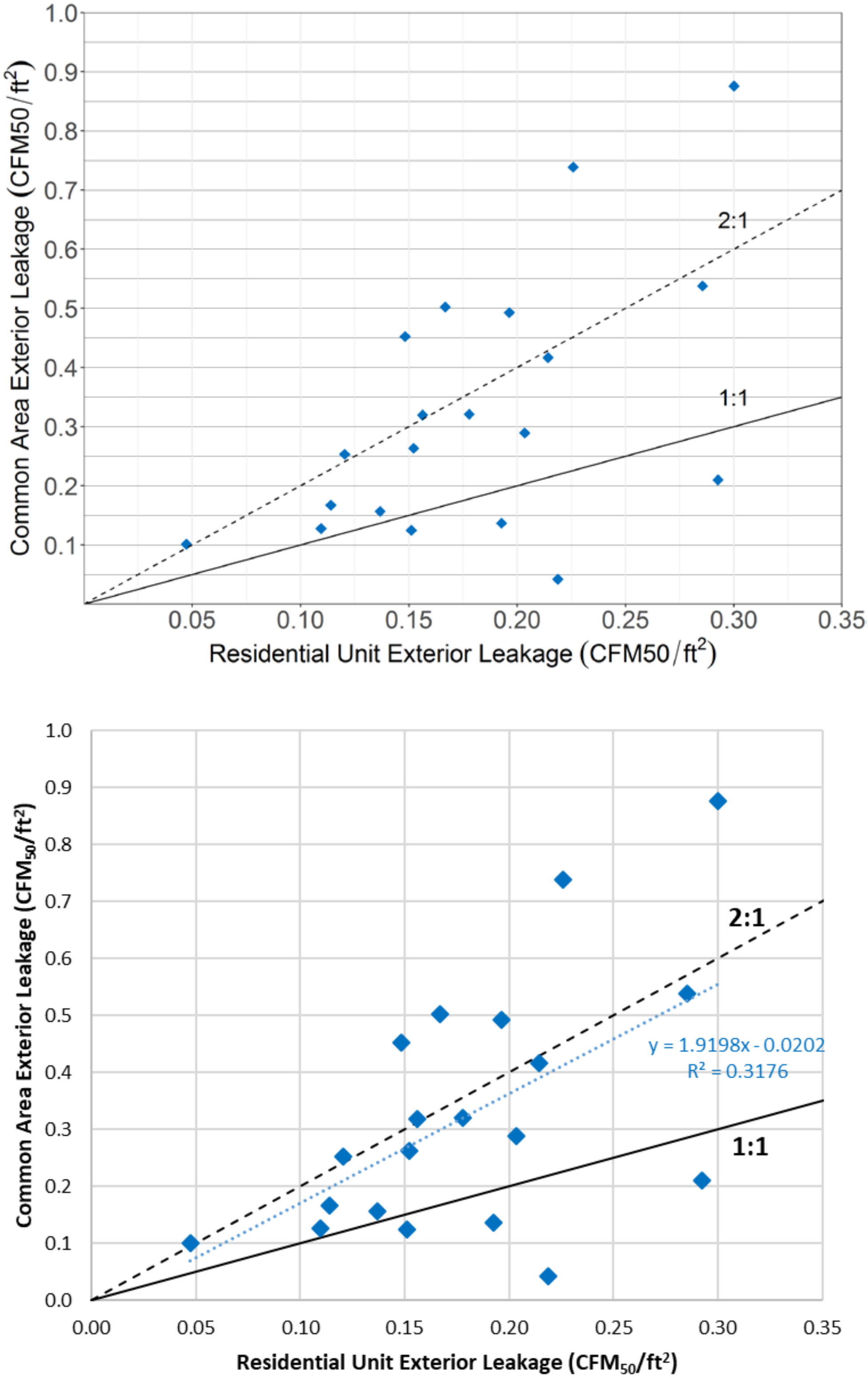


Figure 59. Comparison of Common and Residential Area Leakage (CFM_{50}/ft^2)

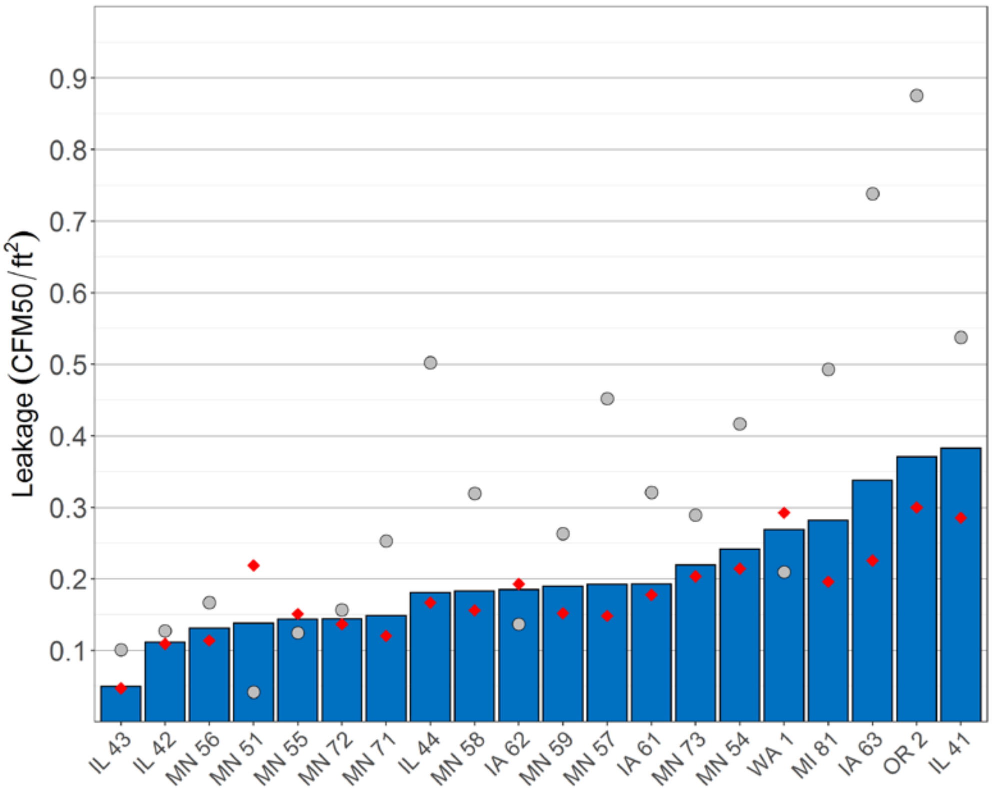


Figure 60. Whole Building (blue bars), Common Area (gray circles), and Residential (red diamonds) Leakage (CFM_{50}/ft^2)

Figure 61 displays the relationship between the percentage of exterior volume-normalized leakage for the common area and the percentage of the building volume that is from the common area. If the volume-normalized leakage of the common area was equal to that for the residential units, the percentage of common area leakage would be equal to the percentage of common area volume and the symbols would fall on the one-to-one line of agreement. However, as noted previously, the common area leakage is less than that for the residential units for only three of the buildings (e.g., three symbols below the one-to-one line).

The figure also shows that the common area portion of each building's volume accounts for 5% to 39% of the total and averages 21%. In addition, the common area portion of each building's exterior leakage accounts for 8% to 54% of the total and averages 29%. For six (30%) of the buildings, the common area accounts for 40% or more of the whole building leakage. For the 16 buildings where the common area was leakier than the residential units, if the surface-area-normalized leakage for the common area exterior envelope was the same as that for the residential units, the whole building leakage would be reduced by an average of 15%. For five of the buildings, the reduction would be 20% or greater.

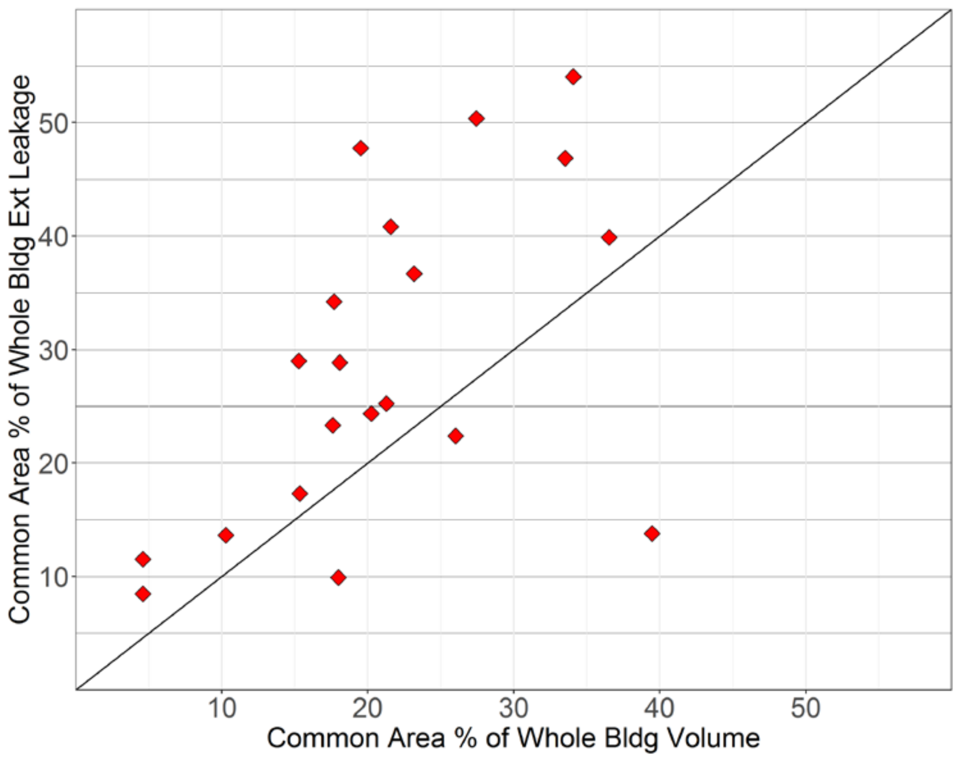


Figure 61. Comparison of Common Area % Whole Building Exterior Leakage and Volume

Although the field protocol did not include an investigation of the types, magnitudes, and locations of individual leaks that could be used to assess why the exterior envelopes of common spaces were leakier than those of the dwelling units, field staff and others familiar with multifamily construction details have suggested many possibilities.

Stairways and especially elevator shafts can have very leaky doors that connect each floor to leaks at the top and bottom of the shafts. Both can have doors opening to underground garages, and stairways often have doors leading to an attic, to the roof, or to the outdoor ground level. Elevator shafts can be vented at the top or well connected to mechanical rooms on the roof which leak to the outside. Trash chutes are vented at the top and lead to a trash bin room at the bottom that often leaks to the outside. Many of the exterior doors of a building open into the common space. Laundry rooms can have leaky dryer vents and sometimes makeup air inlets that have leaky dampers. Hallway ventilation systems often have fire dampers that can be sealed during a test but might still have significant leakage.

Even though the common space exterior wall construction was usually similar to that of the units, it was suggested that there may have been more attention to the details of sealing in the units because it was known that they would get compartmentalization testing. Over half of the buildings were ENERGY STAR-rated, which requires this testing.

4.3 Comparison of Individual Unit Total and Exterior Leakage

One of the project objectives was to document the difference between the total and exterior leakage of individual units. A secondary objective was to identify trends in the difference between the total and exterior leakages. As noted previously, it was anticipated that the common areas of the common-entry buildings would contribute to significant differences in air leakage results between the common-entry and garden-style buildings. Consequently, the analyses of leakage trends were performed separately for common-entry and garden-style buildings.

4.3.1 Common Entry Buildings

Figure 62 displays the cumulative distribution and Figure 63 displays histograms of the volume-normalized exterior and total leakage for the 206 units tested in the 20 common-entry buildings. The sets of exterior and total leakage values are sorted independently for the cumulative distributions. Consequently, for any given percentile, the total leakage and exterior leakage values are not for the same unit. The average exterior leakage was 1.41 ACH_{50} with 25th percentile, median, and 75th percentile values of 0.77, 1.03, and 1.74 ACH_{50}, respectively. The interquartile range (IQR) of 0.97 ACH_{50} was 94% of the median.[17] There was greater variation, or a larger tail, for the higher leakage values. The difference between the median and 10th percentile values was 0.41 ACH_{50}, while the difference between the 90th percentile and median values was 4.5 times greater (1.82 ACH_{50}). There was a similar shape for the distribution of total leakage, but the relative variation was somewhat smaller, and the values were two to four times greater than the exterior leakages at the same percentiles. The average total leakage was 4.10 ACH_{50} with 25th percentile, median, and 75th percentile values of 2.98, 3.70, and 4.98 ACH_{50}, respectively. The IQR of 2.0 ACH_{50} was 54% of the median. The difference between the median and 10th percentile values was 1.16 ACH_{50}, while the difference between the 90th percentile and median values was 2.3 times higher (2.65 ACH_{50}).

[17] IQR = difference between the third and first quartile values.

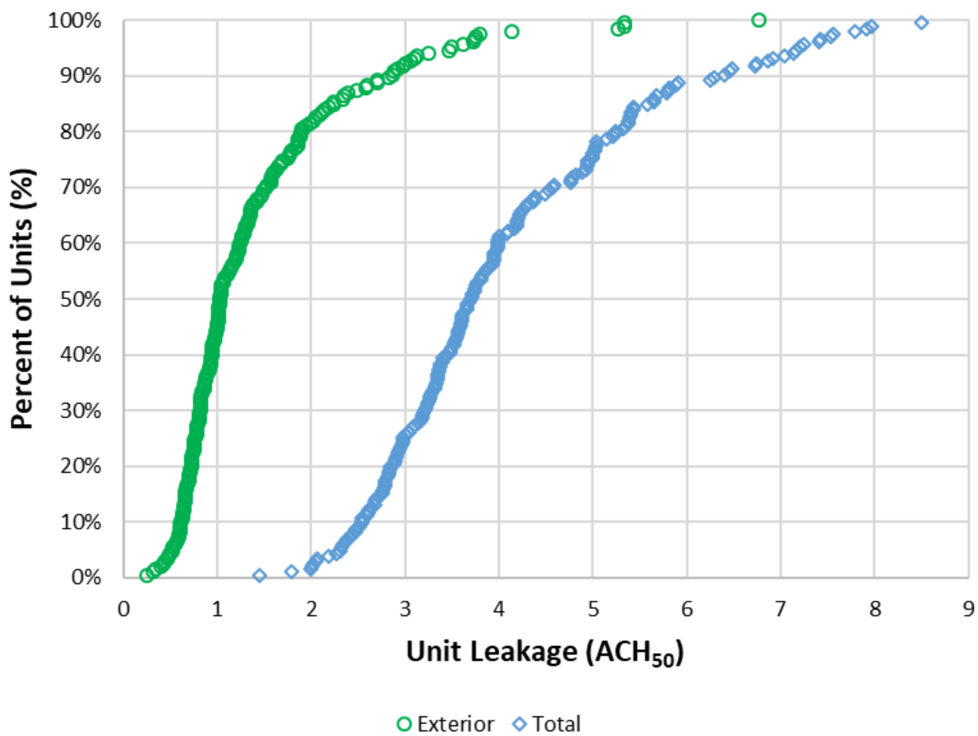
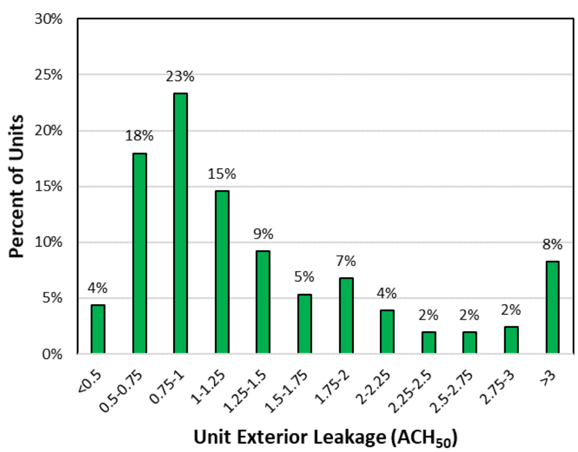


Figure 62. Cumulative Distribution of Unit Total and Exterior Leakage: Common-Entry Buildings (ACH_{50})



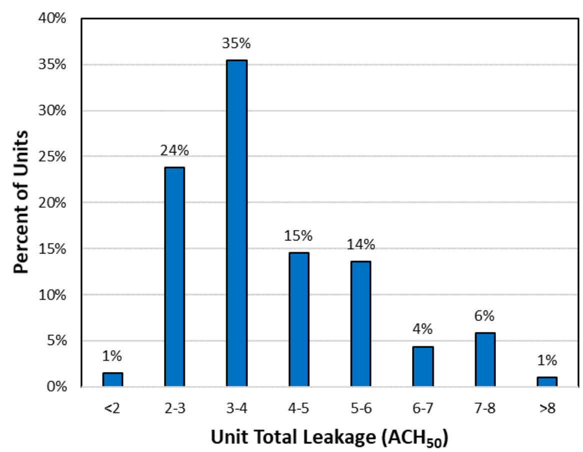


Figure 63. Histograms of Unit Exterior and Total Leakage: Common-Entry Buildings (ACH_{50})

If the same leakage criterion is applied to the exterior and total volume-normalized leakage, the failure rate is considerably higher for the total leakage. For example, 92% of the units had an exterior leakage of 3.0 ACH_{50} or less, but only 26% of the units had a total leakage of 3.0 ACH_{50} or less. While 98% of the units had an exterior leakage of 4.0 ACH_{50} or less, 62% had a total leakage of 4.0 ACH_{50} or less, and 75% of units leaked at 5.0 ACH_{50} or less.

Figure 64 displays the same distribution of total leakage that was included in Figure 62. Instead of sorting the exterior leakage values independently from the total leakage, the exterior leakage associated with the total leakage of a unit is plotted directly to the left (e.g., at the same height) of the total leakage. This shows the large range in exterior leakage that can occur for similar values of total leakage. For example, for total leakages of 4.0 ± 0.2 ACH_{50}, the exterior leakage ranges from 0.90 to 3.10 ACH_{50} with an average of 1.64 ACH_{50} and standard deviation of 0.77 ACH_{50}. The range in exterior leakage is more than five times greater than the range in total leakage. This is primarily due to the higher leakage of the units on the top floor of the buildings with vented attics.

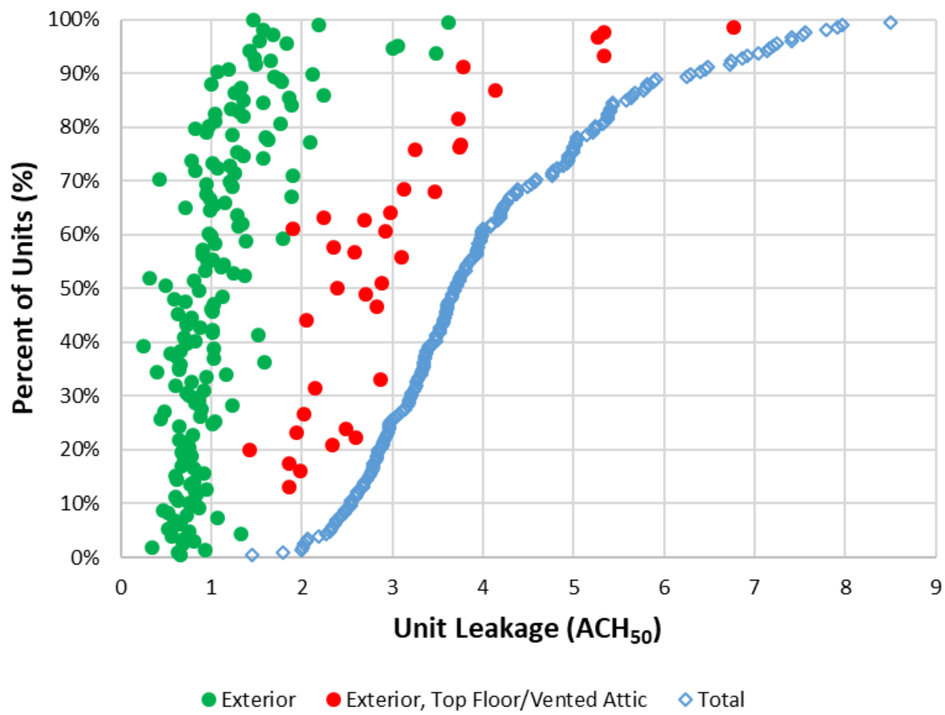


Figure 64. Cumulative Distribution of Unit Total and Exterior Leakage: Common-Entry Buildings (ACH_{50})

Figure 65 shows a box-and-whisker chart for the total (blue) and exterior (green) volume-normalized leakage of the units tested in the 20 common-entry buildings.[18] The buildings are sorted from the lowest median exterior leakage to the left and the higher values to the right. Building IL43 was constructed to PHIUS standards and had the lowest median exterior leakage of 0.42 ACH_{50}. Building OR2, which was not subject to a state code air tightness requirement, had the highest median exterior leakage of 3.0 ACH_{50}.

[18] For each box-and-whisker chart, the median is indicated by the horizontal line inside the box. The bottom of the box is the first quartile value and the top is the third quartile value. The bottom of the lower whisker is the minimum, and the top of the upper whisker is the maximum — excluding outliers that are designated as dots.

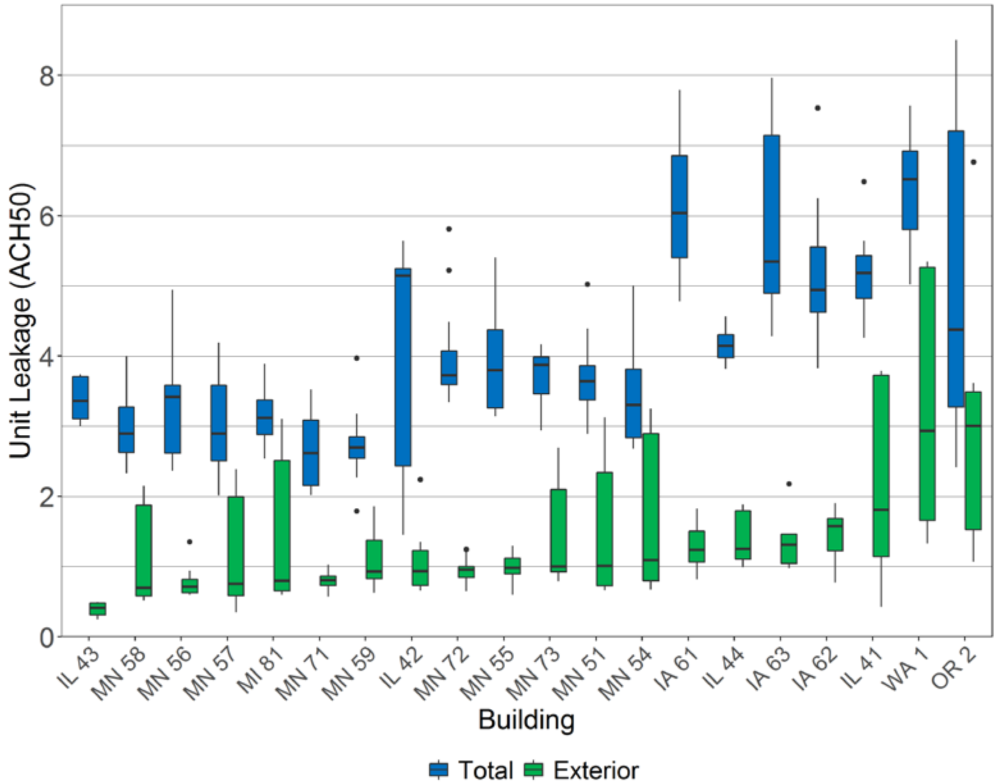


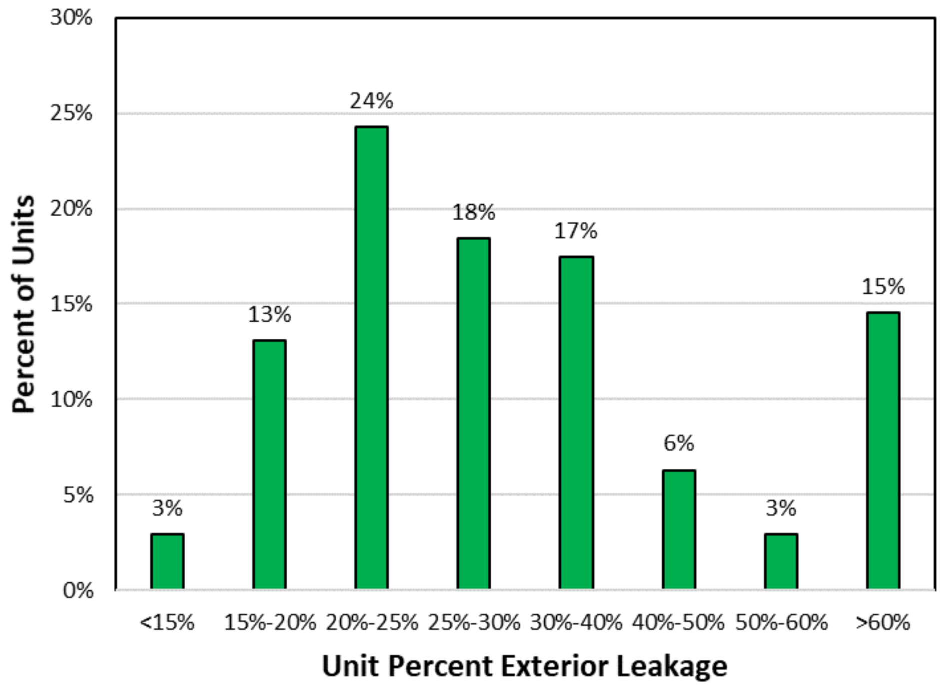
Figure 65. Unit Total and Exterior Leakage by Building: Common-Entry Buildings (ACH_{50})

While there is a general trend for increasing total leakage for buildings with increasing exterior leakage, there is significant variation in the trend of increasing total leakage. A regression of average exterior leakage for the units in a building to average total leakage results in an R^2 of 0.41 and a statistically significant coefficient (0.40). This suggests that there are factors other than simply the magnitude of the total leakage that impact the exterior leakage of a unit.

As indicated by the relative height of the green bars, there is a significant difference in the variation of the exterior volume-normalized leakage of the units tested in each building. For example, for Building MI81, the difference between the maximum and minimum exterior leakage was 178% of the average, while for building MN71 the difference was 57% of the average. The variation in leakage for units in the same building is discussed in Section 4.6.3.

The exterior leakage as a percentage of the total for a unit provides a direct comparison between the two values. Figure 66 displays the cumulative distribution, and Figure 67 displays the histogram of the percent exterior leakage for the 206 units measured in the 20 common-entry buildings. The average percent exterior leakage was 34.3% with 10th, 25th, 50th, 75th, and 90th percentile values of 18.4%, 22.4%, 27.5%, 39.1%, and 69.5%, respectively. The IQR of 16.7% was 61% of the median. There was greater variation, or a larger tail, for the higher percentages. For example, the difference between the median and 10th percentile values was 9.1%, while the difference between the 90th percentile and median values was 4.6 times greater (42.0%). A total of 15% of the units had a percent exterior leakage greater than 60%.

Figure 66. Cumulative Distribution of Unit % Exterior Leakage: Common-Entry Buildings



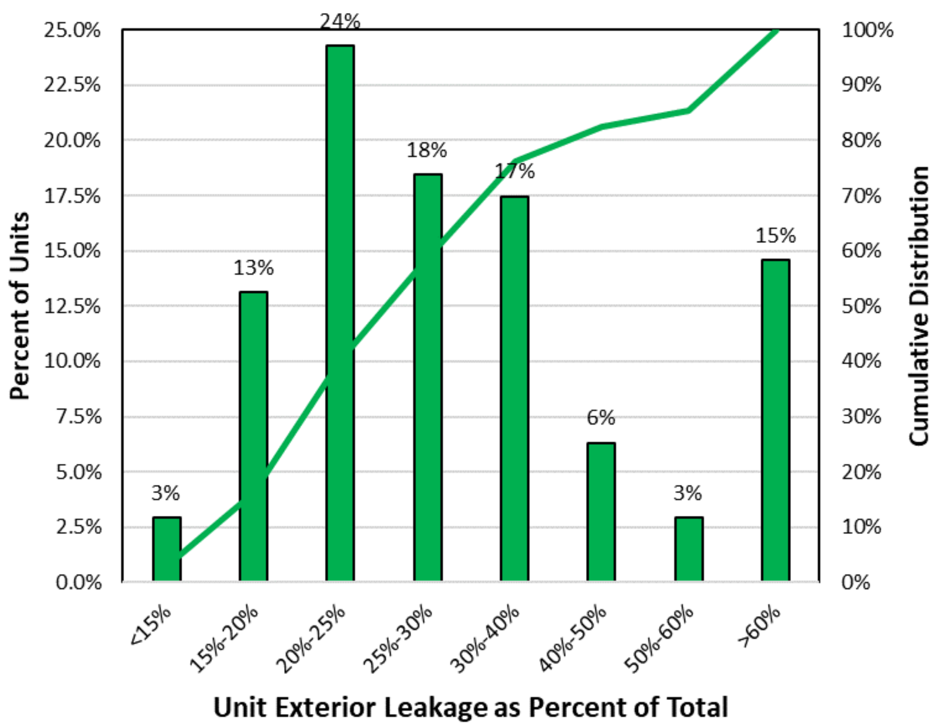


Figure 67. Histogram of Unit % Exterior Leakage: Common-Entry Buildings

The percent exterior leakage for individual units was compiled for each building to examine trends between buildings and within buildings. The median percent exterior leakage by building varied from 12.6% for IL43 to 52.1% for WA1 (See Figure 68). The percent exterior leakage depends on the relative amount of exterior envelope surface area compared to the total. However, it also depends on the relative tightness of the exterior air barrier compared to that for the interior air barrier. The low percent exterior leakage for IL43 was likely due to the strict PHIUS 2015 requirement of 0.05 CFM_{50}/ft^2 for whole building exterior surface-area-normalized leakage compared to the much higher PHIUS limit of 0.30 CFM_{50}/ft^2 for the total leakage of a unit. The variation of percent exterior leakage for units in the same building is discussed in more detail in Section 4.6.3.

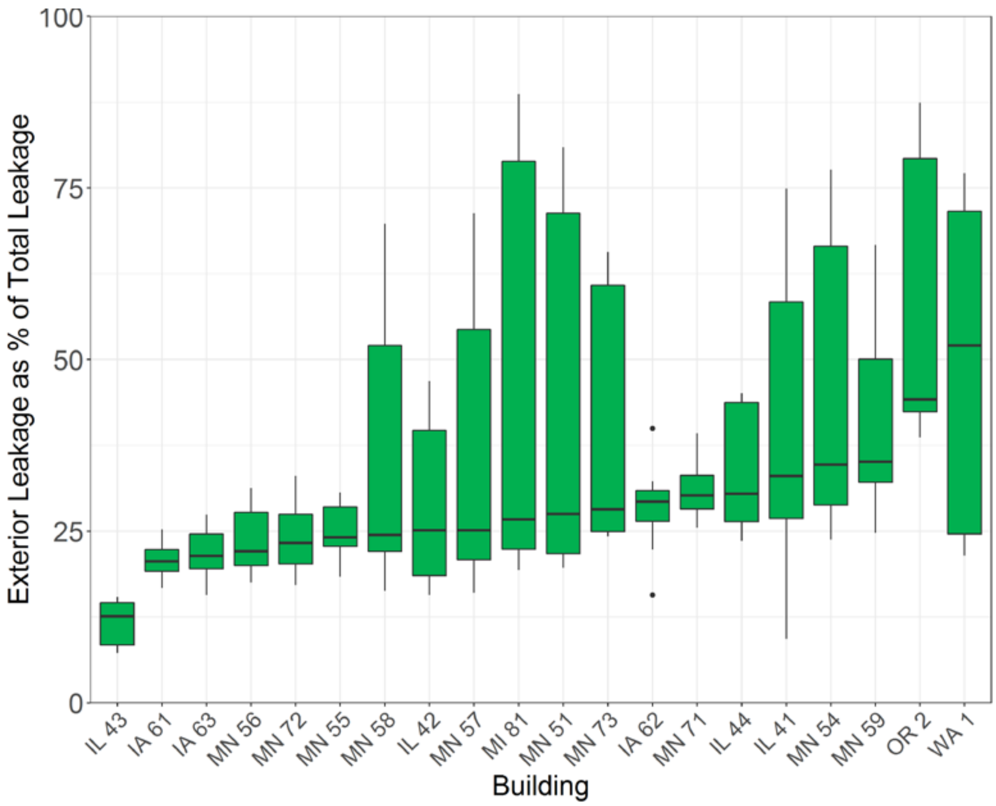


Figure 68. Unit % Exterior Leakage by Building: Common-Entry Buildings

Since the ratio of exterior to total surface area, type of envelope construction, and penetrations through the interior and exterior envelope vary by building level, it is expected that the percent exterior leakage may also vary by building level. Figure 69 below shows the variation in percent exterior leakage by building level for flat-roof (light brown bars) and vented-attic (dark brown bars) buildings. The median and variation in percent exterior leakage is fairly consistent for the two types of buildings and three levels, except for the top floor of the vented-attic buildings. This consistency is confirmed by the cumulative distributions shown in Figure 70. The higher percent exterior leakage appears to be the result of higher exterior leakage for the top floor of vented-attic buildings.

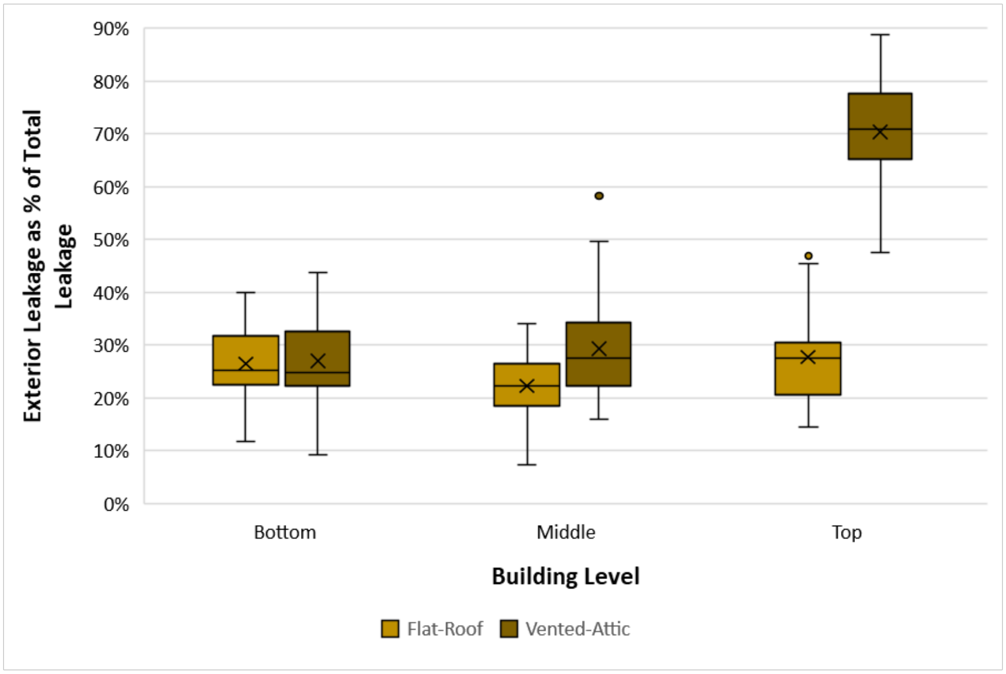


Figure 69. Unit % Exterior Leakage by Building Level and Type: Common-Entry Buildings

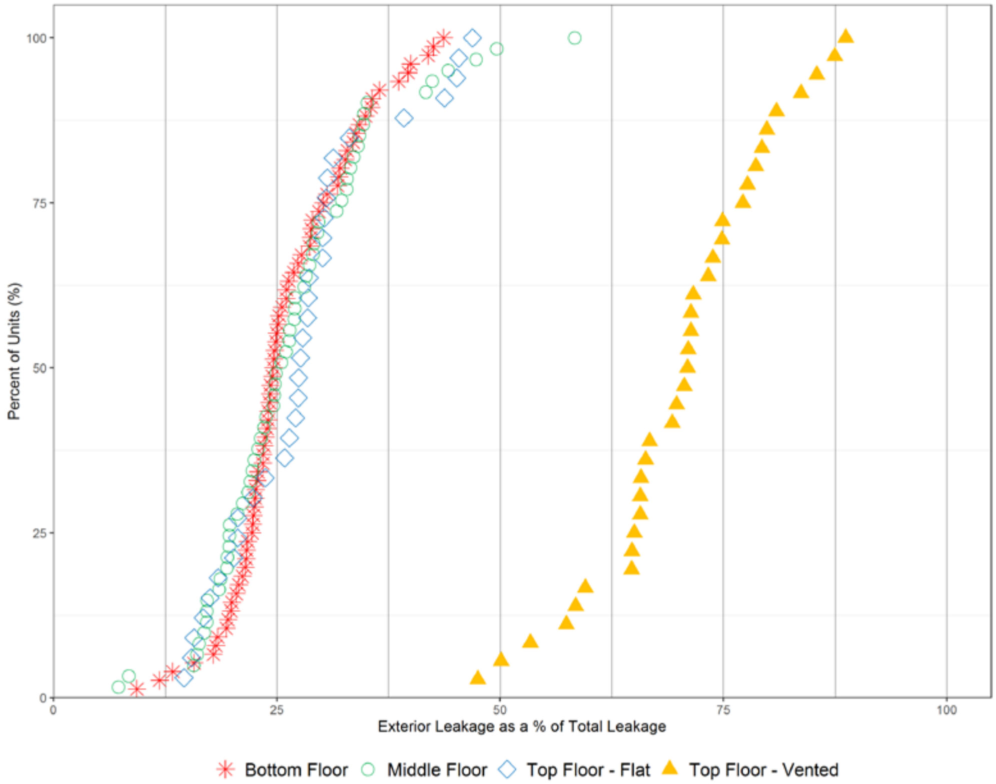


Figure 70. Cumulative Distribution of Unit % Exterior Leakage by Building Level: Common-Entry Buildings

After six common-entry buildings were tested, an extra step was added to the guarded test protocol to estimate the split of the interior leakage of the unit between leakage to adjoining units and the common area. This provided unit leakage to adjoining units and common area for 145 units from 14 buildings. Nine of the buildings had vented attics, and five had flat roofs. The cumulative distributions of percent of total leakage to the exterior, interior,[19] adjoining units, and common area are shown in Figure 71, and the histogram is shown in Figure 72.

The percent leakage to the common areas was greater than that for the leakage to adjoining units over the entire distributions. This indicates that there was generally more interior leakage to the common areas than adjoining units. For 91% of the units the leakage to common areas was greater than the leakage to adjoining units. On average, the percent leakage to common areas was 19 percentage points greater than to adjoining units. Further investigation of the surface-area-normalized leakage is necessary to determine whether the higher leakage to common areas is due to a greater amount of surface area or that surfaces between the unit and common areas are leakier than that between adjoining units. The leakage between units includes the leakage through adjoining walls, floors, and ceilings.

[19] The shape of the distribution for percent interior leakage is the same as for the percent exterior distribution flipped horizontally about the 50th percentile and flipped vertically about the 50% line. For individual units the percent leakage to adjoining units and common area sum to the percent interior leakage. However, since the values of each set of percent leakages are sorted separately, the percent leakage to adjoining units and common areas at a given horizontal line (e.g., percentage of units) do not add to the percent interior leakage along that horizontal line.

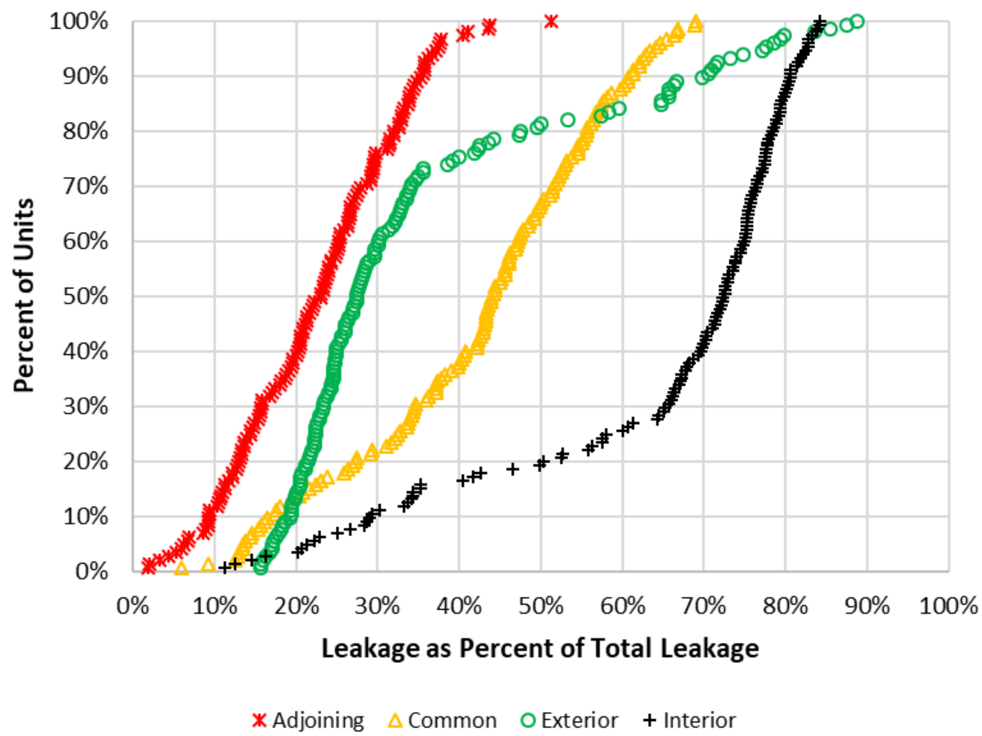


Figure 71. Cumulative Distribution of Unit % Leakage by Type of Surface: Common-Entry Buildings

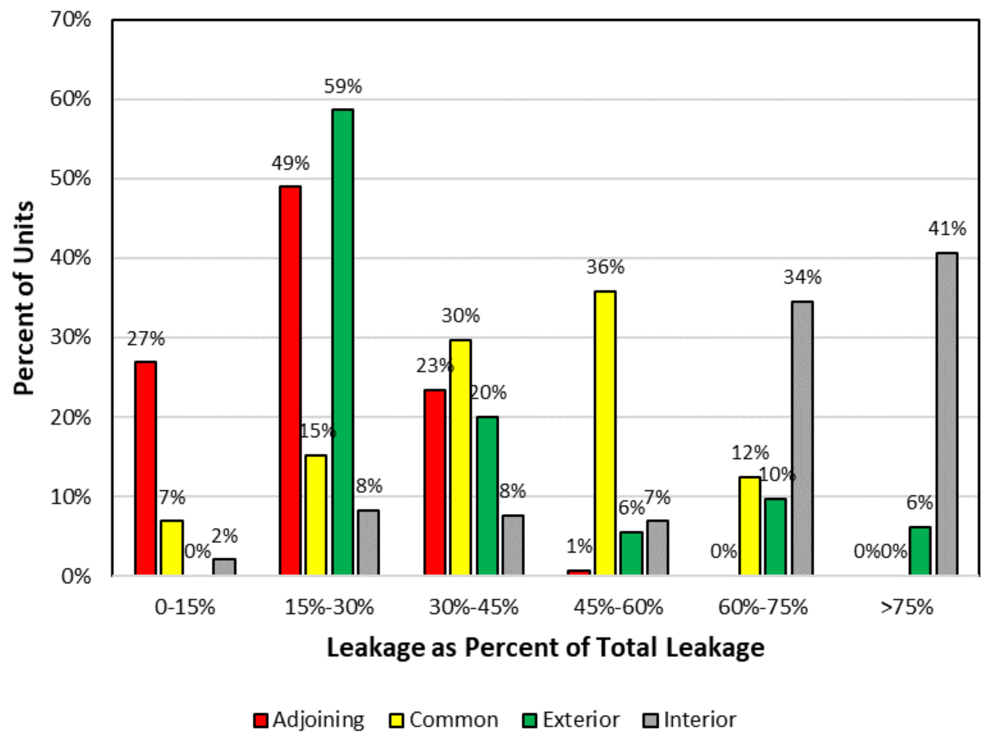


Figure 72. Histogram of Unit % Leakage by Type of Surface: Common-Entry Buildings

The envelope surface-area-normalized leakage provides a direct indicator of the relative leakiness or permeability of each portion of the envelope for a unit. The value is not impacted by the absolute amount of floor area or volume of the unit. Figure 73 displays the cumulative distribution, and Figure 74 displays the histogram of the surface-area-normalized exterior, interior, and total leakage for the 206 units tested. The sets of leakage values are sorted independently for the cumulative distributions. Consequently, for any given percentile, the total, interior, and exterior leakage values are not for the same unit.

The distributions for the three types of leakage are very similar. The median surface-area-normalized leakages were 0.19, 0.17, and 0.17 CFM_{50}/ft^2 for the exterior, interior, and total, respectively. For higher percentiles, there was a wider distribution of exterior leakage than for interior and total leakage. The 75th percentile values were 0.29, 0.25, and 0.24 CFM_{50}/ft^2 for the exterior, interior, and total, respectively. The similarity of the distributions for the three leakages may suggest that the exterior and interior surface-area-normalized leakages may be similar for individual units. However, it is possible for the distributions for the set of leakages to be similar, while individual units may have quite different surface-area-normalized leakages.

Table 45. Summary Statistics for Unit Leakage by Type of Surface: Common-Entry Buildings

	Percent of Total Leakage				Surface Area Normalized Leakage (CFM$_{50}$/ft^2)				
Percentile	Adj. Unit	Common	Interior	Exterior	Total	Adj. Unit	Common	Interior	Exterior
90th	35.5%	61.0%	80.6%	70.3%	0.299	0.158	1.233	0.369	0.396
75th	29.7%	53.8%	77.5%	40.0%	0.240	0.118	0.722	0.250	0.285
50th	23.1%	44.3%	72.6%	27.4%	0.167	0.072	0.519	0.164	0.186
25th	14.4%	32.8%	60.0%	22.5%	0.140	0.051	0.358	0.122	0.119
10th	9.4%	17.5%	29.7%	19.4%	0.124	0.035	0.229	0.091	0.087
Avg.	22.6%	42.1%	64.8%	35.2%	0.194	0.091	0.645	0.202	0.223
Std Dev	10.0%	15.3%	19.1%	19.1%	0.074	0.063	0.510	0.134	0.123

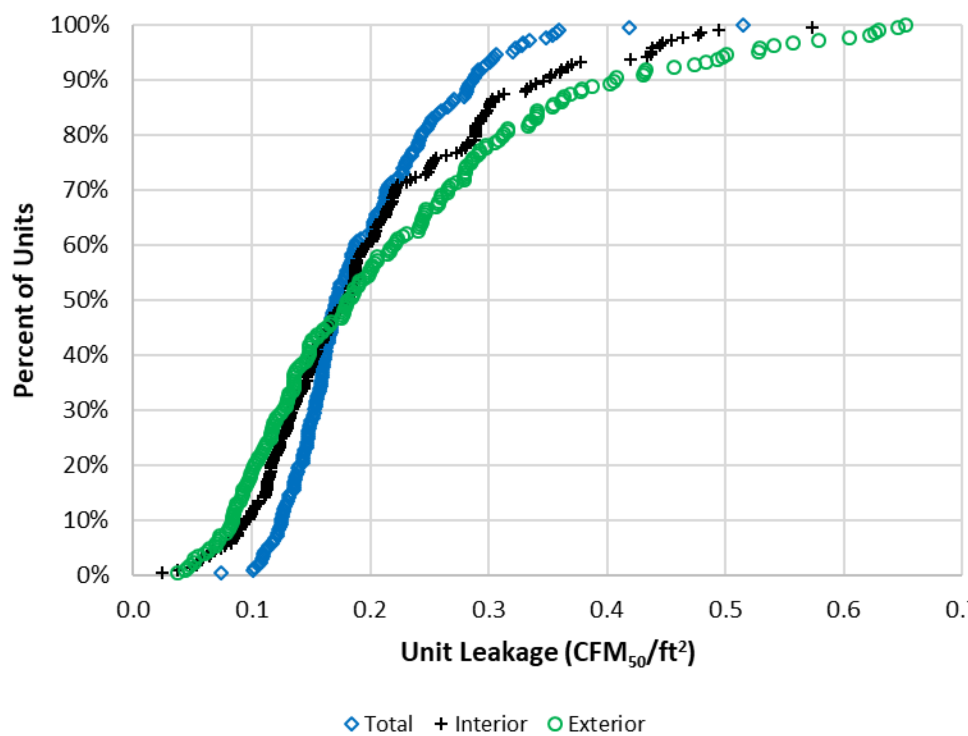


Figure 73. Cumulative Distribution of Unit Leakage by Type of Surface: Common-Entry Buildings (CFM$_{50}$/ft^2)

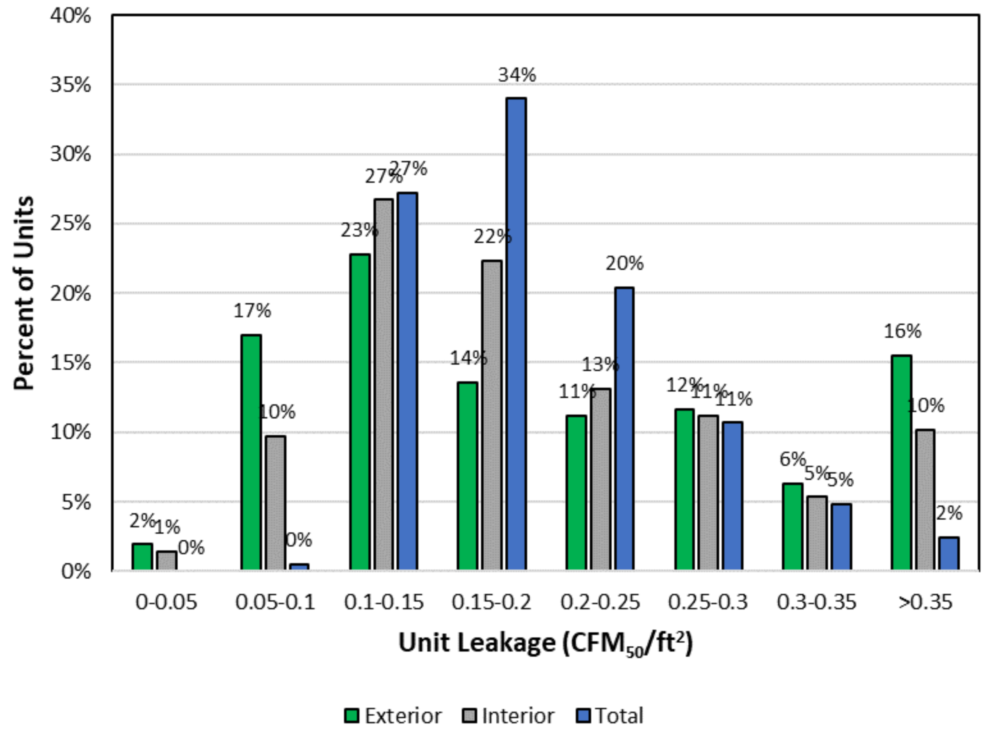


Figure 74. Histogram of Unit Leakage by Type of Surface: Common-Entry Buildings (CFM_{50}/ft^2)

Figure 75 displays a box-and-whisker chart for the envelope surface-area-normalized total and exterior leakage. The median exterior leakage for individual units in a building varied from 0.047 (IL43) to 0.35 (IL41) CFM_{50}/ft^2 and averaged 0.19 CFM_{50}/ft^2 with a standard deviation of 0.07 CFM_{50}/ft^2. There was somewhat less variation in median total leakage between buildings. The median total leakage varied from 0.13 (MN71) to 0.30 (IA61) CFM_{50}/ft^2 and averaged 0.20 CFM_{50}/ft^2 with a standard deviation of 0.05 CFM_{50}/ft^2. There was often good agreement between the surface-area-normalized exterior and total leakage. For 12 of the buildings, the median exterior leakage was within 25% of the median total leakage. However, for three buildings (IL41, MN54, and MI81) the median exterior leakage was more than 50% greater than the median total leakage, and for two buildings (IL42 and IL43), the median exterior leakage was more than 50% less than the median total leakage. This suggests that the construction practices for generating relatively tighter exterior versus interior envelopes can vary significantly by building. The variation of total and exterior leakage for units in the same building is discussed in Section 4.6.3

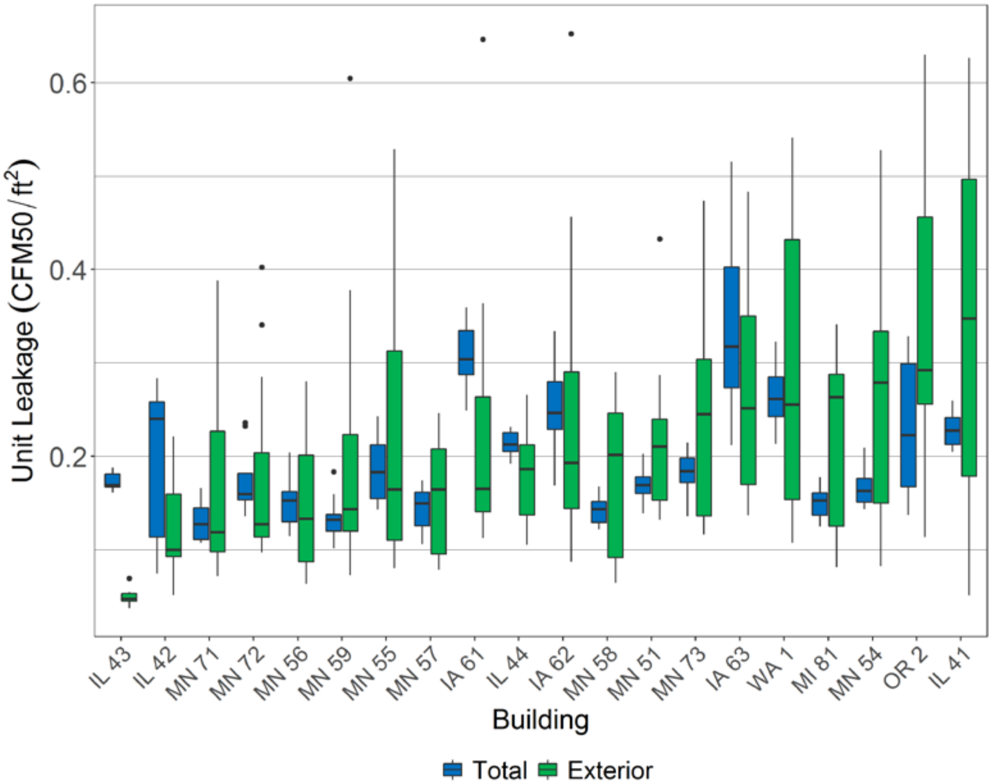


Figure 75. Unit Total and Exterior Leakage by Building: Common-Entry Buildings (CFM_{50}/ft^2)

Figure 76 displays the cumulative distribution of the surface-area-normalized exterior, interior, and total leakage with three separate distributions for the top floor units of the vented-attic buildings and three other distributions for all other units in the dataset. While the surface-area-normalized leakage for the entire unit (e.g., the "Total" distributions) is similar for the top floor units of the vented-attic buildings, as all of the other units, the exterior and interior leakage distributions are quite different. The exterior leakage is significantly higher for the top floor units of the vented-attic buildings (red circles in Figure 76) than that for the other units. This is consistent with the previous results that showed greater percent exterior leakage and volume-normalized exterior leakage for those units. It is interesting that the surface-area-normalized interior leakage is much lower for the top floor units of the vented-attic buildings (red crosses in Figure 76). One possible explanation is that for most units a significant portion of the interior leakage occurs through the cavity between the ceiling of the unit and the floor above. That cavity and leakage path is not present for the top floor unit of the vented-attic buildings.

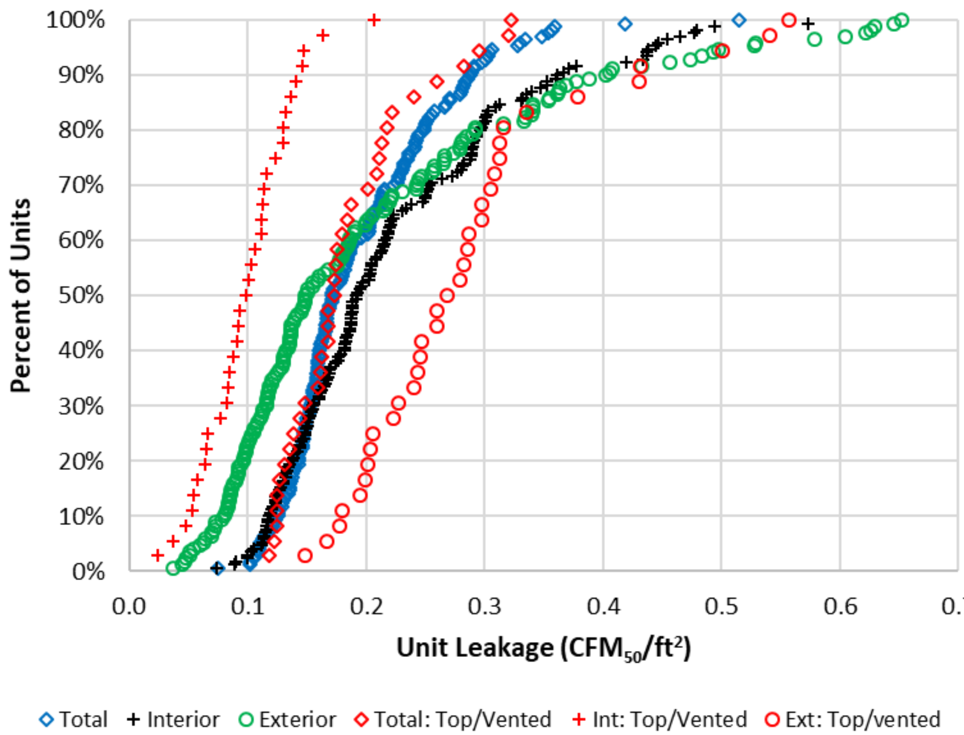


Figure 76. Distribution of Unit Leakage by Type of Surface: Common-Entry Buildings (CFM_{50}/ft^2)

Figure 77 displays the cumulative distribution of the surface-area-normalized interior (left chart) and exterior (right chart) leakage with separate distributions by building level (bottom, middle, and top) and attic type (vented-attic and flat-roof). Some of the distributions are consistent between levels in the building while others vary significantly. For example, the distribution of the surface-area-normalized exterior leakage for flat-roofed buildings is nearly identical for the bottom and top levels. If it is assumed that the leakage of the exterior walls does not vary significantly by level, this suggests that the floors of the bottom-level units have about the same leakage as the ceilings of the top-level units. For the vented-attic buildings, the distributions of the exterior leakage for the middle- and top-level units are similar through the 50th percentile, and then the middle-level units have somewhat higher leakage. Over the entire distribution, the exterior leakage of the bottom-level units is at least 0.10 CFM_{50}/ft^2 greater than that for the units on the other two levels. This suggests that the ceilings of the top-level units are slightly tighter than the exterior walls, and that the floors of the bottom-level units are tighter than the exterior walls.

The results suggest the following general trends for surface-area-normalized leakage:

- The interior leakage of flat-roof buildings is slightly lower on the middle-level than the bottom- and top-levels.
- The interior leakage of the vented-attic buildings is lowest for the top-level units, slightly higher for the middle-level units, and much higher for the bottom-level units.
- The exterior walls of flat-roof buildings are leakier than the bottom-level floors and top-level ceilings. The leakage of the bottom-level floors is slightly greater than the top-level ceilings.
- The exterior walls of the vented-attic buildings are about as leaky as the top-level ceilings and much leakier than the bottom-level floors.

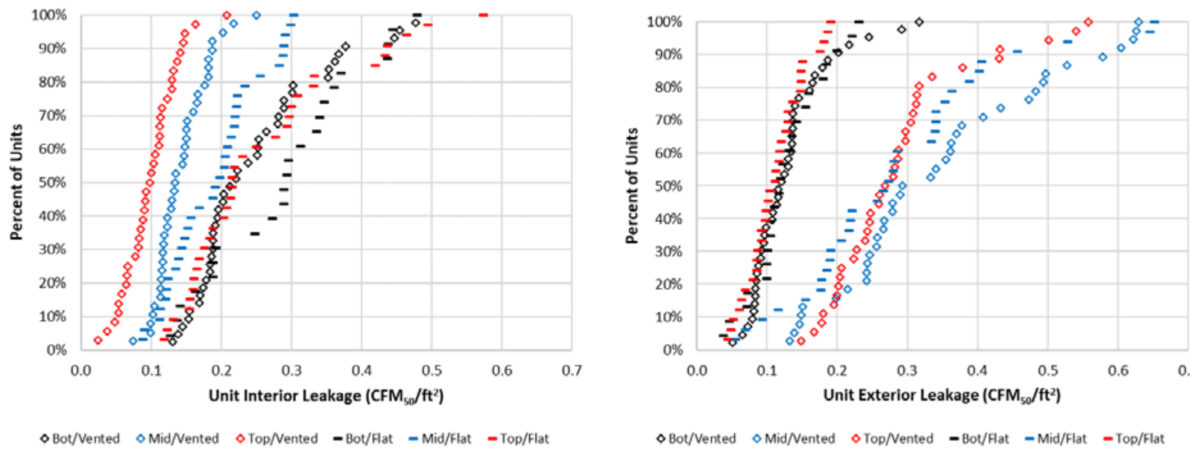


Figure 77. Distribution of Interior and Exterior Leakage by Building Level and Attic Type (CFM$_{50}$/ft^2)

As noted previously, the leakage of individual units to adjoining units and common areas was measured for 145 units from 14 buildings. The cumulative distribution and histogram of surface-area-normalized leakage of five surfaces (adjoining units, common areas, exterior, all interior, and total) is shown in Figure 78 and Figure 79. A breakdown of the common area and adjoining unit surface-area-normalized leakage by building level and attic type is shown in Figure 80. This shows that the surface-area-normalized leakage from units to common areas is significantly greater than the leakage to adjoining units — and it is by far the leakiest portion of the envelope of the units. The median surface-area normalized leakage to the common area is 0.52 CFM$_{50}$/ft^2 which is seven times higher than the median of 0.072 CFM$_{50}$/ft^2 for the adjoining unit leakage. Limited discussions with building inspectors suggest that fire caulking is typically the primary sealing material used on the top plate of these buildings, and that this caulk is known to shrink much more than caulk designed for long-term air sealing.

The distributions of surface-area-normalized leakage of units to common areas are about the same for all three levels of the flat-roof buildings and similar to that for the bottom- and middle-level units of the vented-attic buildings. The distributions of surface-area-normalized leakage to common areas are much lower for the top level of vented-attic buildings. The relationships between the distributions by building level for the surface-area-normalized leakage to adjoining units is similar to those for the common area leakage. The distributions of surface-area-normalized leakage to adjoining units is about the same for all three levels of the flat-roof buildings and similar to that for the bottom-level units of the vented-attic buildings.

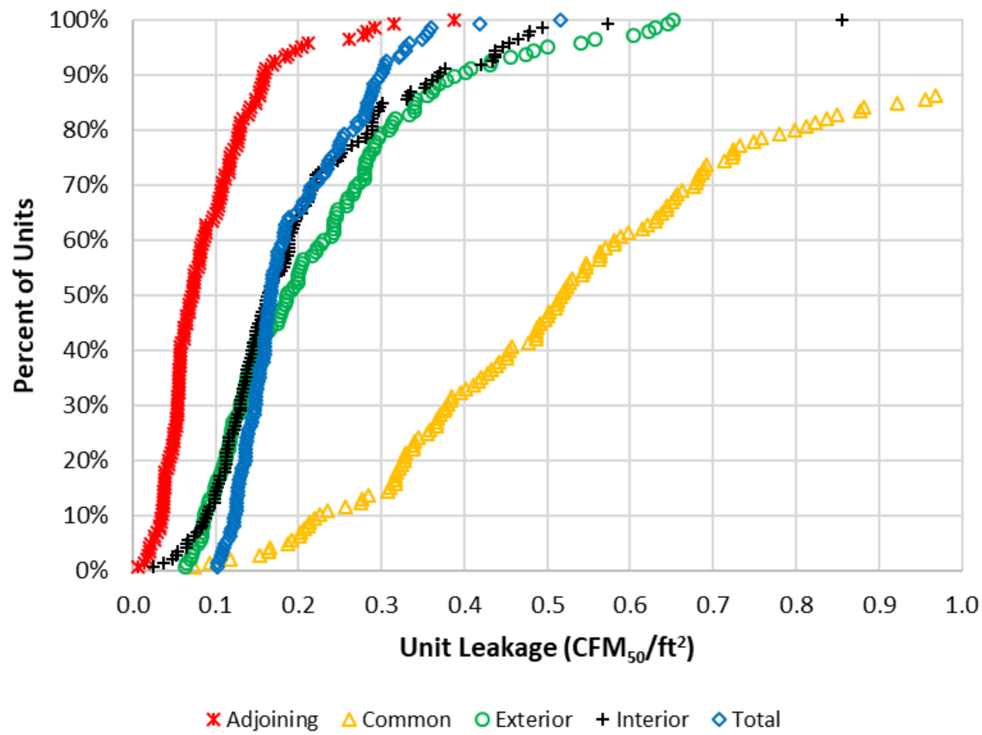


Figure 78. Cumulative Distribution of Unit Leakage by Type of Surface: Common-Entry Buildings (CFM_{50}/ft^2)

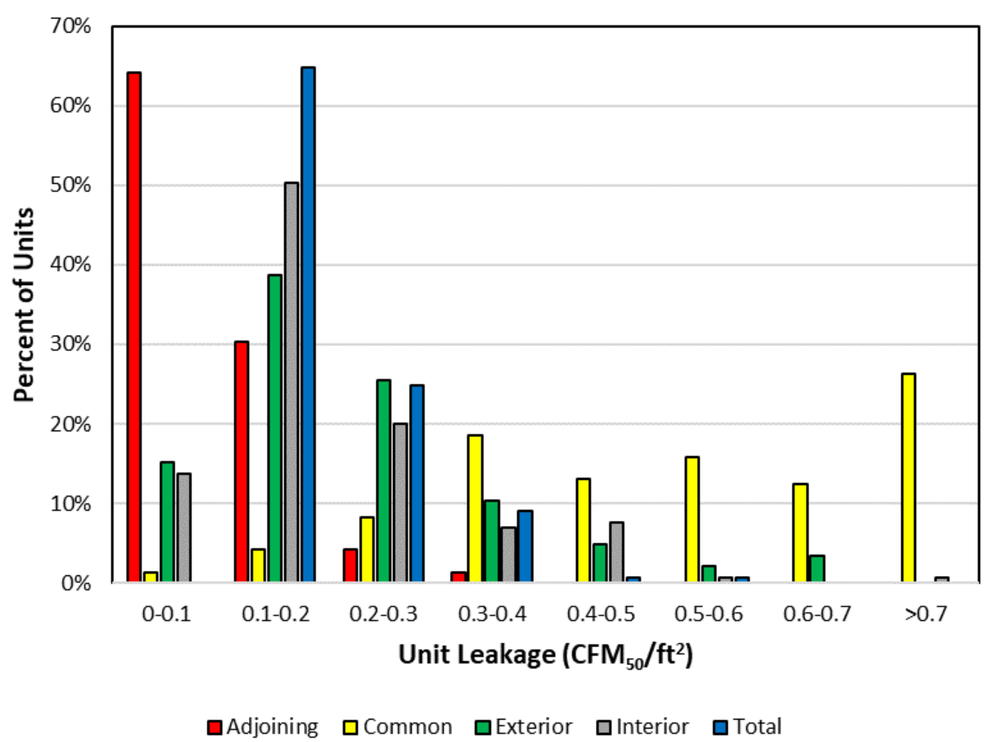


Figure 79. Histogram of Unit Leakage by Type of Surface: Common-Entry Buildings (CFM_{50}/ft^2)

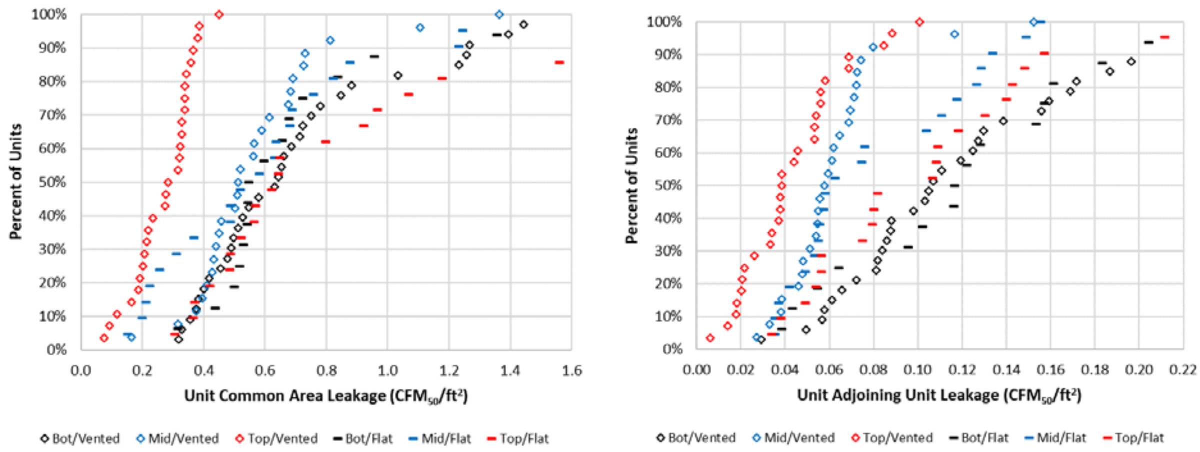


Figure 80. Distribution of Common Area and Adjoining Unit Leakage by Type of Surface and Attic (CFM_{50}/ft^2)

4.3.2 Garden-Style Buildings

Figure 81 displays the cumulative distribution, and Figure 82 displays histograms of the volume-normalized exterior and total leakage for the 68 units tested in the five garden-style buildings. The sets of exterior and total leakage values are sorted independently for the cumulative distributions. Consequently, the total leakage for a given unit is not necessarily equal to the value directly to the right (e.g., at the same percentile). The average exterior leakage was 2.72 ACH_{50} with 25th percentile, median, and 75th percentile values of 1.87, 2.45, and 2.95 ACH_{50}, respectively. The interquartile range (IQR) of 1.08 ACH_{50} was 44% of the median. There was greater variation, or a larger tail, for the higher leakage values. The difference between the median and 10th percentile values was 0.95 ACH_{50}, while the difference between the 90th percentile and median values was 1.8 times greater (1.69 ACH_{50}). There was a similar shape for the distribution of total leakage, but the values were about two times greater than the exterior leakages at the same percentiles. The average total leakage was 5.13 ACH_{50} with 25th percentile, median, and 75th percentile values of 3.94, 4.82, and 5.65 ACH_{50}, respectively. The IQR of 1.71 ACH_{50} was 35% of the median. The difference between the median and 10th percentile values was 1.45 ACH_{50}, while the difference between the 90th percentile and median values was 2.3 times higher (3.34 ACH_{50}).

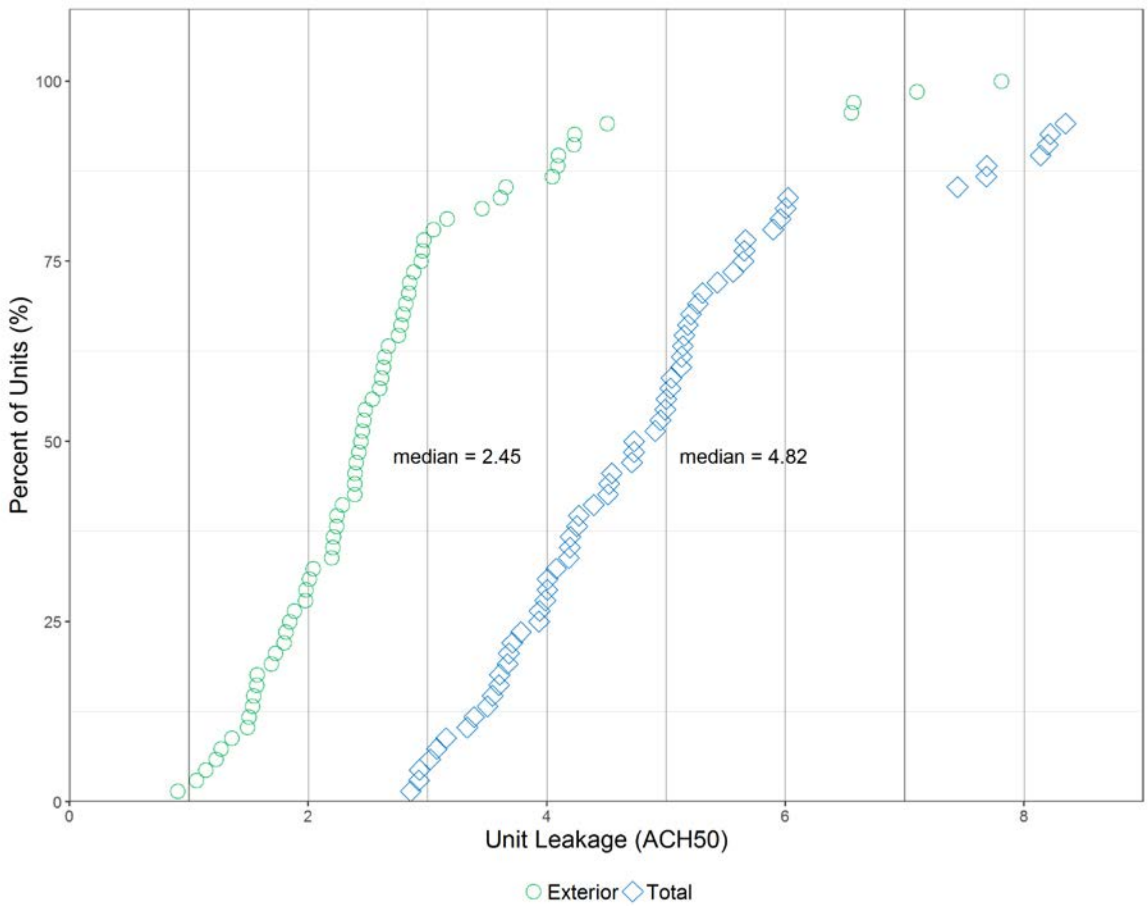


Figure 81. Cumulative Distribution of Unit Total and Exterior Leakage: Garden-Style Buildings (ACH_{50})

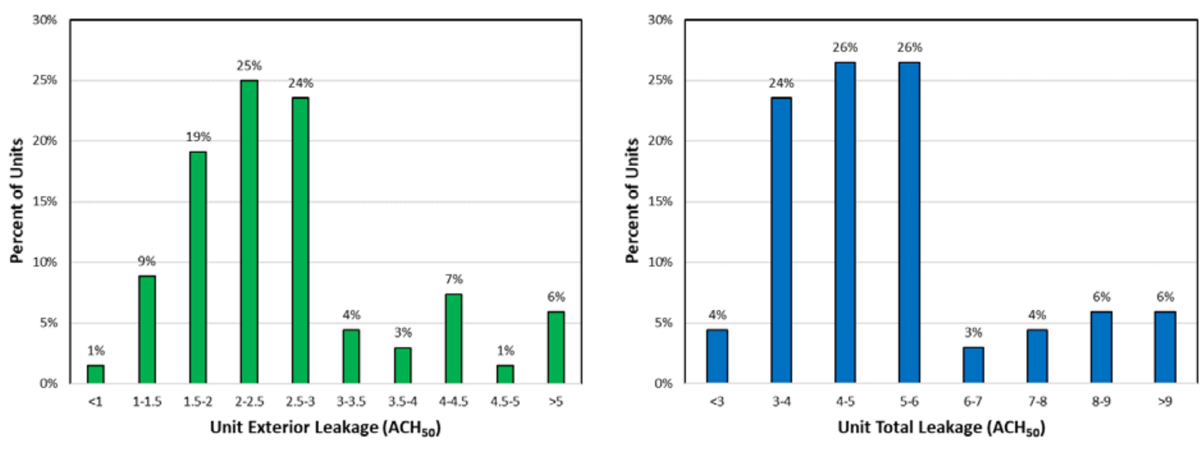


Figure 82. Histograms of Unit Exterior and Total Leakage: Garden-Style Buildings (ACH_{50})

If the same leakage criterion is applied to exterior and total volume-normalized leakage, the failure rate is considerably higher for total leakage. For example, 78% of the units had an exterior leakage of 3.0 ACH_{50} or less, but only 4% of the units had a total leakage of 3.0 ACH_{50} or less. While 85% of the units had an exterior leakage of 4.0 ACH_{50} or less, 28%

had a total leakage of 4.0 ACH_{50}. Finally, 94% of the units had an exterior leakage of 5.0 ACH_{50} or less, and only 54% had a total leakage less than 5.0 ACH_{50}.

Figure 83 displays the same distribution of total leakage that was included in Figure 81. Instead of sorting the exterior leakage values independently from the total leakage, the exterior leakage associated with the total leakage of a unit is plotted directly to the left (e.g., at the same height) of the total leakage. Similar to the results for the common-entry buildings, this shows the large range in exterior leakage that can occur for similar values of total leakage. For example, for total leakages of 5.0 ± 0.2 ACH_{50}, the exterior leakage ranges from 1.36 to 3.16 ACH_{50} with an average of 2.40 ACH_{50} and standard deviation of 0.60 ACH_{50}. The range in exterior leakage is 4.5 times greater than the range in total leakage.

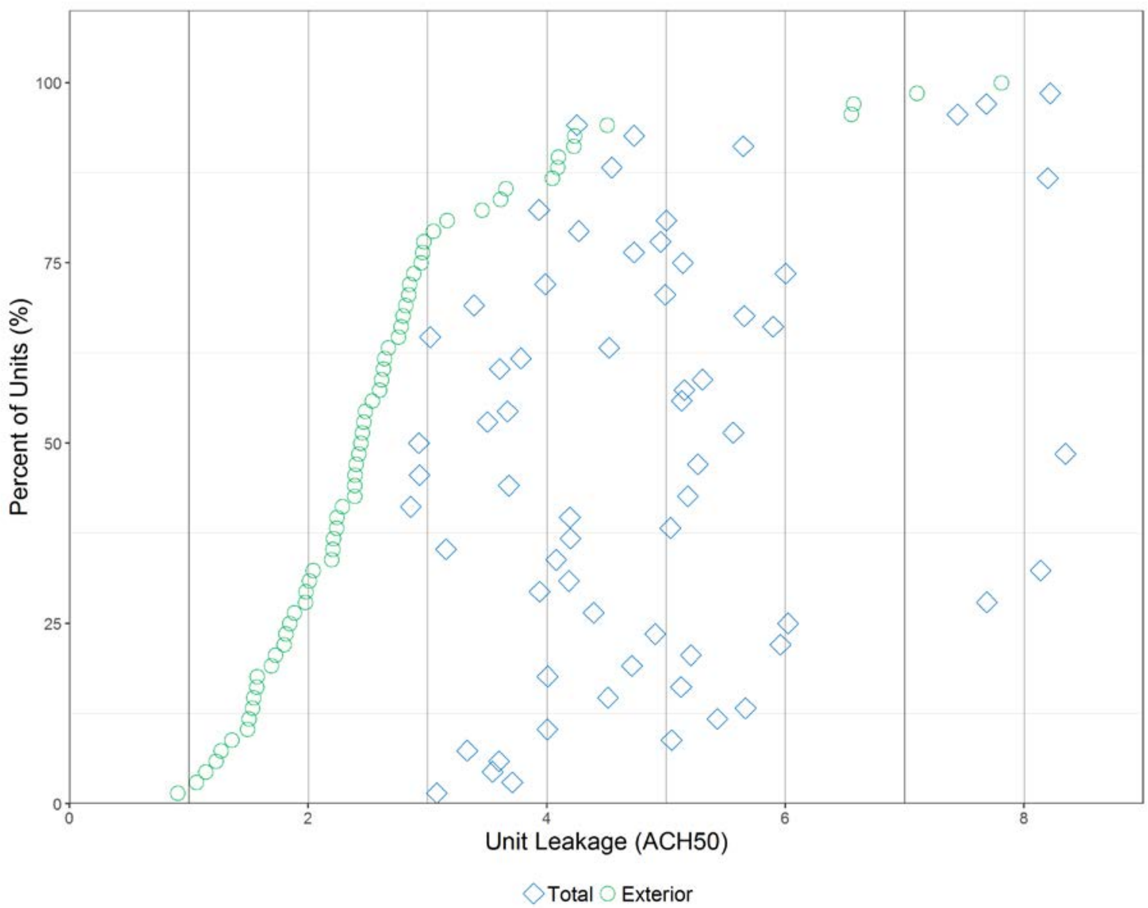


Figure 83. Cumulative Distribution of Unit Total and Exterior Leakage: Garden-Style Buildings (ACH_{50})

Figure 84 shows a box-and-whisker chart for the total (blue) and exterior (green) volume-normalized leakage of the units tested in the five garden-style buildings. The buildings are sorted from the lowest median exterior leakage to the left and the higher values to the right. The two buildings in Minnesota, which has a state code requirement of 3.0 ACH_{50}, had the lowest median exterior leakages of 2.01 and 2.19 ACH_{50}. The two buildings in Washington, which has a state code requirement of 5.0 ACH_{50}, had the highest median exterior leakages of 2.98 and 3.85 ACH_{50}. The building in Oregon had a median exterior leakage of 2.39 ACH_{50}. While Oregon does not have a state code requirement for air leakage testing, the building was participating in a program that included energy efficiency requirements that included air leakage testing. While there was a weak trend for increasing total leakage for buildings with increasing exterior leakage, there is significant variation in the trend of increasing total leakage. This suggests that there are factors other than simply the magnitude of the total leakage that impact the exterior leakage of a unit. Since the five buildings had similar construction characteristics (e.g., vented attics, slab on grade below lowest floor, two or three stories, and house wrap or unknown exterior air barrier), it was not possible to evaluate the impact of these characteristics on the magnitude or variability of the unit leakage.

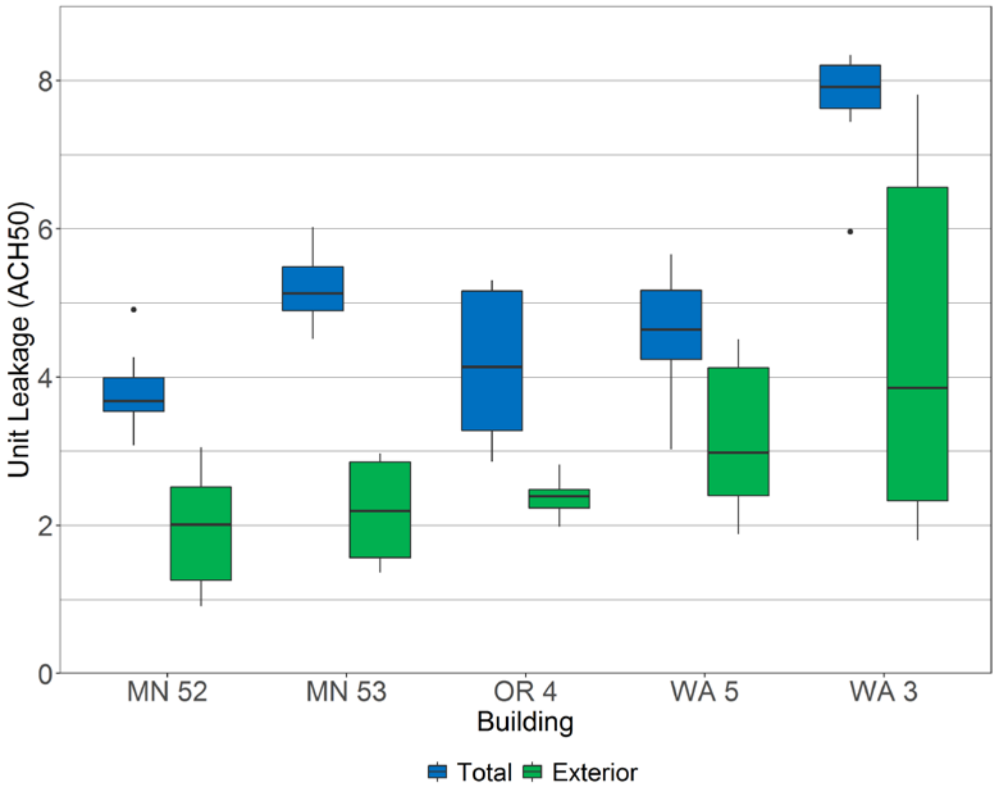


Figure 84. Unit Total and Exterior Leakage by Building: Garden-Style Buildings (ACH_{50})

The exterior leakage as a percentage of the total for a unit provides a direct comparison between the two values. Figure 85 displays the cumulative distribution, and Figure 86 displays the histogram of the percent exterior leakage for the 68 units measured in the five garden-style buildings. The average percent exterior leakage was 54.4% with 10th, 25th, 50th, 75th, and 90th percentile values of 29.3%, 36.7%, 49.4%, 70.7%, and 85.8%, respectively. The IQR of 34% was 69% of the median. There was a somewhat greater variation, or larger tail, for the higher percentages. For example, the difference between the median and 10th percentile values was 20.1%, while the difference between the 90th percentile and median values was 1.8 times greater (36.4%). A total of 35% of the units had a percent exterior leakage greater than 60%. The percent exterior leakage for the units from garden-style buildings was significantly higher than it was for the common-entry buildings. The average percent exterior leakage of 54.4% was 20.1 percentage points higher than the average of 34.3% for the common-entry buildings, and the median of 49.4% was 21.9 percentage points higher.

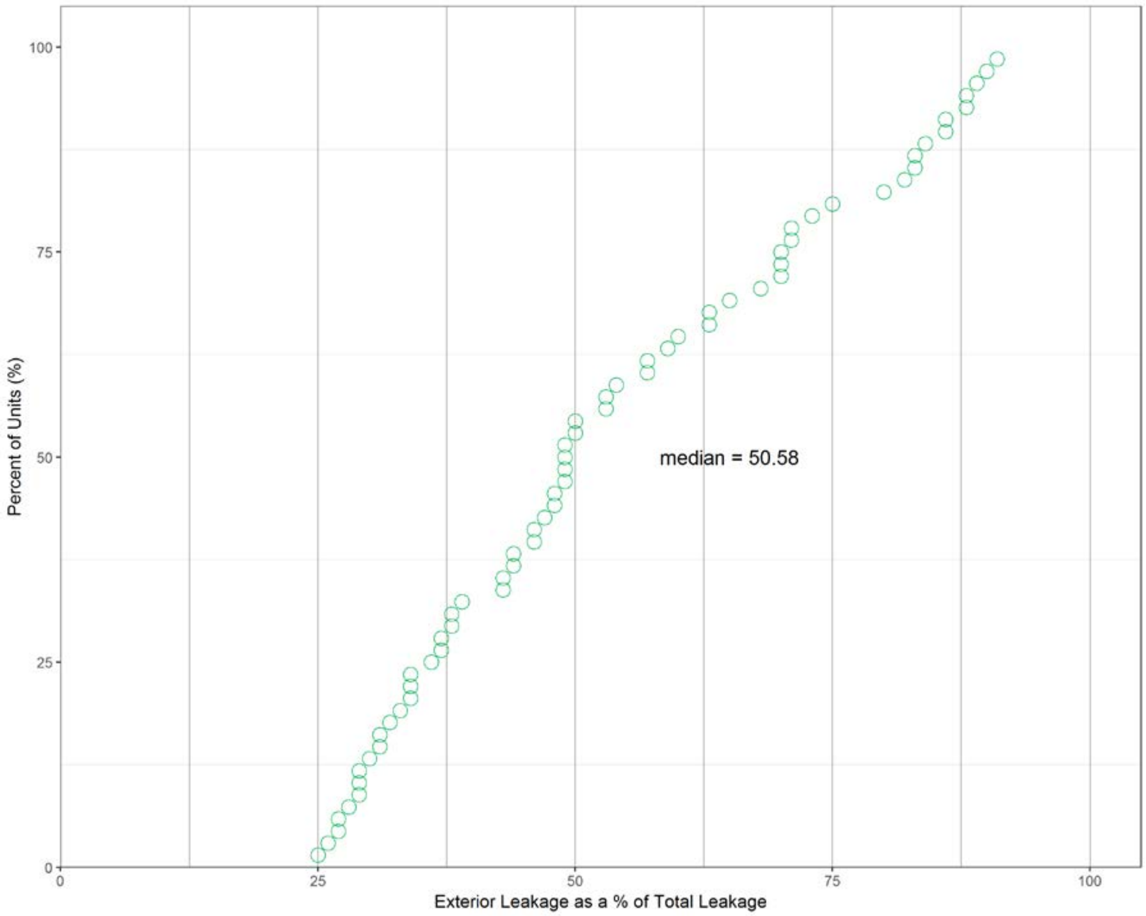
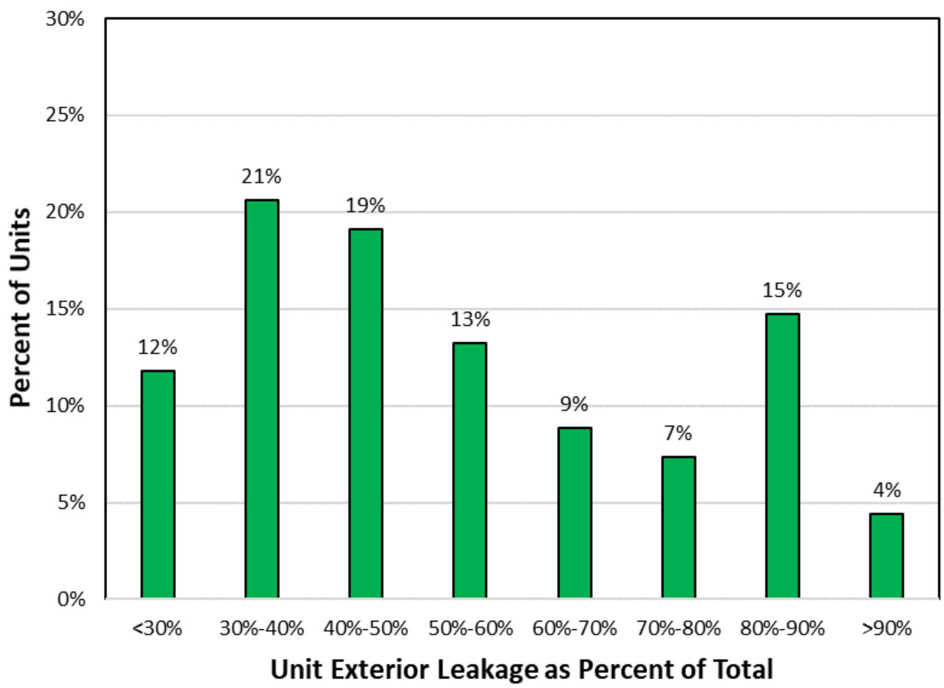


Figure 85. Cumulative Distribution of Unit % Exterior Leakage: Garden-Style Buildings



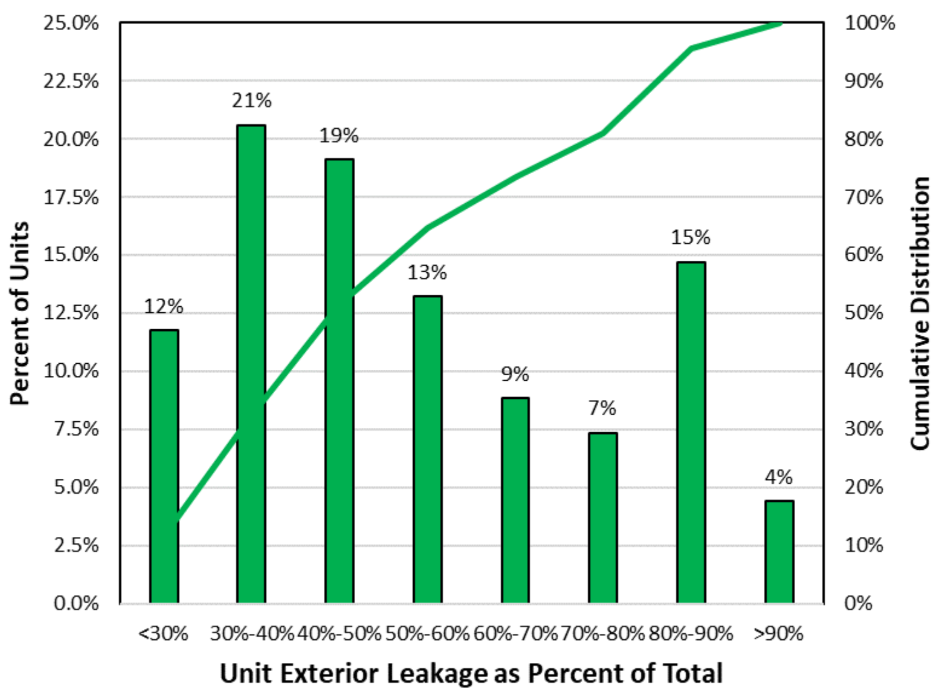


Figure 86. Histogram of Unit % Exterior Leakage: Garden-Style Buildings

The percent exterior leakage for individual units was compiled for each building to examine trends between buildings and within buildings. Even for this small sample of five buildings, the median percent exterior leakage of units in a building varied by almost a factor of two. The median percent exterior leakage by building varied from 40.5% for WA3 to 74.9% for WA5. (See Figure 87.) The variation of percent exterior leakage for units in the same building is discussed in more detail in Section 4.6.3.

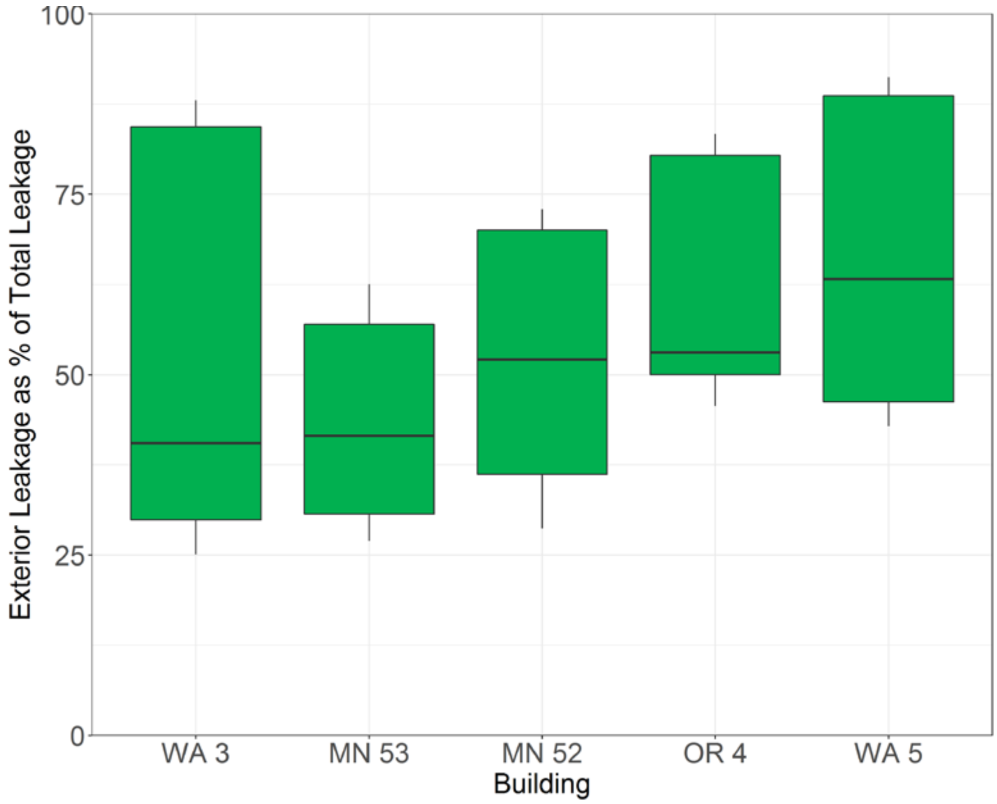


Figure 87. Unit % Exterior Leakage by Building: Garden-Style Buildings

As noted in Section 4.3.1, a number of factors are expected to cause the exterior leakage as a percentage of the total leakage to vary by building level. Figure 88 shows the variation in exterior leakage percentage by building level. All five of these buildings have vented attics, and the results are consistent with those for the common-entry buildings with vented attics. The exterior leakage percentage is about the same for the units on the bottom and middle floors, but it is much higher for the units on the top floor. For the vented-attic, common-entry buildings, the higher exterior leakage percentage was predominantly due to a larger amount of exterior surface area. The surface-area-normalized exterior leakage of the top floor units was slightly less than that for the middle floor units. This relationship was also examined for the garden-style buildings.

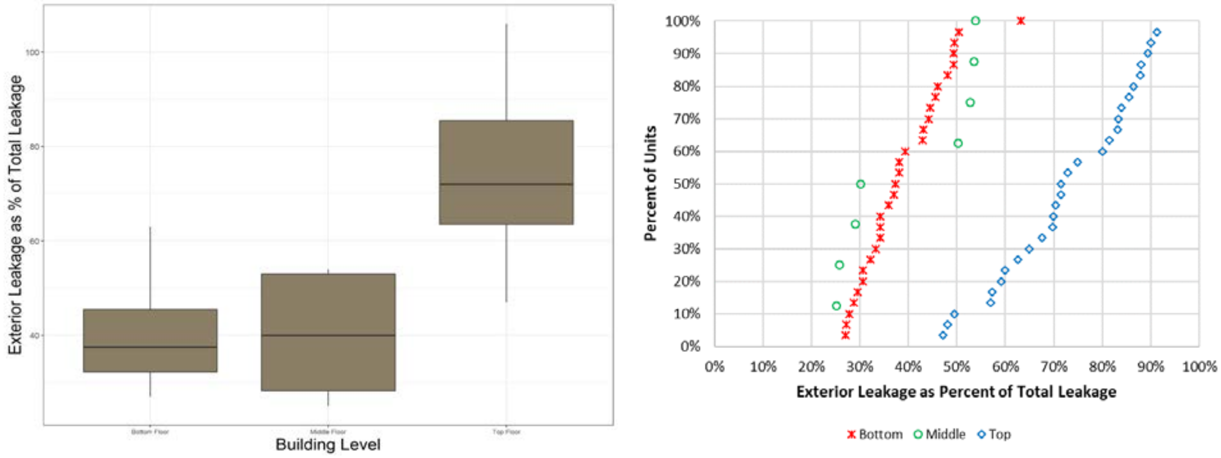


Figure 88. Unit % Exterior Leakage by Building Level: Garden-Style Buildings

The envelope surface-area-normalized leakage provides a direct indicator of the relative leakiness of each portion of the envelope for a unit. Figure 89 displays the cumulative distribution, and Figure 90 displays the histogram of the surface-area-normalized exterior, interior, and total leakage for the 68 units tested. The sets of leakage values are sorted independently for the cumulative distributions. Consequently, for any given percentile, the total, interior, and exterior leakage values are not the values from the same unit.

The distributions for the three types of leakage are somewhat similar for the mid-range percentiles. The median surface area-normalized leakages were 0.25, 0.19, and 0.22 CFM_{50}/ft^2 for the exterior, interior, and total, respectively. (See Table 46.) For the lower percentiles (e.g., up to the 35th percentile) the interior leakages were about two times less than the exterior and total leakages. For higher percentiles, the exterior leakage was significantly greater than the interior and total leakages. The 75th percentile values were 0.33, 0.27, and 0.25 CFM_{50}/ft^2 for the exterior, interior, and total, respectively.

Table 46. Summary Statistics for Unit Leakage by Type of Surface: Garden-Style Buildings

	% Exterior	Surface Area Normalized Leakage (CFM_{50}/ft^2)		
Percentile	**Leakage**	**Total**	**Interior**	**Exterior**
90th	85.8%	0.344	0.316	0.515
75th	70.7%	0.248	0.269	0.326
50th	49.4%	0.221	0.193	0.253
25th	36.7%	0.179	0.104	0.188
10th	29.3%	0.152	0.050	0.130
Avg.	54.4%	0.230	0.199	0.289
Std Dev	21.0%	0.074	0.121	0.153

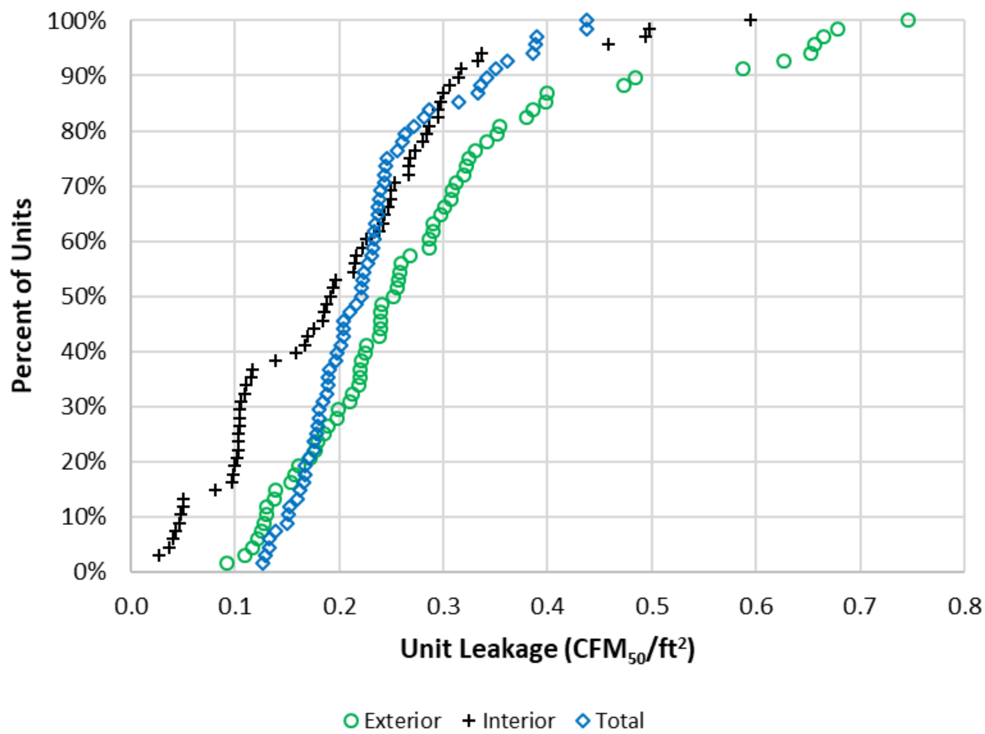


Figure 89. Cumulative Distribution of Unit Leakage by Type of Surface: Garden-Style Buildings (CFM_{50}/ft^2)

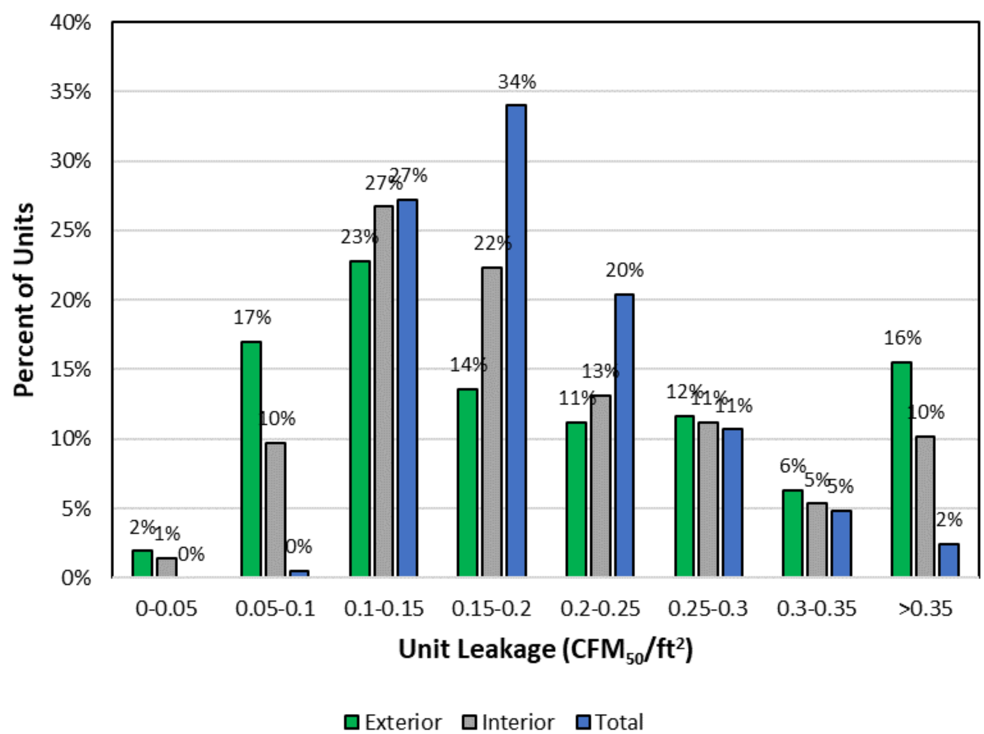


Figure 90. Histogram of Unit Leakage by Type of Surface: Garden-Style Buildings (CFM_{50}/ft^2)

Figure 91 displays a box-and-whisker chart for the envelope surface-area-normalized total and exterior leakage. The buildings are sorted left to right by increasing median exterior leakage. The median exterior leakage by building was similar for the four buildings with the lowest exterior leakage. The median only varied from 0.20 to 0.25 CFM_{50}/ft^2. The median exterior leakage of the units in the fifth building (WA3) was 1.8 times greater (0.39 CFM_{50}/ft^2) than the average for the median of the other four buildings. There was a similar trend for median total leakage. The median total leakage of the units in WA3 was 1.8 times greater (0.36 CFM_{50}/ft^2) than the average for the median of the other four buildings. The variation of total and exterior leakage for units in the same building is discussed in Section 4.6.3.

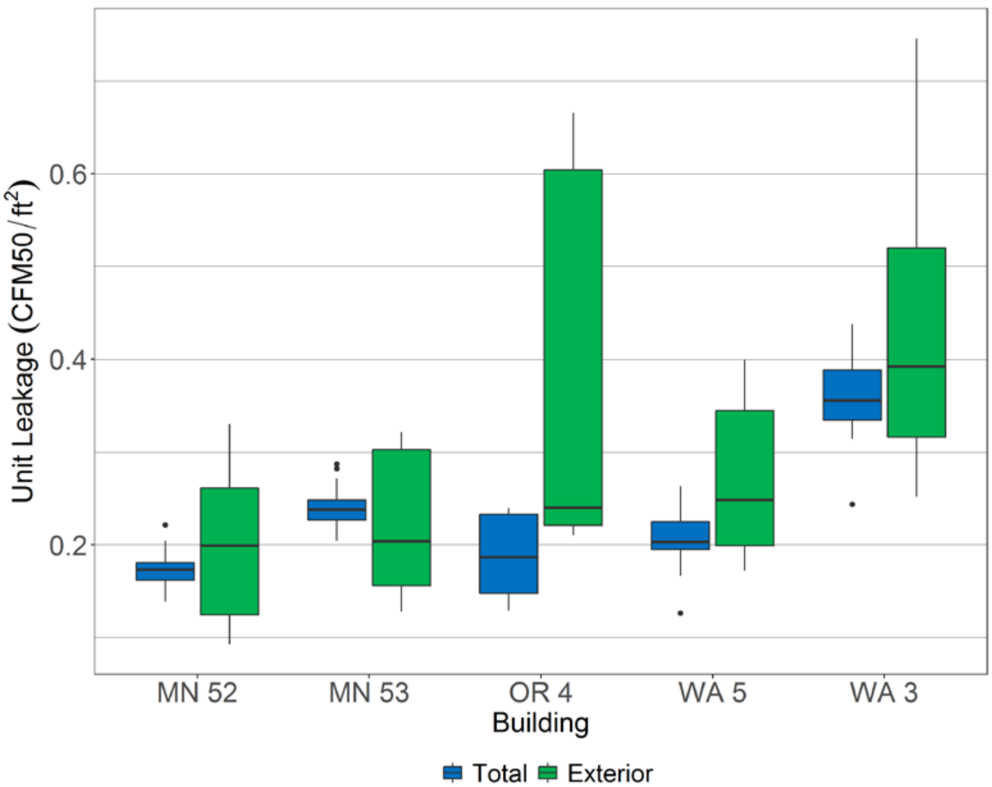


Figure 91. Unit Total and Exterior Leakage by Type of Surface: Garden-Style Buildings (CFM_{50}/ft^2)

There was good agreement between the surface-area-normalized exterior and total leakage. For all five buildings, the median exterior leakage was within 25% of the median total leakage, and the difference was within 15% for three of the five buildings. For four of the five buildings, the median total leakage was less than the median exterior leakage. This suggests that construction practices typically resulted in exterior envelope leakage that was similar to that for the interior envelope. This is different from the common-entry buildings, for which there was greater variation between exterior and interior leakage.

Both the average surface-area-normalized exterior and total leakage were greater than the averages for the units in the common-entry buildings. The average exterior leakage of 0.29 CFM_{50}/ft^2 for the 68 units in the garden-style buildings was 32% greater than the average of 0.22 CFM_{50}/ft^2 for the 206 units in the common-entry buildings. The average total leakage of 0.23 CFM_{50}/ft^2 for the units in the garden-style buildings was 19% greater than the average of 0.19 CFM_{50}/ft^2 for the units in the common-entry buildings. The number of buildings in the sample was too small and not uniformly distributed enough by state to suggest that this trend will hold for a larger population of buildings. Three of the five garden-style buildings are located in Washington, which has a higher leakage requirement of 5.0 ACH_{50}, and Oregon, which does not have a leakage requirement. The sample of 20 common-entry buildings includes only two buildings in Washington and Oregon. However, the trend is similar for a comparison of leakage of units in common-entry and garden-style buildings located in the same state. In Minnesota, the 112 units tested in 10 common-entry buildings had average total and exterior surface-area normalized leakages that were 24% and 5% lower than the average total and exterior leakages of the 32 units in two garden-style buildings. In Washington, the differences in total and exterior leakages were 7% and 16%, respectively, and in Oregon the differences were 26% and 6%, respectively. This confirms a trend for somewhat higher leakage for units in garden-style buildings compared to those in common-entry buildings, but the sample size is small, and these results need to be confirmed with more extensive testing.

Figure 92 displays the cumulative distribution of the surface-area-normalized exterior, interior, and total leakage with three separate distributions by building level (bottom, middle, and top). While the surface-area-normalized leakage for the entire unit (e.g., the "Total" distributions shown in the chart on the right side of Figure 92) are similar for all three levels, the exterior and interior leakage distributions are quite different. Over the entire distribution, the surface-area-normalized exterior leakage of the top-level units was at least 0.10 CFM_{50}/ft^2 greater than the exterior leakage for the bottom-level units. If it is assumed that the leakage of the exterior walls does not vary significantly by level, this suggests that the leakage of the ceilings at the top of the building is greater than the leakage of the bottom level floors. That is consistent with results from the vented-attic common-entry buildings. The trend is reversed for interior leakage. The surface-area-normalized interior leakage was much lower for the top-level units than it was for the bottom-level units. That is consistent with results from the vented-attic common-entry buildings. As noted previously, one possible explanation is that for most units a significant portion of the interior leakage happens through the cavity between the ceiling of the unit and the floor above. That cavity and leakage path is not present for the top-floor units of vented-attic buildings.

Since measurements of middle-level units were obtained for only two buildings, there is less certainty on their leakage trends. For building OR4, the exterior leakage of middle-level (e.g., second floor) units was much higher (average 0.64 CFM_{50}/ft^2) than those for units on the bottom (0.23 CFM_{50}/ft^2) and top (0.23 CFM_{50}/ft^2) levels. If it is assumed that the leakage of exterior walls is similar for each level, the results suggests that the relative leakage of the exterior walls building was significantly greater than the leakage of the bottom-level floors and top-level ceiling. The trend was different for the other building with middle-level unit measurements. The average surface-area-normalized leakage was 0.29, 0.40, and 0.63 CFM_{50}/ft^2 for the bottom, middle, and top-level units. This suggests that the floor of the bottom-level units was tighter than the exterior walls, and the ceiling of the top-level units was leakier than the exterior walls.

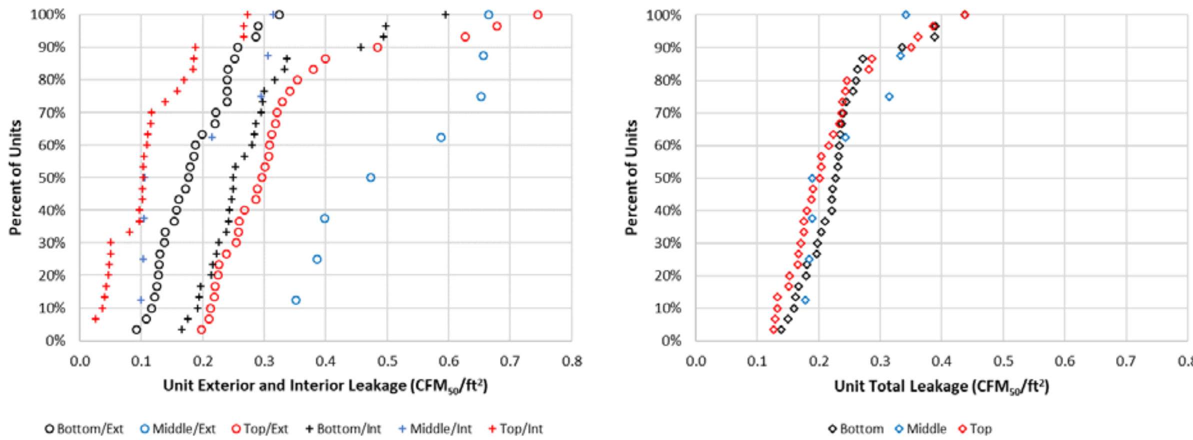


Figure 92. Distribution of Interior and Exterior Leakage by Building Level (CFM_{50}/ft^2)

4.4 Methods to Estimate Exterior Leakage

The exterior portion of envelope leakage is the primary concern for energy use needed to condition uncontrolled air infiltration. However, there are a number of challenges for whole building exterior leakage testing (e.g., all units need to be complete, more extensive equipment is required, and more experienced technicians are required — see

Table 1). In addition, for common-entry buildings, a whole building measurement does not provide the exterior leakage for individual units that is used to model the energy performance of each unit. A guarded test in conjunction with the whole building test can measure the exterior leakage of individual units, but it adds complexity to the test, and there is currently no standard for guarded tests. A reliable method for computing the exterior leakage of an individual unit based on results of a compartmentalization test of total leakage would help simplify the testing process.

The exterior leakage of an individual unit is sometimes estimated by multiplying the total leakage by the ratio of the exterior envelope surface area to total envelope surface area (e.g., surface-area-ratio method). As shown by the two equations below, this method is accurate when the envelope-surface area-normalized exterior leakage (e.g., CFM_{50}/ft^2) is equal to that of the surface-area-normalized total leakage. However, the construction details and penetrations through exterior walls, top-level ceilings, and bottom-level floors are different from those of the demising walls and floors or ceilings between levels. As shown in Figure 93, the surface-area-normalized exterior leakage and surface-area-normalized total leakage often differ by a factor of five, and there appears to be consistent relationships between surface-area normalized exterior leakage and surface-area normalized total leakage for different types of building attics and levels. This section evaluates the accuracy of the surface-area-ratio method, the use of exterior leakage multipliers to improve the accuracy of the method, and an alternative adjacent unit pressure method for computing the exterior leakage of garden-style buildings.

Assume:

$$\frac{CFM50_{ExtA}}{SA_{ExtA}} = \frac{CFM50_{TotA}}{SA_{TotA}} \tag{1}$$

Converts to:

$$CFM50_{ExtA} = CFM50_{TotA}\left(\frac{SA_{ExtA}}{SA_{TotA}}\right) \tag{2}$$

Where:

$CFM50_{ExtA}$ = exterior leakage of Unit A at a pressure difference of 50 Pa
$CFM50_{TotA}$ = total leakage of Unit A at a pressure difference of 50 Pa
SA_{ExtA} = exterior envelope surface area of Unit A
SA_{TotA} = total envelope surface area of Unit A

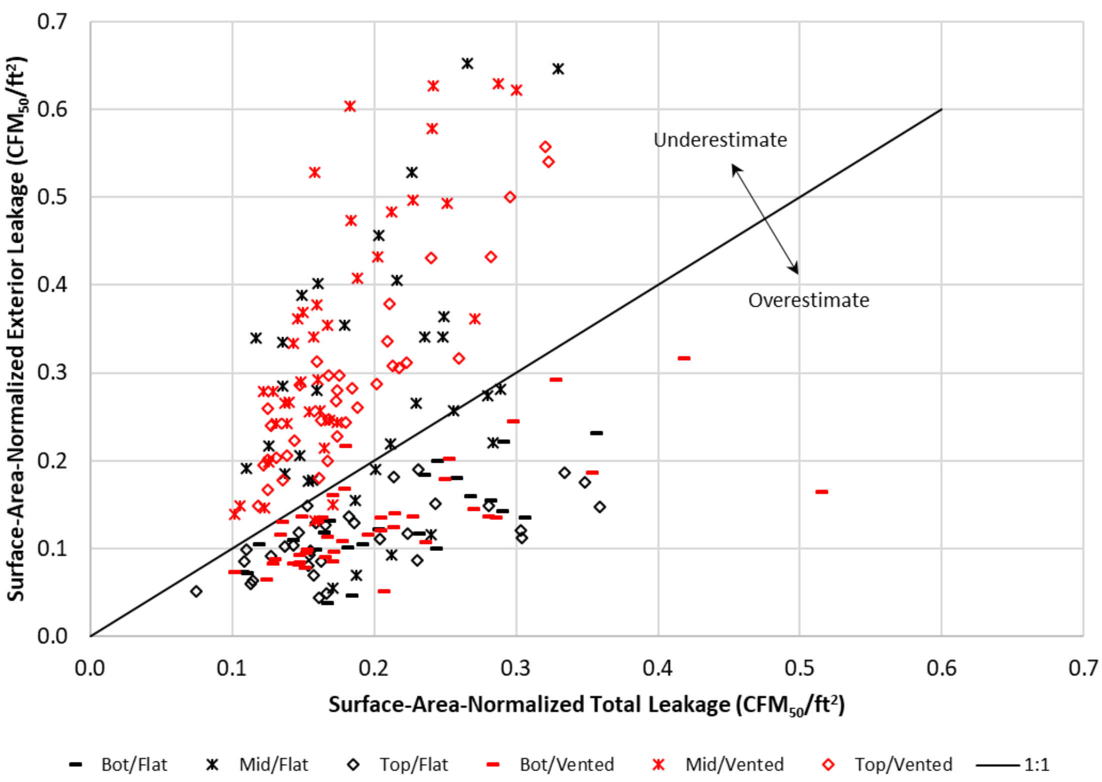


Figure 93. Surface-Area-Normalized Exterior Leakage vs. Total Leakage: Common-Entry Buildings

4.4.1 Surface-Area-Ratio Method for Common-Entry Buildings

The relationship between the measured exterior leakage and exterior leakage calculated from surface-area-ratio method is shown in Figure 94 for the 206 units tested in common-entry buildings. The black diagonal line indicates one-to-one agreement between the measured and calculated values, the blue dashed line indicates that the measured leakage is two times the calculated, and the green dashed line indicates that the calculated is two times the measured. There are a significant number of data points that fall outside the two-to-one lines of agreement. This confirms that the exterior leakage calculated from the surface-area-ratio method often provides highly inaccurate results. In addition, there is strong bias for overestimating and underestimating the exterior leakage by type of building attic and level. For example, the surface-area-ratio method overestimates the measured exterior leakage for all of the bottom- and top-level units of the flat-roof buildings (black dashes) and the exterior leakage is underestimated for 95% (36 of 38) of middle-level units of the vented-attic buildings (red asterisks).

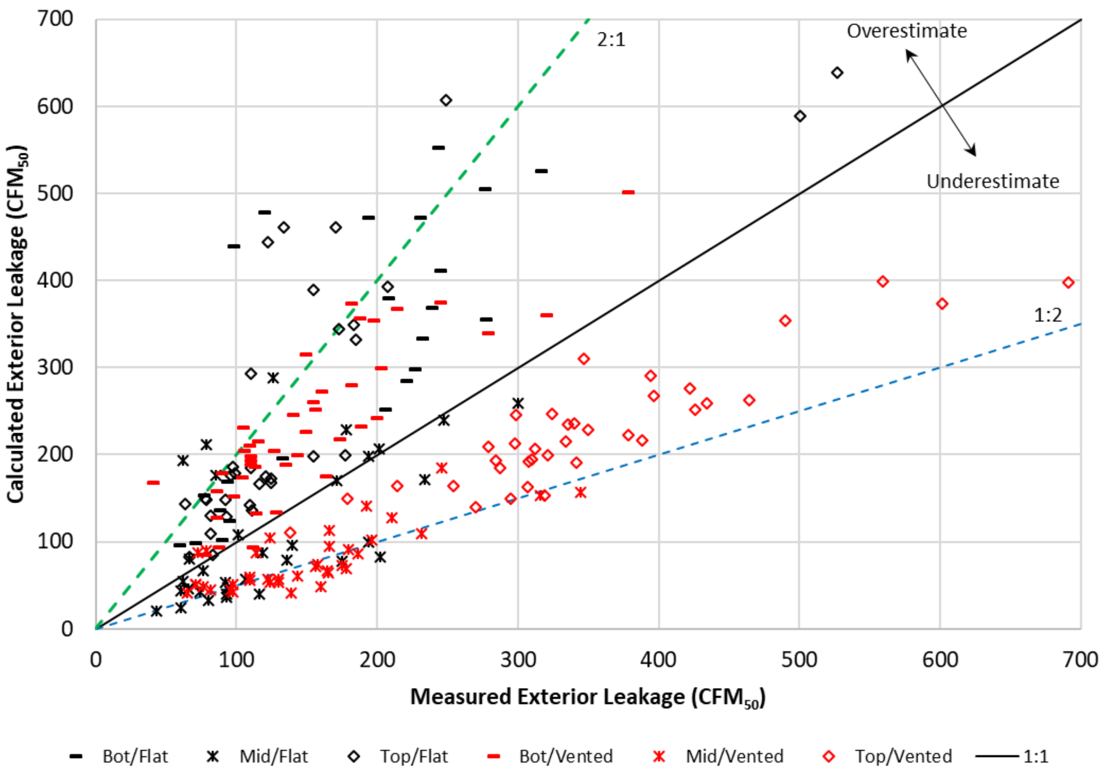


Figure 94. Measured vs. Surface-Area-Ratio Method Calculated Exterior Leakage: Common-Entry Buildings

The percentage difference between the measured exterior leakage and the exterior leakage calculated from the surface-area-ratio method was computed to evaluate the level of agreement between the two values and trends by building attic type and level. The histogram of percentage difference shows that the ratio method overestimates exterior leakage about as often (53% of units) as it underestimates. (See Figure 95.) However, there are more units with an overestimated value than with an underestimated value. For 31% of the units, the exterior leakage is overestimated by more than 50%, while for 14% of the units it is underestimated by more than 50%. The ratio method computes an exterior leakage that is within 25% of the measured value for only 18% of the units. This indicates that for about 80% of the units the error in using the ratio method is at least 10 times greater than a typical total leakage measurement uncertainty of 2%–3%.

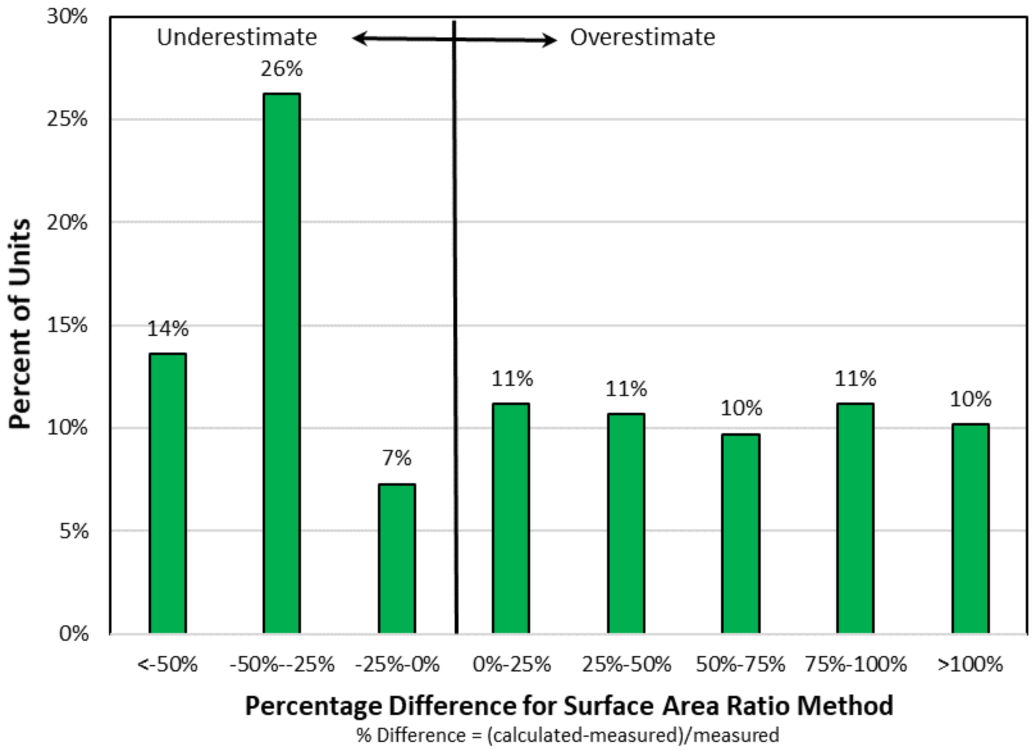


Figure 95. Histogram of Percentage Difference of Measured and Surface-Area-Ratio Calculated Exterior Leakage

Histograms of the percentage difference between the measured exterior leakage and the exterior leakage calculated with the surface-area-ratio method for the two building attic-types and three levels are shown in Figure 96, and the summary statistics are shown in Table 47. The histograms show that none of the six categories of units had a distribution that was centered near zero. This is confirmed by the summary table that shows that the median (i.e., 50th percentile) percentage difference was greater than 25% or less than -25% for all six categories of units. The median value of the absolute percentage difference between the calculated and measured exterior leakage is used as an indication of the level of agreement between the two values. As shown by the results in the last row of Table 47, the median absolute percentage difference for the 206 units tested was 47%. The median absolute percentage difference ranged from 35% for the top floor of the vented attic buildings to 67% for the top floor of the flat-roof buildings. For 10% of the units, the percentage difference between the calculated and measured exterior leakage was greater than 100%.

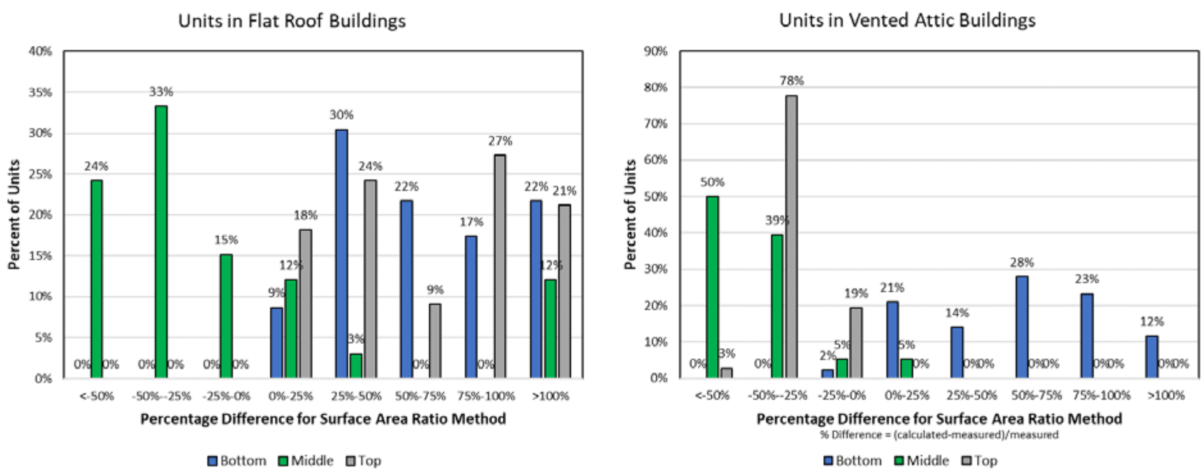


Figure 96. Histograms of Percentage Difference of Measured and Surface Area Ratio Calculated Exterior Leakage by Level and Attic Type

Table 47. % Difference of Measured and Surface Area Ratio Calculated Exterior Leakage

	Total Leakage*Exterior Surface Area/Total Surface Area						
	Flat			Vented			
Percentile	Bottom	Middle	Top	Bottom	Middle	Top	All
90th	28%	-59%	22%	10%	-60%	-46%	-54%
75th	35%	-49%	34%	29%	-56%	-41%	-39%
50th	60%	-28%	**67%**	**61%**	**-50%**	**-35%**	**7%**
25th	90%	2%	92%	81%	-37%	-29%	65%
10th	140%	91%	162%	104%	-25%	-22%	102%
Avg.	85%	-8%	80%	65%	-44%	-34%	20%
Med. APD	60%	42%	67%	61%	50%	35%	47%

As noted previously, there is a consistent trend for the surface-area-ratio method to overestimate and underestimate the measured exterior leakage by type of attic and level. (See Figure 94 and Figure 96.) This indicates that, for this data set, applying an exterior leakage multiplier to the surface-area-ratio method would remove the bias for each of the six categories and considerably improve the accuracy of the calculated value. For each unit, the exterior leakage multiplier was computed from the measured exterior leakage divided by the surface-area-ratio-calculated exterior leakage. The summary statistics for the exterior leakage multipliers for the six categories of units are shown in Table 48, and a box-and-whisker plot is shown in Figure 97. The median exterior leakage multiplier for the bottom- and top-level units of the flat-roof building and bottom-level units of the vented attic are all similar (0.60 to 0.62) and have similar CVs (28% to 29%).[20,21] For those three categories, the surface-area-ratio method consistently overestimates the measured exterior leakage. Applying the exterior leakage multipliers of 0.60 to 0.62 would remove that bias. Groups of units that tended to

[20] The median was selected to represent an appropriate exterior leakage multiplier for a group of units instead of the average, since the average is more significantly impacted by outlier values.
[21] Coefficient of Variation (CV) = standard deviation divided by the average

have an overestimated exterior leakage and multiplier less than 1.0 had a surface-area-normalized exterior leakage that was less than the surface-area-normalized total leakage. It was noted in Section 4.3.1 that the surface-area-normalized exterior leakage of these three categories of units was consistently less than that for the other three categories of units (See Figure 77). The field protocol did not include an assessment of envelope air leakage paths or magnitude. However, seven of the buildings were slab-on-grade and almost all of the others had concrete floors. This suggests that concrete floors of the bottom-level residential units are relatively tight. For the top level of flat-roof buildings, it would be expected that the watertight roofing membrane would have limited air leakage, and that most air leakage would occur through parapets or large penetrations. An exterior leakage multiplier that is nearly the same as that for the bottom-level units suggests that the leakage through the ceiling of the top-level units is relatively low and similar to that of the concrete floors of the bottom level.

Table 48. Exterior Leakage Multiplier: Common-Entry Buildings

	Flat-Roof			Vented-Attic		
Percentile	Bottom	Middle	Top	Bottom	Middle	Top
90th	0.42	0.54	0.38	0.49	1.33	1.28
75th	0.53	0.98	0.52	0.55	1.58	1.40
50th	0.62	1.40	0.60	0.62	2.02	1.54
25th	0.74	1.97	0.75	0.78	2.29	1.70
10th	0.78	2.46	0.82	0.91	2.51	1.84
Avg.	0.61	1.49	0.61	0.66	1.97	1.55
Std. Dev	0.17	0.71	0.18	0.18	0.56	0.23
CV	28%	47%	29%	28%	28%	15%

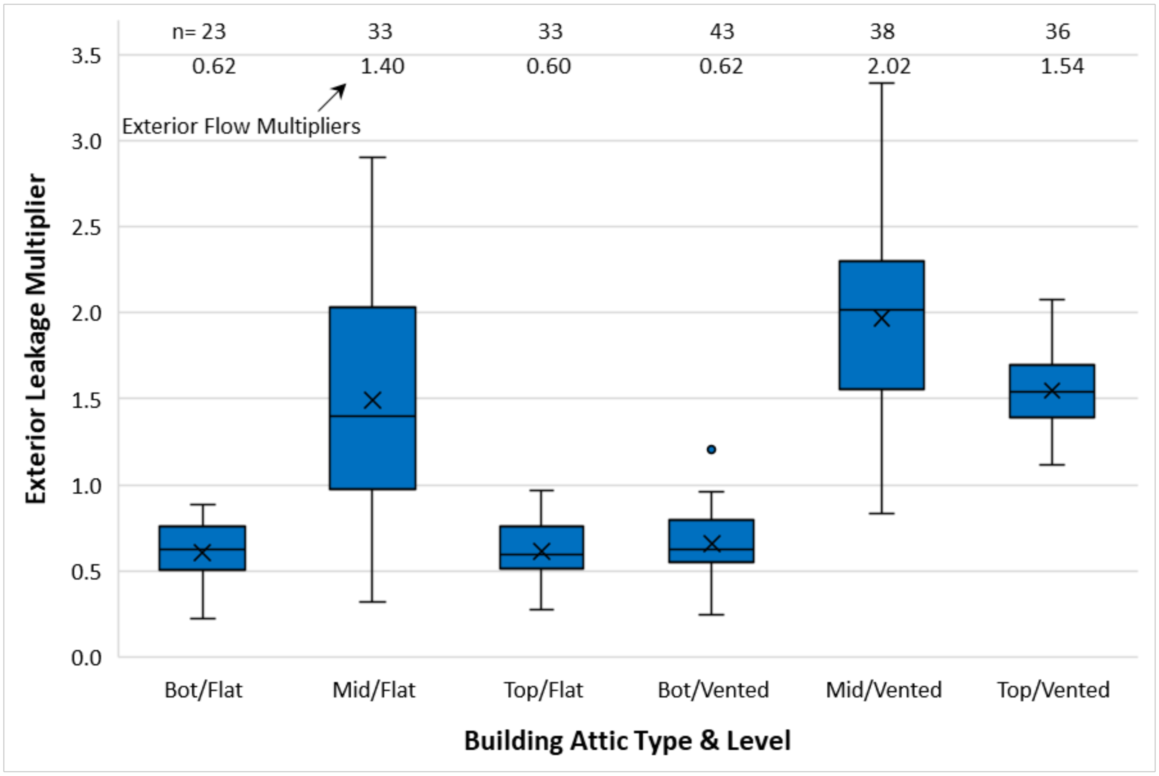


Figure 97. Exterior Leakage Multiplier by Attic Type & Level: Common-Entry Buildings

The other three categories of units had median exterior leakage multipliers of 1.40, 1.54, and 2.02 for the middle level of the flat-roof buildings, middle level of the vented-attic buildings, and top level of the vented-attic buildings, respectively. The top level of the vented attic buildings had the lowest CV of 15%; the CV for the middle-level units was the same as that for the other three categories; and the CV was greatest for the middle-level units of the flat-roof buildings. Since the only exterior surface area of middle-level units is the exterior walls, and those units had exterior leakage multipliers greater than 1.0, it appears that in these buildings, the exterior walls are typically leakier than other portions of the envelope surface. The same is true for the leakage through the ceiling of vented-attic buildings. Again, it was noted in Section 4.3.1 that the surface-area-normalized exterior leakage of these three categories of units was consistently greater than that for the other three categories of units. (See Figure 77.) In addition, the larger outliers for the middle-level units (e.g., long tails or whiskers for the boxes), indicate that there is greater variability in the relative leakage of the exterior walls.

Table 49 shows the percentage difference between the measured exterior leakage and the exterior leakage calculated from the surface-area-ratio method with exterior leakage multipliers for the two building attic types and three levels. (See the second table section from the top.) As expected, the median percentage differences are zero for all six data sets and the entire data set. This indicates that the bias has been removed for each data set. In addition, for five of the six data sets, the median absolute percentage difference was reduced by at least a factor of 3.0 (range: 3.2 to 3.9), and it decreased by a factor of 2.6 (from 47% to 18%) for all 206 units.

Table 49. Percentage Difference of Exterior Leakage for Various Calculation Methods: Common-Entry Buildings

	Total Leakage*Exterior Surface Area/Total Surface Area						
	Flat			**Vented**			
Percentile	**Bottom**	**Middle**	**Top**	**Bottom**	**Middle**	**Top**	**All**
90th	28%	-59%	22%	10%	-60%	-46%	-54%
75th	35%	-49%	34%	29%	-56%	-41%	-39%
50th	**60%**	**-28%**	**67%**	**61%**	**-50%**	**-35%**	**7%**
25th	90%	2%	92%	81%	-37%	-29%	65%
10th	140%	91%	162%	104%	-25%	-22%	102%
Avg.	85%	-8%	80%	65%	-44%	-34%	20%
Med. APD	60%	42%	67%	61%	50%	35%	47%
	Exterior Leakage Multiplier*Total Leakage*Exterior Surface Area/Total Surface Area						
Multiplier	**0.62**	**1.40**	**0.60**	**0.62**	**2.02**	**1.54**	
90th	-20%	-43%	-27%	-32%	-20%	-16%	-34%
75th	-16%	-29%	-20%	-20%	-12%	-9%	-17%
50th	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**
25th	19%	43%	15%	13%	27%	10%	19%
10th	50%	166%	57%	27%	52%	20%	50%
Avg.	15%	29%	8%	3%	12%	2%	10%
Med. APD	18%	38%	20%	16%	16%	10%	18%
	Exterior Leakage Multiplier*Total Leakage*Exterior Surface Area/Total Surface Area						
Multiplier	**0.62**	**1.61**	**0.62**	**0.62**	**1.61**	**1.61**	
90th	-21%	-65%	-21%	-29%	-36%	-13%	-33%
75th	-16%	-45%	-14%	-17%	-30%	-5%	-21%
50th	**-1%**	**-23%**	**8%**	**4%**	**-20%**	**4%**	**0%**
25th	18%	55%	24%	17%	1%	15%	20%
10th	49%	207%	69%	32%	21%	26%	56%
Avg.	14%	27%	16%	6%	-10%	6%	10%
Med. APD	19%	46%	22%	18%	25%	10%	21%
	Total Leakage						
90th	197%	239%	134%	175%	133%	22%	44%
75th	221%	279%	228%	209%	193%	29%	156%
50th	**296%**	**350%**	**262%**	**304%**	**263%**	**41%**	**263%**
25th	336%	440%	385%	345%	343%	53%	347%
10th	438%	492%	493%	397%	417%	73%	444%
Avg.	311%	400%	296%	301%	275%	45%	268%
Med. APD	296%	350%	262%	304%	263%	41%	263%

Med. APD = median of absolute value of percent difference

For simplicity, the median exterior leakage multipliers for three categories of units that have a multiplier less than 1.0 could be replaced by a single median value of 0.62, and the three that are greater than 1.0 replaced by the median of 1.61. Table 49 shows the percentage difference between the measured exterior leakage and the surface-area-ratio-calculated exterior leakage using two multipliers for the two building attic types and three levels. (See the third table section from the top.) This introduces some bias in the calculated values (i.e., median percentage difference ranges from

-23% to 8%), but the overall error in the calculated values does not increase significantly. The median absolute value of the percentage difference for all 206 units only increases from 18% to 21%.

The bottom section of Table 49 shows the percentage difference between the measured total leakage and measured exterior leakage. Using the total leakage in place of the exterior leakage produces extremely high errors. The median absolute value of the percentage difference for all 206 units is 263%. The top-level units of the vented-attic buildings are the only data set that have a median absolute value of the percentage difference less than 250%.

Figure 98 shows the measured exterior leakage versus calculated exterior leakage for the surface-area-ratio method with exterior leakage multipliers (red symbols) and without (black symbols). Exterior leakage multipliers less than 1.0 cause the symbols to move down, and exterior leakage multipliers greater than 1.0 have the opposite effect. This provides a visual representation of what has been described previously. The exterior leakage multipliers cause the red symbols to be distributed about the one-to-one line of agreement. This eliminates the bias in the calculated exterior leakage for each of the six categories of units and improves the percentage difference between the calculated and measured exterior leakage.

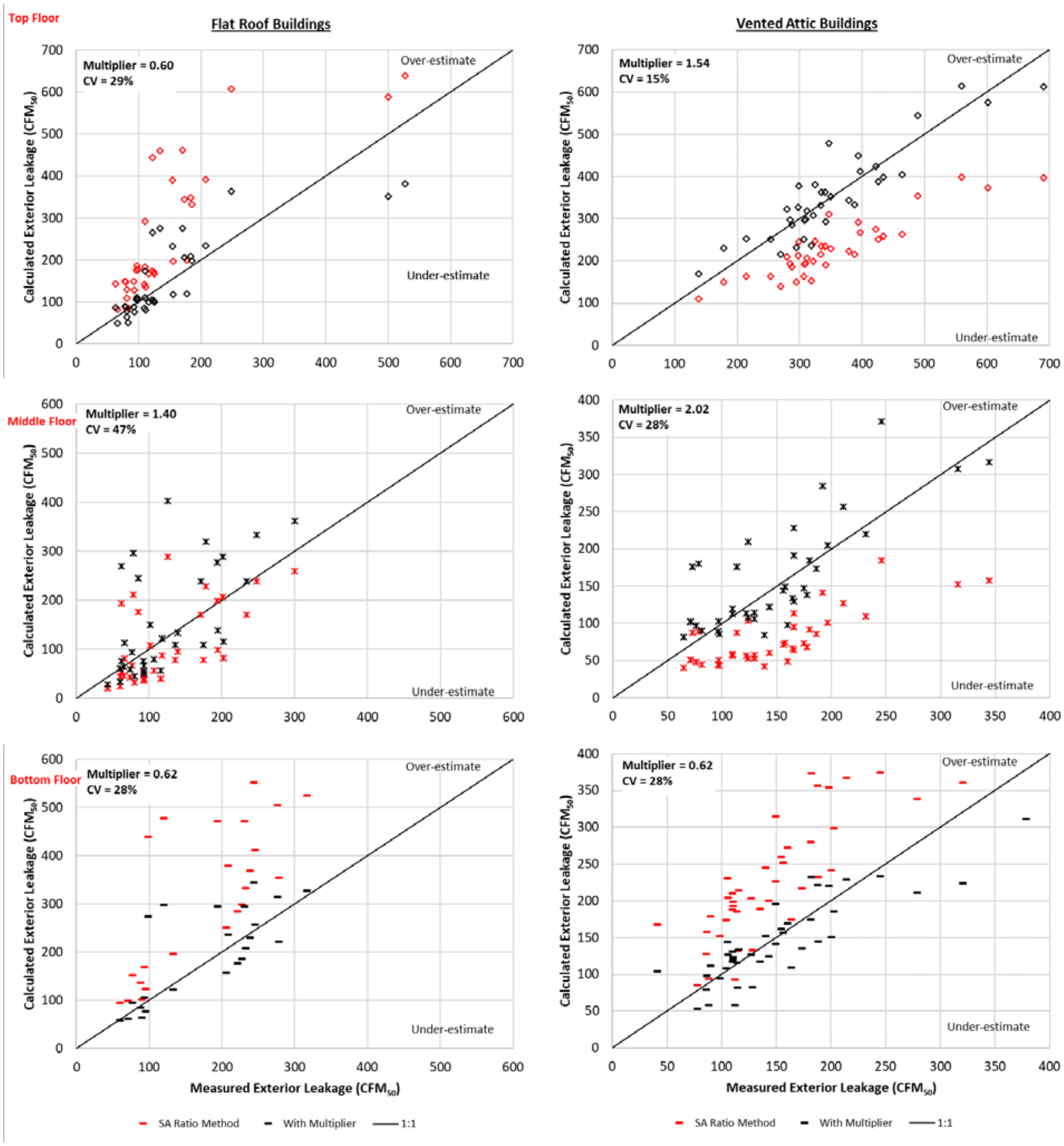


Figure 98. Measured vs. Surface Area Ratio Calculated Exterior Leakage with and Without Exterior Leakage Multiplier

For the exterior leakage multipliers to be useful, they need to provide not only the proper adjustment for the units within a single building, but also an appropriate adjustment for the different multifamily buildings in the data set. The box-and-whisker plots shown in Figure 99 show the variability of the exterior leakage multipliers within a building (e.g., the height of the box) and the variation between buildings. The exterior leakage multipliers for units in the same level of each building are fairly consistent for the bottom and top levels, but there is greater variability for the middle floors. For example, for the bottom-level units of the flat-roof buildings, the CV of the exterior leakage multipliers vary from 3% to

26% and average 13%.[22] In contrast, for the middle level of the flat-roof buildings, the CVs of the exterior leakage multipliers vary from 8% to 40% and average 28%.

The average exterior leakage multipliers for individual buildings vary somewhat more for the flat-roof buildings than they do for the vented-attic buildings. The absolute value of the percentage difference between the building average exterior leakage multiplier for each level and the “simplified” values of 0.62 and 1.61 was computed to provide an indication of the building-to-building variation of the exterior leakage multiplier. For the nine flat-roof buildings, the average absolute value of the percentage difference is 26%. In contrast, the average is 18% for the vented-attic buildings. In addition, for the flat-roof buildings, the building average exterior leakage multiplier is within 25% of the simplified values 56% of the time. For vented-attic buildings, the building average is within 25% of the simplified values 71% of the time. In other words, the simplified exterior leakage multipliers are within 25% of the building average for a little less than three-quarters of the vented-attic buildings and for a little more than half of the flat-roof buildings.

It is important to note that these exterior leakage multipliers and the statistics generated for the percentage difference between calculated and measured exterior leakage are only valid for this set of buildings. While the trends by attic type and level are fairly consistent between buildings, the exterior leakage multipliers rely on similar air sealing details and construction methods. Deviations from the typical practices seen for these buildings could cause large inaccuracies in the exterior leakage multipliers. For example, building IL43 was built to the strict PHIUS 2015 requirement of 0.05 CFM_{50}/ft^2 for whole building surface-area-normalized exterior leakage, and that standard has a much higher limit of 0.30 CFM_{50}/ft^2 for the surface-area-normalized total leakage of a unit. Consequently, the surface-area-normalized exterior leakages were low compared to those for the surface-area-normalized total leakage, and the surface-area-ratio method greatly overestimated exterior leakage. The exterior leakage multipliers for the building were 0.24, 0.34, and 0.28 for the bottom-, middle-, and top-level units, respectively.

Using the computed exterior leakage multipliers should typically provide a better estimate of the exterior leakage than using the surface-area-ratio method without the exterior leakage multipliers. However, for greater confidence, measures of exterior and total leakage similar to those that were conducted for this study should be performed for a sample of units for which the exterior leakage multipliers will be applied. In addition, for energy code compliance purposes, more conservative values for the exterior leakage multipliers (e.g., 0.8 and 2.0) could be used to more confidently ensure that the measured total leakage produces the desired exterior leakage. Regardless, the total leakage should not be used to replace the exterior leakage when the exterior leakage is the value of interest. If the surface-area-ratio method is used, it should be recognized that the computed exterior leakage is typically in error by about 50%.

[22] Standard deviation of the exterior leakage multipliers for the 3–4 units on a level of the same building divided by the average.

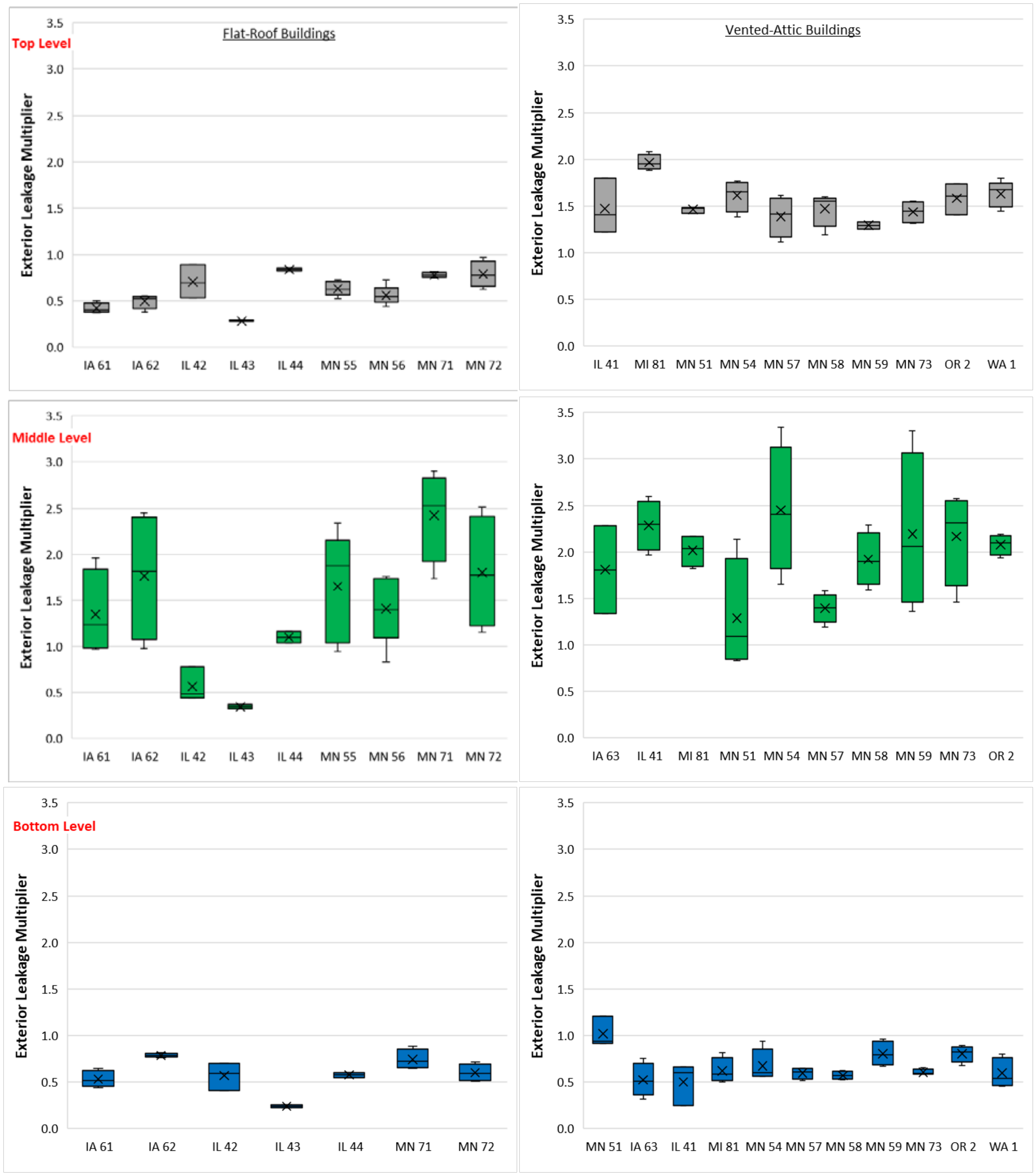


Figure 99. Exterior Leakage Multiplier by Building: Common-Entry Buildings

Section 4.4.3 presents methods for using the pressure change in adjacent units during the compart-mentalization test to estimate the exterior leakage from the total leakage and adjacent unit pressure changes. In general, units with a higher amount of interior leakage will produce larger adjacent unit pressure changes. In addition, the larger interior leakage increases the overall total leakage. That causes a higher calculated exterior leakage which, in turn, causes a positive percentage difference between the surface-area-ratio-calculated leakage and measured exterior leakage. Figure 100

shows the percentage difference between the measured exterior leakage and the exterior leakage calculated from the surface-area-ratio method, with exterior leakage multipliers for data grouped by change in adjacent unit pressure. The results show the expected trend of greater percentage difference for larger changes in the adjacent unit pressure. This suggests that the surface-area-ratio method with exterior leakage multipliers is likely to overestimate the exterior leakage for adjacent unit pressure changes larger (e.g., more negative) than -20 Pa, and
there is minor bias for overestimating when the adjacent unit pressure is -5 to -20 Pa. Section 4.4.3 provides more robust methods for using the adjacent unit induced pressure to compute exterior leakage from the total leakage.

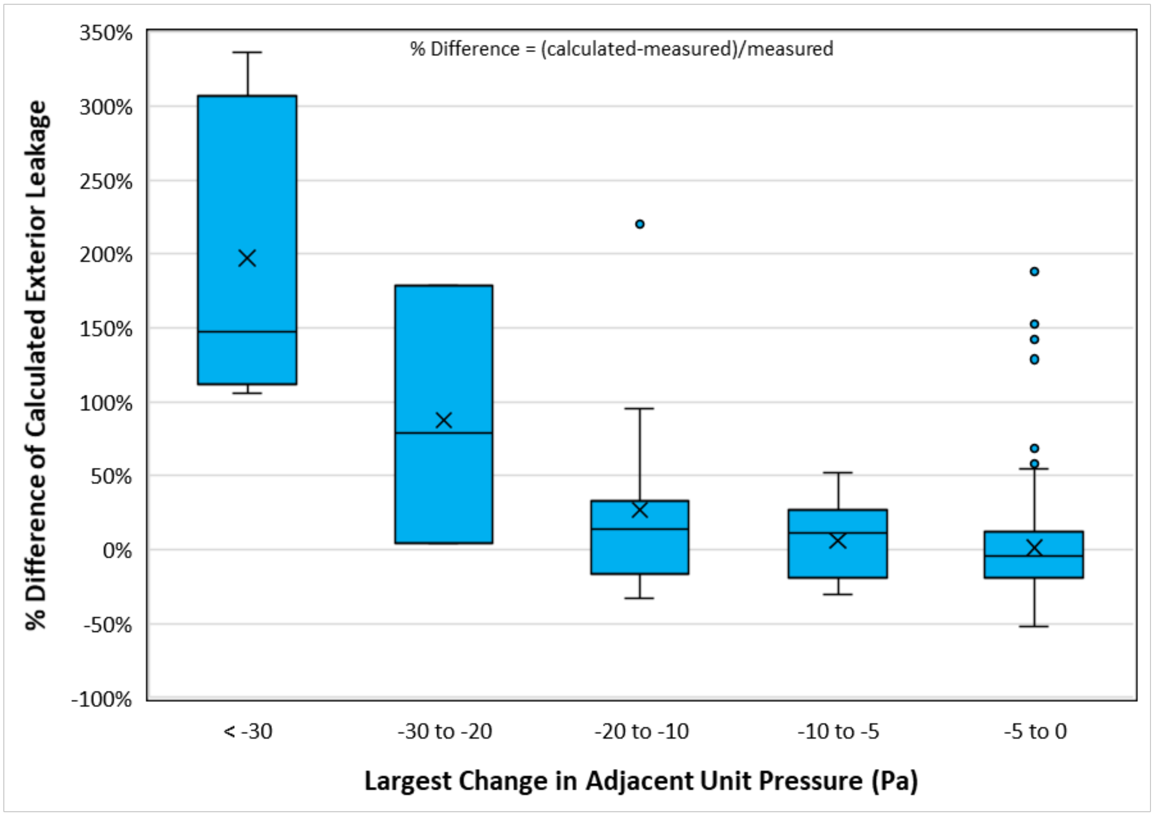


Figure 100. Variation of Percentage Difference of Measured vs. Surface-Area-Ratio-Calculated Exterior Leakage with Exterior Leakage Multipliers by Largest Adjacent Unit Pressure Change

4.4.2 Surface Area Ratio Method for Garden-Style Buildings

The analysis of the accuracy of the surface-area-ratio method completed in the previous section for common-entry buildings was repeated for the five garden-style buildings. Similar to the common-entry buildings, the surface-area-normalized exterior leakage and surface-area-normalized total leakage often differ by a factor of three, and there appears to be consistent relationships between the surface-area-normalized exterior leakage and surface-area-normalized total leakage for different building levels. (See Figure 101.) For example, for the bottom-level units, the surface-area-normalized exterior leakage is almost always less than the surface-area-normalized total leakage and for the middle- and top-level units, the surface-area-normalized exterior leakage is almost always greater than the surface-area-normalized total leakage.

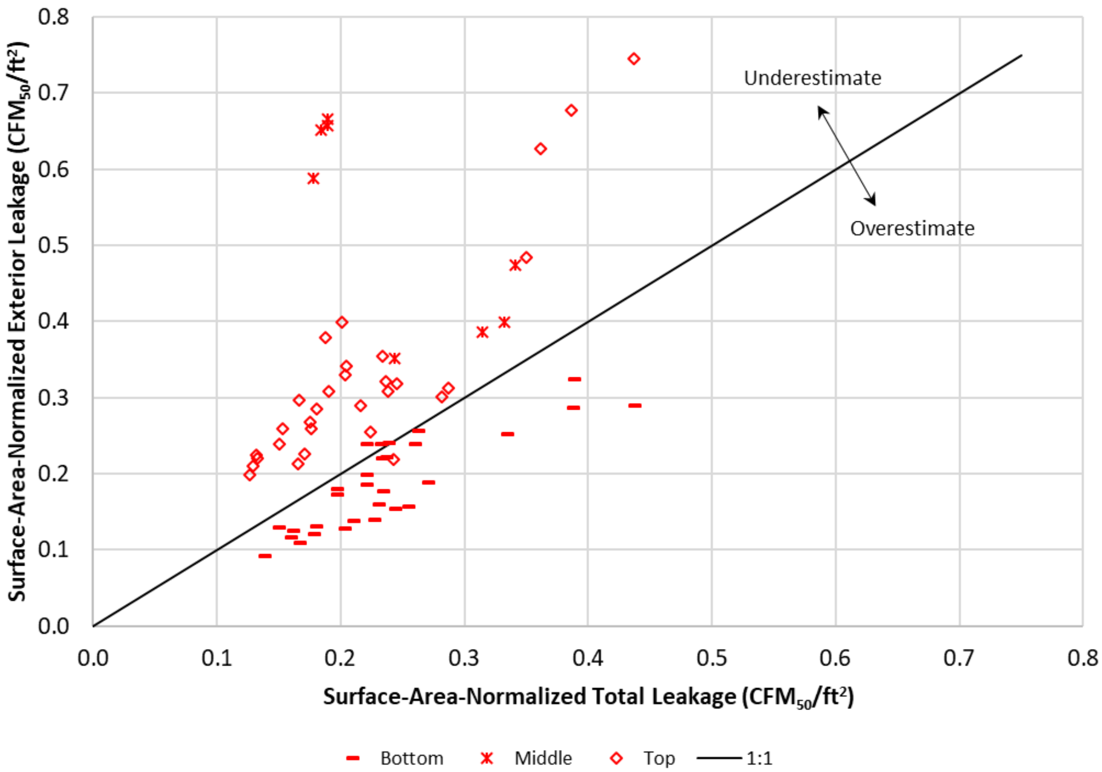


Figure 101. Surface-Area-Normalized Exterior Leakage vs. Total Leakage: Garden-Style Buildings

The relationship between the measured exterior leakage and exterior leakage calculated from surface-area-ratio method for the 68 units tested in garden-style buildings is shown in Figure 102. The black diagonal line indicates one-to-one agreement between the measured and calculated values; the blue dashed line indicates that the measured leakage is two times the calculated; and the green dashed line indicates that the calculated is two times the measured. Compared to the units from the common-entry buildings, there is better agreement between the measured and calculated exterior leakage, but there are still a number of data points that fall near or outside the two-to-one lines of agreement. This confirms that the exterior leakage calculated from the surface-area-ratio method often provides highly inaccurate results. In addition, there is strong bias for overestimating and underestimating the exterior leakage by type of building level. For example, the surface-area-ratio method overestimates the measured exterior leakage for 90% of the bottom-level units and underestimates the exterior leakage for all except one of the middle- and top-level units.

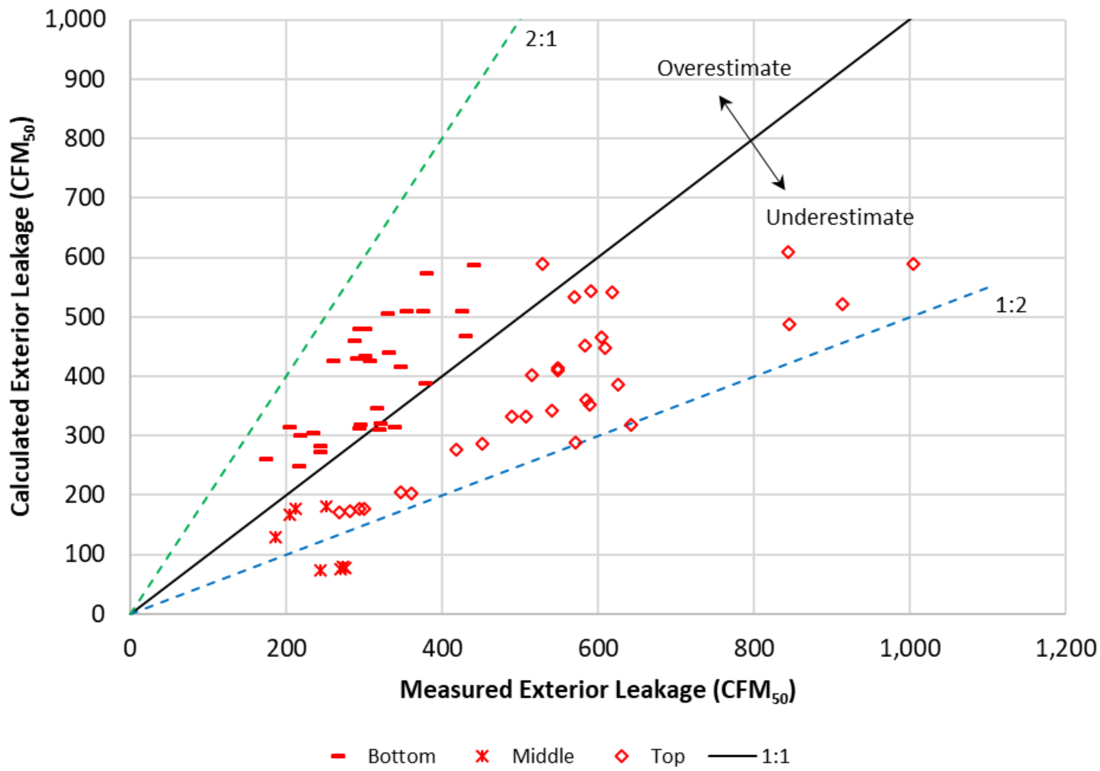


Figure 102. Measured vs. Surface-Area-Ratio Method Calculated Exterior Leakage: Garden-Style Buildings

The percentage difference between the measured exterior leakage and the exterior leakage calculated from the surface-area-ratio method was computed to evaluate the level of agreement between the two values and trends by building level. The histogram of percentage difference shows that the ratio method overestimates exterior leakage slightly less often (41% of units) than it underestimates. (See Figure 103) The distribution is fairly even except for a larger percentage in the -50% to -25% range. The number of units with a large (> 50%) overestimate is about the same as the number with a large underestimate. The ratio method computes an exterior leakage that is within 25% of the measured value for 34% of the units. Overall, the ratio method provides a better estimate of exterior leakage for the garden-style units than it does for the common-entry units. There are fewer large overestimates and underestimates, and about twice as many units are within 25% of the measured value. While the method is more accurate for garden-style units, it is still not very accurate. For about two-thirds of the units, the error in using the ratio method is at least 10 times greater than a typical total leakage measurement uncertainty of 2%–3%.

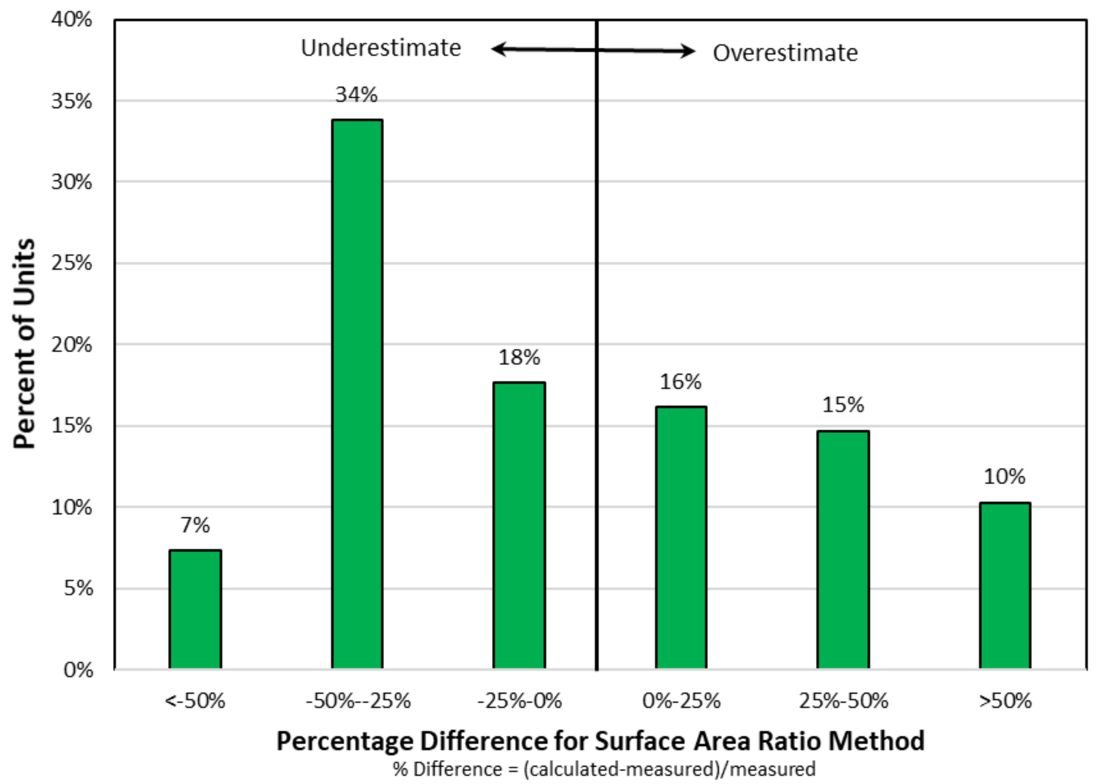


Figure 103. Histogram of Percentage Difference of Measured and Surface-Area-Ratio Calculated Exterior Leakage

Histograms of the percentage difference between the measured exterior leakage and the exterior leakage calculated with the surface-area-ratio method for the three building levels are shown in Figure 104, and the summary statistics are shown in Table 50. The histograms show that none of the three levels of units had a distribution that was centered near zero. This is confirmed by the summary table that shows that the median (i.e., 50th percentile) percentage difference was greater than 30% or less than -30% for all three levels of units. The median value of the absolute percentage difference between the calculated and measured exterior leakage was used as an indication of the level of agreement between the two values. As shown by the results in the last row of Table 50, the median absolute percentage difference for the 68 units tested was 35%. The median absolute percentage difference was fairly consistent for the three levels. It ranged from 33% for the bottom-level units to 50% for the middle-level units. None of the units had a percentage difference that was less than -75% or greater than 75%. This is much better than the common-entry units — 10% of those units had a percentage difference greater than 100%.

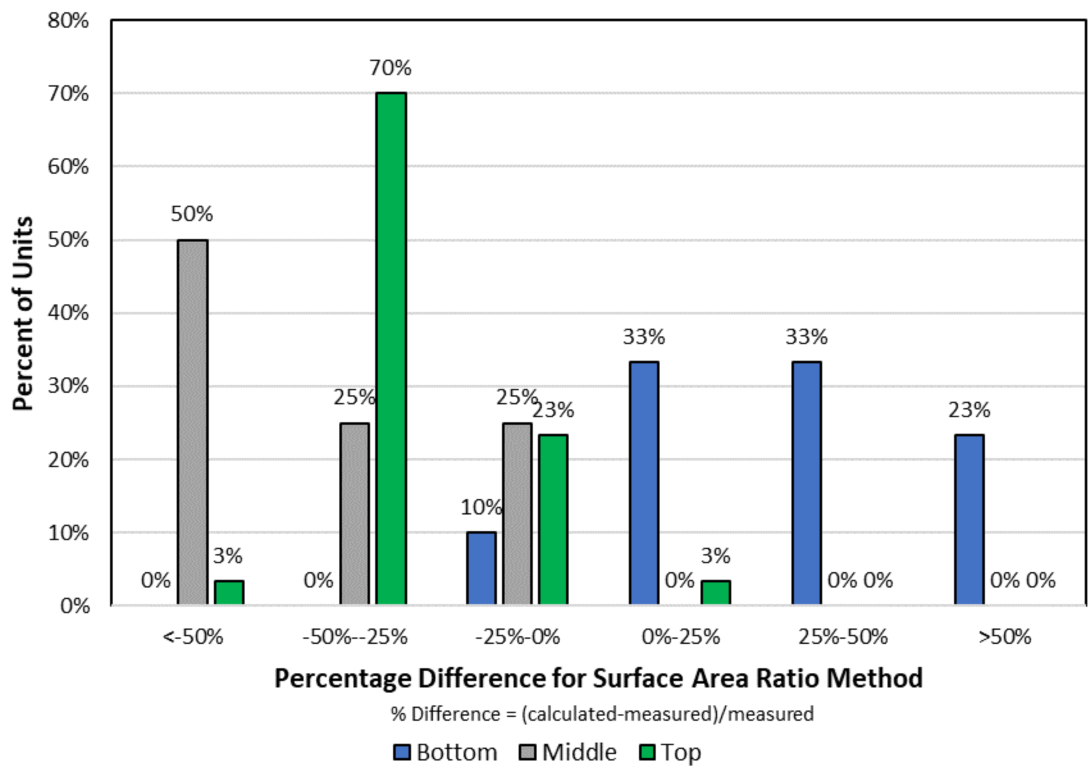


Figure 104. Histogram of Percentage Difference of Surface-Area-Ratio Method by Level

Table 50. Percentage Difference of Surface-Area-Ratio Method by Building Level: Garden-Style Buildings

	Total Leakage*Exterior Surface Area/Total Surface Area			
Percentile	**Bottom**	**Middle**	**Top**	**All**
90th	2%	-72%	-43%	-43%
75th	10%	-71%	-41%	-37%
50th	**33%**	**-50%**	**-37%**	**-14%**
25th	49%	-26%	-25%	22%
10th	59%	-18%	-12%	50%
Avg.	30%	-47%	-32%	-6%
Med. APD	33%	50%	37%	35%

As noted previously, the surface-area-ratio method consistently overestimates and underestimates the measured exterior leakage by building level. (See Figure 102 and Figure 104.) This indicates that for this data set, applying an exterior leakage multiplier to the surface-area-ratio method would remove the bias for each of the three levels and considerably improve the accuracy of the calculated value. For each unit, the exterior leakage multiplier was computed from the measured exterior leakage divided by the surface-area-ratio calculated exterior leakage. The summary statistics for the exterior leakage multipliers for the three levels of units are shown in Table 51, and a box-and-whisker plot is shown in Figure 105. The median exterior leakage multiplier for the bottom-level units was 0.75 and the medians for the middle- and top-level units were 2.38 and 1.58, respectively. The CV for the bottom- and top-level units was quite low (17%), but it was high for the middle-level units (48%). There were only eight middle-level units in the data set, and those were generated from only two buildings. The median exterior leakage multipliers were very similar to those for the common-entry vented-attic buildings. They were 0.62, 2.02, and 1.54 for the bottom-, middle-, and top-levels, respectively. Groups of units that tended to have an overestimated exterior leakage and exterior leakage multiplier less than 1.0 had a surface-area-normalized exterior leakage that was less than that of the surface-area-normalized total leakage. It was noted in Section 4.3.2 that the surface-area-normalized exterior leakage of the bottom-level units was consistently less than that for the other three categories of units. (See Figure 92.) All five buildings were slab-on-grade construction. This suggests that concrete floors of the bottom-level residential units are relatively tight.

Table 51. Exterior Leakage Multiplier: Garden-Style Buildings

	Level		
Percentile	Bottom	Middle	Top
90th	0.63	1.22	1.13
75th	0.67	1.35	1.33
50th	**0.75**	**2.38**	**1.58**
25th	0.91	3.48	1.69
10th	0.98	3.53	1.76
Avg.	0.79	2.39	1.51
Std. Dev	0.14	1.15	0.26
CV	17%	48%	17%

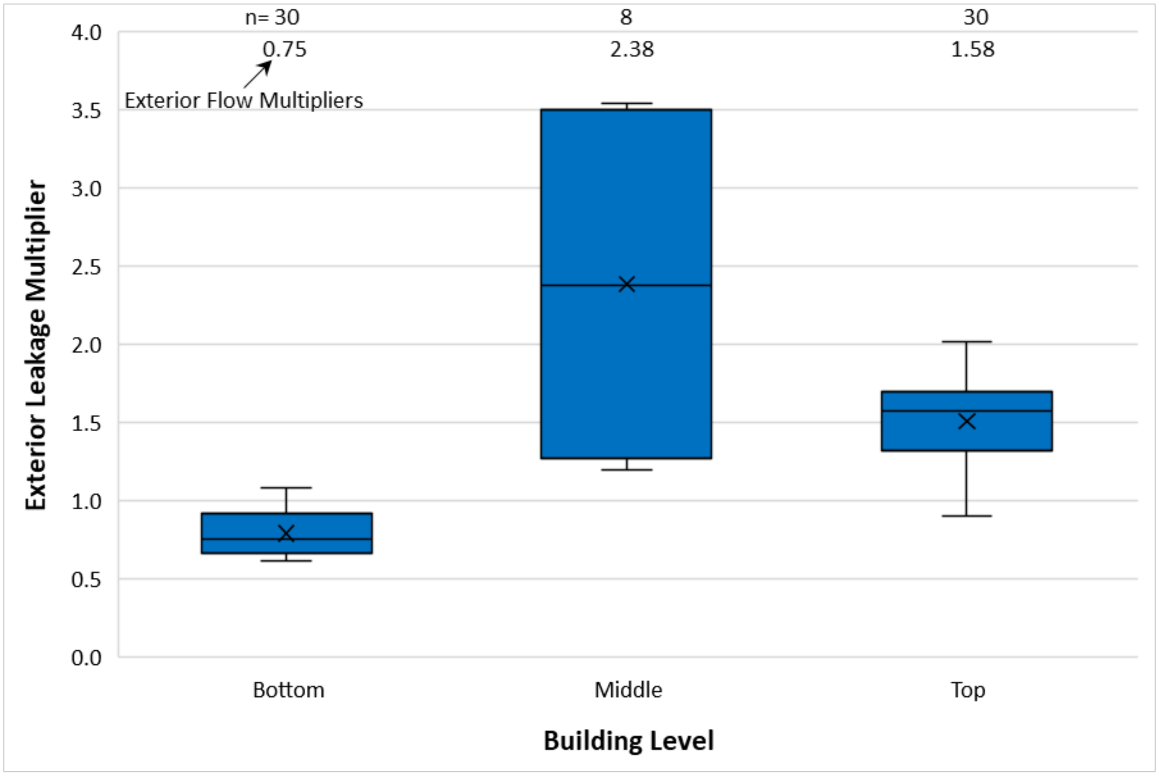


Figure 105. Exterior Leakage Multiplier by Level: Garden-Style Buildings

Since the only exterior surface area of middle-level units is the exterior walls and those units had exterior leakage multipliers greater than 1.0, it appears that the exterior walls in these buildings are typically leakier than other portions of the envelope surface. The same is true for the leakage through the ceiling of these garden-style, vented-attic buildings. This result is consistent with that for the common-entry vented-attic buildings.

Table 52 and Figure 106 show the percentage difference between the measured exterior leakage and the exterior leakage calculated from the surface-area-ratio method, with exterior leakage multipliers for the three building levels. (See the second table section from the top.) As expected, the median percentage differences are zero or close to zero for all three levels and the entire data set.[23] This indicates that the bias has been removed for each data set. In addition, for two of the three data sets, the median absolute percentage difference was reduced by at least a factor of 2.0 (range: 1.03 to 3.78), and it decreased by a factor of 2.3 (from 35% to 15%) for all 68 units. (See Figure 107) This is similar to the results for the common-entry buildings, except the improvement was not as great as that for the middle-level units, which showed a significant difference in the exterior leakage multiplier for the two buildings.

[23] There was an even number (eight) of units in the bottom-level data set. The median is computed from the average of the two middle values. Since the multipliers are highly grouped, the median multiplier does not produce a median percentage difference of zero.

Table 52. Percentage Difference of Exterior Leakage for Various Calculation Methods: Garden-Style Buildings

	Total Leakage*Exterior Surface Area/Total Surface Area			
Percentile	**Bottom**	**Middle**	**Top**	**All**
90th	2%	-72%	-43%	-43%
75th	10%	-71%	-41%	-37%
50th	**33%**	**-50%**	**-37%**	**-14%**
25th	49%	-26%	-25%	22%
10th	59%	-18%	-12%	50%
Avg.	30%	-47%	-32%	-6%
Med. APD	33%	50%	37%	35%
	Exterior Leakage Multiplier*Total Leakage*Exterior SA/Total SA			
Multiplier	**0.75**	**2.38**	**1.58**	
90th	-23%	-33%	-10%	-24%
75th	-17%	-32%	-7%	-12%
50th	**0%**	**18%**	**0%**	**0%**
25th	12%	77%	19%	17%
10th	20%	95%	39%	40%
Avg.	-2%	25%	8%	6%
Med. APD	14%	49%	10%	15%
	Exterior Leakage Multiplier*Total Leakage*Exterior SA/Total SA			
Multiplier	**0.75**	**1.58**	**1.58**	
90th	-23%	-55%	-10%	-24%
75th	-17%	-55%	-7%	-12%
50th	**0%**	**-22%**	**0%**	**0%**
25th	12%	17%	19%	15%
10th	20%	29%	39%	23%
Avg.	-2%	-17%	8%	1%
Med. APD	14%	42%	10%	14%
	Total Leakage			
90th	103%	87%	12%	17%
75th	121%	89%	17%	41%
50th	**166%**	**165%**	**39%**	**102%**
25th	209%	255%	58%	173%
10th	250%	292%	78%	241%
Avg.	169%	178%	41%	114%
Med. APD	166%	165%	39%	102%

Med. APD = median of absolute value of percent difference

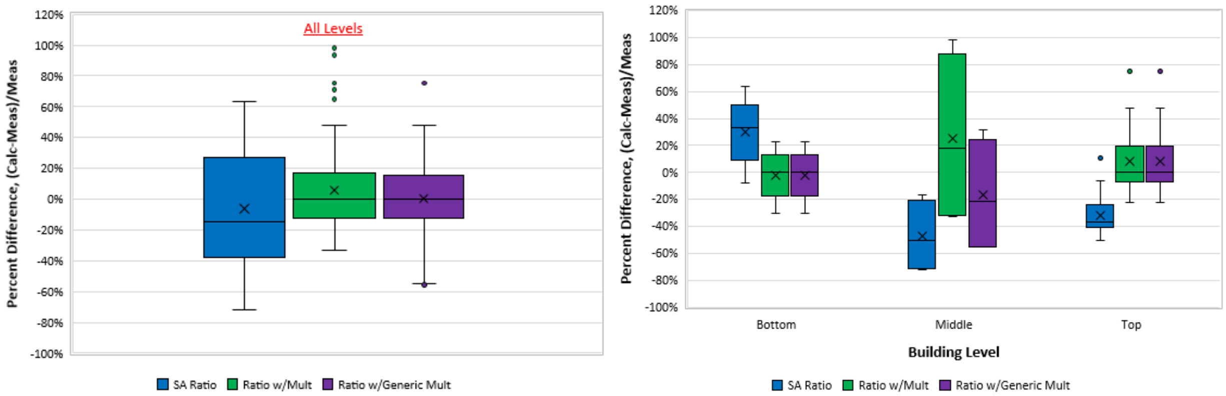


Figure 106. Box-and-Whisker Plots of Percentage Difference of Various Calculation Methods

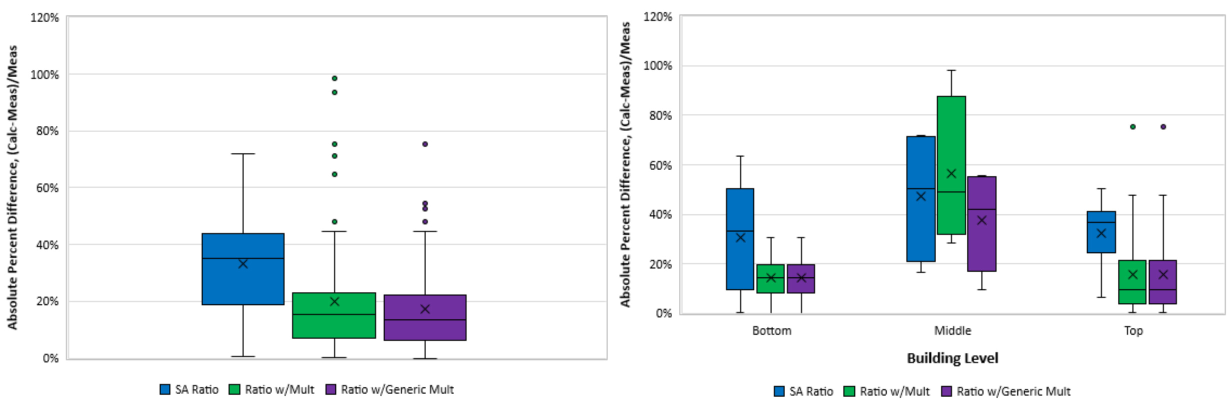


Figure 107. Box-and-Whisker Plots of Absolute Percentage Difference of Various Calculation Methods

For simplicity, the median exterior leakage multipliers for middle- and top-level units could be replaced by a single median value of 1.58 for the combined data set. This is the same as that for the top-level units and only affects the calculation for the middle-level units. Table 52 shows the percentage difference between the measured exterior leakage and the surface-area-ratio method calculated exterior leakage using the two exterior leakage multipliers for the three building levels. (See the third table section from the top.) This shifts the median percentage difference for the middle-level units from 18% to -22% but decreases the median absolute percentage difference for those units from 49% to 42%. The median absolute percentage difference for the entire data set decreases slightly from 15% to 14%. The exterior leakage multiplier of 1.58 for the middle- and top-level units is within 2% of the value determined for the common-entry buildings and the value of 0.75 for the bottom-level buildings is within 20% of the value of 0.62 for the common-entry buildings.

The bottom section of Table 52 shows the percentage difference between the measured total leakage and measured exterior leakage. Using the total leakage in place of the exterior leakage produces large errors. The median absolute value of the percentage difference for all 206 units is 102%. For the top-level units the median absolute percentage difference is only 39%, but it is 166% and 165% for the bottom- and middle-level units, respectively.

Figure 108 shows the measured exterior leakage versus calculated exterior leakage for the surface-area-ratio method with exterior leakage multipliers (red symbols) and without (black symbols). Exterior leakage multipliers less than 1.0

cause the symbols to move down vertically, and exterior leakage multipliers greater than 1.0 have the opposite effect. This provides a visual representation of what has been described previously. The exterior leakage multipliers cause the red symbols to be distributed about the one-to-one line of agreement. This eliminates the bias in the calculated exterior leakage for each of the three levels of units and improves the percentage difference between the calculated and measured exterior leakage.

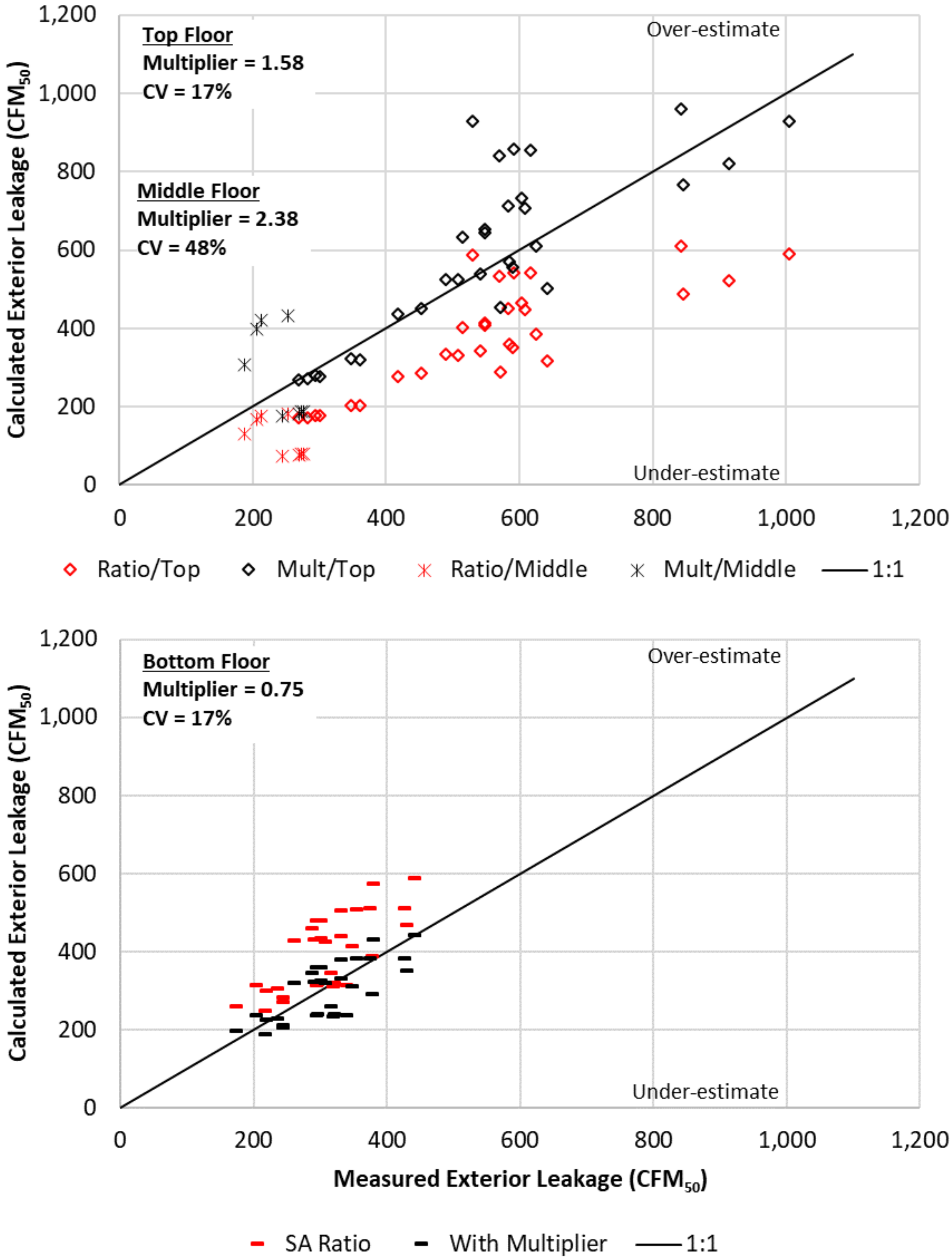


Figure 108. Measured vs. Surface-Area-Ratio Calculated Exterior Leakage with and without Exterior Leakage Multiplier

For the exterior leakage multipliers to be useful, they need to provide not only the proper adjustment for the units within a single building, but also an appropriate adjustment for the different multifamily buildings in the data set. Table

53 shows the CV of the exterior leakage multipliers for units in the same building. The box-and-whisker plots shown in Figure 109 show the variability of the exterior leakage multipliers within a building (e.g., the height of the box) and the variation between buildings. The exterior leakage multipliers for units on the same level of each building are very consistent for all levels of the buildings. Overall, the CVs ranged from 2% to 14% and averaged 8%. This suggests that the air barrier practices were very consistent for each of the buildings.

Table 53. CV of Exterior Leakage Multipliers for Units on the Same Level of the Same Building

	Level		
Bldg. ID	Bottom	Middle	Top
MN 52	11%		9%
MN 53	8%		14%
OR 4	5%	3%	2%
WA 3	9%	9%	11%
WA 5	8%		12%
Average	8%	6%	9%

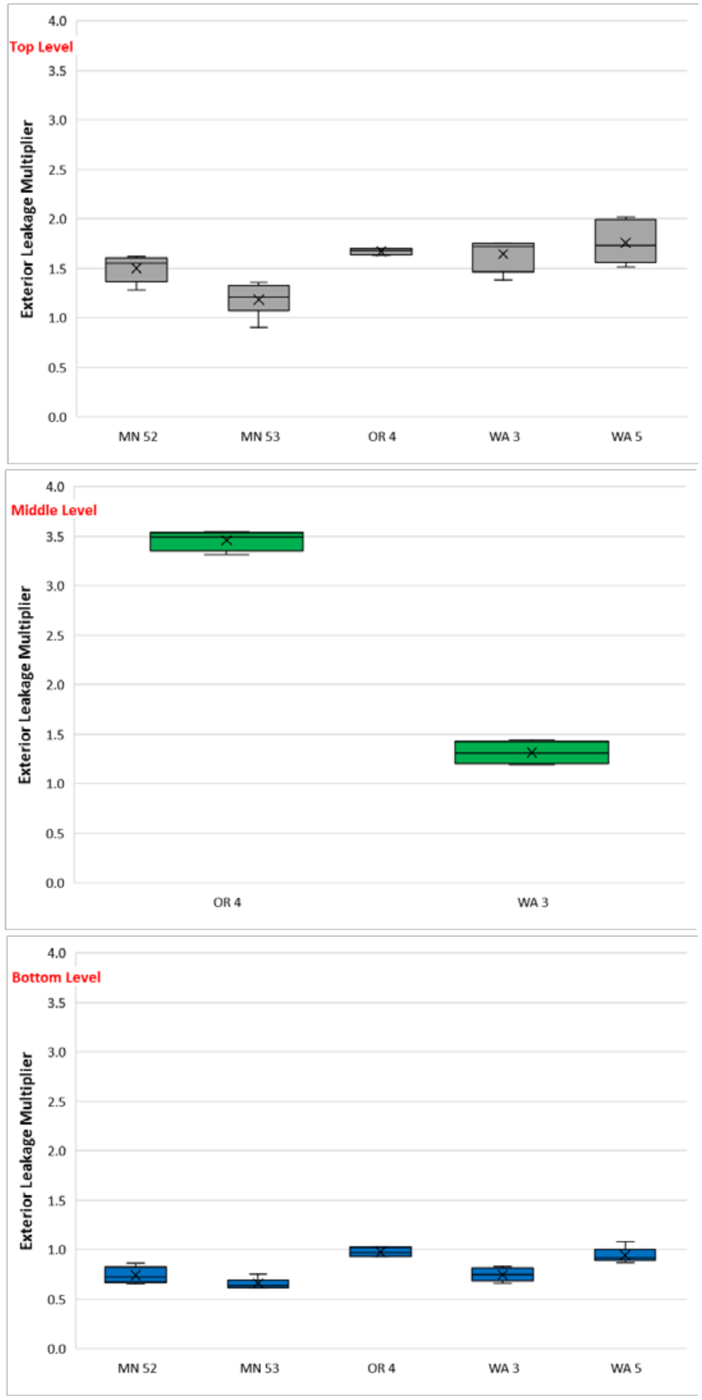


Figure 109. Exterior Leakage Multiplier by Building: Garden-Style Buildings

The average exterior leakage multipliers for individual buildings were consistent for the bottom- and top-level units, but the exterior leakage multipliers were quite different for the two buildings that had middle-level units. The absolute value of the percentage difference between the building average exterior leakage multiplier for each level and the “simplified” values of 0.75 and 1.58 was computed to provide an indication of the building-to-building variation of the exterior leakage multiplier. The median percentage difference for all three levels of all five buildings was 12%, and only the middle-level units of building OR4 had a percentage difference greater than 30%. The building average was within 25% of the simplified values 75% of the time. In other words, the simplified exterior leakage multipliers are within 25% of the building average for three-quarters of the garden-style buildings. This is consistent with the results for the common-entry, vented-attic buildings.

As noted in the previous section, these exterior leakage multipliers and the statistics generated for the percentage difference between calculated and measured exterior leakage are only valid for this set of five buildings. While the trends by building level are fairly consistent between buildings, the exterior leakage multipliers rely on similar air sealing details and construction methods being applied for a building. Deviations from the typical practices seen for these buildings could cause large inaccuracies in the exterior leakage multipliers. For example, the average exterior leakage multipliers for the middle-levels units of buildings OR4 and WA3 differ by a factor of 2.6 (3.46 and 1.31, respectively).

The exterior leakage multiplier of 1.31 for WA3 is only 17% different than the “simple” exterior leakage multiplier of 1.58, but the exterior leakage multiplier of 3.46 is 119% different from 1.58. Either the surface-area-normalized exterior leakage of WA3 was atypically high or the interior was atypically low — or both. For WA3, it was both. The median surface-area-normalized exterior leakage of 0.65 CFM_{50}/ft^2 was 157% greater than the median for all of the units, and the median interior leakage of 0.10 CFM_{50}/ft^2 was 46% less than median for all of the units. Since the field protocol did not include an investigation of air leakage pathways, it is not known what caused the high exterior and low interior leakages. As noted previously, using the computed exterior leakage multipliers should typically provide a better estimate of the exterior leakage than using the ratio method without the exterior leakage multipliers. However, similar measures of exterior and total leakage that were conducted for this study should be performed for a sample of units of the buildings for which the exterior leakage multipliers will be applied to confidently apply the exterior leakage multipliers.

In conclusion, it is important to note that use of these multipliers, while somewhat promising, is also based on a very small set of units and is only internally consistent. These multipliers are only applicable to this set of buildings and may not apply well to another set. Future studies can use this approach as a starting point for comparison.

The following section (4.4.3) presents methods for using the pressure change in adjacent units during the compartmentalization test to estimate the exterior leakage from the total leakage and the adjacent unit pressure changes. In general, units with a higher amount of interior leakage will produce larger adjacent unit pressure changes. In addition, the larger interior leakage increases the overall total leakage. That causes a higher calculated exterior leakage which, in turn, causes a positive percentage difference between the surface-area-ratio method calculated exterior leakage and measured leakage. Figure 110 shows the percentage difference between the measured exterior leakage and the exterior leakage calculated from the surface-area-ratio method with exterior leakage multipliers for bins of change in adjacent unit pressure. The results show the expected trend of greater percentage difference for larger changes in the adjacent unit pressure. This suggests that the surface-area-ratio method with exterior leakage multipliers is likely to overestimate the exterior leakage for adjacent unit pressure changes larger (e.g., more negative) than -15 Pa, and there is little or no bias for overestimating when the adjacent unit pressure is -5 to -15 Pa. This is similar to the results for the common-entry buildings except for that data set the cutoff was -20 Pa instead of -15 Pa. However, the cutoff pressures of -15 Pa and -20 Pa are based on a limited number of tests. For the common-entry buildings there were only 10 tests with an adjacent unit pressure change larger than -15 Pa, and for garden-entry buildings there were only six. Section 4.4.3 provides more robust methods for using the adjacent unit induced pressure to compute exterior leakage from the total leakage.

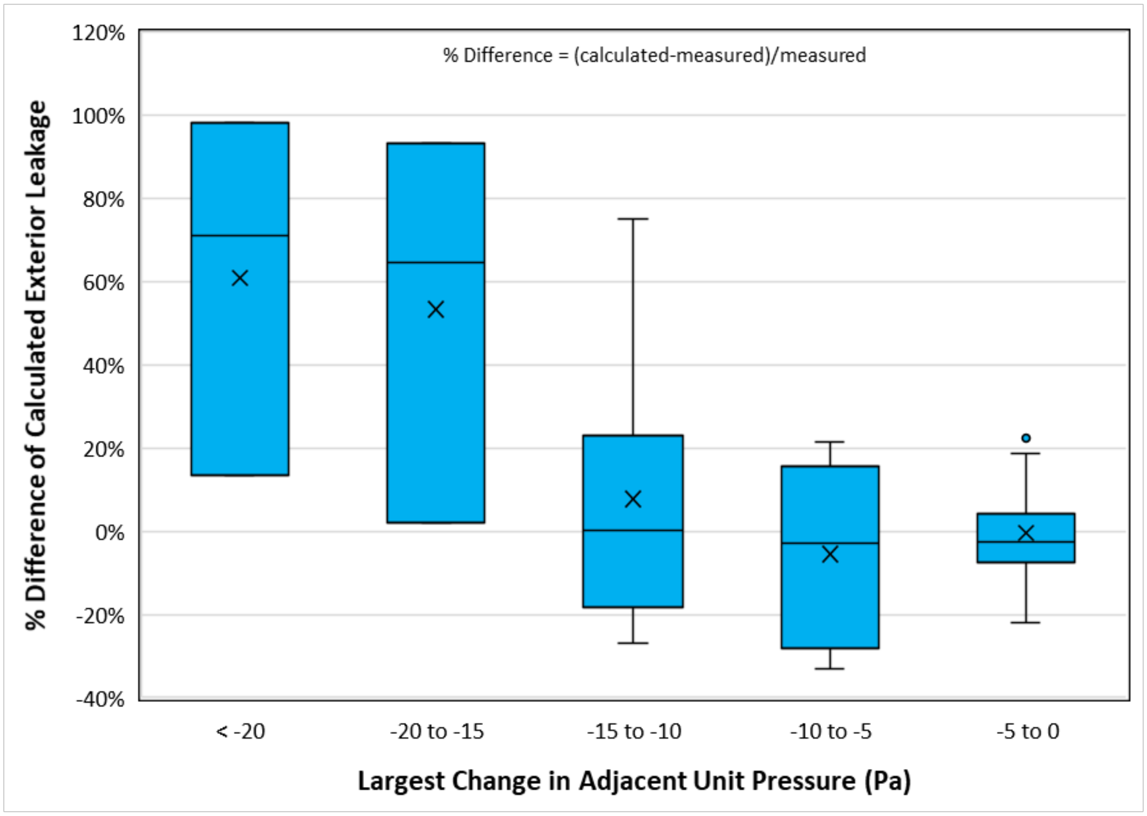


Figure 110. Variation of Percentage Difference of Measured vs. Surface-Area-Ratio Calculated Exterior Leakage with Exterior Leakage Multipliers by Adjacent Unit Pressure Change

4.4.3 Adjoining Unit Pressure Change Method for Garden-Style Buildings

Results from the previous section suggest that the change in pressure of adjacent units when the compartmentalization test is performed is related to the relationship between the exterior and interior leakage of the unit. When there are two adjoining zones with identical exterior leakage and a compartmentalization test is conducted in one zone (A) and the pressure change is measured in the adjacent zone (dP_{OB}), the exterior leakage of the zones ($CFM50_{OA}$) can be estimated by equation C1.6:

$$CFM50_{OA} = \frac{Q_{fan}^{A}}{\left(1+\left(\frac{dP_{OB}}{50}\right)^{n}\right)} \tag{C1.6}$$

Where Q_{fan} is the airflow rate required to produce an induced pressure of 50 Pa and that value is adjusted by a function of the adjacent unit pressure to compute the exterior leakage. The derivation of the equation is included in section Case 1: Two Adjoining Units, Equal Exterior Leakage of Appendix C. This equation assumes that the exponent of the power law leakage relationship for all of the leaks is equal to n. A variation of this equation was used to generate what is commonly referred to as the *Tooley Chart* (Cummings, Withers, and Shirey 1997).

This approach can be extended to produce a similar equation when there are three adjacent zone that all have the same exterior leakage:

$$CFM50_{OA} = \frac{Q^A_{fan}}{\left(1+\left(\frac{dP_{OB}}{50}\right)^n+\left(\frac{dP_{OC}}{50}\right)^n\right)} \tag{C3.6}$$

The derivation of the equation is included in section Case 3: Three Adjoining Units In a Row, No Common Area, Equal Exterior Leakage of Appendix C. This equation assumes that the exponent of the power law leakage relationship for all of the leaks is equal to n. When there are m adjacent zones, this equation is extended to:

$$CFM50_{OA} = \frac{Q^A_{fan}}{\left(1+\sum_{i=1}^{m}\left(\frac{dP_{Oi}}{50}\right)^n\right)} \tag{3}$$

This will be referred to as the “Equal” method, since it assumes that all of the adjacent units have the same exterior leakage. Again, this equation assumes that the exponent of the power law leakage relationship for all of the leaks is equal to n.

A further extension of this approach is to remove the requirement that the exterior leakages of the adjacent units are equal. When a compartmentalization test with all adjacent units are closed is performed for three adjacent units (See Figure 111 – test configuration for unit C is a mirror image of that for unit B), a series of equations can be generated to compute the exterior leakage of all three units:

$$\begin{pmatrix} 1 & -\left(\frac{dP_{OB}}{50}\right)^n & -\left(\frac{dP_{OC}}{50}\right)^n \\ -\left(\frac{dP_{OA}}{50}\right)^n & 1 & -\left(\frac{dP_{OC}}{50}\right)^n \\ -\left(\frac{dP_{OA}}{50}\right)^n & -\left(\frac{dP_{OB}}{50}\right)^n & 1 \end{pmatrix} \begin{pmatrix} CFM50_{OA} \\ CFM50_{OB} \\ CFM50_{OC} \end{pmatrix} = \begin{pmatrix} Q^A_{fan} \\ Q^B_{fan} \\ Q^C_{fan} \end{pmatrix} \tag{C4.12}$$

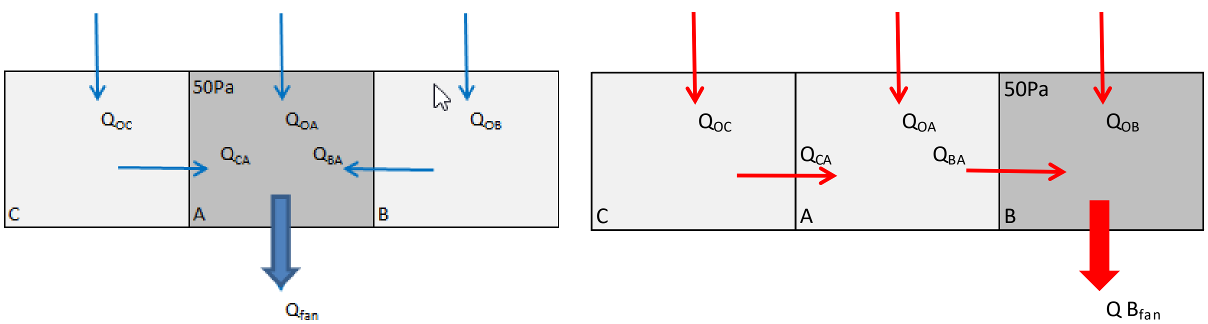


Figure 111. Compartmentalization Test Configuration For the Center and One Side Unit

The derivation of the equation is included in section Case 4: Three Adjoining Units In a Row, No Common Area, Unit Exterior Leakage Not Equal of Appendix C. This equation assumes that the exponent of the power law leakage relationship for all of the leaks is equal to n. This is referred to as the “Matrix” method. The form of this equation can be extended to a larger number of units. One drawback to the method is that a compartmentalization test should be conducted for all units and the pressure change measured in all units for each of those tests.

Both the Equal and Matrix methods can be applied to garden-style buildings to estimate the exterior leakage of each unit. The method can also be applied to units in common-entry buildings, with one caveat. Since the compartmentalization tests for units in common-entry buildings are performed with the common space open to outside, the methods will compute the sum of the leakage to the exterior and common space. The methods do not include a procedure for splitting the computed leakage between the exterior and common space. Consequently, the remainder of this analysis is performed for the units from the garden-style buildings.

The results of these exterior leakage estimate methods are shown in Figures 110-112. Figure 112 graphs the calculated leakage versus the directly measured leakage (the latter being obtained from the individual fan flows during the simultaneous depressurization of all units). The ratio methods (with and without multipliers) of section 4.4.2 are included for comparison. For a method that works perfectly, and in the absence of wind or temperature-induced bias or variability, one would expect to see all of the data points lying on the black line (the line of agreement). The results that lie closest to the line represent the methods that were the
most successful.

As evident in the figure, neither the Equal method nor the Matrix method represent a marked improvement in the estimates as compared with the Ratio method (with multipliers). This was a surprise as it was expected that the adjacent units' pressure response would be useful input in estimating the split between interior and exterior leakage.

In the case of top level units (upper graph in Figure 112), the Matrix method does appear to have significant explanatory power and seems to be a fairly unbiased estimation. It has the advantage over the Ratio methods, as it does not require any measurements of the unit surface areas split (interior versus exterior) but it has a disadvantage that it requires airtightness measurements of more individual units (as compared with the Ratio methods or the Equal method).

For the bottom and middle units, none of the methods seem to provide much predictive power. This null result does not mean that the adjacent unit pressures are irrelevant to this prediction process, it just means that a suitable algorithm could not be derived for this set of buildings. There are several factors which could contribute to this failure. For one thing, real buildings rarely have direct leaks from one unit to another. They have wall (and other) cavities which often connect to multiple units, sometimes distant from the unit under consideration, and connect to the outdoors or attic spaces. These types of intermediate zones are not captured in the derivation of the Equal and Matrix methods. Second, there is a fair amount of wind-induced variability which can interfere with the proper apportioning of the whole-building leakage to the individual units. The intent of the measurements was to induce exactly -50 Pascals in each unit, but when wind is impacting the outdoor references by a significant amount (say, +/- 1 Pa or greater), this can lead to a misallocation of leakage from one unit to another even if the whole-building leakage measurement has a low percentage error. This wind effect would cause random scatter above and below the line of agreement. It is possible that advances in measurement techniques (repeated depressurization cycles, for example) could help reduce the wind effects. Finally, other inaccuracies are likely introduced by leakage type distribution (that is, not all leaks will conform to the model's assumption of an average flow exponent of 0.65) and by leaks that are not symmetric under a change of sign in the pressure across them.

Figure 113 graphs the same data in the form of errors as a fraction of the measured leakage. Again, it is seen that none of the methods are particularly successful in achieving low errors; it also worth mentioning that the "truth" value here (the measured values) are themselves subject to some error. In a study specifically designed to resolve these issues, one would probably need to focus on testing under ideal conditions and/or conducting many repeated measurements to characterize the errors in the actual directly measured exterior leakage values.

Figure 114 is similar to Figure 113, but shows the absolute value of the errors. This means that one cannot as easily see which methods are biased but can more easily see which make closer predictions of the measured leakage most often. None of the methods represent an improvement over the Ratio methods.

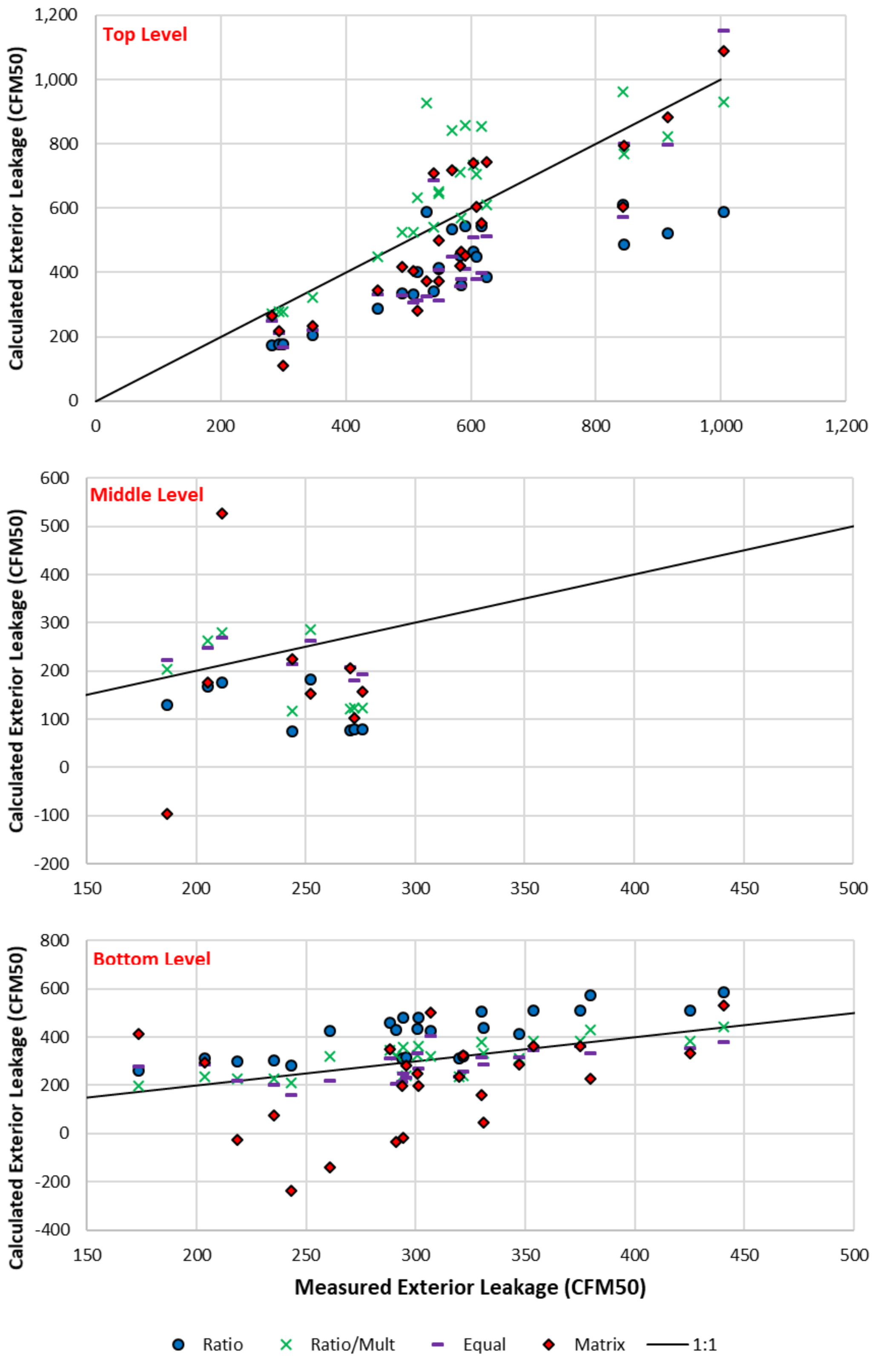
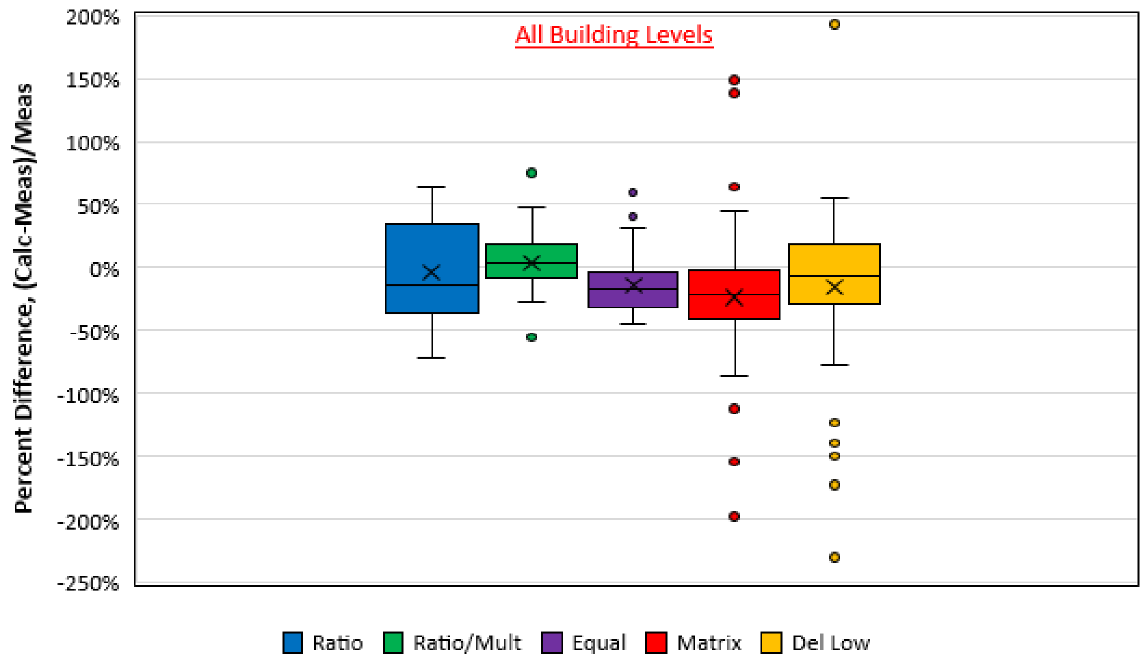


Figure 112. Measured vs Calculated Exterior Leakage for Various Calculation Methods



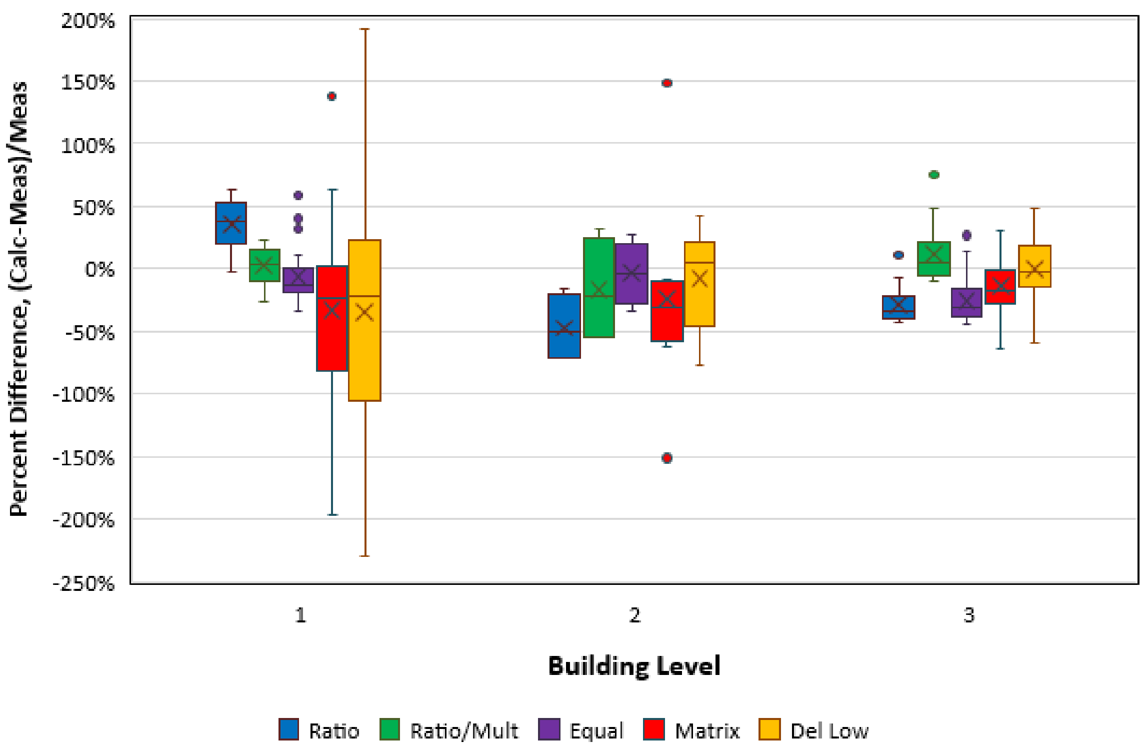


Figure 113. Box and Whisker Plots of % Difference of Exterior Leakage for Various Calculation Methods

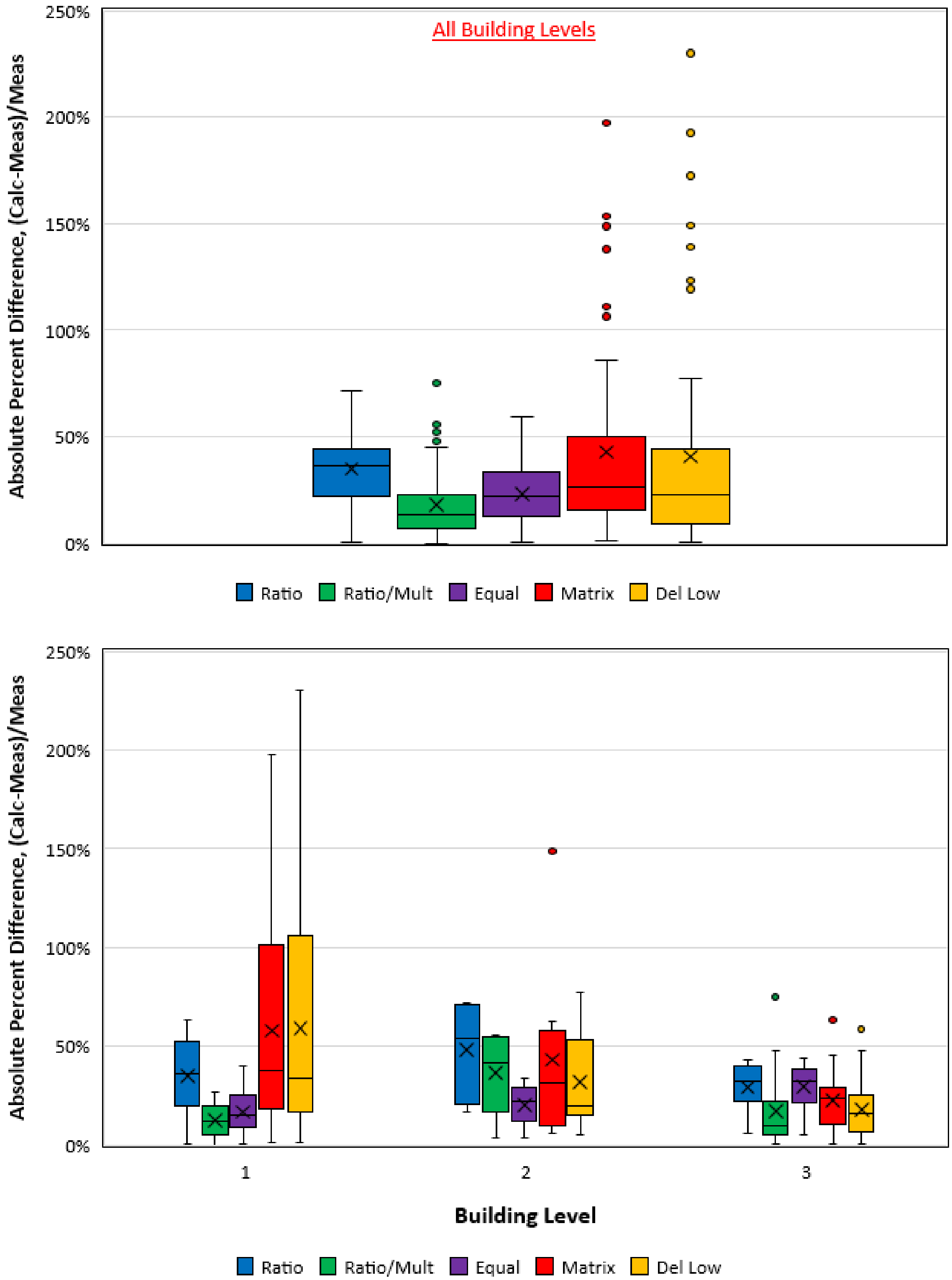


Figure 114. Box and Whisker Plots of Absolute % Difference of Exterior Leakage for Various Calculation Methods

Table 54. Summary Statistics of Exterior Leakage for Various Calculation Methods

	Meas.	Ratio	Ratio/Mult	Equal	Matrix	Del. Low
Percentile	Exterior Leakage (CFM_{50})					
90th	227	170	208	206	14	236
75th	280	285	258	230	191	352
50th	**331**	**405**	**353**	**312**	**311**	**437**
25th	543	482	615	378	473	652
10th	613	543	831	510	713	874
Avg.	**411**	**369**	**435**	**342**	**334**	**483**
Std. Dev.	191	150	237	176	260	310
Percentile	Percentage Difference, (Calc – Meas)/Meas					
90th		-42%	-24%	-38%	-96%	-98%
75th		-37%	4%	-31%	-40%	-28%
50th		**-14%**	**21%**	**-17%**	**-21%**	**-6%**
25th		34%	44%	-5%	-3%	18%
10th		52%	77%	20%	24%	33%
Avg.		**-4%**	**20%**	**-14%**	**-23%**	**-16%**
Std. Dev.		40%	83%	23%	58%	63%
Percentile	Absolute Percentage Difference, (Calc – Meas)/Meas					
90th		10%	14%	7%	6%	5%
75th		22%	18%	13%	16%	10%
50th		**36%**	**30%**	**22%**	**26%**	**23%**
25th		44%	53%	33%	47%	44%
10th		61%	123%	39%	111%	121%
Avg.		**35%**	**52%**	**23%**	**43%**	**41%**
Std. Dev		18%	66%	13%	45%	51%

5. AIR LEAKAGE ENERGY ANALYSIS (SIMULATIONS)

There were two primary goals for the energy use analysis. First, the simulations were used to evaluate the separate effects of the exterior envelope leakage and total (i.e., exterior and interior) envelope leakage to provide guidance on the type of testing required to determine whether buildings meet energy use targets. Second, the results were used to estimate potential savings from bringing buildings that did not meet air leakage code requirements up to code levels (and beyond). To accomplish the goals of this part of the project, a series of apartment unit models with varying levels of exterior and total envelope leakage were simulated using coupled airflow and building energy software.

5.1 Context

The analysis focused on the impact of exterior and total (sum of exterior and interior) unit envelope leakage. Performance maps were generated for a 24-unit, three-story prototype building that complied with IECC 2012 thermal and space conditioning efficiency requirements. A matrix of 28 leakage configurations was established that spanned the range of exterior and total envelope leakages of units measured in the field study. This included volume-normalized total unit leakage that ranged from 2.0 to 14.0 ACH_{50} and exterior leakage that ranged from 0.3 to 10.5 ACH_{50}. Due to the impact that unbalanced ventilation has on building air infiltration, the analysis was performed for intermittent exhaust, continuous exhaust, and continuous balanced ventilation systems. The simulations were performed for the weather patterns of Minneapolis, Minnesota, and Seattle, Washington, which are in Climate Zone 6 (Cold) and Climate Zone 4 (Marine), respectively.

The outputs from this analysis are tables and figures that show the difference in energy use intensity (EUI) for both living units and the whole building (including common areas) over a range of leakage levels. The volume-normalized exterior leakage was selected as the independent variable because it has the largest impact on space conditioning energy use. Since the impact of interior leakage was expected to be somewhat consistent with percentage interior leakage (or 1 - percentage exterior leakage), the dependent variables were plotted for four levels of percentage exterior leakage.

5.2 Methodology

The CONTAM (v 3.3.0.0) multizone airflow and contaminant transport program was coupled with the EnergyPlus™ (v 9.10) multizone building energy modeling software (Crawley et al. 2001) to generate hourly airflow and energy use results. CONTAM was developed by the National Institute of Standards and Technology to calculate time-varying infiltration[24], exfiltration, and zone-to-zone building airflow rates (Dols and Polidoro 2015). The model includes inputs that determine driving forces due to HVAC flows, wind pressures, and thermal buoyancy effects. The driving forces are applied to a user defined network of airflow paths to compute interzone airflow rates. That includes airflow between the outside and each interior zone (e.g., apartment units and common spaces) as well as the airflow between interior zones. The airflow paths (e.g., air leaks between zones) are distributed vertically and on different building faces to account for thermal buoyancy and wind direction effects on building pressures.

CONTAM-generated airflow rates were coupled with an EnergyPlus™ simulation of building heat transfer and energy use (Dols, Emmerich, and Polidoro 2016). At each time step, EnergyPlus™ provides zone air temperatures, HVAC airflow rates, and environmental data to CONTAM. In return, CONTAM provides zone infiltration and inter-zone airflow rates to EnergyPlus™. The coupled model approach has the advantage of generating space conditioning energy use from airflow rates that are based on detailed building air leakage characteristics and driving forces (e.g., wind, thermal, and HVAC flow imbalances). The coupled models are necessary to carefully study the impact of envelope leakage on building energy use and contaminant transport. This method has been used for multiple studies of indoor air quality and energy use for multifamily buildings (Dols and Underhill 2018; Underhill et al. 2019).

5.2.1 Building Geometry

The prototype building was a three-story, common-entry, multifamily building with eight units on each floor and total floor area of 25,464 ft^2 (See Figure 115). The floor plan was the same for each floor. Each unit had a floor area of 950 ft^2 for a building total floor area of 22,800 ft^2 for the residential units. The floor area of the common space was 888 ft^2 for a building total of 2,664 ft^2. The height of each floor was 10 feet. There was a corridor down the center of the building with an elevator shaft on one end of the hallway. The model was originally configured to have a stairwell on the other end of the hallway, but that zone was “opened” to the hallway to allow for airflow directly between the corridor and outside. The garden-style building configuration was not modeled.

[24] Infiltration is the flow of air from outside to inside the building and exfiltration is the flow of air from inside to outside the building.

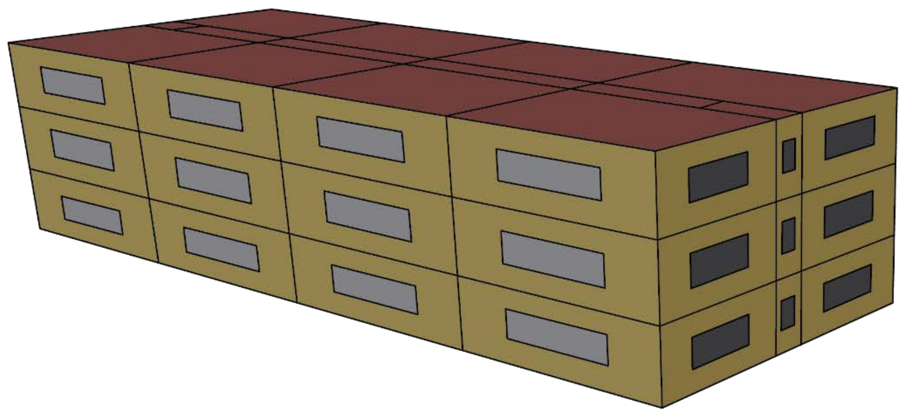


Figure 115. Schematic Representation of the Prototype Building

5.2.2 Building Construction and HVAC

The prototype building had slab-on-grade construction below the lowest floor and an unvented flat roof above the top floor. The thermal properties of the opaque walls, windows, and roof were selected to comply with IECC 2012 for Climate Zones 6 and 7. The exterior walls had stucco cladding with 2"x6" walls that contained R-19 insulation that produced a U-factor of 0.047 Btu/(hr ft^2 F). The roof included R-38 insulation for a U-factor of 0.026 Btu/(hr ft^2 F), and the windows had a U-factor of 0.32 Btu/(hr ft^2 F). Slab insulation was included to produce a F-factor of 0.028 Btu/(hr ft^2 F).

The residential units had a dedicated unitary HVAC system with a direct expansion cooling coil, a natural gas heating coil, and a constant volume supply fan. The supply and return airflow into the units was balanced with no exterior duct leakage. The AFUE of the gas heating system was 80%, and the COP of the cooling was 3.97. The heating set point was 70°F, and the cooling set point was 75°F. The corridors had electric resistance heat with a set point of 60°F. There was no cooling in the corridors. There was no daytime or night setback for the units and corridor temperature control.

Three different ventilation systems were implemented in the residential units: intermittent exhaust, continuous exhaust, and continuous balanced ventilation. The balanced and exhaust systems were operated continuously with an outdoor airflow rate of 51.0 CFM that was sized according to the ASHRAE 62.2 total ventilation rate requirement (ASHRAE 62.2. 2019)[25]. For the balanced system, the outdoor air was introduced into the dedicated unitary HVAC system, and an equal airflow was exhausted from the system. The total supply airflow rate into each unit was equal to the return airflow rate. There was no heat recovery. For the exhaust-only system, a constant airflow rate of 51.0 CFM was drawn from each unit. The intermittent exhaust system included 50 CFM of exhaust airflow for one hour each morning. This system was intended to model a building with no general ventilation and only "spot" ventilation operated on an as-needed basis.

5.2.3 Envelope Air Leakage

Every model was configured so that that the exterior and total leakage was the same for each of the 28 units in the prototype building. This simplification was used so that the results for all units in the building could be averaged or

[25] The standard does not allow an infiltration credit to reduce the mechanical ventilation level for multifamily buildings.

summed to evaluate the impact of variations in the volume-normalized total and exterior leakage on building airflow rates and energy use.[26] A range of exterior and total envelope leakages were selected that approximately spanned the measurements for units from the common-entry buildings in the project. There were seven different levels of volume-normalized leakage (2.0, 3.0, 4.0, 5.0, 7.0, 10.0, and 14.0 ACH_{50}) and four levels of percentage exterior leakage (15%, 30%, 45%, and 75%). The large circles on the four solid lines in Figure 116 indicate the 28 leakage configurations used for the simulations. While none of the units in the project had a measured volume-normalized total leakage greater than 10.0 ACH_{50}, a total leakage of 14.0 ACH_{50} was included as an indicator for the air infiltration and energy use that may be obtained in other states where there is no requirement for measured leakage. In addition, these results can be used for older buildings.

[26] Alternatively, the model could have been configured so that the surface-area-normalized exterior and interior leakage (e.g. CFM_{50}/ft^2) was the same for every unit. However, since the current code is based on volume-normalized exterior or total leakage, it was decided to set the volume-normalized total and exterior leakage to be the same for every unit. In addition, for buildings in the study the measured volume-normalized exterior leakage was fairly consistent for units on the same floor and more consistent than the surface-area-normalized exterior leakage. For example, for common-entry buildings the median CV of the volume-normalized exterior leakage for units on the same floor varied from 11% to 20% for vented attic buildings and 16% to 18% for flat-roof buildings (See Table 55). The median CV of the surface-area-normalized exterior leakage for units on the same floor varied from 13% to 25% for vented attic buildings and 21% to 32% for flat-roof buildings (See Table 57). Moreover, for units on the middle floor for which the only exterior surface area is the exterior walls, the median CVs for the surface-area-normalized exterior leakage measurements were about 50% higher than the median CVs for the volume-normalized exterior leakage.

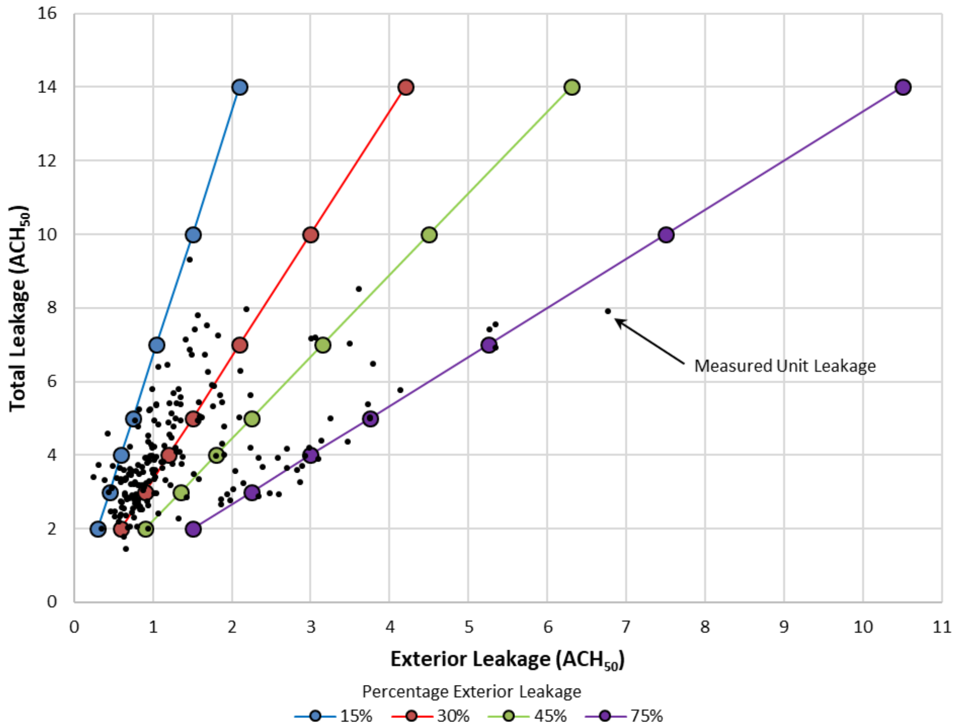


Figure 116. Prototype Building Modelled Total and Exterior Leakage

Figure 116 displays the configuration of the air leakage paths for one level of the CONTAM model. The diamonds represent the air leakage paths. The paths were arranged so that there were three leaks for each horizontal connection between zones (e.g., apartment unit, corridor, or elevator) as well as each zone to the exterior.[27] The three paths at each location were distributed vertically (1.7, 5.0, and 8.3 ft. above floor level). There was also one leak between zones that were vertically adjacent. Interior doors and windows were included in the model, but the leakage of those paths was set to zero. The interior leakage of each unit was the same. There was no leakage through the slab below the bottom level and no leakage through the flat roof. Due to the configuration of the units in the building, it was not possible for every unit to have the same distribution of interior leakage. The corner units had one horizontally adjacent unit, while the inner units had two adjacent units. The second-floor units had two vertically adjacent units while the first- and third-floor units had one adjacent.

[27] The corner units had a total of six leakage paths to the exterior and the inner units had three. The coefficients of the inner unit leaks were adjusted to be twice that of the exterior leaks for the corner units so that the total exterior leakage was the same for all 24 units. Each unit also had a leakage path to the exterior for operable windows and a path to the corridor for a door. All windows and doors were kept closed for the simulations. The window and door leakages were set to zero.

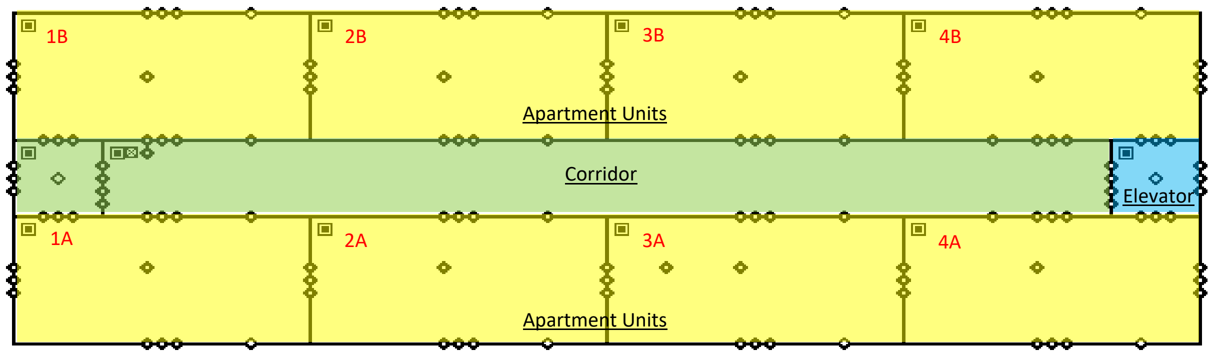


Figure 117. Air Leakage Paths for CONTAM Prototype Building Model

It was expected that the relative amount of interior leakage from a unit to horizontally adjacent units, vertically adjacent units, and the common space (e.g., corridor) would impact the airflow between zones. The change in adjacent unit pressures during the compartmentalization tests suggested that the side-to-side connection between adjacent units was greater than the vertical connection (See Appendix D). Consequently, all units were given a larger leakage to horizontally adjacent units than through the ceiling or floor to vertically adjacent units(i.e., through the ceiling or floor).

An analysis of the ratio of the measured leakage of units to common areas to measured leakage to all adjoining units resulted in a median of 1.85 with 25th and 75th percentile values of 1.25 and 2.78, respectively. As shown in Table 55, interior leakages were selected so that the ratios for the inner units were close to the 25th percentile value and the ratios for the corner units were close to the 75th percentile. The average ratio of 1.84 was nearly identical to the median for the measured leakages. The distribution of unit percentage interior leakage displayed in Table 55 was used for all building simulation models. For each model, the interior leakage was multiplied by the percentages in Table 55 to determine the coefficients for the interior leakage paths.

Table 55. Percentage of Unit Leakage to Other Interior Areas

Unit Location	Common	Horizontal Adjacent	Floor + Ceiling Adjacent	Common/Total Adjacent
1st & 3rd Inner	54%	36%	10%	1.17
1st & 3rd Corner	72%	18%	10%	2.57
2nd Inner	58%	22%	20%	1.38
2nd Corner	69%	11%	20%	2.23

As noted in section 4.2.3, for common-entry buildings the exterior leakage to the common space is often a significant fraction of the whole building leakage. For the 20 common-entry buildings in the project, the exterior leakage to the common space as a percentage of the whole building exterior leakage had a median value of 27%. For each of the leakage models, the coefficients of leakage paths from the exterior to the zone adjacent to the corridor[28] were adjusted so that the sum of the exterior leakage into the corridor was equal to 27% of the whole building exterior leakage (e.g., sum of the exterior leakage to the corridors and residential units). The exterior leakage was the same for all three levels. Since the heating system set-point for the corridors was 10 F less than that for the units, the stack effect would typically

[28] The original model included a stairwell on one end of the corridor. This was converted into an extension of the corridor by replacing the corridor/stairwell door leakage path with a large two-way leakage path and eliminating the large "stairwell" vertical leakage path. This modification was made so that there would be airflow from outdoors into the corridors that was not impeded by a closed door.

be slightly different for exterior leakage to the corridor versus the stack effect for the units. In addition, there would typically be a slight stack effect between the units and corridor.

The following power–law relationship between the airflow rate and pressure difference was used for all leakage paths:

$$Q = c(\Delta P)^n \tag{3}$$

$$Q = airflow\ through\ opening, [cfm]$$
$$n = pressure\ exponent, [dimensionless]$$
$$c = flow\ coefficient, [cfm/Pa^n]$$
$$\Delta P = Pressure\ difference\ across\ building\ [Pa,\ = 0.00402\ in\ of\ water]$$

An exponent of 0.65 was used for all envelope leakage paths.

5.2.4 Driving Forces

CONTAM accounts for the effects of the three, aforementioned driving forces on all the exterior and interior air leakage paths of the building. The non-linear airflow solver of CONTAM adjusts the zone pressures at each time step so that the air mass flow rate entering each zone is equal to the rate leaving the zone. The interior restrictions to air movement between units and common spaces produce more complicated pressure and airflow patterns than occur for idealistic, single-zone models. For example, when the only driving force is due to thermal buoyancy (e.g., stack-only) and equal-sized air leakage paths are evenly distributed vertically, the neutral pressure level (NPL) is located at half of the building height.[29] The pressure difference across the exterior walls varies linearly with distance from the NPL, with the ground-level pressure difference being equal and opposite to the pressure difference at the top of the building. Multizone buildings can be much more complex and cannot generally be characterized by a simple, single NPL.

The three-story multifamily building prototype model described above was used to demonstrate the resultant airflow rates attributable to the driving forces for four cases of exterior and interior leakage. The total leakages of 2.0 and 5.0 ACH_{50} were selected to span the leakage measured for most of the units tested in this project. Two levels of percentage exterior leakage (30% and 75%) were used to help identify whether pressure trends were due to variations in absolute or relative amounts of leakage. A detailed description of the effects of each separate driving force and the combination of the driving forces is included in Appendix D. The following observations were made from the series of simplified conditions applied to the three-story model:

- <u>Stack Effect</u>: The thermal buoyancy or stack effect varies linearly with the difference in the inside to outside air temperature. For colder outside air temperatures, the stack effect tends to produce greater infiltration on the bottom-floor units and greater exfiltration on the top-floor units. Reducing the vertical leakage between units reduces the overall impact of the stack effect, and, for the range of leakage considered in this study, this reduction is determined by the relative and not absolute amount of exterior and interior leakage.
- <u>Exhaust Ventilation</u>: For a constant amount of exhaust ventilation, the depressurization of a unit is primarily a function of the amount of exterior leakage. Smaller exterior leakage creates greater depressurization. The level of unit-to-common-area leakage has a lower impact on depressurization, and the leakage between units has almost no impact.[30] The relative amount of

[29] Neutral pressure level = location on the building exterior where the inside pressure is equal to the outside pressure.
[30] The level of air leakage between units would have more significant impact if there were unit-to-unit variations in exterior and interior leakage.

exterior leakage determines the fraction of air that enters a dwelling unit directly through the exterior walls from the outdoors. For both models with 30% exterior leakage, 75% of the air enters from outdoors, and the two models with 75% exterior leakage have 87% of the air entering from outdoors.

- Stack Effect and Exhaust Ventilation Combined: Adding the exhaust fan airflow to the stack effect causes the stack effect pressure profile to decrease by an amount that is roughly equal to the level of depressurization caused by the exhaust fan without the stack effect. Tighter buildings with adequate exhaust ventilation will have a constant level of ventilation from infiltration over a wide range of outside air temperatures. As the building leakage increases and outside air temperature decreases, a larger portion of the exterior wall will be under positive pressure which will result in increased exfiltration and infiltration.
- Wind Effect: The wind effect varies with the square of the wind velocity and the angle of the wind to the building surface. When no other driving forces are present, there is positive pressure (e.g., infiltration) at windward leakage paths and negative pressure (e.g., exfiltration) at the other locations (based on the assumed wind pressure direction effects). There is significant variation in pressures between zones, which do not always follow similar trends. The ratios of any two airflows for a unit (e.g., infiltration/unit to common) are the same for a model with the same percent exterior leakage. The level of interior leakage often has a significant impact on infiltration and exfiltration for individual units.
- Combined Effects: When wind effects are combined with exhaust and stack effects, the stack pressure profiles retain the characteristic sawtooth profiles with little or no change in the pressure drop between floors or change in the stack pressure with height. The addition of the positive wind pressure on the exterior of the windward unit (2B) results in increased depressurization that is greater for the cases with higher interior leakage. The negative wind pressure on the leeward unit (2A) has little impact on the unit depressurization.

  The infiltration for the windward inner unit 2B was 40%–172% higher than the infiltration for the leeward inner unit 2A. The infiltration for the windward corner unit 1B was 20%–120% higher than the infiltration for the leeward corner unit 1A. The level of interior leakage has a significant impact on infiltration for individual units, but little impact on the average infiltration for all units in the building. The average infiltration for all four units increased with increasing exterior leakage. However, the relative increase in infiltration was much less than that of the relative increase in total leakage. This occurs because the level of envelope leakage has a lower impact on infiltration when there is already significant infiltration due to exhaust ventilation.

5.3 Results

The two primary goals were: (1) evaluate the separate effects of exterior and total envelope leakage to provide guidance on the type of leakage testing required and (2) determine the variation in building space conditioning energy use to estimate the savings potential from bringing buildings that did not meet air leakage code requirements up to code levels (and beyond). The matrix of 28 leakage configurations included volume-normalized total unit leakage that ranged from 2.0 to 14.0 ACH_{50} and exterior leakage that ranged from 0.3 to 10.5 ACH_{50}. Due to the impact that unbalanced ventilation has on building air infiltration, the analysis was performed for intermittent exhaust, continuous exhaust, and continuous balanced ventilation systems.

An hourly computation of zonal airflow rates and building energy use over an entire year was generated for each iteration of envelope leakage and ventilation using the coupled CONTAM-EnergyPlus™ simulation programs. The hourly data was post-processed to determine monthly and annual average infiltration, exfiltration, and inter-zonal airflow rates for each residential unit, all residential units combined, and the whole building. The monthly sum of residential unit space heating gas use and cooling electrical use was generated directly from EnergyPlus™. The monthly totals were summed to compute the annual gas and electric use for the residential units. Those values were divided by the total floor area of the residential units to compute the EUIs for space heating and cooling. Finally, the EUI for the designated code required envelope leakage was subtracted from each iteration of envelope leakage to determine the change in EUI that would occur for a higher or lower envelope leakage.

The results were used to generate charts that display the annual airflow or energy value over the range of volume-normalized exterior unit leakage with data grouped by four levels of percent exterior leakage (15%, 30%, 45%, and 75%; See Figure 119). Linear interpolations of the results from the matrix of 28 leakage configurations were used to tabulate annual airflow and energy values for volume-normalized total leakage that ranged from 2.0 to 10.0 ACH_{50} in increments of 1.0 ACH_{50} and volume-normalized exterior leakage that ranged from 0.25 to 7.5 ACH_{50} in increments of 0.25 and 0.5 ACH_{50}. (See Table 56). Almost all of the tabulated values were bounded by results from the 28 leakage configurations, but a few fell slightly outside that range. This was considered to be acceptable, since the relationships with leakage were primarily linear and the extrapolations from the reported data were minor. Values were not included in the table when they were outside an acceptable range. The table cells are shaded green to red indicating lower to higher values to more easily identify trends. Key results are included in the section below and additional results are included in Appendix E for Minneapolis weather and Appendix F for Seattle weather.

5.3.1 Minnesota

The simulations were performed for the weather patterns of Minneapolis, Minnesota, which is in Climate Zone 6 (Cold). Minneapolis has 8,052 heating degree days (base 65°F, HDD65) and 803 cooling degree days (base 65°F, CDD65). The seasonal variations and histograms of outside air temperature and wind speed for Minneapolis are shown in Figure 118. The monthly average wind speeds range from 9.2 to 12.0 mph, and the annual average is 10.3 mph. The monthly average outside air temperatures range from 10.8 to 71.6°F, and the annual average is 45.1°F.

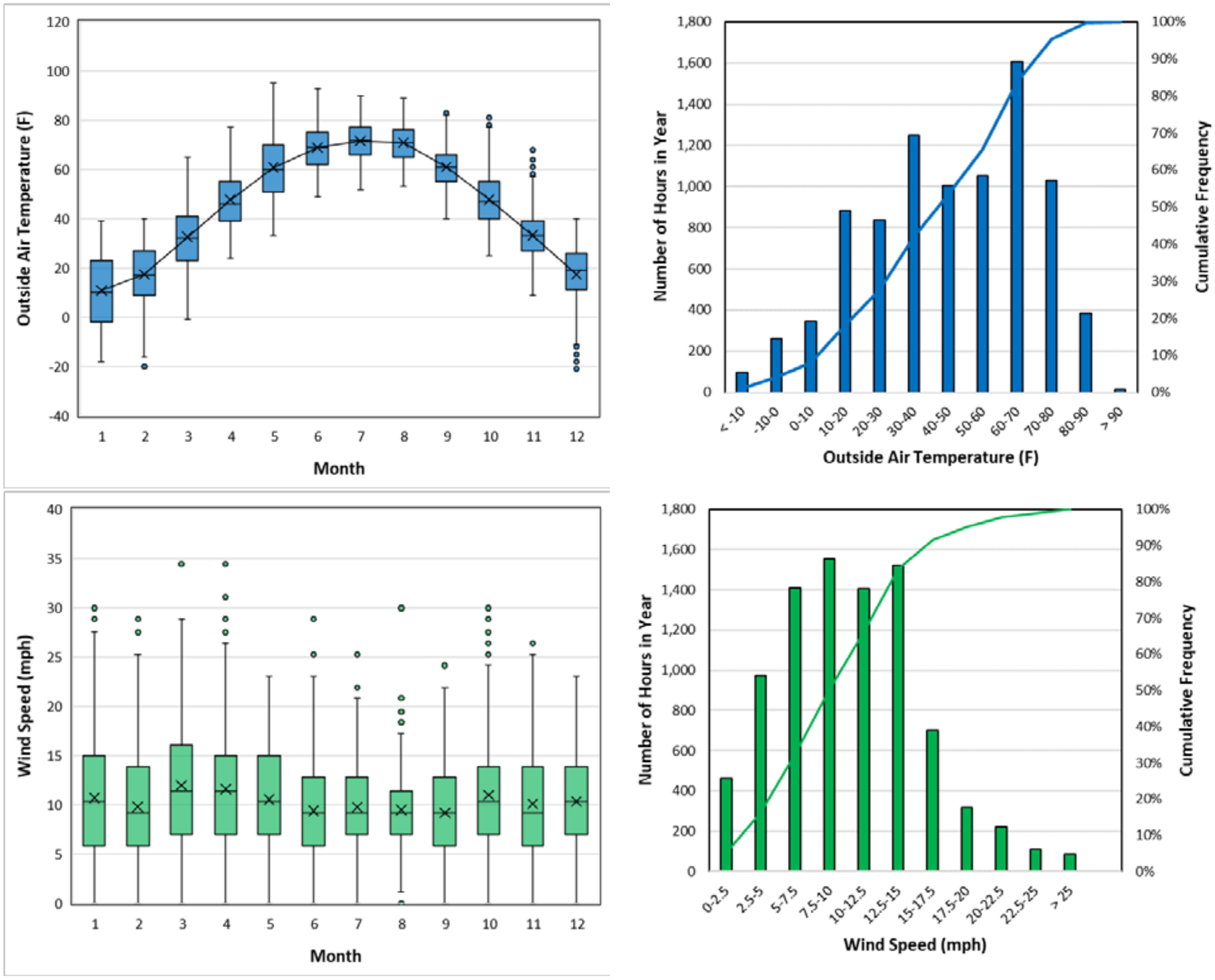


Figure 118. Minneapolis Annual Outside Air Temperature and Wind Speed

5.3.1.1 Continuous Balanced Ventilation

The chart of the annual average air infiltration rate for all units in the building is shown in Figure 119, and Table 56 shows the interpolated values. Since the balanced ventilation system provides the code-required rate for each unit, any air infiltration causes the total ventilation (mechanical ventilation plus infiltration) to be greater than the required amount. The key findings from the annual infiltration rate results are:

- For a low exterior leakage of 1.0 ACH_{50}, the infiltration is less than 10 CFM. For an exterior leakage of 3.0 ACH_{50}, which is required for climate zones 3–7, the infiltration varies from 16 to 23 CFM. The infiltration increases above 51 CFM (the mechanical ventilation flow rate) for an exterior leakage of about 6.0 ACH_{50} (15% exterior leakage) to 10.0 ACH_{50} (75% exterior leakage).
- For the four constant percent exterior leakage curves shown in Figure 119, the relationship between infiltration and exterior leakage is highly linear ($R^2 > 0.999$). Linear regressions of the infiltration rate with exterior leakage yields slopes of 8.65, 7.45, 6.44, and 5.22 CFM/ACH_{50} for exterior leakages of 15%, 30%, 45%, and 75%, respectively. An approximate value of the annual average infiltration can be computed by dividing the unit exterior leakage (reported as CFM_{50}) by 18.3, 21.3, 24.6, and 30.3 CFM_{50}/CFM for percent

exterior leakage of 15%, 30%, 45%, and 75%, respectively. A chart of the “divide by” value is shown in Figure 181 of Appendix F.

- The impact of interior leakage is only marginally significant. For the same exterior leakage, an increase in the percent interior leakage from 55% to 70% (e.g., 45% to 30% exterior leakage) increases the infiltration by about 14%. For an exterior leakage of 3.0 ACH_{50}, that is a 91% increase in interior leakage from 3.7 ACH50 (55% interior) to 7.0 ACH50 (70% interior).
- Table 88 of Appendix F shows the monthly variation of unit average infiltration rates for each of the 28 leakage scenarios. As expected, infiltration is greatest during colder weather when the stack effect is the dominant driving force. For percent exterior leakages of 15%–45%, the highest monthly average infiltration is about 45% greater than the minimum monthly average in the summer. The seasonal variation is greater for 75% exterior leakage, for which the heating season maximum infiltration is about 67% greater than the lowest monthly infiltration.
- Table 89 of Appendix F shows the monthly variation of unit average infiltration rates for a selection of 12 units for four leakage scenarios with approximately equal exterior leakage. As expected, the units on the first floor have greater infiltration than those on the third floor, and the differences between the first and third floors are greater for leakage scenarios with greater interior leakage. For example, for the leakage scenario with 85% interior leakage, in January the three units on the first floor have an average infiltration of 34.3 CFM, while the average for the three units on the third floor is 5.5 CFM. The first-floor unit average infiltration is a factor of 6.2 greater than the average for the third-floor units. For the scenario with 25% interior leakage, the first-floor unit average infiltration is only a factor of 1.2 greater than the average for the third-floor units.
- In addition, the results in Table 89 of Appendix F also show that for the same leakage scenario and weather, there is considerable variation between units on the same floor and that the relative differences can vary by month. For example, for the leakage scenario with 85% interior leakage, in July, corner unit 1A on the first floor has an infiltration rate of 21.5 CFM and corner unit 1B on the first floor has an infiltration of 13.4 CFM. In January, the same first-floor units 1A and 1B have infiltration rates of 35.5 and 40.5 CFM, respectively.

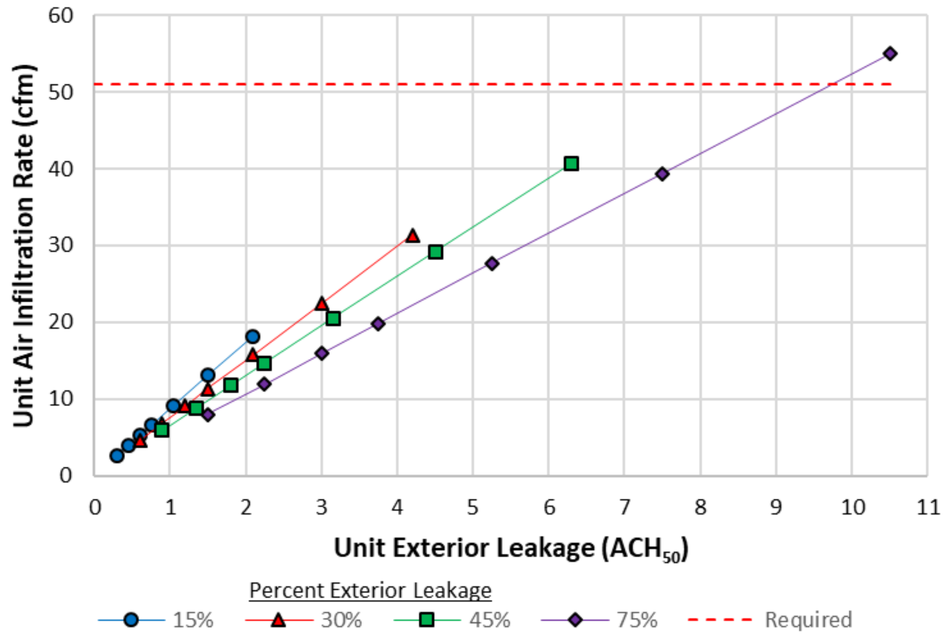


Figure 119. Annual Average Unit Infiltration: Minneapolis Balanced Ventilation

Table 56. Unit Annual Average Infiltration (CFM): Minneapolis Balanced Ventilation

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25	2.2								
0.50	4.0	4.3	4.5	4.6					
0.75	5.3	6.0	6.3	6.6	6.7	6.8			
1.0	6.4	7.3	7.9	8.3	8.6	8.8	8.9	9.0	9.1
1.5	8.0	9.5	10.6	11.3	11.9	12.3	12.6	12.8	13.0
2.0		11.3	12.7	13.7	14.6	15.2	15.8	16.2	16.6
2.5		12.4	14.5	15.8	16.8	17.8	18.5	19.2	19.7
3.0			15.9	17.7	18.9	19.9	21.0	21.8	22.5
3.5			16.8	19.2	20.9	22.0	23.0	24.1	25.0
4.0				20.3	22.5	24.0	25.2	26.1	27.3
4.5				21.0	23.8	25.7	27.1	28.3	29.2
5.0					24.7	27.1	28.9	30.3	31.4
5.5					25.3	28.2	30.4	32.0	33.4
6.0						29.0	31.6	33.6	35.2
6.5						29.6	32.6	34.9	36.8
7.0							33.3	36.0	38.2
7.5							33.8	36.9	39.4

Table 57 displays the reduction in annual average infiltration for a 1.0 ACH_{50} reduction in exterior leakage, and Table 58 shows the same for a 1.0 ACH_{50} reduction in interior leakage. Areas shaded red indicate higher infiltration reduction, and green areas indication less infiltration reduction. The key findings from the impact of exterior and interior envelope sealing on infiltration results are:

- The reduction of air infiltration for reducing exterior envelope leakage by 1.0 ACH_{50} varies significantly with exterior and total leakage. The same is true for reducing interior envelope leakage, but with an opposite trend.
- The infiltration reduction per 1.0 ACH_{50} reduction in exterior leakage is greater for units with lower exterior leakage and higher total (or interior) leakage. The infiltration reduction ranges from 4.2 to 7.5 CFM/ACH_{50} (ratio of high to low reduction = 1.8). This indicates that accurate calculations of infiltration reduction for a change in air leakage should consider the levels of exterior and interior leakage.
- The trend for infiltration reduction due to reduction in interior leakage is opposite of that for exterior leakage reduction. Reduction in infiltration per 1.0 ACH_{50} reduction in interior leakage is greater for units with higher exterior leakage and lower total (or interior) leakage. The infiltration reduction ranges from 0.1 to 3.1 CFM/ACH_{50}. (ratio of high to low reduction = 36). This indicates that for units with higher total leakage and low exterior leakage, reductions in interior envelope leakage have an insignificant impact on infiltration. However, for units with higher exterior leakage and lower total leakage, reducing interior leakage can have 70% as much impact as an equal reduction in exterior leakage.

Table 57. Reduction in Annual Infiltration (CFM) for Reduction of 1.0 ACH_{50} in Exterior Leakage

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25									
0.50									
0.75									
1.0									
1.5		5.5	6.2	6.8	7.3				
2.0		4.9	5.3	5.8	6.3	6.7	7.0	7.3	7.5
2.5		4.4	5.0	5.2	5.5	5.9	6.2	6.6	6.9
3.0			4.6	5.1	5.2	5.4	5.7	6.0	6.2
3.5			4.3	4.7	5.1	5.2	5.2	5.6	5.8
4.0				4.4	4.8	5.1	5.2	5.1	5.4
4.5				4.3	4.5	4.8	5.1	5.2	5.0
5.0					4.4	4.6	4.9	5.1	5.3
5.5					4.3	4.4	4.7	4.9	5.1
6.0						4.3	4.5	4.7	4.9
6.5						4.2	4.4	4.6	4.8
7.0							4.3	4.4	4.6
7.5							4.2	4.3	4.5

Table 58. Reduction in Annual Infiltration (CFM) for Reduction of 1.0 ACH_{50} in Interior Leakage

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25									
0.50		0.33	0.16	0.10					
0.75		0.66	0.37	0.22	0.15	0.11			
1.0		0.97	0.61	0.39	0.26	0.19	0.14	0.11	0.09
1.5		1.52	1.04	0.74	0.58	0.42	0.31	0.24	0.19
2.0			1.35	1.06	0.88	0.66	0.55	0.43	0.34
2.5			2.10	1.26	1.05	0.97	0.73	0.63	0.54
3.0				1.81	1.21	1.03	1.05	0.82	0.65
3.5				2.46	1.64	1.17	0.99	1.11	0.89
4.0					2.14	1.53	1.15	0.95	1.16
4.5					2.71	1.93	1.45	1.13	0.90
5.0						2.38	1.78	1.39	1.11
5.5						2.87	2.16	1.68	1.34
6.0							2.56	1.99	1.60
6.5							3.01	2.34	1.87
7.0								2.71	2.17
7.5								3.11	2.49

While the primary focus of this project was to evaluate impact of envelope leakage on building energy use, a secondary concern is the impact on outside air ventilation and inter-zonal airflow. As displayed in Figure 120, the amount of airflow that enters units from the outside as a percentage of the total airflow into the unit is nearly constant for variations in exterior envelope leakage.[31] As expected, the percentage of airflow from outside is higher for higher percent exterior leakage. However, as shown in Figure 121, the percentage of outside air is not equal to the percent exterior leakage. For an exterior leakage of 15%, the percentage of outside air is more than double the percent exterior leakage, and the two percentages are equal at about 55%. This suggests that for buildings with balanced ventilation, it is not accurate to assume that the percentage of air from outside is equal to the percent exterior leakage.

[31] The total amount of airflow into the unit does not include airflow from the balanced ventilation system or space conditioning system. It only includes air entering through envelope leaks.

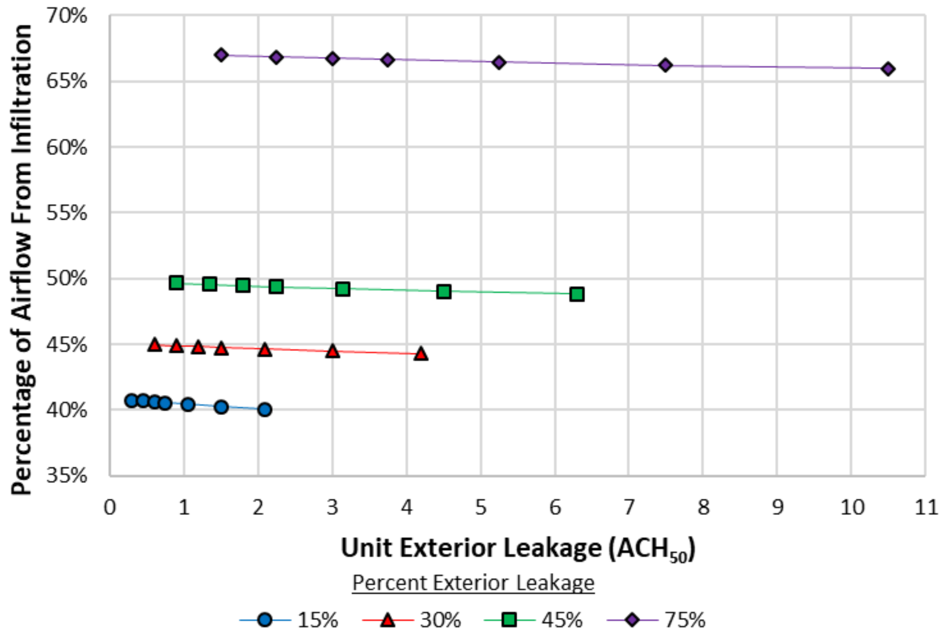


Figure 120. Percentage of Unit Airflow from Infiltration

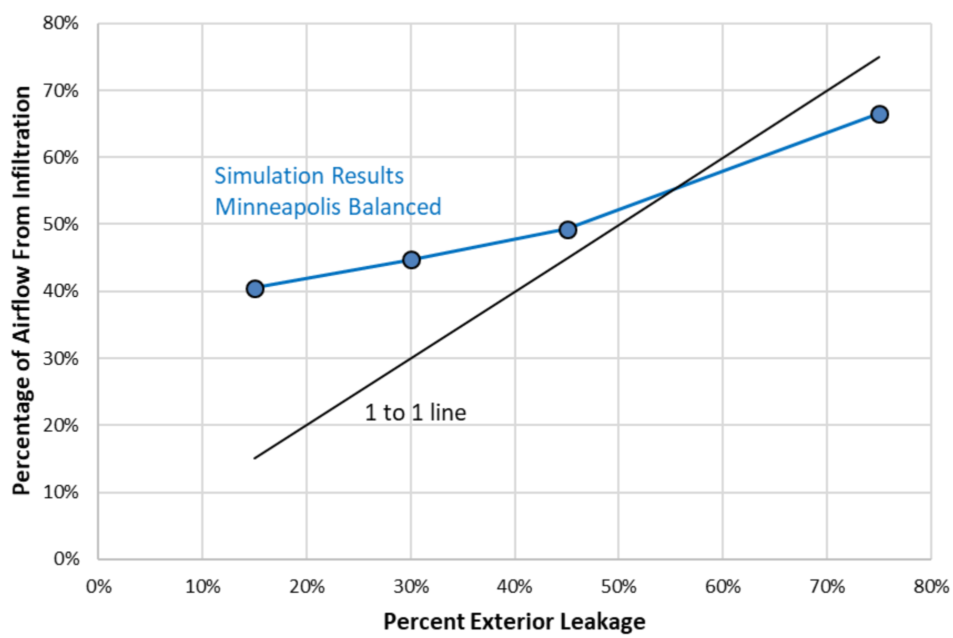


Figure 121. Percentage of Unit Airflow from Infiltration vs. Percent Exterior Leakage

The chart of the EUI for the annual space heating gas use for the residential units is shown in Figure 122. The key findings from the EUI results are:

- For the four constant percent exterior leakage curves, the relationship between EUI and exterior leakage is highly linear ($R^2 > 0.999$). Linear regressions of the EUI with exterior leakage yields slopes of 3.54, 2.96, 2.56, and 2.12 (kBtu/ft^2)/ACH_{50} for percent exterior leakages of 15%, 30%, 45%, and 75%, respectively. The linear relationships and decreasing slopes with increasing percent exterior leakage follow the same trends as those for the variation of annual infiltration and exterior leakage.

- The regression intercepts are 8.7, 8.8, 9.0, and 9.1 kBtu/ft^2 for percent exterior leakages of 15%, 30%, 45%, and 75%, respectively. The intercepts are the approximate space heating needed for the net heat loss through the building shell and the mechanical ventilation load when there is no infiltration. The average intercept is 8.9 kBtu/ft^2.

- The impact of interior leakage is marginally significant. For the same exterior leakage, an increase in the percent interior leakage from 55% to 70% (e.g., 45% to 30% decrease in exterior leakage) increases the EUI by about 15%. This is about the same relative impact as occurs for the average annual infiltration.

- Depending on the percent exterior leakage, an exterior leakage from 2.5 to 4.2 ACH_{50} results in an increase in the EUI that is about equal to the energy use due to heat loss through the envelope and from the non-heat recovery mechanical ventilation.

- Above an exterior leakage of about 1.5 ACH_{50}, increased exterior leakage results in increases in corridor electric space heating. A percent exterior leakage of 15% to 45% and exterior leakage of 2.0 ACH_{50} results in corridor electric space heating use of about 1,000 kWh. The level of space heating decreases with decreasing percent interior leakage.

- The model predicts space cooling electric use of 17,000 to 19,000 kWh with increasing use for lower exterior envelope. The model assumes that windows are kept closed for the entire year. Consequently, during the times when the outside air temperature is lower than the inside temperature and cooling is required, greater exterior leakage results in more “free cooling” from outside air entering the building.[32] In reality, many people would open their windows during those periods and there would be no benefit from increased infiltration. That effect was not included in the modelling.

[32] This occurs due to heat gains from solar, miscellaneous electric use, and people.

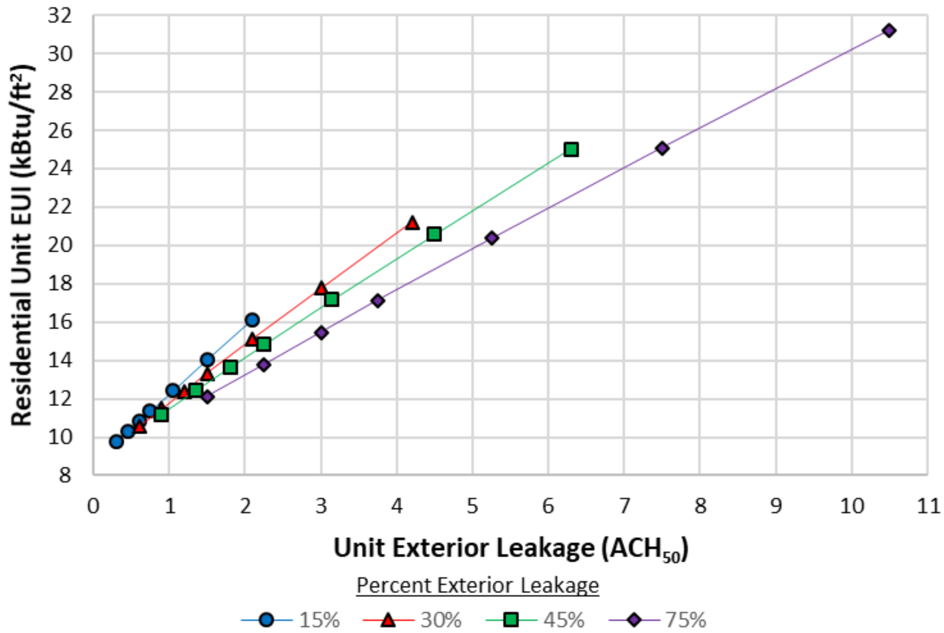


Figure 122. EUI for Residential Units (kBtu/ft^2)

The differences in EUI from the energy-code-required value to the modelled scenarios are shown in Figure 123 and Table 59. For Minneapolis, it was assumed that the code requirement of 3.0 ACH_{50} was applied to the total leakage as measured by a compartmentalization test and that the percent exterior leakage was 30%. This results in a residential unit space heating EUI of 11.47 kBtu/ft^2. An increase in the total leakage to 5.0 ACH_{50} would result in a 16% increase in the EUI to 13.31 kBtu/ft^2.

If it is assumed that the code required leakage of 3.0 ACH50 is applied to the exterior leakage, that level of exterior leakage with a percent exterior leakage of 30% produces an EUI of 17.8 kBtu/ft^2. This is a 55% increase in the EUI compared to that for a 3.0 ACH_{50} total leakage. It shows that the decision to apply the leakage requirement to the exterior leakage or to the total leakage has a very significant impact on the resulting space heating energy use for the building.

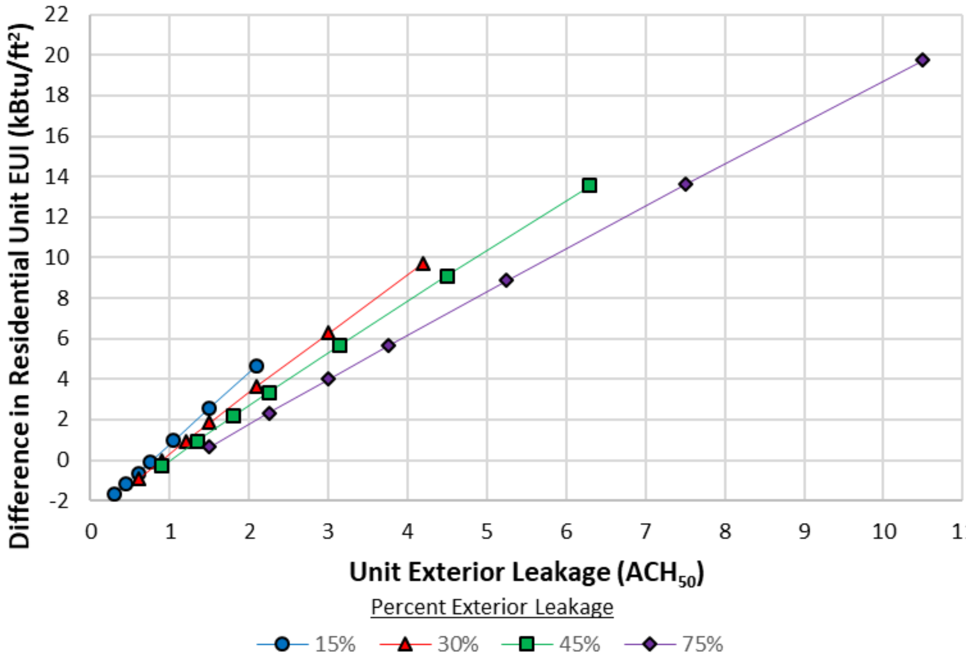


Figure 123. Difference in EUI from Baseline for Residential Units (kBtu/ft²)

Table 59. Difference in EUI from Baseline for Residential Units

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25	-1.85								
0.50	-1.15	-1.02	-0.95	-0.92					
0.75	-0.58	-0.34	-0.19	-0.11	-0.05	0.00			
1.0	-0.10	0.23	0.47	0.63	0.73	0.81	0.87	0.91	0.95
1.5	0.64	1.23	1.59	1.84	2.08	2.25	2.38	2.49	2.57
2.0		2.02	2.54	2.91	3.20	3.43	3.67	3.85	3.99
2.5		2.58	3.35	3.82	4.18	4.51	4.75	5.00	5.23
3.0			4.00	4.65	5.08	5.44	5.79	6.07	6.29
3.5			4.49	5.35	5.92	6.33	6.67	7.04	7.34
4.0				5.92	6.65	7.17	7.56	7.88	8.27
4.5				6.35	7.27	7.92	8.41	8.79	9.09
5.0					7.79	8.58	9.17	9.63	10.00
5.5					8.21	9.15	9.86	10.41	10.85
6.0						9.62	10.46	11.11	11.63
6.5						10.00	10.98	11.74	12.35
7.0							11.43	12.31	13.01
7.5							11.79	12.80	13.61

5.3.1.2 Continuous Exhaust Ventilation

The chart of the annual average air infiltration rate for all units in the building is shown in Figure 124, and Table 60 shows the interpolated values. For a continuous exhaust ventilation system, the mechanical ventilation system does not provide outdoor air directly to the units. Air infiltration through the building envelope is the only source of outdoor air that enters the unit directly from outside and should be equal to or greater than the code required minimum of 51.0 CFM to meet ventilation requirements. The key findings from the annual infiltration rate results are:

- There is little change in the infiltration rate for exterior leakages from 0.3 to 1.3 ACH_{50}. For exterior leakages in this range, the infiltration is 35 to 37 CFM. For an exterior leakage of 3.0 ACH_{50} that is required for climate zones 3–7, the infiltration varies from 43 to 46 CFM. The infiltration increases above the requirement of 51 CFM for an exterior leakage of about 4.5 ACH_{50}.
- Over the modelled exterior air leakage scenarios from 0.5 to 4.5 ACH_{50}, there are only small differences in the infiltration rate for the three percent exterior air leakages of 15%, 30%, and 45%. The differences in infiltration are also small for 75% exterior leakage, except for exterior leakages before about 2.5 ACH_{50} when the infiltration is greater for 75% exterior leakage.
- For exterior leakage rates greater than 1.3 ACH_{50}, the relationship between infiltration and exterior leakage is highly linear (R^2 = 0.995). Linear regression of the infiltration rate with exterior leakage yields a slope of 4.66 CFM/ACH_{50}. This is only 11% less than the slope for the results from the balanced ventilation and 75% exterior leakage scenarios.
- An approximate value of the annual average infiltration can be computed by dividing the unit exterior leakage (reported as CFM_{50}). These values vary from 1 to 21 CFM/CFM_{50} for the range of exterior leakage from 0.3 to 10.5 CFM_{50}. The values do not vary significantly with percent exterior leakage for the range of percent exterior leakage included in the simulations (15% to 75%). A chart of the "divide by" value is shown in Figure 192 of Appendix F.
- Table 88 of Appendix F shows the monthly variation of unit average infiltration rates for each of the 28 leakage scenarios. The continuous exhaust ventilation creates a fairly uniform level of infiltration over the entire year. For percent exterior leakage of 15% to 45%, the level of infiltration is slightly higher in the summer months than the winter months. That trend shifts somewhat for a percent exterior leakage of 75%.
- Table 89 of Appendix F shows the monthly variation of unit average infiltration rates for a selection of 12 units for four leakage scenarios with approximately equal exterior leakage. As expected, the units on the first floor have greater infiltration than those on the third floor, and the differences between the first and third floors are greater for leakage scenarios with greater interior leakage. For example, for the leakage scenario with 85% interior leakage, in January the three units on the first floor have an average infiltration of 60.3 CFM while the average for the three units on the third floor is 17.7 CFM. The first-floor unit average infiltration is a factor of 3.4 greater than the average for the third-floor units. For the scenario with 25% interior leakage, the first-floor unit average infiltration is only a factor of 1.1 greater than the average for the third-floor units. The ratios of differences between the first and third floors are significantly less than those for balanced ventilation which had a ratio of 6.2 for 85% interior leakage and 1.2 for 25% interior leakage. This demonstrates that continuous exhaust ventilation produces less variation in infiltration by season and level of the buildings. However, it is also important to note that balanced ventilation provides

at least the minimum required level of ventilation regardless of outdoor conditions, level of envelope leakage, and location within the building.

- In addition, the results in Table 89 of Appendix F also show that for the same leakage scenario and weather, there is some variation between units on the same floor and that the relative differences can vary by month. For example, for the leakage scenario with 85% interior leakage, in July corner unit 1A on the first floor has an infiltration rate of 47.4 CFM and corner unit 1B on the first floor has an infiltration of 39.4 CFM. In January, the same first-floor units 1A and 1B have infiltration rates of 59.8 and 65.0 CFM, respectively. This is less unit-to-unit variation than occurs for balanced ventilation.

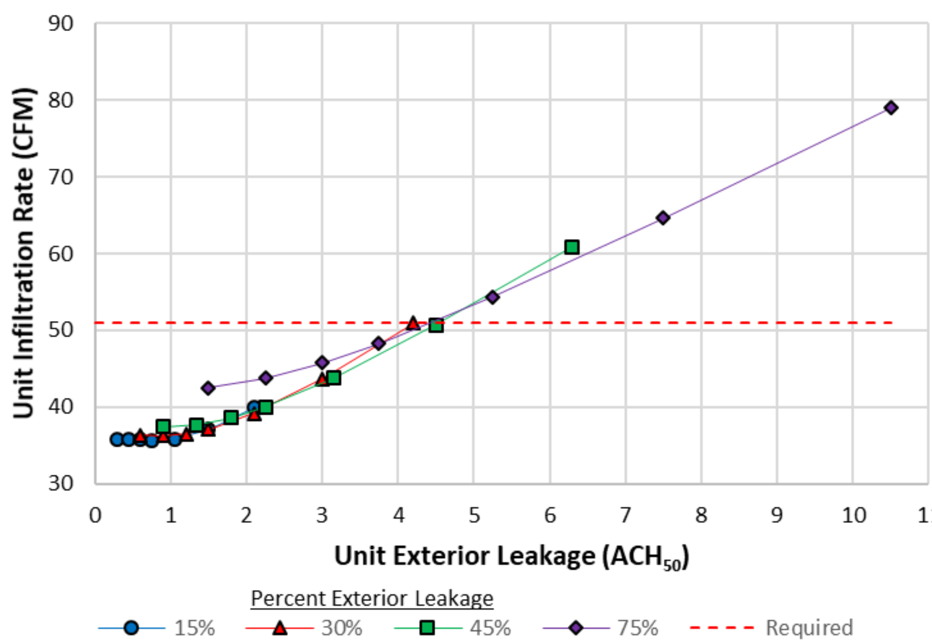


Figure 124. Annual Average Unit Infiltration: Minneapolis Continuous Exhaust Ventilation

Table 60. Unit Annual Average Infiltration (CFM): Minneapolis Continuous Exhaust Ventilation

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25	35.8								
0.50	36.2	35.9	35.7	35.6					
0.75	36.8	36.1	35.9	35.7	35.6	35.5			
1.0	38.2	36.6	36.2	36.0	35.9	35.8	35.8	35.7	35.7
1.5	42.6	38.8	37.5	37.1	37.1	37.1	37.1	37.1	37.1
2.0		42.2	39.9	39.1	38.9	38.9	39.0	39.2	39.2
2.5		45.4	43.0	41.6	41.1	41.1	41.2	41.3	41.4
3.0			45.7	44.4	43.6	43.2	43.4	43.6	43.7
3.5			48.2	47.1	46.4	45.9	45.6	46.0	46.3
4.0				49.5	49.0	48.6	48.3	48.2	48.7
4.5				51.7	51.3	51.1	50.9	50.8	50.7
5.0					53.3	53.4	53.4	53.4	53.5
5.5					55.0	55.4	55.7	55.9	56.1
6.0						57.3	57.8	58.2	58.5
6.5						58.9	59.6	60.2	60.7
7.0							61.3	62.1	62.7
7.5							62.7	63.7	64.6

For continuous exhaust ventilation, evaluating the impact of envelope leakage on inter-zonal airflow helps understand the impact of interior leakage on all building airflows. While the balanced ventilation model results showed that the percentage of airflow from infiltration was nearly constant for constant percent exterior leakage, Figure 125 shows that the percentage of airflow from infiltration decreases for increasing exterior leakage. As indicated by Figure 126, this occurs because the increases in interior air entering units are much greater than increases in infiltration. Figure 127 shows the relationship between the percentage of unit incoming air from infiltration (vertical axis) with the percent exterior leakage. The symbols represent the results for each of the 28 leakage scenarios, and the line specifies the results for the balanced ventilation simulations. This indicates that the percentage of unit air from infiltration is significantly greater than the percent exterior leakage. A possible explanation is that the level of exterior leakage into the common areas limits the amount of air that can be drawn from the common areas into the units. All of the models were configured so that 27% of the building exterior leakage was to the common areas,[33] and 73% was to the residential units. Consequently, it appears that the level of exterior leakage into the common areas limits the airflow into units from interior zones. As noted previously, there is limited airflow between units since the percentage of interior leakage is the same for every unit and the depressurization from exhaust ventilation is about the same for every unit. This shows that for buildings with exhaust ventilation, it is not accurate to assume that the percentage of air from outside is equal to the percent exterior leakage. Particularly for tighter buildings, the level of common area exterior leakage will also impact unit infiltration.

[33] This was based on the median value for all common-entry buildings tested.

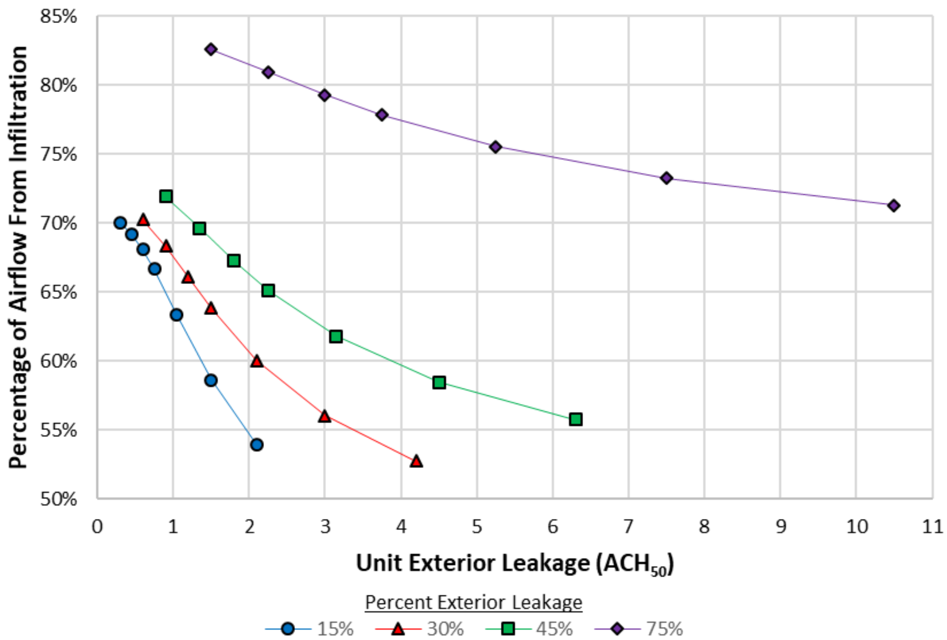


Figure 125. Percentage of Unit Airflow from Infiltration

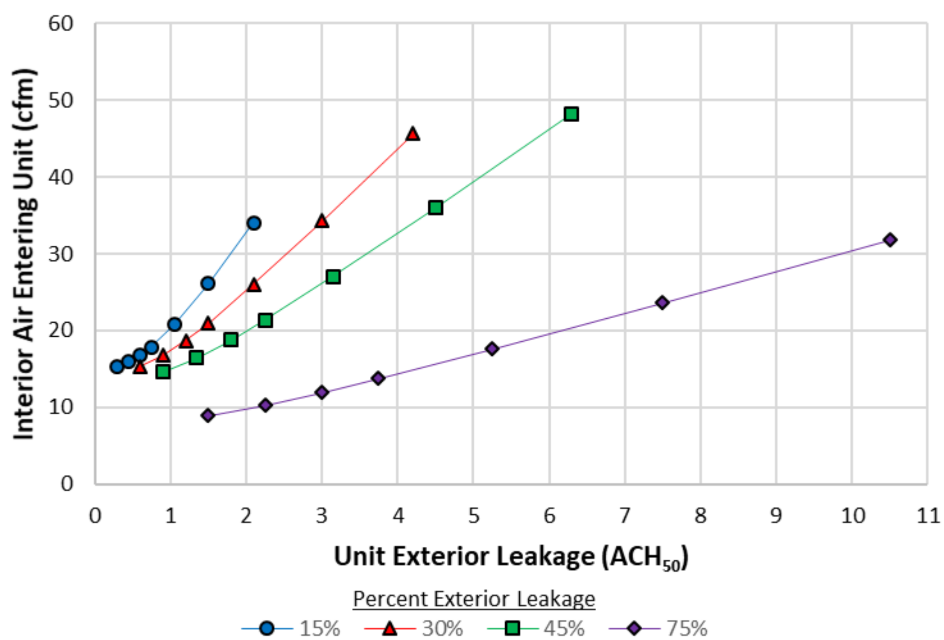


Figure 126. Rate of Air Entering Unit from Other Interior Zones

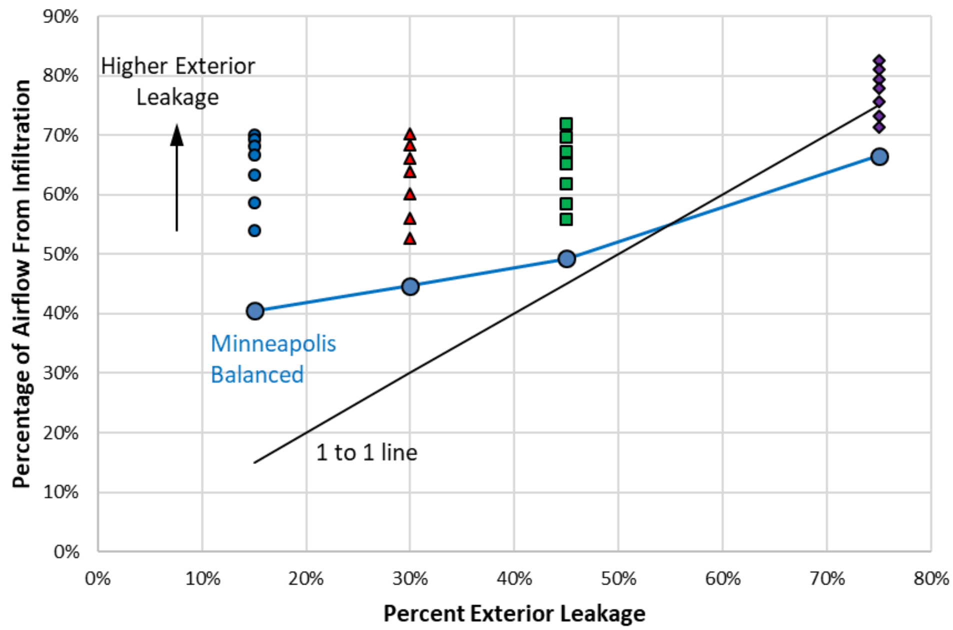


Figure 127. Percentage of Unit Airflow from Infiltration vs. Percent Exterior Leakage

Table 61 displays the reduction in annual average infiltration for a 1.0 ACH_{50} reduction in exterior leakage, and Table 62 shows the same for a 1.0 ACH_{50} reduction in interior leakage. Areas shaded red indicate higher infiltration reduction, and green areas indication less infiltration reduction. The key findings from the impact of exterior and interior envelope sealing on infiltration results are:

- The reduction of air infiltration for reducing exterior envelope leakage by 1.0 ACH_{50} varies significantly with exterior and total leakage. Except for units with exterior leakage greater than 6.0 ACH_{50} and higher percent exterior leakage, sealing interior leakage has almost no impact on infiltration or can even cause infiltration to increase slightly.

- The infiltration reduction per 1.0 ACH_{50} reduction in exterior leakage is greater for increasing total leakage. The infiltration reduction is greatest for percent exterior leakage of about 50%, and it decreases for both decreasing and increasing percent exterior leakage. The infiltration reduction ranges from 1.4 to 5.3 CFM/ACH_{50} (ratio of high to low reduction = 1.8). This indicates that accurate calculations of infiltration reduction for a change in air leakage should consider the level of exterior and interior leakage. The level of infiltration reduction for continuous exhaust ventilation is typically 22% less than that for the same building model with balanced ventilation. However, the ratio of infiltration reduction for exhaust to balanced ventilation varies from 0.25 to 0.96.

- As discussed in the previous section, for most levels of exterior leakage, interior leakage generally has limited impact on infiltration due to constraints from common space exterior leakage. Consequently, sealing interior leakage for buildings with continuous exhaust ventilation typically has no impact on infiltration.

Table 61. Reduction in Annual Infiltration (CFM) for Reduction of 1.0 ACH_{50} in Exterior Leakage

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25									
0.50									
0.75									
1.0									
1.5		2.6	1.7	1.4	1.4				
2.0		4.0	3.3	2.9	2.9	3.0	3.2	3.4	3.5
2.5		2.8	4.3	4.1	4.0	4.1	4.1	4.2	4.4
3.0			3.5	4.5	4.5	4.3	4.5	4.5	4.5
3.5			2.9	4.1	4.8	4.8	4.5	4.9	5.0
4.0				3.8	4.5	5.0	5.1	4.8	5.1
4.5				3.4	4.2	4.7	5.1	5.1	4.6
5.0					3.8	4.4	4.8	5.1	5.3
5.5					3.4	4.1	4.6	5.0	5.3
6.0						4.0	4.4	4.8	5.0
6.5						3.8	4.2	4.6	4.8
7.0							4.0	4.3	4.6
7.5							3.8	4.1	4.4

Table 62. Reduction in Annual Infiltration (CFM) for Reduction of 1.0 ACH_{50} in Interior Leakage

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25									
0.50		-0.31	-0.15	-0.09					
0.75		-0.69	-0.25	-0.15	-0.10	-0.07			
1.0		-1.58	-0.42	-0.17	-0.11	-0.08	-0.06	-0.05	-0.04
1.5		-3.79	-1.23	-0.47	0.00	0.00	0.00	0.00	0.00
2.0			-2.31	-0.83	-0.18	-0.03	0.16	0.12	0.10
2.5			-2.37	-1.42	-0.54	0.06	0.04	0.12	0.13
3.0				-1.31	-0.87	-0.36	0.20	0.16	0.13
3.5				-1.11	-0.74	-0.53	-0.22	0.38	0.31
4.0					-0.53	-0.38	-0.29	-0.14	0.49
4.5					-0.33	-0.24	-0.18	-0.14	-0.11
5.0						0.06	0.05	0.04	0.03
5.5						0.37	0.28	0.21	0.17
6.0							0.50	0.39	0.31
6.5							0.76	0.59	0.47
7.0								0.82	0.66
7.5								1.07	0.86

The chart of the EUI for the annual space heating gas use for the residential units is shown in Figure 128. In general, the trends for the EUI follow the trends for the air infiltration. The key findings from the EUI results are:

- There is little change in the EUI for exterior leakages from 0.3 to 1.3 ACH_{50}. For exterior leakages in this range the EUI is 12.6 to 12.8 kBtu/ft^2. For an exterior leakage of 3.0 ACH_{50}, which is required for climate zones 3–7, the EUI varies from 14.7 to 16.0 kBtu/ft^2. The EUI doubles from the minimum value of 12.6 kBtu/ft^2 for an exterior leakage of about 9.0 ACH_{50}.
- Over the modelled exterior air leakage scenarios from 0.5 to 4.5 ACH_{50}, there are only small differences in the infiltration rate for the three percent exterior air leakages of 15%, 30%, and 45%.
- For exterior leakage rates greater than 1.3 ACH_{50}, the relationship between infiltration and exterior leakage is highly linear. The change in EUI with exterior leakage is somewhat greater for decreasing exterior leakage.
- The impact of interior leakage is only marginally significant. For the same exterior leakage of 3.0 ACH_{50}, an increase in the percent interior leakage from 25% to 70% (e.g., 75% to 30% decrease in exterior leakage) increases the EUI by 8%.
- There is increasing corridor electric space heating for increasing levels of exterior leakage. The annual electric use is below 2,000 kWh for exterior leakage less than 1.5 ACH_{50}, but over 8,000 kWh for exterior leakage greater than 4.0 ACH_{50} and exterior leakage less than 45%. (See Figure 195 in Appendix F.) Adding the electrical space heating and additional floor area of the common area does not change the space heating EUI significantly.
- The model predicts space cooling electric use of 13,900 to 14,700 kWh with increasing use for lower exterior envelope. As noted previously, greater exterior leakage results in more “free cooling” from outside air entering the building when the outside air temperature is below the inside air temperature. In reality, many people would open their windows during those periods and there would be no benefit from increased infiltration. That effect was not included in the modelling.

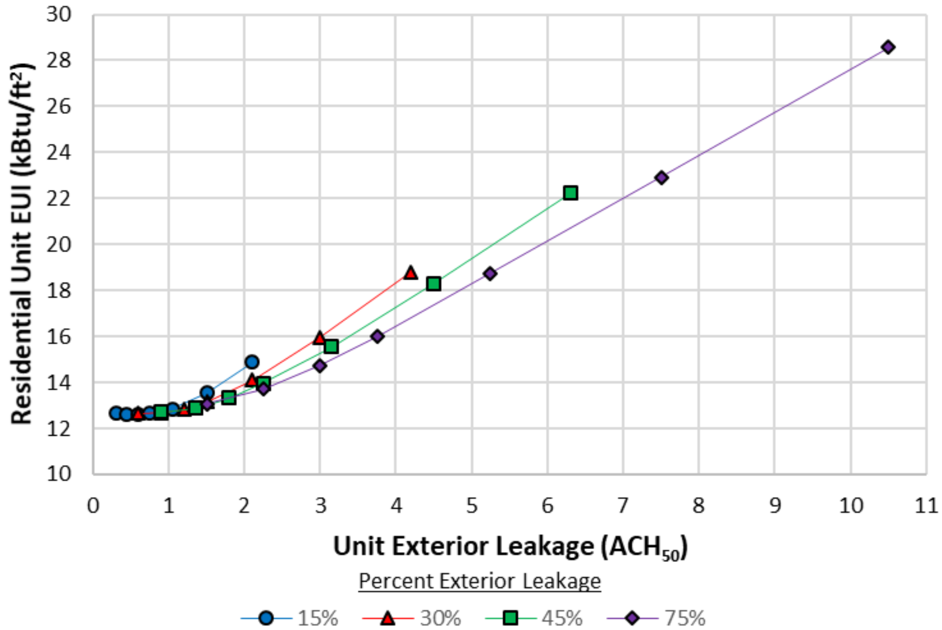


Figure 128. EUI for Residential Units (kBtu/ft^2)

The differences in EUI from the energy code required value to the modelled scenarios are shown in Figure 129 and Table 63. For Minneapolis, it was assumed that the code requirement of 3.0 ACH_{50} was applied to the total leakage as measured by a compartmentalization test and that the percent exterior leakage was 30%. This results in a residential unit space heating EUI of 12.67 kBtu/ft^2. An increase in the total leakage to 5.0 ACH_{50} would result in a 16% increase in the EUI to 13.14 kBtu/ft^2.

If it is assumed that the code required leakage of 3.0 ACH_{50} is applied to the exterior leakage, that level of exterior leakage with a percent exterior leakage of 30% produces an EUI of 15.98 kBtu/ft^2. This is a 26% increase in the EUI compared to that for a 3.0 ACH_{50} total leakage. It shows that the decision to apply the leakage requirement to the exterior leakage or to the total leakage has a very significant impact on the resulting space heating energy use for the building. However, the impact is not as great as for buildings with balanced ventilation.

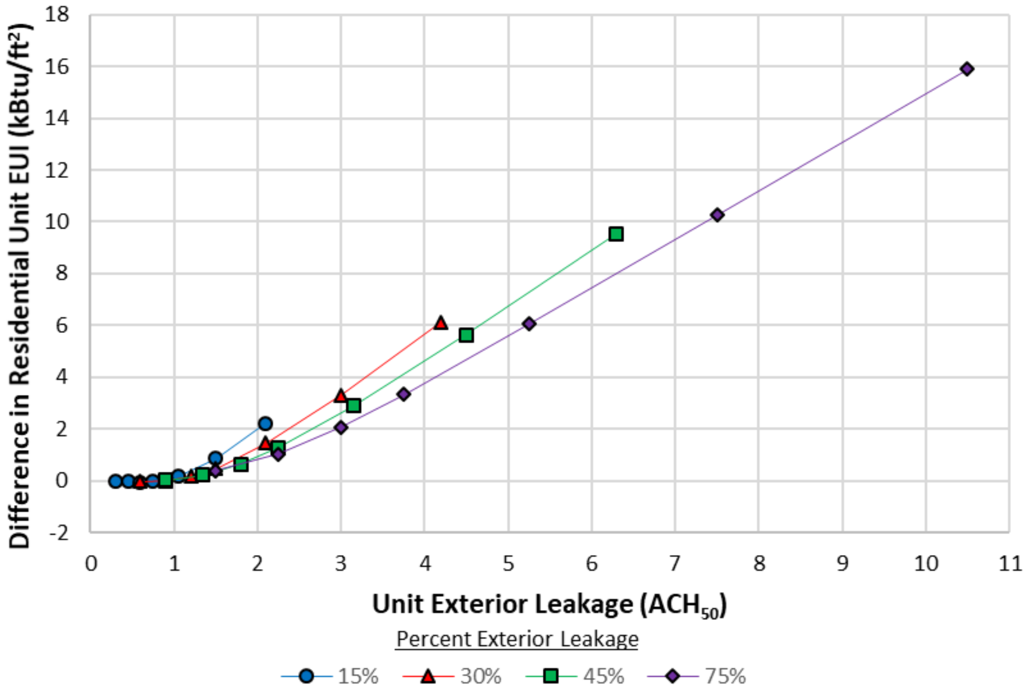


Figure 129. Difference in EUI from Baseline for Residential Units (kBtu/ft²)

Table 63. Difference in EUI from Baseline for Residential Units

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25	-0.02								
0.50	-0.04	-0.04	-0.04	-0.05					
0.75	-0.02	-0.02	-0.02	-0.03	-0.03	-0.03			
1.0	0.05	0.05	0.08	0.11	0.12	0.14	0.15	0.15	0.16
1.5	0.39	0.35	0.41	0.47	0.60	0.70	0.77	0.82	0.87
2.0		0.85	0.91	1.04	1.20	1.35	1.51	1.65	1.75
2.5		1.29	1.53	1.67	1.85	2.06	2.22	2.39	2.55
3.0			2.06	2.34	2.53	2.72	2.96	3.15	3.30
3.5			2.61	3.02	3.29	3.48	3.67	3.96	4.18
4.0				3.64	4.01	4.28	4.48	4.66	4.96
4.5				4.22	4.69	5.03	5.28	5.48	5.64
5.0					5.30	5.74	6.07	6.33	6.53
5.5					5.82	6.38	6.80	7.12	7.38
6.0						6.95	7.46	7.86	8.18
6.5						7.45	8.06	8.54	8.92
7.0							8.60	9.16	9.61
7.5							9.08	9.73	10.26

5.3.1.3 Intermittent Exhaust Ventilation

It was expected that the results for intermittent exhaust ventilation would be similar to those for balanced ventilation. Since the balanced ventilation system operates continuously with exactly matched supply and return airflow, the balanced system does not impact the building pressures. The system only creates added space heating and cooling energy use that increases the EUI by a relatively fixed amount. The intermittent exhaust system included 50 CFM of exhaust airflow for one hour each morning. Consequently, for 23 of the 24 hours each day, the building airflow rates through envelope leaks are identical for the balanced and intermittent exhaust ventilation scenarios. For one hour each day (4% of the entire day), the airflows are similar to those for continuous exhaust ventilation. The one hour of exhaust ventilation is expected to produce results that are similar to those for balanced ventilation with a slight tendency to include some trends seen for continuous exhaust ventilation. Because of the expected similarity of the results, the discussion for this section primarily highlights differences between the results for intermittent exhaust and balanced ventilation.

The chart of the annual average air infiltration rate for all units in the building is shown in Figure 130, and Table 64 shows the interpolated values. The key differences in annual infiltration rate results for intermittent exhaust and balanced ventilation are:

- The annual infiltration rates are slightly higher and within 1.5 CFM or 5% of those for balanced ventilation. The slopes of the regression lines for the relationship between infiltration and exterior leakage are 1%–3% lower than those for balanced ventilation. Due to the intermittent exhaust flow, the intercepts are 1.4 CFM higher than those for balanced ventilation.
- The average “divide by” values are 15.6, 18.9, 22.4, and 27.9 CFM_{50}/CFM for percent exterior leakage of 15%, 30%, 45%, and 75%, respectively. Those are about 10% lower than the values for balanced ventilation. A chart of the “divide by” value is shown in Figure 202 of Appendix F.
- The impact of interior leakage is approximately the same for balanced and intermittent exhaust ventilation.
- Table 102 of Appendix F shows the monthly variation of unit average infiltration rates for each of the 28 leakage scenarios. As expected, infiltration is greatest during colder weather when the stack effect is the dominant driving force. For percent exterior leakages of 15%–45%, the highest monthly average infiltration is about 36% greater than the minimum monthly average in the summer. The seasonal variation is greater for 75% exterior leakage, for which the heating season maximum infiltration is about 57% greater than the lowest monthly.
- Table 103 of Appendix F shows the monthly variation of unit average infiltration rates for a selection of 12 units for four leakage scenarios with approximately equal exterior leakage. As expected, the units on the first floor have greater infiltration than those on the third floor, and the differences between the first and third floors are greater for leakage scenarios with greater interior leakage. For example, for the leakage scenario with 85% interior leakage, in January the three units on the first floor have an average infiltration of 35.5 CFM while the average for the three units on the third floor is 6.0 CFM. The first-floor unit average infiltration is a factor of 5.89 greater than the average for the third-floor units. For the scenario with 25% interior leakage, the first-floor unit average infiltration is only a factor of 1.2 greater than the average for the third-floor units. These results are within 5% of those for balanced ventilation.
- In addition, the results in Table 103 of Appendix F also show that for the same leakage scenario and weather, there is considerable variation between units on the same floor and that the relative differences

can vary by month. For example, for the leakage scenario with 85% interior leakage, in July, corner unit 1A on the first floor has an infiltration rate of 22.6 CFM and corner unit 1B on the first floor has an infiltration of 14.6 CFM. In January, the same first-floor units 1A and 1B have infiltration rates of 36.6 and 41.6 CFM, respectively.

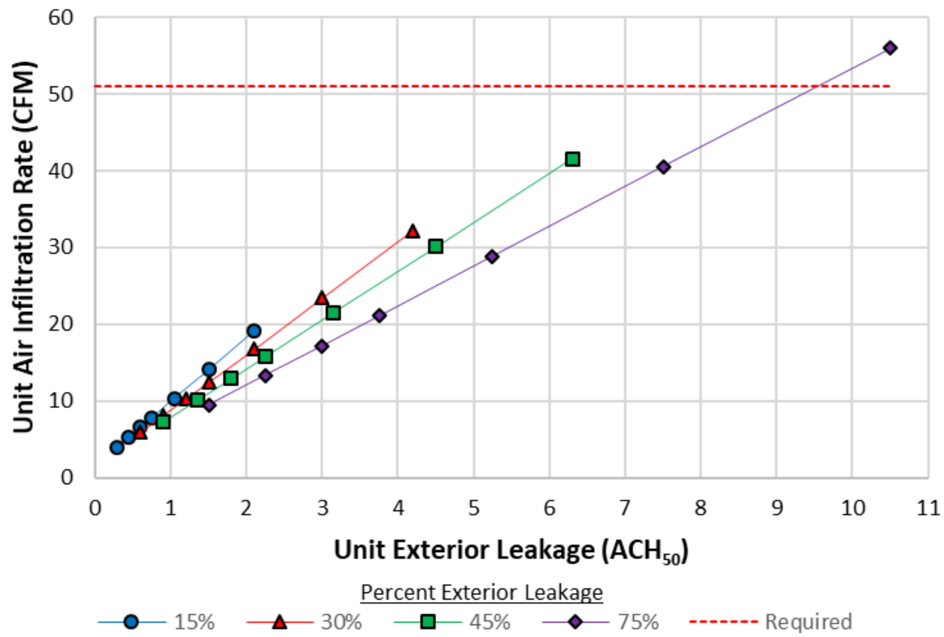


Figure 130. Annual Average Unit Infiltration: Minneapolis Intermittent Exhaust Ventilation

Table 64. Unit Annual Average Infiltration (CFM): Minneapolis Intermittent Exhaust Ventilation

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25	3.6								
0.50	5.3	5.6	5.8	5.9					
0.75	6.6	7.2	7.6	7.8	7.9	8.0			
1.0	7.7	8.6	9.1	9.5	9.8	9.9	10.1	10.2	10.2
1.5	9.5	10.8	11.7	12.4	13.0	13.4	13.7	13.9	14.1
2.0		12.6	13.8	14.8	15.6	16.3	16.8	17.2	17.6
2.5		13.8	15.7	16.9	17.9	18.8	19.5	20.1	20.7
3.0			17.2	18.9	20.0	20.9	22.0	22.8	23.4
3.5			18.1	20.4	22.0	23.1	24.0	25.1	26.0
4.0				21.6	23.6	25.1	26.2	27.1	28.2
4.5				22.4	24.9	26.8	28.2	29.2	30.1
5.0					25.9	28.2	29.9	31.3	32.3
5.5					26.6	29.4	31.5	33.1	34.4
6.0						30.3	32.7	34.7	36.2
6.5						30.8	33.8	36.0	37.8
7.0							34.5	37.2	39.3
7.5							35.1	38.1	40.5

Table 65 displays the reduction in annual average infiltration for a 1.0 ACH_{50} reduction in exterior leakage, and Table 66 shows the same for a 1.0 ACH_{50} reduction in interior leakage. The infiltration reductions for intermittent exhaust ventilation are typically within 5% of those for balanced ventilation.

Table 65. Reduction in Annual Infiltration (CFM) for Reduction of 1.0 ACH_{50} in Exterior Leakage

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25									
0.50									
0.75									
1.0									
1.5		5.4	6.1	6.6	7.1				
2.0		4.9	5.3	5.7	6.1	6.5	6.9	7.2	7.4
2.5		4.4	5.0	5.2	5.5	5.9	6.2	6.5	6.8
3.0			4.6	5.0	5.2	5.3	5.7	6.0	6.2
3.5			4.3	4.7	5.1	5.2	5.2	5.6	5.8
4.0				4.4	4.8	5.1	5.2	5.1	5.4
4.5				4.3	4.5	4.8	5.1	5.2	5.0
5.0					4.4	4.6	4.9	5.1	5.3
5.5					4.2	4.4	4.7	4.9	5.1
6.0						4.3	4.5	4.7	4.9
6.5						4.2	4.4	4.6	4.8
7.0							4.3	4.4	4.6
7.5							4.2	4.3	4.5

Table 66. Reduction in Annual Infiltration (CFM) for Reduction of 1.0 ACH_{50} in Interior Leakage

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25									
0.50		0.30	0.15	0.09					
0.75		0.61	0.34	0.21	0.14	0.10			
1.0		0.87	0.57	0.37	0.25	0.18	0.13	0.10	0.08
1.5		1.30	0.95	0.69	0.56	0.40	0.30	0.23	0.19
2.0			1.20	0.98	0.83	0.63	0.54	0.42	0.33
2.5			1.92	1.15	0.98	0.94	0.70	0.61	0.52
3.0				1.68	1.12	0.97	1.02	0.79	0.63
3.5				2.31	1.54	1.10	0.94	1.08	0.86
4.0					2.03	1.45	1.09	0.90	1.13
4.5					2.58	1.84	1.38	1.07	0.86
5.0						2.28	1.71	1.33	1.06
5.5						2.77	2.08	1.61	1.29
6.0							2.48	1.93	1.54
6.5							2.91	2.26	1.81
7.0								2.63	2.10
7.5								3.02	2.42

Figure 131 shows the percentage of airflow into units that is due to infiltration. For higher levels of exterior leakage, the values are similar to those for balanced ventilation, but they are somewhat higher for low exterior leakage. This shows the influence of the 4% of the time that there is exhaust ventilation. Figure 132 compares the percentage of air infiltration with percent exterior leakage for the two ventilation modes. Intermittent exhaust produces slightly higher percentage infiltration.

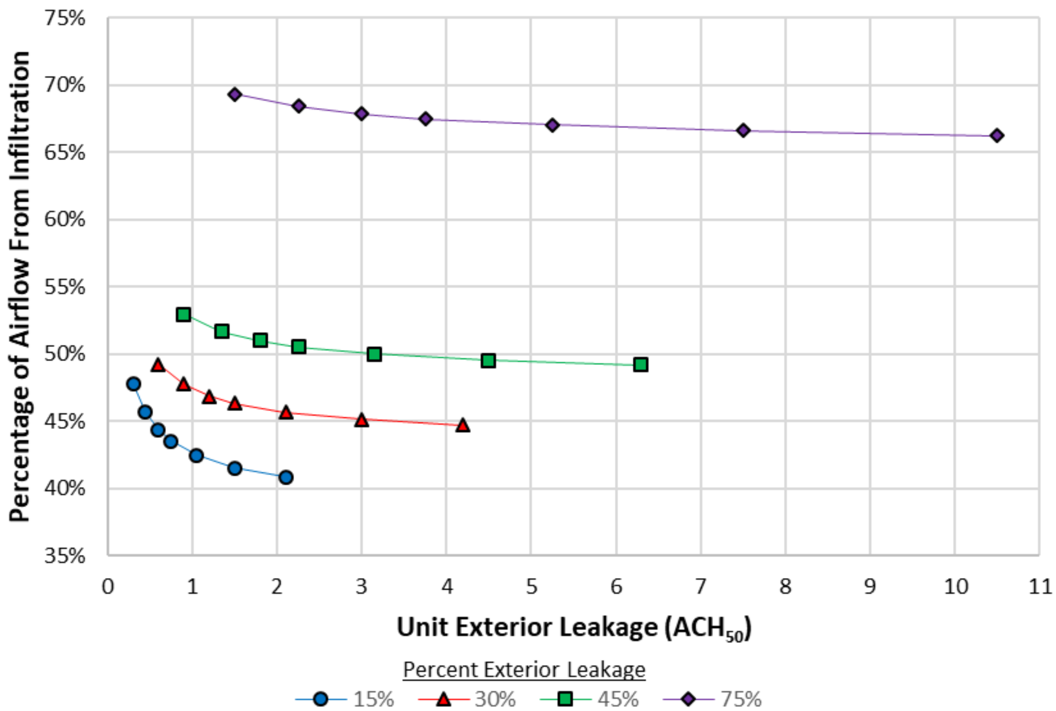


Figure 131. Percentage of Unit Airflow from Infiltration

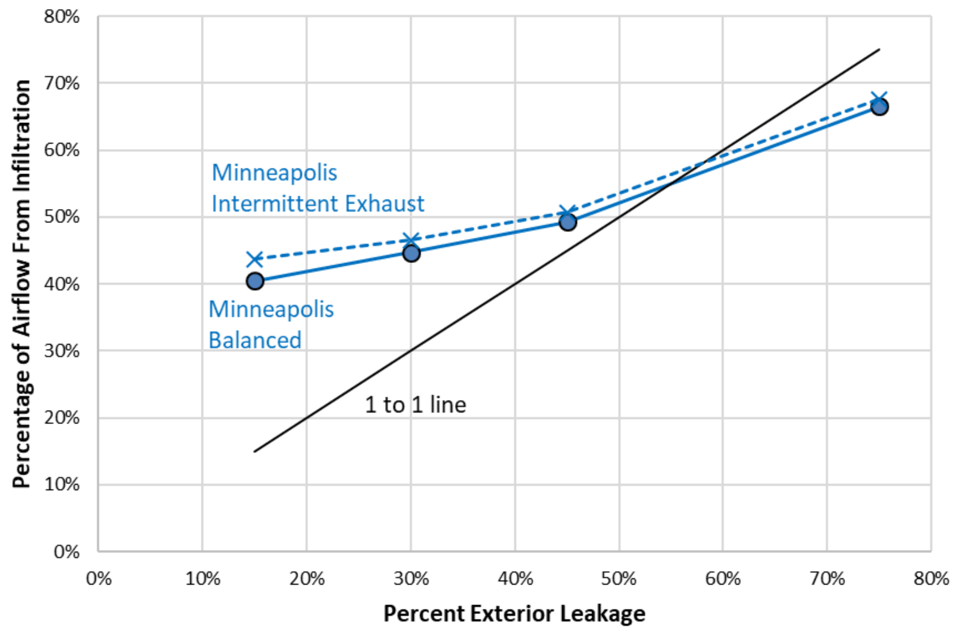


Figure 132. Percentage of Unit Airflow from Infiltration vs. Percent Exterior Leakage

The chart of the EUI for the annual space heating gas use for the residential units is shown in Figure 133. The key findings from the EUI results are:

- For the four constant percent exterior leakage curves, the relationship between EUI and exterior leakage is highly linear ($R^2 > 0.999$). Linear regressions of the EUI with exterior leakage yields slopes of 2.82, 2.51, 2.24, and 1.91 (kBtu/ft^2)/ACH$_{50}$ for percent exterior leakages of 15%, 30%, 45%, and 75%, respectively. The linear relationships and decreasing slopes with increasing percent exterior leakage follow the same trends as those for the variation of annual infiltration and exterior leakage. The slopes are generally within 5% of the values for balanced ventilation.

- The regression intercepts are 2.33, 2.20, 2.17, and 2.05 kBtu/ft^2 for percent exterior leakages of 15%, 30%, 45%, and 75%, respectively. The intercepts are the approximate space heating needed for the net heat loss through the building shell when there is no infiltration. The average intercept is 2.19 kBtu/ft^2. This is 6.7 kBtu/ft$_2$ lower than the intercept for the balanced ventilation scenarios. This is expected since the balanced ventilation system adds a continuous space conditioning load from the 51 CFM of outdoor air.

- The impact of interior leakage is marginally significant. For the same exterior leakage, an increase in the percent interior leakage from 55% to 70% (e.g., 45% to 30% decrease in exterior leakage) increases the EUI by about 12%. This is about the same relative impact as occurs for the average annual infiltration.

- Depending on the percent exterior leakage, an exterior leakage from 0.8 to 1.2 ACH$_{50}$ results in an increase in the EUI that is about equal to the energy use due to heat loss through the envelope.

- Above an exterior leakage of about 1.5 ACH$_{50}$, increased exterior leakage results in increases in corridor electric space heating. A percent exterior leakage of 15% to 45% and exterior leakage of 2.0 ACH$_{50}$ results in corridor electric space heating use of about 1,000 kWh. The level of space heating decreases with decreasing percent interior leakage. These results are very similar to those for balanced ventilation.

- The model predicts space cooling electric use of 14,000 to 18,000 kWh with increasing use for lower exterior envelope. As noted previously, greater exterior leakage results in more "free cooling" from outside air entering the building when the outside air temperature is below the inside air temperature. In reality, many people would open their windows during those periods and there would be no benefit from increased infiltration. That effect was not included in the modelling.

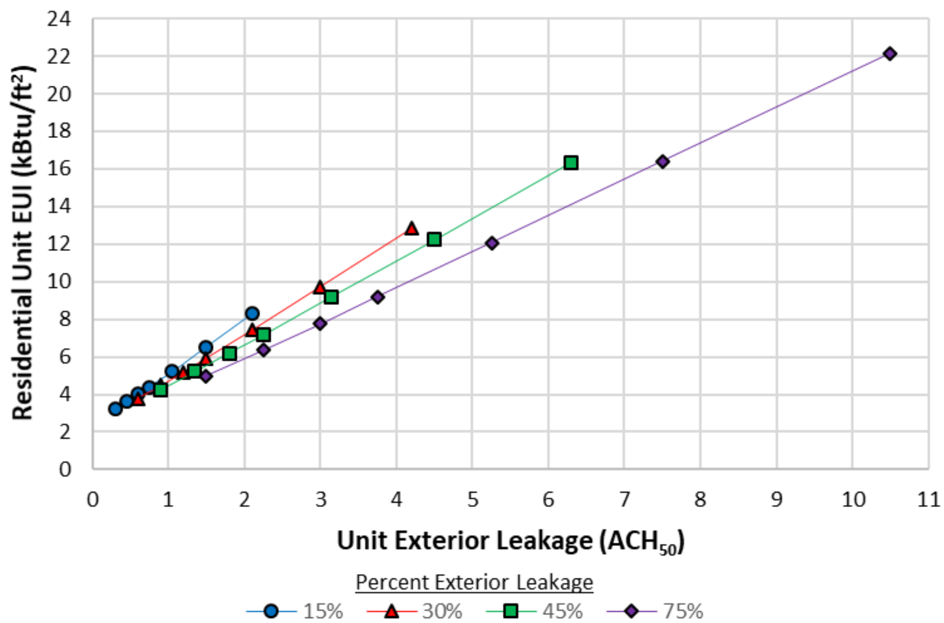


Figure 133. EUI for Residential Units (kBtu/ft^2)

The differences in EUI from the energy-code-required value to the modelled scenarios are shown in Figure 134 and Table 67. An increase in the total leakage from a baseline of 3.0 ACH_{50} to 5.0 ACH_{50} would result in a 32% increase (1.44 kBtu/ft^2) in the EUI from 4.48 to 5.92 kBtu/ft^2. If it is assumed that the code-required leakage of 3.0 ACH_{50} is applied to the exterior leakage, that level of exterior leakage with a percent exterior leakage of 30% produces an EUI of 9.72 kBtu/ft^2. This is a 117% increase in the EUI compared to that for a 3.0 ACH_{50} total leakage. It shows that the decision to apply the leakage requirement to the exterior leakage or to the total leakage has a very significant impact on the resulting space heating energy use for the building.

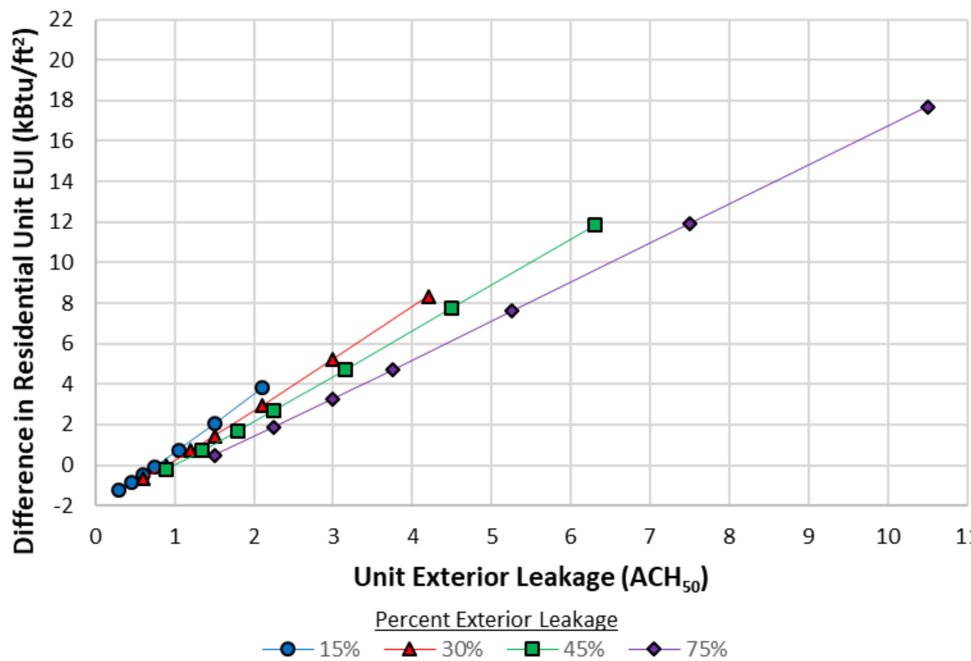


Figure 134. Difference in EUI from Baseline for Residential Units (kBtu/ft^2)

Table 67. Difference in EUI from Baseline for Residential Units

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25	-1.33								
0.50	-0.85	-0.75	-0.71	-0.68					
0.75	-0.44	-0.26	-0.15	-0.08	-0.04	-0.01			
1.0	-0.08	0.18	0.36	0.48	0.56	0.62	0.67	0.70	0.73
1.5	0.50	0.96	1.24	1.44	1.64	1.78	1.89	1.97	2.04
2.0		1.61	2.02	2.32	2.56	2.76	2.96	3.12	3.25
2.5		2.08	2.72	3.10	3.40	3.69	3.90	4.11	4.31
3.0			3.27	3.82	4.18	4.49	4.80	5.04	5.24
3.5			3.70	4.44	4.93	5.28	5.58	5.92	6.18
4.0				4.94	5.58	6.04	6.38	6.67	7.02
4.5				5.34	6.15	6.72	7.15	7.49	7.76
5.0					6.62	7.32	7.85	8.27	8.59
5.5					6.99	7.84	8.48	8.98	9.38
6.0						8.28	9.04	9.63	10.10
6.5						8.63	9.52	10.21	10.77
7.0							9.93	10.73	11.38
7.5							10.27	11.19	11.93

5.3.2 Washington

The simulations were performed for the weather patterns of Seattle, Washington, which is in Climate Zone 4 (Marine). Seattle has 4,949 heating degree days (base 65°F, HDD65) and 290 cooling degree days (base 65°F, CDD65). The seasonal variations and histograms of outside air temperature and wind speed for Minneapolis are shown in Figure 135. The monthly average wind speeds range from 5.0 to 9.5mph and the annual average is 8.4mph. The monthly average outside air temperatures range from 40.1 to 65.8°F and the annual average is 52.2°F.

There are 39% fewer heating degree days for Seattle than for Minneapolis. The more moderate outside air temperatures reduce the stack effect, which results in lower annual average air infiltration. Since infiltration is also impacted by wind and exhaust flows, the overall reduction in airflow rates for Seattle weather compared to Minneapolis is expected to be less than 39%. The impact on space heating energy use is expected to be similar to the percent reduction in heating degree days. Neither location has a high level of cooling degree days. Energy use for space cooling energy use is not expected to be significant compared to that for space heating.

It is expected that a proportional reduction in airflow results for Seattle will generally be consistent for the envelope leakage scenarios and that the trends identified for Minneapolis will be similar for Seattle. Because of the anticipated similarity of the results, the discussion for this section primarily highlights differences between the results for intermittent exhaust and balanced ventilation.

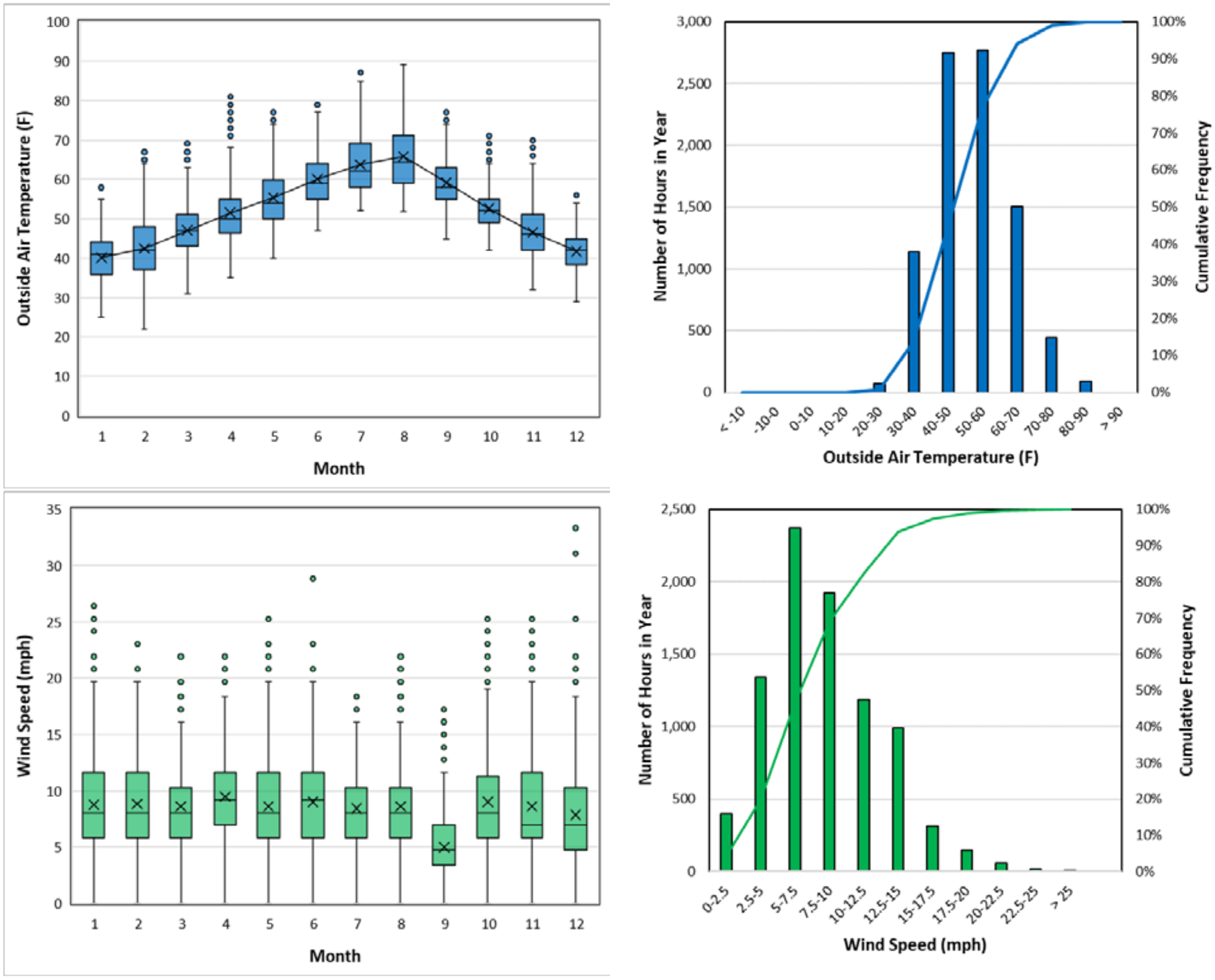


Figure 135. Seattle Annual Outside Air Temperature and Wind Speed

5.3.2.1 Continuous Balanced Ventilation

The chart of the annual average air infiltration rate for all units in the building is shown in Figure 136 and Table 68 shows the interpolated values. Since the balanced ventilation system provides the code required rate for each unit, any air infiltration causes the total ventilation (mechanical ventilation + infiltration) to be greater than the required amount. The key findings from the annual infiltration rate results are:

- For a low exterior leakage of 1.0 ACH_{50} the infiltration is less than 10 CFM. For an exterior leakage of 3 ACH_{50} that is required for climate zones 3–7, the infiltration varies from 14 to 20 CFM. The infiltration increases above 51 CFM (the mechanical ventilation flow rate) for an exterior leakage of about 6.5 ACH_{50} (15% exterior leakage) to 11 ACH_{50} (75% exterior leakage).

- For the four constant percent exterior leakage curves shown in Figure 136, the relationship between infiltration and exterior leakage in highly linear ($R^2 > 0.999$). Linear regressions of the infiltration rate with exterior leakage yields slopes of 7.75, 6.7, 5.80, and 4.55 CFM/ACH_{50} for exterior leakages of 15%, 30%, 45%, and 75% respectively. An approximate value of the annual average infiltration can be computed by dividing the unit exterior leakage (reported as CFM_{50}) by 20.2, 23.4, 27.0, and 34.2 for percent exterior leakage of 15%, 30%, 45%, and 75% respectively. A chart of the "divide by" value is shown in Figure 212 of Appendix G.

- The impact of interior leakage is marginally significant. For the same exterior leakage an increase in the percent interior leakage from 55% to 70% (e.g., 45% to 30% exterior leakage) increases the infiltration by about 14%. For an exterior leakage of 3.0 ACH_{50}, that is a 91% increase in interior leakage from 3.7 ACH_{50} (55% interior) to 7.0 ACH_{50} (70% interior).
- On average, for the same envelope leakage configurations the annual air infiltration for Seattle weather is 11% less that for Minneapolis. In addition, the values used to divide the exterior envelope leakage (CFM_{50}) to get the annual infiltration (CFM) are about 11% greater for Seattle than Minneapolis. This is much less than the 39% lower heating degree days, which suggests that wind is a significant driving force for infiltration at the two locations.

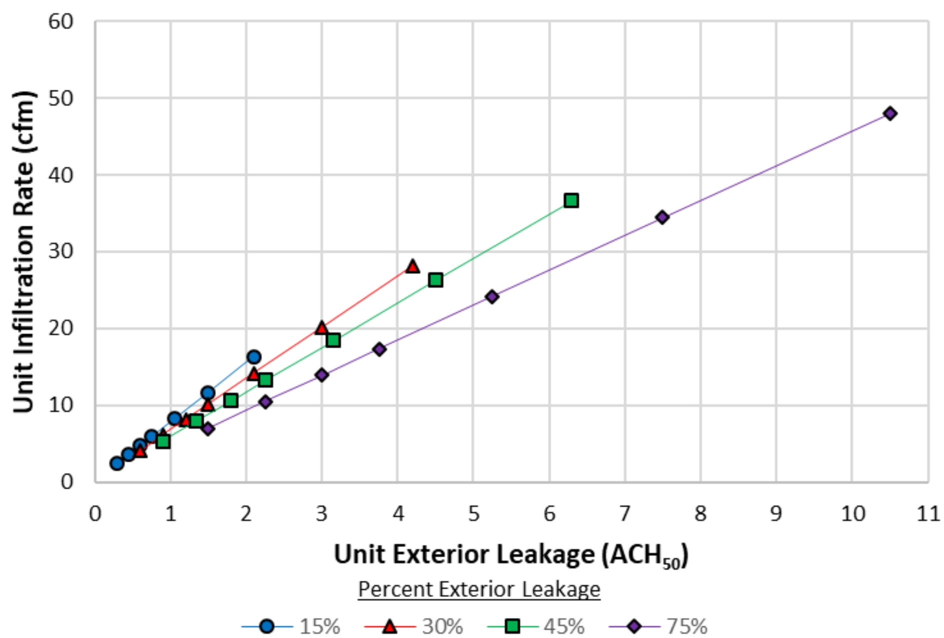


Figure 136. Annual Average Unit Infiltration: Seattle Balanced Ventilation

Table 68. Unit Annual Average Infiltration (CFM): Seattle Balanced Ventilation

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25	2.0								
0.50	3.6	3.9	4.0	4.1					
0.75	4.8	5.4	5.7	5.9	6.0	6.1			
1.0	5.7	6.6	7.1	7.5	7.7	7.9	8.0	8.1	8.2
1.5	7.0	8.5	9.5	10.2	10.7	11.0	11.3	11.5	11.7
2.0		10.0	11.4	12.3	13.1	13.7	14.2	14.6	14.9
2.5		10.8	12.9	14.2	15.2	16.0	16.7	17.2	17.7
3.0			13.9	15.8	17.0	18.0	18.9	19.6	20.2
3.5			14.5	16.9	18.6	19.8	20.7	21.7	22.5
4.0				17.7	19.9	21.4	22.6	23.5	24.5
4.5				18.1	20.8	22.8	24.2	25.4	26.3
5.0					21.4	23.8	25.6	27.0	28.1
5.5					21.7	24.6	26.8	28.5	29.8
6.0						25.0	27.6	29.7	31.3
6.5						25.2	28.3	30.6	32.5
7.0							28.6	31.4	33.6
7.5							28.8	31.9	34.4

Table 69 displays the reduction in annual average infiltration for a 1.0 ACH_{50} reduction in exterior leakage and Table 70 shows the same for a 1.0 ACH_{50} reduction in interior leakage. Areas shaded red indicate higher infiltration reduction and green areas indication less infiltration reduction. The key findings from the impact of exterior and interior envelope sealing on infiltration results are:

- The reduction of air infiltration for reducing exterior envelope leakage by 1.0 ACH50 varies significantly with exterior and total leakage. The same is true for reducing interior envelope leakage, but with an opposite trend.
- The infiltration reduction per 1.0 ACH_{50} reduction in exterior leakage is greater for units with lower exterior leakage and higher total (or interior) leakage. The infiltration reduction ranges from 3.6 to 6.8 CFM/ACH_{50} (ratio of high to low reduction = 1.9). This indicates that accurate calculations of infiltration reduction for a change in air leakage should consider the level of exterior and interior leakage.
- The trend for infiltration reduction due to reduction in interior leakage is opposite of that for exterior leakage reduction. Reduction in infiltration per 1 ACH_{50} reduction in interior leakage is greater for units with higher exterior leakage and lower total (or interior) leakage. The infiltration reduction ranges from 0.1 to 3.2 CFM/ACH_{50}. (ratio of high to low reduction = 42). This indicates that for units with higher total leakage and low exterior leakage, reductions in interior envelope leakage have an insignificant impact on infiltration. However, for units with

higher exterior leakage and lower total leakage, reducing interior leakage can have 85% as much impact as an equal reduction in exterior leakage.

- These results are within 1% to 15% of those for Minneapolis weather.

Table 69. Reduction in Annual Infiltration (CFM) for Reduction of 1 ACH50 in Exterior Leakage

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25									
0.50									
0.75									
1.0									
1.5		5.0	5.6	6.2	6.6				
2.0		4.3	4.8	5.2	5.7	6.0	6.3	6.6	6.8
2.5		3.8	4.4	4.7	5.0	5.4	5.6	5.9	6.2
3.0			3.9	4.4	4.6	4.8	5.2	5.4	5.6
3.5			3.7	4.0	4.4	4.6	4.7	5.0	5.3
4.0				3.8	4.1	4.4	4.6	4.6	4.9
4.5				3.6	3.9	4.2	4.4	4.6	4.5
5.0					3.7	3.9	4.2	4.5	4.6
5.5					3.6	3.8	4.0	4.2	4.4
6.0						3.6	3.8	4.0	4.3
6.5						3.6	3.7	3.9	4.1
7.0							3.6	3.8	3.9
7.5							3.5	3.7	3.8

Table 70. Reduction in Annual Infiltration (CFM) for Reduction of 1 ACH50 in Interior Leakage

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25									
0.50		0.29	0.14	0.09					
0.75		0.59	0.32	0.19	0.13	0.09			
1.0		0.89	0.54	0.34	0.23	0.16	0.12	0.10	0.08
1.5		1.53	0.97	0.66	0.51	0.36	0.27	0.21	0.17
2.0			1.36	0.99	0.78	0.58	0.48	0.38	0.30
2.5			2.12	1.27	1.00	0.87	0.65	0.56	0.47
3.0				1.83	1.22	0.98	0.94	0.73	0.58
3.5				2.48	1.66	1.18	0.96	0.99	0.79
4.0					2.16	1.54	1.16	0.94	1.04
4.5					2.74	1.95	1.47	1.14	0.91
5.0						2.41	1.81	1.40	1.12
5.5						2.91	2.18	1.70	1.36
6.0							2.60	2.02	1.62
6.5							3.05	2.37	1.90
7.0								2.75	2.20
7.5								3.16	2.53

While the primary focus of this project was to evaluate impact of envelope leakage on building energy use, a secondary concern is the impact on outside air ventilation and inter-zonal airflow. As displayed in Figure 137, the amount of airflow that enters units from the outside as a percentage of the total airflow into the unit is nearly constant for variations in exterior envelope leakage. As expected, the percentage of airflow from outside is higher for higher percent exterior leakage. However, as shown in Figure 138, the percentage of outside air is not equal to the percent exterior leakage. For an exterior leakage of 15%, the percentage of outside air is more than double the percent exterior leakage, and the two percentages are equal at about 70%. This suggests that for buildings with balanced ventilation, it is not accurate to assume that the percentage of air from outside is equal to the percent exterior leakage. The trend for Seattle tracks that for Minneapolis weather but is higher by about 4%.

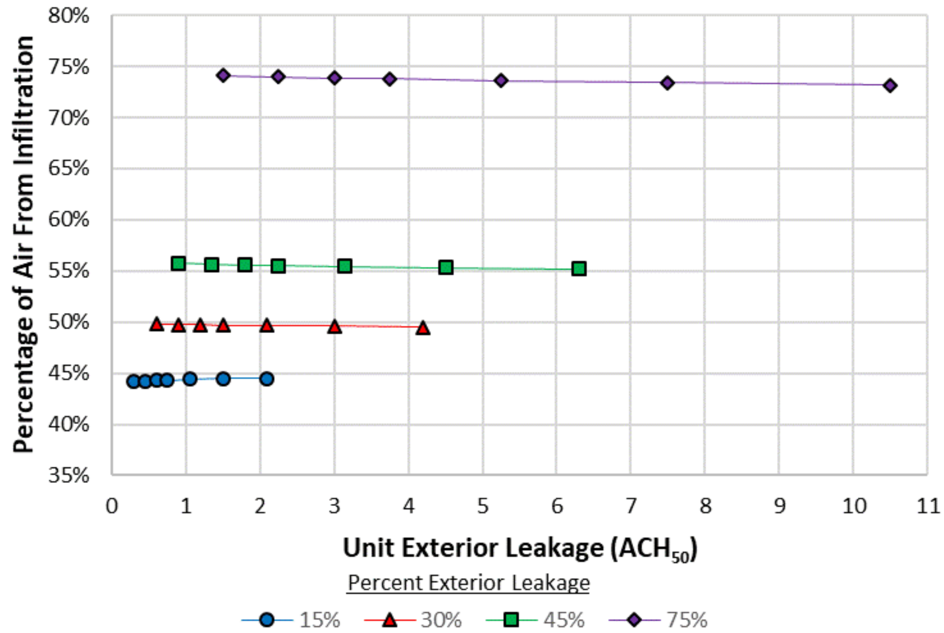


Figure 137. Percentage of Unit Airflow from Infiltration

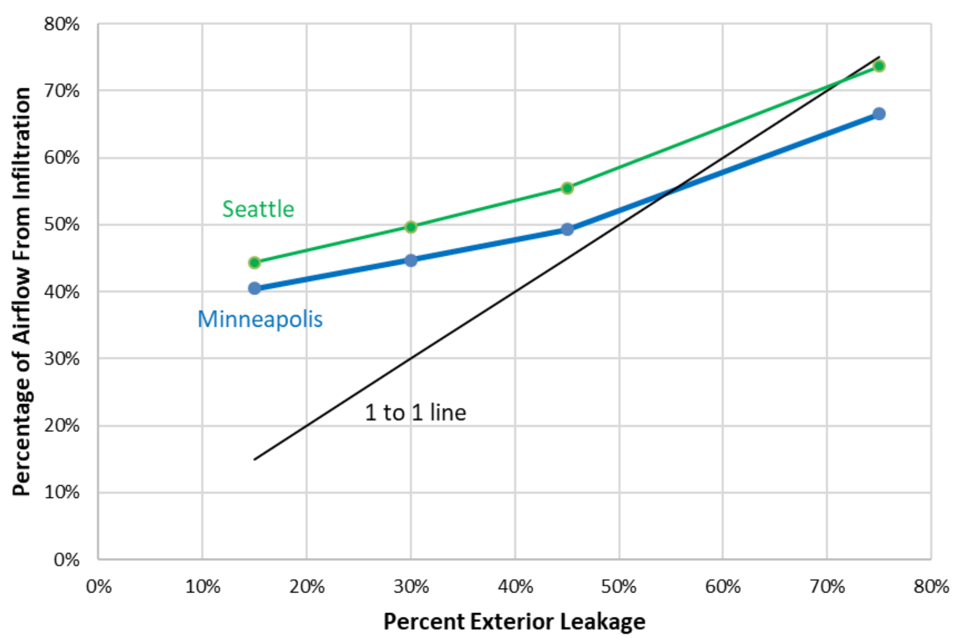


Figure 138. Percentage of Unit Airflow from Infiltration vs. Percent Exterior Leakage

The chart of the EUI for the annual space heating gas use for the residential units is shown in Figure 139. The key findings from the EUI results are:

- For the four constant percent exterior leakage curves, the relationship between EUI and exterior leakage is highly linear ($R^2 > 0.999$). Linear regressions of the EUI with exterior leakage yields slopes of 1.16, 1.14, 1.06, and 0.86 (kBtu/ft^2)/ACH_{50} for percent exterior leakages of 15%, 30%, 45%, and 75%, respectively. The linear relationships and decreasing slopes with increasing percent exterior leakage follow the same trends as those for the variation of annual infiltration and exterior leakage. The slopes are about 60% less than those for Minneapolis weather. This is to be expected because the heating degree days are 36% lower, and the infiltration rates are lower as well.
- The regression intercepts are 1.16, 1.00, 0.87, and 0.75 kBtu/ft^2 for percent exterior leakages of 15%, 30%, 45%, and 75%, respectively. The intercepts are the approximate space heating needed for the net heat loss through the building shell and the mechanical ventilation load when there is no infiltration. The average intercept is 0.95 kBtu/ft^2.
- The impact of interior leakage is marginally significant. For the same exterior leakage, an increase in the percent interior leakage from 55% to 70% (e.g., 45% to 30% decrease in exterior leakage) increases the EUI by about 8%. This is about the same relative impact as occurs for the average annual infiltration.
- Depending on the percent exterior leakage, an exterior leakage from 0.8 to 1.1 ACH_{50} results in an increase in the EUI that is about equal to the energy use due to heat loss through the envelope and from the non-heat recovery mechanical ventilation.
- There is less than 15 kWh/yr of corridor electric space heating for even the leakiest scenarios.
- The model predicts space cooling electric use of 8,000 to 13,500 kWh with increasing use for lower exterior envelope. As noted previously, greater exterior leakage results in more “free cooling” from outside air entering the building when the outside air temperature is below the inside air temperature. In reality, many people would open their windows during those periods and there would be no benefit from increased infiltration. That effect was not included in the modelling.

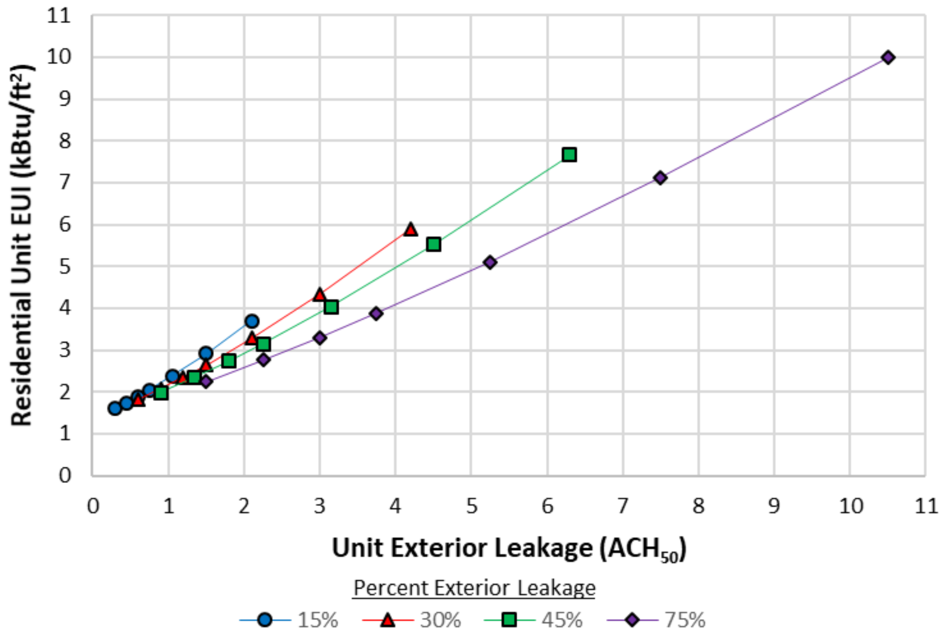


Figure 139. EUI for Residential Units (kBtu/ft²)

The differences in EUI from the energy-code-required value to the modelled scenarios are shown in Figure 140 and Table 71. For Seattle, it was assumed that the code requirement of 5.0 ACH_{50} was applied to the total leakage as measured by a compartmentalization test and that the percent exterior leakage was 30%. This results in a residential unit space heating EUI of 2.71 kBtu/ft^2. An increase in the total leakage to 7.0 ACH_{50} would result in a 25% increase in the EUI to 3.39 kBtu/ft^2.

If it is assumed that the code required leakage of 5.0 ACH50 is applied to the exterior leakage, that level of exterior leakage with a percent exterior leakage of 30% produces an EUI of 6.70 kBtu/ft^2. This is a 150% increase in the EUI compared to that for a 3.0 ACH_{50} total leakage. It shows that the decision to apply the leakage requirement to the exterior leakage or to the total leakage has a very significant impact on the resulting space heating energy use for the building.

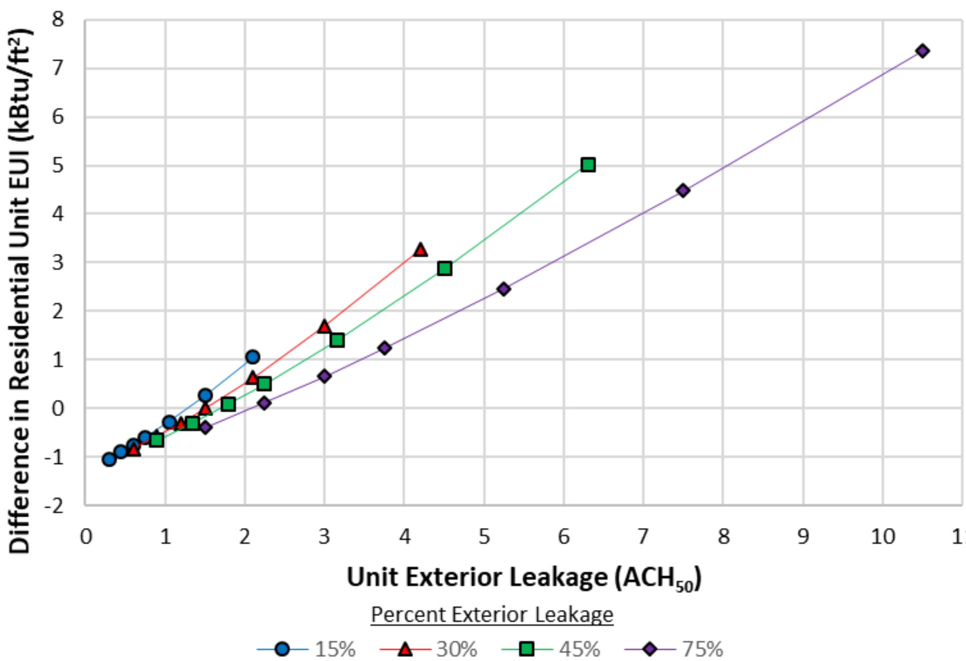


Figure 140. Difference in EUI From Baseline for Residential Units (kBtu/ft²)

Table 71. Difference in EUI From Baseline for Residential Units

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25	-1.08								
0.50	-0.90	-0.86	-0.84	-0.82					
0.75	-0.74	-0.67	-0.62	-0.59	-0.58	-0.56			
1.0	-0.60	-0.50	-0.43	-0.38	-0.34	-0.32	-0.30	-0.28	-0.27
1.5	-0.39	-0.21	-0.08	0.00	0.09	0.15	0.20	0.24	0.27
2.0		0.04	0.22	0.36	0.48	0.57	0.66	0.73	0.79
2.5		0.17	0.49	0.68	0.83	0.97	1.08	1.18	1.27
3.0			0.66	0.95	1.15	1.31	1.47	1.60	1.70
3.5			0.74	1.17	1.45	1.66	1.83	2.01	2.16
4.0				1.29	1.69	1.97	2.18	2.35	2.55
4.5				1.34	1.85	2.22	2.49	2.71	2.88
5.0					1.93	2.41	2.77	3.05	3.27
5.5					1.93	2.53	2.98	3.33	3.61
6.0						2.59	3.14	3.56	3.90
6.5						2.59	3.24	3.74	4.14
7.0							3.28	3.86	4.34
7.5							3.25	3.93	4.48

5.3.2.2 Continuous Exhaust Ventilation

The chart of the annual average air infiltration rate for all units in the building is shown in Figure 141, and Table 72 shows the interpolated values. For a continuous exhaust ventilation system, the mechanical ventilation system does not provide outdoor air directly to the units. Air infiltration through the building envelope is the only source of outdoor air that enters the unit directly from outside and should be equal to or greater than the code required minimum of 51.0 CFM to meet ventilation requirements.

Over the entire range of modeled leakage scenarios there is no more than a 5% difference in annual average infiltration for Minneapolis and Seattle weather. The infiltration for Seattle is up to 3% higher than for Minneapolis for lower leakage and up to 5% lower for higher leakage. With this level of agreement for the airflow rates, the description of the trends for airflow from Minneapolis also apply to the Seattle results. The description of airflow results is not repeated here. The EUI results are described below.

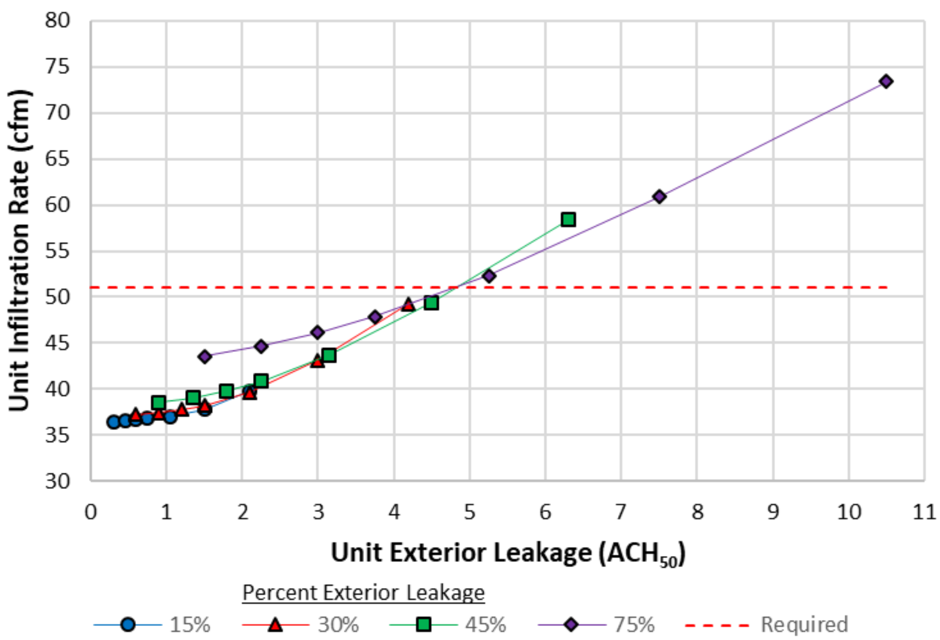


Figure 141. Annual Average Unit Infiltration: Seattle Continuous Exhaust Ventilation

Table 72. Unit Annual Average Infiltration (CFM): Seattle Continuous Exhaust Ventilation

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25	36.4								
0.50	37.0	36.7	36.6	36.5					
0.75	37.9	37.2	36.9	36.8	36.7	36.6			
1.0	39.3	37.8	37.4	37.2	37.1	37.0	36.9	36.8	36.8
1.5	43.6	40.0	38.7	38.2	38.1	38.0	37.9	37.8	37.8
2.0		43.2	40.9	40.0	39.6	39.4	39.5	39.5	39.5
2.5		46.1	43.7	42.2	41.5	41.4	41.3	41.2	41.2
3.0			46.1	44.7	43.7	43.2	43.2	43.2	43.2
3.5			48.1	46.9	46.1	45.5	45.2	45.4	45.5
4.0				48.8	48.2	47.8	47.5	47.3	47.6
4.5				50.4	50.1	49.8	49.7	49.5	49.4
5.0					51.5	51.6	51.7	51.8	51.9
5.5					52.6	53.1	53.5	53.8	54.0
6.0						54.6	55.2	55.6	56.0
6.5						55.7	56.6	57.3	57.9
7.0							57.8	58.7	59.5
7.5							58.8	60.0	60.9

Table 73. Reduction in Annual Infiltration (CFM) for Reduction of 1 ACH50 in Exterior Leakage

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25									
0.50									
0.75									
1.0									
1.5		3.0	2.0	1.7	1.6				
2.0		3.9	3.1	2.6	2.4	2.4	2.5	2.6	2.6
2.5		2.6	3.7	3.5	3.3	3.3	3.3	3.3	3.4
3.0			2.9	3.7	3.7	3.6	3.7	3.7	3.7
3.5			2.0	3.2	3.9	4.0	3.8	4.1	4.3
4.0				2.7	3.6	4.1	4.3	4.1	4.4
4.5				2.3	3.2	3.7	4.1	4.3	4.0
5.0					2.7	3.4	3.9	4.3	4.5
5.5					2.2	3.0	3.7	4.1	4.5
6.0						3.1	3.6	3.9	4.2
6.5						3.1	3.5	3.8	4.1
7.0							3.2	3.6	3.8
7.5							3.0	3.4	3.6

Table 74. Reduction in Annual Infiltration (CFM) for Reduction of 1 ACH50 in Interior Leakage

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25									
0.50		-0.30	-0.15	-0.09					
0.75		-0.68	-0.24	-0.14	-0.09	-0.07			
1.0		-1.53	-0.43	-0.19	-0.13	-0.09	-0.07	-0.05	-0.04
1.5		-3.58	-1.24	-0.53	-0.15	-0.11	-0.08	-0.06	-0.05
2.0			-2.25	-0.95	-0.36	-0.18	0.01	0.01	0.00
2.5			-2.45	-1.47	-0.68	-0.16	-0.12	-0.04	-0.01
3.0				-1.46	-0.97	-0.49	-0.01	-0.01	-0.01
3.5				-1.22	-0.82	-0.58	-0.30	0.17	0.14
4.0					-0.57	-0.41	-0.31	-0.18	0.28
4.5					-0.32	-0.23	-0.17	-0.14	-0.11
5.0						0.14	0.11	0.08	0.07
5.5						0.50	0.38	0.29	0.23
6.0							0.62	0.48	0.38
6.5							0.89	0.69	0.55
7.0								0.93	0.74
7.5								1.20	0.96

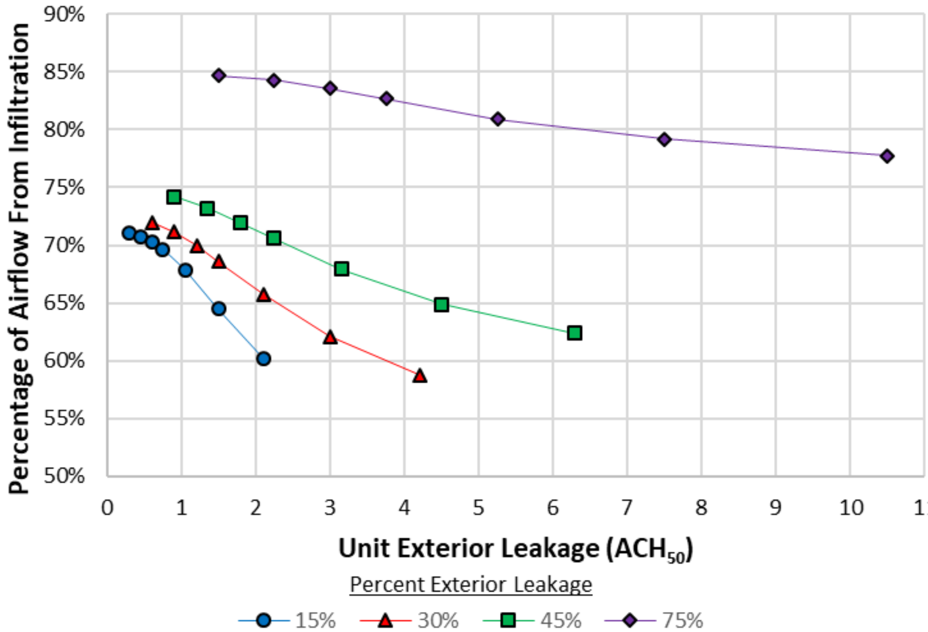


Figure 142. Percentage of Unit Airflow from Infiltration

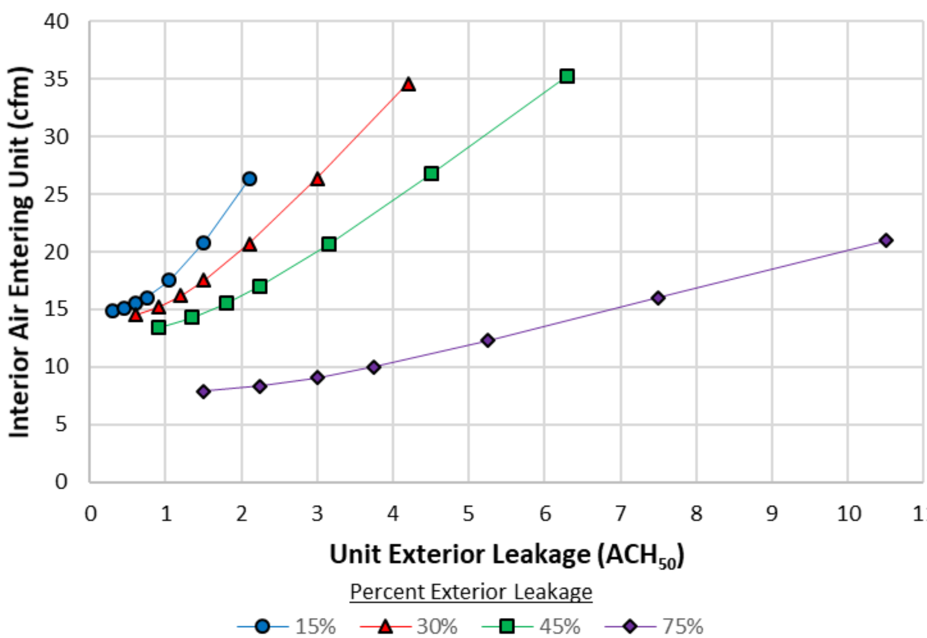


Figure 143 Rate of Air Entering Unit from Other Interior Zones

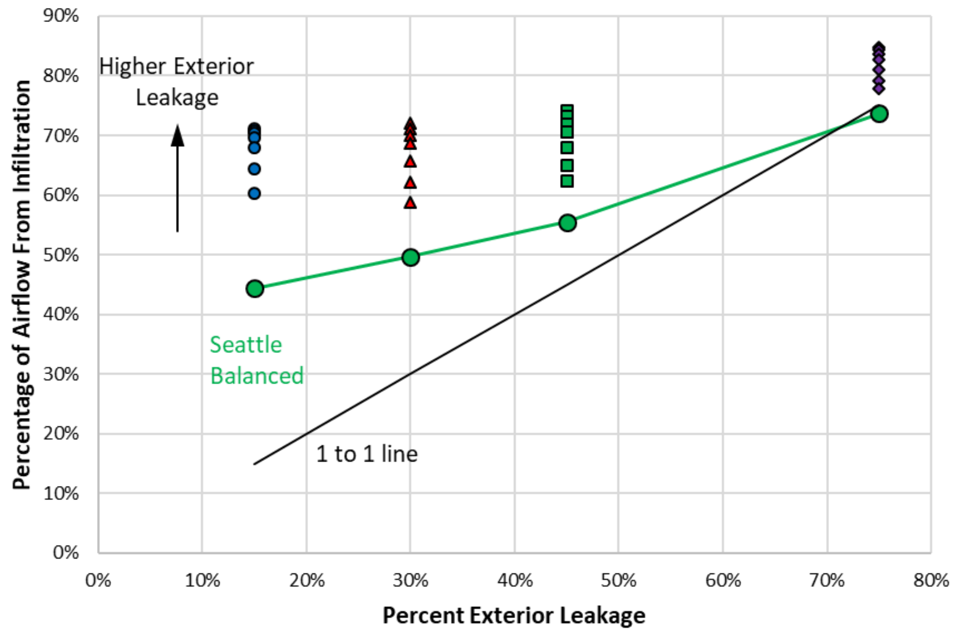


Figure 144. Percentage of Unit Airflow from Infiltration vs. Percent Exterior Leakage

The chart of the EUI for the annual space heating gas use for the residential units is shown in Figure 145. In general, the trends for the EUI follow the trends for the air infiltration. The key findings from the EUI results are:

- There is little change in the EUI for exterior leakages from 0.3 to 1.3 ACH_{50}. For exterior leakages in this range the EUI is 4.29 to 4.34 kBtu/ft^2. For an exterior leakage of 3.0 ACH_{50}, which is required for climate zones 3–7, the EUI varies from 4.93 to 5.52 kBtu/ft^2. The EUI doubles from the minimum value of 4.29 kBtu/ft^2 for an exterior leakage of about 9.0 ACH_{50}.
- Over the modelled exterior air leakage scenarios from 0.5 to 4.5 ACH_{50}, there are only small differences in the infiltration rate for the three percent exterior air leakages of 15%, 30%, and 45%.
- For exterior leakage rates greater than 1.3 ACH_{50}, the relationship between infiltration and exterior leakage is highly linear. The change in EUI with exterior leakage is somewhat greater for decreasing exterior leakage.
- There is less than 25 kWh/yr of corridor electric space heating for even the leakiest scenarios.
- The model predicts space cooling electric use of 5,500 to 8,000 kWh with increasing use for lower exterior envelope. As noted previously, greater exterior leakage results in more “free cooling” from outside air entering the building when the outside air temperature is below the inside air temperature. In reality, many people would open their windows during those periods and there would be no benefit from increased infiltration. That effect was not included in the modelling.

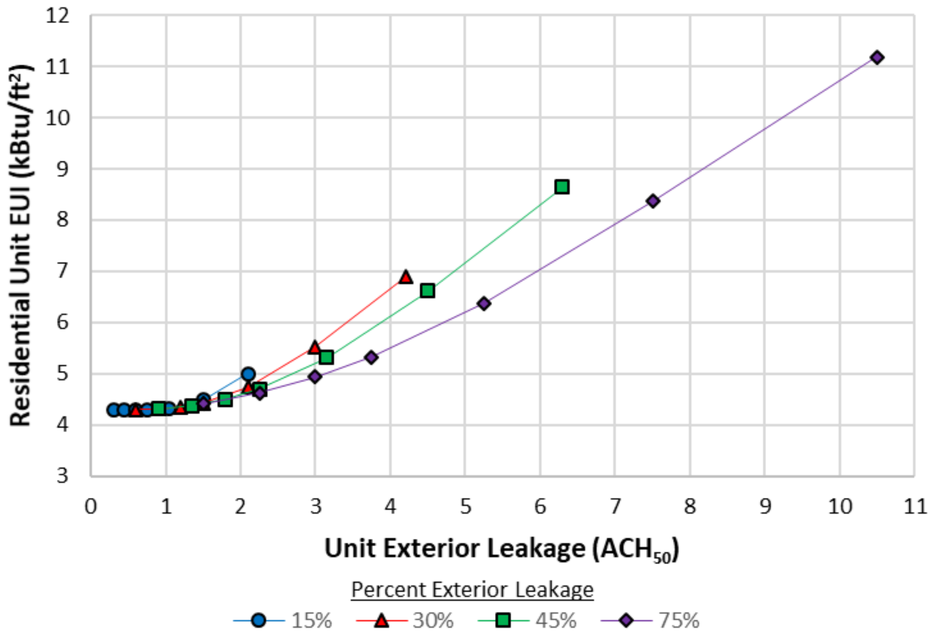


Figure 145. EUI for Residential Units (kBtu/ft2)

The differences in EUI from the energy code required value to the modelled scenarios are shown in Figure 146 and Table 75. For Seattle, it was assumed that the code requirement of 5.0 ACH_{50} was applied to the total leakage as measured by a compartmentalization test and that the percent exterior leakage was 30%. This results in a residential unit space heating EUI of 4.42 kBtu/ft^2. An increase in the total leakage to 7.0 ACH_{50} would result in a 7% increase in the EUI to 4.73 kBtu/ft^2.

If it is assumed that the code required leakage of 5.0 ACH_{50} is applied to the exterior leakage, that level of exterior leakage with a percent exterior leakage of 30% produces an EUI of 7.52 kBtu/ft^2. This is a 76% increase in the EUI compared to that for a 5.0 ACH_{50} total leakage. It shows that the decision to apply the leakage requirement to the exterior leakage or to the total leakage has a very significant impact on the resulting space heating energy use for the building. However, the impact is not as great as for buildings with balanced ventilation.

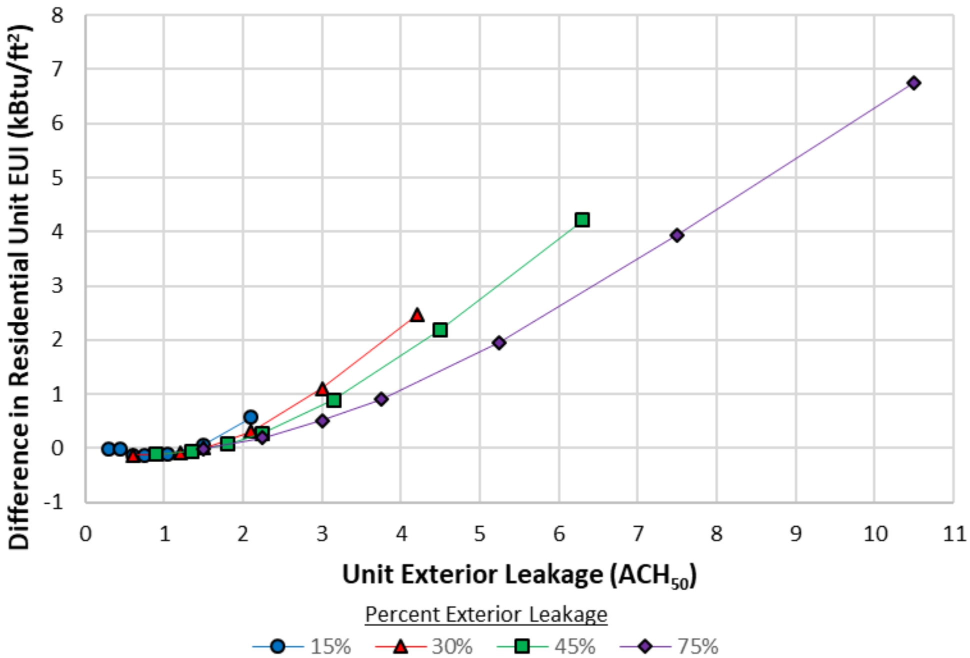


Figure 146. Difference in EUI From Baseline for Residential Units (kBtu/ft²)

Table 75. Difference in EUI From Baseline for Residential Units

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25	-0.13								
0.50	-0.14	-0.14	-0.14	-0.14					
0.75	-0.13	-0.13	-0.13	-0.13	-0.14	-0.14			
1.0	-0.11	-0.11	-0.11	-0.11	-0.11	-0.11	-0.11	-0.11	-0.11
1.5	-0.01	-0.01	-0.01	0.00	0.02	0.04	0.05	0.06	0.07
2.0		0.13	0.15	0.19	0.24	0.28	0.33	0.38	0.41
2.5		0.26	0.36	0.42	0.49	0.58	0.64	0.70	0.74
3.0			0.51	0.65	0.74	0.83	0.94	1.03	1.10
3.5			0.58	0.85	1.02	1.15	1.27	1.41	1.52
4.0				0.97	1.25	1.45	1.60	1.73	1.88
4.5				1.04	1.43	1.70	1.90	2.06	2.19
5.0					1.51	1.90	2.19	2.41	2.59
5.5					1.54	2.04	2.41	2.70	2.94
6.0						2.16	2.62	2.97	3.25
6.5						2.23	2.77	3.19	3.52
7.0							2.87	3.36	3.75
7.5							2.92	3.48	3.94

5.3.2.3 Intermittent Exhaust Ventilation

As noted previously, it was expected that the results for intermittent exhaust ventilation would be similar to those for balanced ventilation. For 23 of the 24 hours each day, the building airflow rates through envelope leaks are identical for the balanced and intermittent exhaust ventilation scenarios. The one hour of exhaust ventilation is expected to produce results that are similar to those for balanced ventilation with a slight tendency to include some trends seen for continuous exhaust ventilation. Because of the expected similarity of the results, the discussion for this section primarily highlights differences between the results for intermittent exhaust and balanced ventilation.

The chart of the annual average air infiltration rate for all units in the building is shown in Figure 147, and Table 76 shows the interpolated values. The key differences in annual infiltration rate results for intermittent exhaust and balanced ventilation are:

- The annual infiltration rates are slightly higher and within 1.5 CFM or 5% of those for balanced ventilation. Due to the intermittent exhaust flow, the infiltration levels off for lower levels of exterior leakage.
- The average "divide by" values are 16.4, 20.6, 24.4, and 31.4 CFM_{50}/CFM for percent exterior leakage of 15%, 30%, 45%, and 75%, respectively. Those are about 20% lower than the values for balanced ventilation. A chart of the "divide by" value is shown in Figure 232 of Appendix G.
- The impact of interior leakage is approximately the same for balanced and intermittent exhaust ventilation.
- Table 123 of Appendix G shows the monthly variation of unit average infiltration rates for each of the 28 leakage scenarios. As expected, infiltration is greatest during colder weather when the stack effect is the dominant driving force. For percent exterior leakages of 15%–45%, the highest monthly average infiltration is about 34% greater than the minimum monthly average in the summer. The seasonal variation is somewhat greater for 75% exterior leakage, for which the heating season maximum infiltration is about 43% greater than the lowest monthly.

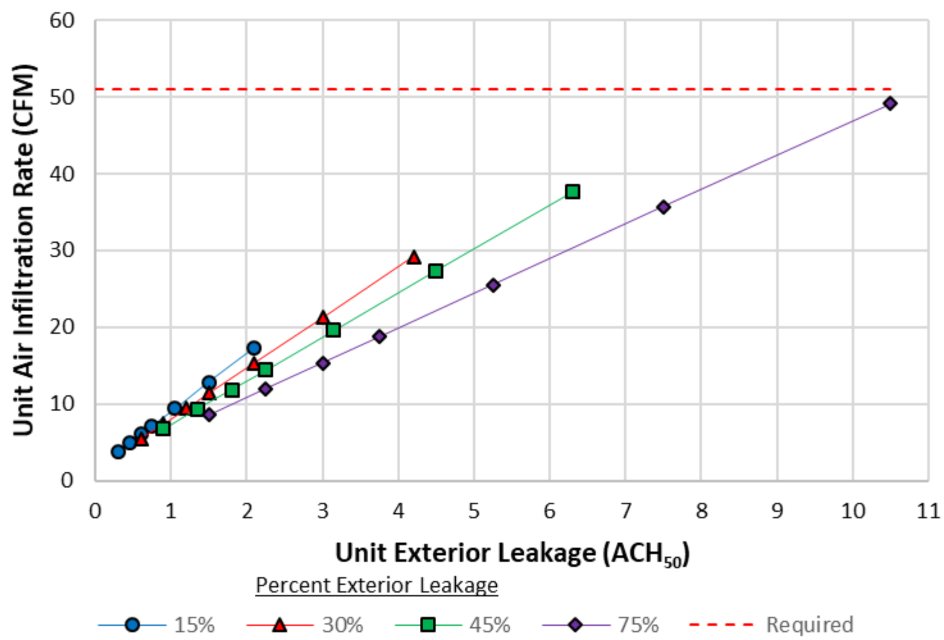


Figure 147. Annual Average Unit Infiltration: Seattle Intermittent Exhaust Ventilation

Table 76. Unit Annual Average Infiltration (CFM): Seattle Intermittent Exhaust Ventilation

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25	3.4								
0.50	5.0	5.2	5.4	5.4					
0.75	6.2	6.7	7.0	7.2	7.3	7.4			
1.0	7.1	7.9	8.4	8.7	8.9	9.1	9.2	9.3	9.4
1.5	8.6	9.9	10.8	11.4	11.9	12.2	12.5	12.7	12.8
2.0		11.4	12.6	13.5	14.3	14.8	15.3	15.7	16.0
2.5		12.3	14.2	15.4	16.3	17.2	17.8	18.3	18.8
3.0			15.3	17.0	18.2	19.1	20.0	20.7	21.2
3.5			15.9	18.3	19.8	20.9	21.8	22.8	23.6
4.0				19.1	21.1	22.6	23.7	24.6	25.6
4.5				19.5	22.1	24.0	25.4	26.5	27.3
5.0					22.7	25.1	26.8	28.1	29.2
5.5					23.0	25.9	28.0	29.6	30.9
6.0						26.4	28.9	30.8	32.4
6.5						26.6	29.5	31.9	33.7
7.0							30.0	32.6	34.8
7.5							30.1	33.2	35.7

Table 77 displays the reduction in annual average infiltration for a 1.0 ACH_{50} reduction in exterior leakage, and Table 78 shows the same for a 1.0 ACH_{50} reduction in interior leakage. The infiltration reductions for intermittent exhaust ventilation are typically within 5% of those for balanced ventilation.

Table 77. Reduction in Annual Infiltration (CFM) for Reduction of 1 ACH50 in Exterior Leakage

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25									
0.50									
0.75									
1.0									
1.5		4.9	5.5	6.0	6.4				
2.0		4.3	4.7	5.1	5.6	5.9	6.2	6.4	6.6
2.5		3.7	4.4	4.6	5.0	5.3	5.6	5.9	6.1
3.0			3.9	4.4	4.6	4.8	5.1	5.4	5.6
3.5			3.6	4.0	4.4	4.6	4.7	5.0	5.3
4.0				3.7	4.1	4.4	4.6	4.6	4.9
4.5				3.6	3.8	4.2	4.4	4.6	4.5
5.0					3.7	3.9	4.2	4.5	4.6
5.5					3.5	3.7	4.0	4.2	4.5
6.0						3.6	3.8	4.0	4.3
6.5						3.5	3.7	3.9	4.1
7.0							3.6	3.8	3.9
7.5							3.5	3.7	3.8

Table 78. Reduction in Annual Infiltration (CFM) for Reduction of 1 ACH50 in Interior Leakage

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25									
0.50		0.26	0.13	0.08					
0.75		0.54	0.30	0.18	0.12	0.09			
1.0		0.79	0.50	0.32	0.21	0.15	0.11	0.09	0.07
1.5		1.32	0.88	0.61	0.48	0.35	0.26	0.20	0.16
2.0			1.21	0.91	0.73	0.55	0.46	0.36	0.29
2.5			1.93	1.16	0.93	0.83	0.62	0.53	0.45
3.0				1.69	1.13	0.92	0.90	0.70	0.56
3.5				2.33	1.56	1.11	0.91	0.96	0.77
4.0					2.05	1.47	1.10	0.89	1.00
4.5					2.61	1.87	1.40	1.09	0.87
5.0						2.32	1.74	1.35	1.08
5.5						2.81	2.11	1.64	1.31
6.0							2.52	1.96	1.57
6.5							2.96	2.30	1.84
7.0								2.68	2.14
7.5								3.08	2.46

Figure 148 shows the percentage of airflow into units that is due to infiltration. For higher levels of exterior leakage, the values are similar to those for balanced ventilation, but they are somewhat higher for low exterior leakage. This shows the influence of the 4% of the time that there is exhaust ventilation. Figure 149 compares the percentage of air infiltration with percent exterior leakage for the two ventilation modes. Intermittent exhaust produces slightly higher percentage infiltration.

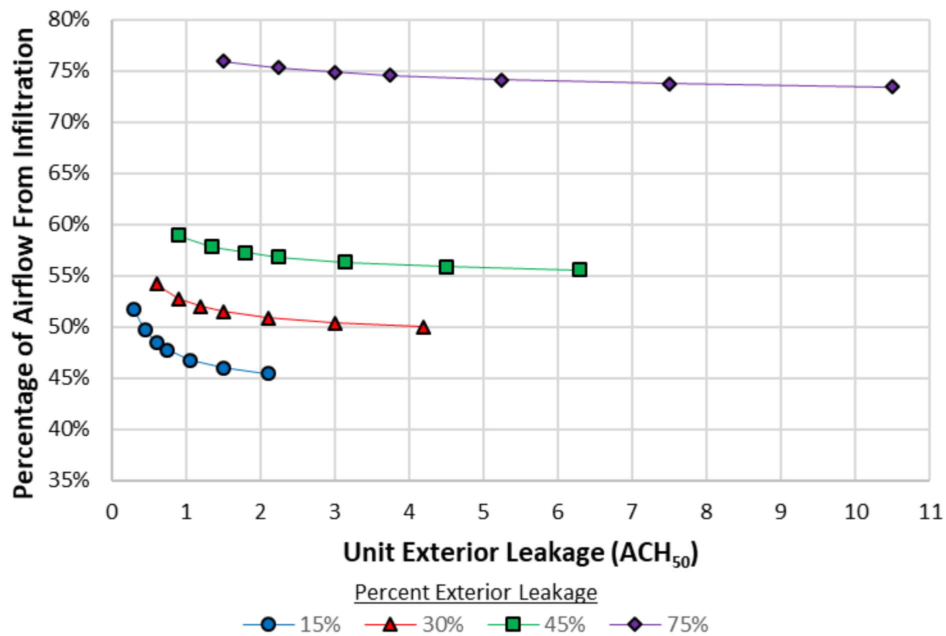


Figure 148. Percentage of Unit Airflow from Infiltration

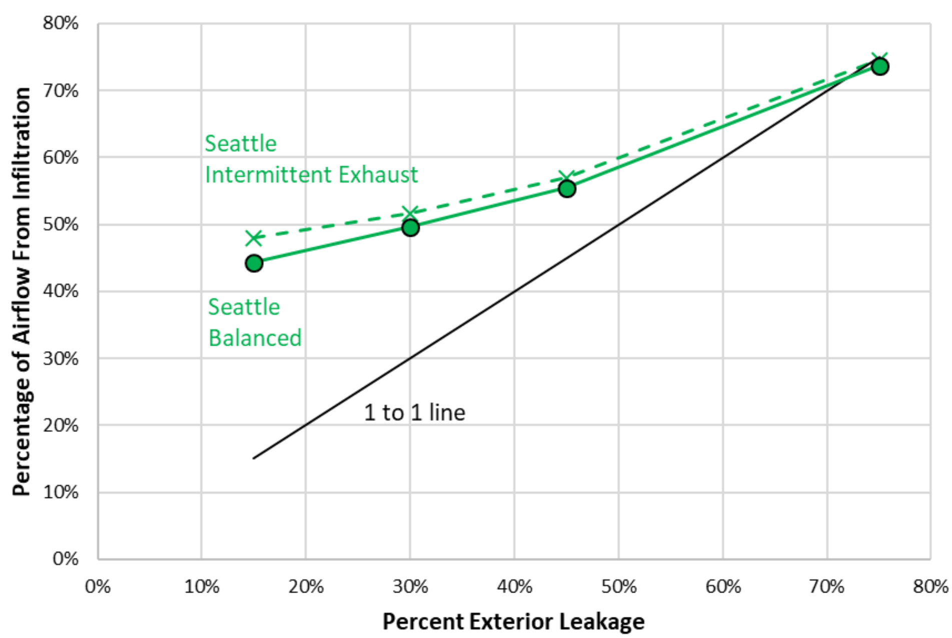


Figure 149. Percentage of Unit Airflow from Infiltration vs. Percent Exterior Leakage

The chart of the EUI for the annual space heating gas use for the residential units is shown in Figure 150. The key findings from the EUI results are:

- For exterior leakage less than 1.0 ACH_{50} the EUI ranges from 0.25 to 0.48 kBtu/ft^2. For an exterior leakage of 3.0 ACH_{50} that is required for climate zones 3–7, the EUI varies from 1.30 to 2.07 kBtu/ft^2. For an exterior leakage of 5.0 ACH_{50}, the EUI varies from 2.2 to 3.4 kBtu/ft^2.
- The impact of interior leakage is significant. For the same exterior leakage, an increase in the percent interior leakage from 25% to 70% (e.g., 75% to 30% decrease in exterior leakage) increases the EUI by about 60%.
- There is less than 25 kWh/yr of corridor electric space heating for even the leakiest scenarios.
- The model predicts space cooling electric use of 8,000 to 15,500 kWh with increasing use for lower exterior envelope. As noted previously, greater exterior leakage results in more "free cooling" from outside air entering the building when the outside air temperature is below the inside air temperature. In reality, many people would open their windows during those periods and there would be no benefit from increased infiltration. That effect was not included in the modelling.

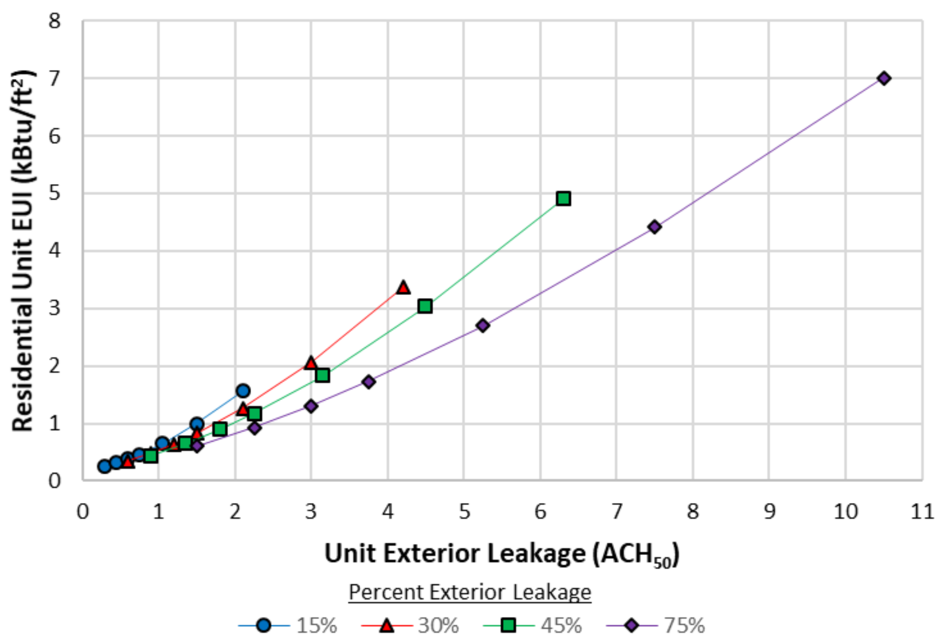


Figure 150. EUI for Residential Units (kBtu/ft^2)

The differences in EUI from the energy-code-required value to the modelled scenarios are shown in Figure 151 and Table 79. An increase in the total leakage from a baseline of 5.0 ACH_{50} to 7.0 ACH_{50} would result in a 43% increase (0.52 kBtu/ft^2) in the EUI from 0.83 to 1.26 kBtu/ft^2. If it is assumed that the code-required leakage of 5.0 ACH_{50} is applied to the exterior leakage, that level of exterior leakage with a percent exterior leakage of 30% produces an EUI of 3.86 kBtu/ft^2. This is over a 300% increase in the EUI compared to that for a 5.0 ACH_{50} total leakage. It shows that the decision to apply the leakage requirement to the exterior leakage or to the total leakage has a very significant impact on the resulting space heating energy use for the building.

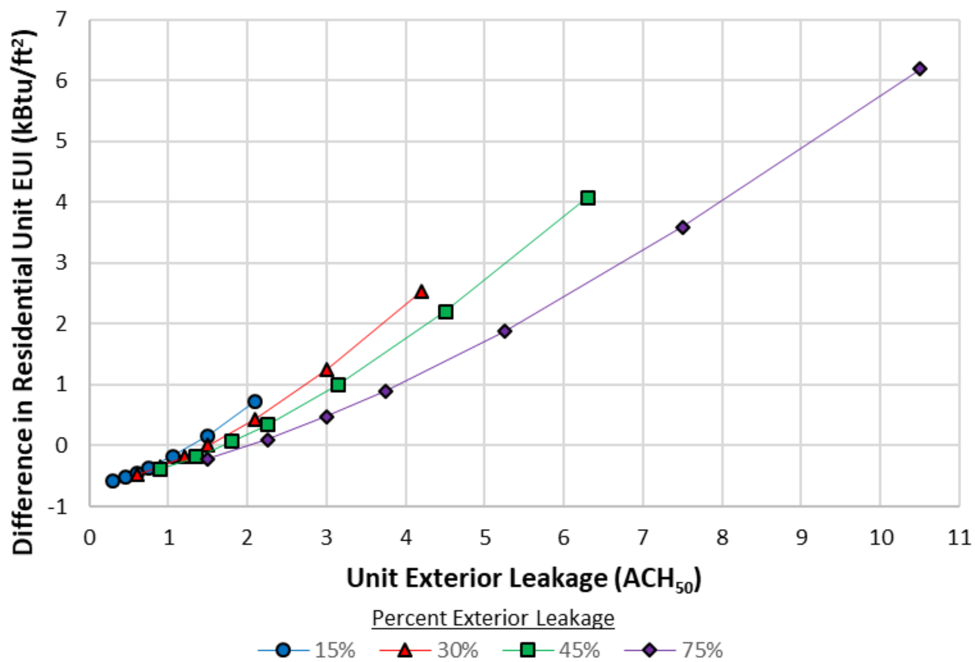


Figure 151. Difference in EUI From Baseline for Residential Units (kBtu/ft²)

Table 79. Difference in EUI From Baseline for Residential Units

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25	-0.58								
0.50	-0.51	-0.50	-0.49	-0.48					
0.75	-0.43	-0.40	-0.38	-0.36	-0.36	-0.35			
1.0	-0.36	-0.30	-0.26	-0.24	-0.22	-0.20	-0.19	-0.19	-0.18
1.5	-0.22	-0.12	-0.05	0.00	0.06	0.10	0.13	0.15	0.17
2.0		0.05	0.16	0.25	0.32	0.39	0.45	0.51	0.55
2.5		0.14	0.35	0.48	0.58	0.69	0.77	0.84	0.90
3.0			0.48	0.68	0.82	0.94	1.07	1.16	1.24
3.5			0.53	0.85	1.07	1.22	1.35	1.50	1.63
4.0				0.95	1.26	1.48	1.64	1.78	1.95
4.5				0.98	1.39	1.68	1.90	2.07	2.20
5.0					1.43	1.83	2.13	2.37	2.56
5.5					1.41	1.92	2.31	2.61	2.85
6.0						1.97	2.45	2.81	3.11
6.5						1.96	2.52	2.96	3.31
7.0							2.54	3.06	3.48
7.5							2.50	3.11	3.59

6. CONCLUSION

The data for this set of 26 sites, spread across 6 states, and including both common-entry and exterior entry ("garden-style") low-rise multifamily buildings, shows that new low-rise multifamily buildings are meeting state-mandated air tightness levels (where specified), at least for exterior leakage (which has direct bearing on extra energy needed to condition outside air that leaks into conditioned space). These buildings were both common entry (where all living units have main doors which open onto shared interior corridors) and garden style (where all living units have main door which open to outside); 80% of test buildings were common entry.

On a whole building basis, results could be tabulated for 24 buildings (as one garden-style building could not be completely tested due to time constraints and another's configuration prevented calculation of whole building results) and all but one building came in below 4.0 ACH_{50}, thereby meeting most states' air tightness limit. (Note the metric here, ACH_{50}, indicates the amount of exterior air leaking through the building shell at a test pressure of 50 Pascals, normalized by the building's volume. This is the most commonly used metric, although another, which normalizes leakage by overall building area (all sides) is expressed as CFM_{50}/ft^2 and is also used in this report (and in similar research.)) Overall, the leakiest buildings were in Washington and Oregon, which had the least stringent exterior leakage limits; Oregon does not require air leakage testing for this type of construction.

When individual living units are examined, the results are still promising, with about 95% of the 274 living units tested meeting a volume-normalized exterior leakage rate of 4.0 ACH_{50} (which is the standard in most states in the study) and 88% coming in at 3.0 ACH_{50} or tighter. These findings are encouraging, but their simple recitation does not indicate there are several issues that still need to be addressed (mentioned below).

Readers are cautioned to note that most of the states involved in the testing have relatively aggressive energy codes, and that the building recruited for the work were often found via performance building programs such as Energy Star and Earth Advantage. This means the buildings would be likely to be tighter than the average new multifamily building in the United States. With this said, some of the conclusions and analysis methods developed in this research could be applied to most multifamily buildings.

These are additional notable findings from the study:

- Buildings with vented attics displayed higher than average exterior leakage, especially from the top living units in the stack. Exterior wall sealing details made no significant difference in exterior leakage.
- Leakage to and from common areas is typically much larger per ft^2 of leakage surface than the living unit leakage to/from outside. More attention should be paid to the construction detailing in these zones in common entry buildings.
- Various methods were evaluated to estimate exterior leakage from total leakage. One method which has been proposed is to use the ratio of a living unit's exterior surface area to the unit's total surface area as the multiplier to get from total leakage to exterior leakage. This method proved to be somewhat useful, but the unit's location in the building (level above grade) had significant bearing on the accuracy of this approach, and the results presented in this report have to be viewed as limited to this set of buildings pending further research.

- In general, living units with a higher amount of interior leakage produced larger adjacent living unit pressure changes during a compartmentalization (single living unit) test. In addition, the larger interior leakage increases the overall total leakage of the unit. That causes a higher calculated exterior leakage which, in turn, causes a positive percentage difference between the surface-area-ratio method calculated exterior leakage and measured leakage. These are notable findings because there are promising methods (discussed in the report) that might be useful in estimating living unit leakage rates from compartmentalization tests.
- Combined air leakage and energy modeling showed that energy savings from reducing exterior air leakage range from modest to considerable (about 5-15% of total living unit heating energy) depending on the starting leakage and amount of improvement. The methodology used for these estimates can be applied to existing (older) low-rise multifamily buildings, as well.
- The energy modeling also showed that a balanced ventilation strategy provides incremental benefits for energy savings if the exterior envelope is tightened below code-required levels, as compared with an exhaust-only system.

Recommendations:

- A major challenge in current codes that address multifamily buildings is the ambiguity on whether total or exterior leakage is to be measured. At this point, the authors recommend whole building tests be performed when possible (vs just compartmentalization tests, which measure combined exterior and interior air leakage), since this allows the most interpretive value.
- This recommendation, though, does imply a much more demanding testing regime, especially for garden-style buildings, since they do not have common corridors which facilitate communication between living units (when living unit doors are opened to corridors during testing).
- The authors recommend that a survey of building detailing be taken at time of testing (including an interview of the construction manager and/or building designer and trade leads). This will assist in interpreting test results, and, if done more proactively, this could eventually lead to reductions in both exterior and interior leakage.
- For outside entry (‘garden style’) buildings, testing is more challenging due to the lack of common areas. If time and/or equipment is limited for these tests, compartmentalization tests might be useful as long as pressures in adjoining units are measured. If adjacent units are depressurized to 5 Pa or more when the test unit is depressurized to – 50 Pa, adjacent unit’s windows can be opened to improve test accuracy. If this is not practical, a multiplier (a simple quadratic relationship was demonstrated for these buildings) can be used to adjust results.

The testing methods and analysis techniques for this type of building are still under development and more discussion by practitioners and analysts will be required to gain more confidence in results and also in ways to speed up testing without sacrificing accuracy.

DEFINITIONS AND ACRONYMS

ACH_{50}	Air changes per hour for a pressure difference of 50 Pa
AFUE	annual fuel utilization efficiency
Btu	British thermal unit
Btu/ft^2-hr-F	British thermal unit per square foot per hour per degree Fahrenheit
Btu/hr	British thermal unit per hour
CEE	Center for Energy and Environment
CFM	cubic feet per minute
CFM_{50}	Envelope leakage rate, cubic feet per minute for a pressure difference of 50 Pa
CFM_{50}/ft^2	CFM50 divided by square feet of envelope surface area
COP	coefficient of performance
DOE	U.S. Department of Energy
EUI	Energy Use Intensity, annual energy use divided by the floor area of the space (kBtu/ft2/yr)

Exterior Leakage Multiplier – Multiplier applied to the surface-area-ratio method for computing the exterior leakage of a unit from the total leakage

F-factor	a measure of insulation around the slab perimeter of a building
F-value	equivalent to F-factor
HVAC	Heating, ventilation, and air conditioning
IECC	International Energy Conservation Code®
Infiltration	flow of air from outside to the inside of the building through envelope leaks
kBtu	thousand British thermal units
kWh	kilowatts
kWh	kilowatt hour
Pa	Pascals
PHIUS	Passive House Institute US
PNNL	Pacific Northwest National laboratory
QC	Quality control

Surface-Area-Normalized Exterior Leakage – Leakage across the exterior surface of the envelope divided by the surface area of the exterior envelope, typically units of CFM_{50}/ft^2

Surface-Area-Normalized Total Leakage – Leakage across the entire or total surface of the envelope divided by the entire surface area of the envelope, typically units of CFM_{50}/ft^2

Surface-Area-Ratio Method – Exterior Leakage calculated from total leakage multiplied by the ratio of the exterior envelope surface area and total envelope surface area, typically units of CFM_{50}

TEC	The Energy Conservatory
Therm	unit of heat equivalent to 100,000 Btu
U-factor	equivalent to U-value
U-value	a measure of thermal conductivity

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APPENDIX A: RESIDENTIAL CODE ENVELOPE TESTING REQUIREMENT

IECC Requirement – 2012 to 2018

<u>2012</u>

R402.4.1.2 Testing.
The building or dwelling unit shall be tested and verified as having an air leakage rate of not exceeding 5 air changes per hour in Climate Zones 1 and 2, and 3 air changes per hour in Climate Zones 3 through 8. Testing shall be conducted with a blower door at a pressure of 0.2 inches w.g. (50 Pascals). Where required by the code official, testing shall be conducted by an approved third party. A written report of the results of the test shall be signed by the party conducting the test and provided to the code official. Testing shall be performed at any time after creation of all penetrations of the building thermal envelope.

During testing:
1. Exterior windows and doors, fireplace and stove doors shall be closed, but not sealed, beyond the intended weatherstripping or other infiltration control measures;
2. Dampers including exhaust, intake, makeup air, backdraft and flue dampers shall be closed, but not sealed beyond intended infiltration control measures;
3. Interior doors, if installed at the time of the test, shall be open;
4. Exterior doors for continuous ventilation systems and heat recovery ventilators shall be closed and sealed;
5. Heating and cooling systems, if installed at the time of the test, shall be turned off; and
6. Supply and return registers, if installed at the time of the test, shall be fully open.

<u>2015</u>

Same as 2012 except the second sentence specifies that the testing is to be performed using either ASTM E 779 or ASTM E 1827:

Testing shall be conducted with a blower door in accordance with ASTM E 779 or ASTM E 1827 and reported at a pressure of 0.2 inches w.g. (50 Pascals).

<u>2018</u>

Same as 2012 and 2015 except RESNET/ICC 380 added as an optional standard for conducting the test:

Testing shall be conducted with a blower door in accordance with RESNET/ICC 380, ASTM E779 or ASTM E1827 and reported at a pressure of 0.2 inches w.g. (50 Pascals).

State Energy Code Testing Requirements

<u>Illinois</u>

The 2015 edition of the IECC went into effect on 1/1/2016. The code was amended to specify that the air leakage rate shall not exceed 5 ACH_{50}. Amendments are shown.

R402.4.1.2 Testing.
The building or dwelling unit shall be tested and verified as having an air leakage rate of not exceeding five air changes per hour <u>(ACH)</u> in Climate Zones ~~1 and 2, and three air changes per hour in Climate~~

~~Zones 3 through 8.~~ 4 and 5. The building or dwelling unit shall be provided with a whole – house mechanical ventilation system as designed in accordance with Section R403.6. Testing shall be conducted in accordance with ASTM E779 or ASTM E1827 and reported at a pressure of 0.2 inches w.g. (50 Pascals). Where required by the code official, testing shall be conducted by an approved third party. A written report of the results of the test, indicating the ACH, shall be signed by the party conducting the test and provided to the code official. Testing shall be performed at any time after ~~creation of~~ all penetrations of the building thermal envelope have been sealed.
Exceptions:

1. For additions, alterations, renovations or repairs to existing buildings, building envelope tightness and insulation installation shall be considered acceptable when the items in Table R402.4.1.1, applicable to the method of construction, are field verified. Where required by the code official, an approved third party independent from the installer, shall inspect both air barrier and insulation installation criteria.
2. For heated attached private garages and heated detached private garages accessory to one- and two-family dwellings and townhouses not more than three stories above grade plane in height, building envelope tightness and insulation installation shall be considered acceptable when the items in Table R402.4.1.1, applicable to the method of construction, are field verified. Where required by the code official, an approved third party independent from the installer, shall inspect both air barrier and insulation installation criteria. Heated attached private garage space and heated detached private garage space shall be thermally isolated from all other habitable, conditioned spaces.

No amendments to the building setup specified in the *During testing*: section.

The 2018 edition of the IECC went into effect on 7/1/19. The code was amended to specify that the air leakage rate shall not exceed 4 ACH_{50}. Amendments are shown.

R402.4.1.2 Testing.
The building or dwelling unit shall be tested and verified as having an air leakage rate of not exceeding ~~five~~ four air changes per hour (ACH) in Climate Zones ~~1 and 2, and three air changes per hour in Climate Zones 3 through 8.~~ 4 and 5. The building or dwelling unit shall be provided with a whole – house mechanical ventilation system as designed in accordance with Section R403.6. Testing shall be conducted in accordance with RESNET/ICC 380, ASTM E779 or ASTM E1827 and reported at a pressure of 0.2 inches w.g. (50 Pascals). Where required by the code official, testing shall be conducted by an approved third party. A written report of the results of the test, indicating the ACH, shall be signed by the party conducting the test and provided to the code official. Testing shall be performed at any time after ~~creation of~~ all penetrations of the building thermal envelope have been sealed.

Exceptions:

1. For additions, alterations, renovations or repairs to existing buildings, building envelope tightness and insulation installation shall be considered acceptable when the items in Table R402.4.1.1, applicable to the method of construction, are field verified. Where required by the code official, an approved third party independent from the installer, shall inspect both air barrier and insulation installation criteria.
2. For heated attached private garages and heated detached private garages accessory to one- and two-family dwellings and townhouses not more than three stories above grade plane in height,

building envelope tightness and insulation installation shall be considered acceptable when the items in Table R402.4.1.1, applicable to the method of construction, are field verified. Where required by the code official, an approved third party independent from the installer, shall inspect both air barrier and insulation installation criteria. Heated attached private garage space and heated detached private garage space shall be thermally isolated from all other habitable, conditioned spaces.
3. For low-rise multifamily buildings, dwelling units shall be tested and verified as having a leakage rate of not exceeding 0.25 cubic feet per minute (CFM) per square foot of enclosure area (all six sides of the dwelling unit) in Climate Zones 1 through 8. Testing shall be conducted with an unguarded blower door at a pressure of 0.2 inches w.g. (50 Pascal). If guarded blower door testing (a test with one or more adjacent units pressurized which should eliminate any leakage between units) is being performed, this exception is not allowed and the standard testing requirements of Section 402.4.1.2 apply. Where required by the code official, testing shall be conducted by an approved third party. For buildings with more than seven units, a sampling protocol is allowed by an approved third party. The sampling protocol requires the first seven units to be tested without any failures. Upon successful testing of those initial seven units, remaining units can be sampled at a rate of 1 in 7. If any sampled unit fails compliance with the maximum allowable air leakage rate, two additional units in the same sample set must be tested. If additional failures occur, all units in the sample set must be tested. In addition, all units in the next sample set must be tested for compliance before sampling of further units can be continued.

No amendments to the building setup specified in the *During testing*: section.

Iowa

The 2012 edition of the IECC went into effect on 4/1/2014. The code was amended to specify that the air leakage rate shall not exceed 4 ACH_{50}.

Michigan

The 2015 edition of the IECC went into effect on 2/8/2016. The code was amended to specify that the air leakage rate shall not exceed 4 ACH_{50}. Amendments are shown.

R402.4.1.2. Testing (prescriptive).
The building or dwelling unit shall be tested and verified as having an air leakage rate of not exceeding 4 air changes per hour ~~5 air changes per hour in Climate Zones 1 and 2, and 3 air changes per hour in Climate Zones 3 through 8~~. Testing shall be conducted with a blower door at a pressure of 0.2 inches (5.08 mm) w.g. (50 pascals). Where required by the code official, testing shall be conducted by a certified independent third party. Certification programs shall be approved by the state construction code commission. A written report of the results of the test shall be signed by the party conducting the test and provided to the code official. Testing shall be performed at any time after creation of all penetrations of the building thermal envelope.

No amendments to the building setup specified in the *During testing*: section.

Minnesota

The 2012 edition of the IECC went into effect on 6/2/2015. No amendments. For Minnesota climate zones the air leakage rate shall not exceed 3 ACH_{50}.

Oregon

Aire leakage testing is not required for low-rise multifamily buildings.

Washington

The 2015 edition of the IECC went into effect on 7/1/2016. The code was amended to specify that the air leakage rate shall not exceed 5 ACH_{50}. Amendments are shown.

R402.4.1.2 Testing.
The building or dwelling unit shall be tested and verified as having an air leakage rate of exceeding 5 air changes per hour ~~in Climate Zones 1 and 2, and 3 air changes per hour in Climate Zones 3 through 8~~. Testing shall be conducted with a blower door at a pressure of 0.2 inches w.g. (50 Pascals). Where required by the code official, testing shall be conducted by an approved third party. A written report of the results of the test shall be signed by the party conducting the test and provided to the code official. Testing shall be performed at any time after creation of all penetrations of the building thermal envelope. <u>Once visual inspection has confirmed sealing (see Table R402.4.1.1), operable windows and doors manufactured by small business shall be permitted to be sealed off at the frame prior to the test.</u>

Item (3) of the *During testing*: section was amended.
3. Interior doors, if installed at the time of the test, shall be open<u>, access hatches to conditioned crawl spaces and conditioned attics shall be open</u>;

The energy code is currently going through the code change process. Changes would likely go into effect in July 2021. The following text has been proposed:

R402.4.1.2 Testing.
The building or dwelling unit shall be tested and verified as having an air leakage rate of not exceeding 5 air changes per hour ~~in Climate Zones 1 and 2, and 3 air changes per hour in Climate Zones 3 through 8~~. Testing shall be conducted with a blower door at a pressure of 0.2 inches w.g. (50 Pascals). For this test only, the volume of the home shall be the conditioned floor area ft2 (m2) multiplied by 8.5 ft. (2.6m). Where required by the code official, testing shall be conducted by an approved third party. A written report of the results of the test shall be signed by the party conducting the test and provided to the code official. Testing shall be performed at any time after creation of all penetrations of the building thermal envelope. <u>Once visual inspection has confirmed sealing (see Table R402.4.1.1), operable windows and doors manufactured by small business shall be permitted to be sealed off at the frame prior to the test.</u>

<u>Exception.</u>
<u>For dwelling units that are accessed directly from the outdoors, other than detached one-family dwellings and townhouses, an air leakage rate not exceeding 0.4 CFM per ft^2 of the dwelling unit enclosure area shall be an allowable alternative. Testing shall be conducted with a blower door at a pressure of 0.2 inches w.g. (50 Pascals) in accordance with RESNET/ICC 380, ASTM E779 or ASTM E1827.</u>

Doors and windows of adjacent dwelling units (including top and bottom units) shall be open to the outside during the test. This exception is not permitted for dwelling units that are accessed from corridors or other enclosed common areas.

Energy Programs

ENERGY STAR v3.1

The certification requires an envelope air leakage test performed by a Rater using a RESNET-approved testing protocol. The Reference Design specifies that the infiltration rate shall be less than or equal to 4 ACH_{50} for climate zones 1 and 2 and 3 ACH_{50} or less for climate zones 3 – 7. For multifamily buildings that are using the Performance Path, the Reference Design leakage rate is the value used to determine the Home Energy Rating Service (HERS) Index Target. That is the highest numerical HERS Index value that each rated dwelling unit may achieve. Consequently, there can be tradeoffs with other energy features that allow the envelope leakage to be higher or lower than the Reference Design value.

Passive House Institute US

The PHIUS (PHIUS 2018) certification for multifamily buildings includes a requirement for the whole building (Section 3.2) and individual dwelling unit envelope leakage

3.2 Airtightness Criterion
Normative:
A whole-building test for air tightness must be performed. See Section 3.8 for further details. If testing at 75 Pa, report the flow coefficient and exponent from the blower door tests.
The certification requirement is as follows:
For buildings of five stories and above that are also of noncombustible* construction:

q50 <= 0.080 CFM_{50}/ft^2 or q75<= 0.110 CFM_{75}/ft^2 of gross envelope area

For all other buildings:

q50 <= 0.060 CFM50/ft2 or q75<= 0.080 CFM75/ft2 of gross envelope area

Gross envelope area is measured at the exterior of the thermal boundary, the same as for the energy model, and includes surfaces in contact with the ground.
* - Non-combustible in this sense is construction that is not subject to mold and rot. This would mean no wood-based framing members or sheet goods, and no wood-based or paper-based insulation.

G-2.3 Dwelling unit compartmentalization
Requirement: ≤0.30 CFM@50 Pa/sqft of dwelling unit shell.
Individual dwelling unit compartmentalization testing shall be performed to test the air barrier integrity of each dwelling unit. Testing shall be performed as an "unguarded" test as described under the section *Procedures for Multifamily Dwelling unit/Building Air Tightness Testing*, Test 1 from the RESNET Guidelines for Multifamily Energy Ratings document, and shall not be adjusted by any multifamily infiltration correction coefficient.

APPENDIX B: AIR LEAKAGE TEST PROTOCOL

Outdoor Pressure Reference

- If the weather forecast indicates a wind speed greater than 25 mph, reschedule the air leakage test. The weather forecast should be obtained using weather.com for the building location for the hours that the test is expected to occur.
- When setting up the test equipment, record the wind speed indicated by weather.com for the test building location. If the wind speed is greater than 10 mph, use at least 2 outdoor pressure reference measurements. The two locations shall be on different sides of the building. When possible, avoid placing the outdoor pressure tap on the windward side of the building. If the wind speed is greater than 10 mph and it is not feasible to use 2 or more outdoor pressure reference measurements, double the specified duration of the period of records.
- Do not use a manifold for multiple outdoor reference tubes. Only one tube per pressure channel.

Pre-Test Building Setup

Table B.1 below specifies the building setup conditions for the air leakage testing. The list was generated by first using the guidance provided by the six items in the *During testing*: subsection of IECC 2012/15/18 R402.4.1.2 Testing (see Appendix A) that describe the building setup for air leakage testing. When an issue was not addressed by these six items, Section 3.2 Procedure to Prepare the Building for Testing of ANSI/RESNET/ICC 380-2016 was used for guidance. Finally, when an issue was not addressed by either of those references (particularly issues regarding large building testing), the Operation Envelope column of Table B.1. *Building Preparation for Test Boundary of* ASTM E3158-18 *(Standard Test Method for Measuring the Air Leakage Rate of a Large or Multizone Building)* was used for guidance.

Table B.1. Building Setup for Air Leakage Tests

Item	Building Setup
Building Envelope	
Ext Windows & Doors	All closed
Interior Doors	All open
Trickle or Through-wall Vents	Closed
Attached Garage: Exterior Doors & Windows	All closed
Unvented Crawlspace (CS)	Open door/hatch between CSV[1]/CS. Close CS exterior doors/hatches.
Vented Crawlspace	Close door/hatch between CSV/CS. CS vents left as found.
Sealed Attic Insulated at Roof Deck	Open door/hatch between CSV/attic.
Unsealed Attics	Close door/hatch between CSV/attic.
Basement: house floor sealed/insulated	House/basement door closed
Basement, others	House/basement door open

Item	**Building Setup**
Heating/Cooling System Setup	
Appliance Operation	Off[2], **turn back on** at end of testing
Solid Fuel Appliances	Chimney dampers & combustion air inlets closed
Combustion Appliance Flue Gas Vent	As found
Distribution System Registers & Grilles	Fully open
Distribution System Balancing Dampers	As found
Dryer doors and AH Access Panels	Closed and latched
Ventilation Penetrations Between the Conditioned Space and Exterior or Unconditioned Space	
Fan Operation	Off[2]
Non-motorized Dampers	As found
Motorized Dampers	Closed & not sealed
Non-dampered Opening for Intermittently Operating Local Exhaust	~~Left open~~ Sealed
Non-dampered Opening for Intermittently Operating Whole Unit and Common Space Ventilation	~~Not sealed~~ Sealed
Non-dampered Opening for Continuously Operating Local Exhaust	Sealed[3]
Non-dampered Opening for Continuously Operating Whole Unit and Common Space Ventilation	Sealed[3]
All Other Non-dampered Intentional Openings[7]	Left open
Ductwork that serves areas inside & outside CSV	Sealed at registers and grilles
Active or Passive Smoke Control Reliefs and Intakes	As found
Intended Powered or Non-powered Openings for Vented Shafts/Stairwells	As found
Other	
Floor Drains & Plumbing	Sealed or traps filled
Waste or Linen Handling Systems	Rooftop chute vent open; chute intake doors closed
Clothes Dryer Outlets	As found; sealed if dryer not installed

Notes:

1. CSC = Conditioned Space Volume
2. Any appliance or fan that is capable of moving air across the building envelope shall be turned off.
3. Preferably at enclosure exterior.

Common Entry Building Tests

Whole Building

This test measures only the **exterior** leakage of the building envelope. It will be performed as a single point depressurization test with a pre and post baseline. It includes the exterior leakage for all of the units and any common space. Interior doors to units (e.g. hallway doors) and other areas adjacent to the building exterior[34] are opened so that the entire building acts as a single zone. One or more blower door fans are installed in one or more exterior doors to the common area (see Figure B.1). The flow rates of the blower door fans are added together to measure the whole building exterior leakage. There is no indication of the leakage of individual units. Also, the measurement includes the exterior leakage of all of the individual units and the common area.

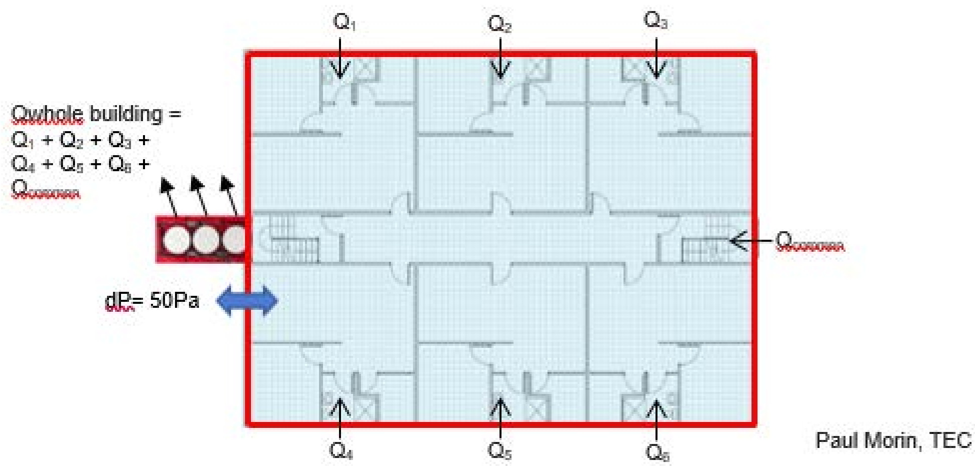


Figure B.1. Whole building test for a single-story common entry building with six units. The flowrate of the three blower door fans at the building entrance are added together to measure the whole building exterior leakage.

1. Setup the building configuration as indicated by Table 1 in the Building Setup section.
2. Open interior doors so that the entire building acts as a single zone. Open hallway doors to all units. Open doors between the common area and other areas adjacent to the building exterior. For 2 and 3-story buildings, open stairwell doors. All exterior doors to the common area are closed.
3. Setup the test equipment for a depressurization test. Use ABAA Informative Appendix X1. Setting Up and Conducting an Airtightness Test for guidance on test setup methods to improve accuracy. The Pressure gauge tubing connections are shown in Appendix B.
4. Determine the altitude of the location and measure the outside and inside air temperature. Or record the outside temperature reported by a weather application. Use the same building altitude for all tests.
5. Start Teclog3 recording. Use the characters “whole building” and the site number in the file name (e.g. “Whole building site 6”). Specify a depressurization test.
6. Cap all test fans. Wait 15 seconds. Record a baseline period of record (POR) for no less than 60 seconds. Click on the recorded baseline POR to determine the average pressure. Use that to adjust the fan-on measurement.
7. Set the master fan control to depressurization with a cruise pressure of -50 Pa + pre baseline. Uncap an appropriate number of fans and activate the cruise control.
8. When the average building envelope pressure has stabilized to within 2.5 Pa of the cruise pressure, record a fan-on POR for no less than 60 seconds. In order for the pressure

[34] An opening should be made between the common area and all areas that have a floor, ceiling or wall that is part of the exterior envelope. This includes hallways, laundry rooms, meeting rooms, offices and other common space.

measurement to be stable, the value must be within 2.5 Pa of the specified cruise pressure and no longer monotonically increasing or decreasing.

9. Turn off and cap all test fans. Wait 15 seconds. Record a baseline period of record (POR) for no less than 60 seconds. Compare the average pre and post baseline envelope pressures and verify that they are within expected variability. Repeat the post baseline if the difference is greater than expected.
10. Measure the outside and inside air temperature. Or record the outside temperature reported by a weather application.
11. Stop TECLOG3 recording. Copy the data file to an additional secure location (e.g. memory stick).

Note – for each of the Single Unit Guarded Exterior tests the air flowrates for the fans in the common entry provide a repeat of this measurement. All of the measurements should be combined to compute an average and standard deviation of the whole building exterior leakage.

Unit Compartmentalization

This test measures the total or sum of the exterior and interior envelope leakage of an individual unit. This test cannot distinguish between the exterior and interior leakage. A single blower door or duct blaster will be installed in each unit separately to measure the total leakage of the unit. For the first portion of the test the hallway doors of all adjacent units will be closed. Each test will be performed as a single point depressurization test with a pre baseline. The induced pressures of the adjacent units will determine whether the hallway doors to those units need to be opened. When the induced pressure is more than -5Pa, the hallway door is opened. After the required hallway doors are opened, the single point test will be repeated. The fan will then be capped and the post baseline measurement made with the hallway doors in the same configuration (e.g. opened as necessary).

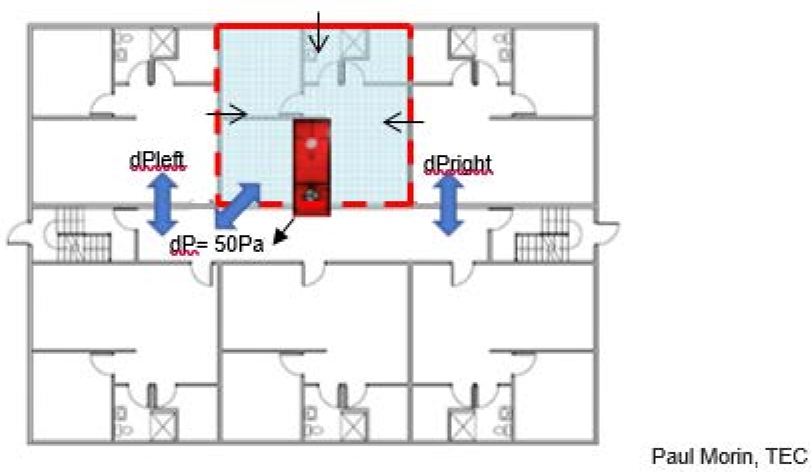


Figure B.2. Compartmentalization test of single unit in a single-story common entry building. The test measures both the exterior (solid red line) and interior (dashed red lines) leakage.

1. If the building has more than 10 units, randomly select 10 units for the compartmentalization tests. Specify a 2 to 4-character ID for each of the test units. This will be used in the POR labels to identify the units.

2. Setup the building configuration as indicated by Table B.1 in the Building Setup section. This is the same configuration as for the whole building test (see Table B.1).
3. Create an opening from the outside to the first floor of the common entry. This can be achieved by opening more or more exterior doors at the first floor. Another option is to open the hallway door and exterior windows of a first floor unit that will not be involved in the testing – either as a test unit or adjacent to a test unit. For 2 and 3-story buildings, open stairwell doors.
4. Install a Blower Door or Duct Blaster fan and digital pressure gauge in the first test unit. Use channel A for the unit with respect to (wrt) hall dP (unit= INP, hall = REF).
    a. Note – the initial protocol used gauges to measure the pressure difference for the units immediately adjacent to the test unit and assumed that the gauges would be moved for each test. This was later modified as described below.
    b. Install pressure gauges to continuously measure the unit to hall dP of every test unit and units immediately adjacent to the test units. With this configuration you do not have to move pressure tubes/gauges of adjoining units when you move the test fan from one test unit to the next. The unit dP tubes and gauges stay in place. This generally means that on each floor the number of pressure measurement channels needs to be equal to the number of test units plus the number of units immediately adjacent to the block of test units (typically 1 or 2).
    c. For example, for a three-story building with four test units on each floor and an adjacent unit on one side of the block of test units the pressure gauge setup would be:
5. #1: Channel A = unit 101/hall, Channel B = unit 103/hall
6. #2: Channel A = unit 105/hall, Channel B = unit 107/hall
7. #3: Channel A = unit 109/hall, Channel B = NC
8. #4: Channel A = unit 201/hall, Channel B = unit 203/hall
9. #5: Channel A = unit 205/hall, Channel B = unit 207/hall
10. #6: Channel A = unit 209/hall, Channel B = NC
11. #7: Channel A = unit 301/hall, Channel B = unit 303/hall
12. #8: Channel A = unit 305/hall, Channel B = unit 307/hall
13. #9: Channel A = unit 309/hall, Channel B = NC
14. #10: Channel A = test unit/hall, Channel B = test fan/unit interior
    a. Assume that the test units are: 103, 105, 107, 109; 203, 205, 207, 209; 303, 305, 307, 309. Unit 101 adjoins unit 103 and there is only common area to the side of unit 109.
15. Measure the outside air temperature or record the outside temperature reported by a weather application. Use the same building altitude for all tests.
16. Start Teclog3 recording. Use the characters “compartmentalization” and the site number in the file name (e.g. “Compartmentalization site 6”). Specify a depressurization test.
17. Close all hallway doors, exterior doors, and windows in ALL of the units in the building. If it is not feasible to close doors and windows in all of the units in the building, close doors and windows of the units adjacent to the test unit. Adjacent units include units connected to the test unit by either walls, floors, or ceilings.
18. Measure the air temperature of the test unit.
19. Cap the test fan. In TECLOG3 specify that the test fan is sealed. Wait 15 seconds. Record a baseline POR for no less than 30 seconds. Click on the recorded baseline POR to determine the average pressure. Use that value to adjust the fan-on measurement. Enter the text “B1 ‘unit ID’” for the POR label (e.g. “B1 1W”).

20. Set the cruise pressure = -50 Pa + pre baseline. Uncap the test fan, install the appropriate size ring and specify the ring size in TECLOG3. Activate the cruise control.
21. When the average building envelope pressure has stabilized to within 1.0 Pa of the cruise pressure, record a fan-on POR for no less than 30 seconds. In order for the pressure measurement to be stable, the value must be within 1.0 Pa of the specified cruise pressure and no longer monotonically increasing or decreasing. Enter the text "R1 'unit ID'" for the POR label (e.g. "R1 1W").
22. Compute the induced pressure of all of the adjoining units (e.g. "fan on" – baseline pressure). For all units with an induced pressure that is larger than -5 Pa, open the hallway door of that unit. If any hallway doors are opened, repeat the test unit leakage measurement. Wait for the test unit pressure to stabilize to within 1.0 Pa of the cruise pressure. Record a fan-on POR for no less than 30 seconds. Enter the text "R2 'unit ID'" for the POR label (e.g. "R2 1W").
23. Turn off and cap the test fan. In TECLOG3 specify that the test fan is sealed. Keep the hallway doors of the adjacent units in the same position as used for previous step. That is, if a hallway door was opened because the induced pressure was larger than -5 Pa, keep that door open. Wait 15 seconds. Record a baseline POR for no less than 30 seconds. Enter the text "B2 'unit ID'" for the POR label (e.g. "B2 1W"). Compare the average pre and post baseline envelope pressures and verify that they are within expected variability. Repeat the post baseline if the difference is greater than expected.
24. Repeat steps 7 through 13 for all test units. The test fan/frame/panel/gauge is moved to the next test unit. The pressure tubes and gauges for the test units and adjacent units are kept in place. There will be a duplicate measurement of the pressure difference for the test unit. One by the gauge that is also measuring the test fan flow and a second by the gauge that stays in place.
25. **Repeated test.** After the last compartmentalization is complete (e.g. pre baseline/fan on/fan on with hall doors open/post baseline), close the hallway doors to the adjacent units and conduct a total of five repeated fan-on measurements on the same unit as your final test. Perform (1) pre-baseline measurement, (2) activate fan and perform five repeated measurements {NO baseline in between measurements}, and (3) turn off/cap fan and perform post-baseline measurement. The baseline and fan-on PORs shall be no less than 30 seconds each. Use the label "Rep" for the unit ID. For example, the labels for the PORs should be: "B1 Rep", "R1 Rep", "R2 Rep", "R3 Rep", "R4 Rep", "R5 Rep", "B2 Rep". The repeat measurements will assist in evaluating measurement precision.
26. Measure the outside air temperature or record the outside temperature reported by a weather application.
27. Stop TECLOG3 recording. Copy the data file to an additional secure location (e.g. memory stick).

Single Unit Guarded Exterior

This test measures the **exterior** leakage of an individual unit. It will be performed as a single point depressurization test with a pre and post baseline. For common entry buildings, an additional fan is installed in an individual unit while the whole building test is conducted (see Figure B.3 and Figure B.3a). The flow through that additional fan (green arrow) is used to measure the exterior leakage of the individual unit. The results from the single unit exterior test and the compartmentalization test provide a direct comparison of the exterior and total leakage for individual units. The air flow rate and pressure difference time history for a typical two-step, guarded test is shown in Figure B.3.c.

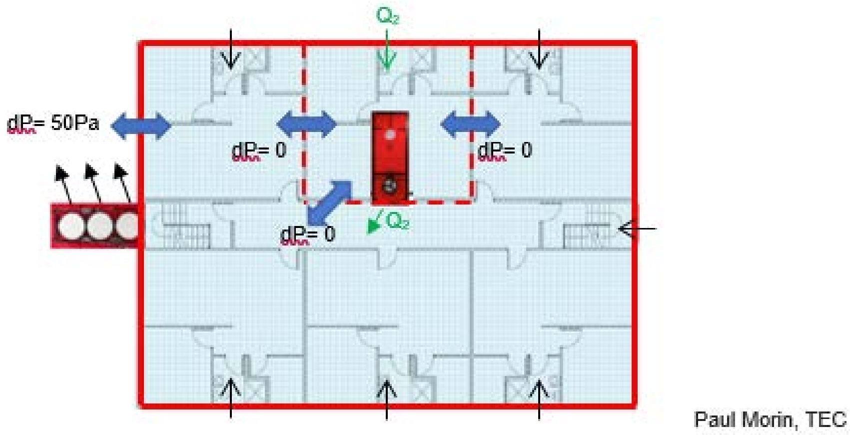
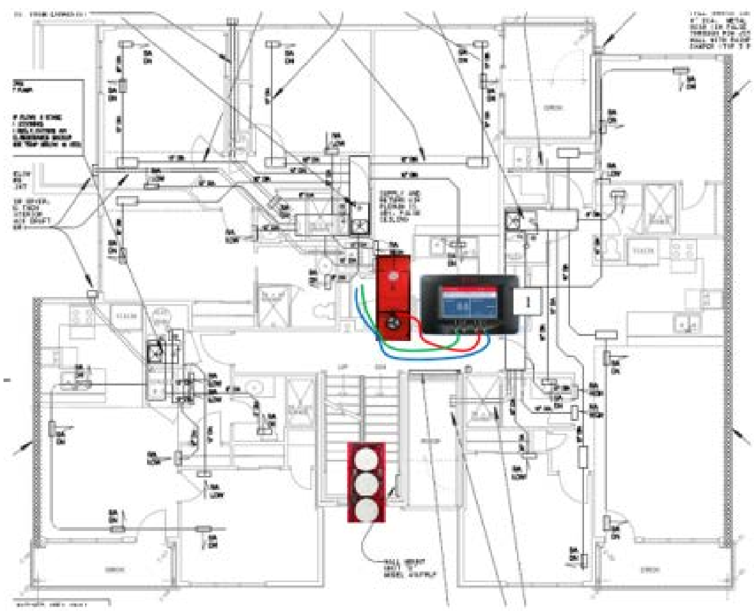


Figure B.3. Single unit guarded exterior test for a single-story common entry building with six units. The fans in the building entrance are adjusted to achieve an induced pressure difference of 50Pa. The fan in the hallway door of unit 2 is adjusted to achieve an induced pressure between unit 2 and the building interior of zero. The flow through that fan (Q2) is equal to the exterior leakage of unit 2.



3 Fan: Left Gauge

Channel	Input	Ref
A	building	outside
B	bottom fan	building

3 Fan: Right Gauge

Channel	Input	Ref
A	middle fan	building
B	top fan	building

Gauge #1 at Unit

Channel	Input	Ref
A	unit	hallway
B	fan	unit

Figure B.3.a. Pressure gauge and tubing configuration for guarded test.

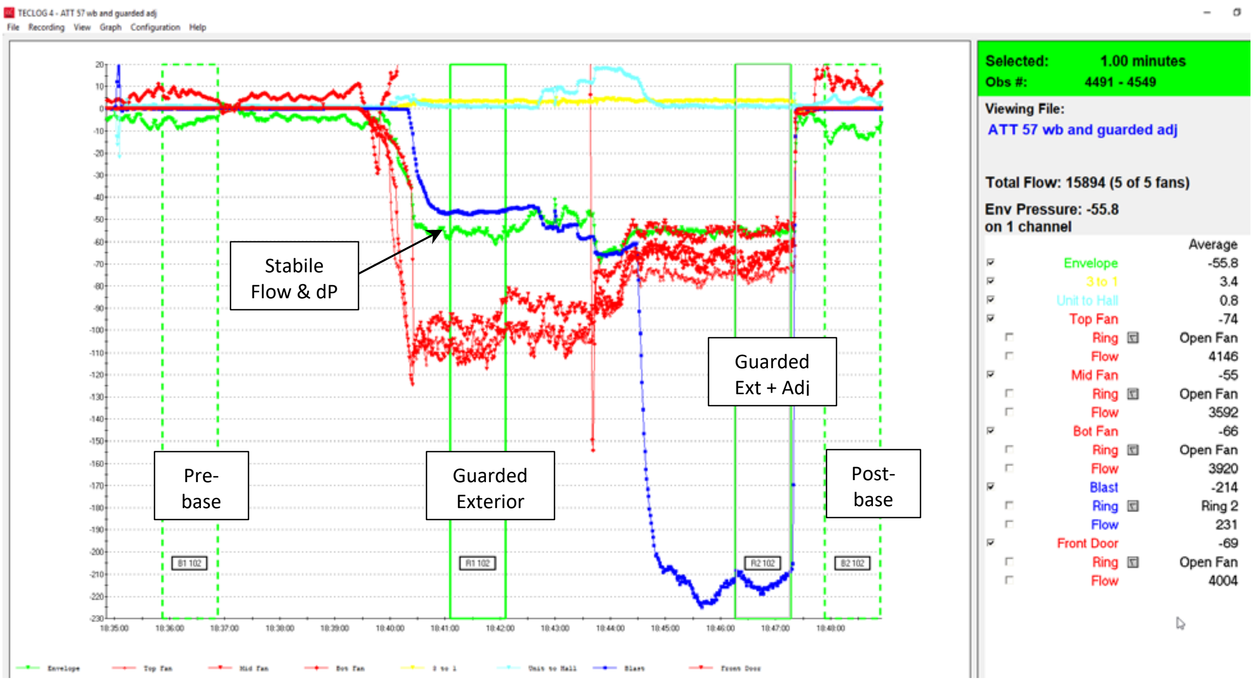


Figure B.3.b. Air flow and pressure time history for a guarded unit depressurization test. Green line = building in/out dP, light blue = unit/hall dP, red lines = building blower door flows, blue line = test unit fan flow. Green rectangles indicate averaging periods.

A second step was added to the guarded test for common entry buildings to measure the sum of the leakage to the exterior and adjacent units. After the initial test the adjacent units were opened to the outside and closed to the hallway (See Figure B.3.c). With this configuration the pressure difference between the test unit and adjacent units is approximately equal to -50 Pa while the induced pressure difference between the test unit and the common areas was zero. The flow rate through the test fan was approximately equal to the sum of the leakage to the exterior and adjacent units. The exterior leakage measured in the first step was subtracted from the measurement of the second step to compute the leakage to adjacent units. In addition, the leakage from the second step was subtracted from the total leakage to compute the leakage to the common areas.

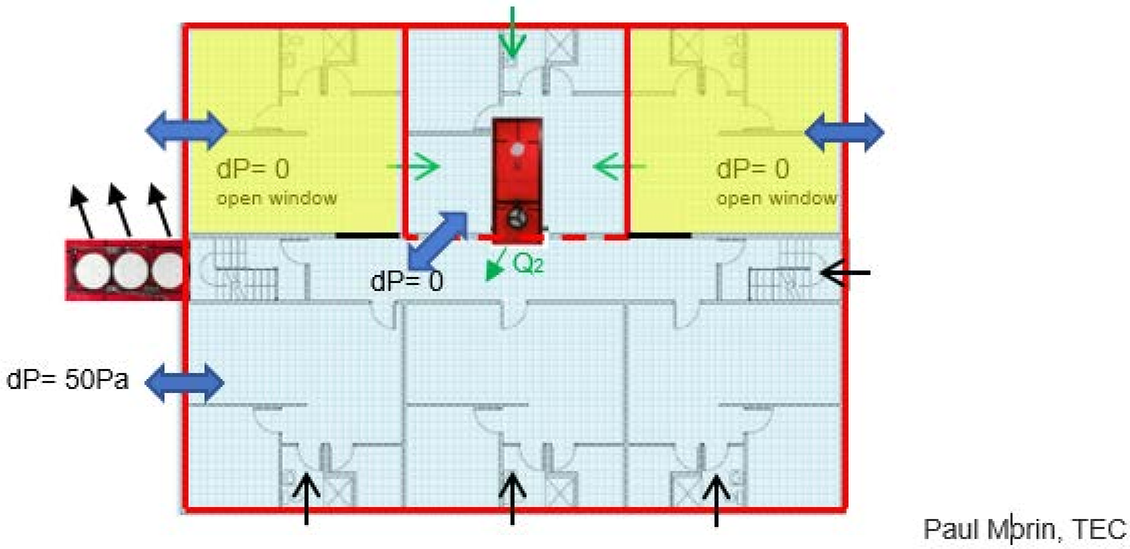


Figure B.3.c. Second portion of single unit guarded test for a single-story common entry building with six units. The adjacent units (shaded yellow) are opened to the outside and closed to the hallway. The fans in the building entrance are adjusted to achieve an induced pressure difference of -50Pa. The fan in the hallway door of unit 2 is adjusted to achieve an induced pressure between unit 2 and the hallway of zero. The flow through that fan (Q_2) is equal to the sum of the leakage between unit 2 and the exterior and adjacent units.

1. Perform these tests on the same set of units for which the compartmentalization tests were performed.
2. Setup the building configuration as indicated by Table 1 in the Building Setup section. This is the same configuration as for the whole building test (see Table 1).
3. Setup interior doors in the same way as the setup for the whole building test. Open hallway doors to all units. Open doors between the common area and other areas adjacent to the building exterior. For 2 and 3-story buildings, open stairwell doors. All exterior doors to the common area are closed.
4. Install test fan(s) in the common entry of the building. Use the same setup as for the whole building test. Install a Blower Door or Duct Blaster fan and digital pressure gauge in the first test unit. The Pressure gauge tubing connections are shown in Appendix B.
5. Measure the outside air temperature or record the outside temperature reported by a weather application. Use the same building altitude for all tests.
6. Unlink the gauge for the test unit from the master control and set the fan adjust rate to 50.
7. Start Teclog3 recording. Use the characters “Guarded exterior” and the site number in the file name (e.g. “Guarded exterior site 6”). Specify a depressurization test.
8. Measure the air temperature of the test unit.
9. Cap all test fans. Wait 15 seconds. Record a baseline POR for no less than 60 seconds. Enter the text “B1 ‘unit ID’” for the POR label (e.g. “B1 1W”). Click on the recorded baseline POR to determine the average pressures for the building/outside and test unit/hallway. Use those values to determine the cruise pressures.
10. Set the cruise pressure for the building = -50 Pa + pre baseline. Set the cruise pressure for the test unit to be equal to the unit/hallway pre baseline value. Uncap the test fan for the individual

unit, install the appropriate size ring and specify the ring size in TECLOG3. Uncap the test fan(s) for the building, install the appropriate size ring(s) and specify the ring size(s) in TECLOG3.

11. Activate the master cruise control for the building test fan(s). Wait for the building pressure to be within 5 Pa of the cruise pressure. Activate the unlinked cruise control for the test unit's gauge.
12. A measurement can be recorded when the following three conditions are met:
    a. The building envelope pressure to stabilizes to within 0.5 Pa of the cruise pressure,
    b. The unit/hallway pressure stabilizes to within 0.2 Pa of the cruise pressure, and
    c. The flow rate of the fan located in the test unit is not monotonically increasing or decreasing.
13. Record a fan-on POR for no less than 60 seconds. Enter the text "R1 'unit ID'" for the POR label (e.g. "R1 1W").
14. [35]Conduct guarded test to measure the sum of leakage to adjacent units and exterior. Continue to operate the fans in the main entry and the guarded unit. Close the hallway door and open a window or exterior door of all adjacent units[36]. That includes: (1) all units above where the upper unit floor overlaps the ceiling of the test unit, (2) all units below where the lower unit ceiling overlaps the floor of the test unit, and (3) all units on the same floor of the test unit that have an interior wall in common with the test unit. Do not close off adjacent common area spaces. A measurement can be recorded when the following three conditions are met:
    a. The building envelope pressure to stabilizes to within 0.5 Pa of the cruise pressure,
    b. The unit/hallway pressure stabilizes to within 0.2 Pa of the cruise pressure, and
    c. The flow rate of the fan located in the test unit is not monotonically increasing or decreasing.
15. Record a fan-on POR for no less than 60 seconds. Enter the text "R2 'unit ID'" for the POR label (e.g. "R2 1W").
16. Do not change the position of the doors/windows of the adjacent units[37]. Turn off and cap the test fan(s) for the building and the fan for the test unit. In TECLOG3 specify that the fans are sealed. Wait 15 seconds. Record a baseline POR for no less than 30 seconds. Enter the text "B2 'unit ID'" for the POR label (e.g. "B2 1W").
17. Repeat steps 8 through 14 for all test units. The test fan and gauge are moved to the next test unit.
18. Measure the outside air temperature or record the outside temperature reported by a weather application.
19. Stop TECLOG3 recording. Copy the data file to an additional secure location (e.g. memory stick).

Garden-Style Building Tests

Garden-Style buildings are characterized by open corridors and open access from individual units to the outside. This design is typical in low rise multifamily in warmer climates. For this type of building, the objective of the whole building test is the same as the common entry buildings but the setup and

[35] Added this step, 2/8/19

[36] The intent is to have the pressure of the adjacent units be approximately equal to that of the exterior.

[37] If you did NOT conduct the optional test, the post-baseline will be performed with the adjacent unit hallway doors open and windows/exterior doors closed. If you DID conduct the optional guarded test, the post-baseline will be performed with the hallway doors of the adjacent units closed and the windows/exterior doors open.

placement of test fans (e.g. Blower doors and Duct Blasters) is different. In overview, the tests needed to determine both total and exterior leakage will be very similar to tests for already described for common entry buildings. For each group of units that shares at least one common interior surface, a whole-building and compartmentalization test series is performed. The building and test equipment setup is the same for the whole building and compartmentalization tests. A test fan and gauge is installed in an exterior door of each unit. Depending on the number of test fans available, it might be necessary to run successive tests using 'buffer units" and then mathematically determine whole building leakage (rather than testing all units simultaneously).

For the Whole Building test of conjoined garden-style units, Blower Door or Duct Blaster fans are operated in every one of the units simultaneously (see Figure B.4 and Figure B.4a). This is sometimes referred to as a fully guarded test. The air flow through each fan measures the exterior leakage for the individual unit and the flows are added together to determine the exterior leakage of the entire building. This test also measures the exterior leakage of individual units.

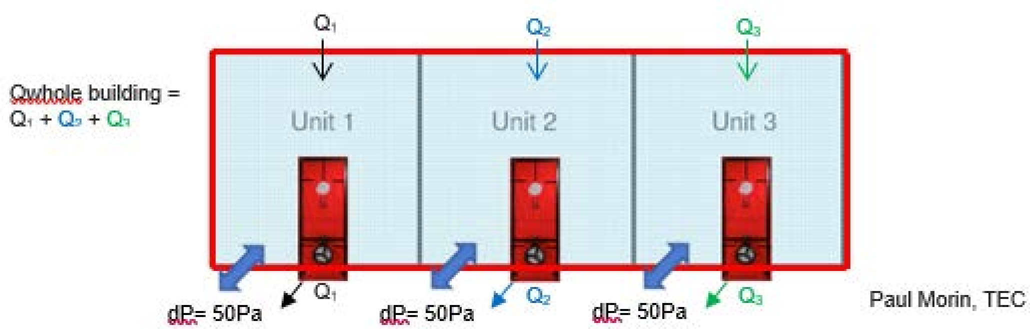


Figure B.4. Whole building test for single story garden-style building with three units. Red lines indicate walls included in leakage measurement. Fan flow from each unit measures exterior leakage for that unit. Flows are added together for exterior leakage of entire building.

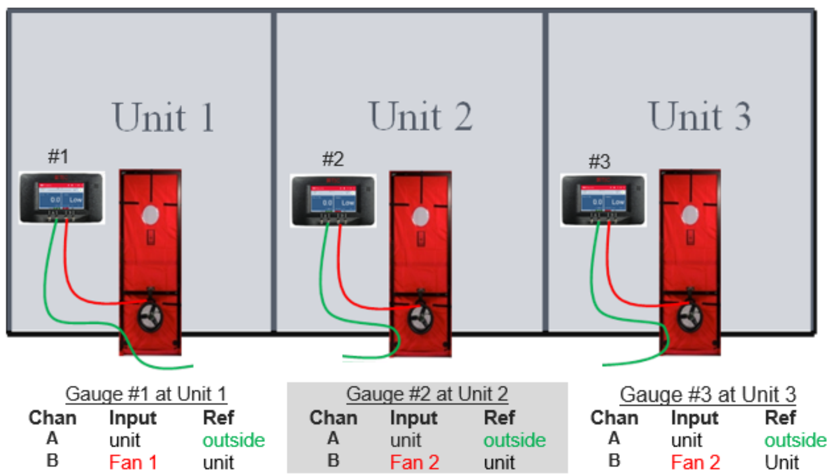


Figure B.4a. Pressure gauge and tubing setup for single story garden-style building with three units. This equipment setup is used for both the whole building (fully guarded) test and the individual unit compartmentalization tests. For the compartmentalization tests only the fan in the test unit is active. The pressure gauges in the adjoining units are used to measure induced pressure in those units

The individual unit Compartmentalization test measures the total or sum of the exterior and interior envelope leakage of an individual unit. This test cannot distinguish between the exterior and interior leakage. The single blower door is operated in each unit separately to measure the total leakage of the unit (Figure B.5).

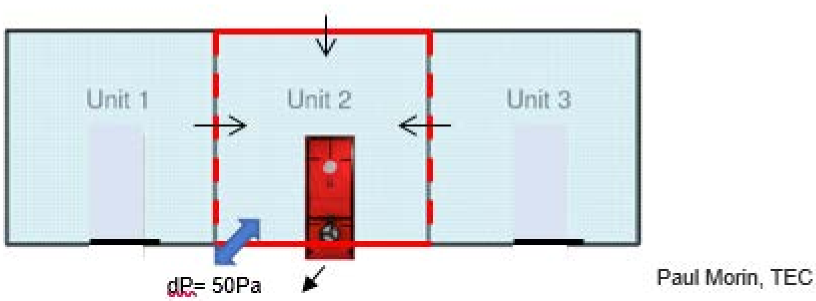


Figure B.5. Compartmentalization test of single unit in a single story garden-style building. The test measures both the exterior (solid red line) and interior (dashed red lines) leakage.

The following is a description of both the Whole Building and Compartmentalization leakage measurements performed on a garden-style building. We assume that we would always have at least 15 blower doors and pressure gauges available, and that the maximum number of units that could be tested is 24.

Whole Building Test: 15 or fewer units

Where the number of test fans available is equal to the number of units, perform a Whole Building Test by installing a test fan in each unit and connecting its paired pressure gauge appropriately to TECLOG3. The details of the tubing connections for a three-unit building are shown at the end of Appendix B. Set up TECLOG3 to allow individual fan control vs activating the master fan control. TECLOG3 will record whole building exterior leakage ($^{ext}Q_{wb}$) and the exterior leakage of each of the units ($^{ext}Q1$, $^{ext}Q2$, $^{ext}Q3$, etc.), during this test. (See detailed steps for the Whole Building Test, above.) Make sure units are labeled clearly during the test (via diagram of redline on digital picture associated with TECLOG3 file or in some other reliable way). Also, determine the interior volume and envelope areas (interior and exterior) so that the normalized leakage rates (e.g. ACH50 and CFM50/sf) can be computed.

Whole Building Test: 16 - 24 units

For cases where there are 16-24 units, the first 15 would be tested simultaneously. Subsequently, some blower doors would be moved and the building would be retested so that all the remaining units, plus some 'buffer' units, are tested together.[38] There would always be an 'overlap' of at least 6 units 'buffer' units in this configuration and TECLOG3 and/or an associated spreadsheet would be configured to keep track of individual unit results. For the configuration below (3-story building, 18 units overall, shown in elevation vs plan view), the first partial 'whole building' test would include the units with yellow highlights. The second test (second figure) would include the units with blue highlights. The middle units (3-3, 3-4, 2-3, 2-4, 1-3, 1-4) would be tested twice.

3-1	3-2	3-3	3-4	3-5	3-6
2-1	2-2	2-3	2-4	2-5	2-6
1-1	1-2	1-3	1-4	1-5	1-6

3-1	3-2	3-3	3-4	3-5	3-6
2-1	2-2	2-3	2-4	2-5	2-6
1-1	1-2	1-3	1-4	1-5	1-6

Figure B.6. The test sequence for using multiple blower doors to test an 18-unit building (12 blower door configuration). First test from one end of the building 12 units. Second test the remaining 6 units plus 6 overlapping units. When the two tests are combined the total exterior leakage is computed.

a. To compute the whole building leakage rate, the two tests would be combined. The results from buffer units 3-4, 2-4, and 1-4 would be removed from the result of the first test and the result from units 3-3, 2-3, and 1-3 would be removed from the second test.
b. The results from the two tests would then be combined so that the sum of all flows in the remaining units would be added together to arrive at the total building exterior leakage.

Compartmentalization Tests

Perform a compartmentalization test (Figure B.5) based on operating the individual fan in each unit to measure the total leakage (totQu). The compartmentalization test procedure for common-entry buildings would be modified since each unit would already have a test fan installed:

[38] Where fewer blower doors are available the same protocol can be used but the maximum number of units in the test building would be reduced or the doors would be repositioned twice. This would still require an overlap between the individual tests so that the "buffer units" are always available.

1. Measure the outside air temperature or record the outside temperature reported by a weather application. Use the same building altitude for all tests.
2. Start Teclog3 recording. Use the characters "compartmentalization" and the site number in the file name (e.g. "Compartmentalization site 6"). Specify a depressurization test.
3. Close all hallway doors, exterior doors, and windows in ALL of the units in the building. If it is not feasible to close doors and windows in all of the units in the building, close doors and windows of the units adjacent to the test unit. Adjacent units include units connected to the test unit by either walls, floors, or ceilings.
4. Measure the air temperature of the test unit.
5. Cap the test fan. In TECLOG3 specify that the test fan is sealed. Wait 15 seconds. Record a baseline POR for no less than 30 seconds. Click on the recorded baseline POR to determine the average pressure. Use that value to adjust the fan-on measurement. Enter the text "B1 'unit ID'" for the POR label (e.g. "B1 1W").
6. Set the cruise pressure = -50 Pa + pre baseline. Uncap the test fan, install the appropriate size ring and specify the ring size in TECLOG3. Activate the cruise control.
7. When the average building envelope pressure has stabilized to within 2.5 Pa of the cruise pressure, record a fan-on POR for no less than 30 seconds. In order for the pressure measurement to be stable, the value must be within 2.5 Pa of the specified cruise pressure and no longer monotonically increasing or decreasing. Enter the text "R1 'unit ID'" for the POR label (e.g. "R1 1W").
8. Compute the induced pressure of all other units (e.g. "fan on" – baseline pressure). For all units with an induced pressure that is larger than -5 Pa, open an exterior door or window of that unit. If any doors/windows are opened, repeat the test unit leakage measurement. Wait for the test unit pressure to stabilize to within 2.5 Pa of the cruise pressure. Record a fan-on POR for no less than 30 seconds. Enter the text "R2 'unit ID'" for the POR label (e.g. "R2 1W").
9. Turn off and cap the test fan. In TECLOG3 specify that the test fan is sealed. Keep the exterior doors/windows of the adjacent units in the same position as used for previous step. That is, if an exterior door or window was opened because the induced pressure was larger than -5 Pa, keep that door/window open. Wait 15 seconds. Record a baseline POR for no less than 30 seconds. Enter the text "B2 'unit ID'" for the POR label (e.g. "B2 1W"). Compare the average pre and post baseline envelope pressures and verify that they are within expected variability. Repeat the post baseline if the difference is greater than expected.
10. Repeat steps 3 through 9 for all test units. In cases where more than 15 units are tested (see Figure B.6), make sure individual unit results are accurately recorded, then move some blower doors and record the compartmentalization test results for each unit in the second test.
11. For the final test unit conduct a total of five repeated fan-on measurements with the hallway doors closed to all adjacent units. The rest of the baseline and fan on measurements are the same as for the tests for the other units. For example, conduct one pre baseline measurement, one measurement with any adjacent unit exterior doors or windows opened, and one post baseline measurement. The baseline and fan-on PORs shall be no less than 30 seconds each. The repeat measurements will assist in evaluating measurement precision.
12. Measure the outside air temperature or record the outside temperature reported by a weather application.
13. Stop TECLOG3 recording. Copy the data file to an additional secure location (e.g. memory stick).

Calculations

The envelope leakage at a reference pressure of 50Pa will be computed using the algorithms specified in Section 9.3 Single-Point Method of ASTM E 1827-11 (2017).

Induced Pressure

Induced pressure differences are computed with the average baseline subtracted from the "fan on" measurement:

$$P_{ind} = P_{test} - P_{base} \tag{1}$$

where

P_{ind} = pressure difference induced by test fan operation, Pa
P_{test} = measured pressure difference with test fan operating, Pa
P_{base} = measured pressure difference with test fan off and capped, Pa

When there is a pre and post baseline measurement the induced pressure is computed by:

$$P_{ind} = P_{test} - (P_{base1} + P_{base2})/2 \tag{2}$$

where

P_{base1} = measured pressure difference with test fan off and capped **before** test fan activated, Pa
P_{base2} = measured pressure difference with test fan off and capped **after** test fan activated, Pa

Air Density Correction

$$\rho_{in} = 0.07517\left(1 - \frac{0.003566*Alt}{528}\right)^{5.2553}\left(\frac{528}{T_{in} + 460}\right) \tag{A4.1}$$

$$\rho_{out} = 0.07517\left(1 - \frac{0.003566*Alt}{528}\right)^{5.2553}\left(\frac{528}{T_{out} + 460}\right) \tag{A4.2}$$

where

Alt = altitude at site, ft
ρ = air density, lb_m/ft^3

T = temperature, ºF

Dynamic Viscosity

$$\mu = \frac{(2.629*10^{-3})(T + 459.7)^{0.5}}{1+\left(\frac{198.7}{T + 459.7}\right)} \tag{A5.2}$$

Air Leakage Rate

First, compute the air flowrate through the fan from the nominal value provided by the fan calibration equation (4):

$$Q_{fan} = Q_{nom}\left(\frac{\rho_{cal}}{\rho_{in}}\right)^{0.5} \tag{4}$$

where

Q_{fan} = fan air flowrate, ft^3/min

Q_{nom} = the fan air flowrate uncorrected for air density and dynamic viscosity, ft^3/min

ρ_{cal} = air density at which the calibration values are valid, lb$_m$/ft^3

Next, compute the air leakage rate equation (6):

$$Q_{env} = Q_{fan}\left(\frac{\rho_{in}}{\rho_{out}}\right) \qquad (6)$$

where

Q_{env} = the air leakage rate, ft^3/min

Use equation A4.3 to compute the air density and test pressure adjusted leakage:

$$Q_{50} = Q_{env1}\left(\frac{50\,Pa}{P_1}\right)^{0.65}\left(\frac{\rho_{out}}{0.07517}\right)^{0.35}\left(\frac{\mu_{out}}{0.04387}\right)^{0.3} \qquad \text{(A4.3)}$$

where

Q_{50} = the estimated air leakage rate, ft^3/min, at 50 Pa

Q_{env1} = average air leakage, Q_{env} at the primary pressure station, ft^3/min

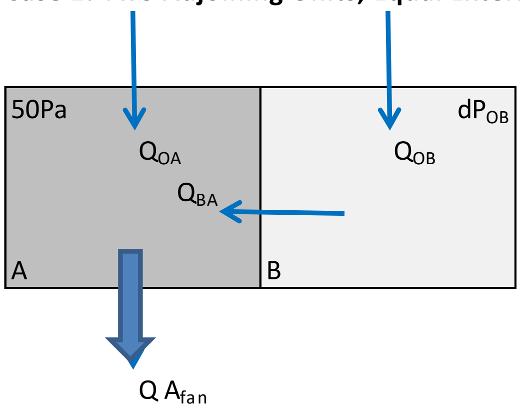
P_1 = average pressure, P_{sta} at the primary pressure station, Pa

Air Leakage Rate Normalization

The air leakage rates will be reported as the air flowrate (CFM) of the unit or building for a pressure difference of 50 Pa. The dimensions of the building will be recorded to convert the leakage rates to normalized values. The leakage rate will be divided by the interior volume (cubic feet) to compute the air changes per hour (ACH) at a pressure difference of 50 Pa (ACH50). In addition, leakage rates will be divided by envelope surface area (sf) to compute the leakage rate per area (CFM50/sf).

APPENDIX C: EQUATIONS FOR EXTERIOR LEAKAGE FROM ADJACENT UNIT PRESSURE CHANGE

Case 1: Two Adjoining Units, Equal Exterior Leakage



Air flow rate power law equation:

$$Q_{ix} = C_{ix} \cdot dP_{ix}^{n} \tag{C1.1}$$

<u>Where:</u>

Q_{ix} = leakage between area i and x

C_{ix} = coefficient for flows between area i and x

dP_{ix} = pressure difference between area i and x

Q_{Ifan} = flow rate for blower door fan in unit i

n = flow exponent

$CFM50_{Oi}$ = exterior leakage of unit i at a pressure difference of 50Pa

O = outside

<u>Assume:</u>

n = same for all flows

Exterior leakage of unit A = exterior leakage of unit B, $C_{OA} = C_{OB}$

$$Q_{BA} = Q_{OB} = C_{OB} \,.\, dP_{OB}^{n} = C_{AB} \cdot dP_{AB}^{n} \tag{C1.2}$$

$$Q^A_{fan} = Q_{OA} + Q_{BA} = (C_{OA} \cdot 50^n) + (C_{OB} \,.\, dP^n_{OB}) \tag{C1.3}$$

$$Q^A_{fan} = (C_{OA} \cdot 50^n) + (C_{OA} \,.\, dP^n_{OB}) \cdot \left(\frac{50^n}{50^n}\right) \tag{C1.4}$$

$$Q^A_{fan} = (C_{OA} \cdot 50^n) \left(1 + \cdot \left(\frac{dP^n_{OB}}{50^n}\right)\right) \tag{C1.5}$$

$$CFM50_{OA} = \frac{Q^A_{fan}}{\left(1+\left(\frac{dP_{OB}}{50}\right)^n\right)} \tag{C1.6}$$

Case 2: Two Adjoining Units, Unequal Exterior Leakage
Same flow configuration as shown for Case 1.

Assume:

n = same for all flows

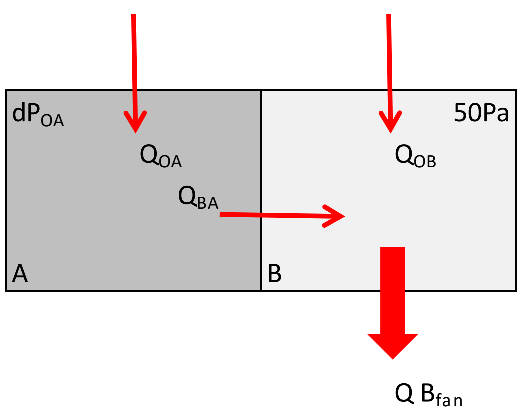
Exterior leakage of unit A is not equal to exterior leakage of unit B, $C_{OA} \neq C_{OB}$

$$Q^A_{fan} = Q_{OA} + Q_{BA} = (C_{OA} \cdot 50^n) + (C_{OB} \,.\, dP^n_{OB}) \tag{C2.1}$$

$$Q^A_{fan} = (C_{OA} \cdot 50^n) + (C_{OB} \,.\, dP^n_{OB}) \cdot \left(\frac{50^n}{50^n}\right) \tag{C2.2}$$

$$CFM50_{OA} = Q^A_{fan} - \left(CFM50_{OB} \,.\, \left(\frac{dP_{OB}}{50}\right)^n\right) \tag{C2.3}$$

Similarly, with blower door fan in unit B[39]:



$$CFM50_{OB} = Q^B_{fan} - \left(CFM50_{OA} \,.\, \left(\frac{dP_{OA}}{50}\right)^n\right) \tag{C2.4}$$

[39] Measurements from test with blower door in unit A are highlighted red and those from the test with the blower door in unit B are highlighted blue.

$$CFM50_{OB} = Q_{fan}^{B} - \left(\left(Q_{fan}^{A} - \left(CFM50_{OB} \cdot \left(\frac{dP_{OB}}{50}\right)^{n}\right)\right) \cdot \left(\frac{dP_{OA}}{50}\right)^{n}\right) \quad \text{(C2.5)}$$

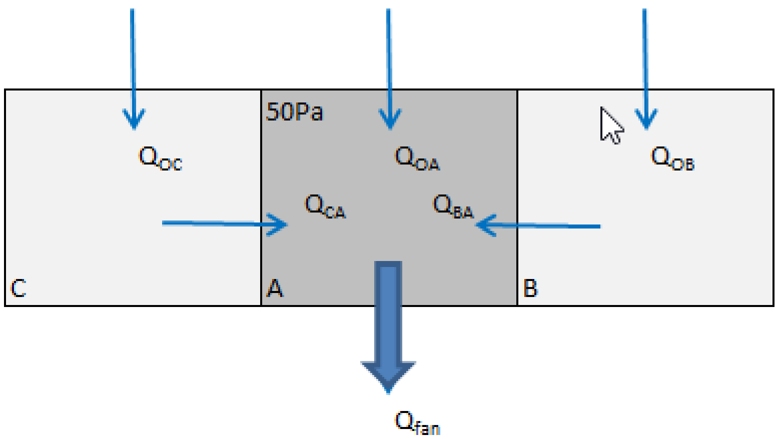
$$CFM50_{OB} = Q_{fan}^{B} - \left(Q_{fan}^{A} \cdot \left(\frac{dP_{OA}}{50}\right)^{n}\right) + \left(CFM50_{OB} \cdot \left(\frac{dP_{OB}}{50}\right)^{n}\left(\frac{dP_{OA}}{50}\right)^{n}\right) \quad \text{(C2.6)}$$

$$CFM50_{OB} - \left(CFM50_{OB} \cdot \left(\frac{dP_{OB}}{50}\right)^{n}\left(\frac{dP_{OA}}{50}\right)^{n}\right) = Q_{fan}^{B} - \left(Q_{fan}^{A} \cdot \left(\frac{dP_{OA}}{50}\right)^{n}\right) \quad \text{(C2.7)}$$

$$CFM50_{OB} = \frac{Q_{fan}^{B} - \left(Q_{fan}^{A} \cdot \left(\frac{dP_{OA}}{50}\right)^{n}\right)}{\left(1 - \left(\frac{dP_{OB}}{50}\right)^{n}\left(\frac{dP_{OA}}{50}\right)^{n}\right)} \quad \text{(C2.8)}$$

Note – the sum of $CFM50_{OA}$ and $CFM50_{AB}$ could be measured directly by opening an exterior door or window of unit B while the test fan in unit A induces a pressure difference of 50Pa. Similar for $CFM50_{OB}$ and $CFM50_{AB}$.

Case 3: Three Adjoining Units In a Row, No Common Area, Equal Exterior Leakage



Assume:

n = same for all flows

Exterior leakage of all three units is the same, $C_{OA} = C_{OB} = C_{OC}$

Interior Unit:

$$Q_{BA} = Q_{OB} = C_{OB} \cdot dP_{OB}^{n} = C_{OA} \cdot dP_{OB}^{n} \quad \text{(C3.1)}$$

$$Q_{CA} = Q_{OC} = C_{OC} \cdot dP_{OC}^{n} = C_{OA} \cdot dP_{OC}^{n} \quad \text{(C3.2)}$$

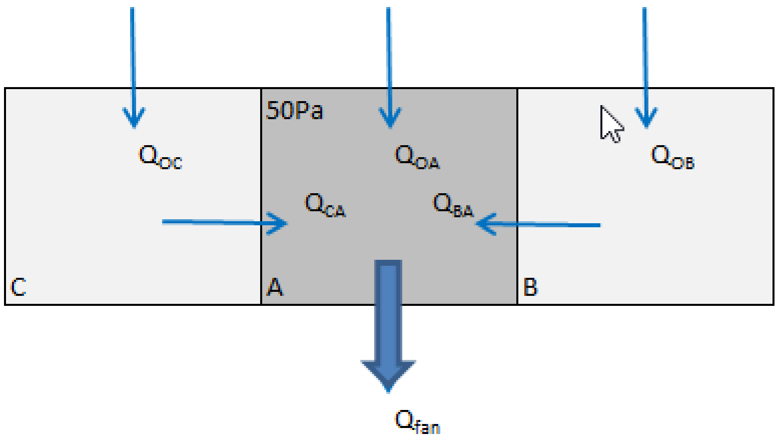
$$Q_{fan}^{A} = Q_{OA} + Q_{BA} + Q_{CA} = (C_{OA} \cdot 50^{n}) + (C_{OA} \cdot dP_{OB}^{n}) + (C_{OA} \cdot dP_{OC}^{n}) \quad \text{(C3.3)}$$

$$Q_{fan}^{A} = (C_{OA} \cdot 50^{n}) + (C_{OA} \cdot dP_{OB}^{n}) \cdot \left(\frac{50^{n}}{50^{n}}\right) + (C_{OA} \cdot dP_{OC}^{n}) \cdot \left(\frac{50^{n}}{50^{n}}\right) \quad \text{(C3.4)}$$

$$Q_{fan}^{A} = (C_{OA} \cdot 50^n)\left(1 + \left(\frac{dP_{OB}}{50}\right)^n + \left(\frac{dP_{OC}}{50}\right)^n\right) \quad \text{(C3.5)}$$

$$CFM50_{OA} = \frac{Q_{fan}^{A}}{\left(1+\left(\frac{dP_{OB}}{50}\right)^n+\left(\frac{dP_{OC}}{50}\right)^n\right)} \quad \text{(C3.6)}$$

Case 4: Three Adjoining Units In a Row, No Common Area, Unit Exterior Leakage Not Equal



Assume:

n = same for all flows

Exterior leakage of the three units are NOT the same, $C_{OA} \neq C_{OB} \neq C_{OC}$

Interior Unit:

$$Q_{BA} = Q_{OB} = C_{OB} \,.\, dP_{OB}^{n} \quad \text{(C4.1)}$$

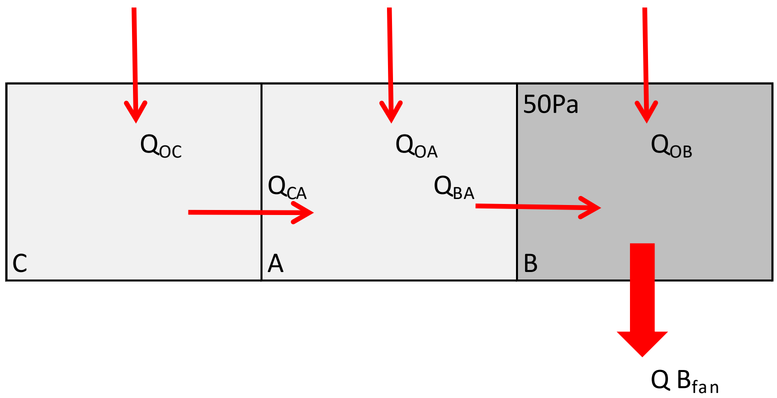
$$Q_{CA} = Q_{OC} = C_{OC} \,.\, dP_{OC}^{n} \quad \text{(C4.2)}$$

$$Q_{fan}^{A} = Q_{OA} + Q_{BA} + Q_{CA} = (C_{OA} \cdot 50^n) + (C_{OB} \,.\, dP_{OB}^{n}) + (C_{OC} \,.\, dP_{OC}^{n}) \quad \text{(C4.3)}$$

$$Q_{fan}^{A} = (C_{OA} \cdot 50^n) + (C_{OB} \,.\, dP_{OB}^{n}) \cdot \left(\frac{50^n}{50^n}\right) + (C_{OC} \,.\, dP_{OC}^{n}) \cdot \left(\frac{50^n}{50^n}\right) \quad \text{(C4.4)}$$

$$CFM50_{OA} = Q_{fan}^{A} - \left(CFM50_{OB} \,.\, \left(\frac{dP_{OB}}{50}\right)^n\right) - \left(CFM50_{OC} \,.\, \left(\frac{dP_{OC}}{50}\right)^n\right) \quad \text{(C4.5)}$$

<u>End Unit:</u>



$$Q_{CA} = Q_{OC} = C_{OC}\, dP_{OC}^{n} \tag{C4.6}$$

$$Q_{OA} = C_{OA} \,.\, dP_{OA}^{n} \tag{C4.7}$$

$$Q_{fan}^{B} = Q_{OB} + Q_{BA} = Q_{OB} + Q_{OA} + Q_{CA} = Q_{OB} + Q_{OA} + Q_{OC} \tag{C4.8}$$

$$Q_{fan}^{B} = (C_{OB} \cdot 50^{n}) + (C_{OA}\, dP_{OA}^{n}) \cdot \left(\frac{50^{n}}{50^{n}}\right) + (C_{OC} \,.dP_{OC}^{n}) \cdot \left(\frac{50^{n}}{50^{n}}\right) \tag{C4.9}$$

$$CFM50_{OB} = Q_{fan}^{B} - \left(CFM50_{OA} \,.\, \left(\frac{dP_{OA}}{50}\right)^{n}\right) - \left(CFM50_{OC} \,.\, \left(\frac{dP_{OC}}{50}\right)^{n}\right) \tag{C4.10}$$

Similarly, for the other end unit:

$$CFM50_{OC} = Q_{fan}^{C} - \left(CFM50_{OA} \,.\, \left(\frac{dP_{OA}}{50}\right)^{n}\right) - \left(CFM50_{OB} \,.\, \left(\frac{dP_{OB}}{50}\right)^{n}\right) \tag{C4.11}$$

This provides three equations (e.g. 4.5, 4.10, and 4.11) and three unknowns (the exterior leakage rates of the three units).

<u>Matrix of Equations for Explicit Solution of Exterior Leakage</u>

$$CFM50_{OA} = Q_{fan}^{A} - \left(CFM50_{OB} \,.\, \left(\frac{dP_{OB}}{50}\right)^{n}\right) - \left(CFM50_{OC} \,.\, \left(\frac{dP_{OC}}{50}\right)^{n}\right) \tag{C4.5}$$

$$CFM50_{OB} = Q_{fan}^{B} - \left(CFM50_{OA} \,.\, \left(\frac{dP_{OA}}{50}\right)^{n}\right) - \left(CFM50_{OC} \,.\, \left(\frac{dP_{OC}}{50}\right)^{n}\right) \tag{C4.10}$$

$$CFM50_{OC} = Q_{fan}^{C} - \left(CFM50_{OA} \,.\, \left(\frac{dP_{OA}}{50}\right)^{n}\right) - \left(CFM50_{OB} \,.\, \left(\frac{dP_{OB}}{50}\right)^{n}\right) \tag{C4.11}$$

Put this in the form of $A \cdot X = B$ and solve for $X = A^{-1} \cdot B$

$$CFM50_{OA} - \left(CFM50_{OB} \,.\, \left(\frac{dP_{OB}}{50}\right)^{n}\right) - \left(CFM50_{OC} \,.\, \left(\frac{dP_{OC}}{50}\right)^{n}\right) = Q_{fan}^{A} \tag{C4.5*}$$

$$-\left(CFM50_{OA}\cdot\left(\frac{dP_{OA}}{50}\right)^{n}\right)+CFM50_{OB}-\left(CFM50_{OC}\cdot\left(\frac{dP_{OC}}{50}\right)^{n}\right)=Q_{fan}^{B} \quad \text{(C4.10*)}$$

$$-\left(CFM50_{OA}\cdot\left(\frac{dP_{OA}}{50}\right)^{n}\right)-\left(CFM50_{OB}\cdot\left(\frac{dP_{OB}}{50}\right)^{n}\right)+CFM50_{OC}=Q_{fan}^{C} \quad \text{(C4.11*)}$$

$$\begin{pmatrix} 1 & -\left(\frac{dP_{OB}}{50}\right)^{n} & -\left(\frac{dP_{OC}}{50}\right)^{n} \\ -\left(\frac{dP_{OA}}{50}\right)^{n} & 1 & -\left(\frac{dP_{OC}}{50}\right)^{n} \\ -\left(\frac{dP_{OA}}{50}\right)^{n} & -\left(\frac{dP_{OB}}{50}\right)^{n} & 1 \end{pmatrix}\begin{pmatrix} CFM50_{OA} \\ CFM50_{OB} \\ CFM50_{OC} \end{pmatrix}=\begin{pmatrix} Q_{fan}^{A} \\ Q_{fan}^{B} \\ Q_{fan}^{C} \end{pmatrix} \quad \text{(C4.12)}$$

This approach can be extended to buildings with 4, 5, 6+ units where matrix A has the same number of rows and columns with dimensions equal to the number of units.

APPENDIX D: APPLICATION OF RESULTS TO LEAKAGE TEST PROTOCOLS

There are air leakage test protocol issues that are unique to multifamily buildings and may not be adequately addressed by standards developed for testing single family houses. The results from the tests conducted for this project may help inform future versions of test protocols for multifamily buildings. For example, for the compartmentalization test of the total leakage of a unit, all of the adjacent units are normally required to be open to the hallway or outside. The compartmentalization tests performed with the adjacent units closed and then opened as necessary provides information as to how often keeping the adjacent units closed has a significant impact on the measurement and guidelines for adjusting the measurement when the adjacent units must remain closed. In addition, the results from the whole building leakage tests of the common-entry buildings were evaluated to determine the distribution of number of blower doors that were needed to test the buildings. Finally, tables of the variation of leakage measurements of tests performed for units on the same floor and the same building are included for the common-entry and garden-style buildings. This information may be useful for refining the number of units and type of units needed for a reliable sampling method. It may also be useful for establishing unit-to-unit variations in leakage for more realistic airflow models of multifamily buildings.

Impact of Adjacent Units on Compartmentalization Results

One open issue for the multifamily air leakage compartmentalization test protocol is whether adjoining units need to be opened to the hallway or outside when the test is conducted. Compartmentalization test protocols to measure the total leakage of a unit often specify that all of the adjacent units should be open to the hallway or outside. This helps assure an equal pressure difference across the exterior and interior portions of the unit's envelope. For tests of newly constructed buildings this can add time to the testing process and requires additional coordination with any other workers in the building. In addition, for occupied buildings it can be challenging to get access to all adjacent units. The compartmentalization tests conducted for this project provided information as to how often keeping the adjacent units closed has a significant impact on the measurement. It also provided guidelines for adjusting the total leakage measurement when the adjacent units must remain closed.

For this project, the compartmentalization test for each unit was initially performed with all of the doors and windows of adjacent units closed. During the baseline and depressurization portions of the test, the pressures between adjacent units and the hallway were also measured to determine the induced pressure created when the test unit was depressurized. If the induced pressure difference in one or more adjacent unit(s) changed by more than 5.0 Pa, a hallway door or exterior window in those adjacent units was opened so that the induced pressure of the units would be close to zero. The compartmentalization test was then repeated and the change in the measured total leakage was computed. It was expected that keeping a unit closed that had a change in pressure less than 5.0 Pa would have little effect on the total leakage measurement.

Adjacent unit pressure data was recorded for 194 common-entry units. Figure 152 displays the cumulative distribution of the largest change in adjacent unit pressure (black crosses) and Figure 153 displays a histogram of the pressure data. A total of 82% of the test units did not have any adjacent units with a change in pressure larger than 5.0[40] Pa. A total of 11% of the units had adjacent units with pressure changes larger than 10.0 Pa and 4% with changes larger than 20.0 Pa. The horizontally adjacent (e.g., side-to-side) units typically had larger changes in pressure than vertically adjacent (e.g.,

[40] The compartmentalization tests were conducted as depressurization tests. Consequently, the induced pressure of the adjacent units was typically negative and the induced pressures shown in the cumulative distribution and histograms are negative. However, it can be confusing to describe induced pressures that are less than a negative value as being a large change. Instead, the description in this section refers to significant changes being larger than a positive value.

up/down) units. The pressure change was larger than 5.0 Pa for 11% of the side-to-side units, but the change was larger than 5.0 Pa for only 5% of the up/down units. In fact, there were only two units for which the pressure change of any adjacent units was larger than 5.0 Pa with the largest change being in an up/down unit. For one of these two units the difference in the up/down and side-to-side pressure change was only 0.6 Pa. Thus, for 99% of the units a concern with keeping adjacent units closed would have been identified by monitoring only the pressure of the side-to-side units.

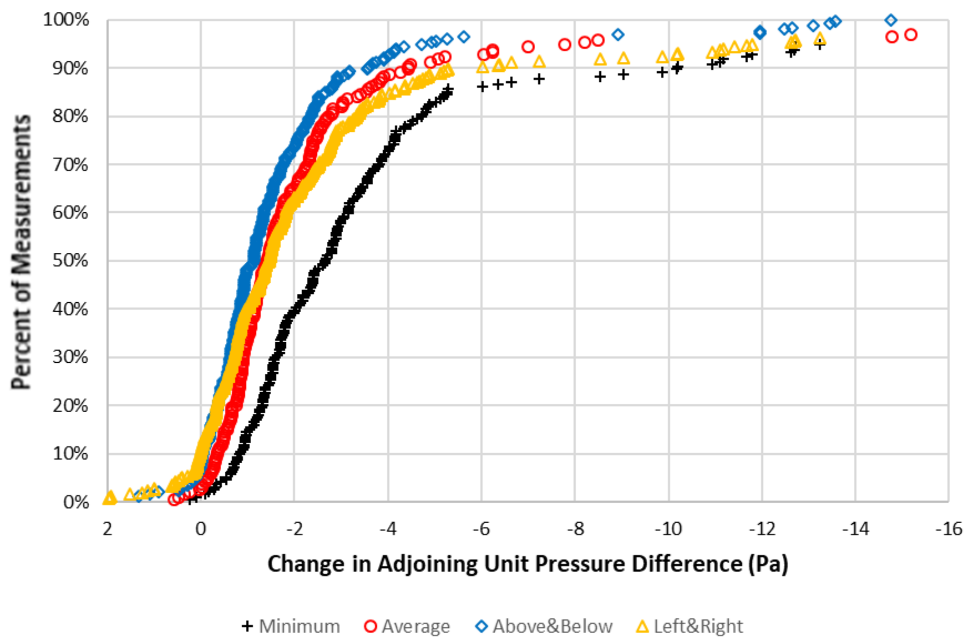


Figure 152. Cumulative Distribution of Change in Adjacent Unit dP For Compartmentalization Test: Common Entry Buildings

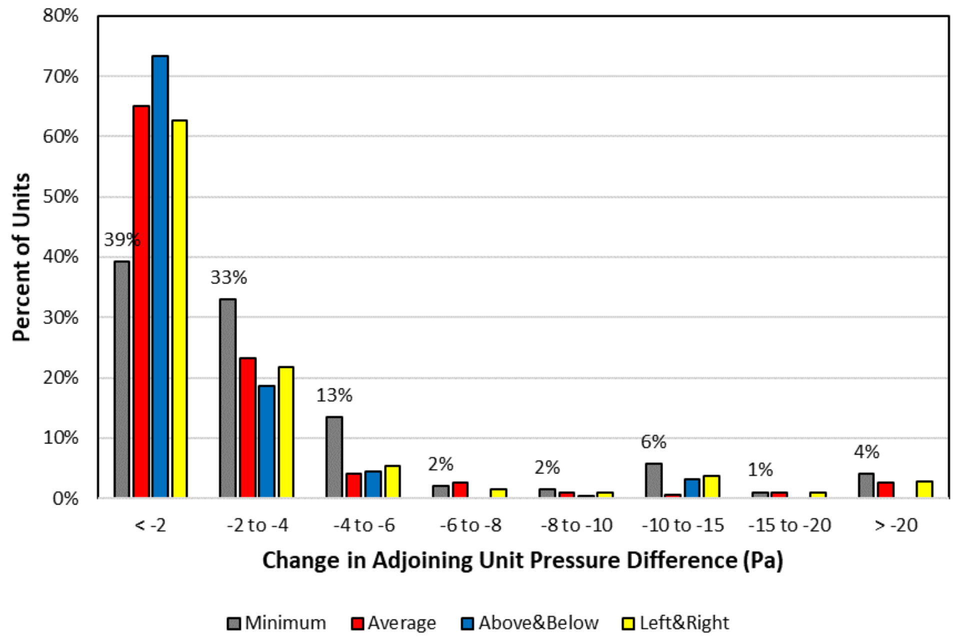


Figure 153. Histogram of Change in Adjacent Unit dP For Compartmentalization Test: Common Entry Buildings

A total of 19% of the units had the extra step of opening one or more of the adjacent units followed by a second compartmentalization test of total leakage. Figure 154 displays a box and whisker plot of the ratio of the total leakage measured with the adjacent unit(s) open (as needed) and closed with the largest change in adjacent unit pressure. A ratio of 1.0 indicates that there was no change in the measured total leakage when adjacent unit(s) were opened. A ratio of 1.1 indicates a 10% increase in the measurement or that the total leakage measurement with the adjacent units closed would have underestimated the total leakage by 10%. For the six units for which the largest change in adjacent unit pressure was between 0.0 and 5.0 Pa the average ratio was 1.002.[41] This is within the leakage measurement error and helps confirm that opening units when the change in pressure is lower than 5.0 Pa will not have a significant effect on the total leakage measurement. Moreover, for the units for which the largest change in adjacent unit pressure was between 5.0 and 10.0 Pa the average ratio was only 1.038. If an uncertainty of 5% is sufficient for the total leakage, it would be acceptable to keep the adjacent units closed when the pressure change in the units is less than 10.0 Pa. When an uncertainty less than 5% is required or the change in adjacent unit pressure is greater than 10.0 Pa, the adjacent unit should be opened or an adjustment made to increase the estimated total leakage. This is particularly important for larger pressure changes. For the 10 units for which the largest change in adjacent unit pressure was larger than 15.0 Pa the average ratio was 1.40.

[41] There were a limited number of units for which adjacent units were apparently not opened as specified by the test protocol. All tests included a pre- and post-baseline measurement. When there was a second test with adjacent units opened, the post-baseline measurement was not averaged with the pre-baseline because the post-baseline was performed with the adjacent unit(s) open. That value is typically the same as the value computed by the field technician when the depressurization test was complete. When no adjacent unit(s) were opened, the post-baseline was averaged with the pre-baseline. In that situation, the reported change in the adjacent unit pressure could be different from the change computed by the field technician after the depressurization test was completed. In addition, there were a limited number of units for which the field technician may not have correctly computed the change in pressure. Finally, there were a small number of cases when the pre-baseline or depressurization averaging periods were modified after the tests were completed.

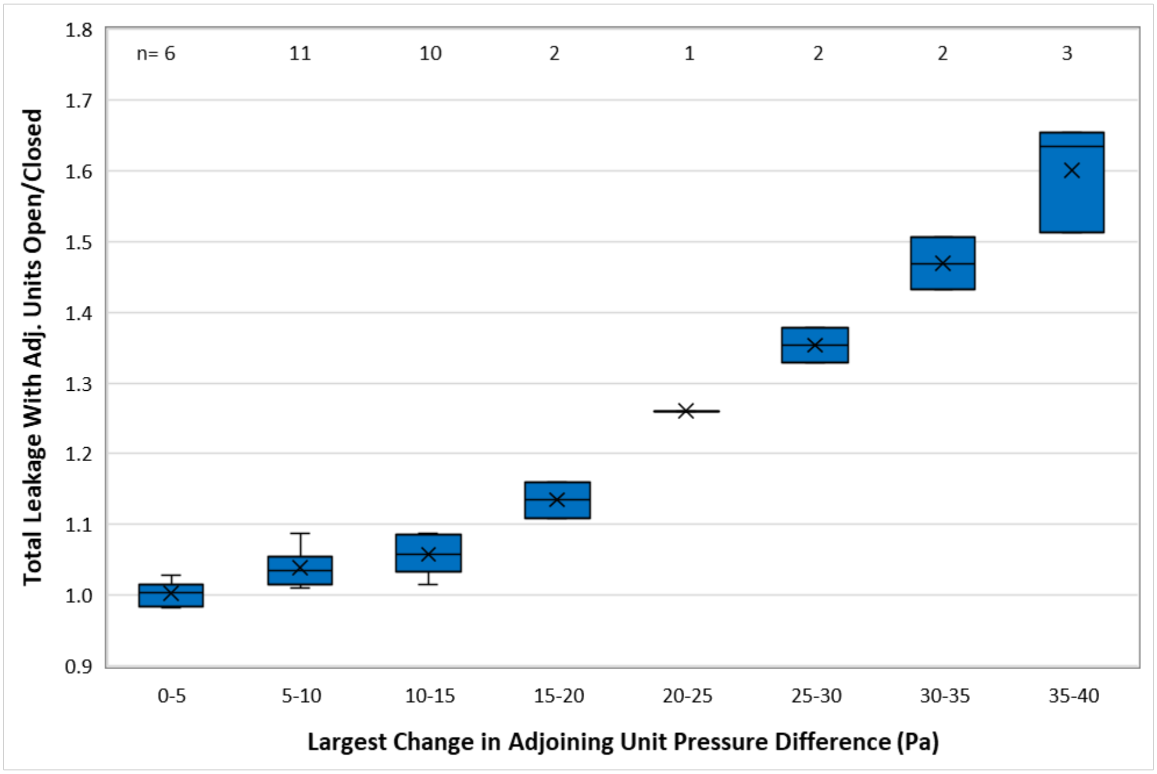


Figure 154. Box and Whisker Plot of the Change in Adjacent Unit dP and Impact on Total Leakage Measurement

Figure 155 displays the relationship between the ratio of the total leakage measured with the adjacent unit(s) open and closed (e.g., open/closed ratio) with the change in adjacent unit pressure. The black crosses represent the largest change in all adjacent units and the red circles represent the average of the adjacent units. There appears to be a strong quadratic relationship between the change in adjacent unit pressure and the open/closed ratio for both the average and largest change in pressure. The regression fit for quadratic equations are shown as dashed lines.[42] The regressions were configured to force an intercept of 1.0 so that the computed ratio would be 1.0 when there is no change in pressure for any of the adjacent units. The quadratic relationship is somewhat stronger for the largest change in pressure ($r^2 = 0.98$) and the largest change in pressure is used as the independent variable for the remainder of this analysis. The equation estimates a ratio of 1.012 for a 5.0 Pa pressure change and a ratio of 1.044 for a 10.0 Pa change. That is consistent with the previous estimate that the error with keeping adjacent units closed would be no greater than 5% for pressure changes less than 10.0 Pa.

[42] The regression fit for the measurements from the units in the garden-style buildings is shown as a solid black line.

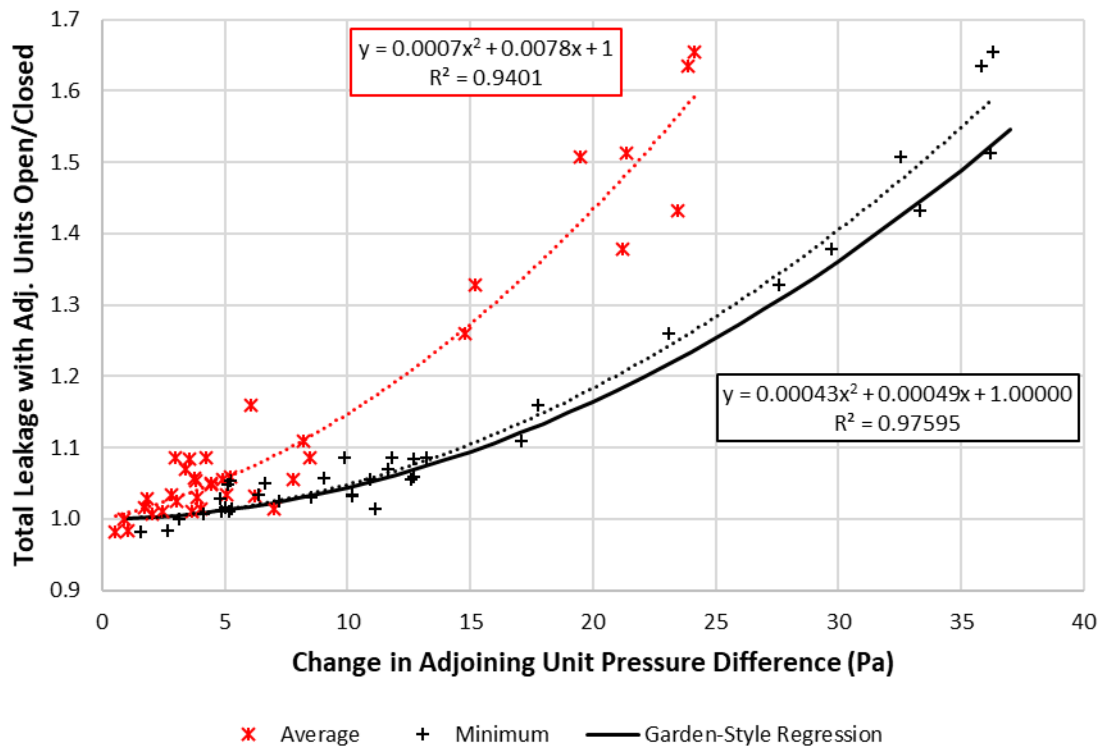


Figure 155. Relationship Between the Change in Adjacent Unit dP and Impact on Total Leakage Measurement

When there is only one adjacent unit (e.g., two zones) and both units have the same exterior leakage, the relationship between the open/closed ratio and change in adjacent unit pressure can be determined from equation (C1.6) of Case 1: Two Adjoining Units, Equal Exterior Leakage shown in Appendix C. When there are two adjacent units (e.g., three zones) and all three zones have the same exterior leakage, the ratio can be computed from equation (C3.5) of Case 3: Three Adjoining Units In a Row, No Common Area, Equal Exterior Leakage in Appendix C. The relationships between the open/closed ratio and largest change in adjacent unit pressure are shown in Figure 156 for the two-zone (green line) and three-zone (blue line) cases. Finally, a CONTAM model was generated with five units on the first floor, five on the second floor and all units having equal exterior leakage. The test unit was the center unit on the first floor. The model was used to generate the relationship between open/closed ratio and largest pressure change shown by the red line in Figure 156. Figure 116 shows that errors due to keeping adjacent units closed grows with the number of units modeled. Equation (C3.5) shows how this error arises, as there are additive terms for units B and C . Similar terms would be required for any additional adjacent units modeled. The error is at least in part due to the use of the *largest* pressure as the independent variable. Any units with pressure responses weaker than the *largest* pressure do not affect the value of the independent variable and are therefore being ignored. Nonetheless, the use of the largest pressure as the independent variable provided the best correlation with the data and is a simple metric which may be used. For real buildings there will be effects not captured by the analysis of Appendix C, particularly that all adjacent units will not have identical leakage. Since the leakage of the largest-responding adjacent unit will be biased low (as that is partly why the pressure response would be high), this approach will tend to overestimate the ratios. This effect would tend to compensate for the fact that we are ignoring units with smaller pressure changes.

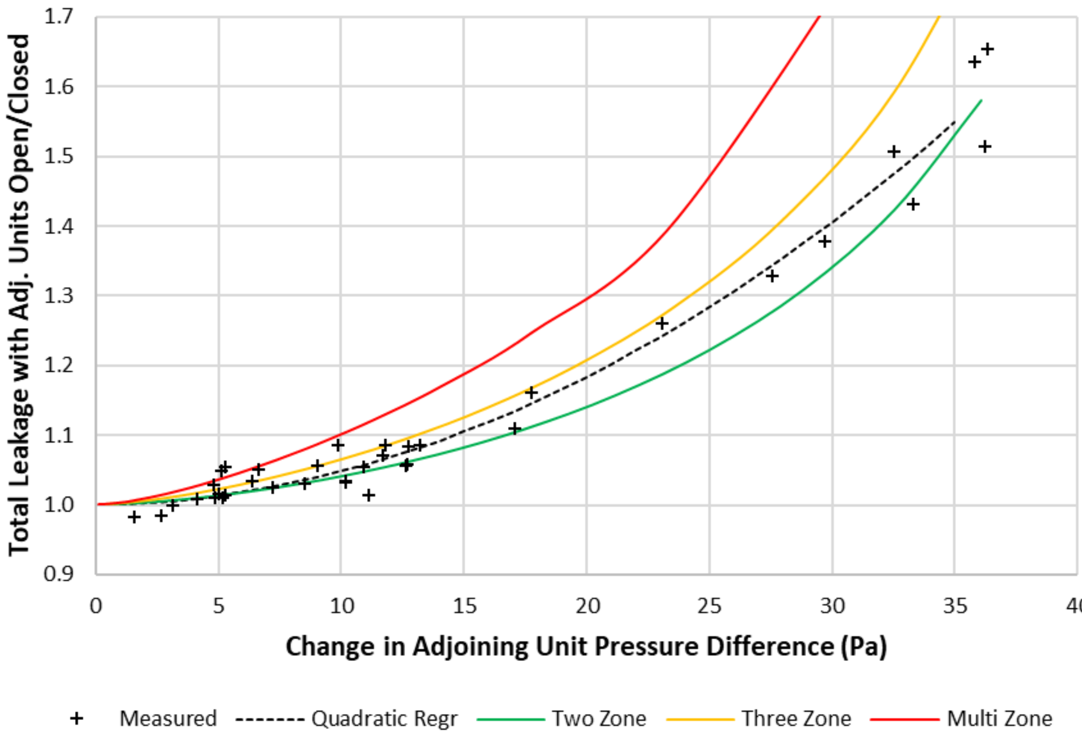


Figure 156. Quadratic Regression and Model Fit to Open/Closed Ratio

Figure 157 displays the percentage difference between the measured open/closed ratio and the ratio computed from the quadratic equation fit for the largest pressure change of adjacent units. This figure demonstrates that errors due to closed doors can be held under 5% for the units studied when using the simple quadratic adjustment.

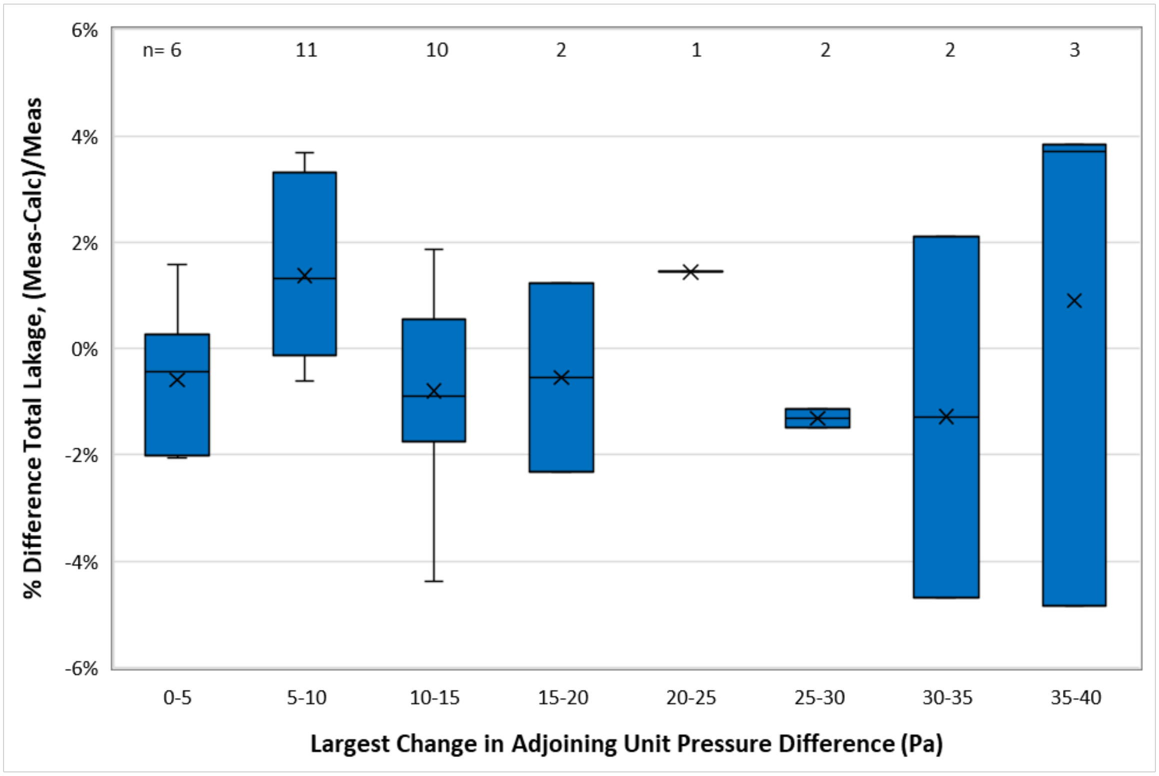


Figure 157. % Difference Between Calculated and Measured Total Leakage for Closed Adjoining Units: Common Entry Buildings

Adjacent unit pressure data was recorded for 68 units in garden-style buildings. Figure 158 displays the cumulative distribution of the largest change in adjacent unit pressure (black crosses) and Figure 159 displays a histogram of the pressure data. A total of 35% of the test units did not have any adjacent units with a change in pressure larger than 5.0 Pa. A total of 38% of the units had adjacent units with pressure changes larger than 10.0 Pa and 4% with changes larger than 20.0 Pa. The common-entry buildings had a much larger percentage of units (85%) with adjacent units that had pressures changes less than 5.0 Pa. However, for both sets of buildings the percentage of units with adjacent units that had pressure changes larger than 20.0 Pa was the same and relatively small (4%).

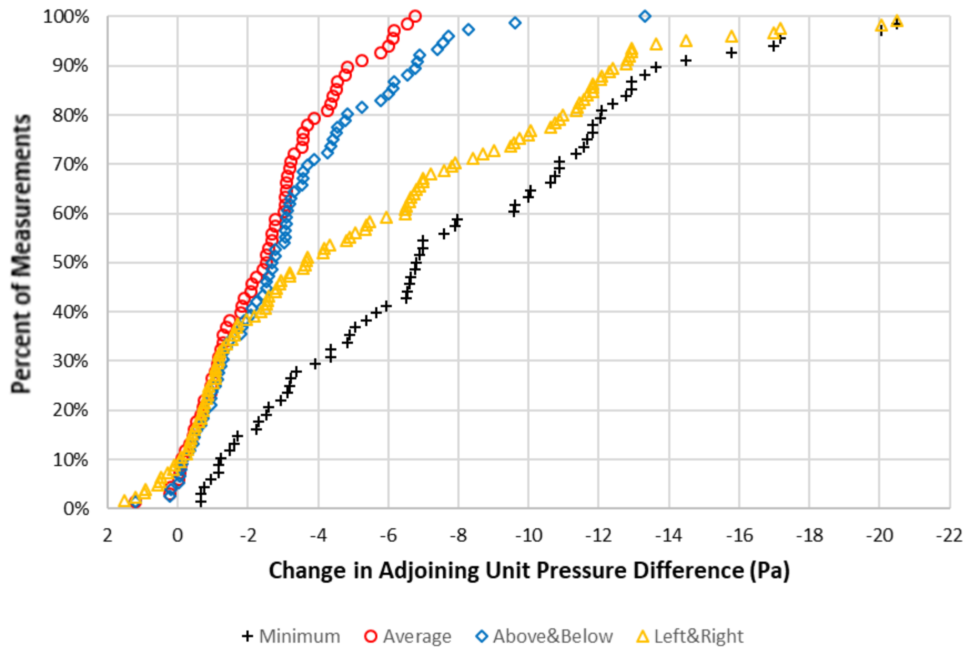


Figure 158. Cumulative Distribution of Change in Adjacent Unit dP For Compartmentalization Test: Garden-Style Buildings

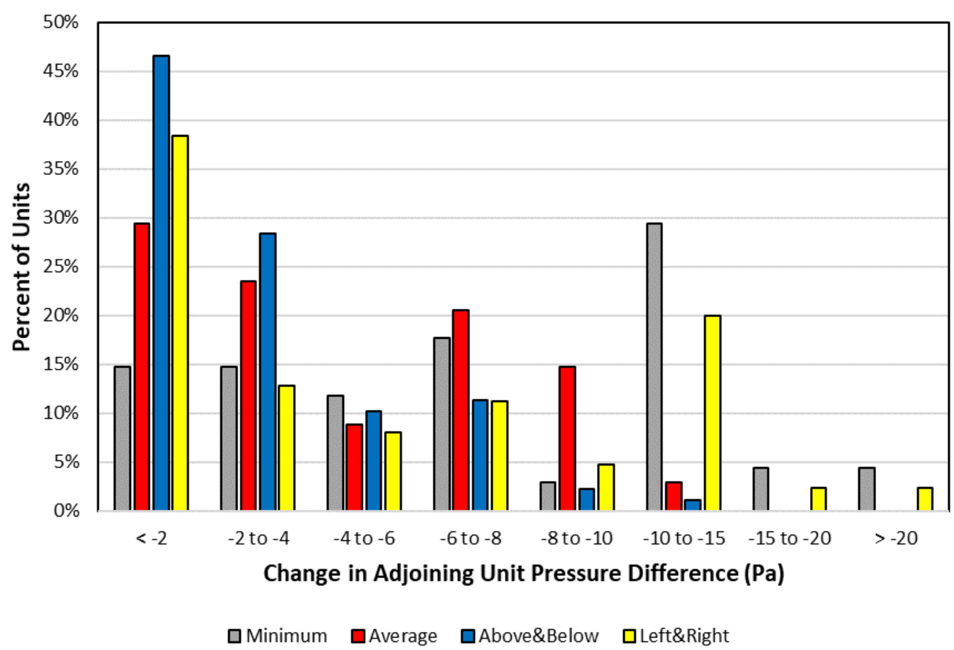


Figure 159. Histogram of Change in Adjacent Unit dP For Compartmentalization Test: Garden-Style Buildings

The horizontally adjacent (e.g., side-to-side) units typically had larger changes in pressure than vertically adjacent (e.g., up/down) units. The pressure change was larger than 5.0 Pa for 45% of the side-to-side units, but only 20% of the up/down units. Of the 68 units tested, there were six units (9%) for which the pressure change of any adjacent units was larger than 5.0 Pa and the largest change was in an up/down unit. This suggests that for Garden-Style buildings, if up/down units are not opened or checked for an acceptable pressure change during the compartmentalization test, about 10% of the tests would result in a measurable reduction in unit total leakage.

A total of 59%[43] of the units had the extra step of opening one or more of the adjacent units followed by a second compartmentalization test of total leakage. Figure 160 displays a box and whisker plot of the ratio of the total leakage measured with the adjacent unit(s) open and closed with the largest change in adjacent unit pressure. For the units for which the largest change in adjacent unit pressure was between 5.0 and 10.0 Pa the average ratio was only 1.010. For the units for which the largest change in adjacent unit pressure was between 10.0 to 15.0 Pa the average ratio was 1.045 and the average pressure change was 11.8 Pa. This suggests that if a total leakage uncertainty of 5% is sufficient, it would be acceptable to keep the adjacent units closed when the pressure change in the units is less than about 12 Pa. When an uncertainty less than 5% is required or the change in adjacent unit pressure is greater than 12 Pa, the adjacent unit should be opened or an adjustment made to increase the estimated total leakage. This is particularly important for larger pressure changes. For the 10 units for which the largest change in adjacent unit pressure was larger than 15.0 Pa the average ratio was 1.15.

[43] The percentage of units with a second test (59%) was less than the percentage with one or more adjacent unit with a pressure change larger than 5.0 Pa (65%). This was largely due to the post-baseline issue noted previously.

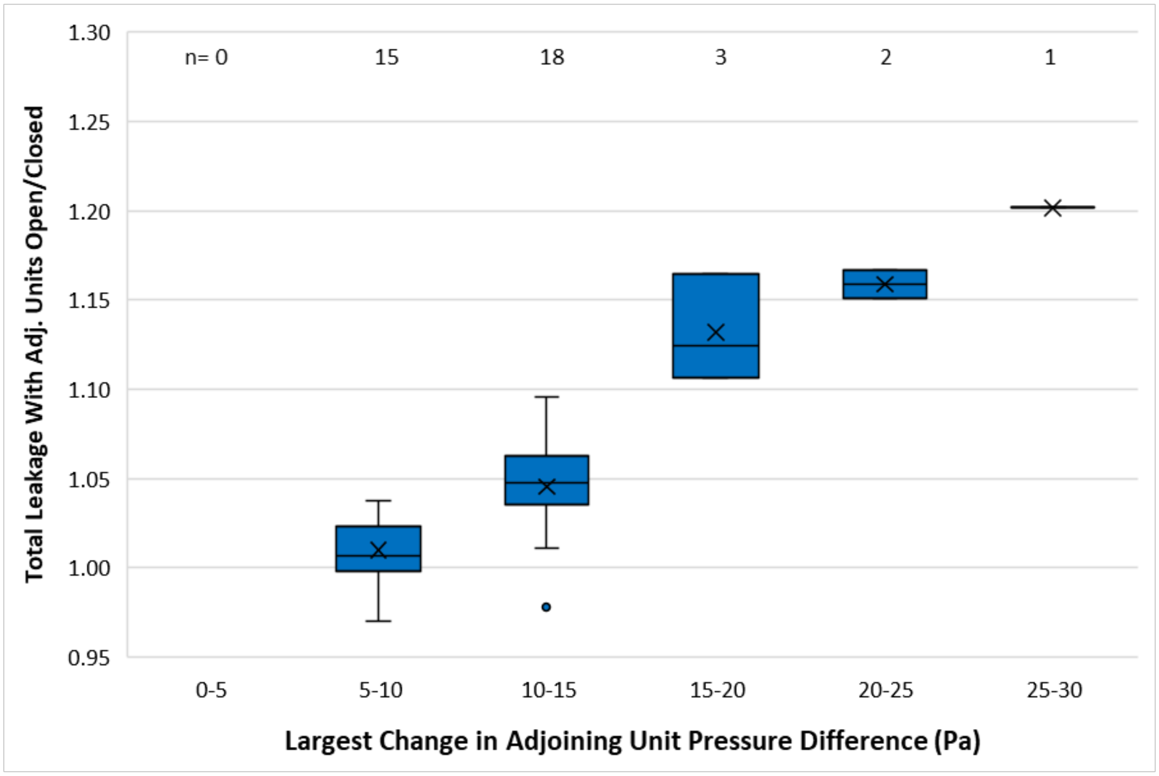


Figure 160. Relationship Between the Change in Adjacent Unit dP and Impact on Total Leakage Measurement: Garden-Style Buildings

Figure 161 displays the relationship between the ratio of the total leakage measured with the adjacent unit(s) open and closed (e.g., open/closed ratio) with the change in adjacent unit pressure. The black crosses represent the largest change in all adjacent units and the red circles represent the average of the adjacent units. There is a fairly strong quadratic relationship between the largest change in adjacent unit pressure and the open/closed ratio ($r^2 = 0.78$), although it is somewhat weaker than for the units from the common-entry buildings ($r^2 = 0.98$). The quadratic relationship for the average change in pressure was relatively poor ($r^2 = 0.32$). Consequently, the largest change in pressure is used as the dependent variable for the remainder of this analysis. The regression fit for quadratic equations are shown as dashed lines. The regressions were configured to force an intercept of 1.0 so that the computed ratio would be 1.0 when there is no change in pressure for any of the adjacent units. The equation estimates a ratio of 1.007 for a 5.0 Pa pressure change and a ratio of 1.049 for a 12.0 Pa change. That is consistent with the previous estimate that the error with keeping adjacent units closed would be no greater than 5% for pressure changes less than 12 Pa.

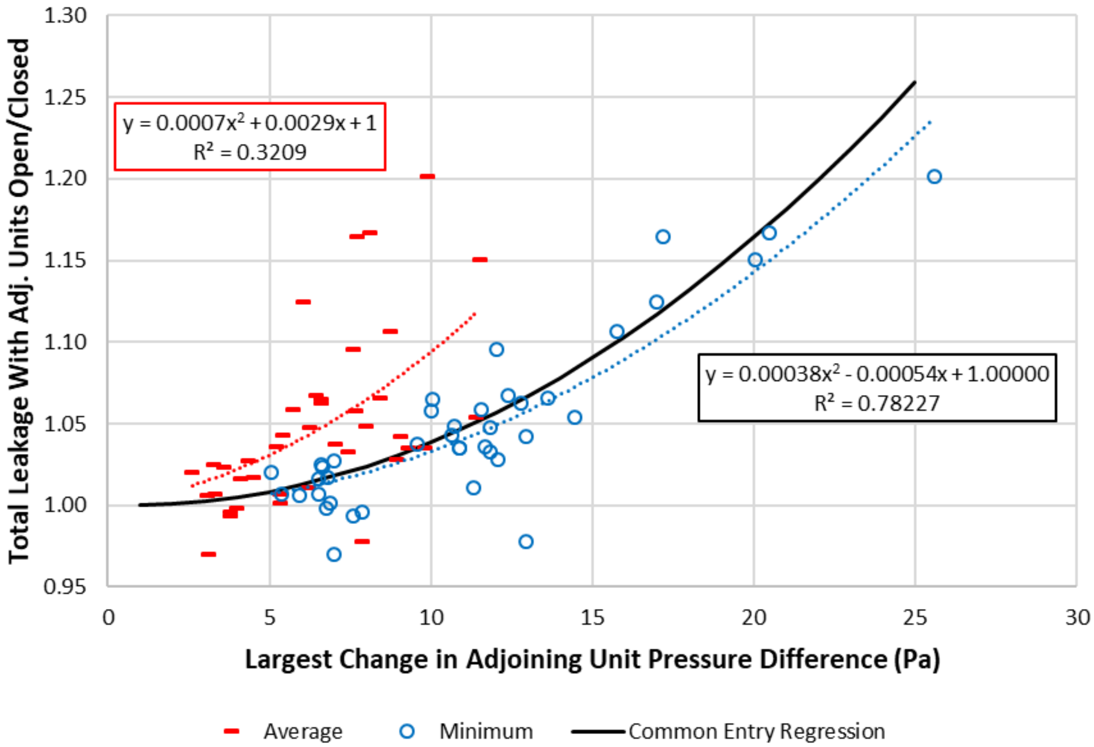


Figure 161. Relationship Between the Change in Adjacent Unit dP and Impact on Total Leakage Measurement: Garden-Style Buildings

The relationships between the open/closed ratio and the largest pressure change in adjacent units for the two-, three-, and multi-zone models with equal exterior leakage are shown in Figure 162. The figure also includes the common-entry and garden-style buildings along with the quadratic regression fits for those data sets and the complete dataset from all of the units.

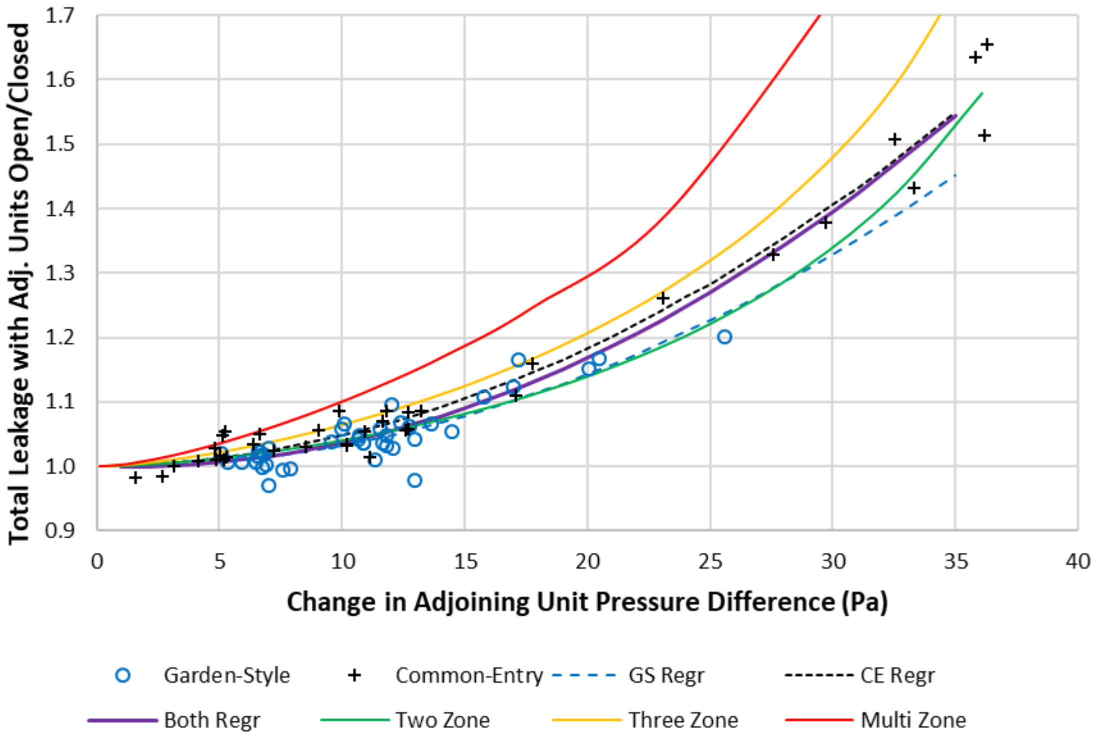


Figure 162. Quadratic Regression and Model Fit to Open/Closed Ratio

Figure 163 displays the percentage difference between the measured open/closed ratio and the ratio computed from the quadratic equation fit for the largest pressure change of adjacent units. Similar to the common-entry buildings, the simple quadratic adjustment is seen to hold nearly all errors under 5% for this sample of buildings. See the discussion of the common-entry buildings, above, for a justification of the use of the *largest* pressure as the independent variable.

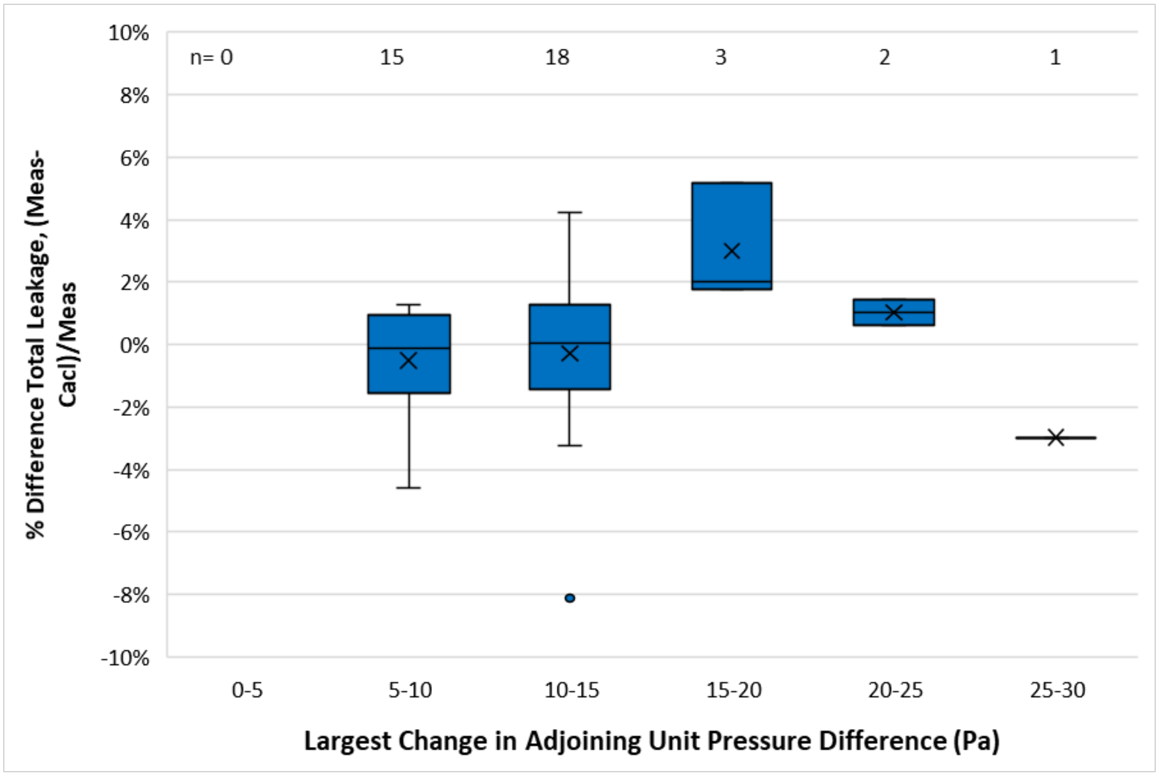


Figure 163. % Difference Between Calculated and Measured Total Leakage for Closed Adjoining Units: Garden-Style Buildings

Number of Blower Door Fans Required for Whole Building Tests

As noted in Table 1, one of the disadvantages of the whole building test is that it requires more equipment than a compartmentalization test. For garden-style buildings, a blower door or some type of test fan is required for each unit to test the entire building simultaneously. It is possible to test a portion of the building as long as all units adjacent to the tested units are pressurized or depressurized to the same pressure as the tested units.[44] Depending on the number of units and test fans available, it may be necessary to conduct more than two whole building tests to obtain a measurement for all of the units.

For common-entry buildings, enough fans must be installed in the building's exterior doors to produce the required test pressure throughout the entire building. There are typically two or more exterior doors in a new multifamily building. If the number of fans exceeds the number of doors, equipment for testing larger buildings is necessary to install more than one fan per exterior door. Fortunately, there are two- and three-fan setups available from multiple companies, and the pressure gauges and fans from house blower door testing can be used for these setups.

A straightforward calculation of the building volume and expected whole building leakage can quickly determine the number of fans that are needed for a test. Figure 164 displays the relationship between the test fan capacity and building floor area for a building with a volume-normalized leakage of 3.0 ACH_{50}. This assumes a fan capacity of 5,000 CFM and a 10 foot height for each floor. For example, a 30,000 ft^2 building with a volume-normalized leakage of 3.0 ACH_{50} would require a fan capacity of 15,000 CFM, or three typical blower door fans. For the common-entry buildings in

[44] This method is not recognized by air leakage test standards. It is likely that the code official would need to approve this approach.

this study, there was about 1,000 ft^2 of residential and common area floor area for each unit. This indicates that three blower door fans would be sufficient to conduct a whole building test of a typical 30-unit multifamily building with a volume-normalized leakage of 3.0 ACH_{50}.

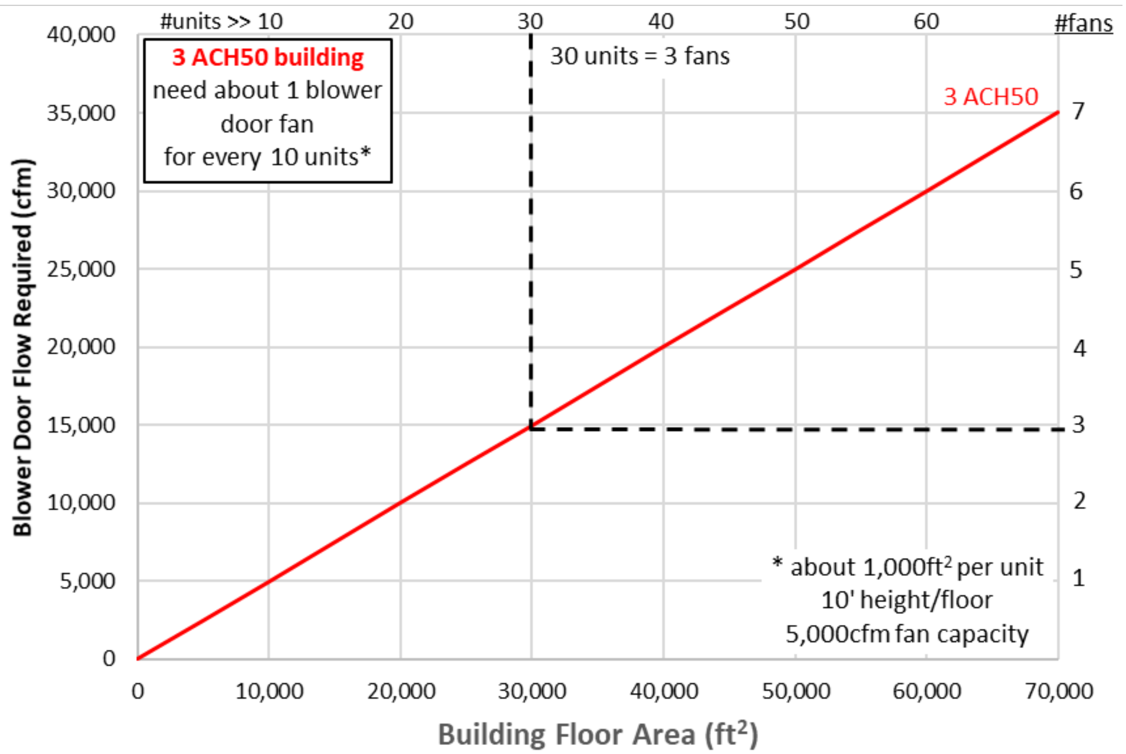


Figure 164. Number of Blower Door Fans for Whole Building Test of a 3.0 ACH_{50} Common-Entry Building

The number of test fans required for a whole building test is a function of not only the size of the building, but also the expected leakage. For new construction envelope leakage tests conducted for code or program requirements, it is typically only necessary to install enough test fan capacity for the required leakage rate and building volume. A lower leakage standard requires fewer test fans.

Figure 165 shows the test fan capacity and number of fans required by building floor area for whole building volume-normalized leakages from 1.0 to 5.0 ACH_{50}. For a typical building with 1,000 ft^2 of floor area per unit, a 45-unit building with a volume-normalized leakage of 2.0 ACH_{50} will require only three test fans. Four of the six states in the project had an average whole building leakage less than 2.0 ACH_{50}. Conversely, a 45-unit building with a volume-normalized leakage of 5.0 ACH_{50} would require eight test fans.

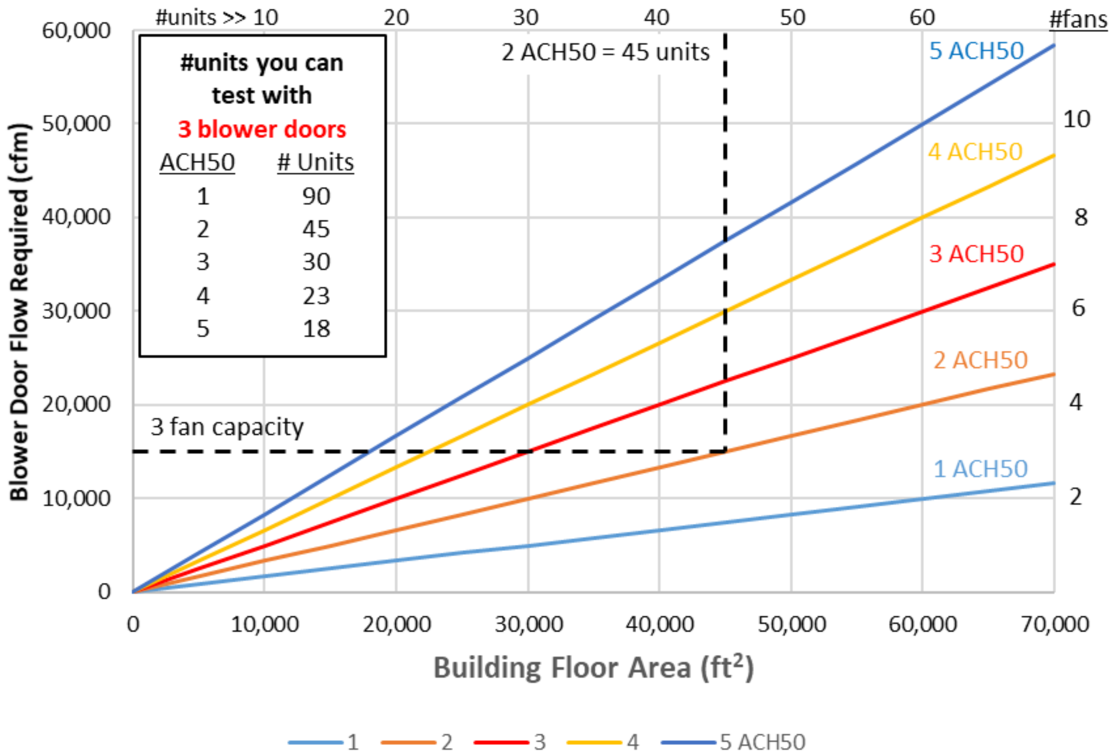


Figure 165. Blower Door Fan Capacity Required for Whole Building Tests

For the 20 common-entry buildings in this project, three blower door fans would have been sufficient to test 90% of the buildings. Figure 166 displays a histogram for the number of fans required based on the measured whole building leakage (blue bars) and the code required leakage (red bars). The table in the figure indicates the percentage of buildings that could have been tested with the specified number of fans. This includes 10% additional capacity over the measured or calculated capacity requirement and also assumes a test fan capacity of 5,000 CFM at a pressure difference of 50 Pa. All of the buildings could have been tested with a single three-fan setup and additional one-fan setup. In addition, 75% of the buildings could have been tested with two one-fan blower door setups. Unless a testing company has sufficient experience with a builder to assume that the building will be sufficiently tighter than the code requirement, it is safest to have enough test fan capacity for a building leakage equal to the code requirement. The red bars in Figure 166 indicate the number of buildings that could be tested with the specified number of fans when it is assumed that the building leakage is equal to that of the code requirement.[45] Since all of the buildings had a measured leakage less than the code requirement, the distribution for the number of fans is significantly greater. Even for this approach to determining the number of fans required, a single three-fan setup would have been sufficient to test almost half of the buildings, and two three-fan setups would have been sufficient to test 80% of the buildings.

[45] This assumes a volume-normalized leakage of 5.0 ACH_{50} for the Oregon building.

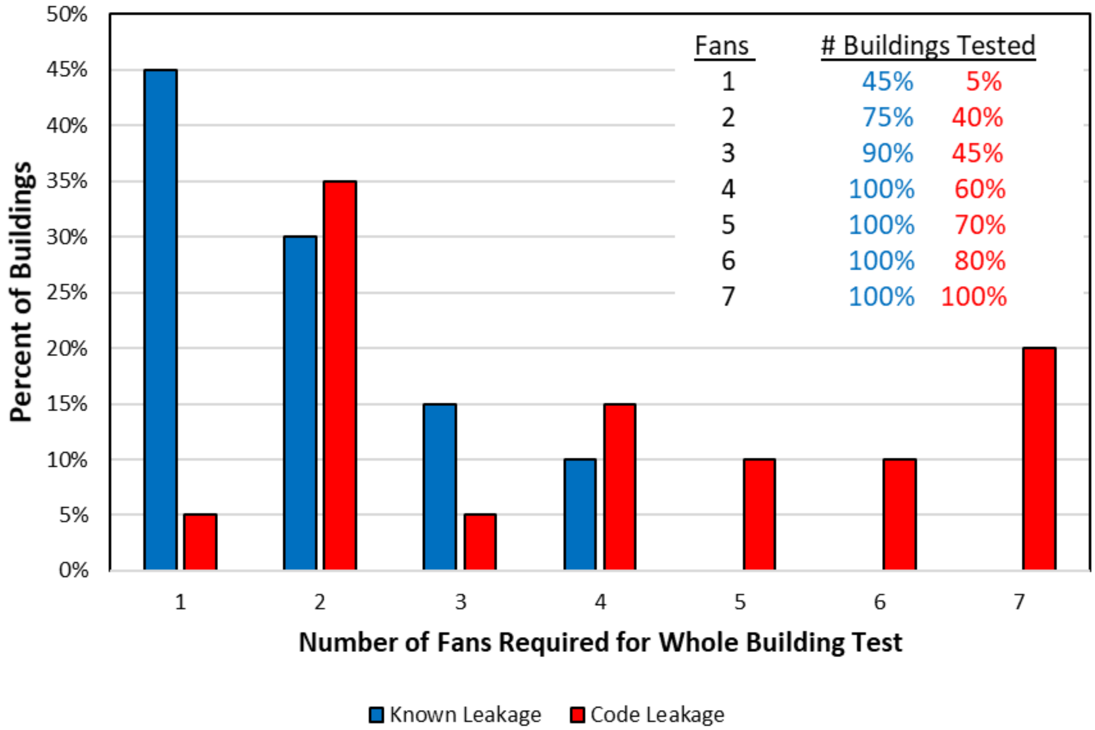


Figure 166. Number of Test Fans Required for Common-Entry Whole Building Tests

Variation in Unit Leakage within a Building

Energy rating and compliance programs often allow a sample of units in a multifamily building to be rated or tested. The amount of unit-to-unit variation in the performance should be used to guide the sampling frequency needed to assure a high degree of confidence that all or almost all units meet the performance criteria. This section presents the variability of multiple leakage characteristics for measurements conducted for units on the same level as well as for all units in the building.

For the 20 common-entry buildings in the project, all of the units were tested when there were 12 or fewer. When there were more than 12 units, a sample of 10 to 12 units was tested. The units were distributed evenly by level so that there were typically three to five units tested on each floor. The units were clustered so that they were adjacent to each other, and the cluster of units was selected to provide the greatest variety of most common floor plans. For three of the five garden-style buildings, all of the units (12 or 16 per building) were tested. For the two larger buildings with 18 and 25 units, a sample of 12 units was tested in each building.

The coefficient of variation (CV) is commonly used to indicate the relative variation of a group of measurements. The CV was computed for measurements of all units on the same level of a building and of all units tested in the building. The values were computed for three leakage characteristics: (1) volume-normalized (total and exterior), (2) surface-area-normalized (total, exterior, interior, to common space, and to adjoining units), and (3) percentage of exterior. The results are grouped by building type (common-entry and garden-style), and the common-entry building results are split by attic type (vented-attic and flat-roof).

Variation in Percent Exterior and Volume-Normalized Leakage

The CVs of percent exterior leakage, volume-normalized total leakage, and volume-normalized exterior leakage for units on the same floor and for the entire building are shown in Table 80 for common-entry buildings. The box-and-whisker plots shown in Figure 167 and Figure 168 provide a visual representation of the variability of the CVs for flat-roof and vented-attic buildings, respectively. The CVs for units tested on the same floor had only weak trends for type of attic and building level. When the CVs for all building attic types and levels are combined (n=76), the median CVs were 12%, 15%, and 18% for percent exterior leakage, volume-normalized total leakage, and volume-normalized exterior leakage, respectively, with IQRs of 10%, 10% and 11%, respectively. This indicates that leakage measurements for units on the same floor typically have CVs from 10% to 20%. However, for about 10% of the buildings, the CVs were 25% or greater.

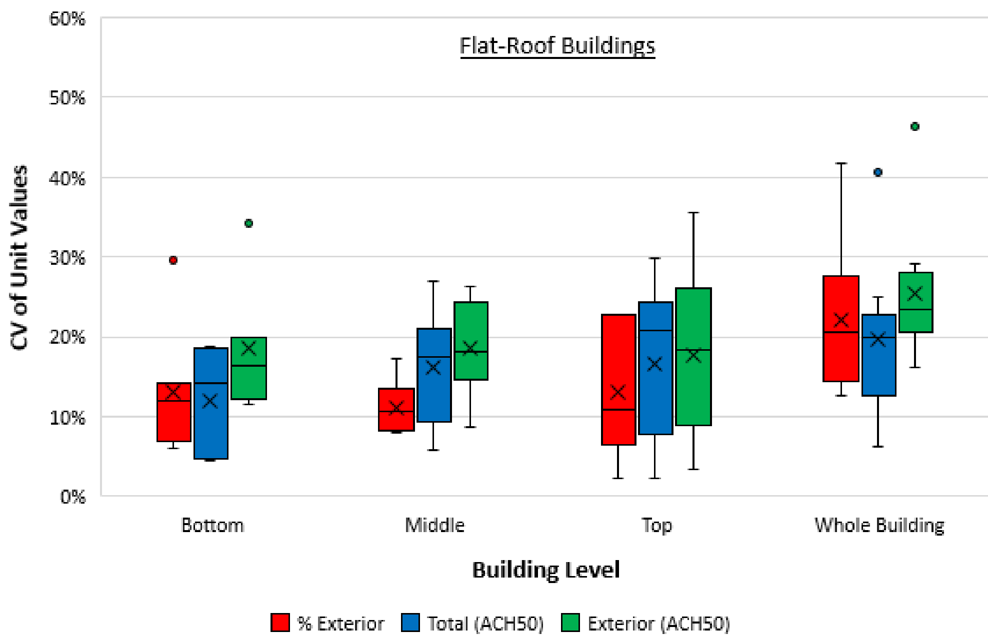


Figure 167. CV of Percent Exterior and Volume-Normalized Leakage for Units on Same Floor or Whole Building: Flat-Roof, Common-Entry Buildings

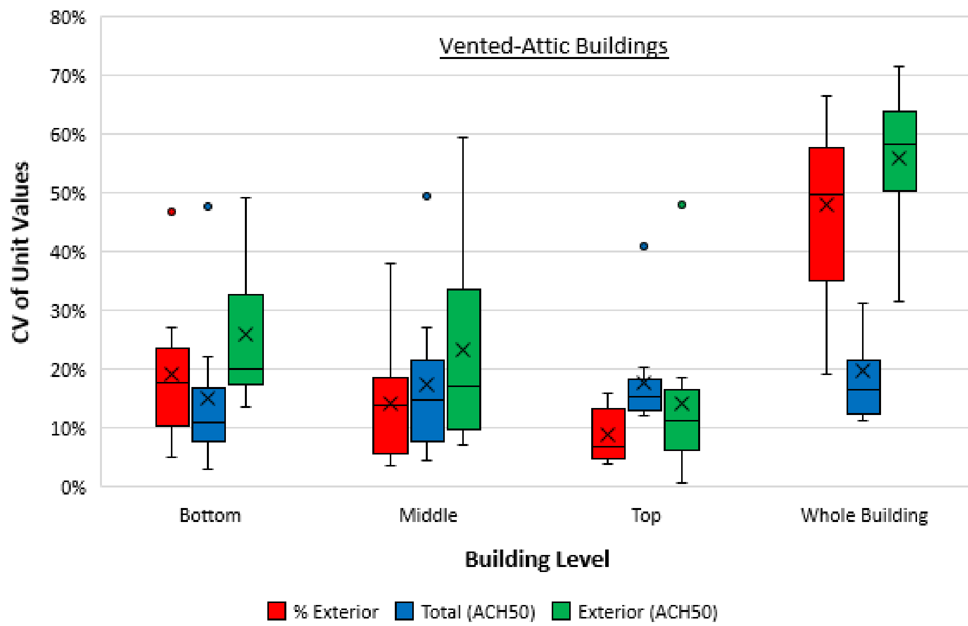


Figure 168. CV of Percent Exterior and Volume-Normalized Leakage for Units on Same Floor or Whole Building: Vented-Attic, Common-Entry Buildings

Table 80. CV of Percent Exterior and Volume-Normalized Leakage for Units on Same Floor or Whole Building: Common-Entry Buildings

	% Exterior Leakage				Vol. Normalized Total Leakage				Vol. Norm. Exterior Leakage			
	Building Level				Building Level				Building Level			
ID	Bottom	Middle	Top	Bldg	Bottom	Middle	Top	Bldg	Bottom	Middle	Top	Bldg
Vented Attic Buildings												
IA 63	24%	5%		19%	22%	7%		31%	31%	14%		32%
IL 41	47%	4%	12%	54%	6%	5%	14%	12%	45%	7%	1%	58%
MI 81	27%	18%	5%	66%	11%	13%	14%	13%	25%	12%	10%	72%
MN 51	10%	38%	7%	61%	10%	20%	21%	16%	17%	59%	14%	62%
MN 54	18%	13%	7%	47%	15%	8%	13%	21%	33%	20%	5%	64%
MN 57	20%	20%	13%	56%	10%	27%	17%	22%	14%	23%	9%	68%
MN 58	9%	17%	16%	58%	16%	16%	18%	17%	16%	10%	7%	62%
MN 59	16%	15%	14%	35%	17%	19%	12%	21%	20%	28%	19%	37%
MN 73	15%	6%	5%	47%	3%	9%	13%	11%	18%	10%	13%	50%
OR 2	5%	7%	5%	35%	48%	50%	41%	41%	49%	50%	48%	56%
WA 1	19%		4%	50%	8%		17%	13%	18%		16%	53%
Avg.	19%	14%	9%	48%	15%	17%	18%	20%	26%	23%	14%	56%
Median	18%	14%	7%	50%	11%	15%	15%	17%	20%	17%	11%	58%
Flat Roof Buildings												
IA 61	6%	11%	9%	13%	14%	16%	10%	16%	20%	26%	18%	22%
IA 62	14%	8%	23%	21%	14%	18%	22%	20%	16%	22%	32%	23%
IL 42	30%	8%	23%	42%	5%	12%	25%	41%	34%	16%	19%	46%
IL 43	8%	10%	4%	28%	8%	7%	2%	9%	16%	17%	6%	25%
IL 44	7%	8%	2%	27%	5%	6%	6%	6%	12%	14%	3%	27%
MN 55		11%	11%	16%		18%	21%	20%		26%	20%	22%
MN 56		17%	23%	21%		22%	30%	25%		19%	36%	29%
MN 71	12%	14%	15%	13%	19%	20%	23%	21%	19%	9%	13%	16%
MN 72	14%	13%	9%	20%	19%	27%	11%	19%	12%	18%	12%	19%
Avg.	13%	11%	13%	22%	12%	16%	17%	20%	19%	19%	18%	26%
Median	12%	11%	11%	21%	14%	18%	21%	20%	16%	18%	18%	23%

For common-entry buildings, the relative variation in percent exterior leakage for all units in a building varied greatly. For example, the CV for building IA61 was only 13%, while for MI81 it was 66%. As noted in Section 4.3.1 (See Figure 69 and Figure 70), the higher percent exterior leakage of the top floor units in vented-attic buildings caused greater variability of the percent exterior leakage within a building. The CV for the percent exterior leakage of the units within a building averaged 22% for flat-roof buildings and was more than twice that (48%) for vented-attic buildings. The results were similar for the volume-normalized exterior leakage for all units in a building. The CV of the volume-normalized exterior leakage for all of the units in each building varied from 16% to 72% and averaged 42%. The median CV of the volume-normalized exterior air leakage for the flat-roof buildings was 23%, and the median CV for the vented-attic buildings was 60% — or 2.5 times higher. This suggests that for vented-attic, common-entry buildings, a sampling strategy should differentiate between levels in the building when testing for exterior leakage. However, and quite interestingly, for those buildings there was only a moderate increase in CV in the volume-normalized total leakage for all units in a building compared to units on the same level (19% versus 15%). In addition, for flat-roof buildings the variability in percent exterior leakage, volume-normalized exterior leakage, and volume-normalized **total** leakage was only slightly greater for all units in a building compared to the variability for units on the same floor. It is important to note that this result is based on this set of 20 buildings and may not apply to all common-entry buildings. A more conservative approach would be to always include level-by-level variations in a sampling strategy.

The CVs of percent exterior leakage, volume-normalized total leakage, and volume-normalized exterior leakage for units on the same floor and for the entire building are shown in Table 81 for garden-style buildings. The box-and-whisker plots shown in Figure 169 provide a visual representation of the variability of the CVs. Similar to the common-entry buildings, the CVs for units tested on the same floor had only weak trends for building level. When the CVs for all three building levels are combined (n=12), the median CVs were 10%, 10%, and 9% for percent exterior leakage, volume-normalized total leakage, and volume-normalized exterior leakage, respectively, with IQRs of 7%, 4% and 8%, respectively. These results are somewhat lower than those for the larger dataset from the common-entry buildings. For all 25 buildings in the study, the median CV for volume-normalized total leakage measurements conducted for units on the same floor was 14%. The median was slightly lower for percent exterior leakage and slightly higher for volume-normalized exterior leakage.

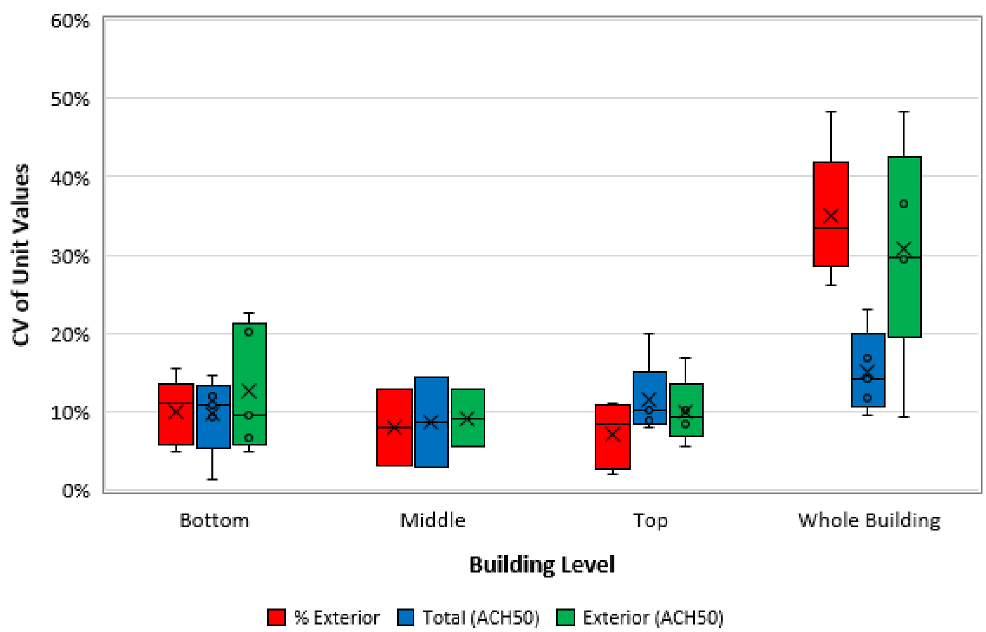


Figure 169. CV of Percent Exterior and Volume-Normalized Leakage for Units on Same Floor or Whole Building: Garden-Style Buildings

Table 81. CV of Percent Exterior and Volume-Normalized Leakage for Units on Same Floor or Entire Building: Garden-Style Buildings

	% Exterior Leakage				Vol. Normalized Total Leakage				Vol. Norm. Exterior Leakage			
	Building Level				Building Level				Building Level			
ID	Bottom	Middle	Top	Bldg	Bottom	Middle	Top	Bldg	Bottom	Middle	Top	Bldg
OR 4	5%	3%	2%	26%	1%	3%	8%	23%	5%	6%	9%	9%
WA 3	7%	13%	8%	48%	11%	14%	10%	14%	7%	13%	8%	48%
WA 5	16%		11%	33%	12%		20%	17%	20%		17%	30%
MN 52	12%		4%	36%	15%		9%	12%	23%		10%	37%
MN 53	11%		11%	31%	9%		10%	9%	9%		5%	29%
Avg.	10%	8%	7%	35%	10%	9%	11%	15%	13%	9%	10%	31%
Median	11%	8%	8%	33%	11%	9%	10%	14%	9%	9%	9%	30%

Compared to the large building-to-building variation for the common-entry buildings, the CV for percent exterior leakage for units in the same building was fairly consistent. For the five garden-style buildings, the CV ranged from 26% for building OR4 to 48% for WA3 and had a median of 33%. The level of consistency between the garden-style buildings is not surprising, since all of the buildings had vented attics, and for the common-entry buildings the most significant variations occurred between the flat-roof and vented-attic buildings. The CV for the percent exterior leakage for all of the units in a building was typically 4.6 times greater than the average CV for the percent exterior leakage of the units on the same floor. The results were similar for the volume-normalized exterior leakage for all units in a building. The CV of the volume-normalized exterior leakage for all of the units in each building varied from 9% (for OR4) to 48% (for WA3) and had a median of 30%. The median of 30% is 3.2 times greater than the median CV of 9% for units tested on the same floor.

Similar to the results for common-entry, vented-attic buildings, the median CV for volume-normalized total leakage of all units in a building is only slightly higher (14%) than the median of 10% for tests of units on the same floor. This suggests that for both garden-style and common-entry vented-attic buildings, a sampling strategy should differentiate between levels in the building when testing for exterior leakage. However, for all buildings there was only a moderate increase in CV in the volume-normalized total leakage for all units in a building compared to units on the same level.

Variation in Surface-Area-Normalized Leakage

The CVs of surface-area-normalized total, exterior, and interior leakage for units on the same floor and the entire building are shown in Table 82 for common-entry buildings with box and whisker plots shown in Figure 170 and Figure 171 for flat-roof and vented-attic buildings respectively.

While the variation in surface-area-normalized leakage between buildings was less than the variation in volume-normalized leakage (ACH_{50}), the variation of surface-area-normalized leakage for units in the same building was generally greater than that for volume-normalized leakage. For example, for six of the eight buildings, the ratio of maximum to minimum surface-area-normalized leakage was greater than 4.0 but the volume-normalized ratio was greater than 4.0 for only two buildings.

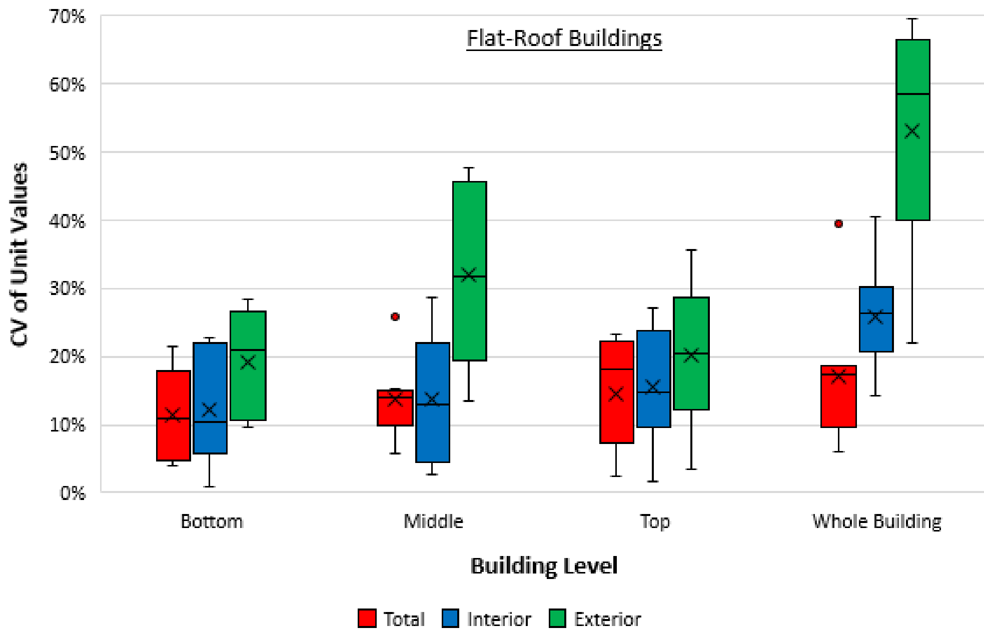


Figure 170. CV of Surface-Area-Normalized Leakage for Units on Same Floor or Whole Building: Flat-Roof, Common-Entry Buildings

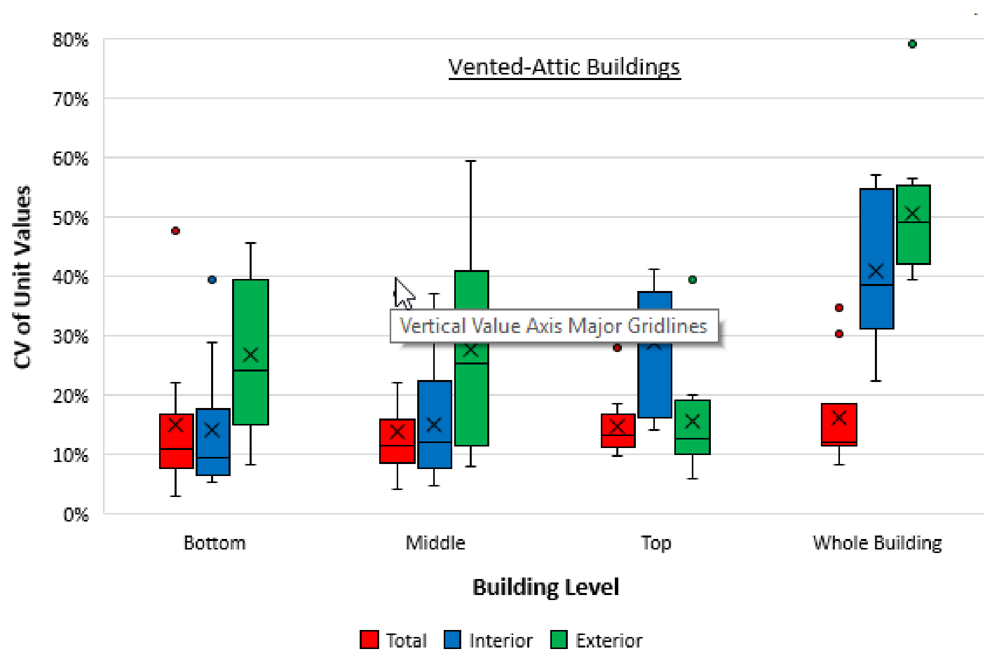


Figure 171. CV of Surface-Area-Normalized Leakage for Units on Same Floor or Whole Building: Vented-Attic, Common-Entry Buildings

Table 82. CV of Surface-Area-Normalized Leakage for Units on Same Floor or Whole Building: Common-Entry Buildings

	Total Leakage				Interior Leakage				Exterior Leakage			
	Building Level				Building Level				Building Level			
ID	Bottom	Middle	Top	Bldg	Bottom	Middle	Top	Bldg	Bottom	Middle	Top	Bldg
Vented Attic Buildings												
IA 63	25%	12%		35%	40%	22%		55%	40%	20%		49%
IL 41	6%	4%	12%	8%	9%	5%	41%	32%	46%	12%	12%	57%
MI 81	8%	10%	12%	11%	10%	13%	33%	57%	22%	11%	12%	42%
MN 51	10%	11%	19%	12%	7%	9%	33%	29%	24%	59%	16%	41%
MN 54	10%	5%	10%	12%	15%	5%	27%	39%	35%	31%	10%	51%
MN 57	8%	22%	14%	15%	5%	23%	32%	31%	10%	25%	14%	40%
MN 58	12%	13%	14%	12%	10%	16%	38%	35%	15%	8%	6%	44%
MN 59	13%	14%	10%	19%	7%	9%	14%	22%	26%	45%	9%	79%
MN 73	4%	10%	13%	13%	6%	11%	14%	42%	8%	25%	19%	48%
OR 2	36%	37%	28%	30%	29%	37%	37%	57%	44%	40%	40%	52%
WA 1	7%		16%	12%	18%		17%	51%	24%		20%	55%
Avg.	13%	14%	15%	16%	14%	15%	29%	41%	27%	28%	16%	51%
Median	10%	12%	13%	12%	10%	12%	33%	39%	24%	25%	13%	49%
Flat Roof Buildings												
IA 61	11%	13%	9%	12%	10%	10%	12%	27%	27%	46%	21%	66%
IA 62	22%	13%	19%	17%	22%	21%	14%	29%	21%	39%	32%	65%
IL 42	5%	15%	22%	39%	14%	3%	25%	40%	28%	48%	36%	47%
IL 43	7%	7%	2%	6%	6%	6%	2%	19%	15%	17%	6%	22%
IL 44	4%	6%	6%	7%	1%	3%	7%	14%	11%	14%	3%	33%
MN 55		14%	23%	19%		13%	22%	22%		45%	26%	70%
MN 56		15%	23%	18%		23%	27%	32%		22%	22%	50%
MN 71	13%	14%	18%	16%	11%	16%	15%	23%	23%	27%	19%	67%
MN 72	18%	26%	10%	19%	23%	29%	15%	26%	10%	32%	18%	59%
Avg.	11%	14%	15%	17%	12%	14%	16%	26%	19%	32%	20%	53%
Median	11%	14%	18%	17%	11%	13%	15%	26%	21%	32%	21%	59%

The CVs of surface-area-normalized unit to common space and adjoining units leakage for units on the same floor and the entire building are shown in Table 83 for common-entry buildings with the box and whisker plots shown in Figure 172 covering both building types. The CVs for leakage to common space are somewhat larger than the CVs for leakage to adjoining units, and both are relatively high: typically above 20% even within floors.

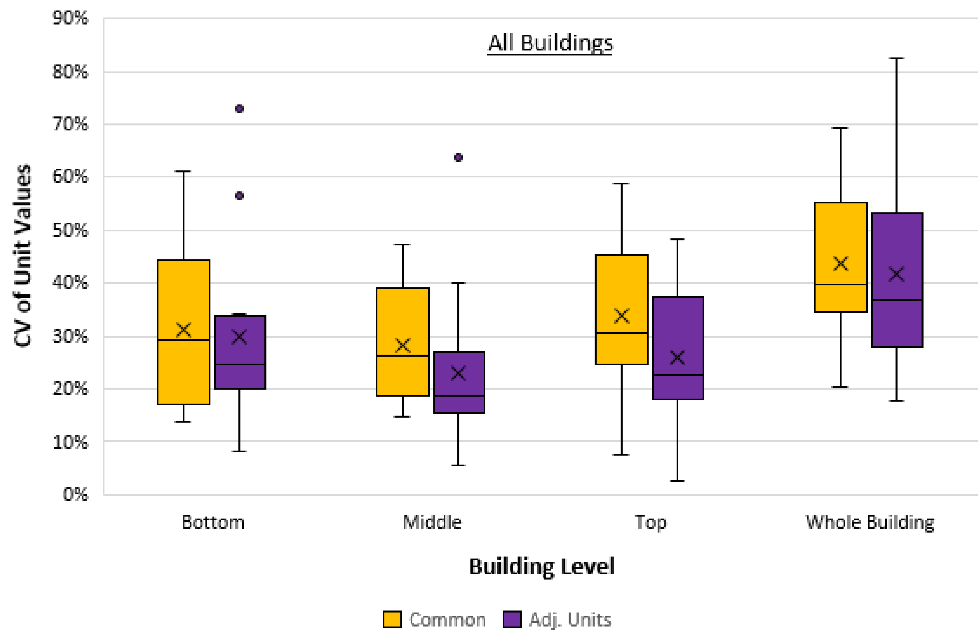


Figure 172. CV of Surface-Area-Normalized Leakage for Units on Same Floor or Whole Building: Common-Entry Buildings

Table 83. CV of Surface-Area-Normalized Leakage for Units on Same Floor or Whole Building: Common-Entry Buildings

	Leakage to Common Areas				Leakage to Adjoining Units			
	Building Level				Building Level			
ID	Bottom	Middle	Top	Bldg	Bottom	Middle	Top	Bldg
Vented Attic Buildings								
IA 63	38%	15%		35%	56%	20%		76%
MI 81	21%	29%	48%	55%	24%	22%	44%	83%
MN 57	39%	19%	29%	34%	21%	19%	22%	37%
MN 58	29%	27%	32%	40%	12%	18%	17%	25%
MN 59	17%	19%	37%	38%	8%	6%	2%	18%
MN 73	18%	17%	7%	36%	31%	11%	23%	42%
OR 2	46%	26%	58%	52%	73%	64%	48%	52%
WA 1	46%		25%	69%	33%		17%	54%
Avg.	32%	22%	34%	45%	32%	23%	25%	48%
Median	33%	19%	32%	39%	28%	19%	22%	47%
Flat Roof Buildings								
IA 61	61%	47%	59%	58%	25%	15%	41%	33%
IA 62	14%	43%	32%	46%	34%	29%	27%	30%
MN 56		26%	29%	55%		18%	21%	19%
MN 71	30%	42%	25%	31%	23%	15%	28%	43%
MN 72	15%	26%	23%	20%	20%	40%	22%	31%
Avg.	30%	37%	33%	42%	26%	23%	28%	31%
Median	22%	42%	29%	46%	24%	18%	27%	31%

The CVs of surface-area-normalized unit to common space and adjoining units leakage for units on the same floor and the entire building are shown in Table 84 for garden-style buildings with the box and whisker plots shown in Figure 173.

For garden-style buildings there was significantly greater variation in surface-area-normalized exterior leakage for units in a building than variation in surface-area-normalized total leakage. It is likely that this was due to greater floor-to-floor variation in exterior leakage than occurs for total leakage. For all units tested in a building the CV for surface-area-normalized total leakage ranged from 10% to 23% with an average of 16% while the exterior leakage ranged from 30% to 56% and averaged 40%.

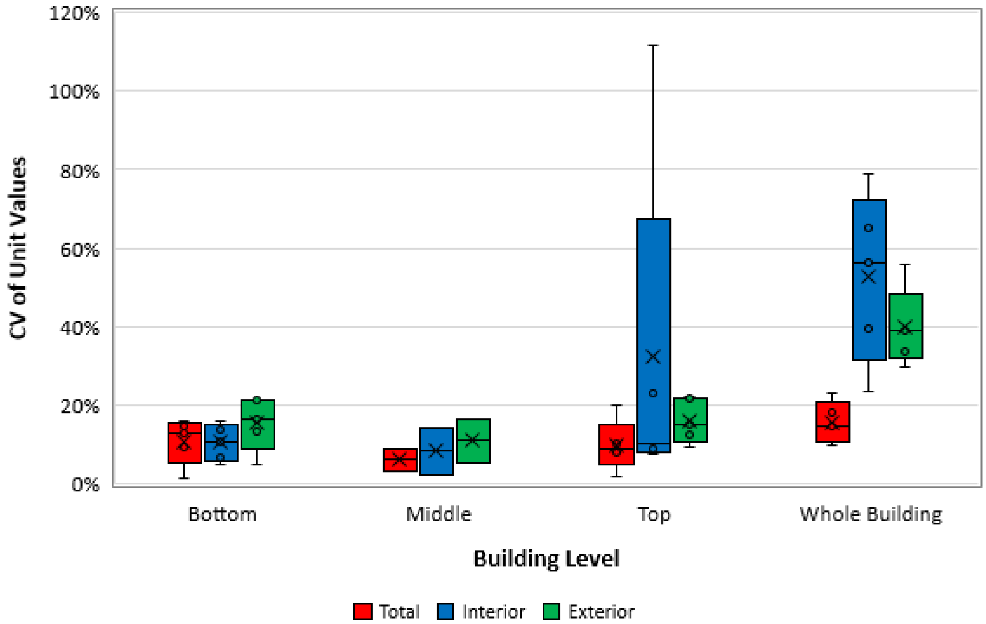


Figure 173. CV of Surface-Area-Normalized Leakage for Units on Same Floor or Whole Building: Garden-Style Buildings

Table 84. CV of Surface-Area-Normalized Leakage for Units on Same Floor or Whole Building: Garden-Style Buildings

	Total Leakage				Interior Leakage				Exterior Leakage			
	Building Level				Building Level				Building Level			
ID	Bottom	Middle	Top	Bldg	Bottom	Middle	Top	Bldg	Bottom	Middle	Top	Bldg
OR 4	1%	3%	8%	23%	5%	2%	7%	65%	5%	6%	9%	56%
WA 3	16%	9%	2%	15%	11%	14%	10%	56%	21%	16%	22%	39%
WA 5	13%		20%	18%	14%		111%	79%	17%		22%	30%
MN 52	15%		9%	12%	16%		9%	39%	21%		15%	41%
MN 53	9%		10%	10%	7%		23%	23%	13%		12%	34%
Avg.	11%	6%	10%	16%	10%	8%	32%	53%	15%	11%	16%	40%
Median	13%	6%	9%	15%	11%	8%	10%	56%	17%	11%	15%	39%

APPENDIX E: BUILDING AIRFLOW DRIVING FORCES

The model includes driving forces due to thermal buoyancy effects induced by temperature differences between zones — effects such as outdoor conditions, wind pressures on the building exterior, and HVAC flows.

Stack Effect

The thermal buoyancy or stack pressure can be computed using the following equation (ASHRAE 2013):

$$\Delta P_s = C_2 \rho_i g (H - H_{NPL})(T_i - T_o)/T_o \quad (4)$$

[46]

$\Delta P_s = pressure\ difference\ due\ to\ stack\ effect\ [in\ wc]$
$C_2 = 0.00598\ (unit\ conversion\ factor)$
$g = 32.2 \frac{ft}{s^2}\ (gravitational\ constant)$
$H = leakage\ path\ height\ [ft]$
$H_{NPL} = height\ of\ neutral\ pressure\ level\ [ft]$
$T = ablsolute\ temperature\ [°R]$
Subscripts
$i = indoor$
$o = outdoor$

For stack-only conditions (e.g., no wind and no HVAC imbalance), the restrictions to airflow caused by the floor/ceiling between each story causes a pressure difference between each floor, resulting in a sawtooth pattern of the pressure across the exterior walls. Figure 174 shows this pattern for an outside air temperature of 30°F and inside air temperature of 70°F. If there were no restrictions to airflow between floors, the inside with respect to outside pressure difference at the bottom of the building would be -4.3 Pa, and the pressure difference at the top of the building would be +4.3 Pa. In addition, units on the first floor would only have air infiltration, and third-floor units would only have air exfiltration. In contrast, the model with 75% of the unit leakage being to the exterior (red line in Figure 174) has a large pressure drop between floors (2.8 Pa); the NPL is located at about the mid-height of each floor; and the ground level pressure is -1.5 Pa, or 35% of what it would be with no vertical restrictions. Since 10% of the interior leakage is between floors for the first- and third-floor units, only 2.5% of the total leakage is between floors. That increases to 7% for the models with 30% exterior leakage (70% interior — solid blue line in Figure 174), and the ground level pressure changes to -2.1 Pa. Figure 174 also shows that the pressure profile is determined by the amount of interior leakage relative to the exterior leakage and not the absolute amount of interior leakage. The model with units that have a total leakage of 2.0 ACH_{50} and exterior leakage of 0.6 ACH_{50} (30% of total) has the same profile as the model with a total leakage of 5 ACH_{50} and exterior leakage of 1.5 ACH_{50}.

[46] 1997 ASHRAE-Fundamentals 25.9 eq. 28

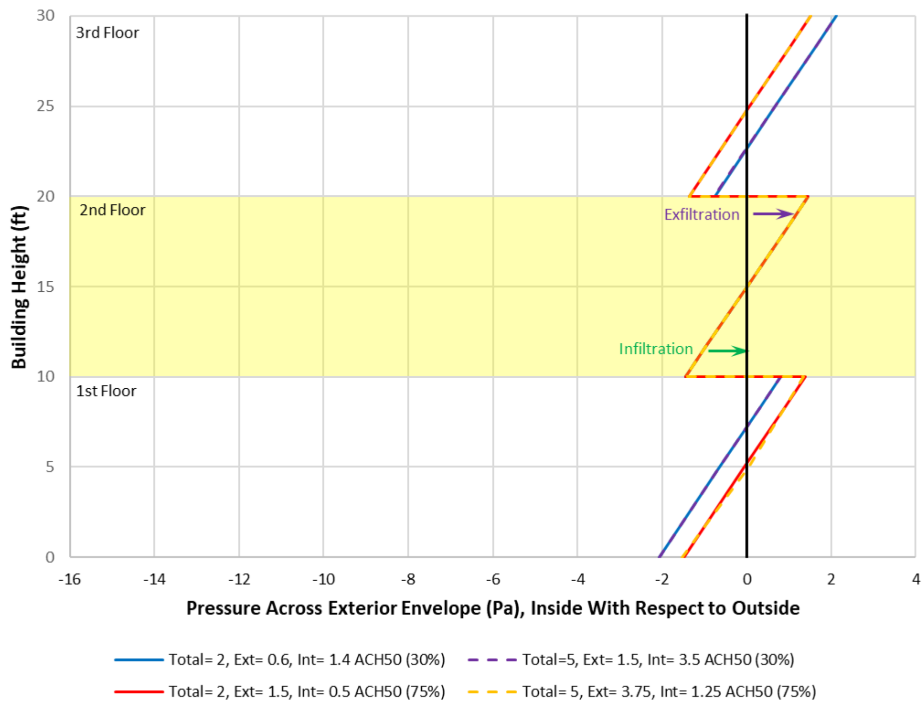


Figure 174. Stack Pressure for 30F Outside Air Temperature

Exhaust Fan

Figure 175 displays the level of unit depressurization for the four air leakage cases when all of the units have a continuously operating exhaust fan with an airflow rate of 51.0 CFM. The depressurization is primarily a function of the level of exterior leakage, with smaller exterior leakage creating greater depressurization. For example, the model with the smallest leakage (0.6 ACH_{50} — solid blue line) has the highest depressurization of -12.4 Pa, and the model with the highest leakage (3.75 ACH_{50} — dashed orange line) has the lowest depressurization of -0.9 Pa. Since all of the units in each building simulation have nearly the same pressure, the level of interior leakage between units has almost no impact on the unit depressurization. However, air is drawn from outside into the corridor and then from the corridor into each unit. Consequently, the level of interior leakage between the unit and corridor impacts the unit pressure. Higher levels of unit-to-corridor leakage reduces the level of unit depressurization needed to draw in air from outside and the corridor to match the air exhausted through the fan. For example, the model results represented by the solid red line and dashed purple line both have models with an exterior leakage of 1.5 ACH_{50}. The model with the greater interior leakage of 3.5 ACH_{50} (dashed purple line) has the lower depressurization of -3.0 Pa compared to the model with an interior leakage of 0.5 ACH50 (solid red line) that produces a depressurization of -3.8 Pa.

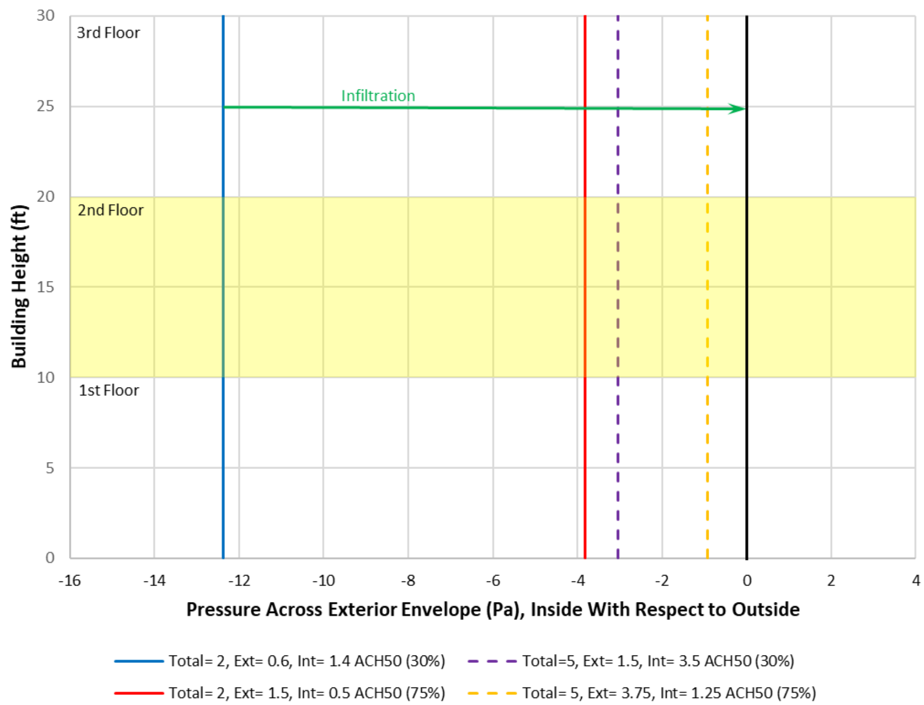


Figure 175. Unit Depressurization Due to Exhaust Ventilation

The relative amount of exterior leakage determines the fraction of air that enters from outside. For both models with 30% exterior leakage, 75% of the air enters from outside — and the two models with 75% exterior leakage have 87% of the air entering directly from outside through the exterior wall of the apartment. The percentage of air entering from outside is much greater than the percentage of exterior leakage because there is almost no airflow through the leakage between units.

Exhaust Fan and Stack

The next version of the model combines the first two models: a stack effect produced by an outside air temperature of 30°F and exhaust airflow of 51 CFM from each unit. Adding the exhaust fan airflow to the stack effect causes the stack effect pressure profile to shift to the left, i.e., raises the NPLs. (See Figure 176.) The amount of the shift is roughly equal to the level of depressurization caused by the exhaust fan without the stack effect. However, the pressures from the two separate driving forces cannot be simply added to determine the combined effect because the leakage path relationship between pressure and flow is non-linear. Adding the exhaust airflow to the stack effect causes a decrease in the pressure drop between floors for the two models with 30% exterior leakage and almost no change in the pressure drop between floors for the models with 75% exterior leakage. This illustrates the complex nature of combined driving forces with nonlinear leakage path relationships for multizone buildings.

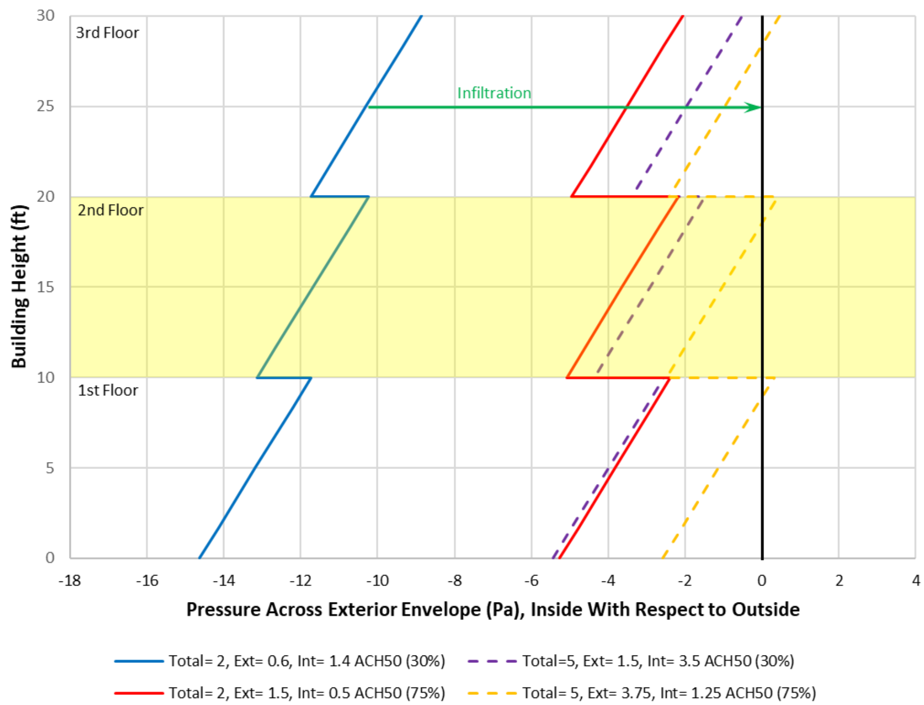


Figure 176. Combined Impact of Stack Effect and Exhaust Ventilation

For the buildings that have units with exterior leakages of 0.6 ACH_{50}, the depressurization from the 51 CFM exhaust fan is significantly greater than the vertical variation in pressure due to the stack effect. The units on all three floors are depressurized from floor to ceiling by at least -8.9 Pa. In addition, the units on all floors would remain depressurized even for an outside air temperature of -20°F.[47] Since there is no exfiltration from any of the units, the amount of air entering a unit is simply equal to the amount of air leaving through the exhaust fan. Furthermore, the fraction of exhaust fan air flow that comes from outside is primarily a function of the percentage exterior leakage and will not change with varying outside temperature. Consequently, the level of infiltration will not change for varying outside air temperatures. In summary, tighter buildings with adequate exhaust ventilation will have a constant level of ventilation from infiltration over a wide range of outside air temperatures.

For the building model with units that have total leakages of 5.0 ACH_{50} and interior leakages of 1.25 ACH_{50} (dashed orange line in Figure 176), portions of the exterior walls have a positive inside with respect to outside pressure difference. This shows that as the building leakage increases and outside air temperature decreases, a larger portion of the exterior wall will be under positive pressure which will result in increased exfiltration and infiltration.

[47] For an outside air temperature of -20F the pressure across the exterior wall at the ground is -17.4 Pa and the wall pressure at the top of the building is -4.6 Pa.

Wind Effect

CONTAM calculates wind pressure using the following equation (Dols and Polidoro 2015):

$$P_w = \frac{\rho V_{met}^2}{2} C_h f(\theta) \qquad (5)$$

$$V_{met} = wind\ speed\ measured\ at\ meteorological\ station$$
$$C_h = wind\ speed\ modifier\ coefficient\ (terrain\ and\ elevation\ effects)$$
$$f(\theta) = wind\ pressure\ profile, a\ function\ of\ wind\ direction$$
$$\theta = angle\ of\ incidence\ between\ wind\ direction\ and\ building\ surface$$

At a height of 13 feet, C_h is equal to 0.17, 0.36, and 0.76 for urban, suburban, and airport terrains, respectively. A value of 0.36 was used for all exterior wall leaks and did not vary by height. The low-rise wall wind pressure coefficient profile developed by Swami and Chandra (1987) was used for exterior wall leakage paths. (See Figure 177.) The profile produces a positive pressure for leaks within about 60 degrees of the wind direction and a negative pressure for all other angles. As shown in Figure 178, the surface wind pressure is above 10 Pa for wind speeds greater than about 20 miles per hour when the wind is perpendicular to the wall surface (i.e., angle of incidence = 0 degrees).

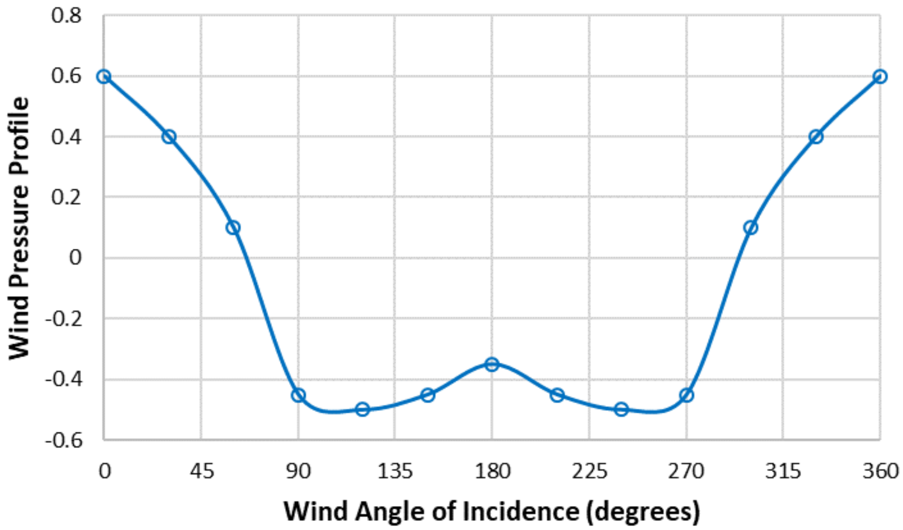


Figure 177. Wind Pressure Profile for Exterior Envelope Leakage Paths

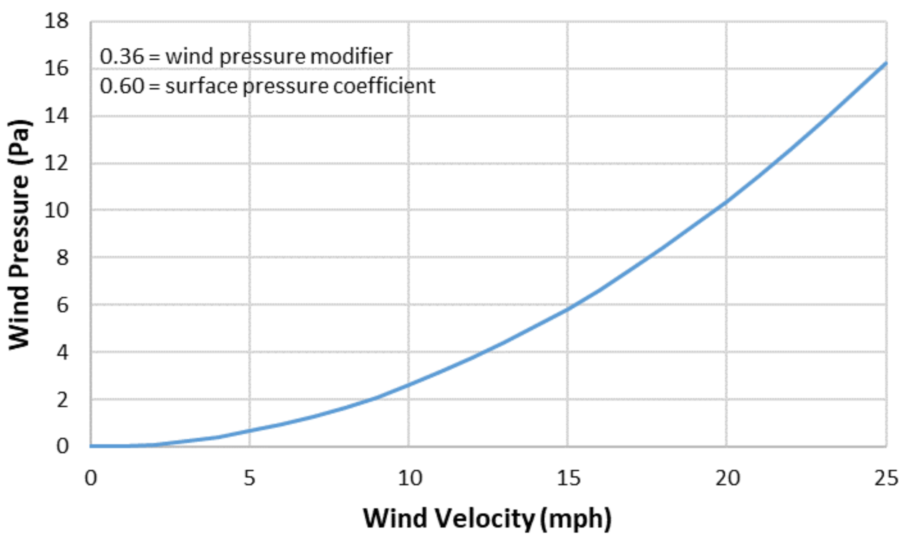


Figure 178. Variation in Wind Pressure with Velocity

The wind effect is typically more complex than the stack and HVAC flow effects. The wind effect varies with the square of the wind velocity and causes either a positive or negative pressure on the building surface depending on the angle of the wind relative to the building surface. (See Figure 177.) This causes nonuniform horizontal airflow between building zones. In addition, for zones with leakage on different sides of the building, wind can cause air infiltration and exfiltration in the same zone. Figure 179 displays the pressure difference across leakage paths and the interior of each zone for the left side of the building model.[48] All leakage path pressure differences represent the pressure in the unit with respect to the pressure of the adjoining area. A negative value indicates that there is airflow into the unit and a positive pressure

[48] The results for the right side of the building would be a mirror image of the left side, and there is no variation with height.

indicates that there is airflow out of the unit. The blue and red values displayed to the left of the unit IDs in the green squares are the zone pressures relative to the outside pressure away from the building. With no stack effect or HVAC flows, the sum of the pressure across an exterior envelope leakage path and the zone pressure is equal to the wind pressure on the building surface at the location of the leakage path.

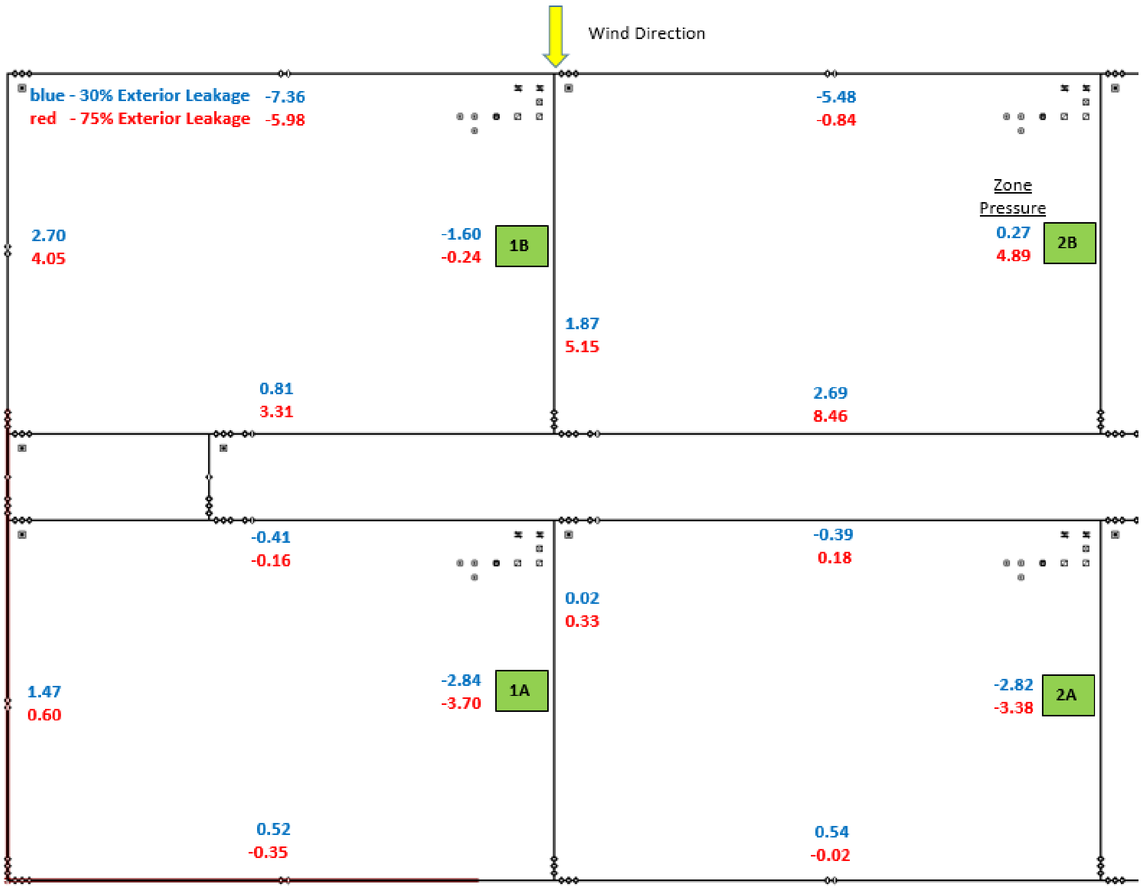


Figure 179. Pressure Differences of Leakage Paths and Zones for 15 mph Wind Speed

The blue and red values indicate the results for building models with 30% and 75% exterior leakages, respectively. The pressure differences are determined by the amount of interior leakage relative to the exterior leakage — not the absolute amount of interior leakage. In most cases, there is a negative pressure difference (i.e., infiltration) at the windward leakage paths and a positive pressure difference at the other locations. The two zones on the leeward side of the building (1A and 2A) and the leakage paths on the leeward side have similar pressure differences. However, there is significant variation in the other pressures that do not always follow similar trends. For example, for the model with 30% exterior leakage, the pressure across the exterior leakage in unit 2B is -5.48 Pa, and that decreases by 85% to -0.84 Pa for the model with 75% exterior leakage. For the windward leak in unit 1B, the pressure difference of -7.36 Pa for the model with 30% exterior leakage decreases by 19% to -5.98 Pa for the 75% exterior leakage model. In addition, the leeward leakage paths in units 1A and 2A have different directions for the 30% and 75% exterior leakage models. The inconsistencies occur not only because the wind pressure varies for each side of the building, but also because the interior zone pressures adjust so that the airflow into the zone is equal to the airflow out of the zone.

The airflow rates for the same 15 mph wind speed applied to the four building models are shown in Table 85.[49] The trends that were noted for the building pressures also occur for the airflow rates: The windward units (1B and 2B) have substantially higher infiltration than the leeward units (1A and 2A), and the ratios of airflows for a model are a function of the percent exterior leakage. The differences in windward and leeward unit infiltration can be extreme. For cases 3 and 4, the infiltration for the windward unit 2B is 10 times higher than the infiltration for the leeward unit 2A. In addition, the airflow results further demonstrate the impact of interior leakage on infiltration and exfiltration. For example, many of the unit airflow rates are quite different in cases 2 and 3 (purple and red, respectively, in Table 85), even though the exterior leakage is the same for those two cases. The air infiltration for unit 2B is 3.4 times higher when the interior leakage is 3.5 ACH_{50} (case 2) than when the interior leakage is 0.5 ACH_{50} (case 3). The average air infiltration for all four units is 22.4 CFM for an interior leakage of 3.5 ACH_{50} and 13.2 CFM for an interior leakage of 0.5 ACH_{50}. This demonstrates that interior leakage can impact average infiltration in a multifamily building. Not surprisingly, the airflow between the units and corridor is much higher for an interior leakage of 3.5 ACH_{50} compared to 0.5 ACH_{50}. The average airflow between a unit and corridor is 25.5 CFM for an interior leakage of 3.5 ACH_{50} and 6.4 CFM for an interior leakage of 0.5 ACH_{50}.

Table 85. Building Model Airflow Rates for 10 mph Wind Speed

Leakage Type	Air Leakage Configuration				Air Leakage Configuration			
Case	1	2	3	4	1	2	3	4
Total (ACH_{50})	2	5	2	5	2	5	2	5
Interior (ACH_{50})	1.4	3.5	0.5	1.25	1.4	3.5	0.5	1.25
Exterior (ACH_{50})	0.6	1.5	1.5	3.75	0.6	1.5	1.5	3.75
% Exterior	30%	30%	75%	75%	30%	30%	75%	75%
Building Model Airflow Rates (CFM)								
Flow Type	**Unit 1B**				**Unit 2B**			
Infiltration	13.6	33.9	29.6	74.1	22.4	55.9	16.6	41.4
Exfiltration	7.1	17.7	23.0	57.6	0.0	0.0	0.0	0.0
To Adjacent Unit	-4.7	-11.7	-3.2	-8.1	4.7	11.7	3.2	8.1
To Corridor	10.9	27.3	9.7	24.2	17.8	44.4	13.4	33.4
Flow Type	**Unit 1A**				**Unit 2A**			
Infiltration	0.0	0.0	4.8	11.9	0.0	0.0	1.6	4.1
Exfiltration	7.2	18.0	6.6	16.6	4.9	12.4	0.0	0.0
To Adjacent Unit	-0.2	-0.6	-0.5	-1.4	0.2	0.6	0.5	1.4
To Corridor	-7.0	-17.5	-1.4	-3.3	-5.1	-12.8	1.1	2.7

Exhaust Fan, Stack and Wind Combined

The final set of simulations were performed for the combination the three driving forces described previously: (1) depressurization from 51.0 CFM exhaust from each unit; (2) stack effect from 30°F outside temperature; and (3) wind effect from 15 mph wind directed perpendicularly toward units 1B and 2B. The charts shown in Figure 180 show the exterior wall pressure profiles for the four leakage cases described previously. The vertical lines represent the depressurization from only the exhaust ventilation, the sawtooth lines represent the combination of exhaust and stack effects, and the dashed lines represent the combination of all three driving forces. The long dash/dot lines on the left

[49] The colors of the numbers in the table for each model are the same as the colors for the model results in the previous charts.

portion of the charts represent the pressure profile for the windward inner unit (2B), and the short dash lines represent the profiles for the leeward inner unit (2A).

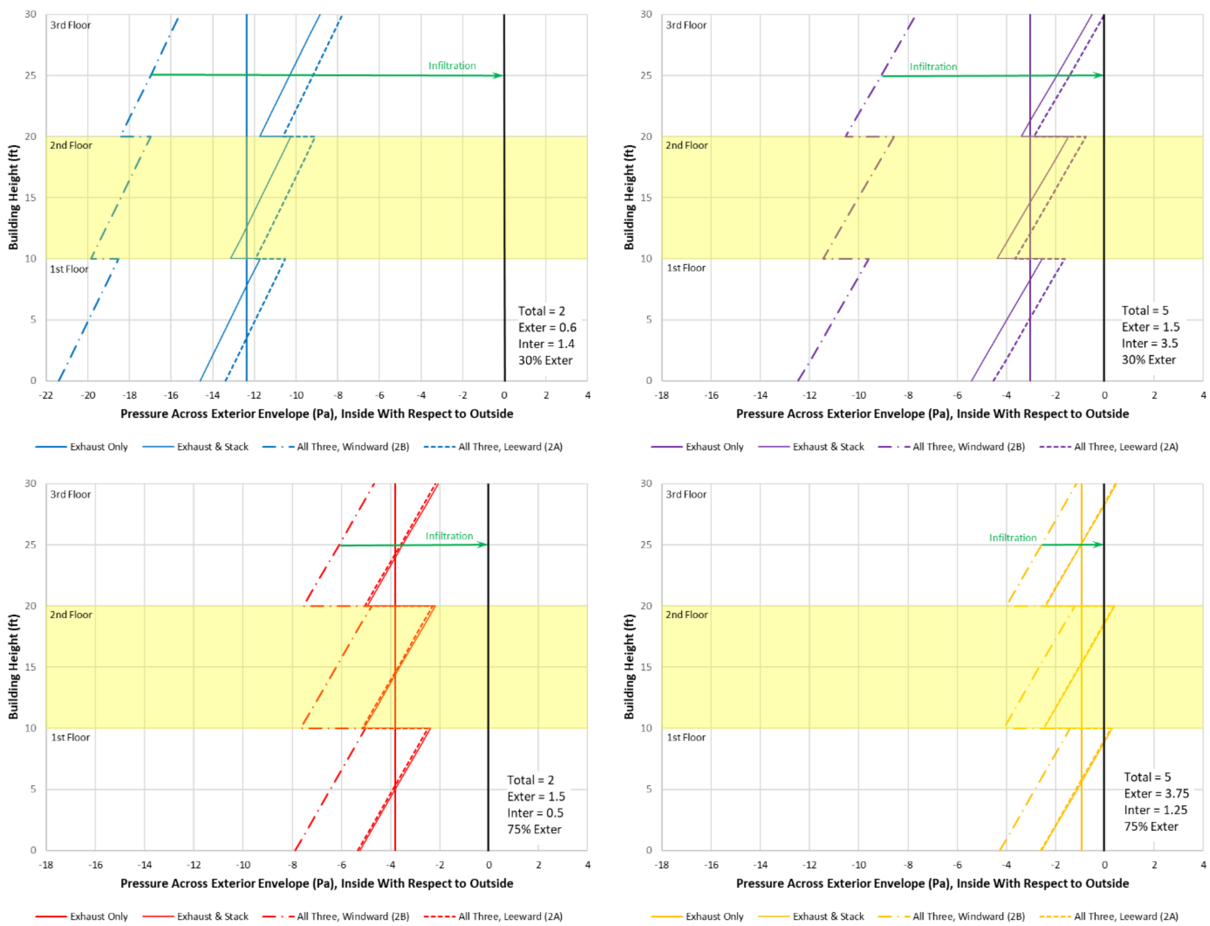


Figure 180. Combined Impact of Stack, Wind, and Exhaust Ventilation

Some key observations from these charts:

- When wind is added to the exhaust and stack effects, the pressure profiles retain the stack effect sawtooth profiles with little or no change in the pressure drop between floors or change in the stack pressure with height, but there is a shift to increased or decreased pressure difference depending on the wind direction.
- The addition of the positive wind pressure on the exterior of the windward unit (2B) results in increased depressurization — as indicated by the shift of the pressure profile to the left of the exhaust + stack profile. The additional depressurization is much greater for the two cases with relatively higher interior leakage (e.g., cases 1 and 2 with 30 % exterior leakage and 70% interior leakage).
- The negative wind pressure on the exterior of the leeward unit (2A) causes little or no change in pressurization, or shift in profile to the right.

Table 86 shows the modelled infiltration rate for the four types of units using the four configurations of unit leakage for the three combined driving forces. Some key observations from this table:

- For all of the units and every leakage configuration, 33% of the units have an infiltration rate greater than or equal to the required ventilation rate of 51.0 CFM. A total of 83% of the unit 2B configurations had an infiltration rate greater than or equal to 51.0 CFM, and 50% of those for unit 1B were greater than or equal to 51.0 CFM. None of the unit 1A and 2A configurations had an infiltration rate greater than 51.0 CFM. This suggests that only units on the windward side of the building will have an infiltration level that meets the ventilation requirement.
- When inner units 2B and 2A are compared with the same envelope leakage and driving forces, the infiltration for the windward unit 2B was 40%–172% higher than the infiltration for the leeward unit 2A. Unit 1B always had the highest infiltration, and unit 1A had the lowest. For the two cases with equal total unit leakage of 2.0 ACH_{50} (cases 1 and 3), the infiltration of unit 1B was about 20% higher than that for unit 1A. For the two cases with equal total unit leakage of 5.0 ACH_{50}, the infiltration of unit 1B was 99% and 120% higher than that for unit 1A for cases 2 and 4, respectively.
- For the two cases with the same exterior leakage of 1.5 ACH_{50} (cases 2 and 3), the impact of the interior leakage varied for each unit. For the two units on the windward side of the building, the greater interior leakage of case 2 resulted in a 36% and 3% higher infiltration for units 2B and 1B, respectively. However, for the two units on the leeward side, the greater interior leakage of case 2 resulted in a 38% and 30% lower infiltration for units 2A and 1A, respectively. For the average infiltration of all four units, the infiltration of case 3 (0.5 ACH_{50} interior leakage) is only 3% greater than that for case 2 (3.5 ACH_{50} interior leakage). This suggests that the level of interior leakage has a significant impact on infiltration for individual units, but little impact on the average infiltration for all units in the building.
- As expected, the average infiltration for all four units increased with increasing exterior leakage. However, the relative increase in infiltration was much less than that of the relative increase in total leakage. For example, the exterior leakage of cases 2 and 3 were 2.5 times greater than the exterior leakage for case 1, but the infiltration for cases 2 and 3 was only 1.21 and 1.25 times greater than that for case 1. This occurs because the level of envelope leakage has a lower impact on infiltration when there is already a significant level of infiltration due to exhaust ventilation.

Table 86. Model Infiltration Rates for 10 mph Wind, 30F, and 51 CFM Exhaust

Leakage Type	**Air Leakage Configuration**				**Air Leakage Configuration**			
Case	1	2	3	4	1	2	3	4
Total (ACH_{50})	2	5	2	5	2	5	2	5
Interior (ACH_{50})	1.4	3.5	0.5	1.25	1.4	3.5	0.5	1.25
Exterior (ACH_{50})	0.6	1.5	1.5	3.75	0.6	1.5	1.5	3.75
% Exterior	30%	30%	75%	75%	30%	30%	75%	75%
Building Model Airflow Rates (CFM)								
Floor	**Unit 1B**				**Unit 2B**			
First	43.9	58.8	51.5	97.9	53.6	91.2	64.4	93.9
Second	41.0	51.8	50.7	97.5	50.9	85.7	62.8	89.9
Third	37.8	45.7	49.1	95.5	48.3	80.6	62.1	87.7
Average	40.9	52.1	50.4	97.0	50.9	85.8	63.1	90.5
Floor	**Unit 1A**				**Unit 2A**			
First	37.0	34.7	43.4	46.8	38.5	39.6	46.4	50.2
Second	34.0	26.1	42.5	44.5	35.4	31.6	44.8	45.8
Third	30.8	17.6	40.9	41.1	32.5	23.5	44.0	42.9
Average	33.9	26.1	42.3	44.1	35.5	31.6	45.1	46.3
	All Four Units							
Average	40.3	48.9	50.2	69.5				

APPENDIX F: AIRFLOW AND ENERGY MODEL RESULTS FOR MINNESOTA

Balanced Ventilation

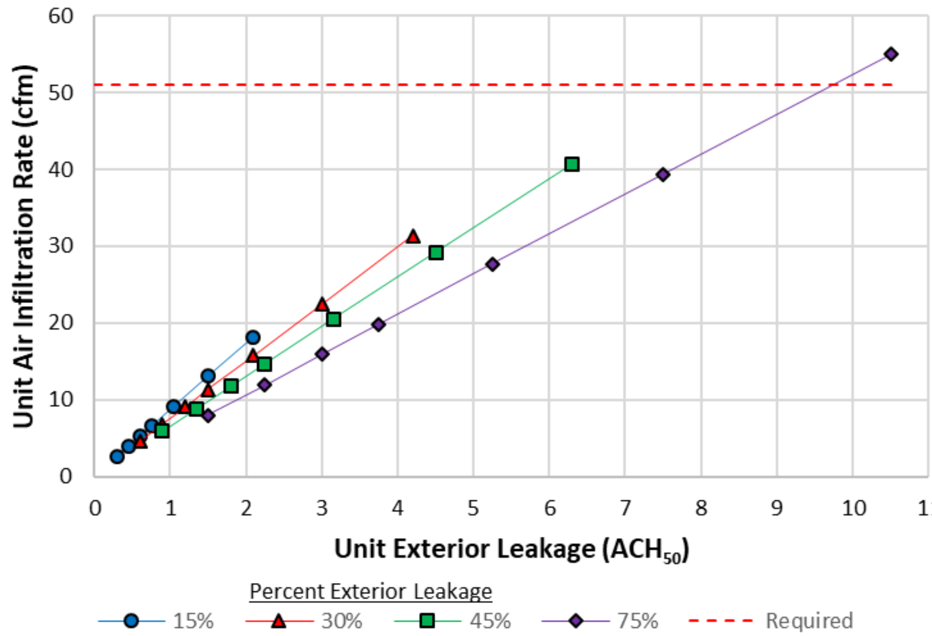


Figure 181. Annual Average Unit Infiltration: Minneapolis Balanced Ventilation

Table 87. Unit Annual Average Infiltration (CFM): Minneapolis Balanced Ventilation

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25	2.2								
0.50	4.0	4.3	4.5	4.6					
0.75	5.3	6.0	6.3	6.6	6.7	6.8			
1.0	6.4	7.3	7.9	8.3	8.6	8.8	8.9	9.0	9.1
1.5	8.0	9.5	10.6	11.3	11.9	12.3	12.6	12.8	13.0
2.0		11.3	12.7	13.7	14.6	15.2	15.8	16.2	16.6
2.5		12.4	14.5	15.8	16.8	17.8	18.5	19.2	19.7
3.0			15.9	17.7	18.9	19.9	21.0	21.8	22.5
3.5			16.8	19.2	20.9	22.0	23.0	24.1	25.0
4.0				20.3	22.5	24.0	25.2	26.1	27.3
4.5				21.0	23.8	25.7	27.1	28.3	29.2
5.0					24.7	27.1	28.9	30.3	31.4
5.5					25.3	28.2	30.4	32.0	33.4
6.0						29.0	31.6	33.6	35.2
6.5						29.6	32.6	34.9	36.8
7.0							33.3	36.0	38.2
7.5							33.8	36.9	39.4

Table 88. Monthly Variation of Unit Average Infiltration (CFM)

Leakage (ACH_{50})		Month												Annual
Exterior	Total	1	2	3	4	5	6	7	8	9	10	11	12	Average
Percent Exterior Leakage = 15%														
0.30	2	2.7	2.6	2.7	3.0	2.9	2.4	2.5	2.1	2.8	2.6	2.5	2.8	2.6
0.45	3	4.1	3.9	4.1	4.5	4.3	3.6	3.7	3.1	4.2	3.9	3.8	4.2	3.9
0.60	4	5.5	5.1	5.4	5.9	5.7	4.7	4.9	4.1	5.6	5.2	5.1	5.6	5.3
0.75	5	6.8	6.4	6.8	7.4	7.1	5.9	6.2	5.1	7.0	6.5	6.3	7.0	6.6
1.05	7	9.5	8.9	9.5	10.4	10.0	8.3	8.6	7.2	9.8	9.1	8.8	9.8	9.2
1.50	10	13.5	12.7	13.5	14.8	14.3	11.8	12.3	10.3	14.0	13.0	12.6	13.9	13.0
2.10	14	18.8	17.6	18.8	20.6	19.9	16.5	17.2	14.3	19.5	18.2	17.5	19.3	18.2
Percent Exterior Leakage = 30%														
0.60	2	4.6	4.3	4.7	5.2	5.0	4.2	4.3	3.6	4.9	4.5	4.3	4.8	4.5
0.90	3	6.9	6.5	7.0	7.7	7.5	6.2	6.5	5.4	7.3	6.8	6.5	7.1	6.8
1.20	4	9.2	8.6	9.3	10.3	10.0	8.3	8.7	7.2	9.8	9.0	8.6	9.5	9.0
1.50	5	11.4	10.7	11.6	12.9	12.5	10.4	10.8	9.0	12.2	11.3	10.8	11.9	11.3
2.10	7	16.0	15.0	16.2	18.0	17.5	14.5	15.1	12.5	17.1	15.7	15.0	16.5	15.8
3.00	10	22.7	21.3	23.1	25.6	25.0	20.7	21.6	17.9	24.4	22.4	21.4	23.5	22.5
4.20	14	31.5	29.6	32.2	35.7	35.0	28.9	30.3	25.0	34.1	31.3	29.8	32.8	31.3
Percent Exterior Leakage = 45%														
0.90	2	6.2	5.7	6.1	6.7	6.5	5.3	5.5	4.6	6.3	5.9	5.7	6.4	5.9
1.35	3	9.3	8.6	9.2	10.1	9.7	7.9	8.2	6.9	9.4	8.8	8.5	9.5	8.8
1.80	4	12.4	11.4	12.2	13.4	12.9	10.6	11.0	9.1	12.5	11.7	11.3	12.6	11.8
2.25	5	15.4	14.2	15.2	16.7	16.1	13.2	13.7	11.4	15.6	14.6	14.1	15.8	14.7
3.15	7	21.5	19.8	21.2	23.4	22.5	18.4	19.2	16.0	21.8	20.3	19.7	22.0	20.5
4.50	10	30.5	28.1	30.2	33.3	32.1	26.3	27.4	22.8	31.1	28.9	28.0	31.2	29.2
6.30	14	42.4	39.1	42.1	46.4	44.9	36.8	38.4	31.8	43.5	40.4	39.0	43.5	40.7
Percent Exterior Leakage = 75%														
1.50	2	9.6	8.7	8.7	9.0	8.0	6.4	6.6	5.7	7.8	7.8	8.2	9.4	8.0
2.25	3	14.4	12.9	13.0	13.5	11.9	9.7	9.9	8.6	11.6	11.7	12.3	14.0	11.9
3.00	4	19.1	17.2	17.3	17.9	15.9	12.9	13.2	11.4	15.4	15.5	16.3	18.7	15.9
3.75	5	23.8	21.5	21.6	22.3	19.8	16.1	16.5	14.2	19.3	19.3	20.4	23.3	19.8
5.25	7	33.2	29.9	30.1	31.2	27.7	22.5	23.1	19.9	26.9	26.9	28.4	32.5	27.7
7.50	10	47.2	42.6	42.8	44.4	39.4	32.0	33.0	28.4	38.4	38.3	40.4	46.2	39.4
10.50	14	65.8	59.3	59.7	61.9	55.1	44.7	46.1	39.7	53.6	53.3	56.4	64.4	55.0

Table 89. Monthly Variation of Infiltration by Unit (CFM)

		Month												Annual
		1	2	3	4	5	6	7	8	9	10	11	12	Average
Floor	Unit	% Exterior Leakage = 15%				Exterior Leakage = 2.10 ACH$_{50}$					Total Leakage = 14 ACH$_{50}$			
1	1A	35.5	33.3	32.8	29.3	21.1	20.3	21.5	18.8	25.4	26.6	32.0	34.6	27.6
1	1B	40.5	40.0	31.5	28.5	20.4	16.4	13.4	17.0	17.5	25.7	32.3	38.1	26.7
1	2A	27.1	22.3	28.6	29.4	25.2	23.7	26.8	18.5	34.6	27.2	26.9	28.4	26.6
2	1A	17.1	17.9	20.4	20.0	16.0	16.7	20.3	15.4	19.8	16.8	19.4	18.8	18.2
2	1B	20.2	22.2	18.1	18.2	14.9	12.8	12.0	13.3	11.9	15.6	18.7	20.6	16.5
2	2A	11.4	10.4	17.8	20.9	20.4	20.4	25.8	15.5	28.6	17.9	15.6	14.4	18.3
3	1A	6.1	8.2	12.2	14.3	12.9	14.5	19.8	13.2	16.0	10.2	10.6	9.1	12.3
3	1B	7.4	10.1	9.6	11.6	11.4	10.5	11.4	10.8	8.8	9.0	9.9	9.2	10.0
3	2A	3.1	4.1	10.5	15.8	17.0	18.3	25.3	13.8	24.0	11.4	8.0	6.7	13.2
Floor	Unit	% Exterior Leakage = 30%				Exterior Leakage = 2.10 ACH$_{50}$					Total Leakage = 7 ACH$_{50}$			
1	1A	26.0	25.1	25.7	24.1	18.3	17.7	19.7	16.6	21.7	21.4	25.1	26.3	22.3
1	1B	28.5	28.9	23.6	22.1	16.9	13.9	12.0	14.1	14.2	19.4	24.1	27.6	20.4
1	2A	18.0	15.0	20.7	22.4	20.0	18.9	22.0	14.6	27.5	20.3	19.2	19.8	19.9
2	1A	17.1	17.5	19.5	19.4	15.7	15.9	19.2	14.8	19.0	16.5	18.9	18.5	17.7
2	1B	18.7	20.2	16.8	17.0	14.1	12.1	11.3	12.1	11.3	14.2	17.4	19.2	15.3
2	2A	10.7	9.4	15.2	18.0	17.3	17.1	21.6	13.1	24.2	15.5	13.6	13.1	15.8
3	1A	10.2	11.7	14.6	15.8	13.7	14.6	18.8	13.5	16.7	12.5	13.7	12.5	14.0
3	1B	11.1	13.2	11.6	13.1	12.0	10.7	10.9	10.7	9.4	10.2	12.0	12.5	11.4
3	2A	5.3	5.4	10.9	14.7	15.3	15.9	21.4	12.1	21.5	11.6	9.2	7.9	12.6
Floor	Unit	% Exterior = 45%				Exterior Leakage = 2.25 ACH$_{50}$					Total Leakage = 5 ACH$_{50}$			
1	1A	23.2	22.8	23.7	23.1	18.1	17.4	19.8	16.4	21.0	20.3	23.3	24.0	21.1
1	1B	23.9	24.4	20.6	20.1	16.1	13.4	11.9	13.0	13.6	16.9	21.1	23.8	18.2
1	2A	14.8	12.2	16.5	18.2	16.3	15.3	17.9	11.8	22.2	16.4	15.5	16.2	16.1
2	1A	18.2	18.4	20.1	20.2	16.5	16.3	19.5	15.4	19.4	17.4	19.6	19.6	18.4
2	1B	18.5	19.6	16.7	17.1	14.5	12.3	11.5	11.9	11.9	13.9	17.2	19.2	15.3
2	2A	10.6	9.0	13.2	15.5	14.6	14.2	17.6	10.9	20.0	13.4	12.2	12.3	13.6
3	1A	14.0	14.8	16.9	17.9	15.0	15.4	19.2	14.5	17.9	14.9	16.3	15.8	16.1
3	1B	13.8	15.4	13.4	14.6	13.0	11.4	11.3	11.0	10.4	11.4	13.9	15.0	12.9
3	2A	7.2	6.2	10.4	13.4	13.2	13.4	17.6	10.2	18.3	10.9	9.3	9.0	11.6
Floor	Unit	% Exterior = 75%				Exterior Leakage = 2.25 ACH$_{50}$					Total Leakage = 3 ACH$_{50}$			
1	1A	19.7	19.7	20.2	20.6	16.8	15.7	18.2	15.1	18.7	18.0	19.9	20.8	18.6
1	1B	17.9	18.0	16.5	17.1	14.6	12.4	11.8	11.4	13.0	13.6	16.7	18.4	15.1
1	2A	11.8	9.6	9.8	10.2	8.1	7.2	7.6	5.6	10.2	9.2	10.0	11.4	9.2
2	1A	18.4	18.5	19.3	19.9	16.4	15.4	18.1	14.8	18.3	17.3	19.0	19.6	17.9
2	1B	16.6	16.9	15.5	16.3	14.2	12.1	11.7	11.1	12.5	12.9	15.8	17.2	14.4
2	2A	10.6	8.7	8.9	9.4	7.6	6.9	7.5	5.4	9.6	8.4	9.1	10.3	8.5
3	1A	17.3	17.5	18.4	19.2	16.0	15.2	18.0	14.6	17.9	16.6	18.1	18.6	17.3
3	1B	15.4	15.9	14.7	15.7	13.7	11.9	11.6	10.9	12.1	12.2	15.0	16.2	13.8
3	2A	9.6	7.8	8.1	8.8	7.3	6.7	7.6	5.2	9.2	7.7	8.2	9.4	8.0

Note – units 1A and 1B are corner units on opposite sides of corridor, unit 2A is an inner unit

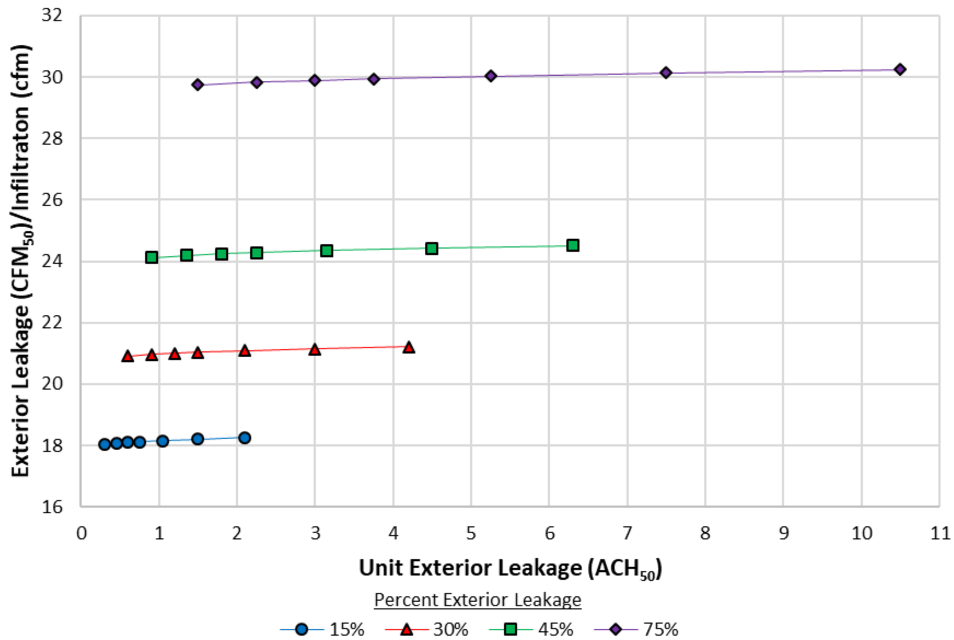


Figure 182. Exterior Leakage Divided by Infiltration

Table 90. Reduction in Annual Infiltration (CFM) for Reduction of 1 ACH50 in Exterior Leakage

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25									
0.50									
0.75									
1.0									
1.5		5.5	6.2	6.8	7.3				
2.0		4.9	5.3	5.8	6.3	6.7	7.0	7.3	7.5
2.5		4.4	5.0	5.2	5.5	5.9	6.2	6.6	6.9
3.0			4.6	5.1	5.2	5.4	5.7	6.0	6.2
3.5			4.3	4.7	5.1	5.2	5.2	5.6	5.8
4.0				4.4	4.8	5.1	5.2	5.1	5.4
4.5				4.3	4.5	4.8	5.1	5.2	5.0
5.0					4.4	4.6	4.9	5.1	5.3
5.5					4.3	4.4	4.7	4.9	5.1
6.0						4.3	4.5	4.7	4.9
6.5						4.2	4.4	4.6	4.8
7.0							4.3	4.4	4.6
7.5							4.2	4.3	4.5

Table 91. Reduction in Annual Infiltration (CFM) for Reduction of 1 ACH50 in Interior Leakage

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25									
0.50		0.33	0.16	0.10					
0.75		0.66	0.37	0.22	0.15	0.11			
1.0		0.97	0.61	0.39	0.26	0.19	0.14	0.11	0.09
1.5		1.52	1.04	0.74	0.58	0.42	0.31	0.24	0.19
2.0			1.35	1.06	0.88	0.66	0.55	0.43	0.34
2.5			2.10	1.26	1.05	0.97	0.73	0.63	0.54
3.0				1.81	1.21	1.03	1.05	0.82	0.65
3.5				2.46	1.64	1.17	0.99	1.11	0.89
4.0					2.14	1.53	1.15	0.95	1.16
4.5					2.71	1.93	1.45	1.13	0.90
5.0						2.38	1.78	1.39	1.11
5.5						2.87	2.16	1.68	1.34
6.0							2.56	1.99	1.60
6.5							3.01	2.34	1.87
7.0								2.71	2.17
7.5								3.11	2.49

Table 92. Ratio of Infiltration Reduction for Reduction of 1 ACH50 in Exterior Leakage and Reduction of 1 ACH50 in Interior Leakage

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25									
0.50									
0.75									
1.0									
1.5		3.6	6.0	9.2	12.5				
2.0			3.9	5.4	7.1	10.1	12.7	17.0	21.9
2.5			2.4	4.1	5.3	6.1	8.5	10.4	12.8
3.0				2.8	4.3	5.2	5.5	7.3	9.5
3.5				1.9	3.1	4.4	5.3	5.0	6.6
4.0					2.2	3.3	4.5	5.4	4.7
4.5					1.7	2.5	3.5	4.6	5.6
5.0						1.9	2.7	3.7	4.7
5.5						1.5	2.2	2.9	3.8
6.0							1.8	2.4	3.1
6.5							1.5	1.9	2.5
7.0								1.6	2.1
7.5								1.4	1.8

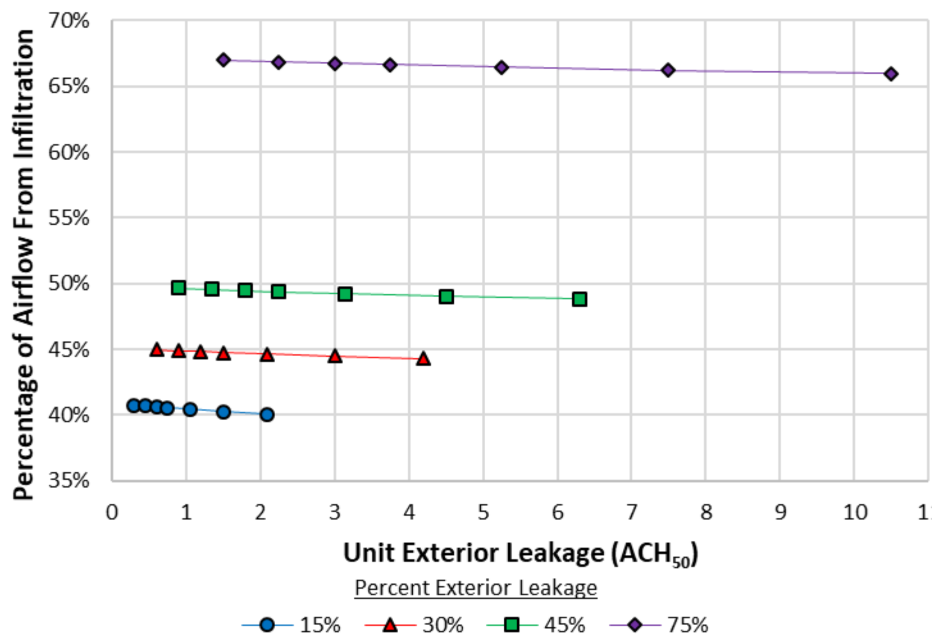


Figure 183. Percentage of Airflow from Outside into Unit: Minneapolis Balanced Ventilation

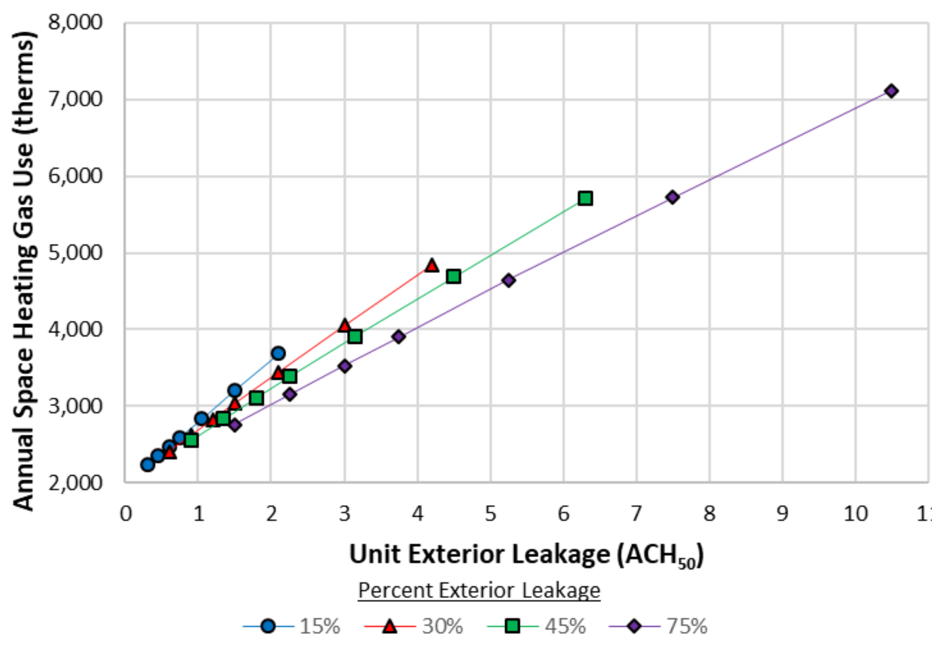


Figure 184. Annual Residential Unit Space Heating Gas Use (Therms)

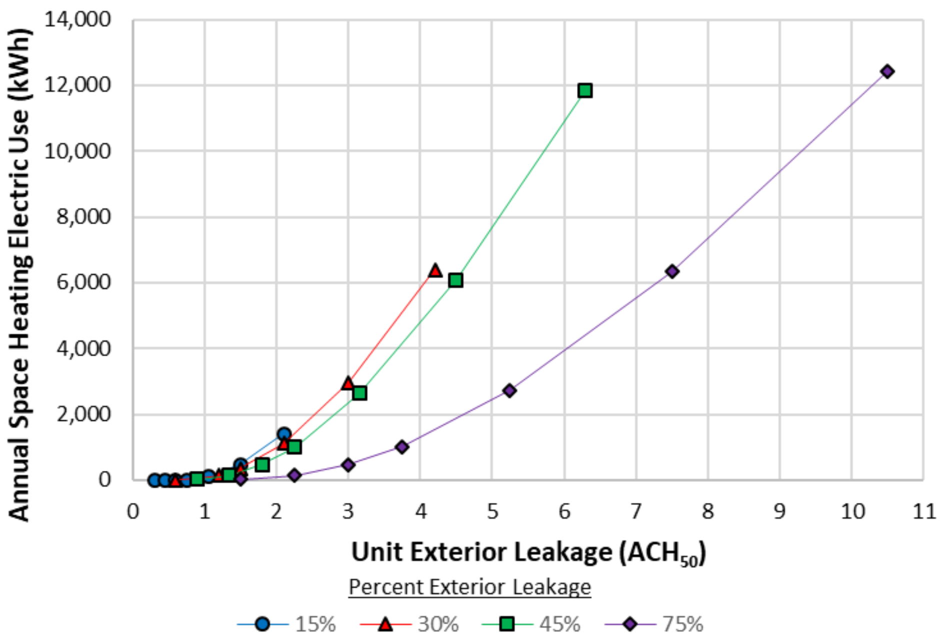


Figure 185. Annual Corridor Space Heating Electric Use (kWh)

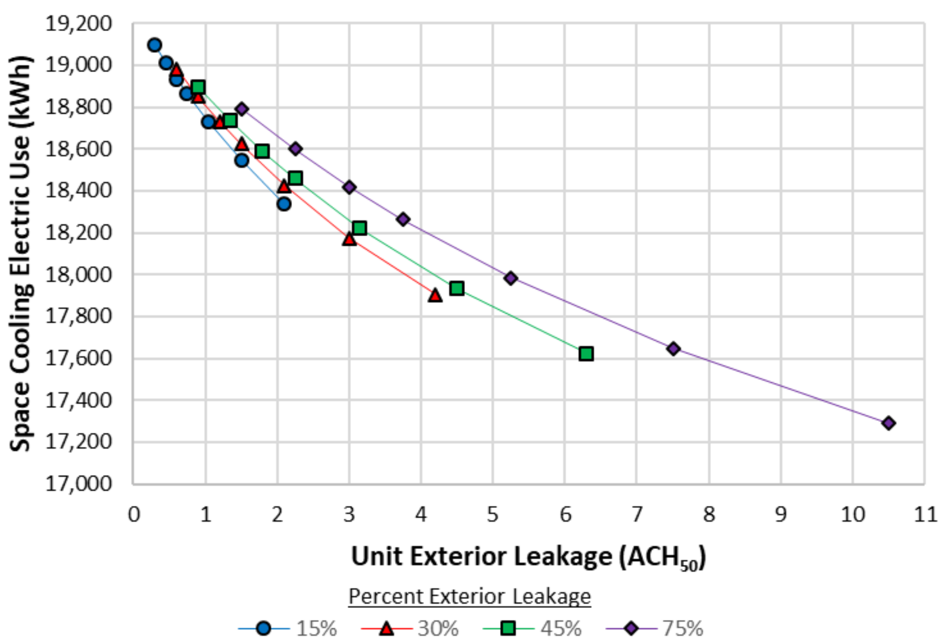


Figure 186. Annual Residential Unit Cooling Electric Use (kWh)

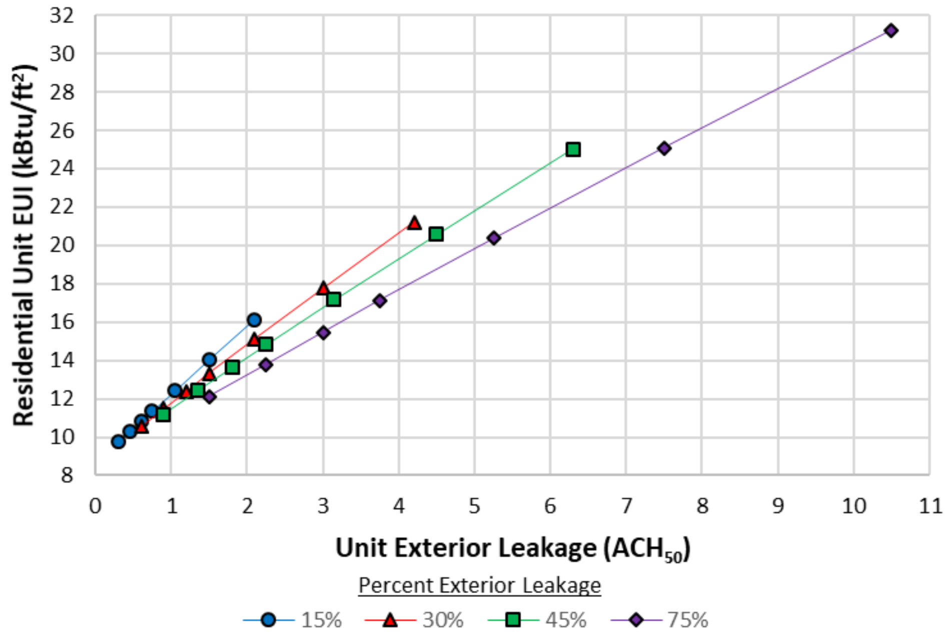


Figure 187. EUI for Residential Units (kBtu/ft²)

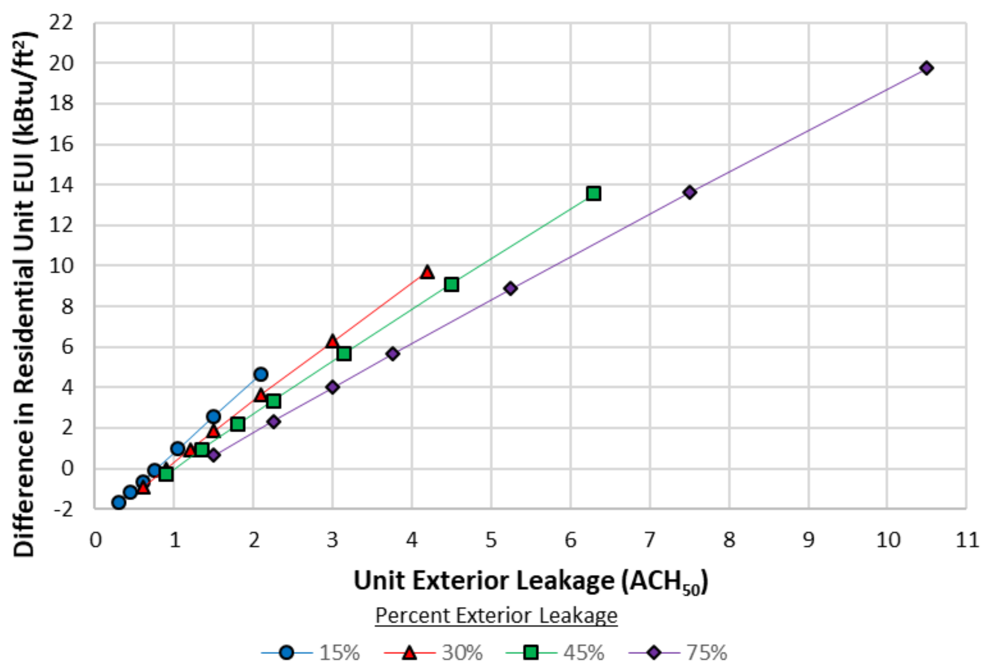


Figure 188. Difference in EUI From Baseline for Residential Units (kBtu/ft²)

Table 93. Difference in EUI From Baseline for Residential Units

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25	-1.85								
0.50	-1.15	-1.02	-0.95	-0.92					
0.75	-0.58	-0.34	-0.19	-0.11	-0.05	0.00			
1.0	-0.10	0.23	0.47	0.63	0.73	0.81	0.87	0.91	0.95
1.5	0.64	1.23	1.59	1.84	2.08	2.25	2.38	2.49	2.57
2.0		2.02	2.54	2.91	3.20	3.43	3.67	3.85	3.99
2.5		2.58	3.35	3.82	4.18	4.51	4.75	5.00	5.23
3.0			4.00	4.65	5.08	5.44	5.79	6.07	6.29
3.5			4.49	5.35	5.92	6.33	6.67	7.04	7.34
4.0				5.92	6.65	7.17	7.56	7.88	8.27
4.5				6.35	7.27	7.92	8.41	8.79	9.09
5.0					7.79	8.58	9.17	9.63	10.00
5.5					8.21	9.15	9.86	10.41	10.85
6.0						9.62	10.46	11.11	11.63
6.5						10.00	10.98	11.74	12.35
7.0							11.43	12.31	13.01
7.5							11.79	12.80	13.61

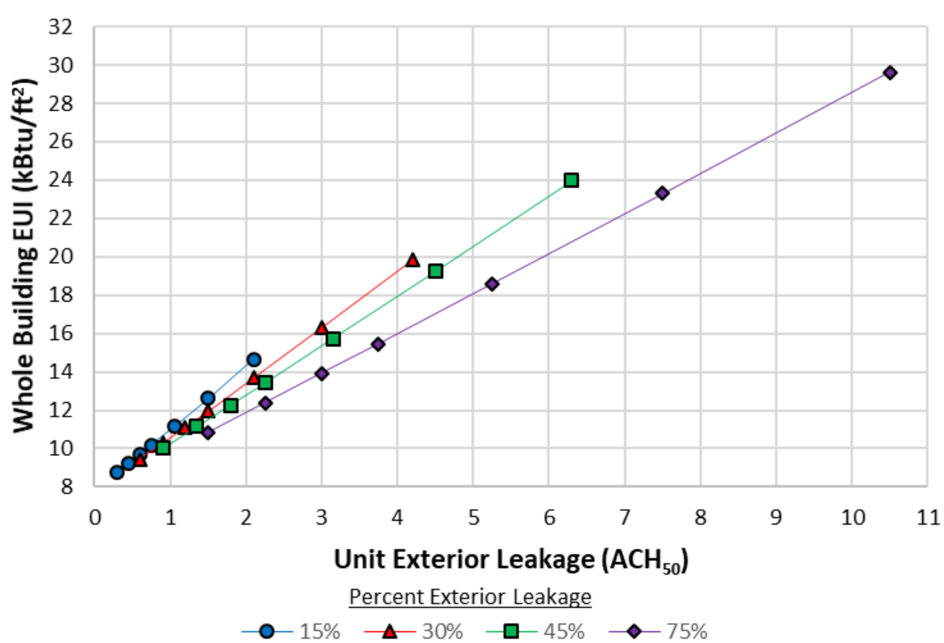


Figure 189. EUI for Whole Building (kBtu/ft²)

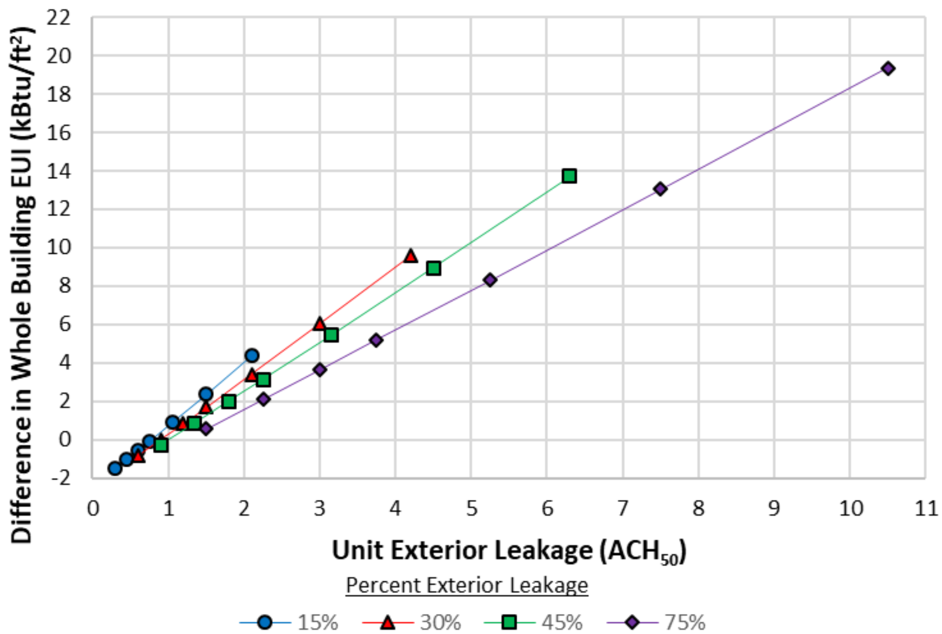


Figure 190. Difference in EUI From Baseline for Whole Building (kBtu/ft^2)

Continuous Exhaust Ventilation

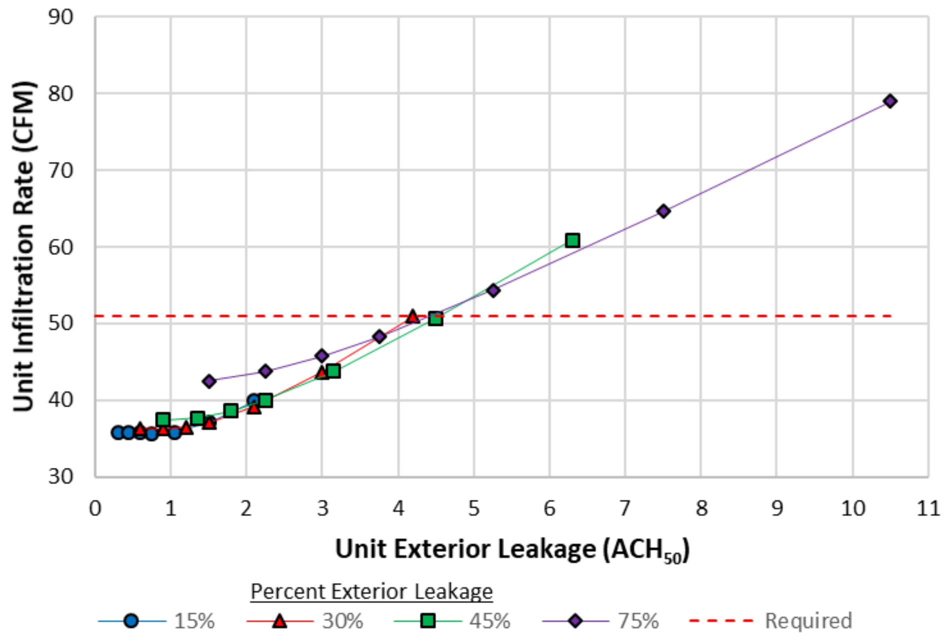


Figure 191. Annual Average Unit Infiltration: Minneapolis Continuous Exhaust Ventilation

Table 94. Unit Annual Average Infiltration (CFM): Minneapolis Continuous Exhaust Ventilation

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25	35.8								
0.50	36.2	35.9	35.7	35.6					
0.75	36.8	36.1	35.9	35.7	35.6	35.5			
1.0	38.2	36.6	36.2	36.0	35.9	35.8	35.8	35.7	35.7
1.5	42.6	38.8	37.5	37.1	37.1	37.1	37.1	37.1	37.1
2.0		42.2	39.9	39.1	38.9	38.9	39.0	39.2	39.2
2.5		45.4	43.0	41.6	41.1	41.1	41.2	41.3	41.4
3.0			45.7	44.4	43.6	43.2	43.4	43.6	43.7
3.5			48.2	47.1	46.4	45.9	45.6	46.0	46.3
4.0				49.5	49.0	48.6	48.3	48.2	48.7
4.5				51.7	51.3	51.1	50.9	50.8	50.7
5.0					53.3	53.4	53.4	53.4	53.5
5.5					55.0	55.4	55.7	55.9	56.1
6.0						57.3	57.8	58.2	58.5
6.5						58.9	59.6	60.2	60.7
7.0							61.3	62.1	62.7
7.5							62.7	63.7	64.6

Table 95. Monthly Variation of Unit Average Infiltration (CFM)

Leakage (ACH_{50})		Month												Annual
Exterior	Total	1	2	3	4	5	6	7	8	9	10	11	12	Average
Percent Exterior Leakage = 15%														
0.30	2	32.9	33.9	34.7	35.8	37.4	37.9	38.4	37.9	37.2	35.9	34.7	33.5	35.8
0.45	3	32.7	33.7	34.5	35.8	37.5	38.0	38.5	37.9	37.4	35.9	34.5	33.3	35.8
0.60	4	32.5	33.4	34.3	35.8	37.6	38.1	38.5	37.8	37.5	35.8	34.4	33.2	35.8
0.75	5	32.3	33.0	34.1	35.9	37.7	38.1	38.6	37.8	37.7	35.8	34.2	33.1	35.7
1.05	7	32.5	32.9	34.4	36.3	38.1	38.3	38.6	37.6	38.1	35.9	34.1	33.3	35.9
1.50	10	34.3	34.1	36.0	37.9	39.4	38.9	39.3	37.8	39.6	36.9	35.2	35.1	37.1
2.10	14	38.0	37.2	39.4	41.6	42.4	40.6	41.5	39.1	42.5	39.8	38.2	38.9	40.0
Percent Exterior Leakage = 30%														
0.60	2	33.0	34.0	34.9	36.4	38.2	38.6	39.1	38.4	38.1	36.4	34.9	33.7	36.3
0.90	3	32.7	33.4	34.6	36.6	38.5	38.8	39.2	38.3	38.5	36.4	34.6	33.5	36.3
1.20	4	32.8	33.2	34.9	37.1	39.0	39.0	39.4	38.2	39.0	36.6	34.6	33.7	36.5
1.50	5	33.5	33.6	35.6	37.9	39.8	39.4	39.8	38.4	39.9	37.1	35.0	34.5	37.1
2.10	7	36.0	35.5	38.1	40.6	42.2	40.9	41.5	39.2	42.4	39.1	36.9	37.2	39.2
3.00	10	41.1	40.1	43.1	46.2	47.2	44.2	45.5	41.8	47.2	43.7	41.4	42.6	43.7
4.20	14	48.9	47.2	50.9	54.9	55.2	50.2	52.0	46.6	55.1	51.1	48.5	50.7	51.0
Percent Exterior Leakage = 45%														
0.90	2	33.8	34.6	35.8	37.7	39.6	39.9	40.3	39.4	39.5	37.5	35.8	34.6	37.4
1.35	3	33.8	34.3	36.0	38.4	40.4	40.4	40.7	39.5	40.4	37.8	35.8	34.8	37.7
1.80	4	34.8	34.8	36.9	39.6	41.7	41.1	41.5	39.7	41.7	38.7	36.4	35.9	38.6
2.25	5	36.5	36.0	38.5	41.4	43.4	42.1	42.7	40.3	43.4	40.0	37.6	37.7	40.0
3.15	7	41.1	39.8	42.6	45.9	47.6	44.8	45.9	42.4	47.5	43.6	41.2	42.3	43.7
4.50	10	48.9	46.7	50.1	54.2	55.1	50.2	51.9	46.7	54.9	50.5	48.0	50.4	50.7
6.30	14	60.0	56.7	61.0	66.3	66.3	58.8	61.0	53.9	65.8	60.8	58.0	61.8	60.9
Percent Exterior Leakage = 70%														
1.50	2	38.7	39.5	41.0	43.1	45.0	45.1	45.6	44.5	44.9	42.6	40.8	39.7	42.6
2.25	3	40.1	40.2	42.3	44.7	46.8	46.1	46.8	45.1	46.6	43.8	41.6	41.0	43.8
3.00	4	43.0	42.3	44.4	47.0	48.9	47.6	48.4	46.1	48.6	45.5	43.3	43.7	45.7
3.75	5	46.9	45.5	47.2	49.8	51.4	49.3	50.3	47.3	51.0	47.6	45.9	47.3	48.3
5.25	7	55.5	52.9	54.1	56.8	57.1	53.3	54.7	50.4	56.4	53.1	52.5	55.5	54.4
7.50	10	68.6	64.4	65.8	68.8	67.1	60.4	62.3	56.5	66.2	63.2	63.5	68.3	64.6
10.50	14	86.3	80.2	81.8	85.5	81.4	71.4	73.7	66.1	80.3	77.4	78.5	85.7	79.0

Table 96. Monthly Variation of Infiltration by Unit (CFM)

		Month												Annual
		1	2	3	4	5	6	7	8	9	10	11	12	Average
Floor	Unit	% Exterior Leakage = 15%				Exterior Leakage = 2.10 ACH_{50}					Total Leakage = 14 ACH_{50}			
1	1A	61.2	58.5	59.0	54.9	46.8	46.9	47.4	45.6	51.3	52.4	57.3	59.8	53.4
1	1B	67.7	67.2	59.0	54.7	47.4	42.5	39.4	45.5	44.9	53.6	60.0	65.0	53.8
1	2A	52.0	46.5	52.8	54.6	50.1	50.9	52.5	44.0	59.8	51.2	51.3	52.8	51.6
2	1A	37.7	39.2	43.5	42.1	39.0	42.0	45.9	41.1	43.3	40.0	40.7	39.2	41.1
2	1B	43.1	46.9	42.9	41.7	39.7	37.9	37.8	41.1	36.8	40.5	42.4	43.2	41.1
2	2A	29.2	27.4	38.4	42.1	42.5	46.1	51.1	39.6	52.3	39.4	35.3	32.9	39.7
3	1A	18.6	22.4	28.8	30.1	31.0	36.8	44.1	36.2	35.3	27.4	25.9	22.0	29.9
3	1B	21.5	27.8	26.8	28.7	31.4	32.8	36.1	36.0	28.1	27.1	26.0	24.0	28.9
3	2A	12.9	13.4	25.6	30.9	35.1	41.0	49.5	34.9	44.7	28.0	21.7	17.6	29.7
Floor	Unit	% Exterior Leakage = 30%				Exterior Leakage = 2.10 ACH_{50}					Total Leakage = 7 ACH_{50}			
1	1A	49.2	48.7	50.9	48.8	43.7	44.6	45.9	43.6	47.3	46.5	48.9	49.4	47.3
1	1B	54.3	55.6	50.6	48.3	44.2	41.1	39.3	43.5	42.1	47.3	50.7	53.2	47.5
1	2A	41.4	38.2	45.5	48.5	47.2	48.6	50.7	42.5	55.5	45.9	44.1	43.6	46.0
2	1A	36.6	38.1	41.9	41.4	39.0	41.6	45.0	40.7	42.5	39.2	39.6	38.3	40.3
2	1B	40.6	44.0	41.1	40.6	39.6	38.3	38.3	40.6	37.3	39.5	40.6	41.0	40.1
2	2A	29.2	27.6	37.1	41.1	42.5	45.6	49.8	39.7	50.8	38.7	34.7	32.6	39.2
3	1A	26.3	28.8	33.6	34.4	34.2	38.4	43.9	37.8	37.7	32.0	31.2	28.9	34.0
3	1B	28.8	33.3	32.1	33.1	34.8	35.3	37.3	37.6	32.3	31.7	31.3	30.2	33.1
3	2A	19.7	19.1	29.5	34.4	38.0	42.7	49.0	36.9	46.3	32.0	26.5	23.7	33.2
Floor	Unit	% Exterior = 45%				Exterior Leakage = 2.25 ACH_{50}					Total Leakage = 5 ACH_{50}			
1	1A	45.0	45.4	47.7	47.2	43.3	44.2	45.9	43.3	46.2	44.7	46.0	46.1	45.4
1	1B	48.1	49.8	46.8	45.8	43.7	41.5	40.2	42.9	42.0	44.7	46.6	47.7	45.0
1	2A	38.5	36.1	42.8	46.4	46.8	48.1	50.3	42.7	53.8	44.4	41.8	40.8	44.4
2	1A	37.8	39.2	42.4	42.8	40.5	42.3	45.4	41.5	43.3	40.3	40.4	39.7	41.3
2	1B	40.1	42.7	41.0	41.1	40.9	39.7	39.7	41.0	39.1	39.9	40.5	40.6	40.5
2	2A	31.1	29.6	37.4	41.6	43.7	46.1	49.6	40.8	50.6	39.7	35.8	34.1	40.1
3	1A	31.8	33.6	37.3	38.5	37.5	40.3	44.6	39.7	40.3	35.9	35.4	34.0	37.4
3	1B	33.0	36.1	35.5	36.4	37.9	37.8	39.1	39.0	36.0	35.1	34.8	34.0	36.2
3	2A	25.1	24.1	32.6	37.4	41.0	44.5	49.3	39.2	47.9	35.4	30.6	28.2	36.3
Floor	Unit	% Exterior = 75%				Exterior Leakage = 2.25 ACH_{50}					Total Leakage = 3 ACH_{50}			
1	1A	44.0	44.8	46.7	48.0	46.1	46.3	47.8	45.9	47.0	45.5	45.5	45.4	46.1
1	1B	43.4	44.4	44.7	45.5	46.2	45.2	44.9	44.9	45.4	44.2	44.2	43.8	44.7
1	2A	39.7	39.3	42.7	45.5	47.9	48.6	50.0	46.3	50.5	45.1	42.4	41.2	45.0
2	1A	42.2	43.3	45.4	47.0	45.6	46.0	47.9	45.6	46.5	44.5	44.2	43.9	45.2
2	1B	41.5	42.7	43.4	44.5	45.7	44.9	44.9	44.6	44.9	43.1	42.8	42.2	43.8
2	2A	37.5	37.1	40.9	43.9	46.8	47.9	49.6	45.6	49.4	43.5	40.5	39.0	43.5
3	1A	40.3	41.7	43.9	45.7	44.7	45.3	47.6	45.0	45.5	43.2	42.7	42.1	44.0
3	1B	39.4	40.8	41.8	43.1	44.7	44.3	44.7	44.0	44.0	41.7	41.2	40.3	42.5
3	2A	35.8	35.5	39.6	42.9	46.3	47.7	49.9	45.4	48.9	42.5	39.1	37.3	42.6

Note – units 1A and 1B are corner units on opposite sides of corridor, unit 2A is an inner unit

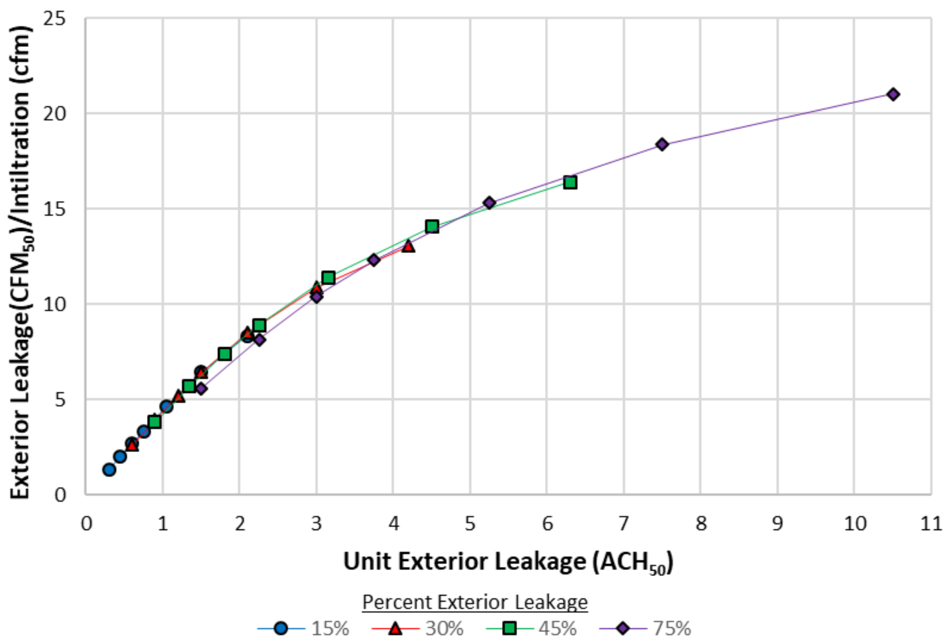


Figure 192. Exterior Leakage Divided by Infiltration

Table 97. Reduction in Annual Infiltration (CFM) for Reduction of 1 ACH50 in Exterior Leakage

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25									
0.50									
0.75									
1.0									
1.5		2.6	1.7	1.4	1.4				
2.0		4.0	3.3	2.9	2.9	3.0	3.2	3.4	3.5
2.5		2.8	4.3	4.1	4.0	4.1	4.1	4.2	4.4
3.0			3.5	4.5	4.5	4.3	4.5	4.5	4.5
3.5			2.9	4.1	4.8	4.8	4.5	4.9	5.0
4.0				3.8	4.5	5.0	5.1	4.8	5.1
4.5				3.4	4.2	4.7	5.1	5.1	4.6
5.0					3.8	4.4	4.8	5.1	5.3
5.5					3.4	4.1	4.6	5.0	5.3
6.0						4.0	4.4	4.8	5.0
6.5						3.8	4.2	4.6	4.8
7.0							4.0	4.3	4.6
7.5							3.8	4.1	4.4

Table 98. Reduction in Annual Infiltration (CFM) for Reduction of 1 ACH50 in Interior Leakage

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25									
0.50		-0.31	-0.15	-0.09					
0.75		-0.69	-0.25	-0.15	-0.10	-0.07			
1.0		-1.58	-0.42	-0.17	-0.11	-0.08	-0.06	-0.05	-0.04
1.5		-3.79	-1.23	-0.47	0.00	0.00	0.00	0.00	0.00
2.0			-2.31	-0.83	-0.18	-0.03	0.16	0.12	0.10
2.5			-2.37	-1.42	-0.54	0.06	0.04	0.12	0.13
3.0				-1.31	-0.87	-0.36	0.20	0.16	0.13
3.5				-1.11	-0.74	-0.53	-0.22	0.38	0.31
4.0					-0.53	-0.38	-0.29	-0.14	0.49
4.5					-0.33	-0.24	-0.18	-0.14	-0.11
5.0						0.06	0.05	0.04	0.03
5.5						0.37	0.28	0.21	0.17
6.0							0.50	0.39	0.31
6.5							0.76	0.59	0.47
7.0								0.82	0.66
7.5								1.07	0.86

Table 99. Ratio of Infiltration Reduction for Reduction of 1 ACH50 in Exterior Leakage and Reduction of 1 ACH50 in Interior Leakage

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25									
0.50									
0.75									
1.0									
1.5		-0.7	-1.4	-2.9	-1265				
2.0			-1.4	-3.5	-16.1	-111	20.4	27.7	36.1
2.5			-1.8	-2.9	-7.5	70.9	95.6	35.9	33.0
3.0				-3.4	-5.1	-12.1	22.2	28.5	35.6
3.5				-3.7	-6.5	-9.1	-20.7	12.7	16.5
4.0					-8.5	-13.2	-17.8	-34.2	10.4
4.5					-12.7	-19.9	-28.5	-37.2	-42.0
5.0						72.8	106.5	146.0	188.4
5.5						11.1	16.7	23.2	30.9
6.0							8.8	12.2	16.1
6.5							5.6	7.7	10.2
7.0								5.3	7.0
7.5								3.8	5.1

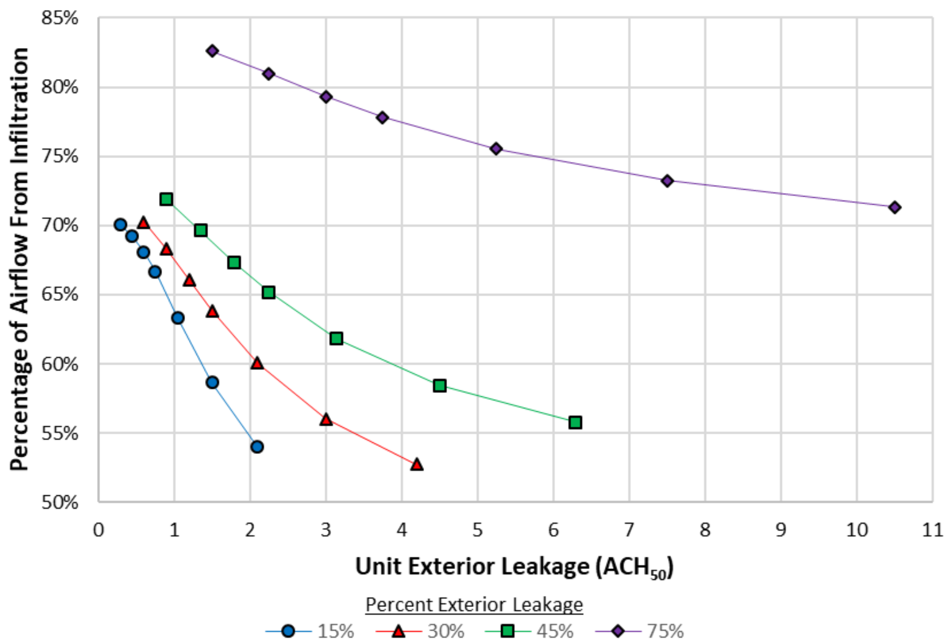


Figure 193. Percentage of Airflow from Outside Into Unit

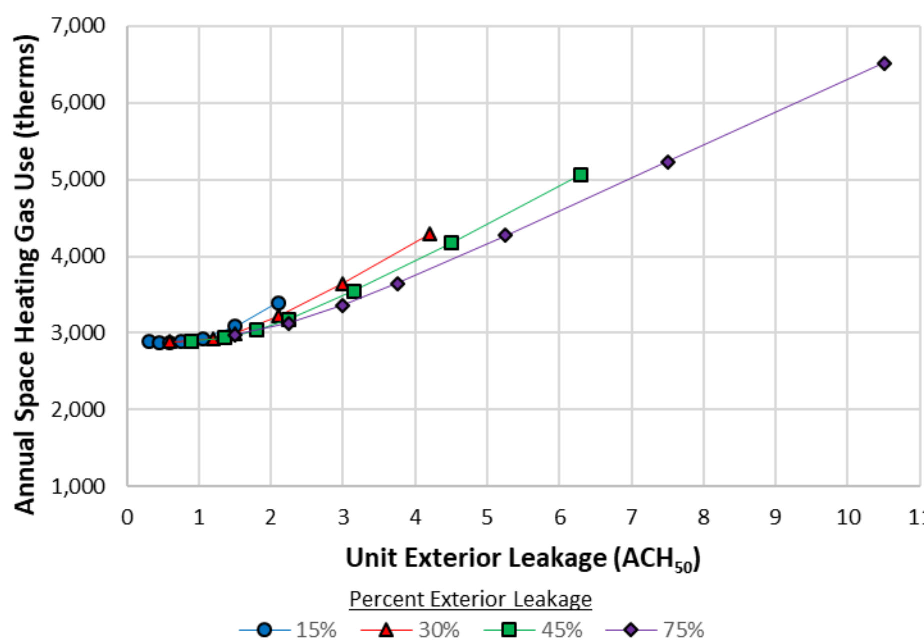


Figure 194. Annual Residential Unit Space Heating Gas Use (Therms)

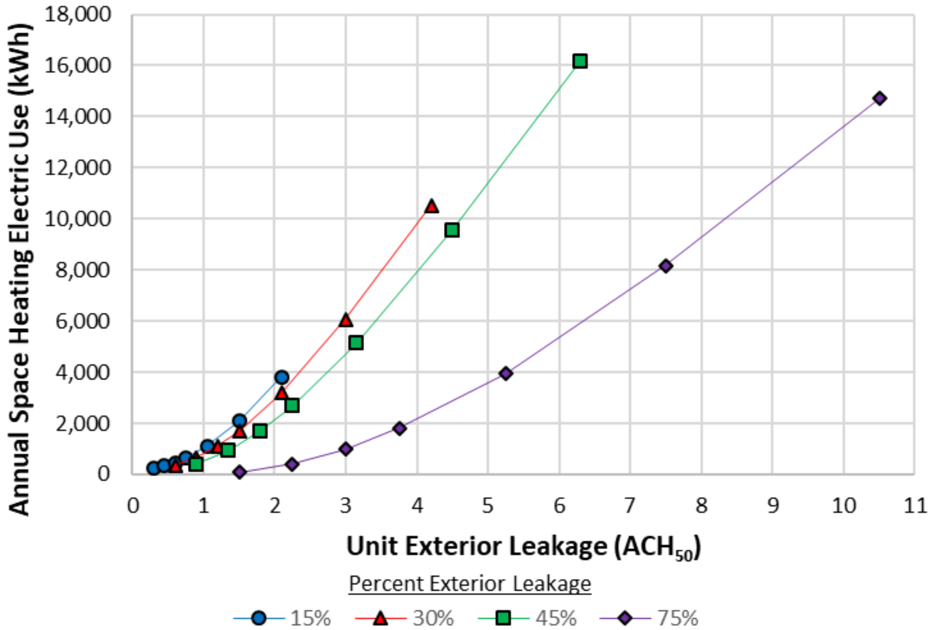


Figure 195. Annual Corridor Space Heating Electric Use (kWh)

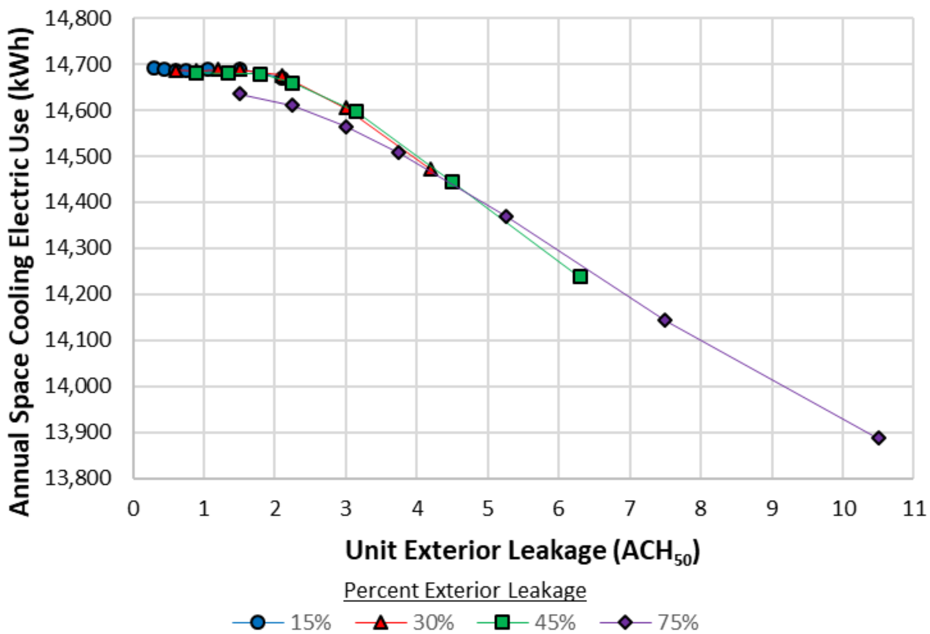


Figure 196. Annual Residential Unit Cooling Electric Use (kWh)

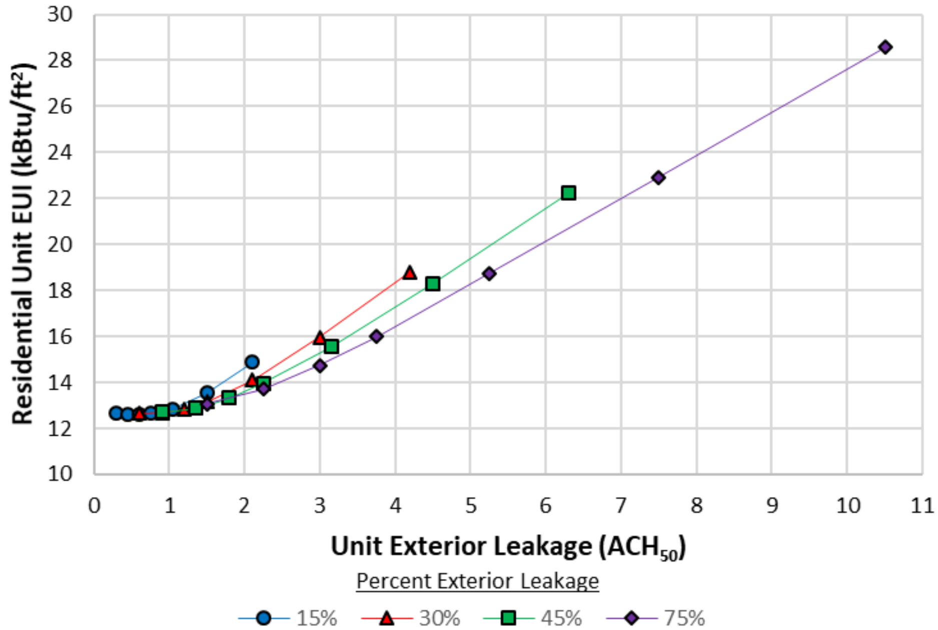


Figure 197. EUI for Residential Units (kBtu/ft²)

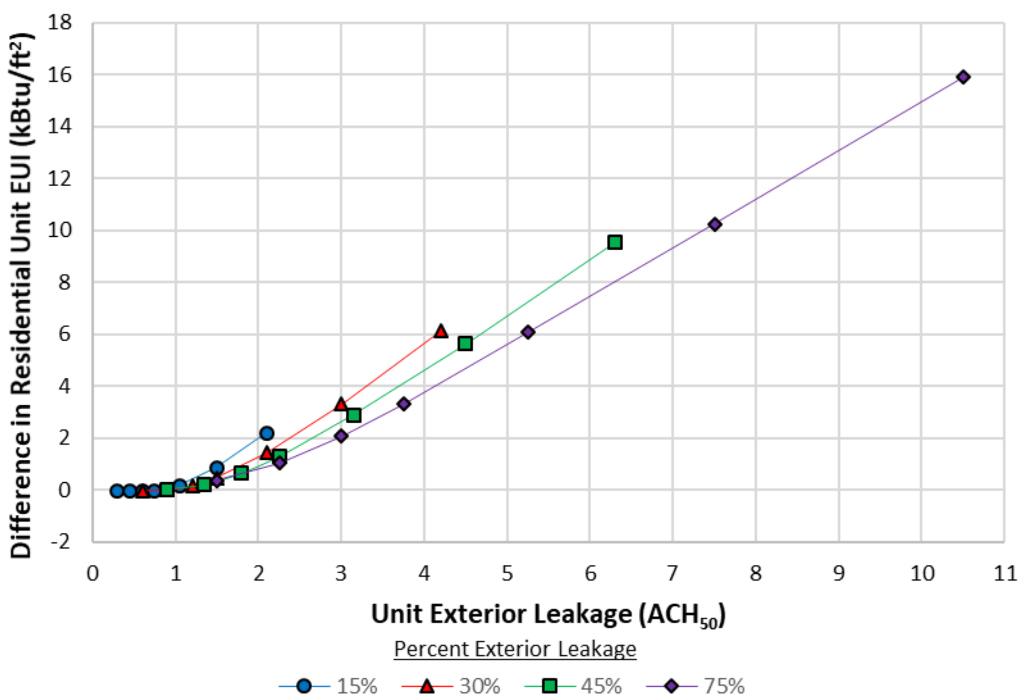


Figure 198. <u>Difference</u> in EUI From Baseline for Residential Units (kBtu/ft²)

Table 100. Difference in EUI From Baseline for Residential Units

Ext. Lkg.	Unit Total Leakage (ACH$_{50}$)								
(ACH$_{50}$)	2	3	4	5	6	7	8	9	10
0.25	-0.02								
0.50	-0.04	-0.04	-0.04	-0.05					
0.75	-0.02	-0.02	-0.02	-0.03	-0.03	-0.03			
1.0	0.05	0.05	0.08	0.11	0.12	0.14	0.15	0.15	0.16
1.5	0.39	0.35	0.41	0.47	0.60	0.70	0.77	0.82	0.87
2.0		0.85	0.91	1.04	1.20	1.35	1.51	1.65	1.75
2.5		1.29	1.53	1.67	1.85	2.06	2.22	2.39	2.55
3.0			2.06	2.34	2.53	2.72	2.96	3.15	3.30
3.5			2.61	3.02	3.29	3.48	3.67	3.96	4.18
4.0				3.64	4.01	4.28	4.48	4.66	4.96
4.5				4.22	4.69	5.03	5.28	5.48	5.64
5.0					5.30	5.74	6.07	6.33	6.53
5.5					5.82	6.38	6.80	7.12	7.38
6.0						6.95	7.46	7.86	8.18
6.5						7.45	8.06	8.54	8.92
7.0							8.60	9.16	9.61
7.5							9.08	9.73	10.26

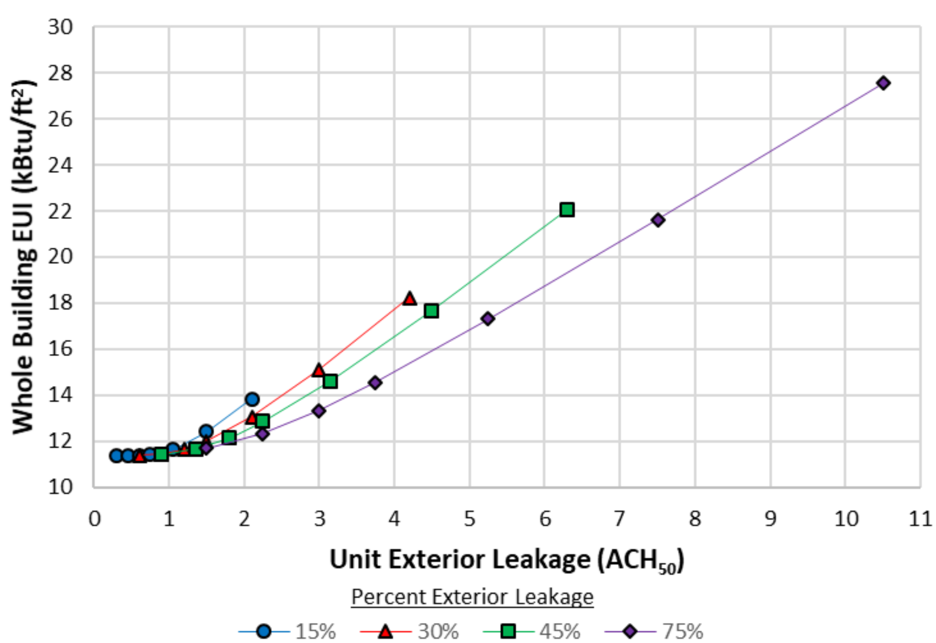


Figure 199. EUI for Whole Building (kBtu/ft^2)

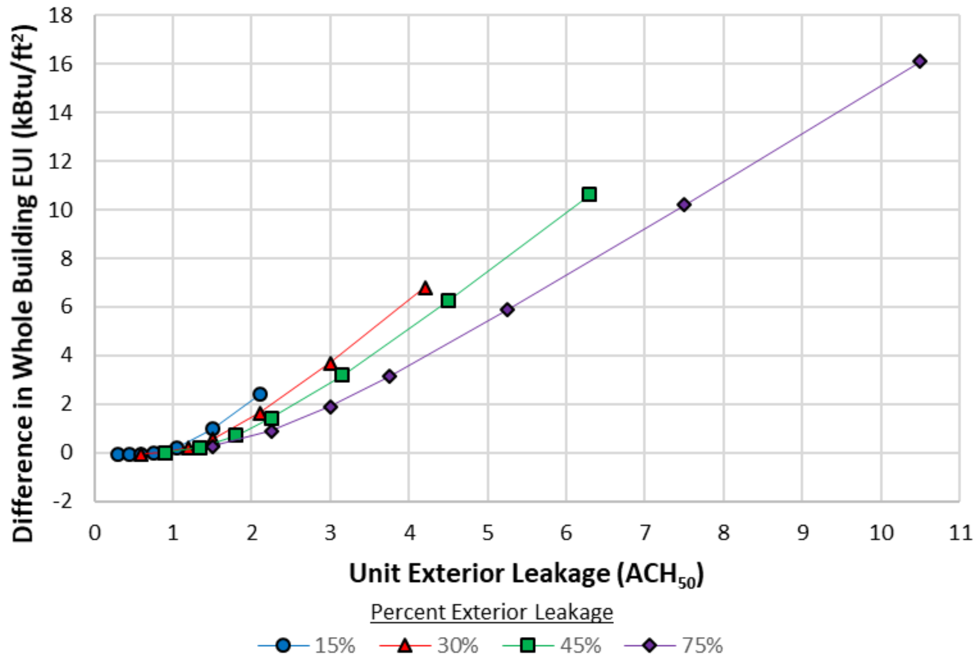


Figure 200. Difference in EUI From Baseline for Whole Building (kBtu/ft²)

Intermittent Exhaust Ventilation

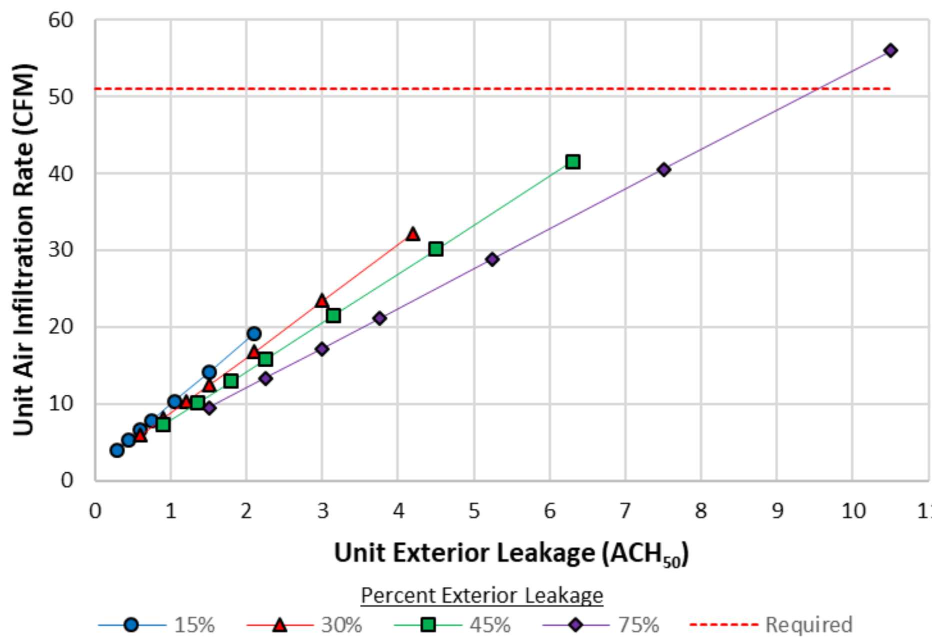


Figure 201. Annual Average Unit Infiltration: Minneapolis Intermittent Exhaust Ventilation

Table 101. Unit Annual Average Infiltration (CFM): Minneapolis Intermittent Exhaust Ventilation

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25	3.6								
0.50	5.3	5.6	5.8	5.9					
0.75	6.6	7.2	7.6	7.8	7.9	8.0			
1.0	7.7	8.6	9.1	9.5	9.8	9.9	10.1	10.2	10.2
1.5	9.5	10.8	11.7	12.4	13.0	13.4	13.7	13.9	14.1
2.0		12.6	13.8	14.8	15.6	16.3	16.8	17.2	17.6
2.5		13.8	15.7	16.9	17.9	18.8	19.5	20.1	20.7
3.0			17.2	18.9	20.0	20.9	22.0	22.8	23.4
3.5			18.1	20.4	22.0	23.1	24.0	25.1	26.0
4.0				21.6	23.6	25.1	26.2	27.1	28.2
4.5				22.4	24.9	26.8	28.2	29.2	30.1
5.0					25.9	28.2	29.9	31.3	32.3
5.5					26.6	29.4	31.5	33.1	34.4
6.0						30.3	32.7	34.7	36.2
6.5						30.8	33.8	36.0	37.8
7.0							34.5	37.2	39.3
7.5							35.1	38.1	40.5

Table 102. Monthly Variation of Unit Average Infiltration (CFM)

Leakage (ACH_{50})		Month												Annual
Exterior	Total	1	2	3	4	5	6	7	8	9	10	11	12	Average
Percent Exterior Leakage = 15%														
0.30	2	4.0	3.9	4.1	4.4	4.3	3.8	4.0	3.6	4.2	4.0	3.9	4.1	4.0
0.45	3	5.3	5.1	5.4	5.8	5.7	5.0	5.1	4.5	5.6	5.3	5.1	5.4	5.3
0.60	4	6.6	6.3	6.7	7.2	7.0	6.1	6.3	5.5	7.0	6.6	6.3	6.7	6.5
0.75	5	7.9	7.5	8.0	8.6	8.4	7.3	7.5	6.5	8.3	7.8	7.5	8.1	7.8
1.05	7	10.4	10.0	10.6	11.5	11.2	9.5	9.9	8.5	11.0	10.3	9.9	10.7	10.3
1.50	10	14.4	13.6	14.5	15.8	15.3	13.0	13.4	11.5	15.1	14.1	13.5	14.8	14.1
2.10	14	19.6	18.5	19.8	21.6	20.9	17.5	18.2	15.4	20.6	19.2	18.4	20.2	19.2
Percent Exterior Leakage = 30%														
0.60	2	5.8	5.6	6.0	6.5	6.4	5.6	5.8	5.1	6.3	5.9	5.6	6.0	5.9
0.90	3	8.0	7.6	8.2	9.0	8.8	7.6	7.8	6.8	8.7	8.1	7.7	8.2	8.0
1.20	4	10.2	9.7	10.4	11.5	11.3	9.6	9.9	8.5	11.0	10.3	9.8	10.5	10.2
1.50	5	12.4	11.7	12.7	14.0	13.7	11.6	12.0	10.2	13.4	12.4	11.8	12.8	12.4
2.10	7	16.8	15.9	17.2	19.0	18.6	15.6	16.2	13.7	18.2	16.8	16.0	17.4	16.8
3.00	10	23.4	22.1	24.0	26.5	26.0	21.6	22.6	18.9	25.4	23.4	22.3	24.3	23.4
4.20	14	32.2	30.4	33.1	36.6	35.9	29.8	31.2	25.9	35.0	32.2	30.6	33.5	32.2
Percent Exterior Leakage = 45%														
0.90	2	7.4	7.0	7.4	8.1	7.8	6.7	6.9	6.1	7.7	7.2	7.0	7.5	7.2
1.35	3	10.3	9.7	10.4	11.3	11.0	9.3	9.6	8.3	10.7	10.1	9.7	10.6	10.1
1.80	4	13.3	12.4	13.3	14.6	14.1	11.8	12.2	10.5	13.8	12.9	12.4	13.6	12.9
2.25	5	16.3	15.2	16.3	17.8	17.2	14.4	14.9	12.7	16.8	15.7	15.2	16.7	15.8
3.15	7	22.3	20.7	22.2	24.4	23.6	19.5	20.3	17.1	23.0	21.4	20.7	22.8	21.5
4.50	10	31.3	28.9	31.1	34.2	33.1	27.3	28.4	23.8	32.2	29.9	28.9	32.0	30.1
6.30	14	43.1	39.8	43.0	47.3	45.8	37.7	39.3	32.8	44.5	41.3	39.9	44.2	41.6
Percent Exterior Leakage = 70%														
1.50	2	10.8	10.0	10.1	10.5	9.5	8.0	8.2	7.3	9.3	9.3	9.6	10.6	9.5
2.25	3	15.4	14.1	14.3	14.8	13.4	11.2	11.4	10.1	13.1	13.1	13.6	15.2	13.3
3.00	4	20.1	18.3	18.5	19.2	17.2	14.3	14.7	12.9	16.9	16.9	17.5	19.7	17.2
3.75	5	24.8	22.5	22.8	23.6	21.1	17.4	17.9	15.6	20.6	20.6	21.5	24.3	21.1
5.25	7	34.2	31.0	31.2	32.3	28.9	23.7	24.4	21.2	28.2	28.2	29.5	33.5	28.8
7.50	10	48.1	43.6	43.9	45.5	40.6	33.2	34.2	29.6	39.6	39.5	41.4	47.2	40.5
10.50	14	66.6	60.2	60.7	63.0	56.2	45.9	47.3	40.8	54.7	54.4	57.3	65.3	56.0

Table 103. Monthly Variation of Infiltration by Unit (CFM)

		Month												Annual
		1	2	3	4	5	6	7	8	9	10	11	12	Average
Floor	Unit	% Exterior Leakage = 15%				Exterior Leakage = 2.10 ACH_{50}					Total Leakage = 14 ACH_{50}			
1	1A	36.6	34.5	34.2	30.6	22.3	21.4	22.6	20.1	26.6	28.0	33.2	35.7	28.8
1	1B	41.6	41.2	32.8	29.9	21.7	17.6	14.6	18.3	18.7	27.2	33.5	39.2	27.9
1	2A	28.2	23.5	29.9	30.7	26.3	24.9	27.9	19.7	35.8	28.5	28.1	29.5	27.8
2	1A	18.0	18.9	21.4	20.9	17.0	17.7	21.4	16.5	20.8	17.8	20.4	19.6	19.2
2	1B	21.1	23.2	19.2	19.2	16.0	13.8	13.1	14.5	13.0	16.7	19.7	21.5	17.6
2	2A	12.1	11.3	18.7	21.9	21.3	21.4	26.8	16.6	29.7	18.9	16.5	15.2	19.2
3	1A	6.6	8.7	12.8	14.8	13.6	15.3	20.8	14.2	16.8	10.8	11.2	9.6	12.9
3	1B	8.0	10.6	10.2	12.1	12.2	11.3	12.4	11.8	9.5	9.6	10.5	9.8	10.7
3	2A	3.4	4.6	11.1	16.3	17.7	19.1	26.3	14.7	24.9	12.0	8.6	7.2	13.9
Floor	Unit	% Exterior Leakage = 30%				Exterior Leakage = 2.10 ACH_{50}					Total Leakage = 7 ACH_{50}			
1	1A	26.9	26.2	27.0	25.3	19.4	18.9	20.9	17.9	22.9	22.7	26.2	27.2	23.4
1	1B	29.6	30.0	24.8	23.4	18.1	15.1	13.1	15.3	15.4	20.8	25.3	28.7	21.6
1	2A	19.0	16.2	22.0	23.7	21.1	20.2	23.2	15.9	28.8	21.6	20.5	20.9	21.1
2	1A	17.9	18.5	20.6	20.3	16.6	16.9	20.3	16.0	20.0	17.5	19.8	19.4	18.6
2	1B	19.6	21.1	17.9	18.0	15.3	13.2	12.4	13.3	12.4	15.3	18.3	20.1	16.4
2	2A	11.5	10.3	16.3	19.0	18.3	18.3	22.8	14.3	25.4	16.5	14.6	13.9	16.8
3	1A	10.9	12.4	15.3	16.5	14.4	15.5	19.8	14.6	17.5	13.3	14.5	13.2	14.8
3	1B	11.8	13.9	12.4	13.8	12.9	11.7	12.0	11.8	10.3	11.0	12.7	13.2	12.3
3	2A	5.9	6.1	11.7	15.6	16.2	17.0	22.6	13.2	22.5	12.4	10.1	8.6	13.5
Floor	Unit	% Exterior = 45%				Exterior Leakage = 2.25 ACH_{50}					Total Leakage = 5 ACH_{50}			
1	1A	24.2	23.9	24.8	24.2	19.1	18.5	20.9	17.7	22.2	21.5	24.3	25.0	22.2
1	1B	24.9	25.4	21.7	21.3	17.3	14.6	13.1	14.3	14.9	18.2	22.1	24.8	19.3
1	2A	15.8	13.4	17.8	19.6	17.5	16.7	19.2	13.2	23.6	17.7	16.8	17.3	17.4
2	1A	19.0	19.3	21.1	21.2	17.5	17.3	20.5	16.6	20.5	18.4	20.5	20.4	19.4
2	1B	19.4	20.5	17.8	18.1	15.6	13.4	12.6	13.1	13.0	15.1	18.2	20.0	16.4
2	2A	11.5	10.0	14.4	16.7	15.8	15.5	18.9	12.2	21.3	14.6	13.3	13.3	14.8
3	1A	14.7	15.6	17.8	18.7	15.9	16.3	20.2	15.6	18.8	15.7	17.1	16.6	16.9
3	1B	14.6	16.2	14.3	15.4	14.1	12.5	12.4	12.2	11.5	12.3	14.7	15.8	13.8
3	2A	8.0	7.1	11.4	14.4	14.3	14.7	18.9	11.5	19.5	12.0	10.3	9.8	12.7
Floor	Unit	% Exterior = 75%				Exterior Leakage = 2.25 ACH_{50}					Total Leakage = 3 ACH_{50}			
1	1A	20.8	20.8	21.4	21.8	18.0	16.9	19.4	16.5	19.9	19.3	21.1	21.8	19.8
1	1B	18.9	19.1	17.7	18.3	15.9	13.7	13.1	12.8	14.4	15.0	17.9	19.5	16.3
1	2A	13.0	11.0	11.3	11.8	9.7	8.9	9.3	7.3	11.9	10.8	11.6	12.8	10.8
2	1A	19.4	19.6	20.4	21.0	17.6	16.7	19.4	16.2	19.6	18.5	20.1	20.6	19.1
2	1B	17.6	17.9	16.7	17.5	15.5	13.5	13.0	12.5	13.9	14.2	16.9	18.3	15.6
2	2A	11.8	10.0	10.4	11.0	9.2	8.6	9.2	7.0	11.2	9.9	10.5	11.6	10.0
3	1A	18.3	18.6	19.6	20.3	17.1	16.4	19.3	16.0	19.0	17.8	19.2	19.6	18.4
3	1B	16.4	16.9	15.9	16.8	15.1	13.2	13.0	12.3	13.5	13.5	16.0	17.2	15.0
3	2A	10.7	9.1	9.6	10.3	8.8	8.4	9.3	6.9	10.8	9.2	9.5	10.6	9.4

Note – units 1A and 1B are corner units on opposite sides of corridor, unit 2A is an inner unit

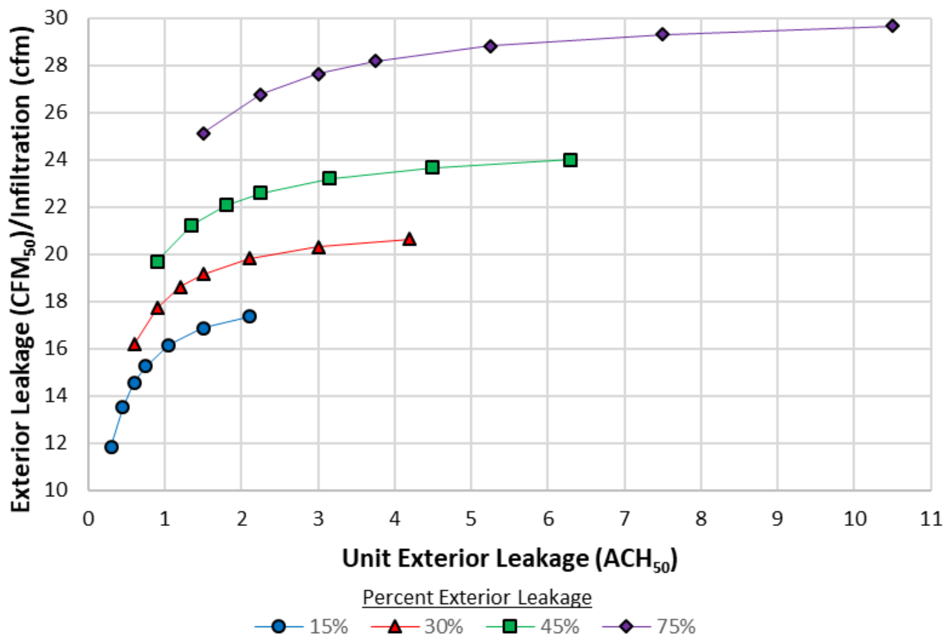


Figure 202. Exterior Leakage Divided by Infiltration

Table 104. Reduction in Annual Infiltration (CFM) for Reduction of 1 ACH50 in Exterior Leakage

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25									
0.50									
0.75									
1.0									
1.5		5.4	6.1	6.6	7.1				
2.0		4.9	5.3	5.7	6.1	6.5	6.9	7.2	7.4
2.5		4.4	5.0	5.2	5.5	5.9	6.2	6.5	6.8
3.0			4.6	5.0	5.2	5.3	5.7	6.0	6.2
3.5			4.3	4.7	5.1	5.2	5.2	5.6	5.8
4.0				4.4	4.8	5.1	5.2	5.1	5.4
4.5				4.3	4.5	4.8	5.1	5.2	5.0
5.0					4.4	4.6	4.9	5.1	5.3
5.5					4.2	4.4	4.7	4.9	5.1
6.0						4.3	4.5	4.7	4.9
6.5						4.2	4.4	4.6	4.8
7.0							4.3	4.4	4.6
7.5							4.2	4.3	4.5

Table 105. Reduction in Annual Infiltration (CFM) for Reduction of 1 ACH50 in Interior Leakage

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25									
0.50		0.30	0.15	0.09					
0.75		0.61	0.34	0.21	0.14	0.10			
1.0		0.87	0.57	0.37	0.25	0.18	0.13	0.10	0.08
1.5		1.30	0.95	0.69	0.56	0.40	0.30	0.23	0.19
2.0			1.20	0.98	0.83	0.63	0.54	0.42	0.33
2.5			1.92	1.15	0.98	0.94	0.70	0.61	0.52
3.0				1.68	1.12	0.97	1.02	0.79	0.63
3.5				2.31	1.54	1.10	0.94	1.08	0.86
4.0					2.03	1.45	1.09	0.90	1.13
4.5					2.58	1.84	1.38	1.07	0.86
5.0						2.28	1.71	1.33	1.06
5.5						2.77	2.08	1.61	1.29
6.0							2.48	1.93	1.54
6.5							2.91	2.26	1.81
7.0								2.63	2.10
7.5								3.02	2.42

Table 106. Ratio of Infiltration Reduction for Reduction of 1 ACH50 in Exterior Leakage and Reduction of 1 ACH50 in Interior Leakage

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25									
0.50									
0.75									
1.0									
1.5		4.2	6.4	9.6	12.6				
2.0			4.4	5.8	7.4	10.3	12.8	17.1	22.1
2.5			2.6	4.5	5.6	6.3	8.8	10.5	13.0
3.0				3.0	4.6	5.5	5.6	7.5	9.8
3.5				2.0	3.3	4.7	5.5	5.2	6.7
4.0					2.3	3.5	4.8	5.6	4.8
4.5					1.8	2.6	3.7	4.9	5.8
5.0						2.0	2.8	3.8	5.0
5.5						1.6	2.2	3.0	4.0
6.0							1.8	2.4	3.2
6.5							1.5	2.0	2.6
7.0								1.7	2.2
7.5								1.4	1.9

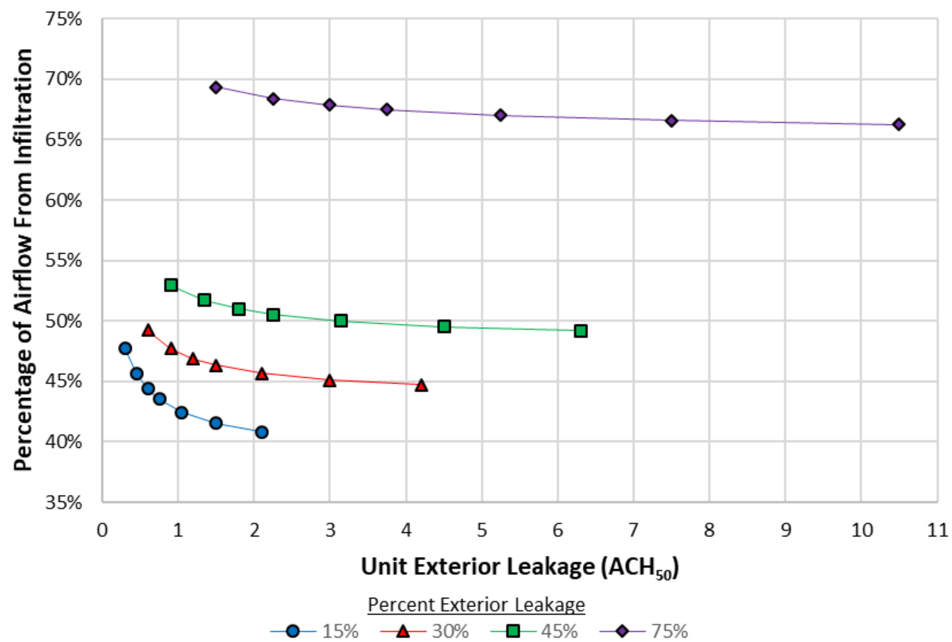


Figure 203. Percentage of Airflow from Outside Into Unit

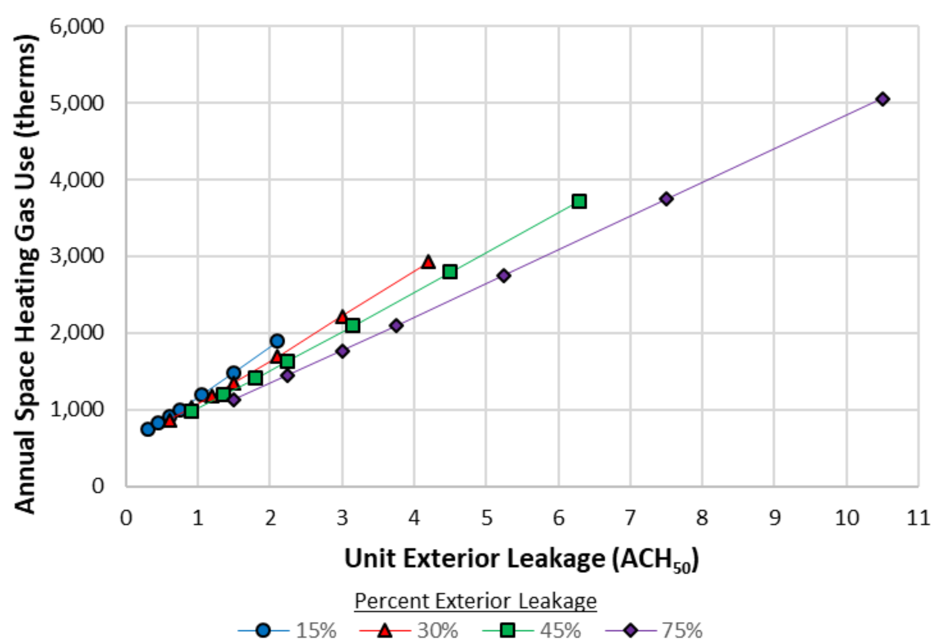


Figure 204. Annual Residential Unit Space Heating Gas Use (Therms)

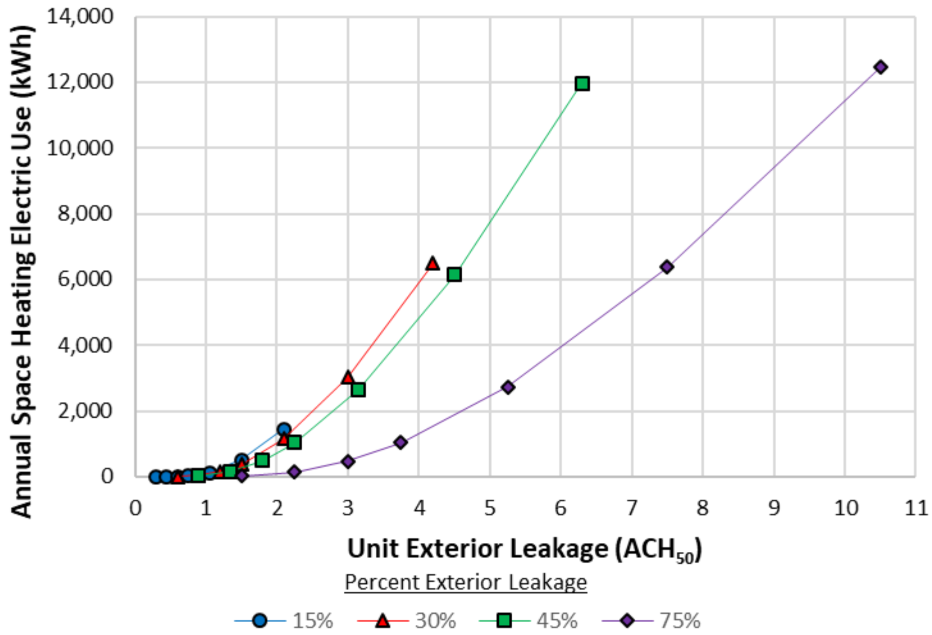


Figure 205. Annual Corridor Space Heating Electric Use (kWh)

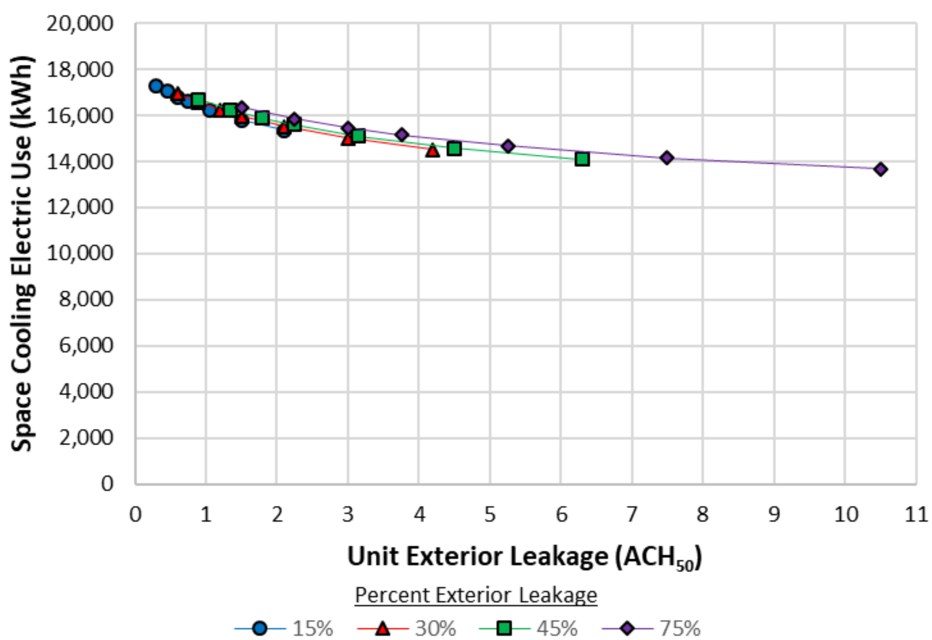


Figure 206. Annual Residential Unit Cooling Electric Use (kWh)

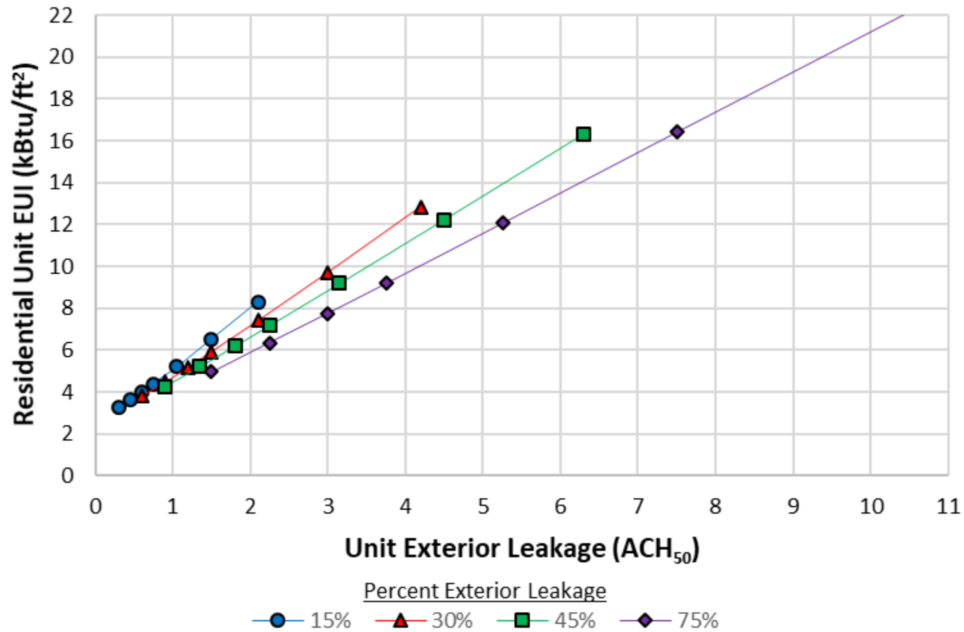


Figure 207. EUI for Residential Units (kBtu/ft^2)

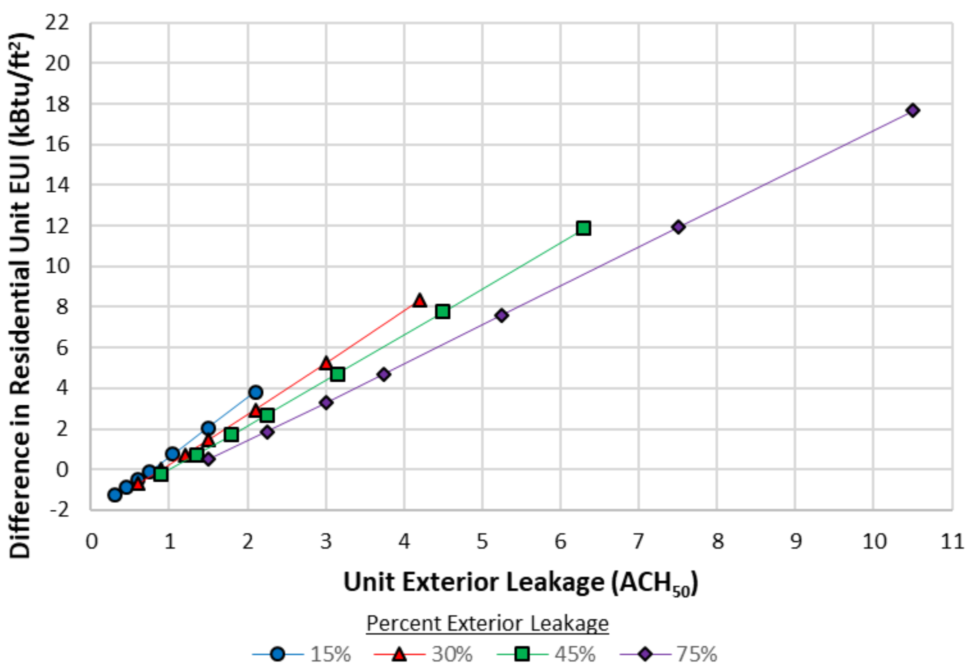


Figure 208. Difference in EUI From Baseline for Residential Units (kBtu/ft^2)

Table 107. Difference in EUI From Baseline for Residential Units

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25	-1.33								
0.50	-0.85	-0.75	-0.71	-0.68					
0.75	-0.44	-0.26	-0.15	-0.08	-0.04	-0.01			
1.0	-0.08	0.18	0.36	0.48	0.56	0.62	0.67	0.70	0.73
1.5	0.50	0.96	1.24	1.44	1.64	1.78	1.89	1.97	2.04
2.0		1.61	2.02	2.32	2.56	2.76	2.96	3.12	3.25
2.5		2.08	2.72	3.10	3.40	3.69	3.90	4.11	4.31
3.0			3.27	3.82	4.18	4.49	4.80	5.04	5.24
3.5			3.70	4.44	4.93	5.28	5.58	5.92	6.18
4.0				4.94	5.58	6.04	6.38	6.67	7.02
4.5				5.34	6.15	6.72	7.15	7.49	7.76
5.0					6.62	7.32	7.85	8.27	8.59
5.5					6.99	7.84	8.48	8.98	9.38
6.0						8.28	9.04	9.63	10.10
6.5						8.63	9.52	10.21	10.77
7.0							9.93	10.73	11.38
7.5							10.27	11.19	11.93

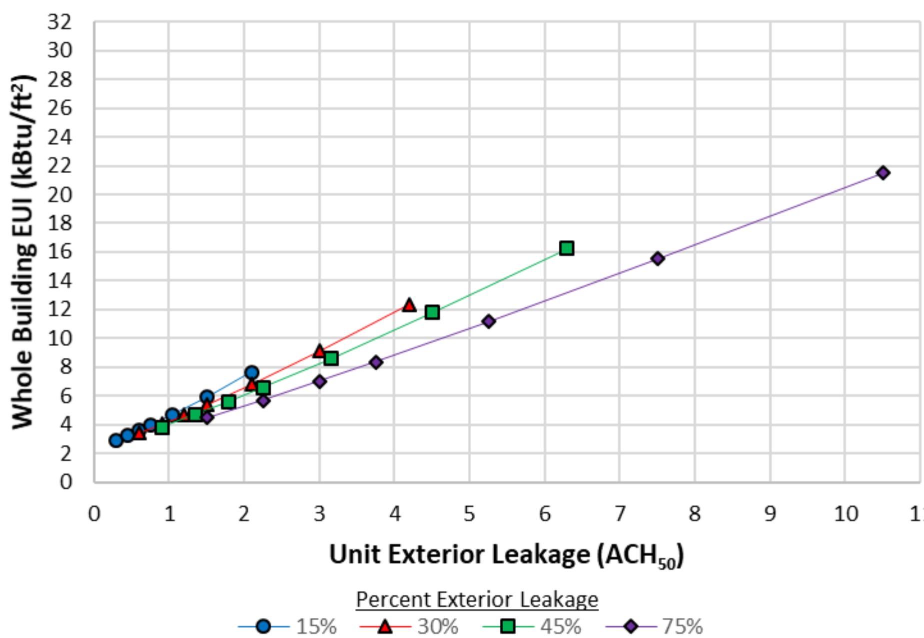


Figure 209. EUI for Whole Building (kBtu/ft²)

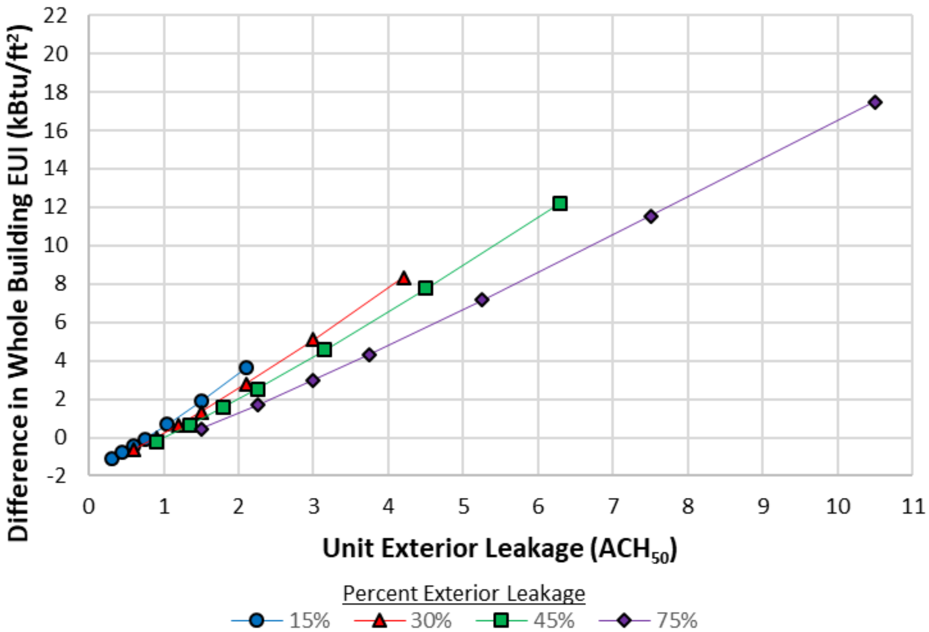


Figure 210. Difference in EUI From Baseline for Whole Building (kBtu/ft^2)

APPENDIX G: AIRFLOW AND ENERGY MODEL RESULTS FOR WASHINGTON

Balanced Ventilation

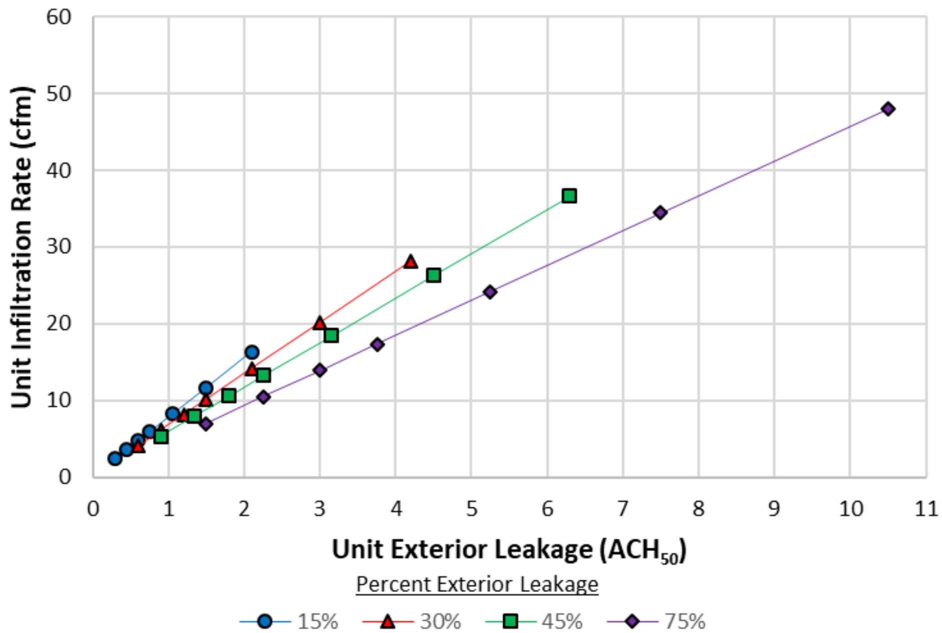


Figure 211. Annual Average Unit Infiltration: Seattle Balanced Ventilation

Table 108. Unit Annual Average Infiltration (CFM): Seattle Balanced Ventilation

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25	2.0								
0.50	3.6	3.9	4.0	4.1					
0.75	4.8	5.4	5.7	5.9	6.0	6.1			
1.0	5.7	6.6	7.1	7.5	7.7	7.9	8.0	8.1	8.2
1.5	7.0	8.5	9.5	10.2	10.7	11.0	11.3	11.5	11.7
2.0		10.0	11.4	12.3	13.1	13.7	14.2	14.6	14.9
2.5		10.8	12.9	14.2	15.2	16.0	16.7	17.2	17.7
3.0			13.9	15.8	17.0	18.0	18.9	19.6	20.2
3.5			14.5	16.9	18.6	19.8	20.7	21.7	22.5
4.0				17.7	19.9	21.4	22.6	23.5	24.5
4.5				18.1	20.8	22.8	24.2	25.4	26.3
5.0					21.4	23.8	25.6	27.0	28.1
5.5					21.7	24.6	26.8	28.5	29.8
6.0						25.0	27.6	29.7	31.3
6.5						25.2	28.3	30.6	32.5
7.0							28.6	31.4	33.6
7.5							28.8	31.9	34.4

Table 109. Monthly Variation of Unit Average Infiltration (CFM)

Leakage (ACH_{50})		Month												Annual
Exterior	Total	1	2	3	4	5	6	7	8	9	10	11	12	Average
Percent Exterior Leakage = 15%														
0.30	2	2.8	2.6	2.5	2.5	2.2	2.3	2.0	2.2	1.6	2.5	2.7	2.5	2.4
0.45	3	4.2	3.8	3.7	3.7	3.3	3.4	3.0	3.3	2.3	3.8	4.0	3.8	3.5
0.60	4	5.6	5.1	5.0	5.0	4.3	4.5	4.0	4.4	3.1	5.0	5.4	5.1	4.7
0.75	5	7.0	6.3	6.2	6.2	5.4	5.6	5.1	5.5	3.9	6.2	6.7	6.3	5.9
1.05	7	9.7	8.9	8.7	8.7	7.6	7.9	7.1	7.7	5.4	8.7	9.4	8.9	8.2
1.50	10	13.9	12.6	12.4	12.4	10.8	11.2	10.1	10.9	7.7	12.4	13.4	12.6	11.7
2.10	14	19.4	17.6	17.2	17.2	15.0	15.7	14.1	15.3	10.8	17.3	18.7	17.6	16.3
Percent Exterior Leakage = 30%														
0.60	2	4.8	4.4	4.3	4.3	3.7	3.9	3.5	3.9	2.7	4.3	4.7	4.4	4.1
0.90	3	7.3	6.6	6.5	6.5	5.6	5.9	5.3	5.8	4.0	6.5	7.0	6.6	6.1
1.20	4	9.7	8.8	8.6	8.6	7.4	7.8	7.0	7.7	5.3	8.6	9.4	8.8	8.1
1.50	5	12.1	11.0	10.7	10.7	9.3	9.8	8.8	9.6	6.6	10.8	11.7	11.0	10.2
2.10	7	16.9	15.3	15.0	15.0	12.9	13.7	12.3	13.4	9.2	15.0	16.3	15.3	14.2
3.00	10	24.0	21.8	21.3	21.3	18.4	19.5	17.5	19.2	13.1	21.4	23.3	21.8	20.2
4.20	14	33.6	30.4	29.7	29.7	25.7	27.2	24.4	26.8	18.2	29.9	32.5	30.4	28.2
Percent Exterior Leakage = 45%														
0.90	2	6.4	5.8	5.7	5.6	4.8	5.1	4.5	4.9	3.5	5.6	6.2	5.8	5.3
1.35	3	9.6	8.7	8.5	8.3	7.2	7.6	6.7	7.4	5.3	8.4	9.2	8.7	8.0
1.80	4	12.7	11.6	11.3	11.1	9.5	10.1	9.0	9.9	7.0	11.2	12.3	11.6	10.6
2.25	5	15.9	14.4	14.1	13.8	11.9	12.6	11.2	12.3	8.7	14.0	15.3	14.5	13.2
3.15	7	22.2	20.1	19.6	19.3	16.6	17.6	15.7	17.2	12.2	19.5	21.4	20.2	18.5
4.50	10	31.6	28.6	27.9	27.4	23.6	25.0	22.3	24.5	17.3	27.7	30.5	28.8	26.3
6.30	14	44.1	40.0	38.9	38.2	32.9	34.9	31.2	34.3	24.1	38.5	42.6	40.1	36.6
Percent Exterior Leakage = 75%														
1.50	2	8.5	7.9	7.6	7.3	6.4	6.4	5.7	6.1	4.9	7.4	8.1	7.8	7.0
2.25	3	12.7	11.7	11.3	11.0	9.6	9.6	8.6	9.2	7.3	11.0	12.1	11.7	10.5
3.00	4	16.9	15.6	15.1	14.6	12.7	12.8	11.4	12.2	9.7	14.6	16.1	15.6	13.9
3.75	5	21.0	19.5	18.7	18.1	15.8	16.0	14.3	15.3	12.0	18.2	20.1	19.4	17.4
5.25	7	29.4	27.2	26.1	25.2	22.1	22.4	20.0	21.3	16.8	25.3	28.1	27.1	24.2
7.50	10	41.9	38.6	37.0	35.8	31.3	31.8	28.5	30.4	23.8	35.9	40.0	38.6	34.4
10.50	14	58.5	53.9	51.5	49.7	43.3	44.4	39.7	42.5	33.1	49.9	55.7	53.9	48.0

Table 110. Monthly Variation of Infiltration by Unit (CFM)

		Month												Annual
		1	2	3	4	5	6	7	8	9	10	11	12	Average
Floor	Unit	% Exterior Leakage = 15%					Exterior Leakage = 2.10 ACH_{50}				Total Leakage = 14 ACH_{50}			
1	1A	31.7	26.2	24.9	28.4	24.7	23.7	19.3	17.4	15.5	27.1	30.3	30.0	24.9
1	1B	18.3	22.5	20.2	20.2	21.3	18.3	18.7	17.9	18.2	17.9	14.8	17.5	18.8
1	2A	47.0	33.6	33.4	36.5	27.8	29.6	21.5	22.0	16.6	37.1	45.6	42.6	32.8
2	1A	20.1	14.5	14.2	18.5	15.2	16.5	13.3	12.6	6.8	17.9	20.0	17.7	15.6
2	1B	7.4	11.9	10.6	11.8	12.9	11.9	13.5	13.5	9.7	9.7	5.7	6.6	10.4
2	2A	33.7	21.1	22.0	26.3	18.8	22.2	15.4	17.0	7.9	27.2	33.7	28.8	22.9
3	1A	12.8	8.1	7.9	11.3	9.0	11.4	9.1	9.4	2.5	11.3	13.6	10.1	9.7
3	1B	2.6	5.8	5.6	7.1	7.7	8.1	10.1	10.9	5.1	5.6	1.9	2.0	6.1
3	2A	23.0	13.0	13.6	17.1	11.8	16.1	10.6	13.0	3.2	18.5	24.3	17.9	15.2
Floor	Unit	% Exterior Leakage = 30%					Exterior Leakage = 2.10 ACH_{50}				Total Leakage = 7 ACH_{50}			
1	1A	24.8	19.2	18.6	21.6	18.3	18.8	15.2	14.1	10.8	21.2	24.1	22.7	19.1
1	1B	13.2	17.3	15.5	16.3	17.0	15.1	15.8	15.5	13.6	13.9	10.6	12.4	14.7
1	2A	36.0	24.7	25.0	27.8	20.6	22.7	16.2	17.1	11.5	28.4	35.1	32.0	24.8
2	1A	19.4	13.7	13.6	16.8	13.7	15.3	12.2	11.7	6.7	16.7	19.4	17.0	14.7
2	1B	7.9	12.2	10.9	12.2	12.9	11.8	13.1	13.3	9.7	10.0	6.1	7.2	10.6
2	2A	28.9	18.3	19.0	21.9	15.7	18.5	12.8	14.2	7.1	22.9	28.8	24.7	19.4
3	1A	14.9	9.5	9.6	12.7	10.0	12.4	9.8	9.9	3.9	12.9	15.4	12.4	11.1
3	1B	4.3	8.3	7.4	8.9	9.6	9.3	11.0	11.6	6.7	7.0	3.3	3.7	7.6
3	2A	22.6	13.0	13.9	16.8	11.6	15.0	10.0	11.9	4.2	18.0	23.3	18.6	14.9
Floor	Unit	% Exterior = 45%					Exterior Leakage = 2.25 ACH_{50}				Total Leakage = 5 ACH_{50}			
1	1A	22.8	17.0	16.7	18.9	15.8	17.2	13.8	13.2	9.5	19.2	22.6	20.5	17.3
1	1B	12.2	16.4	14.7	15.8	16.3	14.7	15.4	15.3	12.5	13.5	10.0	11.6	14.0
1	2A	28.6	19.7	20.0	21.6	16.0	17.8	12.6	13.6	9.3	22.5	28.1	25.4	19.6
2	1A	19.9	14.0	14.0	16.3	13.2	15.2	12.0	11.9	7.0	16.7	20.0	17.4	14.8
2	1B	9.2	13.5	12.1	13.4	13.9	12.7	13.8	14.1	10.2	11.1	7.4	8.5	11.6
2	2A	24.3	16.0	16.4	17.9	13.0	15.2	10.5	11.7	6.7	19.0	24.2	21.1	16.4
3	1A	17.0	11.2	11.3	13.7	10.9	13.3	10.5	10.6	5.2	14.3	17.4	14.5	12.5
3	1B	6.7	11.0	9.8	11.3	11.8	11.0	12.4	12.9	8.4	9.1	5.3	6.2	9.6
3	2A	20.6	12.7	13.2	14.8	10.4	13.0	8.7	10.2	4.9	16.0	20.9	17.5	13.6
Floor	Unit	% Exterior = 75%					Exterior Leakage = 2.25 ACH_{50}				Total Leakage = 3 ACH_{50}			
1	1A	18.9	14.0	14.0	14.8	12.4	14.4	11.6	11.8	7.8	15.7	19.0	16.6	14.3
1	1B	11.6	15.0	13.5	15.0	14.8	13.7	14.0	14.3	10.5	12.9	10.0	11.0	13.0
1	2A	14.0	11.1	10.9	10.7	8.4	8.3	6.3	6.6	6.3	11.1	13.5	13.0	10.0
2	1A	18.3	13.2	13.3	14.2	11.8	13.9	11.1	11.5	7.2	15.2	18.4	15.9	13.7
2	1B	10.7	14.2	12.8	14.3	14.1	13.1	13.6	13.9	9.9	12.2	9.3	10.2	12.4
2	2A	12.9	10.1	10.0	9.8	7.6	7.6	5.8	6.1	5.5	10.2	12.4	11.9	9.2
3	1A	17.4	12.4	12.6	13.5	11.2	13.4	10.7	11.1	6.7	14.5	17.6	15.1	13.0
3	1B	10.0	13.5	12.2	13.7	13.6	12.7	13.2	13.6	9.4	11.6	8.7	9.5	11.8
3	2A	12.1	9.3	9.2	9.1	7.1	7.1	5.4	5.8	5.1	9.5	11.6	11.1	8.5

Note – units 1A and 1B are corner units on opposite sides of corridor, unit 2A is an inner unit

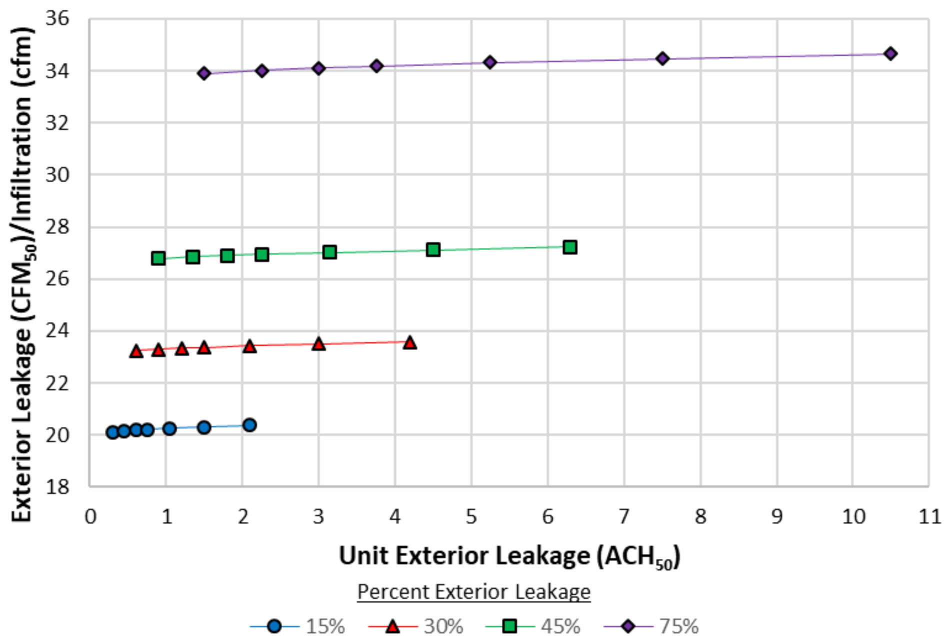


Figure 212. Exterior Leakage Divided by Infiltration

Table 111. Reduction in Annual Infiltration (CFM) for Reduction of 1 ACH50 in Exterior Leakage

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25									
0.50									
0.75									
1.0									
1.5		5.0	5.6	6.2	6.6				
2.0		4.3	4.8	5.2	5.7	6.0	6.3	6.6	6.8
2.5		3.8	4.4	4.7	5.0	5.4	5.6	5.9	6.2
3.0			3.9	4.4	4.6	4.8	5.2	5.4	5.6
3.5			3.7	4.0	4.4	4.6	4.7	5.0	5.3
4.0				3.8	4.1	4.4	4.6	4.6	4.9
4.5				3.6	3.9	4.2	4.4	4.6	4.5
5.0					3.7	3.9	4.2	4.5	4.6
5.5					3.6	3.8	4.0	4.2	4.4
6.0						3.6	3.8	4.0	4.3
6.5						3.6	3.7	3.9	4.1
7.0							3.6	3.8	3.9
7.5							3.5	3.7	3.8

Table 112. Reduction in Annual Infiltration (CFM) for Reduction of 1 ACH50 in Interior Leakage

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25									
0.50		0.29	0.14	0.09					
0.75		0.59	0.32	0.19	0.13	0.09			
1.0		0.89	0.54	0.34	0.23	0.16	0.12	0.10	0.08
1.5		1.53	0.97	0.66	0.51	0.36	0.27	0.21	0.17
2.0			1.36	0.99	0.78	0.58	0.48	0.38	0.30
2.5			2.12	1.27	1.00	0.87	0.65	0.56	0.47
3.0				1.83	1.22	0.98	0.94	0.73	0.58
3.5				2.48	1.66	1.18	0.96	0.99	0.79
4.0					2.16	1.54	1.16	0.94	1.04
4.5					2.74	1.95	1.47	1.14	0.91
5.0						2.41	1.81	1.40	1.12
5.5						2.91	2.18	1.70	1.36
6.0							2.60	2.02	1.62
6.5							3.05	2.37	1.90
7.0								2.75	2.20
7.5								3.16	2.53

Table 113. Ratio of Infiltration Reduction for Reduction of 1 ACH50 in Exterior Leakage and Reduction of 1 ACH50 in Interior Leakage

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25									
0.50									
0.75									
1.0									
1.5		3.2	5.8	9.3	12.9				
2.0			3.5	5.2	7.2	10.3	13.1	17.5	22.6
2.5			2.1	3.7	5.0	6.2	8.7	10.6	13.2
3.0				2.4	3.8	4.9	5.5	7.4	9.7
3.5				1.6	2.7	3.9	4.9	5.1	6.6
4.0					1.9	2.9	4.0	4.9	4.7
4.5					1.4	2.1	3.0	4.1	5.0
5.0						1.6	2.3	3.2	4.1
5.5						1.3	1.8	2.5	3.3
6.0							1.5	2.0	2.6
6.5							1.2	1.6	2.2
7.0								1.4	1.8
7.5								1.2	1.5

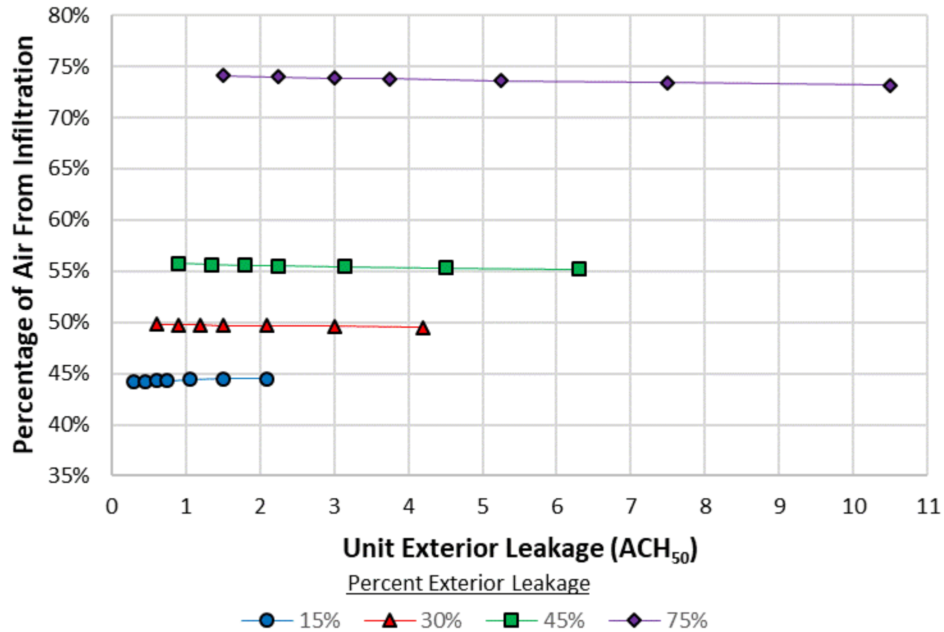


Figure 213. Percentage of Airflow from Outside into Unit: Seattle Balanced Ventilation

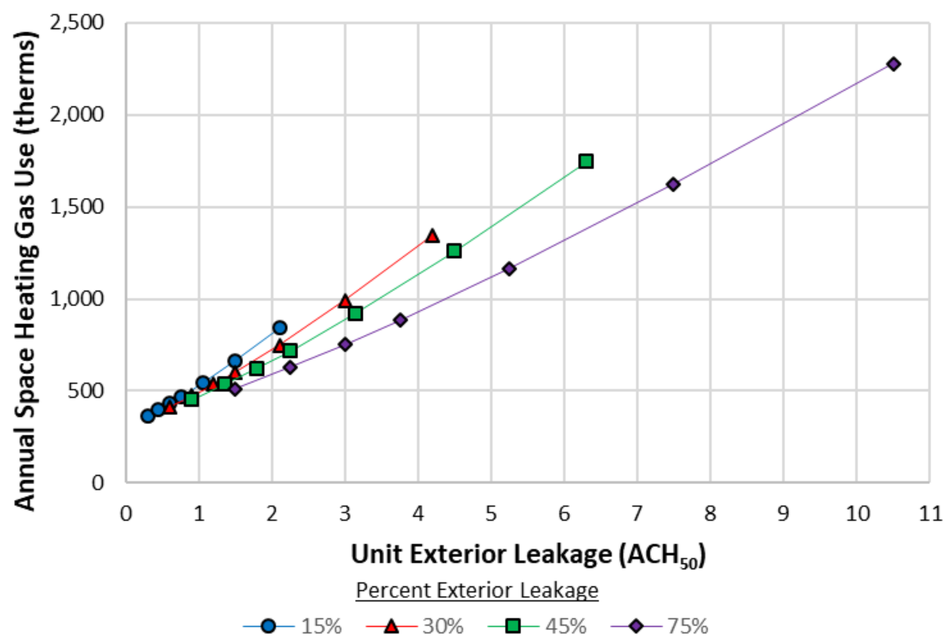


Figure 214. Annual Residential Unit Space Heating Gas Use (Therms)

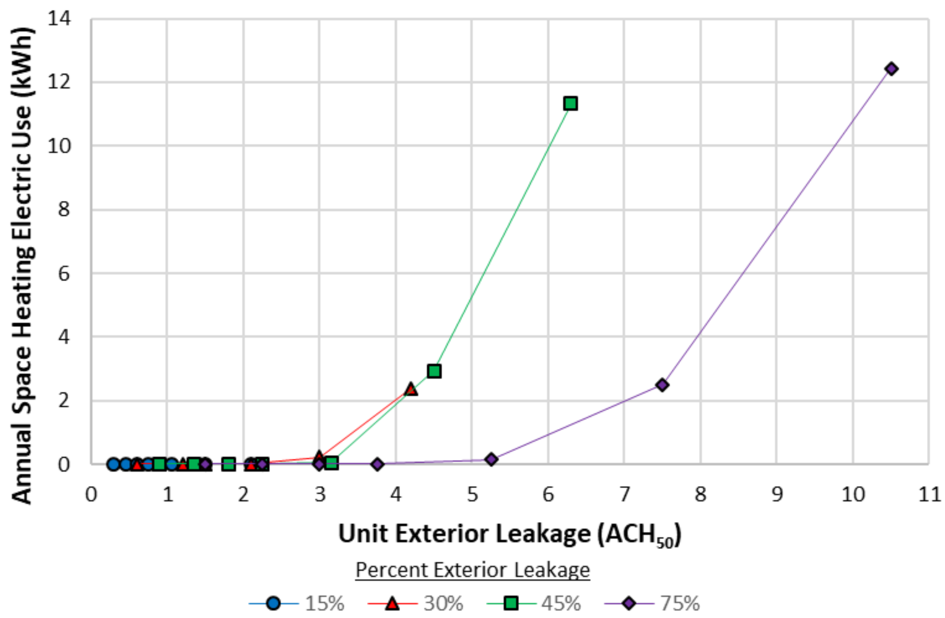


Figure 215. Annual Corridor Space Heating Electric Use (kWh)

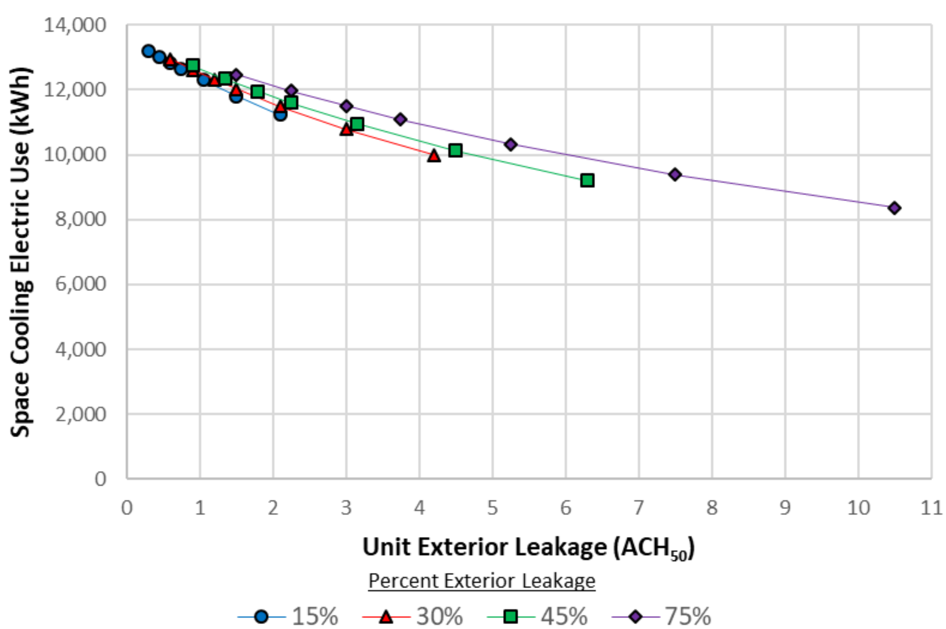


Figure 216. Annual Residential Unit Cooling Electric Use (kWh)

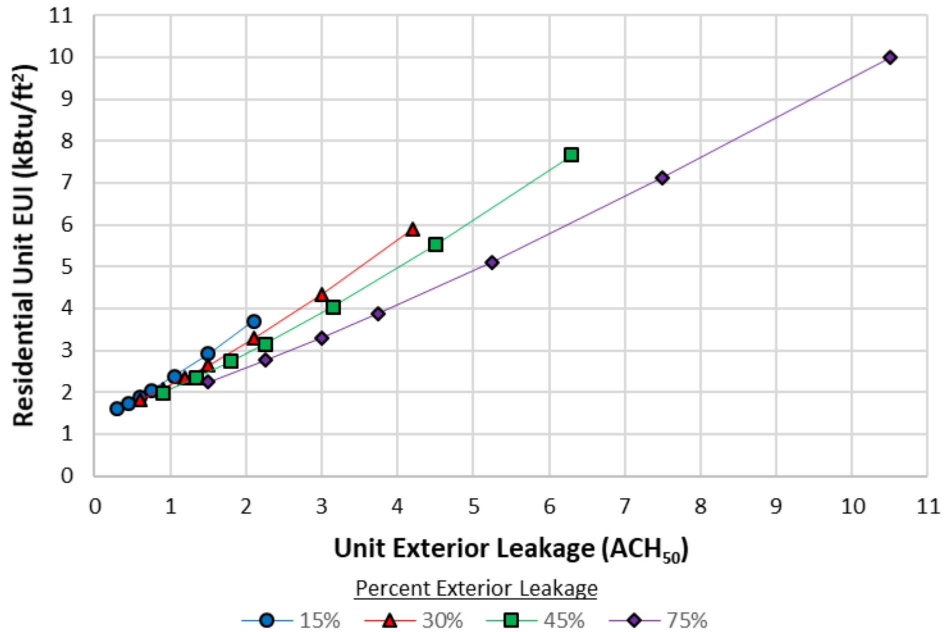


Figure 217. EUI for Residential Units (kBtu/ft²)

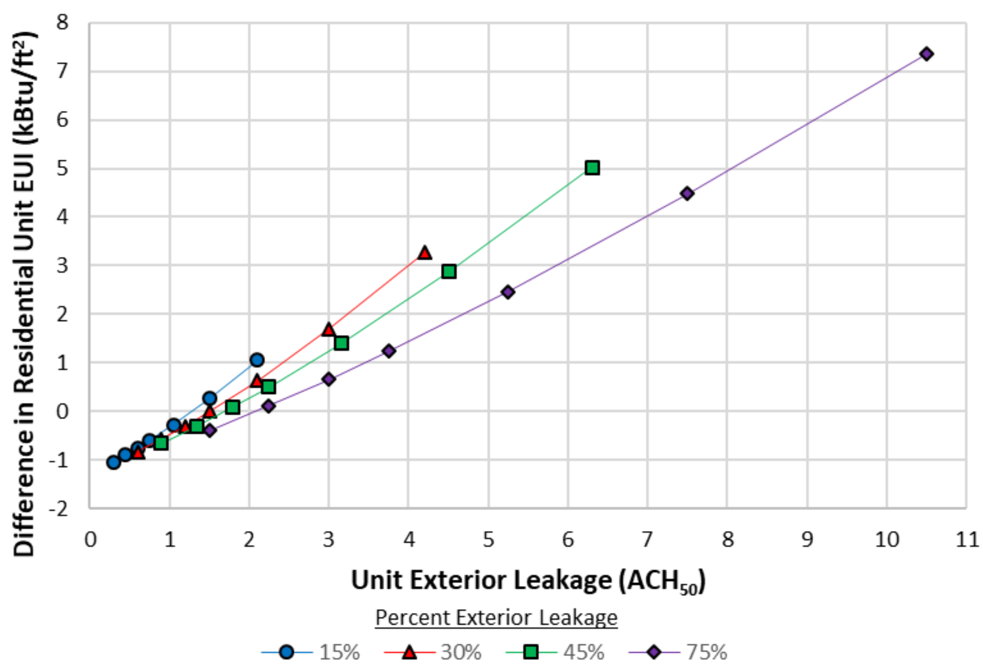


Figure 218. Difference in EUI From Baseline for Residential Units (kBtu/ft²)

Table 114. Difference in EUI From Baseline for Residential Units

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25	-1.08								
0.50	-0.90	-0.86	-0.84	-0.82					
0.75	-0.74	-0.67	-0.62	-0.59	-0.58	-0.56			
1.0	-0.60	-0.50	-0.43	-0.38	-0.34	-0.32	-0.30	-0.28	-0.27
1.5	-0.39	-0.21	-0.08	0.00	0.09	0.15	0.20	0.24	0.27
2.0		0.04	0.22	0.36	0.48	0.57	0.66	0.73	0.79
2.5		0.17	0.49	0.68	0.83	0.97	1.08	1.18	1.27
3.0			0.66	0.95	1.15	1.31	1.47	1.60	1.70
3.5			0.74	1.17	1.45	1.66	1.83	2.01	2.16
4.0				1.29	1.69	1.97	2.18	2.35	2.55
4.5				1.34	1.85	2.22	2.49	2.71	2.88
5.0					1.93	2.41	2.77	3.05	3.27
5.5					1.93	2.53	2.98	3.33	3.61
6.0						2.59	3.14	3.56	3.90
6.5						2.59	3.24	3.74	4.14
7.0							3.28	3.86	4.34
7.5							3.25	3.93	4.48

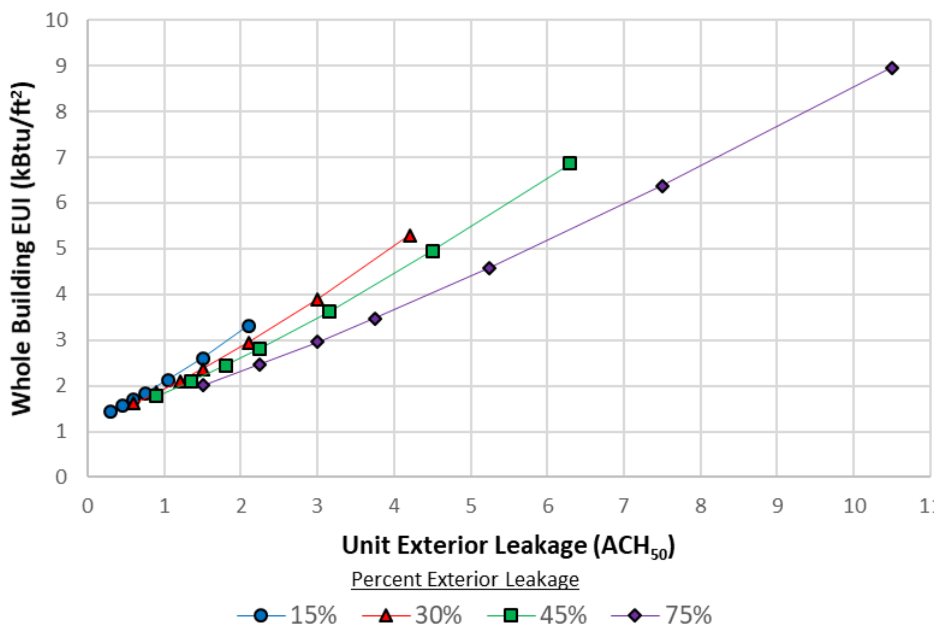


Figure 219. EUI for Whole Building (kBtu/ft²)

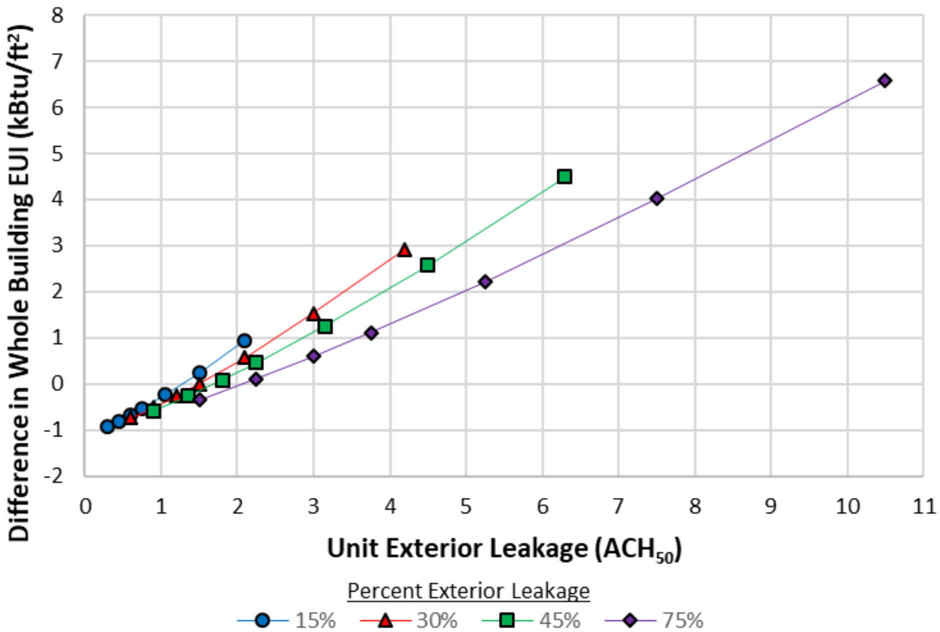


Figure 220. Difference in EUI From Baseline for Whole Building (kBtu/ft²)

Continuous Exhaust Ventilation

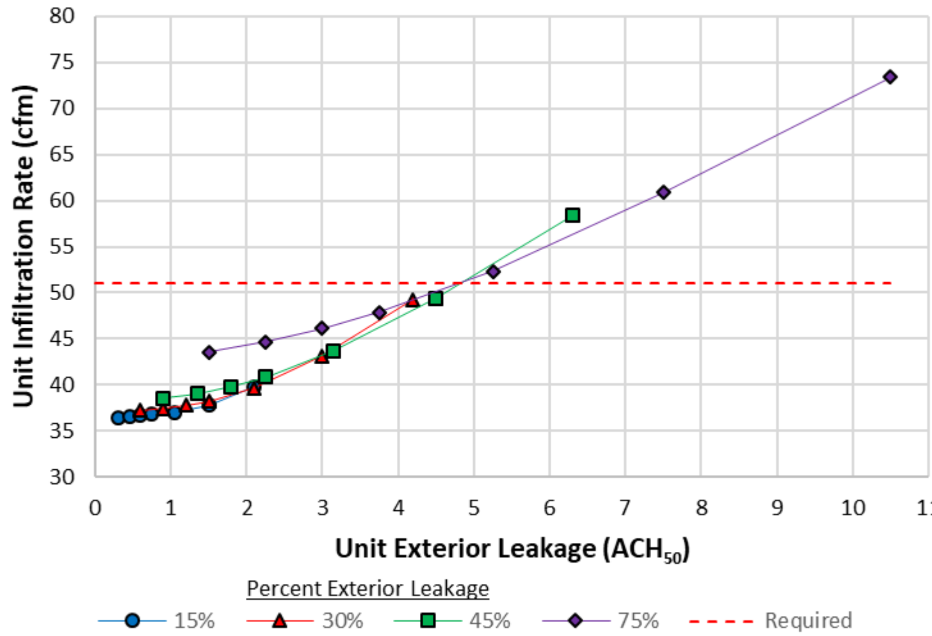


Figure 221. Annual Average Unit Infiltration: Seattle Continuous Exhaust Ventilation

Table 115. Unit Annual Average Infiltration (CFM): Seattle Continuous Exhaust Ventilation

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25	36.4								
0.50	37.0	36.7	36.6	36.5					
0.75	37.9	37.2	36.9	36.8	36.7	36.6			
1.0	39.3	37.8	37.4	37.2	37.1	37.0	36.9	36.8	36.8
1.5	43.6	40.0	38.7	38.2	38.1	38.0	37.9	37.8	37.8
2.0		43.2	40.9	40.0	39.6	39.4	39.5	39.5	39.5
2.5		46.1	43.7	42.2	41.5	41.4	41.3	41.2	41.2
3.0			46.1	44.7	43.7	43.2	43.2	43.2	43.2
3.5			48.1	46.9	46.1	45.5	45.2	45.4	45.5
4.0				48.8	48.2	47.8	47.5	47.3	47.6
4.5				50.4	50.1	49.8	49.7	49.5	49.4
5.0					51.5	51.6	51.7	51.8	51.9
5.5					52.6	53.1	53.5	53.8	54.0
6.0						54.6	55.2	55.6	56.0
6.5						55.7	56.6	57.3	57.9
7.0							57.8	58.7	59.5
7.5							58.8	60.0	60.9

Table 116. Monthly Variation of Unit Average Infiltration (CFM)

Leakage (ACH_{50})		Month												Annual
Exterior	Total	1	2	3	4	5	6	7	8	9	10	11	12	Average
Percent Exterior Leakage = 15%														
0.30	2	35.6	35.9	36.1	36.4	36.6	37.1	37.3	37.6	37.0	36.6	36.1	35.6	36.5
0.45	3	35.8	36.0	36.2	36.4	36.6	37.1	37.3	37.7	37.1	36.8	36.4	35.8	36.6
0.60	4	36.0	36.1	36.4	36.5	36.6	37.2	37.4	37.8	37.2	36.9	36.6	35.9	36.7
0.75	5	36.2	36.2	36.5	36.5	36.6	37.2	37.4	37.9	37.3	37.0	36.8	36.1	36.8
1.05	7	36.7	36.5	36.9	36.6	36.5	37.2	37.3	38.0	37.4	37.3	37.4	36.5	37.0
1.50	10	38.1	37.5	37.8	37.2	36.8	37.6	37.4	38.5	37.7	38.2	38.8	37.6	37.8
2.10	14	41.4	40.3	40.3	39.5	38.3	39.0	38.4	39.7	38.2	40.5	41.7	40.4	39.8
Percent Exterior Leakage = 30%														
0.60	2	36.5	36.7	36.9	37.0	37.2	37.7	37.9	38.4	37.8	37.4	37.1	36.5	37.3
0.90	3	36.9	36.9	37.2	37.1	37.1	37.8	37.9	38.5	37.9	37.7	37.6	36.8	37.5
1.20	4	37.5	37.3	37.6	37.3	37.1	37.9	38.0	38.7	38.0	38.1	38.3	37.3	37.8
1.50	5	38.4	37.8	38.2	37.6	37.3	38.2	38.0	39.0	38.2	38.6	39.1	38.0	38.2
2.10	7	40.8	39.8	40.0	39.2	38.2	39.1	38.7	40.1	38.7	40.4	41.4	39.9	39.7
3.00	10	45.8	44.1	44.0	43.0	41.0	42.0	41.0	42.8	39.8	44.2	46.1	44.3	43.2
4.20	14	53.9	51.3	50.7	49.7	46.3	47.6	45.6	48.0	42.4	50.8	53.6	51.3	49.3
Percent Exterior Leakage = 45%														
0.90	2	37.9	38.0	38.3	38.2	38.2	38.9	39.0	39.6	38.9	38.7	38.6	37.8	38.5
1.35	3	38.9	38.5	38.9	38.5	38.3	39.2	39.1	40.0	39.2	39.3	39.6	38.6	39.0
1.80	4	40.2	39.5	39.9	39.2	38.6	39.6	39.4	40.6	39.5	40.3	41.0	39.6	39.8
2.25	5	41.9	40.8	41.2	40.2	39.3	40.4	40.0	41.4	39.9	41.5	42.6	41.0	40.8
3.15	7	46.1	44.4	44.5	43.3	41.4	42.7	41.8	43.7	40.9	44.6	46.5	44.5	43.7
4.50	10	54.0	51.3	50.9	49.6	46.2	47.7	45.9	48.5	43.1	50.8	53.8	51.3	49.4
6.30	14	65.6	61.5	60.7	59.1	54.0	56.0	53.0	56.5	47.8	60.4	64.7	61.6	58.4
Percent Exterior Leakage = 70%														
1.50	2	43.1	43.0	43.3	43.2	43.2	43.9	44.0	44.7	43.8	43.9	43.8	42.9	43.6
2.25	3	44.8	44.3	44.7	44.2	43.8	44.8	44.5	45.6	44.3	45.2	45.6	44.3	44.7
3.00	4	46.9	46.0	46.4	45.7	44.8	45.9	45.5	46.8	44.9	46.8	47.6	46.0	46.1
3.75	5	49.4	48.1	48.3	47.6	46.1	47.5	46.6	48.4	45.6	48.7	49.9	48.0	47.8
5.25	7	55.9	53.7	53.3	52.4	49.7	51.2	49.7	52.1	47.3	53.2	55.6	53.5	52.3
7.50	10	67.7	64.2	63.0	61.4	57.0	58.6	55.8	58.9	51.6	62.2	66.4	64.4	60.9
10.50	14	83.6	78.5	76.7	74.3	67.8	69.9	65.6	69.5	59.7	75.2	81.4	79.0	73.4

Table 117. Monthly Variation of Infiltration by Unit (CFM)

		Month												Annual
		1	2	3	4	5	6	7	8	9	10	11	12	Average
Floor	Unit	% Exterior Leakage = 15%				Exterior Leakage = 2.10 ACH_{50}					Total Leakage = 14 ACH_{50}			
1	1A	59.4	55.7	53.4	56.8	53.7	52.1	48.1	46.4	46.3	55.1	57.4	58.1	53.5
1	1B	47.3	50.2	48.5	47.3	48.6	46.1	46.4	45.6	47.9	45.8	43.9	46.5	47.0
1	2A	72.6	62.1	60.6	63.5	56.0	56.8	49.5	49.8	47.6	63.9	71.4	69.0	60.2
2	1A	44.1	40.7	40.1	45.4	43.1	43.2	40.6	40.0	36.5	43.9	44.6	43.4	42.1
2	1B	31.2	35.6	35.2	35.6	38.0	36.7	38.9	39.1	38.2	34.4	30.1	31.0	35.3
2	2A	58.8	47.8	48.2	52.9	45.8	48.4	42.4	44.0	38.0	53.7	59.8	55.6	49.6
3	1A	28.7	25.3	26.0	32.8	31.0	33.3	32.3	32.9	25.2	31.7	31.1	27.8	29.9
3	1B	15.2	21.2	21.2	23.7	26.9	26.9	30.7	32.0	27.1	21.9	15.7	15.1	23.2
3	2A	44.5	33.0	34.9	41.3	34.3	39.3	34.7	37.5	27.0	42.3	47.1	40.8	38.1
Floor	Unit	% Exterior Leakage = 30%				Exterior Leakage = 2.10 ACH_{50}					Total Leakage = 7 ACH_{50}			
1	1A	51.3	48.3	47.1	50.5	48.3	47.6	44.7	43.6	42.7	49.3	50.7	50.5	47.9
1	1B	41.0	43.9	43.0	42.5	44.0	42.3	43.2	42.9	44.1	41.6	39.2	40.5	42.3
1	2A	64.2	54.7	54.5	57.4	51.1	52.6	46.8	47.6	44.4	58.1	64.0	61.0	54.7
2	1A	42.4	39.5	39.2	43.4	41.7	42.0	40.0	39.7	36.7	42.5	43.2	41.7	41.0
2	1B	31.8	35.4	35.2	35.6	37.5	36.6	38.6	38.9	38.1	34.8	31.2	31.6	35.4
2	2A	55.9	46.3	46.9	50.8	44.7	47.3	42.3	43.9	38.4	51.6	56.8	52.8	48.2
3	1A	33.5	30.5	31.0	36.0	34.6	36.2	35.1	35.5	30.2	35.3	35.3	32.7	33.8
3	1B	22.7	27.3	27.4	28.9	31.1	30.9	33.9	34.8	31.7	27.8	23.0	22.5	28.5
3	2A	47.8	37.9	39.4	44.1	38.2	42.0	37.8	40.2	32.4	45.2	49.7	44.7	41.6
Floor	Unit	% Exterior = 45%				Exterior Leakage = 2.25 ACH_{50}					Total Leakage = 5 ACH_{50}			
1	1A	47.9	45.2	44.6	47.3	45.6	45.6	43.3	42.8	41.6	46.8	48.2	47.1	45.5
1	1B	39.5	42.0	41.5	41.3	42.5	41.3	42.3	42.2	42.7	40.7	38.5	39.2	41.1
1	2A	60.1	51.7	52.0	54.5	49.0	50.9	46.1	47.3	43.7	55.4	60.3	57.2	52.4
2	1A	42.7	39.8	39.8	42.8	41.4	42.0	40.3	40.3	37.7	42.5	43.7	41.8	41.3
2	1B	34.0	37.0	36.9	37.2	38.5	37.8	39.4	39.8	38.9	36.6	33.7	33.8	37.0
2	2A	54.7	46.3	47.1	50.0	44.8	47.3	43.1	44.8	39.8	51.1	55.5	51.9	48.0
3	1A	37.3	34.3	34.7	38.1	36.8	38.3	37.2	37.6	33.7	38.0	38.8	36.3	36.8
3	1B	28.6	32.2	32.2	33.2	34.6	34.3	36.5	37.2	34.9	32.5	28.8	28.4	32.8
3	2A	49.9	41.3	42.6	45.9	40.8	44.2	40.4	42.6	36.2	47.2	51.2	47.0	44.1
Floor	Unit	% Exterior = 75%				Exterior Leakage = 2.25 ACH_{50}					Total Leakage = 3 ACH_{50}			
1	1A	46.1	44.4	44.4	45.1	44.4	45.3	44.4	44.9	43.8	45.8	47.2	45.4	45.1
1	1B	42.6	43.8	43.8	44.0	44.2	44.0	44.4	44.6	44.3	44.0	42.6	42.4	43.7
1	2A	51.8	48.1	48.7	49.5	47.3	48.8	46.9	48.0	45.7	50.3	52.2	50.4	49.0
2	1A	45.1	43.3	43.4	44.2	43.5	44.6	43.8	44.4	43.0	45.0	46.3	44.3	44.3
2	1B	41.4	42.7	42.8	43.1	43.3	43.2	43.9	44.2	43.5	43.1	41.6	41.2	42.8
2	2A	50.0	46.5	47.1	48.0	45.9	47.6	45.9	47.1	44.5	48.9	50.6	48.7	47.6
3	1A	43.4	41.6	41.9	42.8	42.2	43.5	42.8	43.6	41.8	43.6	44.9	42.7	42.9
3	1B	39.8	41.3	41.4	41.9	42.2	42.1	43.0	43.4	42.4	41.9	40.2	39.7	41.6
3	2A	48.9	45.3	46.1	47.1	45.1	47.0	45.4	46.8	43.8	48.1	49.7	47.6	46.8

Note – units 1A and 1B are corner units on opposite sides of corridor, unit 2A is an inner unit

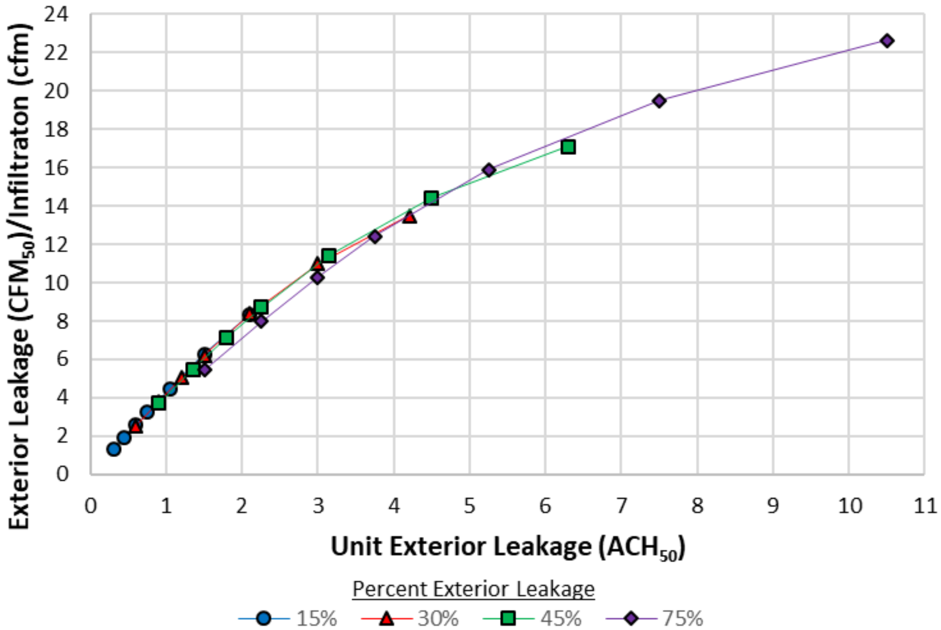


Figure 222. Exterior Leakage Divided by Infiltration

Table 118. Reduction in Annual Infiltration (CFM) for Reduction of 1 ACH50 in Exterior Leakage

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25									
0.50									
0.75									
1.0									
1.5		3.0	2.0	1.7	1.6				
2.0		3.9	3.1	2.6	2.4	2.4	2.5	2.6	2.6
2.5		2.6	3.7	3.5	3.3	3.3	3.3	3.3	3.4
3.0			2.9	3.7	3.7	3.6	3.7	3.7	3.7
3.5			2.0	3.2	3.9	4.0	3.8	4.1	4.3
4.0				2.7	3.6	4.1	4.3	4.1	4.4
4.5				2.3	3.2	3.7	4.1	4.3	4.0
5.0					2.7	3.4	3.9	4.3	4.5
5.5					2.2	3.0	3.7	4.1	4.5
6.0						3.1	3.6	3.9	4.2
6.5						3.1	3.5	3.8	4.1
7.0							3.2	3.6	3.8
7.5							3.0	3.4	3.6

Table 119. Reduction in Annual Infiltration (CFM) for Reduction of 1 ACH50 in Interior Leakage

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25									
0.50		-0.30	-0.15	-0.09					
0.75		-0.68	-0.24	-0.14	-0.09	-0.07			
1.0		-1.53	-0.43	-0.19	-0.13	-0.09	-0.07	-0.05	-0.04
1.5		-3.58	-1.24	-0.53	-0.15	-0.11	-0.08	-0.06	-0.05
2.0			-2.25	-0.95	-0.36	-0.18	0.01	0.01	0.00
2.5			-2.45	-1.47	-0.68	-0.16	-0.12	-0.04	-0.01
3.0				-1.46	-0.97	-0.49	-0.01	-0.01	-0.01
3.5				-1.22	-0.82	-0.58	-0.30	0.17	0.14
4.0					-0.57	-0.41	-0.31	-0.18	0.28
4.5					-0.32	-0.23	-0.17	-0.14	-0.11
5.0						0.14	0.11	0.08	0.07
5.5						0.50	0.38	0.29	0.23
6.0							0.62	0.48	0.38
6.5							0.89	0.69	0.55
7.0								0.93	0.74
7.5								1.20	0.96

Table 120. Ratio of Infiltration Reduction for Reduction of 1 ACH50 in Exterior Leakage and Reduction of 1 ACH50 in Interior Leakage

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25									
0.50									
0.75									
1.0									
1.5		-0.8	-1.6	-3.1	-10.7				
2.0			-1.4	-2.8	-6.7	-13.4	356	471	602
2.5			-1.5	-2.4	-4.9	-21.2	-28	-79	-290
3.0				-2.6	-3.8	-7.3	-279	-357	-445
3.5				-2.6	-4.8	-6.8	-13	24	31
4.0					-6.2	-10.1	-14	-23	16
4.5					-9.7	-16.1	-24	-32	-37
5.0						24	37	52	68
5.5						6.1	9.7	14.1	19.2
6.0							5.8	8.2	11.1
6.5							3.9	5.5	7.3
7.0								3.8	5.1
7.5								2.8	3.8

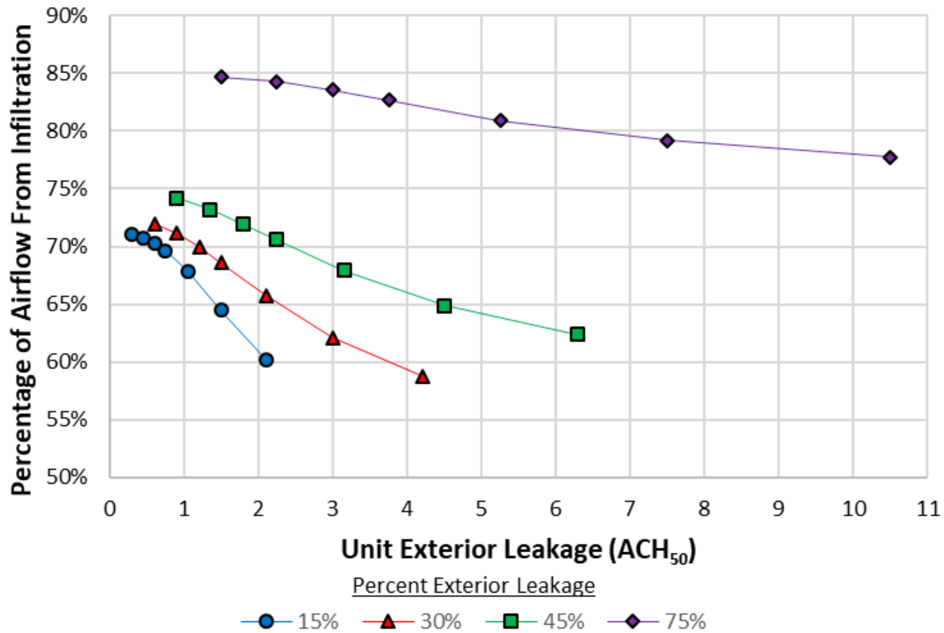


Figure 223. Percentage of Airflow from Outside Into Unit

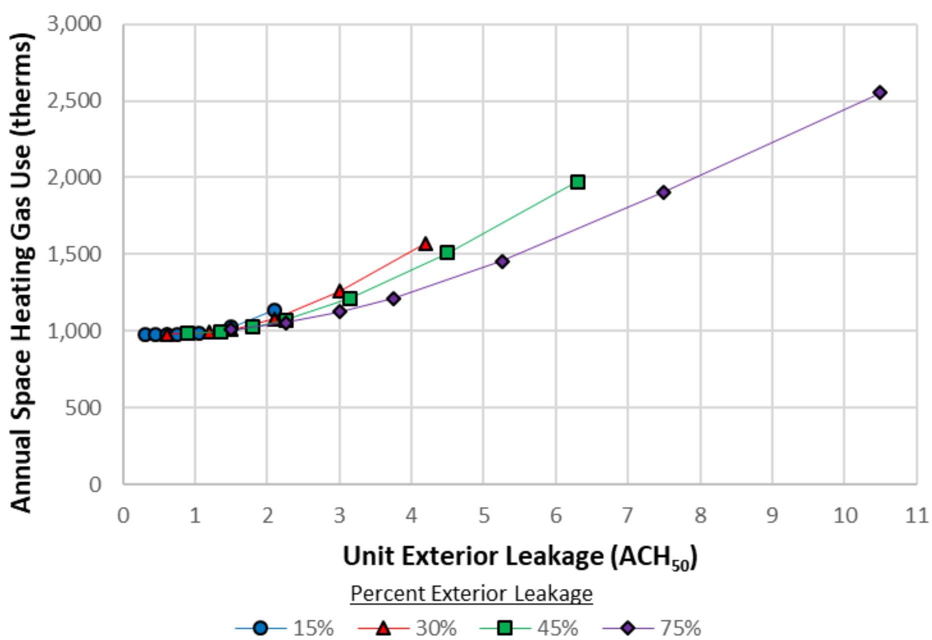


Figure 224. Annual Residential Unit Space Heating Gas Use (Therms)

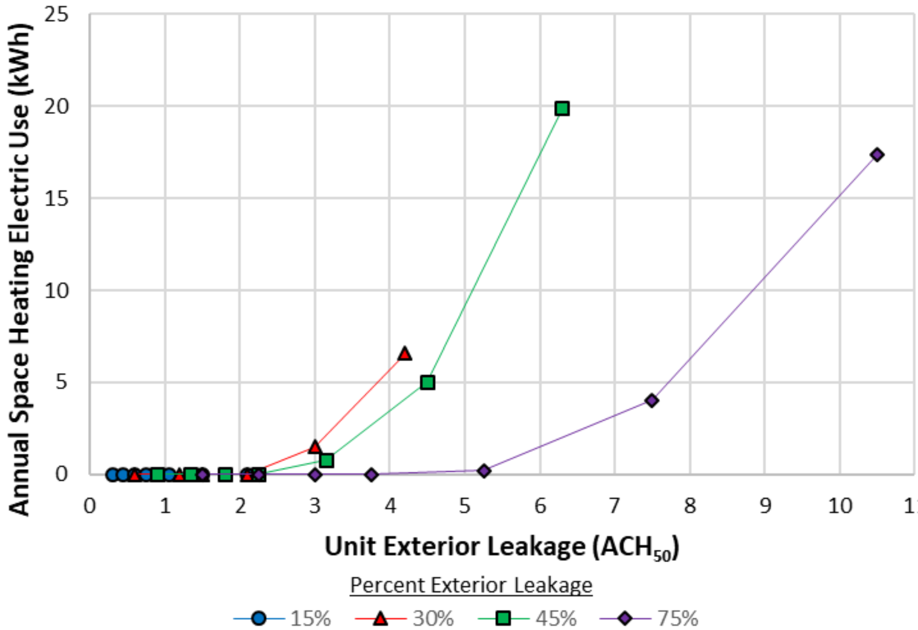


Figure 225. Annual Corridor Space Heating Electric Use (kWh)

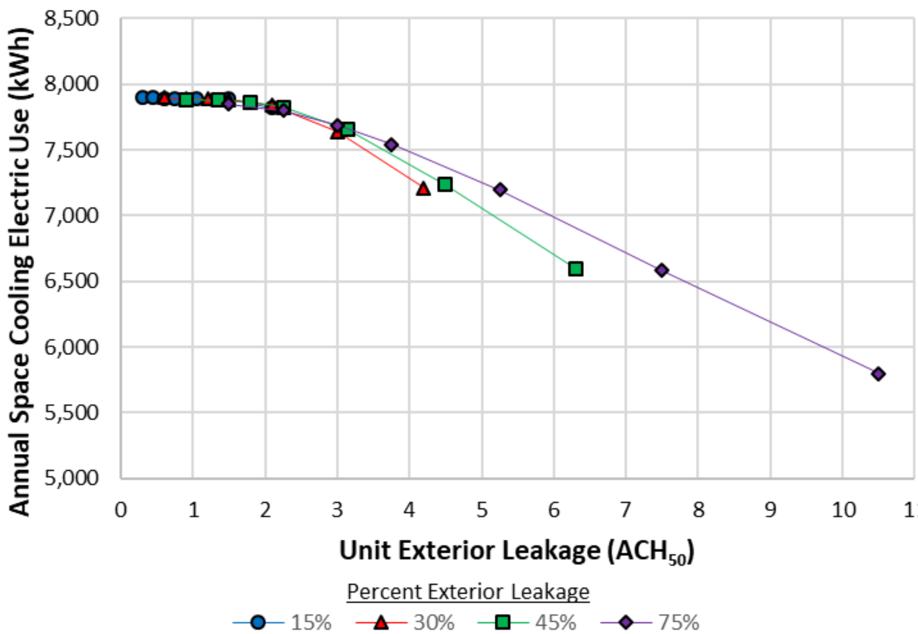


Figure 226. Annual Residential Unit Cooling Electric Use (kWh)

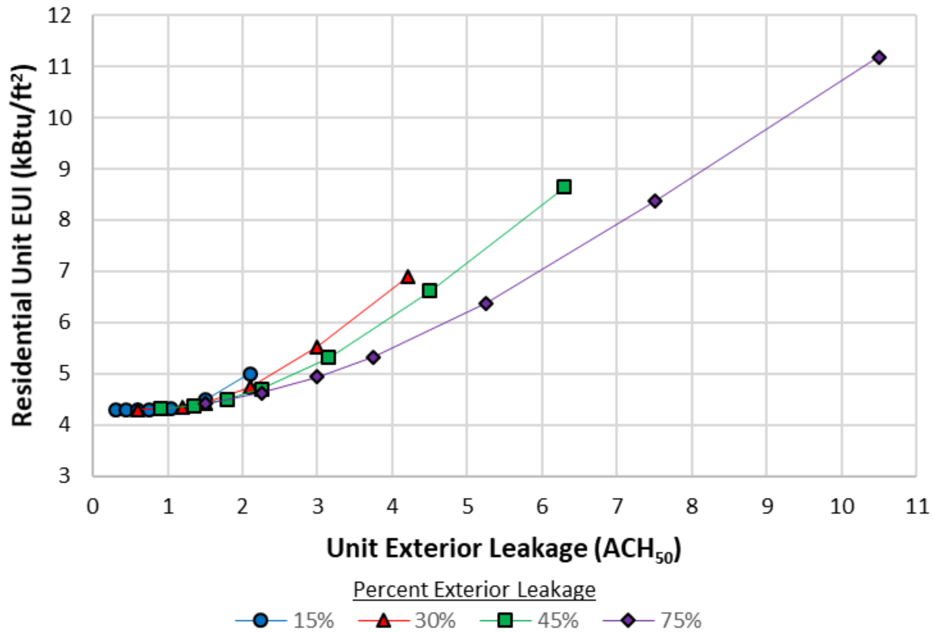


Figure 227. EUI for Residential Units (kBtu/ft^2)

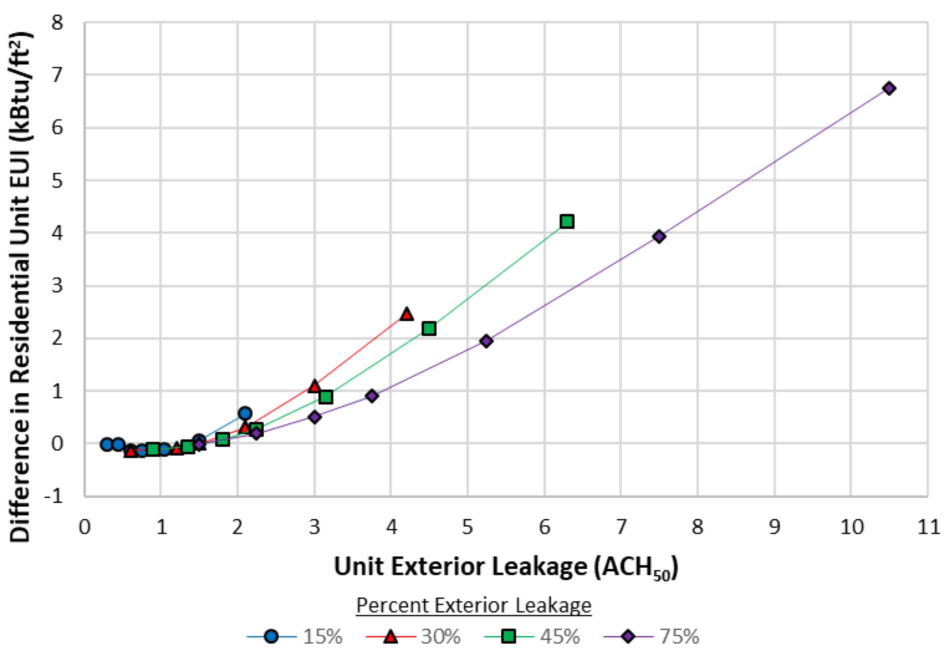


Figure 228. <u>Difference</u> in EUI From Baseline for Residential Units (kBtu/ft^2)

Table 121. Difference in EUI From Baseline for Residential Units

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25	-0.13								
0.50	-0.14	-0.14	-0.14	-0.14					
0.75	-0.13	-0.13	-0.13	-0.13	-0.14	-0.14			
1.0	-0.11	-0.11	-0.11	-0.11	-0.11	-0.11	-0.11	-0.11	-0.11
1.5	-0.01	-0.01	-0.01	0.00	0.02	0.04	0.05	0.06	0.07
2.0		0.13	0.15	0.19	0.24	0.28	0.33	0.38	0.41
2.5		0.26	0.36	0.42	0.49	0.58	0.64	0.70	0.74
3.0			0.51	0.65	0.74	0.83	0.94	1.03	1.10
3.5			0.58	0.85	1.02	1.15	1.27	1.41	1.52
4.0				0.97	1.25	1.45	1.60	1.73	1.88
4.5				1.04	1.43	1.70	1.90	2.06	2.19
5.0					1.51	1.90	2.19	2.41	2.59
5.5					1.54	2.04	2.41	2.70	2.94
6.0						2.16	2.62	2.97	3.25
6.5						2.23	2.77	3.19	3.52
7.0							2.87	3.36	3.75
7.5							2.92	3.48	3.94

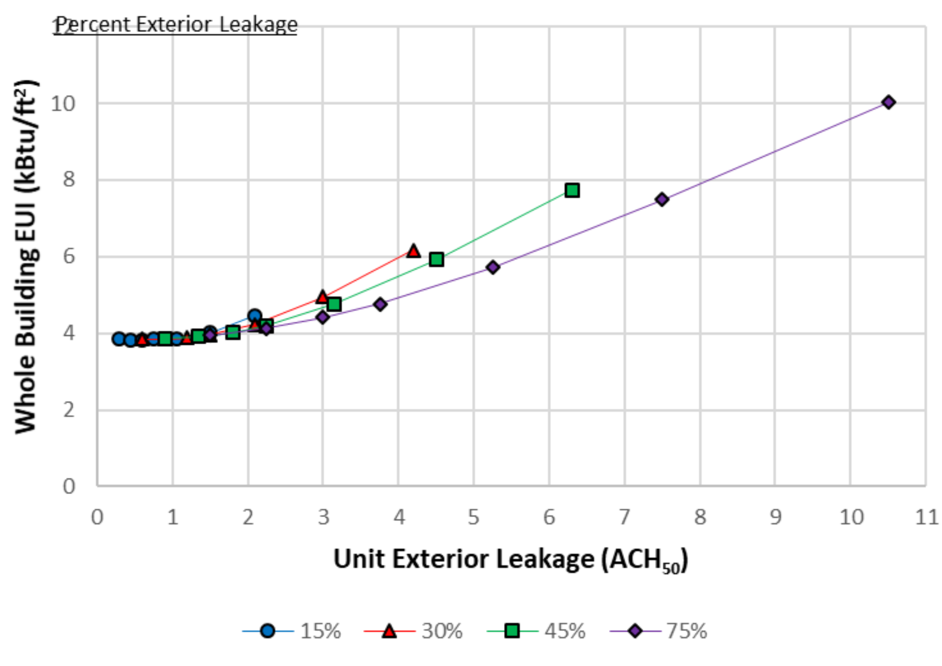


Figure 229. EUI for Whole Building (kBtu/ft²)

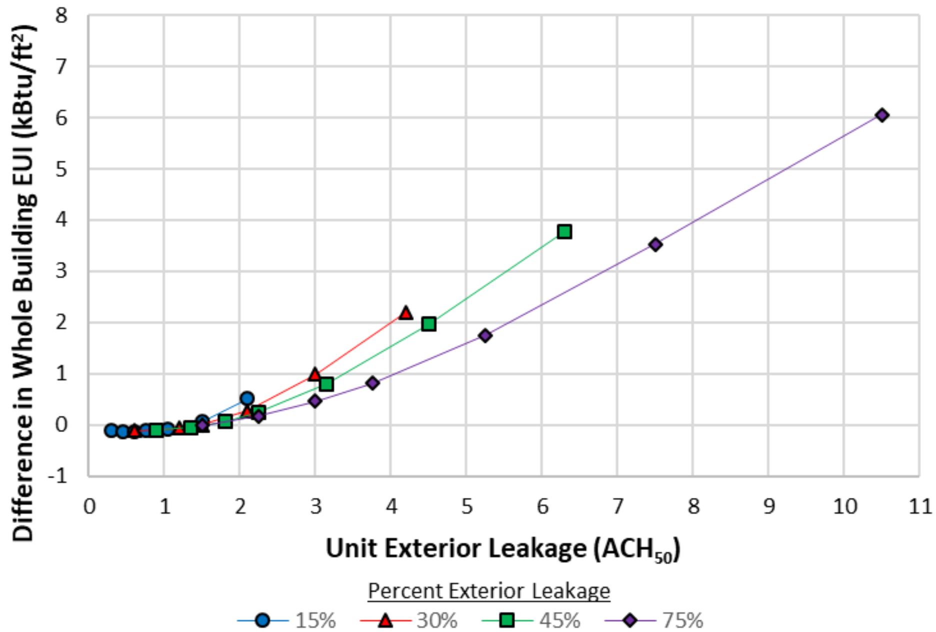


Figure 230. Difference in EUI From Baseline for Whole Building (kBtu/ft²)

Intermittent Exhaust Ventilation

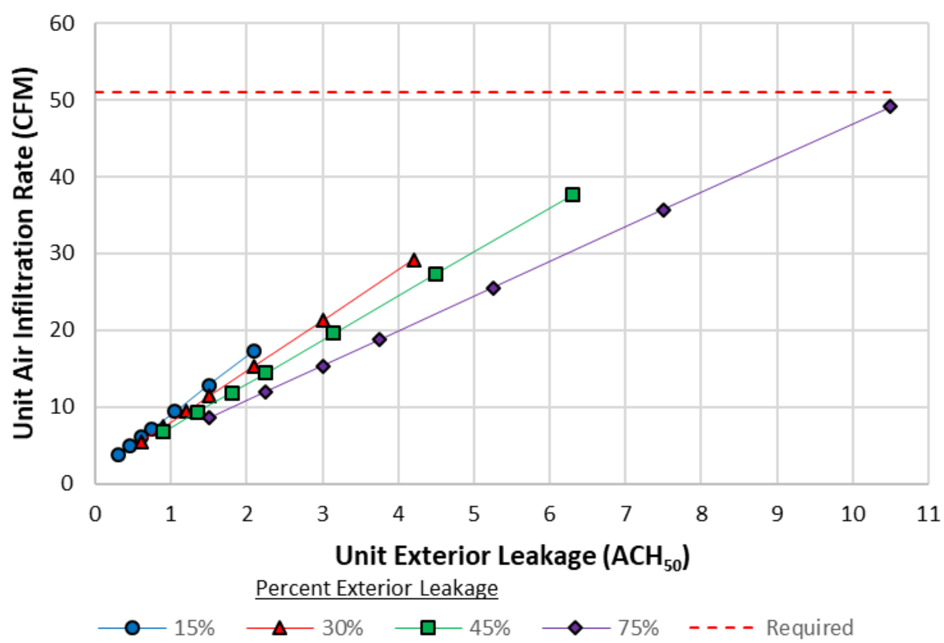


Figure 231. Annual Average Unit Infiltration: Seattle Intermittent Exhaust Ventilation

Table 122. Unit Annual Average Infiltration (CFM): Seattle Intermittent Exhaust Ventilation

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25	3.4								
0.50	5.0	5.2	5.4	5.4					
0.75	6.2	6.7	7.0	7.2	7.3	7.4			
1.0	7.1	7.9	8.4	8.7	8.9	9.1	9.2	9.3	9.4
1.5	8.6	9.9	10.8	11.4	11.9	12.2	12.5	12.7	12.8
2.0		11.4	12.6	13.5	14.3	14.8	15.3	15.7	16.0
2.5		12.3	14.2	15.4	16.3	17.2	17.8	18.3	18.8
3.0			15.3	17.0	18.2	19.1	20.0	20.7	21.2
3.5			15.9	18.3	19.8	20.9	21.8	22.8	23.6
4.0				19.1	21.1	22.6	23.7	24.6	25.6
4.5				19.5	22.1	24.0	25.4	26.5	27.3
5.0					22.7	25.1	26.8	28.1	29.2
5.5					23.0	25.9	28.0	29.6	30.9
6.0						26.4	28.9	30.8	32.4
6.5						26.6	29.5	31.9	33.7
7.0							30.0	32.6	34.8
7.5							30.1	33.2	35.7

Table 123. Monthly Variation of Unit Average Infiltration (CFM)

Leakage (ACH_{50})		Month												Annual
Exterior	Total	1	2	3	4	5	6	7	8	9	10	11	12	Average
Percent Exterior Leakage = 15%														
0.30	2	4.2	4.0	3.9	3.9	3.6	3.7	3.5	3.7	3.0	3.9	4.1	3.9	3.8
0.45	3	5.5	5.2	5.1	5.1	4.6	4.8	4.5	4.7	3.8	5.1	5.4	5.2	4.9
0.60	4	6.9	6.4	6.3	6.3	5.7	5.8	5.4	5.8	4.5	6.3	6.7	6.4	6.0
0.75	5	8.2	7.6	7.5	7.5	6.7	6.9	6.4	6.8	5.2	7.5	8.0	7.6	7.2
1.05	7	10.9	10.1	9.9	9.9	8.8	9.1	8.3	9.0	6.7	9.9	10.6	10.0	9.4
1.50	10	14.9	13.7	13.5	13.5	11.9	12.3	11.3	12.1	8.9	13.5	14.5	13.7	12.8
2.10	14	20.3	18.6	18.3	18.2	16.0	16.7	15.2	16.4	11.9	18.3	19.7	18.6	17.4
Percent Exterior Leakage = 30%														
0.60	2	6.2	5.8	5.7	5.7	5.1	5.3	5.0	5.3	4.1	5.7	6.1	5.8	5.5
0.90	3	8.5	7.9	7.8	7.8	6.9	7.2	6.6	7.1	5.4	7.8	8.3	7.9	7.4
1.20	4	10.9	10.0	9.9	9.8	8.7	9.1	8.3	9.0	6.6	9.9	10.6	10.0	9.4
1.50	5	13.2	12.1	12.0	11.9	10.5	11.0	10.0	10.9	7.9	12.0	12.9	12.1	11.4
2.10	7	17.9	16.4	16.2	16.1	14.0	14.8	13.4	14.6	10.4	16.2	17.4	16.4	15.3
3.00	10	25.0	22.8	22.4	22.3	19.4	20.5	18.5	20.2	14.2	22.5	24.3	22.8	21.2
4.20	14	34.4	31.4	30.8	30.7	26.6	28.1	25.4	27.8	19.3	30.9	33.4	31.3	29.2
Percent Exterior Leakage = 45%														
0.90	2	7.7	7.2	7.1	6.9	6.2	6.4	5.9	6.4	5.0	7.0	7.6	7.2	6.7
1.35	3	10.8	10.0	9.8	9.6	8.5	8.9	8.1	8.8	6.7	9.7	10.6	10.0	9.3
1.80	4	13.9	12.8	12.6	12.3	10.8	11.3	10.3	11.2	8.3	12.4	13.6	12.8	11.9
2.25	5	17.0	15.6	15.3	15.0	13.1	13.7	12.5	13.6	10.0	15.2	16.6	15.6	14.4
3.15	7	23.2	21.2	20.8	20.4	17.7	18.6	16.8	18.4	13.4	20.6	22.6	21.3	19.6
4.50	10	32.6	29.7	29.1	28.4	24.7	26.0	23.4	25.6	18.4	28.8	31.6	29.7	27.3
6.30	14	45.1	41.0	40.0	39.2	33.9	35.9	32.2	35.3	25.1	39.6	43.6	41.1	37.7
Percent Exterior Leakage = 70%														
1.50	2	10.0	9.4	9.2	8.9	7.9	8.0	7.3	7.7	6.4	8.9	9.7	9.4	8.6
2.25	3	14.1	13.2	12.9	12.4	11.0	11.1	10.1	10.7	8.8	12.5	13.6	13.1	12.0
3.00	4	18.2	17.0	16.6	16.0	14.1	14.2	12.9	13.7	11.1	16.1	17.6	16.9	15.3
3.75	5	22.3	20.8	20.2	19.5	17.2	17.3	15.7	16.7	13.4	19.6	21.5	20.7	18.7
5.25	7	30.5	28.4	27.5	26.6	23.3	23.6	21.3	22.6	18.0	26.7	29.3	28.3	25.5
7.50	10	43.0	39.8	38.3	37.1	32.5	33.0	29.6	31.6	25.0	37.2	41.1	39.8	35.7
10.50	14	59.6	55.0	52.7	51.0	44.6	45.5	40.9	43.7	34.3	51.1	56.9	55.0	49.2

Table 124. Monthly Variation of Infiltration by Unit (CFM)

		Month												Annual
		1	2	3	4	5	6	7	8	9	10	11	12	Average
Floor	Unit	% Exterior Leakage = 15%				Exterior Leakage = 2.10 ACH_{50}					Total Leakage = 14 ACH_{50}			
1	1A	33.0	27.6	26.5	29.9	26.0	24.9	20.5	18.6	16.7	28.6	31.6	31.3	26.3
1	1B	19.6	23.9	21.9	21.7	22.6	19.5	20.0	19.2	19.5	19.4	16.2	18.8	20.2
1	2A	48.1	35.0	34.9	37.9	29.1	30.7	22.6	23.2	17.8	38.5	46.8	43.8	34.0
2	1A	21.1	15.7	15.3	19.6	16.4	17.6	14.4	13.7	8.1	19.0	21.0	18.8	16.7
2	1B	8.4	13.0	11.7	12.9	14.0	12.9	14.6	14.6	11.0	10.8	6.7	7.6	11.5
2	2A	34.8	22.3	23.2	27.4	19.9	23.3	16.5	18.2	9.1	28.3	34.8	30.0	24.0
3	1A	13.4	8.8	8.4	11.9	9.7	12.2	9.9	10.3	3.3	12.0	14.2	10.7	10.4
3	1B	3.1	6.3	6.1	7.6	8.4	8.8	10.9	11.7	5.9	6.1	2.3	2.5	6.6
3	2A	23.8	13.9	14.3	17.9	12.7	17.0	11.6	14.1	4.2	19.4	25.1	18.8	16.1
Floor	Unit	% Exterior Leakage = 30%				Exterior Leakage = 2.10 ACH_{50}					Total Leakage = 7 ACH_{50}			
1	1A	25.9	20.6	20.0	22.9	19.6	20.0	16.5	15.3	12.1	22.5	25.4	24.0	20.4
1	1B	14.4	18.6	17.0	17.7	18.3	16.2	17.1	16.7	14.9	15.3	11.9	13.7	16.0
1	2A	37.2	26.1	26.5	29.1	21.9	24.0	17.5	18.4	12.8	29.7	36.5	33.3	26.1
2	1A	20.4	14.9	14.7	17.8	14.8	16.4	13.3	12.9	7.9	17.8	20.4	18.0	15.8
2	1B	8.9	13.3	12.0	13.2	14.0	12.9	14.3	14.4	10.9	11.1	7.2	8.2	11.7
2	2A	30.0	19.6	20.2	23.0	16.9	19.7	14.0	15.5	8.4	24.1	30.0	25.9	20.6
3	1A	15.6	10.3	10.4	13.5	10.9	13.3	10.7	10.9	4.9	13.7	16.1	13.2	12.0
3	1B	5.0	9.1	8.2	9.7	10.5	10.2	12.0	12.5	7.8	7.8	4.0	4.5	8.4
3	2A	23.6	14.1	14.9	17.8	12.7	16.2	11.2	13.1	5.3	19.0	24.3	19.6	16.0
Floor	Unit	% Exterior = 45%				Exterior Leakage = 2.25 ACH_{50}					Total Leakage = 5 ACH_{50}			
1	1A	23.9	18.3	18.1	20.2	17.0	18.4	15.0	14.4	10.8	20.4	23.7	21.7	18.5
1	1B	13.4	17.7	16.1	17.1	17.5	15.8	16.6	16.6	13.8	14.8	11.4	12.8	15.3
1	2A	30.0	21.3	21.5	23.0	17.4	19.2	14.0	15.0	10.7	23.9	29.6	26.8	21.0
2	1A	20.9	15.1	15.1	17.4	14.4	16.4	13.1	13.0	8.2	17.8	21.0	18.4	15.9
2	1B	10.3	14.6	13.2	14.5	15.0	13.8	15.0	15.2	11.4	12.3	8.5	9.6	12.8
2	2A	25.7	17.4	17.8	19.3	14.3	16.6	11.9	13.1	8.0	20.3	25.7	22.5	17.7
3	1A	17.8	12.1	12.2	14.6	11.9	14.4	11.5	11.7	6.3	15.2	18.2	15.3	13.5
3	1B	7.6	11.9	10.7	12.2	12.8	12.0	13.5	13.9	9.5	10.0	6.2	7.1	10.6
3	2A	21.8	14.0	14.4	16.0	11.7	14.3	10.1	11.6	6.2	17.2	22.2	18.8	14.9
Floor	Unit	% Exterior = 75%				Exterior Leakage = 2.25 ACH_{50}					Total Leakage = 3 ACH_{50}			
1	1A	20.1	15.3	15.4	16.1	13.7	15.7	12.9	13.2	9.3	17.0	20.2	17.8	15.6
1	1B	12.9	16.3	15.0	16.4	16.1	15.0	15.5	15.6	11.9	14.3	11.5	12.4	14.4
1	2A	15.8	12.8	12.7	12.3	10.0	10.0	8.0	8.3	7.8	12.7	15.3	14.8	11.7
2	1A	19.4	14.5	14.7	15.5	13.1	15.2	12.5	12.8	8.6	16.4	19.6	17.1	15.0
2	1B	12.1	15.5	14.3	15.6	15.4	14.4	15.0	15.3	11.4	13.6	10.7	11.5	13.7
2	2A	14.6	11.8	11.7	11.4	9.3	9.3	7.5	7.8	7.1	11.8	14.2	13.6	10.8
3	1A	18.5	13.6	13.8	14.7	12.5	14.6	12.0	12.4	8.1	15.7	18.7	16.2	14.2
3	1B	11.2	14.8	13.5	15.0	14.8	13.9	14.6	14.9	10.8	12.9	10.0	10.8	13.1
3	2A	13.7	10.9	10.8	10.7	8.7	8.8	7.1	7.4	6.7	11.1	13.4	12.7	10.2

Note – units 1A and 1B are corner units on opposite sides of corridor, unit 2A is an inner unit

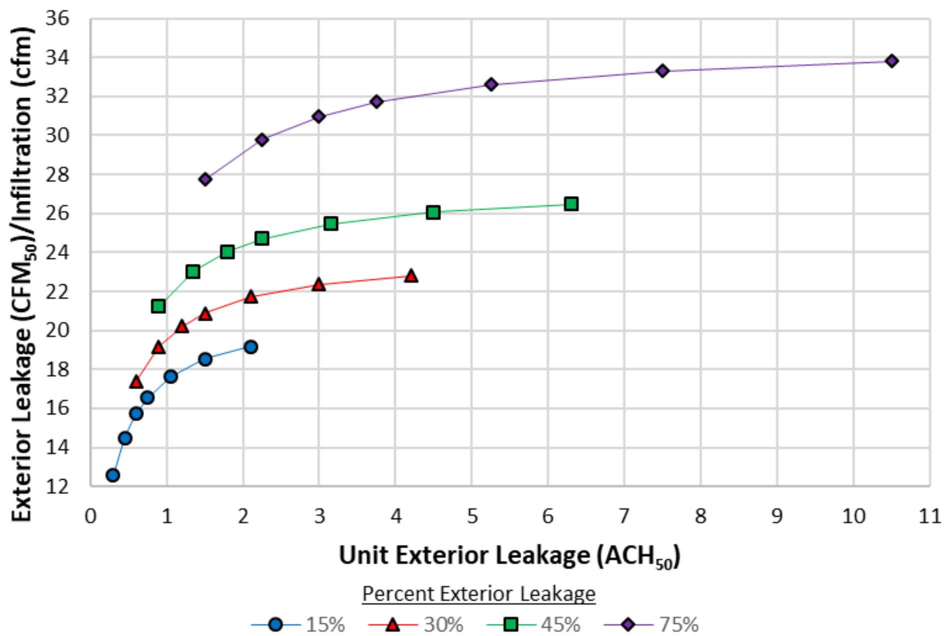


Figure 232. Exterior Leakage Divided by Infiltration

Table 125. Reduction in Annual Infiltration (CFM) for Reduction of 1 ACH50 in Exterior Leakage

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25									
0.50									
0.75									
1.0									
1.5		4.9	5.5	6.0	6.4				
2.0		4.3	4.7	5.1	5.6	5.9	6.2	6.4	6.6
2.5		3.7	4.4	4.6	5.0	5.3	5.6	5.9	6.1
3.0			3.9	4.4	4.6	4.8	5.1	5.4	5.6
3.5			3.6	4.0	4.4	4.6	4.7	5.0	5.3
4.0				3.7	4.1	4.4	4.6	4.6	4.9
4.5				3.6	3.8	4.2	4.4	4.6	4.5
5.0					3.7	3.9	4.2	4.5	4.6
5.5					3.5	3.7	4.0	4.2	4.5
6.0						3.6	3.8	4.0	4.3
6.5						3.5	3.7	3.9	4.1
7.0							3.6	3.8	3.9
7.5							3.5	3.7	3.8

Table 126. Reduction in Annual Infiltration (CFM) for Reduction of 1 ACH50 in Interior Leakage

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25									
0.50		0.26	0.13	0.08					
0.75		0.54	0.30	0.18	0.12	0.09			
1.0		0.79	0.50	0.32	0.21	0.15	0.11	0.09	0.07
1.5		1.32	0.88	0.61	0.48	0.35	0.26	0.20	0.16
2.0			1.21	0.91	0.73	0.55	0.46	0.36	0.29
2.5			1.93	1.16	0.93	0.83	0.62	0.53	0.45
3.0				1.69	1.13	0.92	0.90	0.70	0.56
3.5				2.33	1.56	1.11	0.91	0.96	0.77
4.0					2.05	1.47	1.10	0.89	1.00
4.5					2.61	1.87	1.40	1.09	0.87
5.0						2.32	1.74	1.35	1.08
5.5						2.81	2.11	1.64	1.31
6.0							2.52	1.96	1.57
6.5							2.96	2.30	1.84
7.0								2.68	2.14
7.5								3.08	2.46

Table 127. Ratio of Infiltration Reduction for Reduction of 1 ACH50 in Exterior Leakage and Reduction of 1 ACH50 in Interior Leakage

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25									
0.50									
0.75									
1.0									
1.5		3.7	6.3	9.8	13.2				
2.0			3.9	5.6	7.6	10.7	13.4	17.9	23.0
2.5			2.3	4.0	5.3	6.4	9.0	10.9	13.5
3.0				2.6	4.1	5.2	5.7	7.7	10.0
3.5				1.7	2.8	4.1	5.1	5.2	6.9
4.0					2.0	3.0	4.2	5.1	4.9
4.5					1.5	2.2	3.2	4.2	5.2
5.0						1.7	2.4	3.3	4.3
5.5						1.3	1.9	2.6	3.4
6.0							1.5	2.1	2.7
6.5							1.2	1.7	2.2
7.0								1.4	1.8
7.5								1.2	1.5

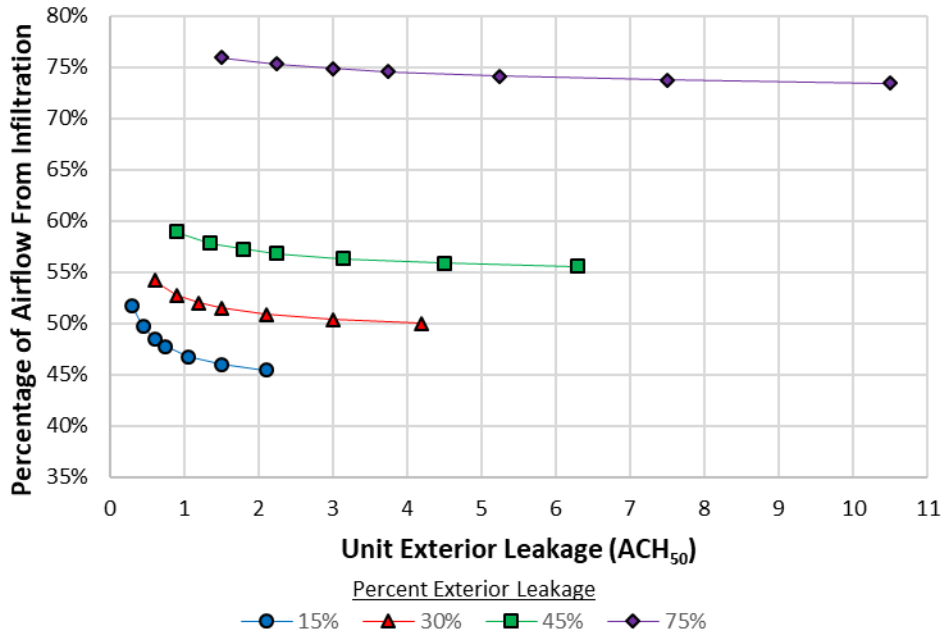


Figure 233. Percentage of Airflow from Outside Into Unit

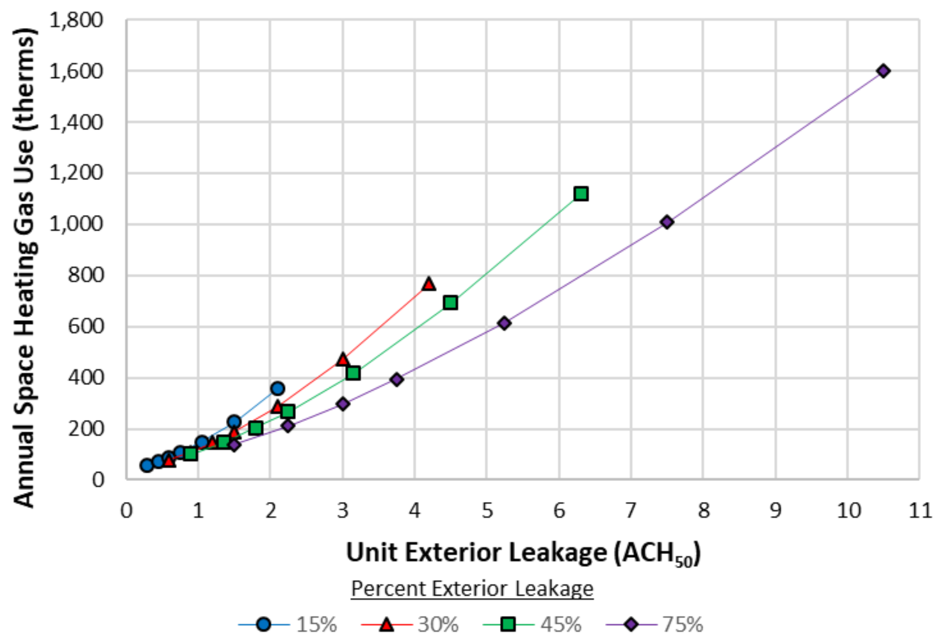


Figure 234. Annual Residential Unit Space Heating Gas Use (Therms)

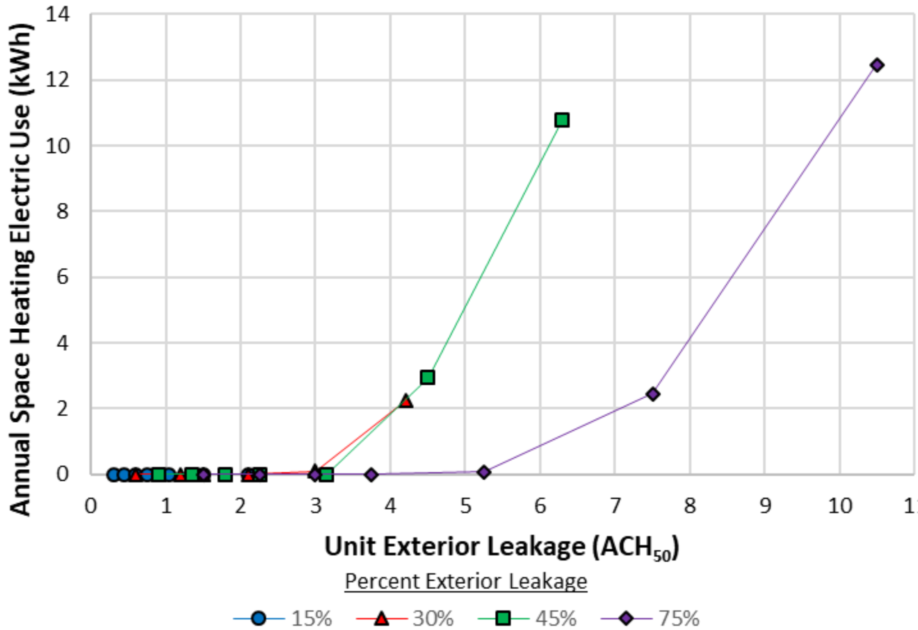


Figure 235. Annual Corridor Space Heating Electric Use (kWh)

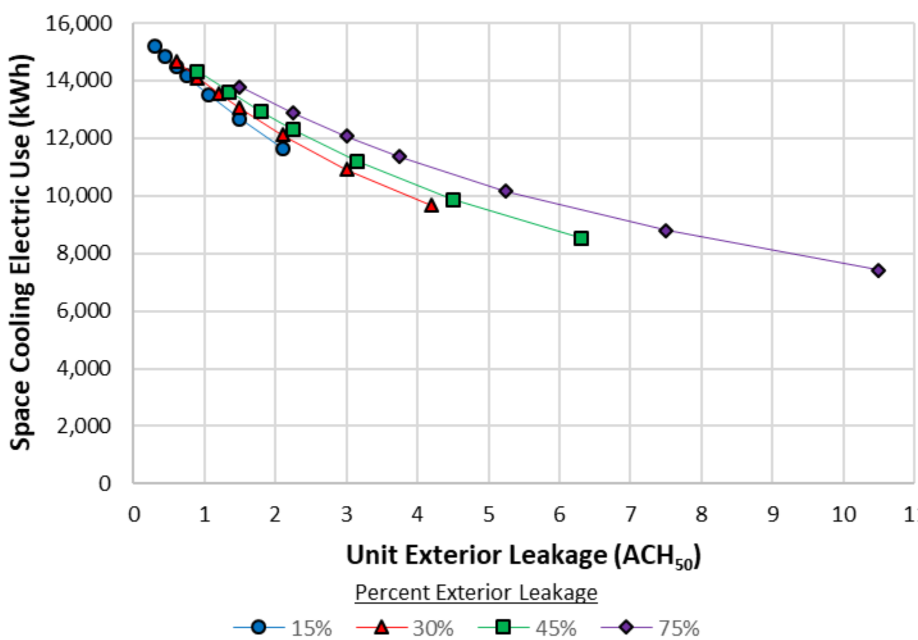


Figure 236. Annual Residential Unit Cooling Electric Use (kWh)

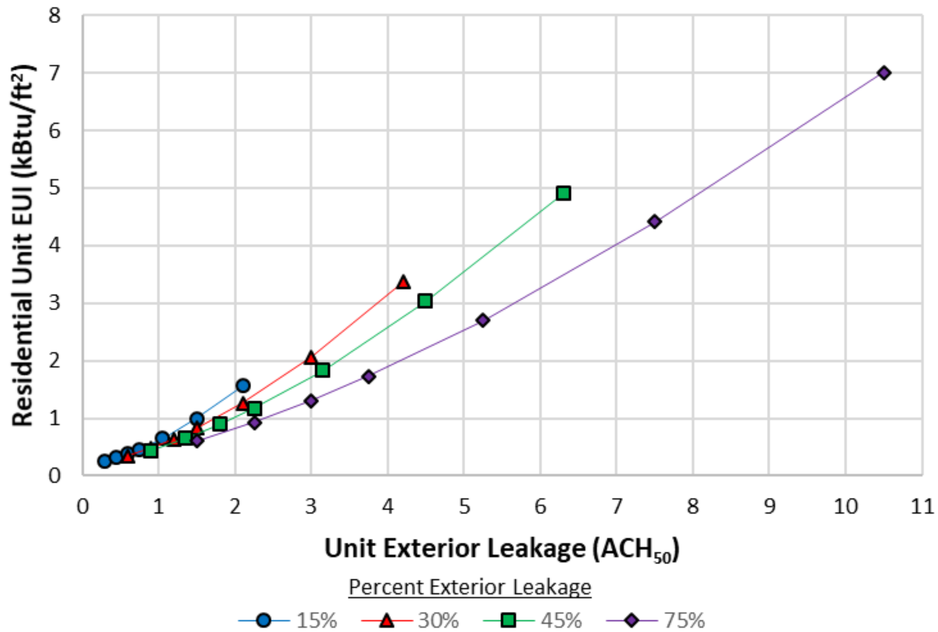


Figure 237. EUI for Residential Units (kBtu/ft²)

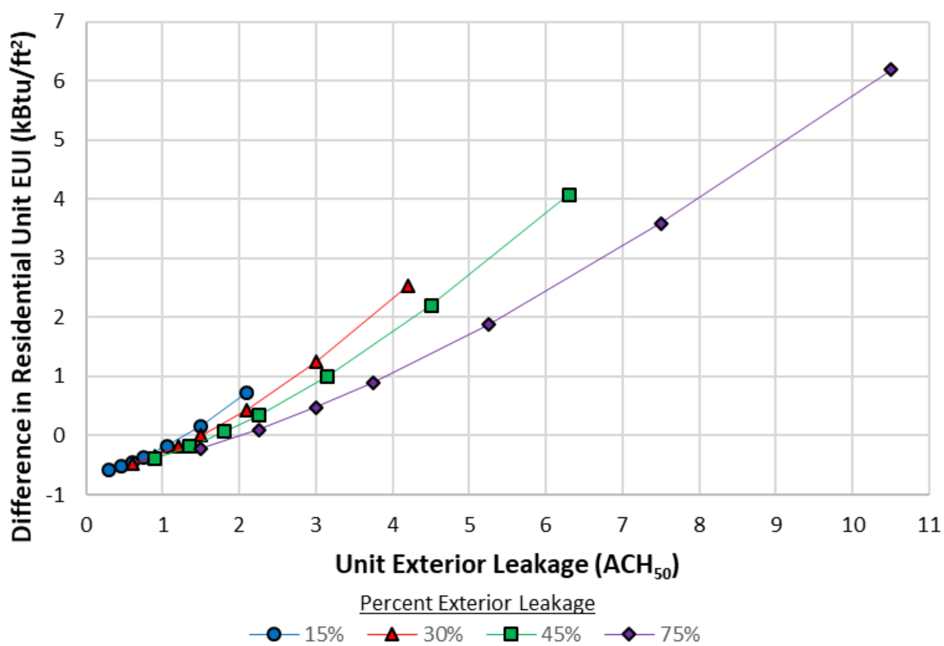


Figure 238. Difference in EUI From Baseline for Residential Units (kBtu/ft²)

Table 128. Difference in EUI From Baseline for Residential Units

Ext. Lkg.	Unit Total Leakage (ACH_{50})								
(ACH_{50})	2	3	4	5	6	7	8	9	10
0.25	-0.58								
0.50	-0.51	-0.50	-0.49	-0.48					
0.75	-0.43	-0.40	-0.38	-0.36	-0.36	-0.35			
1.0	-0.36	-0.30	-0.26	-0.24	-0.22	-0.20	-0.19	-0.19	-0.18
1.5	-0.22	-0.12	-0.05	0.00	0.06	0.10	0.13	0.15	0.17
2.0		0.05	0.16	0.25	0.32	0.39	0.45	0.51	0.55
2.5		0.14	0.35	0.48	0.58	0.69	0.77	0.84	0.90
3.0			0.48	0.68	0.82	0.94	1.07	1.16	1.24
3.5			0.53	0.85	1.07	1.22	1.35	1.50	1.63
4.0				0.95	1.26	1.48	1.64	1.78	1.95
4.5				0.98	1.39	1.68	1.90	2.07	2.20
5.0					1.43	1.83	2.13	2.37	2.56
5.5					1.41	1.92	2.31	2.61	2.85
6.0						1.97	2.45	2.81	3.11
6.5						1.96	2.52	2.96	3.31
7.0							2.54	3.06	3.48
7.5							2.50	3.11	3.59

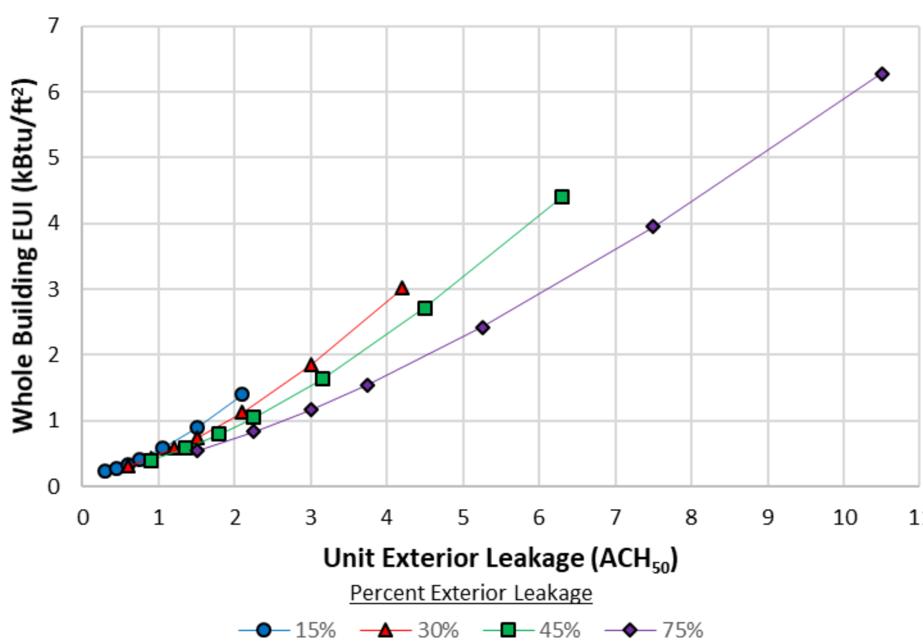


Figure 239. EUI for Whole Building (kBtu/ft²)

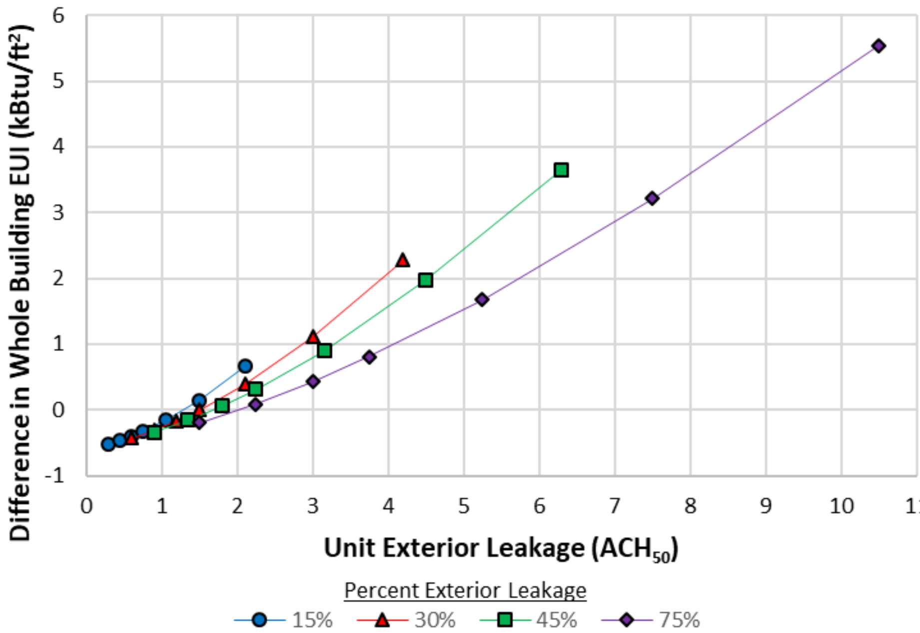


Figure 240. Difference in EUI From Baseline for Whole Building (kBtu/ft^2)