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Applying Large Datasets to Developing a Better Understanding of Air Leakage Measurement in Homes

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ABSTRACT

Air tightness is an important property of building envelopes. It is a key factor in determining infiltration and related wall-performance properties such as indoor air quality, maintainability and moisture balance. Air leakage in U.S. houses consumes roughly 1/3 of the HVAC energy but provides most of the ventilation used to control IAQ. There are several methods for measuring air tightness that may result in different values and sometimes quite different uncertainties. The two main approaches trade off bias and precision errors and thus result indifferent outcomes for accuracy and repeatability. To interpret results from the two approaches, various questions need to be addressed, such as the need to measure the flow exponent, the need to make both pressurization and depressurization measurements and the role of wind in determining the accuracy and precision of the results. This article uses two large datasets of blower door measurements to reach the following conclusions. For most tests the pressure exponent should be measured but for wind speeds greater than 6 m/s a fixed pressure exponent reduces experimental error. The variability in reported pressure exponents is mostly due to changes in envelope leakage characteristics. It is preferable to test in both pressurization and depressurization modes due to significant differences between the results in these two modes.

Introduction

Air tightness in homes refers to the holes in the building envelope that are unintentional. The openings used for intentional ventilation, such as open windows or passive vents are not considered part of the air tightness of the envelope. The holes we are concerned about are the small cracks between building components or open chases inside interior partitions that connect to interstitial spaces such as attics and crawlspaces. Although all building envelopes have some leakage, this study focuses on residential buildings – particularly low-rise, single-family homes.

We usually measure air tightness in order to quantify the natural air exchange that happens due to wind blowing on a house or indoor-outdoor temperatures creating stack pressures. This natural air exchange is called infiltration and is a significant part of the heating and cooling (and humidity) load for a home and also contributes dilution air for indoor pollutants. This has been recognized for many years and testing to determine air leakage is a key part of Federal Weatherization Programs, Home Energy Ratings (RESNET 2006), and home performance diagnostics and indoor air quality standards (ASHRAE Standard 62.2-2010). In this study we focus on how these effects influence the practical end-uses for the envelope leakage data.

Quantifying air tightness involves measuring the flow through the building envelope as a function of the pressure across the building envelope. This relationship often fits a power law, which is the most common way of expressing the data and is used in measurement standards in the US (ASTM E779-2010), Canada (CGSB 149.10 (1986)) and Europe (ISO 9972 (2006)). The power law relationship has the form

$$Q = C\Delta P^n \tag{1}$$

where C [m^3/sPa^n] is the flow coefficient and n is the pressure exponent, Q is air flow (m^3/s) and ΔP is the pressure difference (Pa).

The following air tightness metrics have been used over the years (in rough order of popularity):

- Q_{50} – air flow at 50 Pa envelope pressure difference. This has been the traditional value since blower door techniques became popular. It is low enough for standard blower doors to achieve in most houses and high enough to be reasonably independent of weather influences. When single-point measurements are made, it is almost always at 50 Pa.
- ACH_{50} – Q_{50} converted to air changes per hour by dividing by house volume and converting for time. I.e., cfm is multiplied by 60 to get cubic feet per hour and m^3/s is multiplied by 3600 to get m^3 per hour.
- ELA_4 – Equivalent leakage area at 4 Pa. This is the area of an orifice that would have the same flow as the building envelope at a pressure difference of 4 Pa. This is part of the ASTM standard.

- NL – derived from ELA_4, the Normalized Leakage area is normalized by house floor area and the number of stories and is referred to in ASHRAE Standard 62.2 as part of a method to estimate infiltration.
- ELA_{10}– Equivalent leakage area at 10 Pa. This is the area of an orifice that would have the same flow as the building envelope at a pressure difference of 10 Pa. This is part of the CGSB standard.
- C – the envelope leakage coefficient usually expressed in units of cfm/Pa^n or m^3/sPa^n

In this study we will focus on the metric of ELA_4 as it is the most relevant for users attempting to estimate air change rates for energy or indoor air quality applications. In addition, homes usually have envelope pressures of about 4 Pa, or less, and the ELA_4 metric is therefore referenced to the range of pressures a home typically experiences. In contrast, Q_{50} is measured at much higher pressures than the house normally experiences. When Q_{50} is used as the starting point for the calculation of infiltration it needs to be converted to a lower pressure. A key issue examined by this study is the differences between determining ELA_4 by measuring both C and n in Equation 1and extrapolating Q_{50} results down to lower pressures using a fixed exponent. For such cases the average exponent found from large datasets is often used, which has been found by Orme et al. (1994) and Sherman and Dickerhoff (1998) to be approximately 0.65.

Measurement Techniques

The basic measurement techniques used in the above standards, utilize a blower to move air in out of the building while simultaneously measuring the resulting pressures across the envelope. This blower is usually mounted in a doorway – the most convenient opening to use for testing. Hence, this testing is often referred to as “Blower Door” testing. The Blower Door incorporates a flowmeter to measure the air flow. Most Blower Doors use a calibrated orifice approach to measuring the flow – in which a pressure difference across a calibrated orifice is used. The technique for air flow measurement is important because wind pressure fluctuations during the test apply to the measurement of air flow as well as the envelope pressure differences. Measurements are recorded of the steady-state flow through the blower necessary to maintain a steady pressure across the building envelope – usually at set envelope pressure stations. A key issue addressed in this paper is that the indoor-outdoor temperature difference and wind blowing around the home also change the envelope pressures. Most blower door techniques attempt to account for this by measuring envelope pressures with the blower off and subtracting these pressures from the target pressure stations.

Another measurement technique is to use a Blower Door to pressurize the house to 50 Pa and record the flow through the blower, Q_{50}.This single point test uses the same equipment and requires the same set-up as the multipoint testing but only measures at a single pressure station.

Blower door measurements are now a standard technique applied to thousands of homes for measuring air leakage. Several systems are commercially available that package the

blower, door assembly, and pressure gauges together in a cost-effective way that allows for widespread use of the technique by a wide range of users.

Exploring The Measurement Techniques

In this study we focus on two measurement approaches to determine the parameter of interest: ELA_4:

1. Multi-point testing with C and n fitted to Equation 1.
2. Single-point testing to determine Q_{50}, with an assumed exponent, n.

We will examine the uncertainties in air tightness determinations using these two techniques using two large datasets containing thousands of test results.

DATA SOURCES

In any one measurement for any one house there are a host of parameters which could affect a fan pressurization measurement. We would like to be able to isolate the impact that specific factors have on our determination of air tightness. To do so we will use two large datasets, one intensive and one extensive. A key issue to be examined is to examine the variation in pressure exponents to separate variations in the underlying exponent (due to the home envelope characteristics) from noise in the measurement of that exponent.

In our current study we have two data sets. One set of measurements uses the same blower door technique and apparatus for each test which includes data points for the ASTM and CGSB test methods – i.e., over a range of about 10 to 100 Pa across the building envelope. The second data set includes measurements grouped together from many studies and programs and uses a variety of techniques and equipment – with the majority also being multi-point measurements roughly following the ASTM standard.

We have been collecting blower door data and compiling it in the LBNL Residential Diagnostics Database for several years. Currently we have measurements from approximately 175,000 homes in the US. Half of the homes were previously analyzed by McWilliams and Jung (2006), and the other half of the data was newly added to the database in the past year. Because analysis of the newly added data is ongoing, the summary statistics provided here may be revised in subsequent publications. The previous version of the database contained mostly single-family detached houses (98%), with the remaining being either multi-family dwellings and mobile homes. The majority of the newly added data is also single-family detached houses (72%), but there are many more multi-family dwellings (6%) and mobile homes (21%). The reason for this is that approximately half the newly added data were gathered from weatherization assistance programs, where multi-family dwellings and mobile homes are eligible to participate. Residential energy efficiency programs and various research studies contributed the remaining half of the newly added data.

This database contains enough variation across several key parameters to allow its use as a high quality reference database and as the foundation of predictive tools. The basic characteristics of the homes are included, such as floor area, number of stories, location (e.g. city, county, zip code), and year built. The median home in the data is about 150 m^2 in floor area and built in 1960's. Newly added homes tend to be larger and built more recently. Single story homes are the most common, but there is also a significant portion of two story homes, especially from the newly added data. Figure 1 shows the number of homes represented in different states. Previous data (McWilliams and Jung (2006)) was dominated by two data sources: Ohio weatherization programs and energy efficient homes in Alaska. In the new database, the population of homes is more diverse between states. Ohio and Alaska remain the leading states with the most data, but the newly added data also bring the data counts to exceed 5,000+ in other states: California, Florida, Idaho, Minnesota, New Jersey, Texas, Utah, and Washington. There are 39 states with more than ten homes represented in the database.

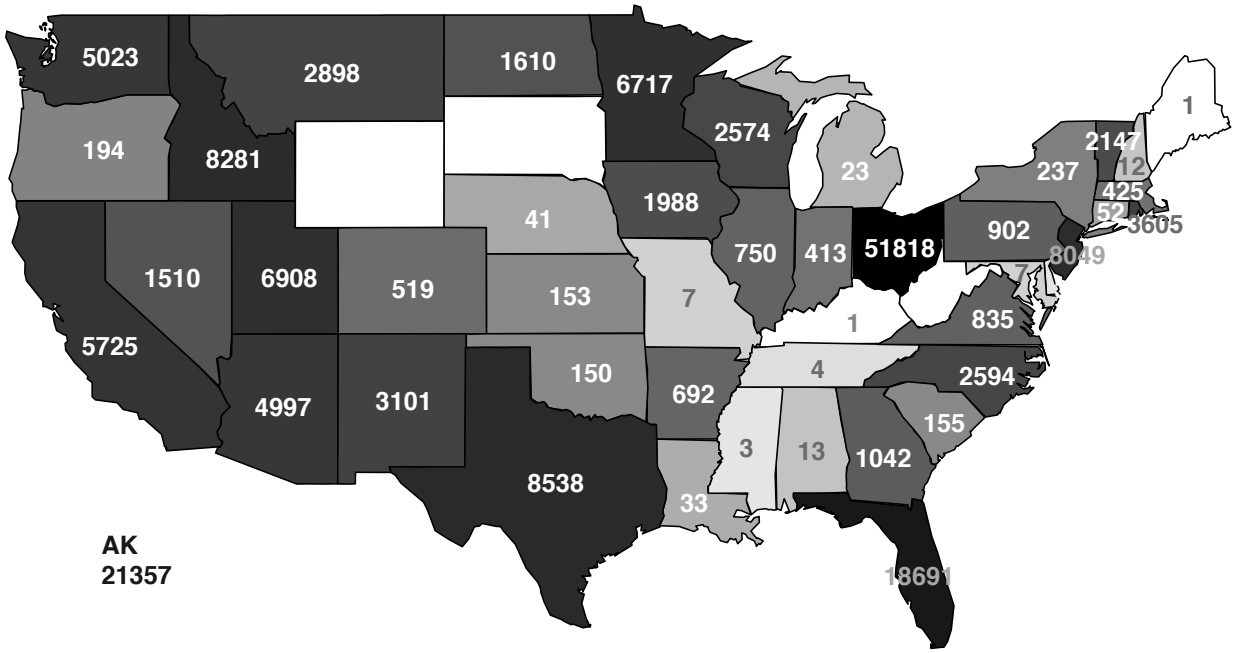

Figure 1. Number of homes represented in Residential Diagnostic Database.

A more refined analysis of the new LBNL database is currently underway and will be the subject of future publications. Most of the blower door data are single-point measurements at 50 Pa pressure difference. NL is the metric used in our analysis of this data. The distribution of NL is roughly lognormal. Figure 2 shows the summary statistics of NL in the form of boxplots for data previously analyzed in 2006, and separately for data added recently. Data are grouped by programs for which the blower door measurements were collected. Multi-family and mobile homes are excluded, but because not all house type is known in the data provided to us, Figure 2 likely includes a small fraction of them. Overall, there is a factor of 10 difference in normalized leakage across homes in the US. Homes

that participated in weatherization assistance programs (WAPs) tend to have higher air leakage. There is a decrease in normalized leakage when homes are retrofitted, from both WAPs and residential energy efficiency programs. McWilliams and Jung (2006) found that the energy efficient homes from Alaska have especially low normalized leakage. The newly added data show homes from recent research studies (i.e., “others” in Figure 2) have normalized leakage values that are similar to the Alaskan homes.

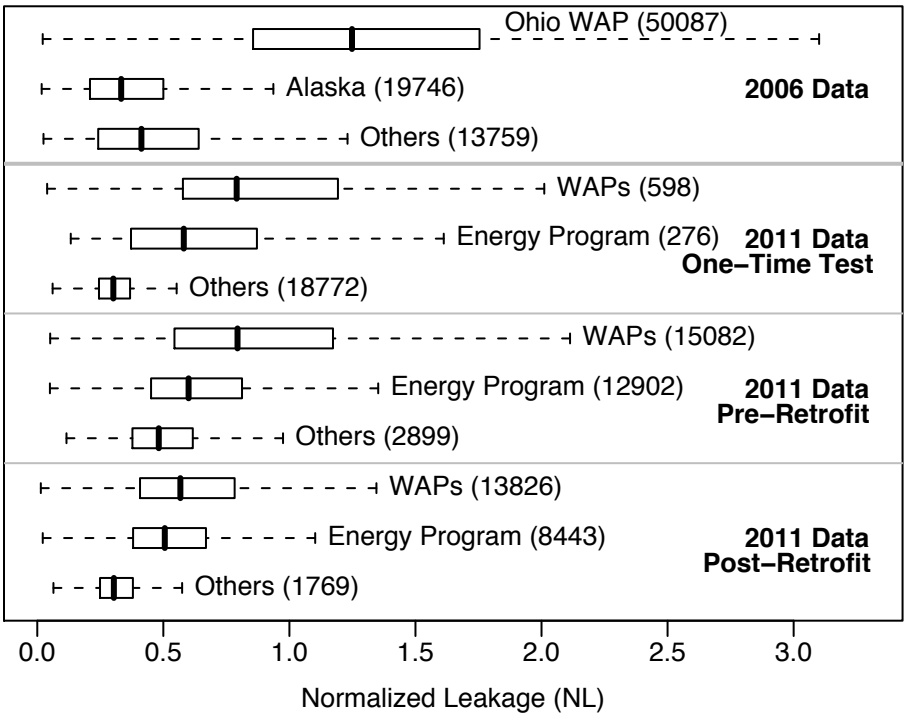

Figure 2. Summary of normalized leakage analyzed previously in 2006, and from newly added data (2011). Boxplots show the median and interquartile range (25th and 75th percentile), and the whiskers show the extent of data excluding the outliners. Data are grouped by sources and are separated into pre- and post-retrofit if known. The values in parentheses are the number of NL values included in each boxplot.

Some questions are best answered by repeated measurements of the same house in the same configuration. Such measurements will tell us how various measurement factors affect the measurement result when the underlying building (and tightness) have not changed. To do this, we used a dataset from the Alberta Home Heating Research Facility (AHHRF) located south of Edmonton, Alberta, Canada (for more construction details of AHHRF see Wilson and Walker (1991 and 1992)). The facility consists of six test houses, each constructed in a different way in order to examine different heating and ventilating strategies. The houses were unoccupied and the fan pressurisation test system was automated, which allowed almost 7500 fan pressurisation tests to be performed. Wind speed, wind direction, and ambient temperature data were taken from meteorological towers at the test site.

The flow rates were measured using a laminar element flowmeter, and were corrected for pressure and temperature changes. Pressure and flow rate measurements were taken over 15 seconds (at about 10 samples per second) and averaged for each data point. The uncertainty in the measured flows is estimated to be 0.001 m^3/s or 1%.

The indoor-outdoor pressure difference was measured using a pressure averaging manifold that had a pressure tap on each exterior wall of the building. This manifold was used to average the wind pressure effects on the four walls. The intent is to measure the pressure acting across the building leaks both when measuring offsets before the blower door is operated and during door blower operation. This does not necessarily reduce the noise in the pressure signal due to wind effects that depends more on the length and diameter of tubing used and the exposure of the end of the tubing to the wind. Instead it removes any biases due to the mean wind. For example, if one were only to measure on an upwind wall a positive wind pressure would be recorded – which would only be the correct offset for that upwind wall. Conversely, if the wind is blowing parallel to the wall used for the measurement, a negative pressure would be recorded. Similarly to the first example, this would be the correct offset for that wall but not for the upwind and downwind walls. When all four walls are sampled via the manifold we get a wind pressure that is more typical for all the walls of the building. The CGSB Standard gives detailed instructions on how to fabricate a manifold to specifically perform time averaging if the pressure signal, but that technique was not used in this study. Although recommended, it is not required that a four-wall pressure averaging manifold be used and in practise this is very rarely done. Instead a single pressure tube is used that is often not wall mounted and simply used as an outside static pressure reference – a fundamentally different approach compared to how the ASTM and CGSB standards are attempting to measure pressure differences across the walls or facades of the building being tested. In some ways, the single external static pressure has some advantages when reducing wind effects because it removes the effects of the pressure changes due to airflow around the house.

The single external static pressure is therefore, likely to be less sensitive to wind pressure fluctuations in the sense that its signal to noise ratio will be lower. However, the actual building leaks see the larger wind pressure fluctuations due to air flow around the building that are better captured by the four-point manifold used in the AHHRF tests. In an ideal experiment we want to know the wind effects on every building leak and correct for this effect with high time resolution data. This is completely impractical. However, the four-point pressure manifold is closer to this because it measures pressures on the building facades rather than an ambient static pressure. In summary, the method used to measure envelope pressure differences in the AHHRF tests is closer to the true pressure across the leaks, however it may be more sensitive to wind speed and direction fluctuations. Therefore it is not possible to determine if this increases or decreases the sensitivity to wind effects for the AHHRF tests compared with more typical tests.

Another wind pressure related complication in comparing the AHHRF tests to other tests is that the AHHRF study used a laminar flow element connected to outside via a flexible duct to measure the envelope air flows. It is likely that this reduced the sensitivity of the air flow

measurement to wind fluctuations compared to a typical blower door – but we do not know by how much.

In summary, the effect of wind on the pressure and flow measurements at AHHRF could be greater or less than a more typical blower door test. Without detailed side-by-side comparisons it is not possible to say if there are any significant differences. For the purposes of this study we assume that the wind sensitivities are similar enough between the procedures that we can make meaningful recommendations.

Offset pressures due to stack and wind effects with the fan not in operation were measured between each data point. A damper was closed over the fan opening for each offset reading because the fan opening can change the pressure distribution of the building significantly. Typically 20 pressure stations were recorded for each test that ranged from less than 1 Pa to 100 Pa and included both the ASTM and CGSB required pressure stations. The least squares analysis used to determine C, n, and ELA_4 was based on that in ASTM E779 that only uses test pressures greater than 10 Pa. Tests with pressure exponents less than 0.5 or greater than one were eliminated (following the instructions in ASTM E779, and as done in the field based on the data in the LBNL database).

Of the almost 7500 tests, 6007 were included in our final analysis. Tests were eliminated due to the above limits on pressure exponent, or lack of a low-wind speed test for a particular home configuration, and in some cases due observed errors in the recorded data. The houses were tested in a total of 97 configurations of open and closed flues, windows and passive vents, pressurization and depressurization, resulting in a wide range of total envelope air leakage, leakage distribution and air flow paths. 2902 tests were performed with no additions to the envelope leakage and a further 2365 with the furnace flue open. Typically there were 30 to 100 tests in each configuration. The best test in each configuration was determined by first looking for low wind speed tests to reduce the uncertainty in the test results from fluctuating wind pressures. For the low wind speed tests, Walker et al. (1998) estimated the uncertainty in the envelope pressure measurement to be 0.1 Pa. Low wind speed was defined as an average wind speed during the test below 1.5 m/s. A total of 301 tests met this low wind speed criterion. For each configuration, these low wind speed tests were analyzed to find the test with the least wind-induced variability (a combination of minimal least squares fitting error and visual observation of the data) in the measured pressures and flows. This test was then used as the reference for all the other tests in a given configuration. The C, n, Q_{50}, ELA_4 and NL from the low wind speed test were the reference for other tests for comparison. The analysis expresses all of the results relative to this reference.

Figure 3 shows an example of the results from a low wind speed reference test together with the results of a least squares fit of a power law to the data. In this case n=0.66 and the figure shows how this pressure exponent is valid over the almost two full orders of magnitude of pressure difference from 1 Pa to 100 Pa. Figure 4 shows a test from a very windy day with significant scatter caused by changing wind pressures – particularly below 10 Pa. Because of this, standards for envelope leakage testing limit low envelope pressure measurements to around 10 Pa. In this study we used the approach taken in

ASTM E779 and limited the lowest envelope pressures used in the analysis to 10 Pa – even for low wind speed tests such as that illustrated in Figure 3.

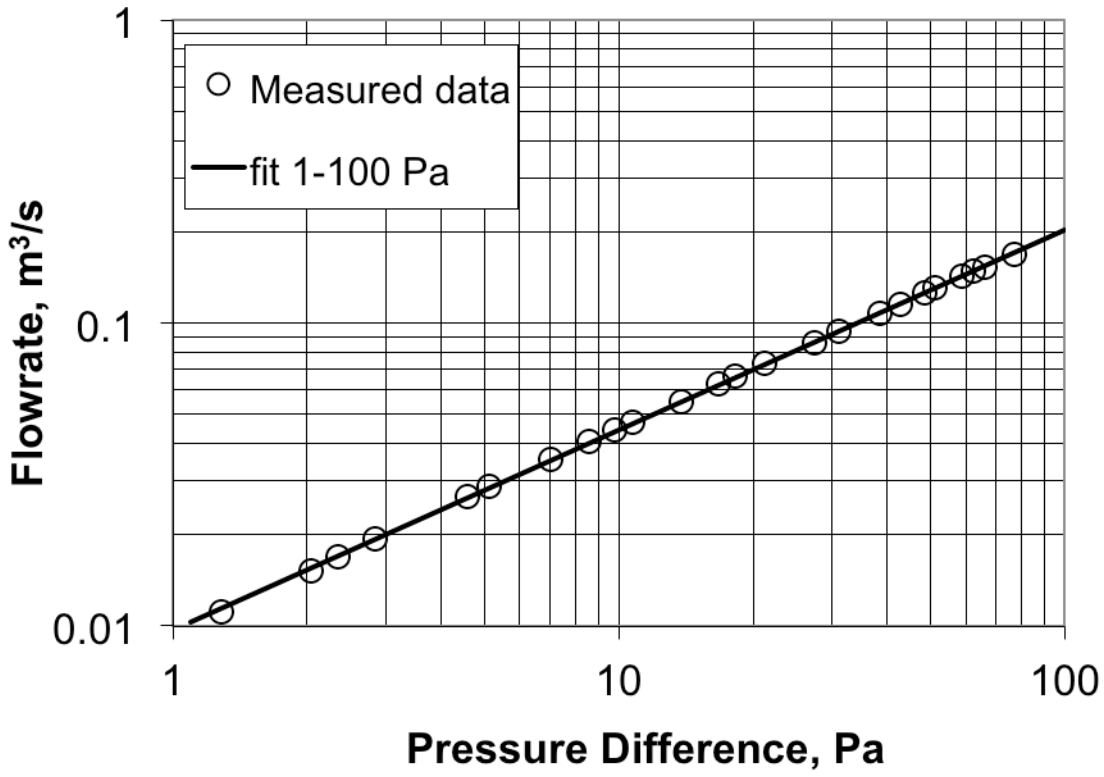

Figure 3. Example of a reference low wind speed test from the AHHRF

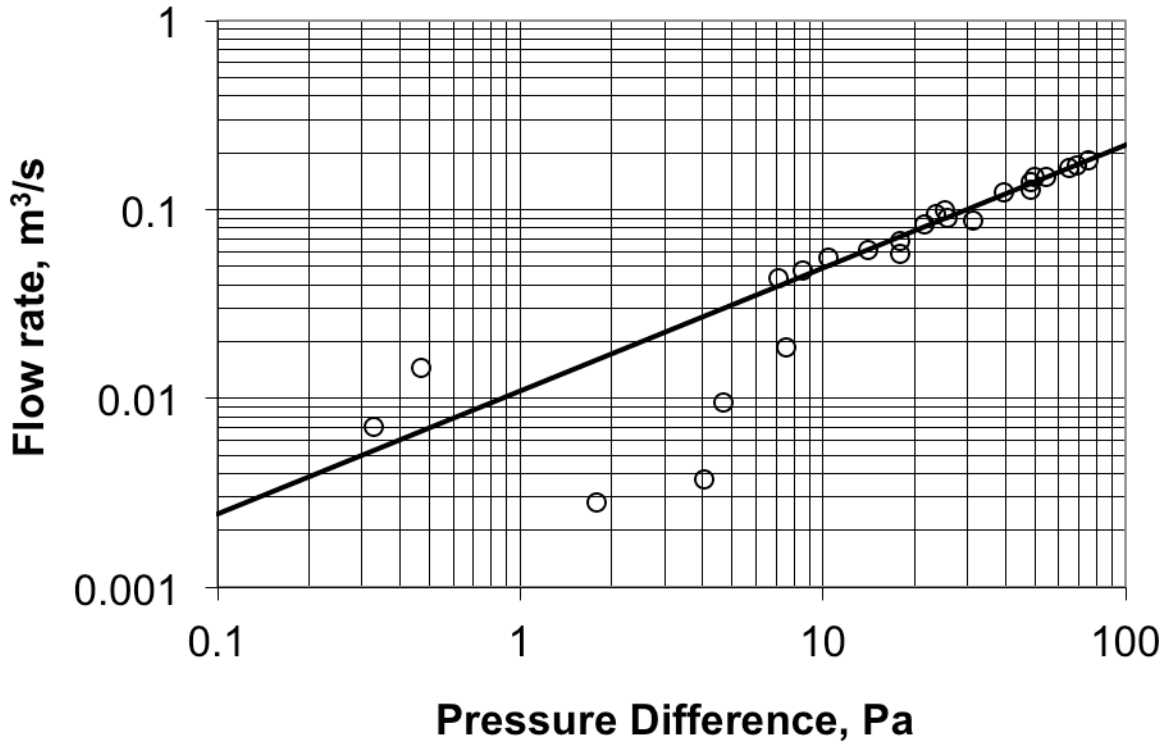

Figure 4. Example of a test where wind speed and direction fluctuations make for poor low pressure data (below 10 Pa) from the AHHRF

ANALYSIS AND DISCUSSION

In analyzing the data it is important to determine one's objectives. Generally speaking we wish to find the most representative estimate of the leakage so it can be used in energy or IAQ modeling. Normally this translates into finding the estimate of the leakage that has the lowest total error. Error can come from systematic equipment errors, random noise or biases in the measurement and analysis approach. We can combine these errors together to get the total error and select our approach based on the minimum total error.

In some home performance programs with third-party verification, it may be desirable maximize repeatability at the expense of increased total error. When using the more repeatable method in a calculation, it should be discounted by that additional error. For example – if a target envelope leakage needs to be met, a more repeatable test that has a larger error should be required to meet a lower target.

The largest uncertainty in using blower door data comes from the fact that the measurements are taken at a pressure range well above the pressures that the leaks normally see because of the difficulties of the confounding nature of the weather-induced natural pressures.

The higher the pressures at which blower door measurements are made, the less the weather-induced pressures matter. If our sole goal was making precise measurements, we would choose to make measurements only at the highest pressure differences practical. Unfortunately, the more precise the blower door measurements are, the larger the extrapolation error becomes making the most precise measurements, the least accurate ones.

If the all houses followed the same power-law (i.e. had the same, known flow exponent), the extrapolation error would be minimized and we would be best off by making high pressure blower door measurements. To examine the consistency of exponent, we look at all of the measured exponents in the Residential Diagnostics Database (about 7000 measurements), most of which are from the newly added data. These measurements include about ten homes where blower door tests were performed under various configurations, such as including or excluding basement and/or attic. The measurements also include the pre- and post-retrofit measurements from about 1800 homes.

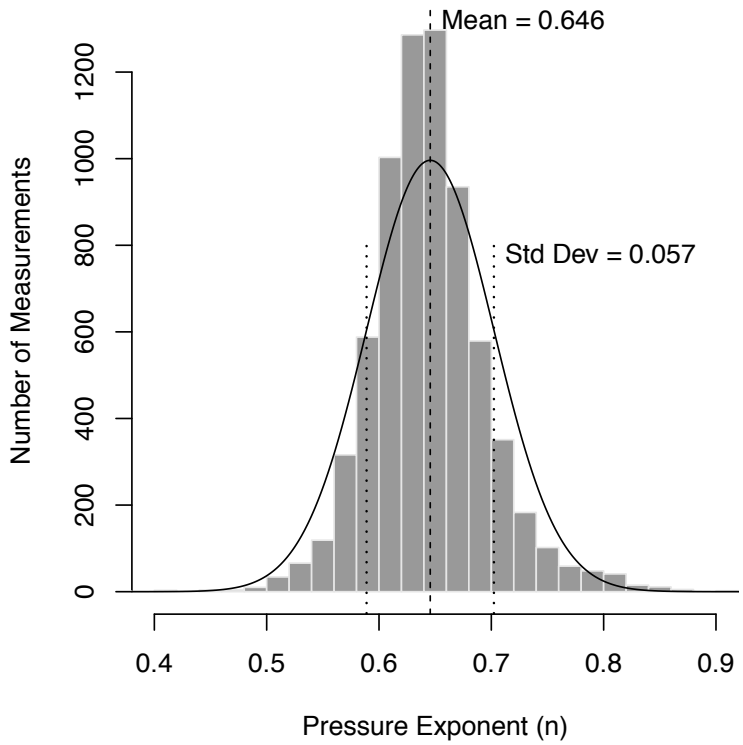

Figure 5: Distribution of pressure exponents of from Residential Diagnostic Database.

The distribution of pressure exponent from the LBNL Residential Diagnostics Database are shown in Figure 5. The mean of the distribution is near the results of previous studies and the commonly used rule-of-thumb: i.e., an exponent of 0.65. If one, a priori, decided

to select a given exponent (e.g., 0.65) to extrapolate from high pressures (e.g., 50 Pa) to the pressure range of interest (e.g., 4 Pa), there would be an extrapolation uncertainty even if the high pressure measurement were perfect. In this case, there would be a 29% error if the exponent were incorrect by 0.1. If one was interested in the flow at 1 Pa rather than 4 Pa (as some models use), the error becomes 48%.

These errors are sufficiently large that one could conclude that making single-point blower door measurements at high pressures is an unacceptable procedure for quantitative measurements. I.e., it might be a fine quality control mechanism and reproducible measurement for regulatory purposes, but the result is too uncertain to use. It could, however, be that the variation of the exponent seen in the leakage database is due not to a variation in the underlying exponent but rather noise in the measurement of that exponent. If this were the case, one could conceivably get a *better* result by measuring at high pressures and using a fixed exponent.

To investigate this issue we examine the AHHRF data where the pressure exponent is well known for the reference low wind speed tests. Figure 6 shows the distribution of pressure exponent for all 6007 tests. The mean of 0.649 is very close to the mean of the LBNL Residential Diagnostics Database of 0.646. The standard deviation (SD) is slightly larger at 0.073 compared to 0.057. In both datasets the variability represented by the standard deviation includes both noise due to measurement uncertainty and differences between leakage configurations from home to home. To estimate the fraction of this variability due to different home leakage configurations, we can examine the low wind speed tests only. The 301 low wind speed tests do not have variability due to wind and only have variability due to changes in envelope leakage configurations. Figure 7 shows the distribution of exponents for low wind speed tests only. The mean of 0.631 is slightly lower than for all tests. This indicates that increased wind fluctuations could result in higher pressure exponents. Many observations of individual tests from this data set confirms this hypothesis. This increase in exponent is expected, given the non-linear relationship between pressure and air flow. Analytical details of this non-linearity induced exponent bias will be discussed in future work.

The standard deviation of the pressure exponent for the low wind speed tests (SD_L) is reduced to 0.063. The standard deviation for the low wind speed tests is almost entirely due to the true variability in pressure exponent between different house configurations. If we assume that wind speed fluctuations and different leakage configurations are independent and are the only two parameters contributing to the standard deviation, then Equation 2 can be used to estimate the standard deviation due to wind speed fluctuations (SD_W).

$$SD_W = \sqrt{SD^2 - SD_L^2} \quad \textbf{(2)}$$

Substituting the above values for SD and SD_L, then SD_W is 0.037 – or about one half of that due to true leakage variation. This result also shows that the majority of the standard deviation for all the tests is explained by the difference in actual exponents – rather than

wind-induced errors. I.e., the wind-induced pressure exponent uncertainty is smaller than the true variability from home to home in the pressure exponent. Another observation from Figures 6 and 7 is the departures from the normal distribution – in particular a peak at a lower exponent than the mean value. This is due to tests with open flues and windows that tend to have a pressure exponent closer to 0.5. The observation of this data artifact in all the tests, not just low wind speed, is another indicator that the variability in the test results is due to actual variability in the pressure exponent.

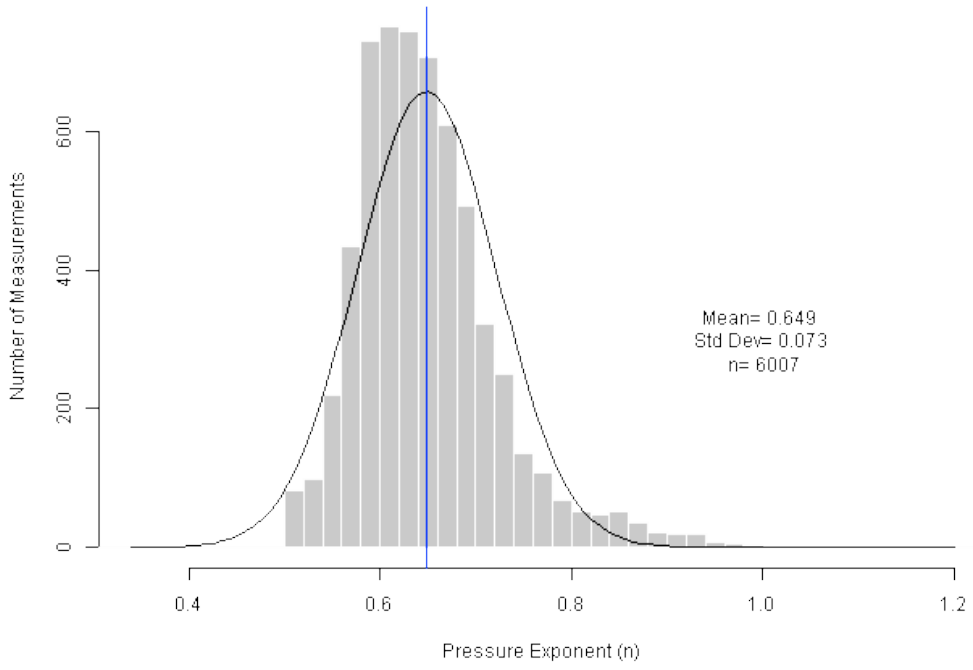

Figure 6. Distribution of exponents from AHHRF for all tests

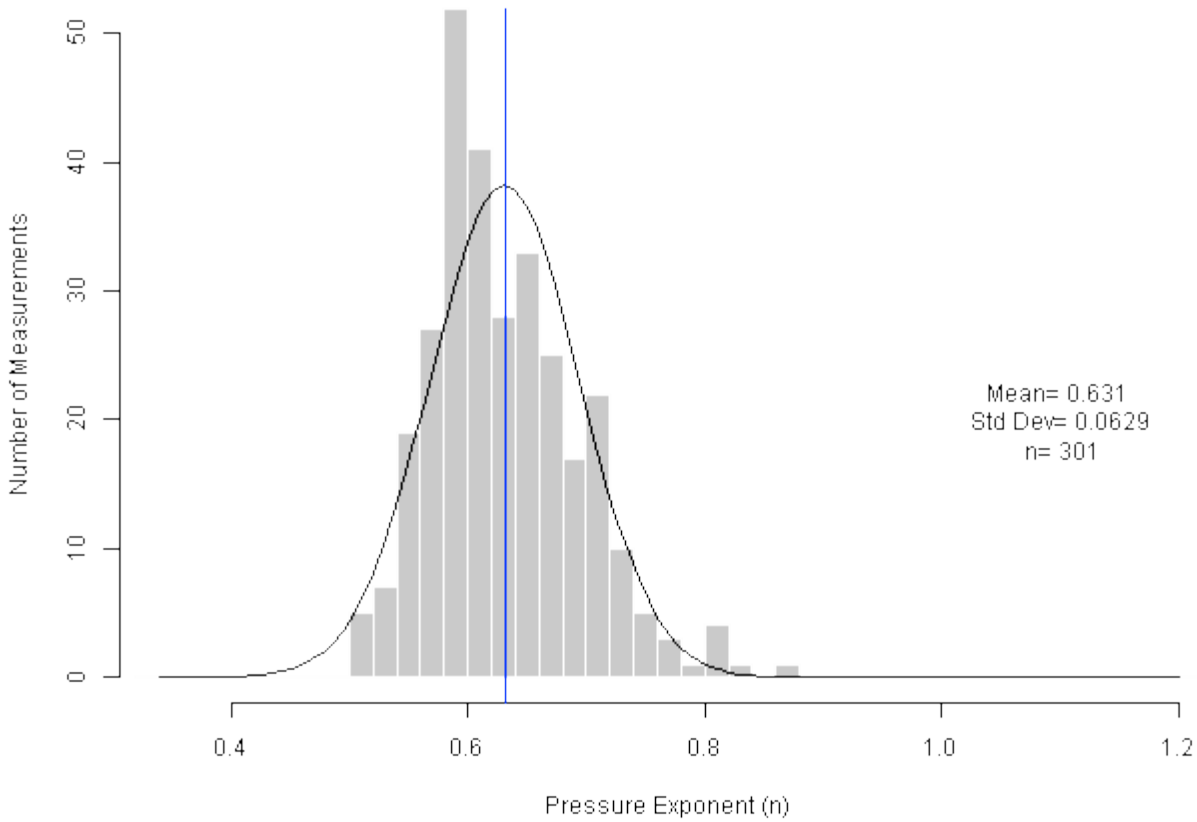

Figure 7. Distribution of exponents from AHHRF for low wind speed tests only

If the variation in exponent is due to changes in building leakage configuration then we would expect to see different exponents for different configurations. In particular, the AHHRF dataset had homes tested with and without open flues typical of natural draft gas appliances or fireplaces. There was a total of 14 pairs of tests that only differed by flue configuration. The exponents from the low wind speed tests within each configuration were averaged. The open flue cases had pressure exponents that averaged 0.075 lower than the closed flue cases. This is expected because the flues have a pressure exponent of 0.5 that is lower than the 0.65 average for all leakage configurations, thus the inclusion of a flue should lower the pressure exponent.

We also examined the 21 cases where a house was tested in the same configuration for pressurization and depressurization. As for the open/closed flue analysis, all low wind speed tests in each configuration were averaged. The depressurization tests had pressure exponents higher by 0.074 than pressurization tests. The difference between pressurization and depressurization likely is caused by valving action in some of the leak sites.

Both the open/closed flue and pressurization/depressurization comparisons show that the variability in pressure exponent due to changes in building leakage configuration is significant which implies that assuming a fixed pressure exponent can introduce significant errors. In these two cases the errors in applying a fixed pressure exponent are about 0.075. The extrapolation error from 50 Pa down to 4 Pa (for 4 Pa leakage area calculations) can be estimated by adding or subtracting 0.075 from the fixed pressure exponent of 0.65 and extrapolating with these higher and lower pressure exponents. The results of the extrapolations can then be used to estimate the error due to using the fixed exponent. To determine the extrapolation error in determining ELA_4, we use the definition of ELA_4 in Equation 3:

$$ELA_4 = \frac{Q_4}{C_D}\sqrt{\frac{\rho}{2\Delta P}} \quad \textbf{(3)}$$

Where Q_4 (m^3/s) is the envelope air flow at 4 Pa, C_D is a fixed discharge coefficient, ΔP is the reference pressure of 4 Pa, and ρ is air density (kg/m^3). The error in calculating ELA_4 then depends linearly on the error in calculating Q_4, so the fractional error in ELA_4 is the same as the fractional error in Q_4. Q_4 is given by:

$$Q_4 = C(4)^n \quad \textbf{(4)}$$

Q_{50} is given by:

$$Q_{50} = C(50)^n \quad \textbf{(5)}$$

When using the air flow at 50 Pa (Q_{50}) and a fixed pressure exponent, then we need to convert Q_{50} to Q_4 by combining Equations 4 and 5:

$$Q_4 = Q_{50}\left(\frac{4}{50}\right)^n \quad \textbf{(6)}$$

Equation 6 was used to first calculate Q_4 with an exponent of 0.65. The Q4 was recalculated by adding or subtracting 0.075 from the fixed pressure exponent of 0.65, i.e., using exponents of 0.725 and 0.575. The resulting extrapolation errors in estimating ELA_4 for using the higher and lower exponents based on exponent variability due to using pressurization or depressurization or due to changes in flue/fireplace opening were 17% to 21%. We obtain two estimates for the error due to the non-linear nature of this calculation resulting in the errors being asymmetric.

To look more generally at the effects of envelope leakage characteristics changing the exponent, we can use the same approach, but adding and subtracting the standard deviation in exponent for the low wind speed tests (shown in Figure 7) of 0.063. The

resulting the extrapolation errors for fixing the exponent are 15% and 17%. Combining these two results indicate that the error in fixing the exponent at 0.65 and ignoring actual changes in exponent are 15% to 21%, with a typical value of 18%.

Similarly, we can use the estimate of wind-induced exponent variability of 0.037 to estimate extrapolation errors for getting the wrong pressure exponent due to wind pressure fluctuations. The resulting errors are 9% and 10%. These results imply that fixing the exponent roughly doubles the expected uncertainty in estimating ELA_4 and that if aiming for a target leakage the fixed exponent tests should account for this by meeting a specification about 10% better than if a multi-point test is used to determine the exponent.

In addition to looking at extrapolation errors from variability in exponents, there may also be a difference in the physical size of the holes in the envelope (ELA_4) between pressurization and depressurization due to valving action. To examine this issue we used the low wind speed ELA_4 results calculated separately for pressurization and depressurization for the same 21 configurations used above for the exponent extrapolation calculations. On average, the pressurization ELA_4 was 3% higher than depressurization. This average difference is small compared to the 24% RMS difference between the pressurization and depressurization ELA_4.

Differences in between pressurization and depressurization can also be caused by biases or asymmetries in the measurement protocol itself. For example, if there is a bias in measuring the no-flow indoor-outdoor pressure difference it will impact pressurization and depressurization differently. If there is no actual difference between pressurization and depressurization leakages, each would represent an independent estimate of the true leakage and averaging them together would therefore reduce the uncertainty.

In general, the average ELA of pressurization and depressurization will be the quantity of interest since in normal operation the envelope will have areas of both pressurization and depressurization. Because the mean difference is small compared to the RMS difference a reasonable estimate of the uncertainty due to performing only pressurization or depressurization rather than averaging both together is half of the RMS difference, or 12%.

Wind-Induced Errors

Just because there is real variation in the exponent, however, does not mean there are not large uncertainties induced by the wind in ELA_4. To explore this aspect we use the low-wind measurements in the Alberta homes as our truth standard to determine the correct ELA_4 and see how the result changes when the identical configuration is tested at higher wind speeds. Two methods were used to calculate ELA_4 for comparison to the correct value from low wind speed tests: Using fitted C and n and using Q_{50} and n fixed at 0.65. Figure 8 shows the fractional Root Mean Square (RMS) errors in estimated ELA_4 for the fitted C and n and Q_{50} and n fixed at 0.65 binned every 1 m/s of wind speed (measured on site on a 10 m high weather tower). The fixed pressure exponent errors do not change much with wind speed but the fitted exponent results show lower errors at low

wind speed and increasing error with wind speed. The fitted n results give lower RMS errors up to about 6 m/s, after which the fixed exponent gives less variability. This implies that an optimum would be to use fitted C and n for wind speeds below 6 m/s and a fixed exponent at higher wind speeds.

Figure 9 shows the average fractional errors binned by wind speed for the two approaches to calculating ELA_4. Similar to the RMS errors, the fitted C and n results are better at low wind speed and worse at high wind speed (≥6 m/s) compared to the fixed pressure exponent results. The increasing bias error with wind speed is expected due to the non-linear relationship between pressure and flow – the details of this characteristic will be discussed in future papers.

Figure 10 shows the distribution of the number of tests in each bin. This distribution follows the classic Weibull distribution of atmospheric wind speeds. Only 7% of the tests were above 6 m/s so if we had to choose one method we would choose the fitted C and n as they give lower errors for the majority of tests. If we want to estimate uncertainty for a typical test we can look at the uncertainties for the wind speeds that are most common: 2-4 m/s. In this range the wind-induced RMS errors for fitted C and n are about 10%, and for fixed exponent, about 17%. If we want to use a 6 m/s changeover from fitted C and n to fixed exponent, then below 6 m/s the fitted C and n error is about 10% and fixed exponent about 18%. Above 6 m/s the fitted C and n error is in the 25-30% range, while the fixed exponent stays the same at about 18%.

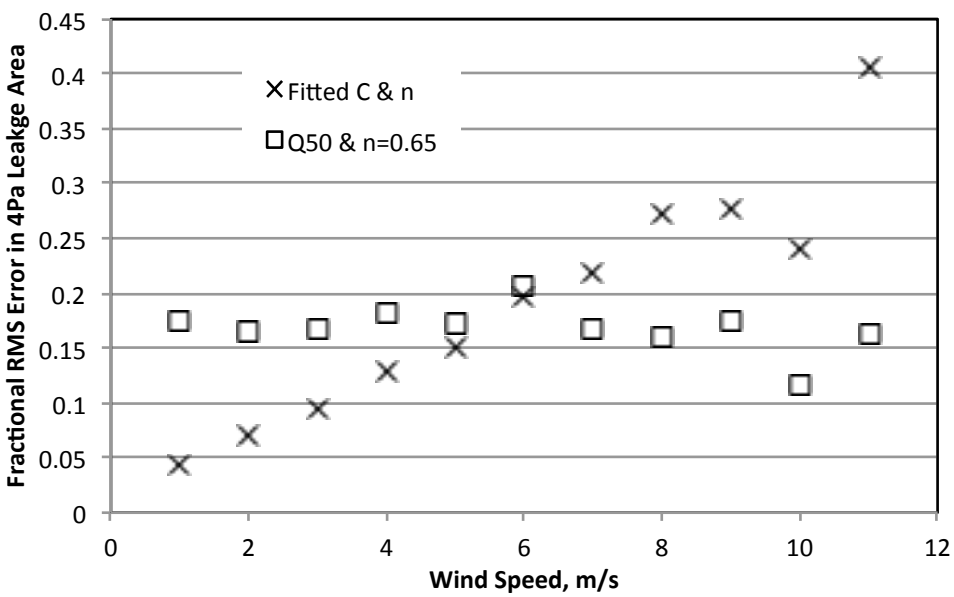

Figure 8. The fractional Root Mean Square (RMS) errors in 4Pa Leakage Area (ELA_4) binned every 1 m/s of wind speed.

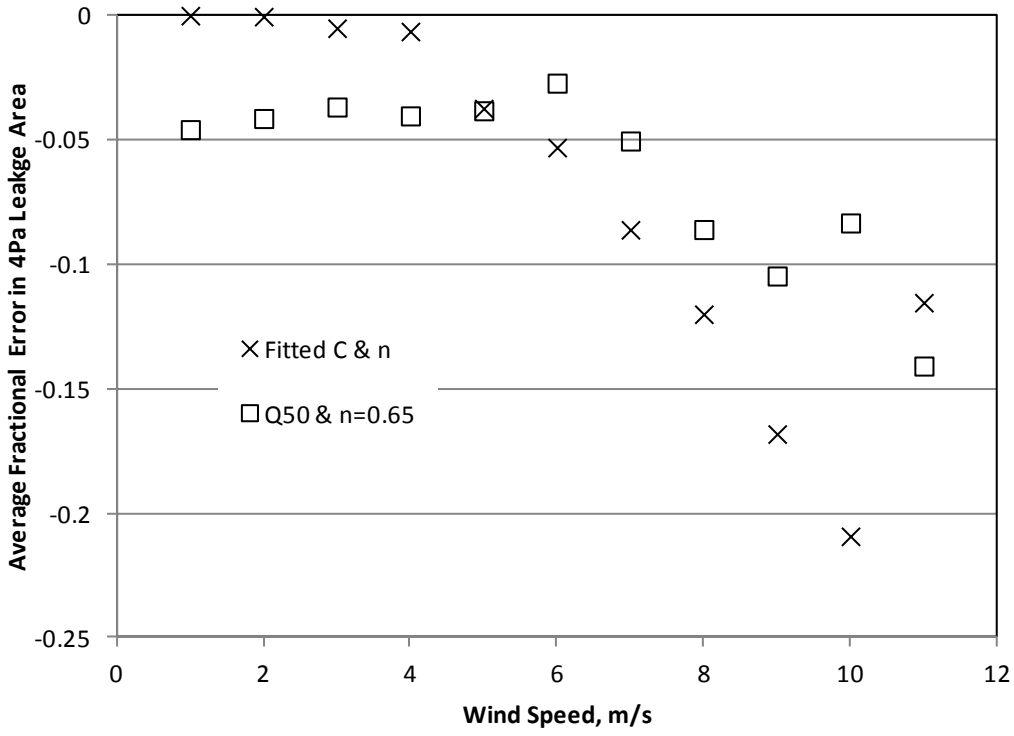

Figure 9. Average Fractional Error in 4 Pa Leakage Area binned every 1 m/s of wind speed

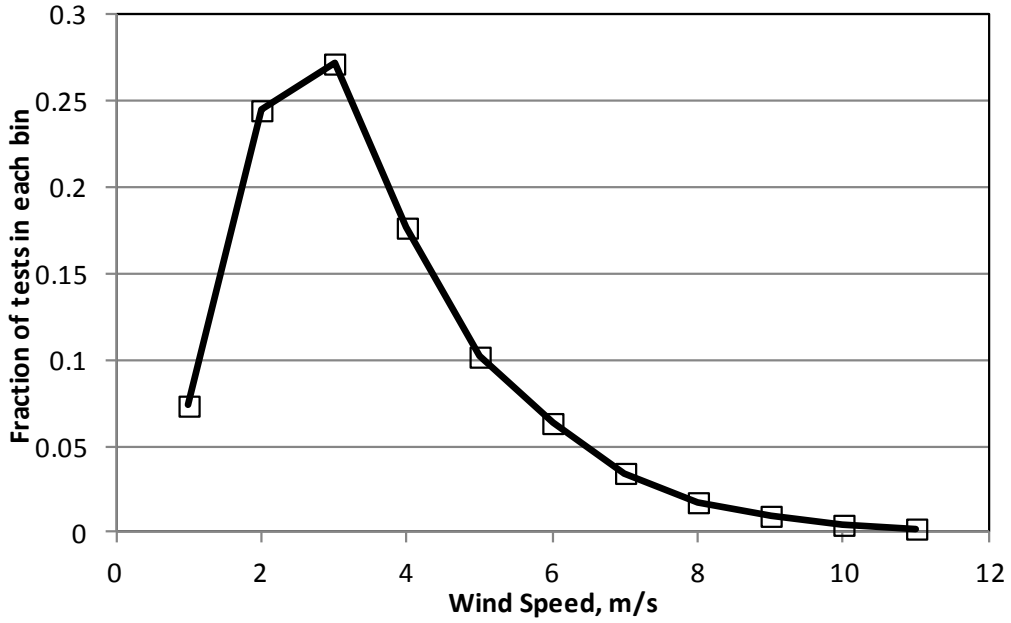

Figure 10. Fraction of tests in each wind speed bin.

CONCLUSIONS

One of the key issues of this report is determining whether measuring the leakage based on a multipoint test is superior to a single-point test. This debate centers on whether the relative increase in (wind) noise caused by measuring at lower pressures significantly improves the exponent (and hence the extrapolation).

Careful analysis of the data allows us to conclude that a small part of the variations seen in exponents is likely due to wind noise, and that the variation in the exponent is dominated by actual variations in the hydrodynamics of the leaks. Knowing that the measured variations in exponents are predominantly "real" allows us to estimate the total error and the error components of different measurement approaches. Although our data supports the conventional wisdom that the flow exponent is approximately 0.65 on average over a large population of homes, using such a fixed number to extrapolate from precise high pressure measurements to the pressure range of interest will result in substantial uncertainty since the actual exponent truly varies.

With respect to an individual building, this error is repeatable and robust in that additional measurements cannot reduce it—i.e., it is a bias error. When using such a measurement, then, one should discount the value appropriately as is discussed below.

Similarly, there is a bias associated with not measuring both pressurization and depressurization. Because of valving of leaks, there can be a physical difference between pressurization and depressurization. Because of asymmetries in some measurement procedures, there can be a systemic difference between pressurization and depressurization. Averaging the pressurization and depressurization test results reduces both these biases.

In summary, multipoint testing is typically 10 percentage points better at estimating ELA_4 than single point testing – primarily due to extrapolation errors introduced by using fixed exponents and has bigger advantages at lower wind speeds (<3 m/s). However, for wind speeds above about 6 m/s the single point testing is recommended due to its reduced sensitivity to wind pressure fluctuations.

Recommendations for Testing

Generally a measurement of air tightness is used to meet some requirement and is intended to be used in an energy or ventilation calculation. Different measurement approaches will result in different total errors. These errors need to be accounted for by reducing whatever "credit" the air leakage is intended to get. In the recommendations below, we list the amount of reduction needed for different situations. For example. if the air leakage is being used in ASHRAE Standard 62.2 towards an infiltration credit, it should be reduced by whatever reduction is listed (e.g., 10%). If on the other hand, it is meeting an air tightness target for energy purposes it should be increased by the same margin.

- *Use of Multi-point Methods*: The results of this study indicate the following:

    - 90% of the time multipoint methods have lower errors in estimating ELA4 than fixed exponent single point testing.
    - Below 6 m/s reduce any credit by 10%
    - Above 6 m/s reduce any credit by 25-30%
    - If wind speed is not measured, reduce credit by 10% (because high wind speeds are rare, the overall result is dominated by the <6 m/s results).
- *Use of Single-Point Methods*: Such tests may be desirable when repeatability is very important, but the large potential inaccuracies mean that any "credit" needs to be reduced by about 18% (or 10% relative to multipoint testing).
- *Measure both Pressurization and Depressurization*: In most homes leaks will be subjected to both positive and negative pressures over the course of the year. It is best to get an average. Both pressurization and depressurization tests should be done and the average value used. If this is not done any credit needs to be reduced by 12%. Note that this uncertainty is independent of the uncertainty in 1. and 2., above and needs to be added to those errors. For example, the credit for single point depressurization test needs to have credit reduced by 22% compared to a combined pressurization and depressurization multipoint test.

One example is the envelope leakage limits in building codes and standards. The 2012 International Energy Conservation Code (ICC 2011) requires envelope leakage to be less than 3 ACH50 (Air Changes per Hour at 50 Pa). If this is measured with a single point depressurization only test (the most common approach in the US) then the requirement becomes 22% less than this, or 2.34 ACH50.

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