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# Using Adjacent Unit Pressures to Compute Exterior Leakage from Compartmentalization Tests

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# ABSTRACT

In the United States, compartmentalization measurement of individual unit total leakage is the most common method of air leakage testing multifamily buildings. There are several advantages to this method: (1) The measurement includes interior leakage, which affects contaminant and sound transfer; (2) the test is easier to perform than others; (3) many people are qualified to perform the test; and (4) units can be tested earlier in the construction process than with other methods. However, exterior leakage has the greatest impact on energy performance. Energy models sometimes use the total leakage multiplied by the ratio of the exterior to total envelope surface area to estimate the exterior leakage, but measurements show that the method can yield inaccurate results. Guarded test methods can measure exterior leakage but are more difficult to perform.

This paper evaluates the use of pressure changes in adjacent units during compartmentalization tests to estimate exterior leakage. An equation derived for two adjacent units with equal leakage was extended for multiple adjacent units. Further, a series of equations was derived to relate the air leakage measurements and pressure changes in adjacent units to the exterior leakage of the tested unit. The matrix of equations can be used to directly compute the exterior leakages without needing to assume that they are equal.

Compartmentalization tests and adjacent unit pressure measurements were conducted for 68 units in five garden-style (i.e., separate entries) multifamily buildings. Exterior leakage measurements from guarded tests were compared to values from compartmentalization tests using the two computation methods — one assuming equal leakage and the other unequal. The agreement between the measurements and the two calculation methods were evaluated.

# INTRODUCTION

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). In addition, for commonentry 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. 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, referred to in this paper as the surface-area-ratio method. This method is accurate when the leakage per unit area is the same for the interior and exterior portions of the envelope. However, the construction details and penetrations through exterior walls, top-level ceilings, and bottom-level floors are different from

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those of the demising walls and floors or ceilings between levels. 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. This paper evaluates the accuracy of the surface-area-ratio method and an alternative adjacent unit pressure method for computing the exterior leakage of garden-style buildings.

# METHODOLOGY

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 all or a large fraction of the units was measured with compartmentalization tests. Third, guarded tests were conducted on the same set of units to measure the exterior leakage of each unit. The guarded tests were added to provide a direct comparison between the exterior leakages was used to estimate the exterior leakage of any common space. 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). The project final report provides a more detailed description of the test protocol (Bohac et al. 2020).

# **Compartmentalization Test: Unit Total Leakage**

This test measures the total, or sum, of the exterior and interior envelope leakage of an individual unit, but does not distinguish between the exterior and interior leakage. Consequently, the result has an uncertain relationship to the building's energy use. 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).

# **Guarded Test: Unit Exterior Leakage**

This test measures the exterior leakage of an individual unit. This is simply each unit's leakage measurement from the wholebuilding test. As shown in Figure 1, 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.





#### **Air Leakage Equations**

**Equal Exterior Leakage**. For buildings with multiple adjacent units, compartmentalization test results can be used to estimate the exterior leakage. When compartmentalization tests are performed for three adjacent units with all adjacent units closed and the induced pressures measured in the adjacent units, an equation can be generated to compute the exterior leakage of the test unit. The derivation of equation (2) for test unit A is included in the project final report (Bohac et al. 2020). The derivation assumes that the exponent of the power law leakage relationship for all of the leaks is the same value and the exterior leakage of each unit is the same. This will be referred to as the "Equal" method, since it assumes that all of the adjacent units have the same exterior leakage. A variation of this equation was used to generate what is commonly referred to as the Tooley Chart (Cummings, Withers, and Shirey 1997). Equation (3) can be used when there are multiple adjacent units.

Envelope air flows are governed by the following power law equation:

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

Where:

 $Q_{ix}$  = 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

 $Q^{i}_{fan} =$  flow rate for blower door fan in unit i

n = flow exponent

 $CRM50_{Oi}$  = exterior leakage of unit i at a pressure difference of 50 Pa O = outside

$$CFM50_{OA} = \frac{Q_{fan}^{A}}{\left(1 + \left(\frac{dP_{OB}}{50}\right)^{n} + \left(\frac{dP_{OC}}{50}\right)^{n}\right)}$$
(2)

When there are m adjacent zones, this equation is extended to:

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

**Unequal Exterior Leakage**. An extension of this approach is to remove the requirement that the exterior leakages of the adjacent units are equal. When compartmentalization tests are performed for three adjacent units with all adjacent units closed and the induced pressures measured in the adjacent units (see Figure 2), a series of equations can be generated to compute the exterior leakage of all three units. The equations can be arranged into the matracies shown in equation (4). The derivation of these equations is included in the project final report (Bohac et al. 2020). This is referred to as the "Matrix" method. This approach can be extended to buildings with four, five, six, or more units where Matrix A has the same number of rows and columns with dimensions equal to the number of units. One drawback to the method is that a compartmentalization test must be conducted for all units and the pressure change measured in all units for each of those tests.



Figure 2. First two compartmentalization tests for three adjoining units with unequal exterior leakage

$$\begin{pmatrix} 1 & -\left(\frac{dP_{OB}}{50}\right)^n & -\left(\frac{dP_{OC}}{50}\right)^n \\ -\left(\frac{dP_{OA}}{50}\right)^n & 1 & -\left(\frac{dP_{OC}}{50}\right)^n \\ -\left(\frac{dP_{OA}}{50}\right)^n & -\left(\frac{dP_{OB}}{50}\right)^n & 1 \end{pmatrix} \begin{pmatrix} CFM50_{OA} \\ CFM50_{OB} \\ CFM50_{OC} \end{pmatrix} = \begin{pmatrix} Q_{fan}^A \\ Q_{fan}^B \\ Q_{fan}^C \end{pmatrix}$$
(4)

#### RESULTS

The five garden-style buildings were located in three states: two in Minnesota, one in Oregon, and two in Washington. The buildings had two or three stories with average floor area for each unit that ranged from 782 to 1,459 ft<sup>2</sup> (73 to 136 m<sup>2</sup>). All of the units in the three buildings with 12 and 16 units were tested. A subset of 12 units were tested for the buildings with 18 and 25 units. The tested units were concentrated at one portion of the building so that the guarded test and adjacent unit calculation methods could be applied to those units. The volume normalized whole-building air leakage ranged from 1.97 to 4.72 ACH<sub>50</sub> and averaged 2.83 ACH<sub>50</sub>. The surface area normalized whole-building leakage ranged from 0.20 to 0.37 CFM50/ft<sup>2</sup> (3.7 to 6.8 (m<sup>3</sup>/hr)/m<sup>2</sup>) and averaged 0.29 CFM50/ft<sup>2</sup> (5.3 (m<sup>3</sup>/hr)/m<sup>2</sup>). The surface-area-normalized total leakage for individual units ranged from 0.13 to 0.44 CFM50/ft<sup>2</sup> (3.7 to 8.0 (m<sup>3</sup>/hr)/m<sup>2</sup>) and averaged 0.22 CFM50/ft<sup>2</sup> (4.0 (m<sup>3</sup>/hr)/m<sup>2</sup>). The exterior leakage as a percentage of the total averaged 54% with 25th and 75th percentile values of 37% and 71%, respectively. The percent exterior leakage varied significantly by level of the building. The median values were 38% and 40% for the bottom and middle level units respectively but was 72% for the top-level units. This was likely due to higher exterior leakage through the ceilings of the top-level units for these vented attic buildings.

#### Surface-Area-Ratio Method

The relationship between the measured exterior leakage using the guarded test method and exterior leakage calculated from surface-area-ratio method for the 68 units is shown in Figure 3. 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. This shows 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 3. Measured vs. surface-area-ratio method calculated exterior leakage

The percentage difference between the measured exterior leakage and the exterior leakage calculated from the surface-arearatio method was computed to evaluate the level of agreement between the two values and trends by building level. The ratio method overestimates exterior leakage slightly less often (41% of units) than it underestimates. The ratio method computes an exterior leakage that is within 25% of the measured value for 34% of the units. 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%.

When the data is grouped by building level, none of the three levels of units had a distribution that was centered near zero. The median 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. 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%.

Figure 4 displays the calculated leakage versus the directly measured leakage (the latter have been obtained from the individual fan flows during the simultaneous depressurization of all units). The ratio method is 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 (see upper graph in Figure 4), 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 area splits (interior versus exterior), but it also has the disadvantage of requiring 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 Pa 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 5 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 is also worth mentioning that the "truth" values 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 or conducting many repeated measurements to characterize the errors in the actual directly measured exterior leakage values. Figure 6 is similar to Figure 5 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.



Figure 4. Measured vs. calculated exterior leakage for various calculation methods



Figure 5. Box-and-whisker plots of % difference of exterior leakage for various calculation methods



Figure 6. Box-and-whisker plots of absolute % difference of exterior leakage for various calculation methods

The exterior leakage values were calculated using the matrix method and different filter threshold levels ranging from 0 (e.g., none) to -3.5 Pa. The filters are intended to account for several factors. First of all, for cases where the measured induced pressure has the wrong sign (is greater than zero when depressurizing), the filter is designed to screen them out as they are the likely the result of random wind-induced noise. Secondly, the filter might account for cases where there are zones other than dwelling units themselves that may be important leakage paths, thus violating the assumptions of the model. In this case, the filter could be used as an empirical adjustment for modeling error. The dashed lines on the chart below show the percent difference of (sum(Meas)-sum(Calc))/Sum (Meas) by building. The solid lines show the avg(Abs(Meas-Calc)) for the filter level divided by the same value for filter = 0 Pa. So, there is better agreement between measured and calculated Q50 values when the solid line is < 1.0, and there is generally better agreement when the dashed line is closer to 0%. There are some inconsistent trends here. From the perspective of the algebraic error (the dashed lines), a filter threshold of around -2.0 Pa seems appropriate, whereas the mean absolute errors (the solid lines) seem to suggest something closer to zero. WA3 is an exception where a value of -1 Pa seems optimal for the mean absolute errors. Taken together, a simple filter threshold yields a modest improvement in the measured errors. There may be other, more direct approaches to address the wind noise and modeling errors, such as signal processing techniques and explicit changes to the model.



Figure 10. Impact of filter pressure threshold on agreement of calculated with measured exterior leakage

# CONCLUSION

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 test 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 the 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 using the induced pressure change of adjacent units provides some improvement in the computed exterior leakage. Additional investigation is required to further improve the methods. It is important to note that the results discussed here apply only to the five buildings tested. 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.

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