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Exterior and Total Envelope Leakage of New U.S. Low-Rise Multifamily Buildings

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ABSTRACT HEADING

Envelope air leakage testing of new residential buildings is becoming more common in the United States as state energy codes and energy efficiency programs add testing requirements. Leakage testing procedures and standards for single-family homes are straightforward; however, for low-rise multifamily buildings, there is little consensus on what type of envelope leakage should be applied to the standard or how leakage should be measured. The three most common testing approaches measure the following values: (1) whole building exterior leakage; (2) individual unit total leakage (i.e., to the exterior, other units, and common spaces); and (3) individual unit exterior leakage. Each method has advantages and disadvantages regarding cost and availability of qualified testing agencies, as well as construction phases in which the tests can occur and value for energy performance versus indoor air quality.

This paper provides results of U.S. Department of Energy–funded research that included all three measurements on 25 low-rise multifamily buildings in six states. The research sought to inform the development and application of testing protocols by documenting typical leakage rates, the impact of various design and construction practices, the relationships between exterior and total leakage rates for individual units, and the effects of common area leakage. The measurements showed that the exterior leakage averaged about 30% of the total for units in common-entry buildings, and there was typically more leakage to common areas than to the outside. In addition, the surface-area-normalized exterior leakage was greater for common areas than dwelling units. For units in garden-style buildings (i.e., separate entries), the exterior leakage averaged 54% of the total. All of the buildings met or exceeded the code requirement for whole building exterior leakage, but only 33% of individual units had total leakage values below the maximum.

INTRODUCTION

Over the past fifteen years, there has been increased interest in the United States 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 occupants with the benefit of increased ventilation. As U.S. 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. 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. Since the 2012 version, IECC section R402.4 has required envelope air leakage testing with a

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leakage rate criterion of 5.0 ACH_{50} for Climate Zones 1 and 2, and 3.0 ACH_{50} for Climate Zones 3 through 8. 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. 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 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).

BACKROUND

A 2004 state-of-the-art review by Sherman and Chan reports on techniques to measure building airtightness and what has been learned from these measurements. While most of the reported measurements are from single-family houses or whole building testing of multifamily buildings, there are a few studies where the airtightness of individual apartments were measured and the airtightness of interior walls, floors, and shafts were determined. The report has sections describing the basic physics of the tests, details of various test procedures, the metrics commonly used to report the results of tests, and summaries of a large database of tests that have been reported. Over 100 references are given, with some described in detail.

In a 2015 report for the U.S. Department of Energy's Building America Program, Ueno and Lstiburek describe the importance of both interior and exterior leaks to control air, smoke, odor, and sound transfer between units and between inside and outside. A case study is reported where major air leakage paths were diagnosed, and experimental air sealing details were added to several units of a multifamily test building. Important considerations for meeting fire codes when designing alternative details for partition walls are discussed.

A Canada Mortgage and Housing report by Finch, Ricketts, and Bombino in 2013 gives an overview of test procedures and standards used by various programs and countries around the world. It recommends a standard for compartmentalization of apartments in Canada of 0.4 CFM/ft^2 at 75 Pascals (Pa) (7.31 $(m^3/hr)/m^2$). It has a good section on qualitative testing to locate leakage paths and case studies of air leakage sites. The importance of leakage of HVAC penetrations is presented. There is a database of a large number of tests on multifamily buildings done by several testing contractors. Most data is for whole building tests, but there are detailed data on six units where whole building, compartmentalization, and guarded tests were completed and analyzed.

A study by Rohr, Kaschuba-Holgrave, Rolfsmeier, and Solcher in 2018 tested eight new apartments in Germany containing 6–11 units on 3–4 floors using 2–8 blower door fans for each test. Whole building, unguarded compartmentalization, and guarded compartmentalization tests were performed on most units in each building to measure exterior and interior leakages. The average interior leakage of each dwelling unit was about 30% of the total, and all buildings met the German whole building requirements of an n50 of 1.5 h-1 and an envelope permeability, q50, of 2.5 $(m^3/hr)/m^2$ (0.14 CFM_{50}/ft^2). Leakage sites were investigated and included leaks between top floors and attics, elevator shafts, chaseways to underground garages, and electrical, water, and plumbing penetrations. In two buildings, a calculation of the maximum allowable component leakage for surfaces and joints according to German standards was made and only accounted for an average of 18% of the measured leakage.

METHODOLOGY

The subject of this study was low-rise multifamily buildings. That included buildings of predominantly residential occupancy that have no more than three stories above grade (Davis et al. 2020). 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 project team conducted three types of envelope leakage tests on each building. 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 (which is the amount of outside air that comes from outside the conditoned space and therefore adds to the building heating and cooling load). 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. 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. A sample of up to 12 units was measured with compartmentalization tests. The third method is referred to as a guarded test. These were conducted on the same set of units that received a compartmentalization test. The tests were conducted 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.

The building test set up for the tests complied with IECC 2012 (R402.4.1.2 Testing) requirements. As necessary, ANSI/RESNET/ICC 380-2016 (RESNET 2016) and ASTM E3158-18 (Standard Test Method for Measuring the Air Leakage Rate of a Large or Multizone Building) were used to determine set up requirements not covered by IECC 2012. 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 Pa. The project final report provides a more detailed description of the test protocol (Bohac et al. 2020).

Whole Building Test: 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 1 — 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. The testing is more straightforward in common-entry budilings since the living unit entry doors open into a common corridor and the test can be done all at once.

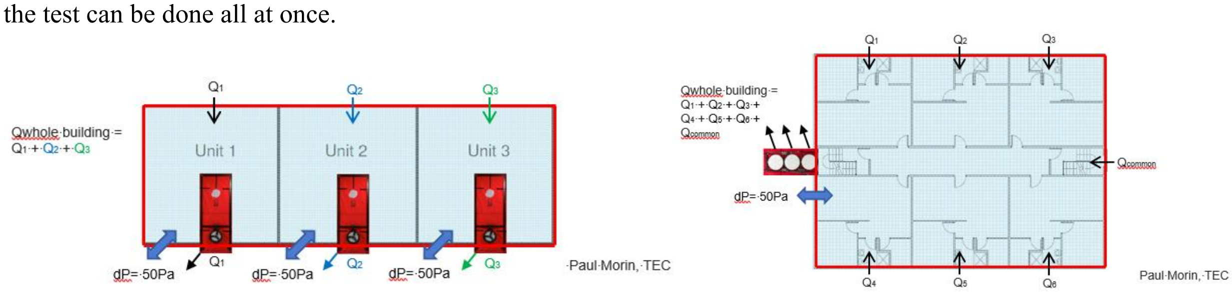

Figure 1. Whole building test for garden-style (left) and common entry (right) buildings

Compartmentalization Test: Unit Total Leakage

This test measures the total, or sum, of the exterior and interior envelope leakage of an individual unit and does not distinguish between the exterior and interior leakage. Consequently, the result has an uncertain relationship to the building's energy use. Figure 2 shows 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). Adjacent units should be open to the outdoors 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, for this project, the units were first tested with adjacent units closed. The inside-to-outside pressure differences of all vertically and horizontally adjacent units were monitored during the test. The objective was to evaluate whether the induced pressure difference of the closed adjacent units during the compartmentalization test could be used to estimate the fraction of total leakage that was to the exterior. After the first total leakage measurement, the induced pressure differences of the adjacent units were computed. When an induced pressure was more than 5 Pa, a window or exterior door of that unit was opened, then the single-point depressurization test was repeated. Finally, the test fan was sealed, and the baseline pressure difference recorded with the windows and exterior doors in the same configuration (i.e., opened as necessary).

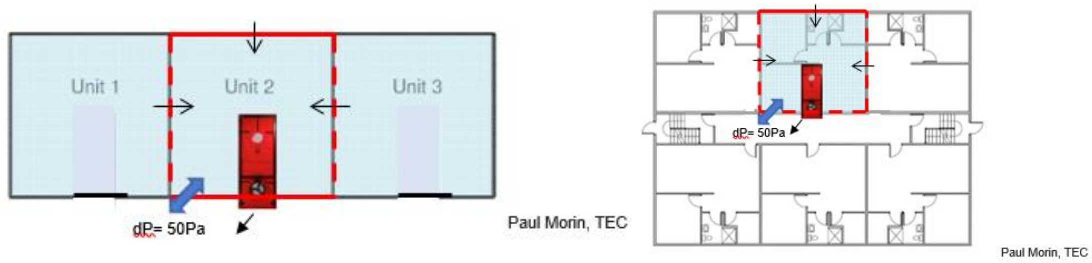

Figure 2. Compartmentalization test of single unit in a garden-style (left) and common entry (right) building

Guarded Test: Unit Exterior Leakage

This test measures the exterior leakage of an individual unit. For garden-style buildings, it is simply each unit's leakage measurement from the whole building test. As shown in Figure 3, 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. 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 3, 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.

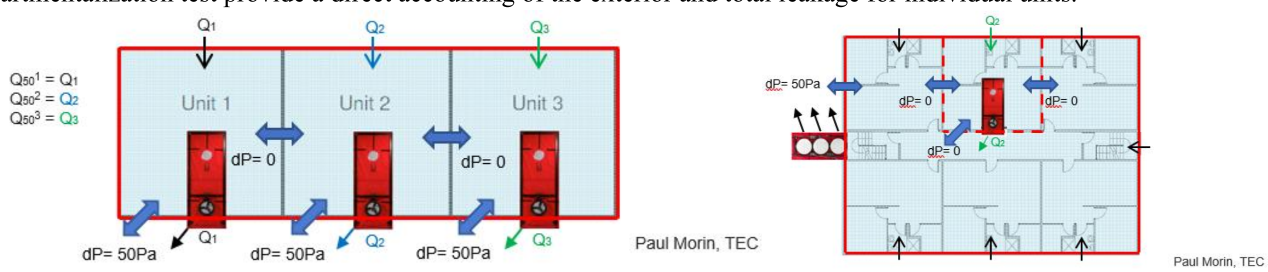

Figure 3. Guarded unit exterior leakage test for three units in a single-story garden-style building

RESULTS

The 25 test buildings were located in the Pacific Northwest and Midwest. 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. Results are presented in both volume-normalized (n50) and surface-area normalized format q_{50} (CFM_{50}/ft^2, $(m^3/hr)/m^2$).

As noted above, all states in the study required airtightness 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 16 (64%) of the buildings were being certified for an energy efficiency program: 14 for ENERGY STAR Certified Homes, one for Passive House Institute US (PHIUS), and one for an Iowa financing program that required a maximum HERS score. The PHIUS 2015 certification required a whole building leakage no greater than 0.05 CFM_{50}/ft^2 (0.91 $(m^3/hr)/m^2$) and individual unit total leakage no greater than 0.3 CFM_{50}/ft^2 (5.48 $(m^3/hr)/m^2$).

Building Characteristics

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. 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 10–12 units was tested. The total floor area of the buildings ranged from 6,676 to 72,721 ft^2 (620 to 6,756 m^2) and averaged 33,043 ft^2 (3,070 m^2). The exterior envelope of the buildings ranged from 11,266 to 76,884 ft^2 (1,047 to 7,143 m^2) and averaged 37,611 ft^2 (3,494 m^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 (40 m^2), the highest was 1,490 ft^2 (138 m^2) and the overall average was 860 ft^2 (80 m^2). The percentage of whole building floor area that was taken up by the residential units varied from 60% to 95% and averaged 79%.

Information was gathered for key construction characteristics that may impact envelope leakage. 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.

The two garden-style buildings in Minnesota had two stories, and the three buildings in Oregon and Washington had three stories. 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 (1,029 to 2,169 m^2) and averaged 17,145 ft^2 (1,593 m^2). The exterior envelope of the buildings ranged from 12,354 to 32,212 ft^2 (1,148 to 2,993 m^2) and averaged 22,922 ft^2 (2,130 m^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 (73 m^2), the highest was 1,459 ft^2 (136 m^2), and the overall average was 1,105 ft^2 (103 m^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.

Whole Building Leakage

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 Figure 4). 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.

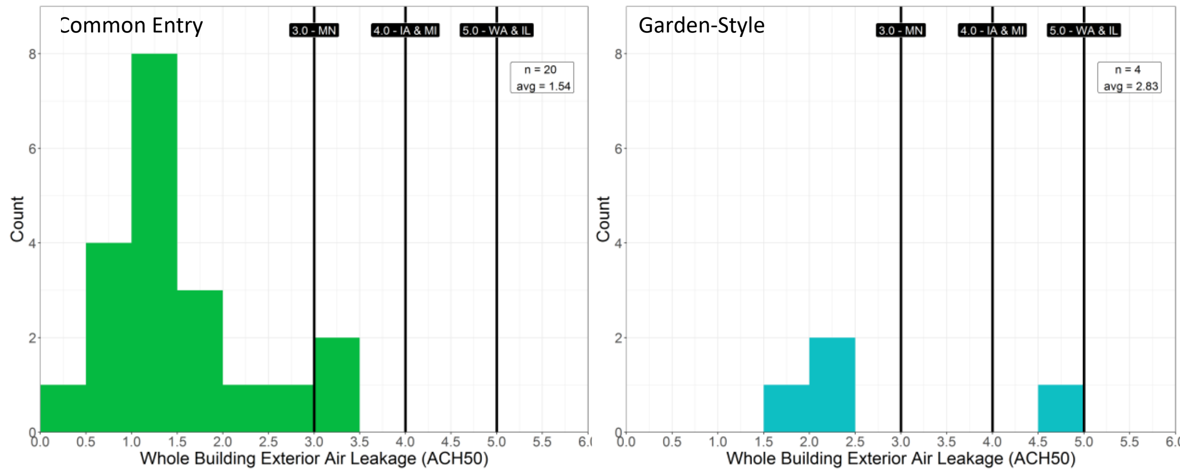

Figure 4. Whole building exterior air leakage (ACH_{50})

Figure 5 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. 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). 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. 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.

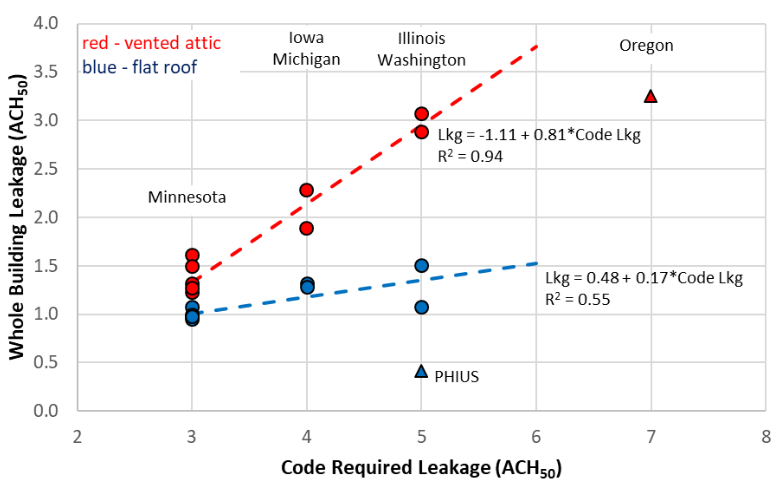

Figure 5. Impact of Code Required Leakage and Attic Type on Whole Building Leakage (ACH50)

The whole building surface-area-normalized exterior leakage of the common-entry buildings ranged from 0.05 to 0.38

CFM_{50}/ft^2 (0.91 to 6.95 ($m^3/hr)/m^2$) with an average of 0.20 CFM_{50}/ft^2 (3.66 ($m^3/hr)/m^2$). (See Figure 6.) 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 (7.31 ($m^3/hr)/m^2$), 85% were below 0.30 CFM_{50}/ft^2 (5.48 ($m^3/hr)/m^2$), and 55% were below the U.S. Army Corps of Engineers (USACE) requirement of 0.19 CFM_{50}/ft^2 (3.47 ($m^3/hr)/m^2$).

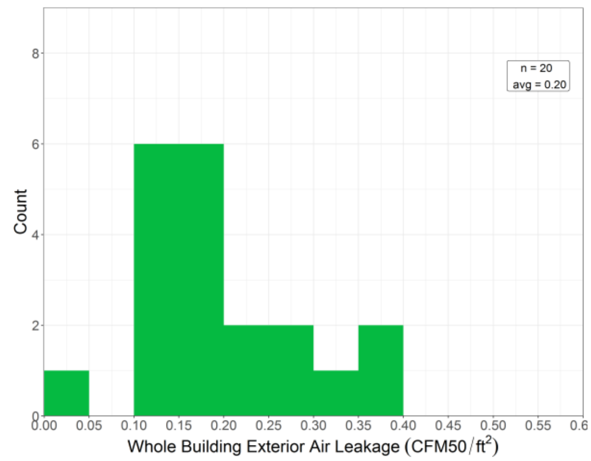

Figure 6. Whole building exterior air leakage (CFM_{50}/ft^2)

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} (See Figure 4). 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.

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 (3.66 to 8.59 ($m^3/hr)/m^2$) and averaged 0.29 CFM_{50}/ft^2. (5.30 ($m^3/hr)/m^2$). 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 (7.31 ($m^3/hr)/m^2$), three were below 0.30 CFM_{50}/ft^2 (5.48 ($m^3/hr)/m^2$), and none were below the USACE requirement of 0.19 CFM_{50}/ft^2 (3.47 ($m^3/hr)/m^2$).

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. 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}. 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.

Individual Unit

Common-Entry Buildings. Figure 7 displays the cumulative distribution 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. There was greater variation, or a larger tail, for the higher leakage values. 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.

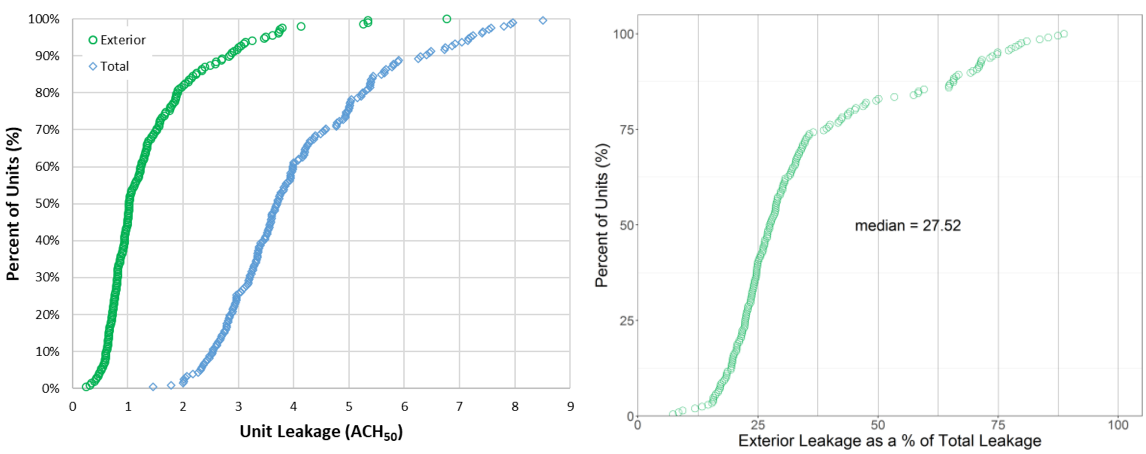

Figure 7. Cumulative Distribution of Unit Leakage and Percent Exterior Air Leakage: Common-Entry

The exterior leakage as a percentage of the total for a unit provides a direct comparison between the two values. Figure 7 also displays the cumulative distribution of the percent exterior leakage. The average percent exterior leakage was 34.3% with 25th, median, and 75th, and 90th percentile values of 22.4%, 27.5%, and 39.1% respectively. 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%). 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. 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 (0.91 $(m^3/hr)/m^2$) for whole building exterior surface-area-normalized leakage compared to the much higher PHIUS limit of 0.30 CFM_{50}/ft^2 (5.48 $(m^3/hr)/m^2$) for the total leakage of a unit.

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 8 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. The higher percent exterior leakage appears to be the result of higher exterior leakage for the top floor of vented-attic buildings.

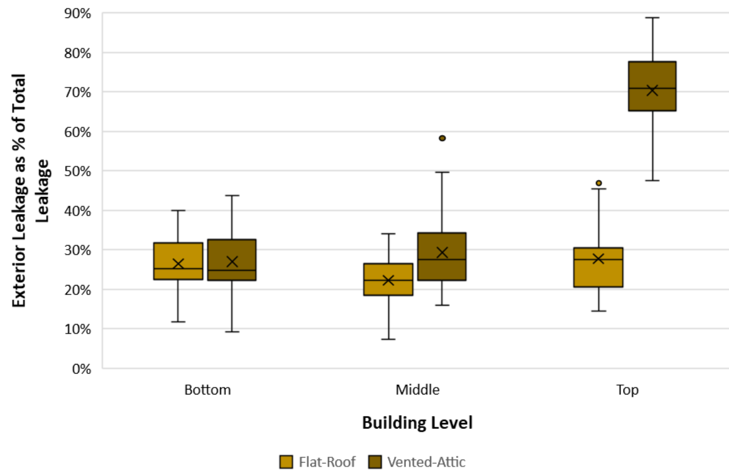

Figure 8. Unit % Exterior Leakage by Building Level and Type: Common-Entry Buildings

The leakage of individual units to adjoining units and common areas was measured for 145 units from 14 buildings. The cumulative distribution of surface-area-normalized leakage of five surfaces (adjoining units, common areas, exterior, all interior, and total) is shown in Figure 9. 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 (9.51 $(m^3/hr)/m^2$) which is seven times higher than the median of 0.072 CFM_{50}/ft^2 (1.32 $(m^3/hr)/m^2$) 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.

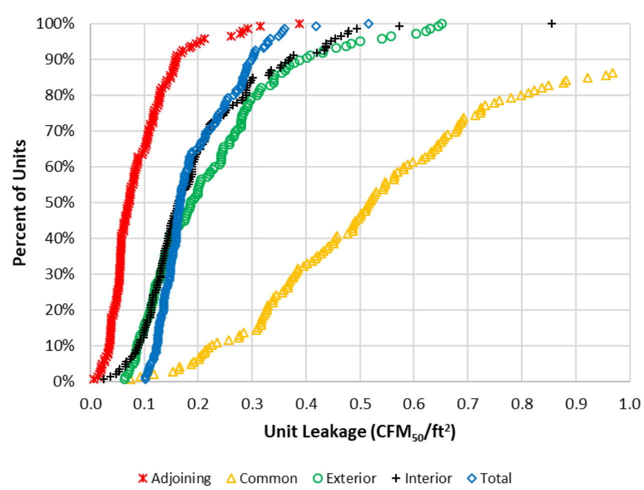

Figure 9. Cumulative Distribution of Unit Leakage by Type of Surface: Common-Entry Buildings (CFM_{50}/ft^2)

Garden-Style Buildings. Figure 10 displays the cumulative distribution of the volume-normalized exterior and total leakage for the 68 units tested in the five garden-style buildings. 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. There was greater variation, or a larger tail, for the higher leakage values. 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.

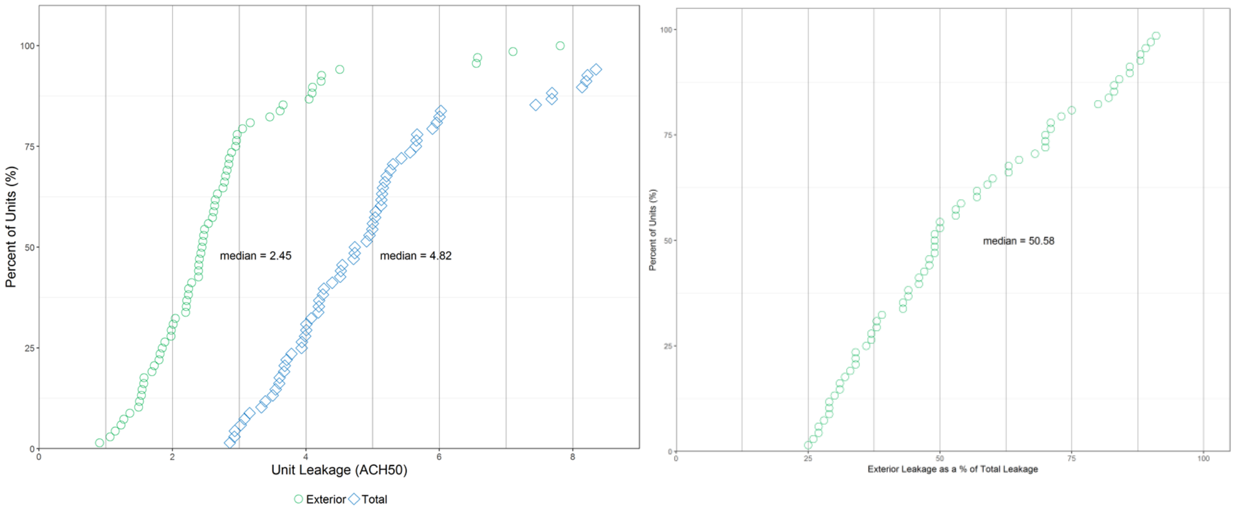

Figure 10. Cumulative Distribution of Unit Leakage and Percent Exterior Air Leakage: Garden-Style

Figure 10 displays the cumulative distribution of the percent exterior leakage. The average percent exterior leakage was 54.4% with 25th, median, and 75th percentile values of 36.7%, 49.4%, and 70.7%, respectively. There was a somewhat greater variation, or larger tail, for the higher percentages. 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. 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. 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.

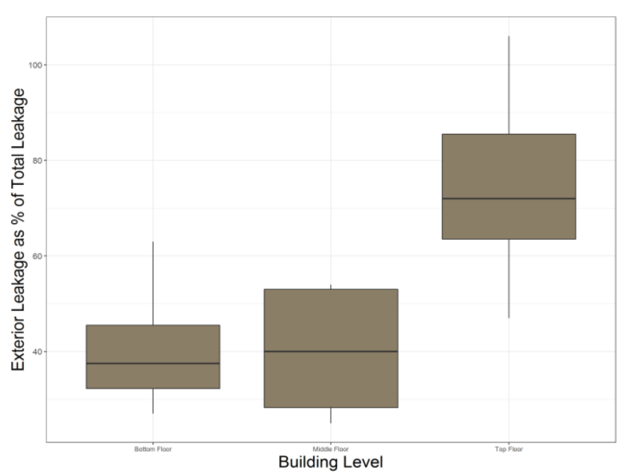

Figure 11. Unit % Exterior Leakage by Building Level and Type: Garden-Style Buildings

Figure 12 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 (1.83 $(m^3/hr)/m^2$) 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, 11.70 $(m^3/hr)/m^2$) than those for units on the bottom (0.23 CFM_{50}/ft^2, 4.20 $(m^3/hr)/m^2$) and top (0.23 CFM_{50}/ft^2, 4.20 $(m^3/hr)/m^2$) 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 (5.30, 7.31, 11.52 $(m^3/hr)/m^2$) 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.

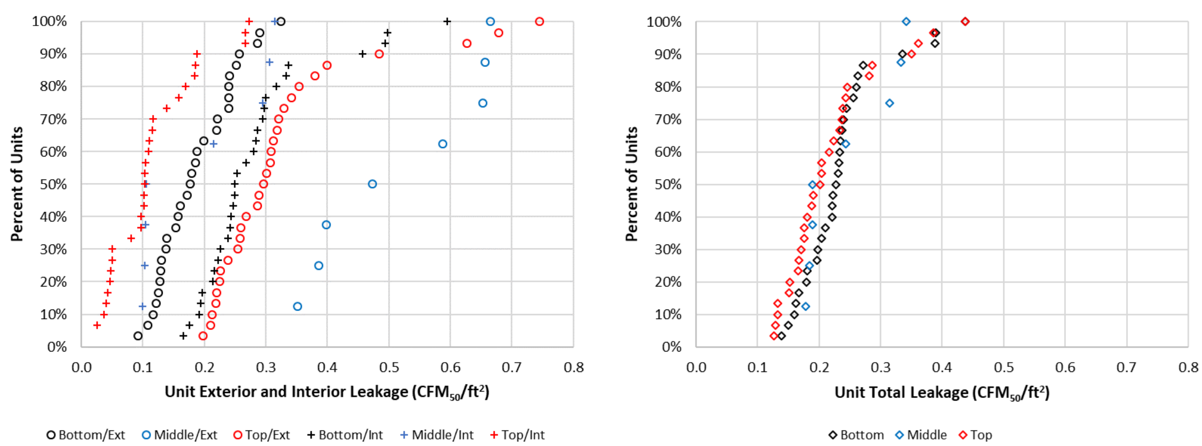

Figure 12. Distribution of Interior and Exterior Leakage by Building Level (CFM_{50}/ft^2): Garden-Style Buildings

CONCLUSION

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). All but one building came in below 4.0 ACH_{50}, which meets most states' airtightness limits. 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 (5.48 $(m^3/hr)/m^2$), and 58% were below the USACE requirement of 0.19 CFM_{50}/ft^2 (3.47 $(m^3/hr)/m^2$).

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.

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. 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 (3.66 $(m^3/hr)/m^2$); 62% had leakage less than the State of Illinois requirement of 0.25 CFM_{50}/ft^2 (3.66 $(m^3/hr)/m^2$); and 88% were below the proposed State of Washington maximum leakage of 0.40 CFM_{50}/ft^2 (7.31 $(m^3/hr)/m^2$). The average for all of the units was 0.24 CFM_{50}/ft^2 (4.39 $(m^3/hr)/m^2$).

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.

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.

It is important to note that the results discussed here apply only to the 25 buildings tested from 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 of the buildings (64%) 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.

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NOMENCLATURE

q50 = *surface area normalized air leakage for a pressure difference of 50 Pa,* CFM_{50}/ft^2 or $(m^3/hr)/m^2$

n50 = *air changes per hour for a pressure difference of 50 Pa*

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