

# ESTIMATES OF UNCERTAINTY IN MULTI-ZONE AIR LEAKAGE MEASUREMENTS

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## ABSTRACT

Although standards for single-zone air leakage tests are well established and widely used, there is no existing standard for testing air leakage between adjacent zones. While a range of test procedures have been used to determine inter-zone leakage using fan-pressurization, the accuracy of the methods can vary significantly. Using field measurements and simulations, we have compared the uncertainty in the leakage between two adjacent zones for different measurement and calculation methods. We present the most accurate methods for determining inter-zone leakage between two adjacent zones, based on field and simulation results.

In multi-family housing buildings, air leakage from a single zone to the outside is often measured by pressurizing adjacent units to the same test pressure. We have investigated how sources of uncertainty affect zone-to-outside leakage test results using the guarded zone test method. We considered two sources of uncertainty that are common in the guarded test: 1) pressure fluctuations in the different units, and 2) interconnected zones that are not pressurized during the test. Adjacent units are pressurized in the guarded test to isolate leakage to the outside, but it is difficult in practice to ensure a zero-pressure drop across boundaries, and wind-driven pressure fluctuations can lead to increasing uncertainty in the test results. We also consider interconnected zones that are not pressurized directly in the guarded test method, because leakage to these zones is not always equivalent to leakage to the outdoors. We modelled a building with three adjacent units with an analytical model using the statistical computing program R. Fluctuations in the pressure and variability in leakage parameters are based on field observations and in the analysis, the collection of data is simulated using Monte Carlo techniques. While the uncertainty in leakage to outside due to pressure fluctuations and calibration error in guarded test results is relatively small (4-14%), leakage to interstitial zones may have a much more substantial impact (on the order of 30-100% of the leakage directly to the outdoors). The implications of the test results and uncertainty with respect to air-sealing efforts are discussed.

## KEYWORDS

Air tightness, multi-zone, uncertainty

## 1. INTRODUCTION

Both performing and interpreting results from air leakage tests are significantly more complicated in multi-zone buildings than in single zone spaces. Often, the objective is to quantify either the leakage from a single unit to the outdoors, or the leakage from one zone to another, both of which require isolating the leakage flow through one interface from the overall network of airflows between conditioned zones, interstitial spaces and the outdoors. In this paper, we explore several factors that impact the accuracy and interpretation of multi-zone leakage measurement results in two scenarios: (i) house with an attached garage, and (ii) a three-unit row house as an example of multi-family buildings.

Section 2 in this paper summarizes results of a detailed study to analyse the accuracy of different methods used to determine leakage between two adjacent zones. The section refers to a house and attached garage zone, but any two adjacent zones could be considered. While a number of strategies have been used to determine interzonal leakage, currently no standard exists for this measurement. Because the interzonal leakage is often small relative to the

overall leakage of either zone, this quantity can be difficult to resolve using fan pressurization tests. We compare the uncertainty associated with different techniques.

Section 3 considers uncertainty in determining the leakage to the outdoors from a single unit in a multi-zone building. To determine the air leakage to outside from a single unit in a multi-zone building, one common method is the 'guarded' test. The zone of interest as well as any adjacent conditioned zones (beside, above and/or below) are pressurized to the same test pressure to minimize leakage to adjacent zones in the measured leakage (Modera et al., 1986; Furbringer et al., 1988; Feustel, 1989). In multi-zone buildings, however, an individual unit might also have connections to unguarded zones such as interstitial spaces and hallways that may be unconditioned or partially conditioned. In Section 3, we examine how measurement uncertainty as well as leakage to unguarded zones can impact leakage estimates from guarded tests of individual units in multi-zone buildings.

In this study, air leakage flow through an interface from Zone A to Zone B,  $q_{AB}$ , is assumed to behave:

$$q_{AB} = C_{AB} P_{AB}^{n_{AB}} \quad (1)$$

where  $P_{AB}$  is the pressure in zone A relative to that in Zone B,  $C_{AB}$  is a flow coefficient proportional to the leakage area in that interface, and  $n_{AB}$  is the pressure exponent for that interface. If a blower door is placed in the AB interface, flow *through the blower door* is indicated by  $Q_{AB}$  (lower case q refers to flow through leaks). We modelled these interzonal flows with control volume based models using the statistical computing package, R.

## 2. LEAKAGE BETWEEN TWO ADJACENT ZONES

There are many possible approaches to determining the air leakage between two adjacent zones. The objective of this study was to determine the simplest fan-pressurization (blower door) test that will reliably deliver accurate results. Various data collection and analysis methods were compared using both simulated data sets as well as field data. Results of the field data and simulations were used to identify the most robust methods and to quantify the uncertainty of the different methods. Additional details of the methodology can be found in Hult et al. (2012).

In the field, single-zone blower door tests are often performed by taking flow rate measurements at a single pressure (typically 50 Pa), rather than fitting a curve to measurements over a range of pressure differences. The ASTM and ISO standards to determine air leakage using fan pressurization require measurements over a range of pressure differences to improve the accuracy of extrapolation to calculate the air leakage at low, operational pressure differences (ASTM, 2010; ISO, 2006). This study used simulations and field data to compare tests where measurements are taken at a single pressure difference vs. at multiple pressure differences, as well as different test methods using one or two blower doors. First, the methods used to generate and analyze the synthesized data are presented. A discussion of the results of the synthesized data analysis follows.

## Diagnostic methods

A number of methods have been developed to determine leakage between adjacent zones (some focusing specifically on the house and attached garage scenario), but there is no existing standard for how to make this measurement. Parallels exist between interzonal leakage methods and ASTM test methods for measuring duct leakage (E1554-07) which also

include methods to distinguish leakage to the outside from total leakage and employ more than one pressurization device. A number of strategies have been explored to use a single blower door to test interzonal leakage in buildings with two or more zones. Blasnik and Fitzgerald (1992) provide an accessible overview to the benefits of interzonal leakage testing to facilitate air sealing and describe several strategies to determine the leakage between adjacent zones using different single blower door tests. Several of the most common methods using different sets of single blower door tests are outlined in the following subsection. Additional test methods as well as two blower door tests are not described in detail here but are included in Hult et al. (2012).

The blower door is used to measure the flow rate  $Q$  through a door in the interface segment denoted by the subscript (HO for house-outside, HG for house-garage, and GO for garage-outside interface).  $P$  is the pressure difference across the interface indicated by the subscript.

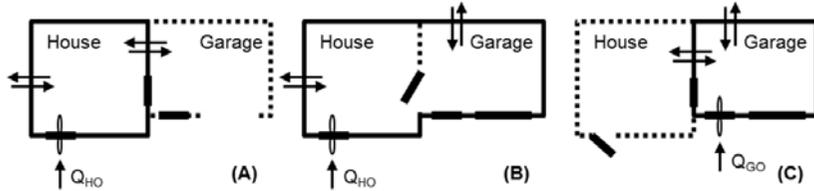


Figure 1 Three single zone methods using test configurations A, B & C. The three zones refer to the house (A), the garage (C), and then the combined house/garage zone (B).

**Three Single Zone Method.** Emmerich et al. (2003) used results from the 3 configurations illustrated in Figure 3 to calculate the leakage between the two zones. This is equivalent to performing three single zone tests, where the single zone contains the HO+HG interface, the GO+HG interface, and then the HO+GO interface:

$$Q_{HO,A} = C_{HO}P_{HO,A}^{n_{HO}} + C_{HG}P_{HG,A}^{n_{HG}} \quad (2)$$

$$Q_{GO,B} = C_{GO}P_{GO,B}^{n_{GO}} + C_{HG}P_{GO,B}^{n_{HG}} \quad (3)$$

$$Q_{HO,C} = C_{HO}P_{HO,C}^{n_{HO}} + C_{GO}P_{GO,C}^{n_{GO}} \quad (4)$$

where  $C_{HO}$ ,  $C_{GO}$  and  $C_{HG}$  are the flow coefficients and  $n_{HO}$ ,  $n_{GO}$  and  $n_{HG}$  are the pressure exponents associated with the leakage through each envelope segment.

Similarly to determining the leakage of a single zone, this system can be solved for the coefficients using measurements at a single pressure difference if the pressure exponent assumed; a value of  $n=0.65$  is common (Chan et al., 2012). Alternately, the parameters  $C_{ij}$  and  $n_{ij}$  can be determined explicitly if measurements are taken at multiple pressure differences. Emmerich et al. (2003) took measurements at 4 to 7 pressure differences for 4 houses with attached garages. Using a slightly different formulation of the equations above, they determined a value of  $n$  and  $C$  for each single zone control volume using linear regression, from which the leakage flow through each interface could be determined. If  $n$  is not assumed, the system has 3 equations and 6 unknowns. The calculation methods used in this section are described in the *Methods* subsection below.

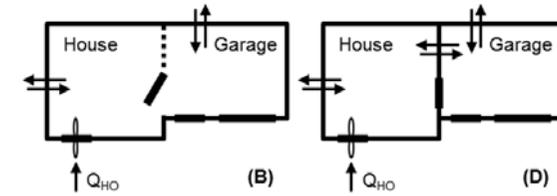


Figure 2 Standard Method, using configurations B & D.

**Standard two test method.** For determining house-garage leakage, Blasnik and Fitzgerald (1992) recommend completing a pair of tests with the blower door in the house-outside interface and the garage door closed. In the first test, the door between the house and garage is closed (D), and then in the second test the door between the house and garage is opened (B), as shown in Figure 2. Blasnik and Fitzgerald outlined the test at a single pressure ( $P=50$  Pa), but the house zone pressure can also be increased over a range of pressure differences (Offermann 2009). This test method is convenient to use because although it requires two tests, the blower door only needs to be installed once.

The following equations govern the air leakage in the D configuration:

$$Q_{HO,D} = C_{HO}P_{HO,D}^{n_{HO}} + C_{HG}P_{HG,D}^{n_{HG}} \quad (5)$$

$$C_{GO}P_{GO,D}^{n_{GO}} = C_{HG}P_{HG,D}^{n_{HG}} \quad (6)$$

Configuration B is the same as shown in Figure 1 for the three single-zone method, which is described by Equation (3). As in the three single zone case, this system of equations can be solved either using measurements at a single test pressure,  $P_{HO}$ , or using measurements at a range of pressure differences. As for the three Single Zone method, for single pressure difference testing, we need to assume a pressure exponent,  $n$ , and we can solve for the flow coefficient,  $C_{HG}$ .

**Garage 0/1 method.** Alternately, the interzonal leakage can also theoretically be determined using two tests without moving the blower door using configurations A and D: the home is pressurized with the garage closed and then open. In practice, however, these configurations do not provide significantly different conditions to determine the interzonal leakage.

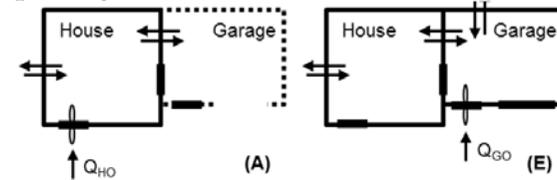


Figure 3 LBNL IzLT, using configurations A & E.

**LBNL IzLT.** While the Standard B/D method is convenient because it does not require moving the blower door, other test configuration pairs are also possible. Given that the blower door can be installed in doorways in each of the three interfaces (HO, HG, and GO), and the remaining interface doors can each be either open or closed, 12 unique configuration pairs can be used to determine the interzonal leakage. Hult et al. (2012) explored the 12 pairs and identified the LBNL IzLT method as the most robust pair of single blower door tests to

determine interzonal leakage. Figure 3 illustrates configurations A and E used in the LBNL IzLT method. By applying control volume analysis to the house zone in A and the house and garage zones in E, the problem can be described by the three equations resulting from applying control volume analysis to the house zone in A and the house and garage zones in E.

For some configurations (e.g., A and C), the blower door could be placed in either doorway to the pressurized zone.

## Simulations

Two approaches were used to assess interzonal leakage measurement strategies: Monte Carlo simulations and field tests. Simulation results are discussed below and field results from 6 houses are discussed in more detail in Hult et al. (2012, 2013). The simulations allow for a more thorough exploration of the parameter space, but require some assumptions about the nature of actual leakage and measurement noise. The field tests were helpful to bound conditions such as the magnitude of leakage quantities and wind-induced fluctuations, but were limited in terms of how many tests could be performed.

To determine the uncertainty in the total leakage from a single zone, it is possible to use uncertainty propagation techniques (Sherman and Palmiter, 1995). However, the non-linear system of equations makes it difficult to estimate the uncertainty in the interzonal leakage case. Instead, we used Monte Carlo simulations to mimic the collection of blower door measurements. In each simulation, a set of exact leakage parameters was selected, then the exact flow rates were calculated at a set of pressure differences for a given testing configuration. For multiple pressure difference tests, the 6 pressure differences used were 12.5, 25, 37.5, 50, 62.5, and 75 Pa. Then, to simulate the effects of measurement noise, randomly chosen fluctuations from a normal distribution with zero mean and a varied standard deviation were added to generate each ‘measured’ flow rate and pressure. The air leakage parameters  $C_{ij}$  and  $n_{ij}$  were then fit to these simulated ‘measured’ data. The leakage flows calculated from these fitted parameters  $C_{ij}$  and  $n_{ij}$  were then compared with the ‘exact’ leakage rates specified initially, allowing us to assess the error resulting from the added noise and the assumptions of each calculation method. In the results shown in this paper, the standard deviation of the fluctuations in the pressure was 0.5 Pa and 10 cfm for flow rate, and the interzonal leakage area as a fraction of the house to outside leakage area was  $C_{HG}/C_{HO}=0.05$  (sensitivity to these parameters was found to be low, as discussed in Hult et al. (2012)).

Because the fluctuations were chosen randomly from a specified distribution, results vary to some extent between subsequent simulations, in the same way field test results at the same site may vary between repeated tests. Therefore, for convergence 500-1000 simulations were run for each set of conditions to determine the typical (median) uncertainty as well as the range (one standard deviation above and below the median). Other factors taken into account in the selection of parameters and simulation of measurements include:

- Difference between pressurization & depressurization leakage parameters due to valving effects (mean difference between pressurization and depressurization and then variation about that mean),
- Distribution of actual pressure exponents vs. assumed value ( $n=0.65$ )
- Uncertainty in the mean pressure exponent in distribution
- Calibration error in pressure and flow rate measurements

Additional details of the Monte Carlo simulation methods can be found in Hult et al. (2012).

Other issues that were explored in detail in Hult et al. (2012) include additional possible testing configurations, sensitivity to fluctuations in pressure and flow rate measurements, and sensitivity to the magnitude of the interzonal leakage relative to the house leakage ( $C_{HG}/C_{HO}$ ) and the relative leakage in the two zones ( $C_{GO}/C_{HO}$ ). The report also compared various calculation methods including: fitting coefficients  $C_{ij}$  and pressure exponents  $n_{ij}$  values to pressurization and depressurization data separately or jointly; fitting or specifying  $n_{HG}$  for the interzonal leakage explicitly; and fitting  $C_{ij}$  but assuming a fixed  $n$  for all leakage interfaces.

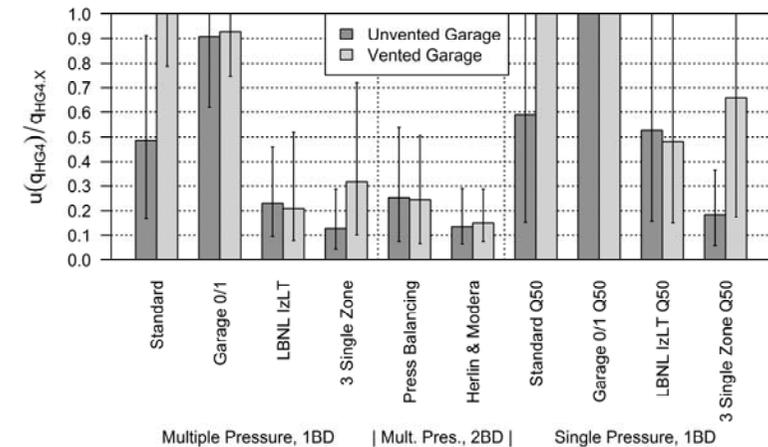


Figure 4 Comparison of the uncertainty resulting from different measurement methods to estimate interzonal leakage using simulated data. Bars show the median uncertainty  $u(q_{HG4})$  in the interzonal leakage, scaled by the exact interzonal leakage and error bars show one standard deviation above and below the median. Single Blower Door tests (left) and Two Blower Door tests (center) using multiple pressure differences. For single pressure difference methods (right), measurements were taken at 50 Pa. Bars are truncated at 100% uncertainty but several extend above.

## House-garage results

Simulations were used to compare the uncertainty resulting from different test configurations and calculation methods under the same conditions. Figure 4 compares the uncertainty in the interzonal leakage using different test methods, for the case when both zones are relatively tight (unvented garage,  $C_{GO}/C_{HO}=0.7$ ), and the case when the garage zone has a much larger leakage area than the house zone (vented garage,  $C_{GO}/C_{HO}=8$ ).

Figure 4 summarizes the results from the synthesized data analysis. The pair of single door configurations with the lowest uncertainty was the LBNL IzLT Method using multiple pressure differences. While other pairs of single blower door configurations had similar results when the leakage area of the two zones was comparable, the LBNL IzLT Method was more accurate when the second zone was much leakier than the house (vented garage case). The Three Single Zone method requires three blower door tests instead of two, but the results were excellent when the leakage area of the two zones was comparable: for the unvented garage case, the median uncertainty in  $q_{HG4}$  was 13% of itself when multiple pressure differences were used. When the garage zone was vented, the uncertainty increased but only to 32% of  $q_{HG4}$ . The Standard Method used by Blasnik and Fitzgerald (1992) and Offermann (2009) provided relatively consistent results if the two zones had comparable leakage area (uncertainty is about 50% of  $q_{HG4}$  at  $C_{GO}/C_{HO}=0.7$ ), but when  $C_{GO}/C_{HO}=8$ , the uncertainty is

near 100% of  $q_{HG4}$ . Although this uncertainty may seem small relative to the total house leakage, we found that the calculated values were often not meaningful because a good fit to the measured data could not be found (Hult et al. 2012). Results for Garage 0/1 Method are also included to show that the performance was also poor and the test should be avoided.

Analysis of the simulation results suggests that the Two Blower Door methods can be used to determine the interzonal leakage to within 20%. The method developed by Herrlin and Modera (1988) was used to determine  $q_{HG4}$  to within 16%, regardless of  $C_{GO}/C_{HO}$  or  $C_{HG}/C_{HO}$ . This measurement routine was also largely insensitive to fluctuations in the measured quantities, making it a very robust choice if two blower doors are available for use. The Pressure Balancing Method led to an uncertainty of approximately 25% of  $q_{HG4}$ . Overall, the simulations suggest that using a single pressure difference (e.g., 50 Pa) lead to unreliable estimates of the interzonal leakage. If  $C_{GO}/C_{HO}$  is not large (i.e., less than 3), simulation results indicate the uncertainty using the Three Single Zone Method is relatively low. However, the field test results indicated that the Three Single Zone Method was not reliable using a single pressure difference. Overall, the configuration sets that performed well in the simulations discussed above also had the most consistent results in the field tests (Hult et al., 2012; Hult et al., 2013).

### 3. GUARDED METHOD IN MULTIZONE BUILDINGS

We examine the sources of uncertainty in the guarded test method to determine leakage to outdoors from a single unit in a multi-zone building. In this method, adjacent zones are raised to the same test pressure to minimize leakage to other conditioned spaces.

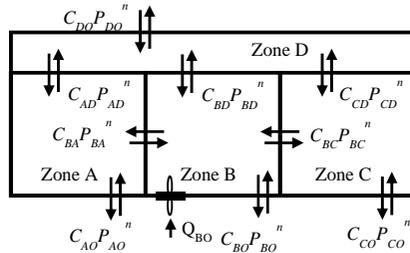


Figure 5: Schematic of guarded test on Zone B, with adjacent Zones A and C also pressurized, and all three zones are connected to the outside and to a common Zone D.

#### 3.1. Uncertainty in the guarded method

In this subsection, we use a similar approach to the simulations in the previous section to explore how sensitive the guarded test method is to calibration error and fluctuations in the pressure measurements. To explore this question, we simulate the testing of Zone B in Figure 5, assuming in this case that there was no leakage to the interstitial Zone D from A B or C. Following the approach as described in Section 2, test measurements are simulated at pressures between 12.5 and 75 Pa and we assume the measured pressure can fluctuate from the effective pressure in each zone by a random perturbation with standard deviation  $u(P) = 0.5$  Pa, the measured flow fluctuation has standard deviation  $u(Q)=10$ cfm, and the calibration errors for pressure and flow are 1 and 3% respectively.

Several studies have used tracer gas methods to estimate the air leakage between units to typically 15-30% of a unit's total infiltration (e.g., Francisco and Palmiter, 1994; Bohac et al. 2007). However, limited information is available on where the actual leakage area is located, and how units interact with interstitial spaces to lead to this air exchange in multi-zone

buildings. Therefore, we will explore the impact of leakage to non-guarded spaces over a feasible parameter space. If the interzonal leakage area is small relative to the leakage area to the outside ( $C_{BA}/C_{BO}=C_{BC}/C_{BO}=0.1$ ), then uncertainty in the leakage to the outside is 4%. If the interzonal leakage area is increased relative to the leakage area to the outside ( $C_{BA}/C_{BO}=C_{BC}/C_{BO}=0.5$ ), the uncertainty in the measured leakage is 14%. Thus, unless the interzonal leakage and/or pressure fluctuations are unusually high, the impact of measurement noise and calibration error is not expected to lead to significant uncertainty in guarded tests.

#### 3.2. Flow to interstitial spaces

In multifamily buildings, there may be pathways from an individual room or apartment unit through wall cavity, hallway, attic, basement or other conditioned or semi-conditioned spaces that are unlikely to be pressurized during a guarded test. A guarded test prevents air exchange only between the zone of interest (Zone B), and the adjacent, pressurized zones (Zone A & C). In a guarded test, the flow quantity measured in the test will include leakage from the zone of interest to the outside, as well as leakage from the zone of interest to any other zones that have not been pressurized, i.e.,  $Q_{meas}=q_{BO}+q_{BD}$  (Figure 5). The impact of the number of zones leaking to the interstitial zone was also explored by also simulating cases where Zone C or Zones A & C were sealed off from the other zones.

It is important to distinguish between leakage directly to the outdoors and leakage to interstitial spaces. Interstitial zones may be partially conditioned, in which case there is a smaller energy loss associated with air exchange between interstitial spaces and the conditioned zone, relative to air exchange with the outdoors. These zones are also more protected from weather than exterior walls, and so there are likely to be lower driving pressure differences across leaks at the interface between the zone of interest and the interstitial zone, compared with leaks in exterior walls. For these reasons, it is important to acknowledge that leakage area to non-guarded spaces is not equivalent to leakage area to the outside, even if leakage through the interstitial space eventually flows to the outdoors.

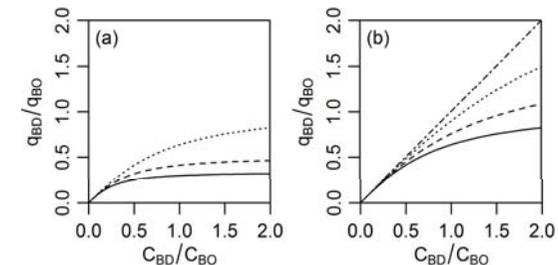
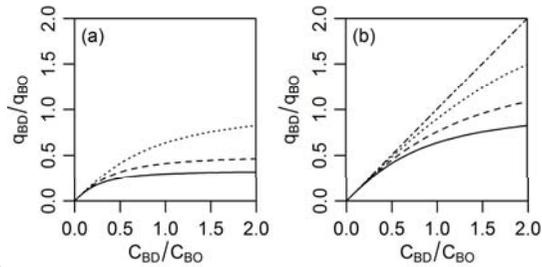


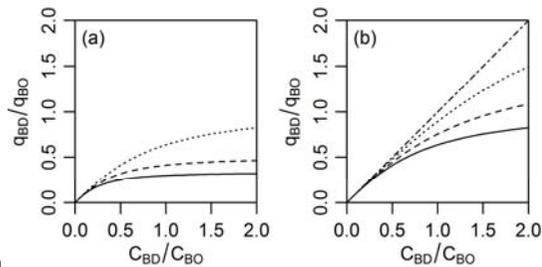
Figure 6: Ratio of leakage flow from B to D relative to the leakage from B to outside ( $q_{BD}/q_{BO}$ ) as a function of the leakage area ratio. In (a), Zone D has the same leakage area to the outside as Zone B, in (b), Zone D has three times the leakage area to the outside as Zone B. The dotted curve (...) assumes only one room zone (Zone B), the dashed (- -) has two room zones (Zone A & B), and the solid curve (—) has three room zones (A,B & C). The dashdot curve (-.-) shows the limit as  $C_{DO}$  becomes very large relative to  $C_{BO}$ .

In this section, we explore what fraction of the measured leakage in a guarded test might actually be leakage to interstitial zones. We use the model of three adjacent units all connected to a common forth zone, shown in Figure 5. Here, the leakage area between each of Zones A, B & C and the outside are equal and held constant. The leakage area between Zone D and the outside is varied to simulate a range in the degree of connectedness to the outside. The guarded test method was simulated, so zero direct leakage flow was assumed between conditioned zones.



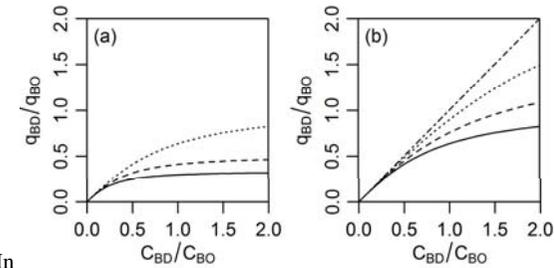
For a guarded test,

Figure 6 shows how much leakage flow there is to the interstitial zone compared with the leakage flow to the outdoors ( $q_{BD}/q_{BO}$ ), as the leakage area ratio is varied for those interfaces. The leakage flow rate  $q_{BO}$  is constant across all cases and we examine the magnitude of the flow from Zone B to the interstitial space relative to this quantity. As the leakage area to the interstitial zone is increased, the total leakage flow ‘measured’ in the simulated guarded test of Zone B increases because of the additional leakage to Zone D. Overall, the actual leakage area in the interface directly between the zone of interest in the outdoors may only be one half to two thirds of the leakage flow resulting from the guarded test.



In

Figure 6(a), the interstitial space has the same leakage area to the outside as each of the conditioned zones (i.e.,  $C_{DO} = C_{AO} = C_{BO} = C_{CO}$ ). Here, the leakage flow ratio to the interstitial zone increases with the leakage area ratio but once the leakage area to the interstitial zone is as large as the leakage area to the outside, the increase in the leakage flow to the interstitial zone diminishes. For example, if the leakage area to non-guarded zones in Zone B is evenly divided between leakage area to the outside and leakage area to the interstitial space, then the total ‘measured’ leakage flow from the guarded test will be about 30% higher than the ‘actual’ leakage flow directly to the outdoors. In this case, sealing one square inch of leakage area in the BD interface will have less effect on the measured leakage than sealing one square inch in the interface between B and the outside, both because Zone D is slightly pressurized and because it may be partially conditioned. The number of guarding zones connected to the interstitial zone also has a substantial impact on how much leakage there is to the interstitial zone: the more guarding zones that are also connected to the interstitial space, the lower the leakage flow from the zone of interest to the interstitial space.



In

Figure 6 (b), the leakage between the interstitial zone and the outdoors is increased so that  $C_{DO} = 3C_{BO}$ . This represents a case where the interstitial zone is more connected to the outdoors or simply a larger interstitial space. As the leakage area between the interstitial space and the outdoors increases, all curves approach the limiting curve shown in Figure 5(b), where leakage to the interstitial space behaves like leakage directly to the outdoors. In the case shown in (b), the leakage flow to the interstitial zone continues to rise with increasing leakage area to this zone. Thus if there is significant leakage area to an interstitial zone not very well sealed from the outdoors, leakage to this interstitial zone may constitute a significant fraction of the measured leakage in a guarded test.

#### 4. CONCLUSIONS

Uncertainty can be significant when using fan pressurization methods to determine the leakage between two adjacent zones and care should be taken to use recommended testing configurations and to use measurements at multiple pressure differences. When using the guarded method in a multi-zone building to determine the leakage to the outdoors, uncertainty due to measurement noise and calibration error is estimated to be relatively small, but leakage to unguarded interstitial zones may have a large impact on results. If all flow measured in the guarded test is assumed to be between the zone of interest and the outdoors, and if the neglected interstitial zones are significant, then air leakage measurements may give misleading estimates of building airtightness. This is because the actual leakage area in the interface directly between the zone of interest in the outdoors may only be one half to two thirds of the leakage flow resulting from the guarded test. Thus, care should be taken when interpreting the results of guarded leakage tests in multi-zone buildings so that the possible energy savings due to leakage directly to the outdoors are not overestimated.

#### 5. ACKNOWLEDGEMENTS

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#### 6. REFERENCES

- ASTM. (2007). Standard E1554-07, Standard Test Methods for Determining Air Leakage of Air Distribution Systems by Fan Pressurization. ASTM Book of Standards, American Society of Testing and Materials.
- ASTM. (2010). *Standard E779-10, Test Method for Determining Air Leakage by Fan Pressurization*. ASTM Book of Standards, American Society of Testing and Materials, Vol. 4 (11).
- Blasnik, M. and J. Fitzgerald. (1992). In Search of the Missing Leak. *Home Energy* 9(6).

- Bohac, D.L., J.E. Fitzgerald, M.J. Hewett and D. Grimsrud. (2007). Measured change in multifamily unit air leakage and airflow due to air sealing and ventilation treatments. *Proceedings of Buildings X: Thermal Performance of the Exterior Envelopes of Whole Buildings*.
- Chan W.R., J. Joh, and M.H. Sherman. (2012). Analysis of Air Leakage Measurements from Residential Diagnostics Database. LBNL Report, LBNL-5967E.
- Emmerich, S.J., J.E. Gorfain and C. Howard-Reed. (2003). Air and Pollutant Transport from Attached Garages to Residential Living Spaces – Literature Review and Field Tests. *International Journal of Ventilation* 2(3).
- Feustel, H.E. (1989). Measurements of air permeability in multizone buildings. *Energy and Buildings* 14:103–16.
- Francisco, P., and L. Palmiter. (1994). Infiltration and ventilation measurements on three electrically-heated multi-family buildings. *Proceedings of the 1994 ACEEE Summer Study on Energy Efficiency in Buildings*, 5:97-104.
- Furbringer, J.M., C. Roecker, and C.A. Roulet. (1988). The use of a guarded zone pressurization technique to measure air flow permeabilities of a multi-zone building. *Proceedings of the 9th AIVC Conference—Effective Ventilation*, IEA AIVC, Gent, Belgium, 233–49.
- Herrlin, M.K. and M.P. Modera. (1988). Analysis of errors for a fan-pressurization technique for measuring inter-zonal air leakage. *Proceedings of the 9th AIVC Conference: Effective Ventilation* 1:215-232, LBL-24193.
- Hult, E.L., D.J. Dickerhoff, and P.N. Price. (2012). Measurement methods to determine air leakage between adjacent zones. LBNL Report, LBNL-5887E.
- Hult, E. L., M.H. Sherman, and I. Walker. (2013). Blower-door techniques for measuring interzonal leakage. *Proceedings of Buildings XI: Thermal Performance of the Exterior Envelopes of Whole Buildings*.
- ISO. (2006). Standard 9972:2006(E), Thermal performance of buildings—Determination of air permeability of buildings—Fan pressurization method. International Organization for Standardization.
- Modera, M.P., R.C. Diamond, and J.T. Brunzell. (1986). Improving Diagnostics and Energy Analysis for Multifamily Buildings: A Case Study. LBNL Report, LBL-20247.
- Offermann, F. J. (2009). Ventilation and Indoor Air Quality in New Homes. Report CEC-500-2009-085. California Air Resources Board and California Energy Commission, PIER Energy-Related Environmental Research Program.
- Sherman, M. and L. Palmiter. (1995). Uncertainties in Fan Pressurization Measurements. *Airflow Performance of Building Envelopes, Components and Systems, ASTM STP 1255*, Mark P. Modera and Andrew K. Persily, Eds., American Society for Testing and Materials. 266-283.