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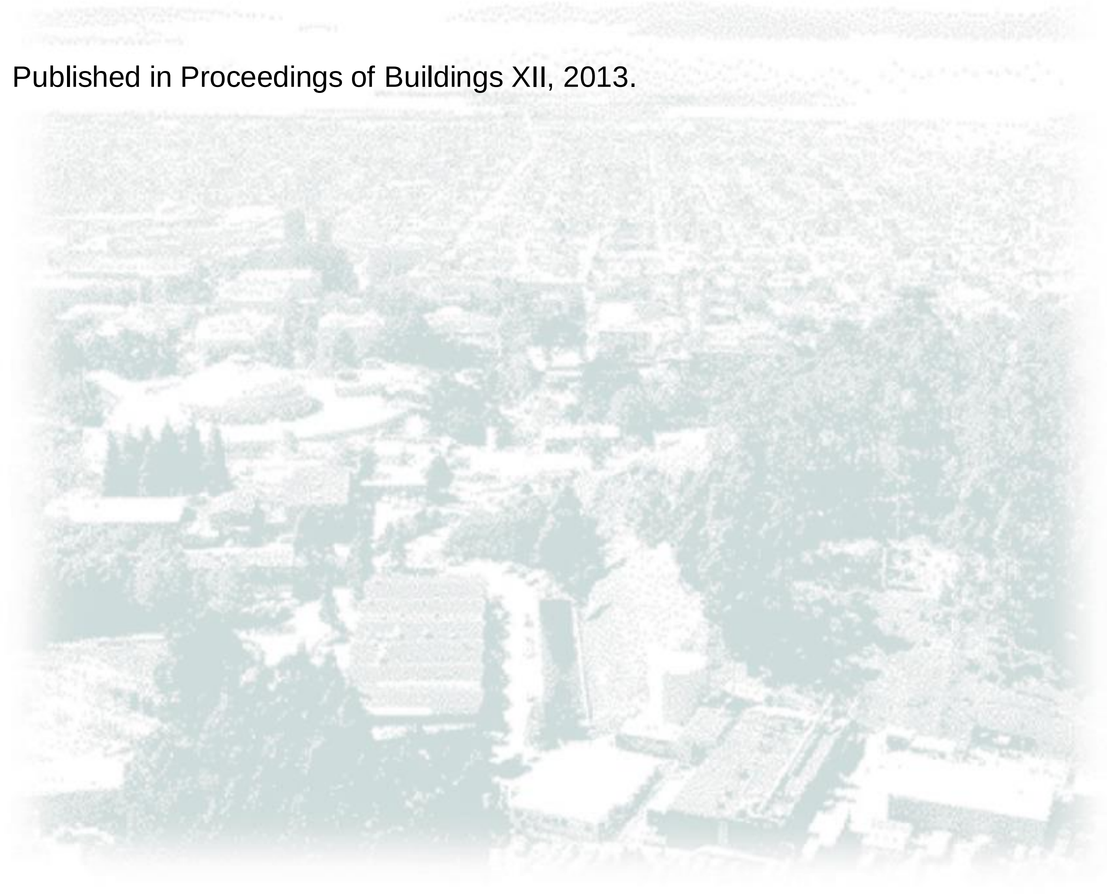

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Disclaimer

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Abstract

The standard blower door test methods, such as ASTM E779, describe how to use a single blower door to determine the total leakage of a single-zone structure such as a detached single-family home. There are no standard test methods for measuring interzonal leakage in a two-zone or multi-zone building envelope such as might be encountered in with an attached garage or in a multifamily building. Some practitioners have been using techniques that involve making multiple measurements with a single blower door as well as combined measurements using multiple blower doors. Even for just two zones there are dozens of combinations of one-door and two-door test protocols that could conceivably be used to determine the interzonal air tightness. We examined many of these two-zone configurations using both simulation and measured data to estimate the accuracy and precision of each technique for realistic measurement scenarios. We also considered the impact of taking measurements at a single pressure versus over multiple pressures. We compared the various techniques and evaluated them for specific uses. Some techniques work better in one leakage regime; some are more sensitive to wind and other noise; some are more suited to determining only a subset of the leakage values. This paper makes recommendations on which techniques to use or not use for various cases and provides data that could be used to develop future test methods.

Introduction

Interzonal leakage can have a negative impact on indoor air quality, due to transport from an attached garage to a house, between townhouses or between units in multi-family housing. In the house-garage case, transfer of automotive exhaust fumes into the home is of particular concern. Interzonal leakage testing methods are also used for energy efficiency objectives to identify leakage pathways in multi-family homes or single-family homes with adjacent attic or basement zones. While a number of strategies have been used to determine interzonal leakage, currently no standard exists for this measurement. Determining leakage between adjacent zones poses a much greater challenge than determining the total leakage in, say, a single family home. This is because typically the interzonal leakage is a small fraction of the total zone leakage; isolating the interzonal leakage effectively requires calculating a small quantity difference from larger quantities each with some uncertainty. The accuracy necessary for measurement of interzonal leakage depends to some extent on the purpose of the measurement. While air sealing a building, it can be useful to quantify interzonal leakage along different possible leakage pathways to determine where to focus air sealing efforts. In that case, inaccuracies of 50% or more may be acceptable. If a guideline or standard for acceptable interzonal leakage for indoor air quality purposes were being considered, higher measurement accuracy would be necessary. To address the question of whether it would be feasible to enforce such a standard, it is necessary to investigate how accurately interzonal leakage can be determined with fan pressurization methods.

The objective of this study was to identify the most accurate methods to quantify interzonal leakage using fan-pressurization (blower door) testing. While infrared and smoke techniques can give a qualitative indication of interzone leakage, blower door methods provide quantitative metrics. Tracer gas methods can be used to determine leakage under operational conditions, but are typically more expensive and time consuming than blower door tests. 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. This information can be used to assess the trade-off between the accuracy of the methods and the time and effort required to use the 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 only at a single pressure (typically 50 Pa (1.0 lb_f/ft^2)), 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). In this study, the uncertainty in the interzonal leakage associated with single and multiple pressure difference methods was compared using simulation and field test results.

Background

A number of studies have developed methods 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.

Study objectives

The objective of this study was to determine a) if blower door tests can be used to determine the leakage between a house and an attached garage to a degree of accuracy sufficient for developing standards or regulations, and b) what is the simplest blower door test that will reliably deliver accurate interzonal leakage results. This study used simulations and field data to assess:

- Single pressure difference vs. multiple pressure difference tests,
- Different methods using one or two blower doors.

First, the most common testing methods are outlined. Then the methods used to generate and analyze the synthesized data are presented. A discussion of the results of the synthesized data analysis follows. Then, results are presented on the analysis of field data collected in a variety of configurations in order to examine the agreement between the different techniques in practice. Because the true interzonal leakage at the field sites is not known, the accuracy of the tests in the field cannot be directly determined. Finally, conclusions from the study are presented in the form of a decision tree on how to select a testing method.

Diagnostic methods

Several methods using different sets of single blower door tests are outlined in this subsection, including:

- Three single zones method
- Conventional two-test method
- Garage 0/1 method
- LBNL IzLT method

Methods that use two blower doors simultaneously include:

- Pressure balancing method
- Herrlin & Modera (1988) method

These methods and similar variations have been used most often, however other methods are possible (Nylund 1981, Love and Passmore 1987, Wouters et al. 1988, NYSERDA 1995, ALA 2006). Additional test methods as well as two blower door tests are not described in detail but are included in Hult et al. (2012). The LBNL IzLT was developed in this study and is described in more detail in Hult et al. (2012), referred to there as the '991/190 method.’

The blower door is used to measure the flow rate Q, where the subscript in the equations that follow indicate the location of the door (HO for house-outside interface segment, HG for house-garage, and GO for garage-outside interfaces). P is the pressure difference across the interface indicated by the subscript. In each method, the measured pressure differences and the fan flow rate are used to calculate the leakage parameters.

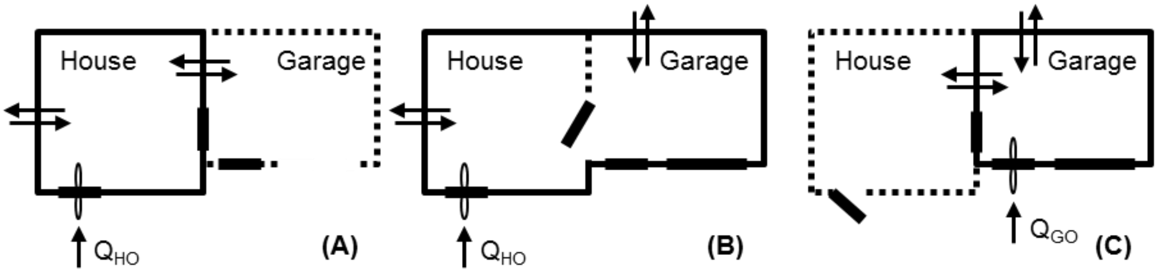

Figure 1 Three single zone methods using test configurations A, B & C.

Three Single Zone Method. Emmerich et al. (2003) used results from the 3 configurations illustrated in Figure 1 to calculate the leakage between the two zones. This is equivalent to performing three single zone tests, where the single zone is bounded by the HO+HG interface (A), the HO+GO interface (B), and then the GO+HG interface (C):

$$Q_{HO,A} = C_{HO}P_{HO,A}^{n_{HO}} + C_{HG}P_{HG,A}^{n_{HG}} \tag{1}$$

$$Q_{HO,B} = C_{HO}P_{HO,B}^{n_{HO}} + C_{GO}P_{GO,B}^{n_{GO}} \tag{2}$$

$$Q_{GO,C} = C_{GO}P_{GO,C}^{n_{GO}} + C_{HG}P_{GO,C}^{n_{HG}} \tag{3}$$

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 is assumed; a value of n=0.65 is common (Chan et al. 2012). Alternately, the parameters C_{ij} and n_{ij} can both be fitted 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 study are described in the *Methods* section below.

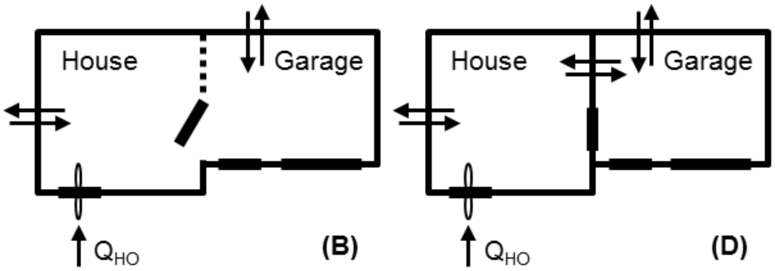

Figure 2 Conventional Two-Test Method, using configurations B & D.

Conventional two test method. For determining house-garage leakage, Blasnik and Fitzgerald 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 opened (B), and then in the second test the door between the house and garage is closed (D) as shown in Figure 2. In configuration (D), only the house zone is directly pressurized (or depressurized) by the blower door, but due to the leakage in the HG interface, the garage zone will also become slightly pressurized relative to the outdoors, and both P_{HO} and P_{HG} are recorded. Blasnik and Fitzgerald performed this test pair at a single pressure (P=50 Pa (1.0 lb_f/ft^2)), 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 first test, with the door between the house and garage open (configuration B), leads to Equation 2. Then the following equations govern the air leakage in the D configuration:

$$Q_{HO,D} = C_{HO}P_{HO,D}^{n_{HO}} + C_{HG}P_{HG,D}^{n_{HG}} \tag{4}$$

$$C_{GO}P_{GO,D}^{n_{GO}} = C_{HG}P_{HG,D}^{n_{HG}}. \tag{5}$$

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 difference values for P_{HO}. As for the 3 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 open and then closed, measuring both P_{HO} and P_{HG}. In practice, however, these configurations do not provide significantly different conditions to be able to determine the interzonal leakage as indicated in the *Results* section, because P_{HG} is typically very close to P_{HO} in (E).

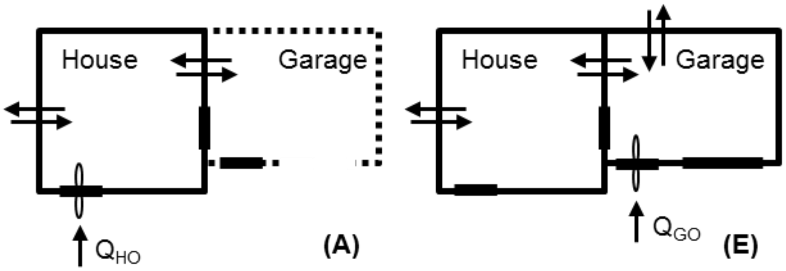

Figure 3 LBNL IzLT, using configurations A & E.

LBNL IzLT. While the Conventional B/D method is convenient because it does not require moving the blower door location, 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 3 equations.

For some configurations (e.g., A and C), the blower door could be placed in either doorway to the pressurized zone. The remaining configuration referred to in this paper as configuration F is when the blower door is placed between the two adjacent zones and all other doors are closed.

METHODS

Two approaches were used to assess interzonal leakage measurement strategies: Monte Carlo simulations and field tests, both described in more detail below. 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 measure conditions such as the magnitude of leakage quantities and wind-induced fluctuations, but were limited in terms of how many tests could be performed.

Monte Carlo Simulation

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 (0.26, 0.52, 0.78, 1.04, 1.31 and 1.57 lb_f/ft^2). Then, to simulate the effects of measurement noise, randomly chosen fluctuations from a normal distribution with zero mean and a specified standard deviation were added to generate each ‘measured’ flow rate and pressure. Using this new set of ‘measured’ data, each calculation strategy was then used to fit the leakage parameters C_{ij} and n_{ij}. 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.

Because the fluctuations were chosen randomly from the 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, 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 offset and fluctuation),
- 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). Although beyond the scope of this report, additional considerations were addressed in the Hult et al. (2012) including the importance of completing pressurization and depressurization testing and the number of pressure differences tested.

Field Tests

Blower door tests were completed at 7 houses in order to compare the results obtained from the various test configuration pairs. Data from House 1 was not used because at the end of the testing it was found that the attic access had blown open at some undetermined time. Field testing was completed independently from the synthesized data analysis, therefore the two blower door methods completed at the field sites did not include the procedure described by Herrlin and Modera (1988). In addition, configuration E was not tested at House 2 or 7. At each site, the house to outdoors and house to garage pressure differences were measured using a digital manometer (Energy Conservatory DG 700), with an uncertainty of 1% of the pressure measurement or 0.2 Pa (0.004 lb_f/ft^2), whichever is greater. Blower door tests were completed using one or two blower doors from The Energy Conservatory, controlled by a laptop computer. Details of the field sampling are described in Hult et al. (2012). For field tests, measurements were taken at 5 Pa (0.1 lb_f/ft^2) pressure increments between 0 and 75 Pa (1.6 lb_f/ft^2), where the upper limit depended on the leakage area of the pressurized zone. Calculation procedures used pressure differences of 10 Pa (0.21 lb_f/ft^2) and higher for multiple pressure difference tests. Single pressure difference tests were at 50 Pa (1.0 lb_f/ft^2), but because 50 Pa could not always be reached the tests were also performed at 35 Pa (0.73 lb_f/ft^2).

Calculation methods

As described in the study objectives, a number of different calculation methods were explored in Hult et al. (2012). The method with the lowest uncertainty for a range of conditions was found to be the 5 parameter fitting method. In this method, pressure measurements are collected for pressurization and depressurization conditions. The pressure offset was determined from the mean pressure difference measured when the blower door was installed but off. After pressure offsets are subtracted, a set of coefficients C_{HO}, C_{HG}, C_{GO} and pressure exponents n_{HO} and n_{GO} are fit jointly to pressurization and depressurization data. A fixed pressure exponent of n_{HG} = 0.65 is assumed. An optimization solver was used to determine the best fit values of the parameters, where the objective function minimized was the sum of the square of the difference between the measured and predicted airflow rate. This optimization has been implemented by the authors in Microsoft Excel as well as in the statistical programming package, R. This 5 parameter fitting method was used for all multiple pressure difference tests in this study.

For the single pressure difference methods, n=0.65 is assumed for all envelope interfaces. This results in a system of 3 or 4 linear equations (depending on the test configurations chosen) in terms of three parameters: C_{HO}, C_{HG} and C_{GO}. For cases resulting in 3 equations, the system was solved to determine the 3 coefficients explicitly. In cases resulting in 4 equations, the coefficients are the least squares best fit to the data.

RESULTS

Simulation results

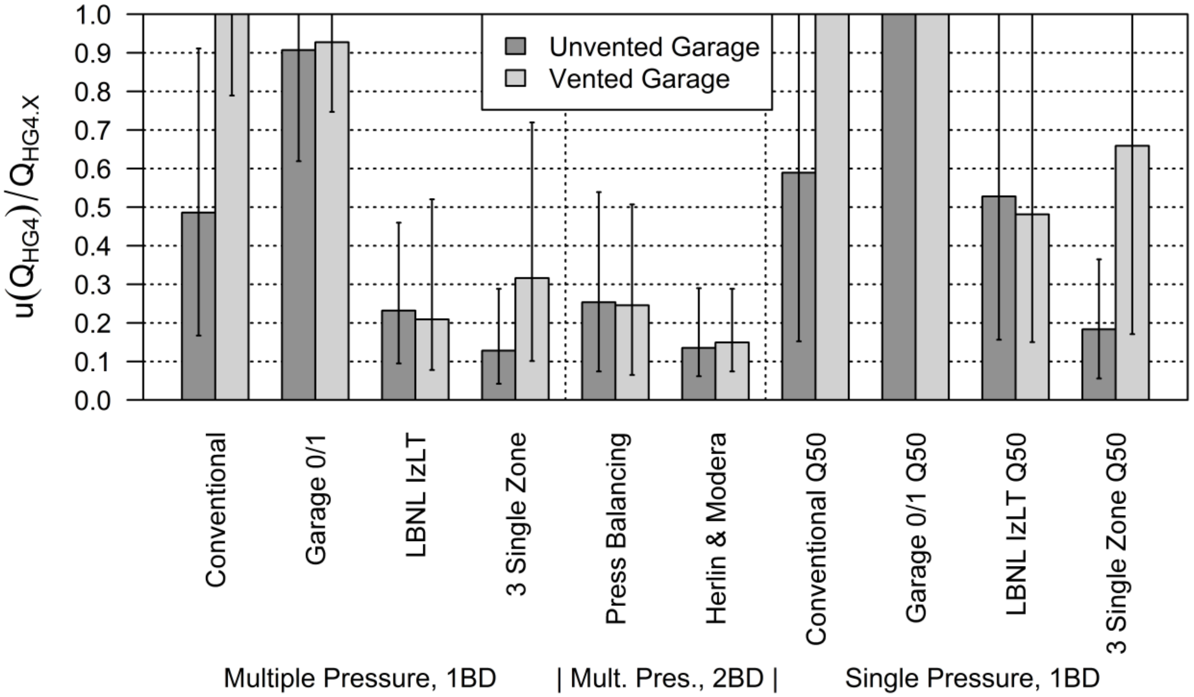

Figure 4 Comparison of the uncertainty resulting from different measurement methods to estimate interzonal leakage using simulated data. Bars show the median uncertainty u(Q_{HG4}) in the interzonal leakage, scaled by the exact interzonal leakage and error bars show one standard deviation above and below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

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, $C_{GO}/C_{HO}=8$). In this comparison, it was assumed that the standard deviation of the fluctuations in the pressure was 0.5 Pa (0.01 lb_f/ft^2) 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)).

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 very leaky (the mirror image pair of C & D are recommended if the first zone has higher leakage area). The Three Single Zone method requires an additional test but the results were excellent when the leakage area of the two zones was comparable: for $C_{GO}/C_{HO}=0.7$, the median uncertainty in Q_{HG4} was 13% of itself when multiple pressure differences were used. When the garage zone was very leaky (C_{GO}/C_{HO}=8), the uncertainty increased but only to 32% of Q_{HG4}. When the interzonal leakage fraction C_{HG}/C_{HO} is larger, the accuracy of the methods tested tended to improve: the uncertainty of the Three Single Zone method was less than 20% for all cases when C_{HG}/C_{HO} was greater than 0.15. The Conventional Two-Test 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 uncertainty of approximately 25% of Q_{HG4}.

Overall, the simulations suggest that using a single pressure difference (e.g., 50 Pa (1.0 lb_f/ft^2)) 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 in the following subsection indicated that the Three Single Zone Method was not reliable using a single pressure difference. Under very calm conditions, fluctuations in the measured pressure may be as low as 0.1 or 0.2 Pa (0.002 or 0.004 lb_f/ft^2) and this may lower the expected uncertainty slightly for single pressure difference tests, compared to the results shown here which assume fluctuations with an average magnitude of 0.5 Pa (0.01 lb_f/ft^2).

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.

Field testing

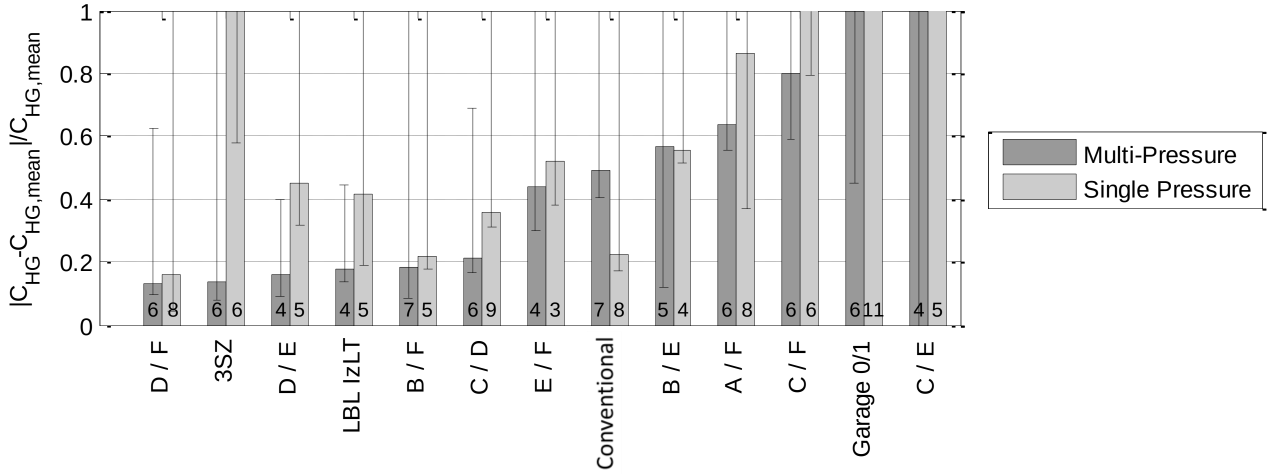

Figure 5 Estimated error in different methods based on field results. Bars show the median deviation from best estimate of the interzonal leakage area, for field test data from all houses. Multi-pressure methods (left bar) and single pressure methods at 50 Pa and 35 Pa(right) are shown. Error bars show the maximum and minimum deviations and the number of tests performed is shown at the base. The best estimate $C_{HG,mean}$ *is the uncertainty-weighted mean of the multiple-pressure method results.*

The results of applying different test methods in the field are summarized in Figure 5. The most consistent methods included the LBNL IzLT and Three Single Zone methods using multiple pressure differences. Consistent with the simulation results, results from single pressure difference tests generally had higher deviations from the best estimate of the interzonal leakage. The number of tests performed with each method was relatively low, but the minimum and maximum values illustrate the wide range of deviations found for all single pressure difference methods as well as many multiple pressure difference methods. Thus, although many test methods are possible, most of them are unreliable. Although the simulations suggested that the Three Single Zone method using a single pressure difference may have relatively low uncertainty, the field test results did not reflect this. While the median deviation for the Conventional Two-Test Method using a single pressure difference is low compared with the simulation result, this result is based on a limited number of tests. Overall, the agreement with simulation results is good: the Three Single Zone and LBNL IzLT multiple pressure difference methods performed well, and the single pressure difference tests as well as the multi-point Garage 0/1 methods were unreliable.

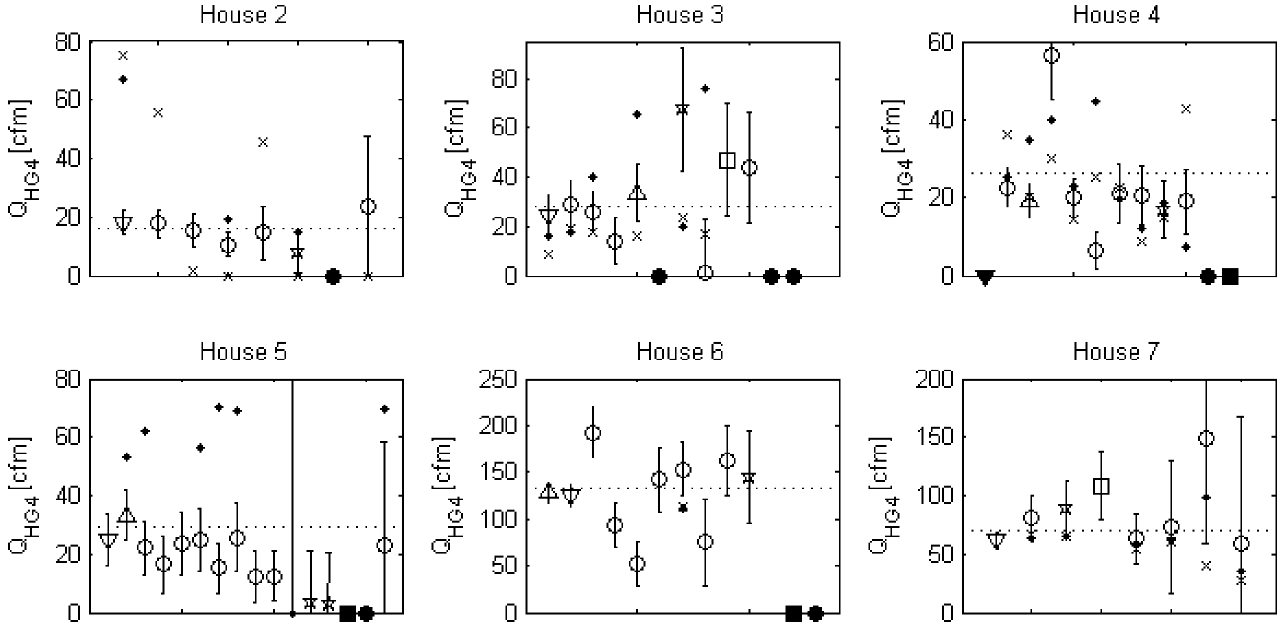

Figure 6 Interzonal leakage at 4 Pa (Q_{HG4}) from field data for houses 2-7. The symbol represents the test type. For each home, test configurations are ordered by the expected uncertainty of the multiple pressure difference tests, □ is the Three Single Zone, Δ is the LBNL IzLT, ☆is Conventional, and □ is the Garage 0/1 method, ○ is all other multi-pressure configurations. Failed tests are plotted as filled symbols at 0. Error bars on the multi-pressure results show the uncertainty predicted by simulation results. Single pressure difference results are shown above or below the corresponding configuration using multiple pressure differences: x for tests at 50 Pa and ● for tests at 35 Pa. The dashed line shows the uncertainty-weighted mean of the multi-pressure difference results.

Table 1 Parameters resulting from the field test configuration set of single blower door tests with the lowest uncertainty as estimated from the simulation results. The configuration method used and estimated uncertainty is shown by the left-most, non-zero symbol in each subplot of Figure 6. Here, u(P) is the standard deviation of the pressure difference measured when the blower door is off, to give a metric of the uncertainty in the pressure measurement.

	House 2	House 3	House 4	House 5	House 6	House 7
u(P) [Pa]	0.61	1.42	0.46	0.49	0.35	0.78
C_{HO} [cfm/Pa^n]	211	585	146	239	119	273
C_{HG} [cfm/Pa^n]	7.3	9.8	9.2	10.2	52	25
C_{GO} [cfm/Pa^n]	160	117	102	771	1129	166
n_{HO}	0.60	0.50	0.67	0.60	0.63	0.62
n_{GO}	0.60	0.49	0.57	0.53	0.55	0.51
Q_{GO}/Q_{HO}	0.76	0.20	0.60	2.9	8.5	0.53
Q_{HG}/Q_{HO}	0.037	0.021	0.061	0.046	0.45	0.096

Looking at the test results at each house provides additional insight into the performance of different methods. From Figure 6, it is clear that different testing and calculation methods led to different leakage flow rates for the same house, tested on the same day. From Figure 6 and Table 1, the Conventional Two-Test Method performed reasonably well when the interzonal leakage is larger than 5% of the house to outside leakage (House 4, 6, and 7) but was further from the mean when the interzonal leakage is small (House 2, 3, and 5). The Garage I/O method performed poorly as expected. Failed tests are defined as tests in which one or more of the fitted parameter values fell at the boundary constraint value during the optimization, i.e., no good fit was found within the domain. Constraints were $0.4<n_{ij}<1.2$ and $0.01<C_{ij}<4000$.

Looking at the single pressure difference test results in Figure 6, in general there was large variability in test results. *Why were the single point results so variable?* To extrapolate from higher pressures down to find the leakage flow at 4 Pa, a pressure exponent of 0.65 was assumed. The pressure exponent fitted to fan pressurization measurements has been shown to vary across single family residences in the US, with a mean value of 0.65 and a standard deviation of 0.057 (Walker et al., 2013). When determining the leakage flow at 4 Pa from a single zone, this variability in the pressure exponent can increase the uncertainty from about 4% if n is known exactly to about 14% if n=0.65 is assumed. The interzonal leakage, however, is typically small relative to the total house and garage leakage, and so this uncertainty associated with the pressure exponent is compounded. In summary, if the assumption that n=0.65 happens to be correct, then using a single pressure difference method may give consistent, accurate results. If the pressure exponent is not precisely 0.65, this assumption can lead to inaccurate (but repeatable) results.

It is possible that an interzonal leakage test at a single pressure will agree with test results taken at multiple pressure differences, but this was not typically the case in our field measurements. At house 7, the single pressure tests at both 35 and 50 Pa were consistent and agree well with the multiple pressure difference results. In other cases, such as House 5, the set of single pressure tests was self-consistent, but there is a substantial offset between the single and multiple pressure difference results. This was also the case at House 3, where single pressure tests clustered for the more reliable configurations (at the left of the figure), but were substantially lower than the leakage calculated from the multiple pressure difference tests. Large differences between tests at 35 Pa and 50 Pa (e.g., House 3) suggested that the pressure exponents assumed for the building envelope segments may not have been equal to the assumed pressure exponent. Table 1 indicates that the pressure exponents fitted at House 3 were indeed much lower than 0.65 (n_{HO}=0.50, n_{GO}=0.49). Larger scale field testing would be needed in order to draw conclusions about how n_{GO} or n_{HG} might differ from n_{HO} on average.

Recommended procedure

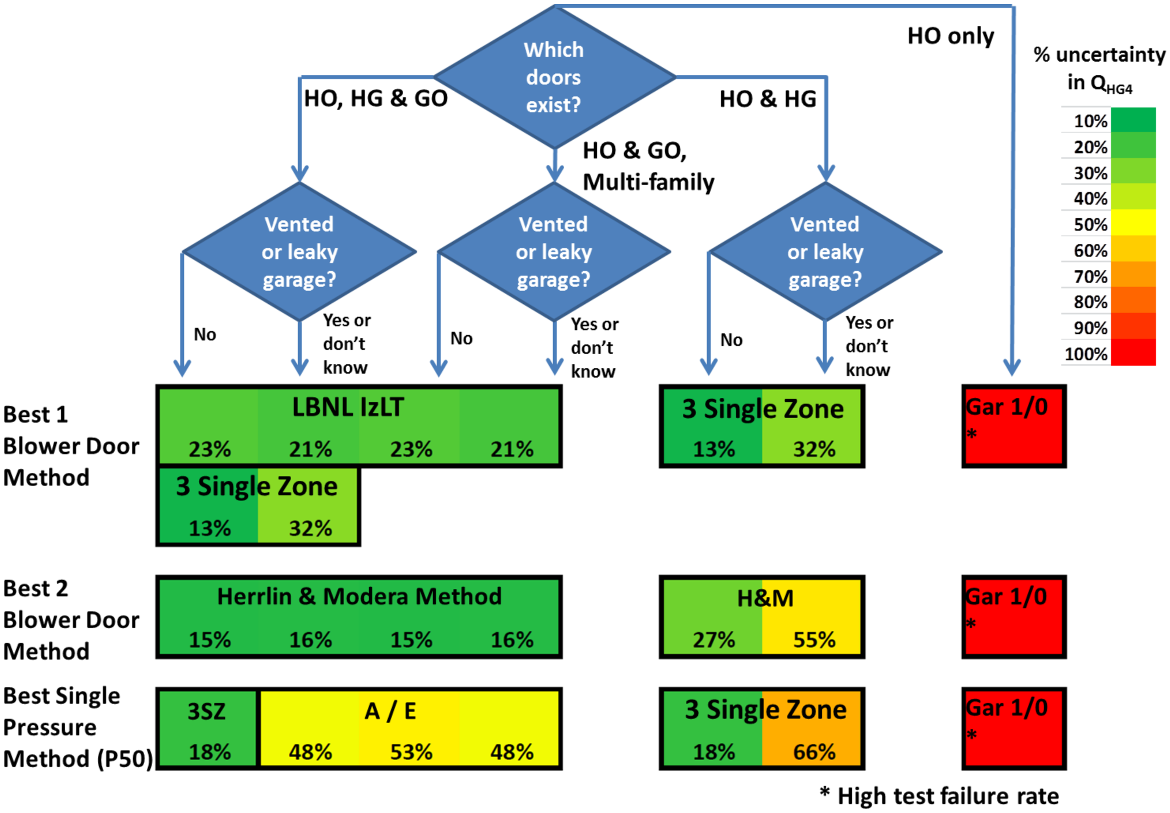

Figure 7 Decision tree for choosing testing method. HO, HG, and GO refer to whether doors exist in the house-outdoors, house-garage, and garage-outdoors interfaces. Shading indicates the median uncertainty in Q_{HG4} from the simulation analysis, assuming $u(P)=0.5$ Pa, $C_{HG}/C_{HO}=0.05$, for the unvented garage case, $C_{GO}/C_{HO} = 0.7$ and for the vented garage case, $C_{GO}/C_{HO} = 8$.

Figure 7 provides a decision tree for choosing a testing method, showing the expected uncertainty for each approach. The goal is to illustrate the best choices as well as the impact of making worse choices. This chart does not include variable wind fluctuations, which did not tend to change which tests performed best. Walking through the decision chart, the first question to consider in choosing a testing strategy is where it is possible to mount the blower door. Some homes will have doors in the HO, GO, and HG interfaces, but some homes will have only some of these doorways. If it is known that the garage is vented directly to the outdoors (through intentional or unintentional means), this can significantly increase the uncertainty of the best test options. If it is not known whether the garage zone is vented or leaky, it should be assumed that it is (this is a conservative assumption because uncertainty tends to be higher if the garage leakage area is high). If all doorways are available, the best test option is the 3 Single Zone Method followed by the LBNL IzLT Method if there is a preference to only run two test configurations rather than 3. If higher accuracy is desired, or if high fluctuations due to wind are expected, it may be desirable to use the two blower door method of Herrlin and Modera (1988). The uncertainty for single pressure difference methods are listed for reference to show the increased uncertainty for these tests. The chart can be followed the same way if there are HO and HG doorways or HO and GO doorways present. If there is only a doorway in the HO interface to mount the blower door and there is no opening between the house and garage zones, the only test configuration pair possible is the Garage 0/1 Method, which cannot be reliably used to determine the interzonal leakage.

In practice, it is difficult to obtain accurate results when the leakage area of one zone is much greater than the other, both because larger uncertainties tend to occur in this scenario and because it is difficult to establish high pressures in the leaky zone. In the discussion of how to determine the leakage between a house and a vented attic, Blasnik and Fitzgerald (1992) suggest temporarily sealing attic vents during testing to improve accuracy. This strategy would also be a quick and straightforward means to improve the accuracy when testing leakage between a house and vented garage, provided the vents can be temporarily sealed.

Although the house-garage scenario is considered in this paper, similar techniques using a single blower door in a series of different configurations could be applied to develop methods for testing a row of townhouses or other multi-family building configurations. For two connected units with a single shared interface, there are typically doors connecting each zone to the outside, but not connecting the two units to each other. Thus the LBNL IzLT Method is likely to be the best choice if only one blower door is available.

CONCLUSION

The best single blower door methods (LBNL IzLT, Three Single Zone) were used to determine the interzonal leakage to within 20% of its value, based on simulation results and supported by field measurements. Poor testing and calculation methods can lead to errors of up to 100% in the interzonal leakage area. The choice of analysis method can reduce uncertainty in the calculation of house-garage leakage significantly. Making the assumption that the pressure exponent for the interzonal wall is 0.65 was better than fitting for that pressure exponent, regardless of how many pressure differences were used. Additionally, the uncertainty was reduced by fitting a single set of parameters to both pressurization and depressurization data.

Two blower doors can be used simultaneously to reduce the uncertainty slightly further. The best of the measurement and analysis methods was the method developed by Herrlin and Modera (1988) which used two blower doors simultaneously to determine the interzonal leakage to within 16%, over the range of expected conditions. When two blower doors are used simultaneously, there is a large range of combinations of pressure differences at which testing can be performed. While some two blower door methods consistently obtained accurate results, many did not give accurate results. Care should be taken to follow recommended testing procedures.

The single pressure difference approach could not reliably be used to determine interzonal leakage due to uncertainty in measured quantities and the pressure exponents in the different interfaces. If the objective is simply to identify which interzonal partitions may have high leakage flows for air-sealing purposes, using single point testing may be sufficient. However, if the objective is to determine whether interzonal leakage is below a threshold level in a standard, higher accuracy is necessary. Analysis of field datasets confirmed that performance across test methods was consistent with the analysis of synthesized data sets.

NOMENCLATURE

P_{ij} = pressure across interface indicated by subscript

Q_{ij} = flow rate [cfm] through blower door in interface indicated by subscript

C_{ij} = flow coefficient

n_{ij} = pressure exponent

Q_{HG4} = leakage flow [cfm] through the house-garage interface at 4 Pa

Subscripts

HG = house-garage interface

HO = house-outside interface

GO = garage-outside interface

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