ERNEST ORLANDO LAWRENCE
BERKELEY NATIONAL LABORATORY

Evaluation of the Repeatability of the Delta Q Duct Leakage Testing Technique Including Investigation of Robust Analysis Techniques and Estimates of Weather Induced Uncertainty

Darryl Dickerhoff and Iain Walker

Environmental Energy Technologies Division

August 2008

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of the Building Technologies Program, U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

INTRODUCTION

The DeltaQ test is a method of estimating the air leakage from forced air duct systems. Developed primarily for residential and small commercial applications it uses the changes in blower door test results due to forced air system operation. Previous studies established the principles behind DeltaQ testing, but raised issues of precision of the test, particularly for leaky homes on windy days.

Details of the measurement technique are available in an ASTM Standard (ASTM E1554-2007). In order to ease adoption of the test method, this study answers questions regarding the uncertainty due to changing weather during the test (particularly changes in wind speed) and the applicability to low leakage systems. The first question arises because the building envelope air flows and pressures used in the DeltaQ test are influenced by weather induced pressures. Variability in wind induced pressures rather than temperature difference induced pressures dominates this effect because the wind pressures change rapidly over the time period of a test. The second question needs to answered so that DeltaQ testing can be used in programs requiring or giving credit for tight ducts (e.g., California's Building Energy Code (CEC 2005)).

DeltaQ modeling biases have been previously investigated in laboratory studies where there was no weather induced changes in envelope flows and pressures. Laboratory work by Andrews (2002) and Walker et al. (2004) found biases of about 0.5% of forced air system blower flow and individual test uncertainty of about 2% of forced air system blower flow. The laboratory tests were repeated by Walker and Dickerhoff (2006 and 2008) using a new ramping technique that continuously varied envelope pressures and air flows rather than taking data at pre-selected pressure stations (as used in ASTM E1554-2003 and other previous studies). The biases and individual test uncertainties for ramping were found to be very close (less than 0.5% of air handler flow) to those found in for the pressure station approach.

Walker and Dickerhoff also included estimates of DeltaQ test repeatability based on the results of field tests where two houses were tested multiple times. The two houses were quite leaky (20-25 Air Changes per Hour at 50Pa (0.2 in. water) (ACH50)) and were located in the San Francisco Bay area. One house was tested on a calm day and the other on a very windy day. Results were also presented for two additional houses that were tested by other researchers[1] in Minneapolis, MN and Madison, WI, that had very tight envelopes (1.8 and 2.5 ACH50). These tight houses had internal duct systems and were tested without operating the central blower - sometimes referred to as control tests. The standard deviations between the multiple tests for all four houses were found to be about 1% of the envelope air flow[2] at 50 Pa (0.2 in. water) (Q50) that led to the suggestion of this as a rule of thumb for estimating DeltaQ uncertainty. Because DeltaQ is based on measuring envelope air flows it makes sense for uncertainty to scale with envelope leakage. However, these tests were on a limited data set and one of the objectives of the current study is to increase the number of tested houses.

This study focuses on answering two questions:
1. What is the uncertainty associated with changes in weather (primarily wind) conditions during DeltaQ testing?
2. How can these uncertainties be reduced ?

The first question is addressing issues of repeatability. To study this five houses were tested as many times as possible over a day. Weather data was recorded on-site - including the local windspeed. The result from these five houses were combined with the two Bay Area homes from the previous studies. The variability of the tests (represented by the standard deviation) is the repeatability of the test method for that house under the prevailing weather conditions. Because the testing was performed over a day a wide range of wind speeds was achieved following typical diurnal variations of low wind in the early morning and greatest winds in the late afternoon/early evening. Typically about ten tests were performed in each house.

[1] The Energy Conservatory, Minneapolis.
[2] 35 to 50 cfm (17 to 25 L/s) for the leaky houses and about 5 cfm (2.5 L/s) for the tight houses

To answer the second question, different data analysis techniques were investigated that looked at averaging techniques, elimination of outliers, limiting leak pressures, etc. in order to minimize the influence of changing wind conditions during the test. The objective was to find a reasonable compromise between test precision and robustness - because many of the changes to the analysis to make the test more robust limit its ability to examine wide ranges of pressures and leakage flows.

A secondary goal of this study is to show that DeltaQ uncertainties are acceptable for testing low leakage systems. Therefore houses with low duct leakage were deliberately chosen to be tested. This is important for utility and weatherization programs that give credits for tight ducts and for codes and standards that may refer to DeltaQ testing. In particular the following organizations/standards bodies are thinking about adopting DeltaQ testing, but before doing so they want to see DeltaQ applied to the low leakage situations they wish to address: California's Building Energy Code (CEC 2005), ASHRAE Standard 62.2 (ASHRAE 2007), RESNET (Residential Energy Services Network) and the US EPA EnergyStar homes Program. This issue is always going to somewhat subjective, but a key criterion will be having repeatability uncertainty below the low-leakage limits being proposed. These low leakage limits are typically 6% of air handler flow, or a range of about 60 cfm to 120 cfm (30 to 60 L/s) depending on system size.

DELTAQ RAMPING

DeltaQ Test outline

Just like an envelope leakage test, the DeltaQ test measures the pressure difference across the building envelope while simultaneously measuring the airflow through the blower used to change the envelope pressure difference. The DeltaQ test uses the fact that changing the pressure difference across the house envelope also changes the pressure difference across duct leaks and therefore changes the duct leakage flows. The magnitudes (and for some leaks, the direction) of airflow through the duct leaks are different when the forced air system blower is on or off. The ramping technique gradually increases the envelope pressure difference from zero to about 50 Pa and back down to zero over a period of about 90 seconds.
This ramping procedure was applied to the four parts of the DeltaQ test:

1. House *depressurized* with forced air system blower *OFF*
2. House *depressurized* with forced air system blower *ON*
3. House *pressurized* with forced air system blower *ON*
4. House *pressurized* with forced air system blower *OFF*

Because the orifice plates used in most blower doors can only be used over a limited range of air flows and resulting envelope pressure differences, it was found that two orifice plates need to be used. The ramping procedure needs to be applied for each orifice. Therefore, in each of the four parts there are actually two ramps: one for each orifice plate. Figure 1 shows the envelope pressures from an example DeltaQ ramping test. In addition to the envelope pressures during the test, Figure 1 also shows the baseline pressure measurements that are made at the beginning and end of each test. These baseline pressure differences serve two purposes: the first is that they are averaged and subtracted from the other envelope pressures to remove the effect of stack and wind pressures from the envelope pressures because the pressures used in the analyses must be only those induced by blower door operation. The second is to serve as a guide to determining if a test has too much wind speed variability resulting in excessive measurement errors. This will be discussed in more detail later. The baseline pressures were averaged for 30 seconds before and 30 seconds after the ramping.

Figure 2 illustrates the pressure-flow data pairs corresponding to the envelope pressures in Figure 1 after baseline subtraction[3]. A slight difference between the data taken with the two orifice plates due to inaccuracies in their calibrations (The manufacturer's accuracy specification is ±3% of flow.) illustrating the necessity of pairing central fan ON/OFF data only for a given blower door orifice, i.e., not using central blower ON data from one orifice with central blower OFF data from another orifice.

[3] In most cases the baseline pressures are small and the influence on the leakage flows is negligible. In very windy cases the baseline pressure changes can lead to changes in estimated duct leakage air flows up to 30 cfm (15 L/s) by adopting the correct baseline pressure subtraction.

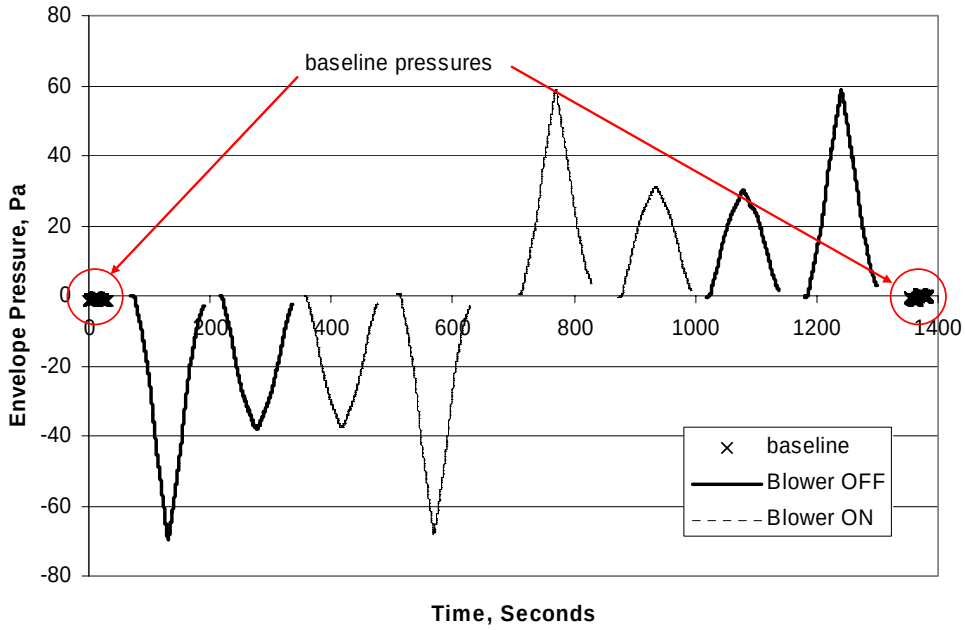


Figure 1. Envelope pressures during a DeltaQ test

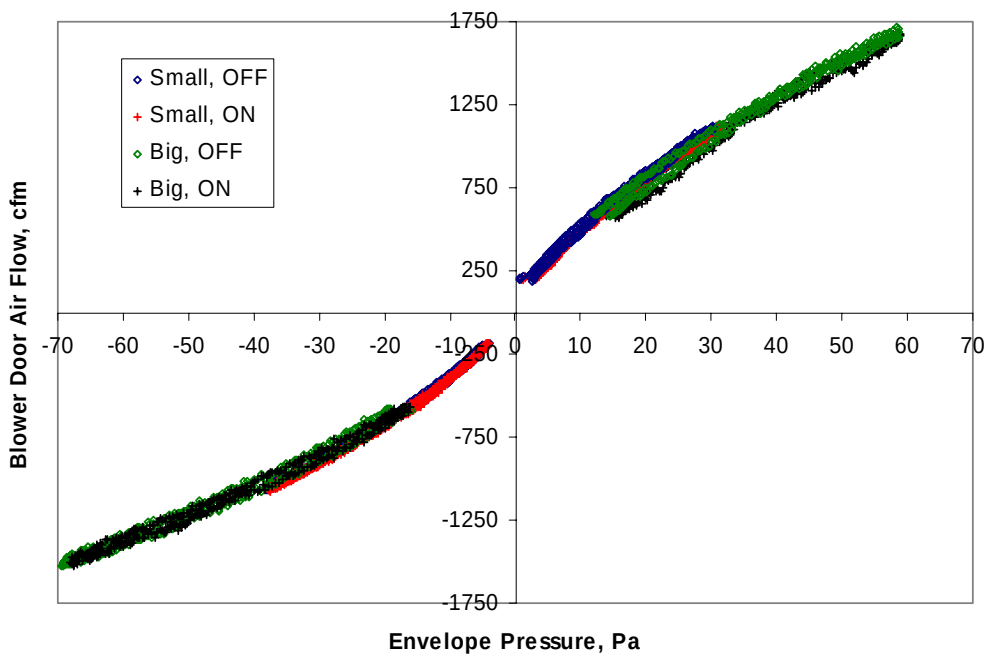


Figure 2. Envelope pressures and Blower Door air flows from a DeltaQ test

The data in this study were taken using an automated blower door[4]. The blower door was controlled by software from a computer that simultaneously measured the blower door air flow and envelope pressure difference while controlling the blower door fan motor. Provision was made in the software to repeat any section of the test (i.e., any of the eight ramps in Figure 1) if deemed necessary. Circumstances typically requiring retesting of a particular section are: if a pressure tube is stepped on during the test, forgetting to change the blower door reference to be outside for pressurization, having the incorrect blower orifice installed, and, probably most important, a gust of wind that leads to erroneous data. In this study, retests were made only for physical problems like stepping on the pressure tubing or improper pressure sensor connections. Retesting was not done for wind related difficulties.

DeltaQ data analysis

The DeltaQ analysis requires the calculation of the change in blower door flow at a particular envelope pressure. Previous studies (and the previous ASTM E1554 -2003 test method) acquired data at fixed envelope pressure stations that made the calculation of this difference fairly straight forward. For ramping data we do not have the convenience of data at fixed pressure stations that are suitable for the difference calculation. Instead, the ramping data needs to be binned over fixed envelope pressure ranges. The size of the bins is a compromise between small bins that result in a higher resolution description of the DeltaQ function but are more susceptible to noise and larger bins that offer less resolution of the DeltaQ function but are more robust and are better at averaging out the effects of noisy signals. Before the data were binned, the average of the baseline pressures was subtracted from all the envelope pressures. Only matched pairs of forced air system blower on and off data were used. If either the ON or OFF bin at a given envelope pressure difference had insufficient data then the data were not used in the fitting or the DeltaQ function. Each bin must have at least three pressure/flow pairs above and below the center of the bin to have sufficient data for the bin to be included in the analysis.

The blower door air flow difference between the central blow on and central blower off data (the "DeltaQ") was calculated at each bin center. The data bins only had data from a single orifice because of slight changes in calibration between blower door orifices. The DeltaQ values were only calculated between ON and OFF bins that had data from the same orifice. Because the air flow and envelope pressure ranges of the orifices overlap, this sometimes results in more than one DeltaQ data point at a given envelope pressure. In the example in Figure 1 this means that the DeltaQ air flow differences are calculated between ramps 1 and 4 for large orifice depressurization, between ramps 2 and 3 for small orifice depressurization, between ramps 5 and 8 for large orifice pressurization and finally between ramps 6 and 7 for small orifice pressurization.

The DeltaQ function was derived previously (Dickerhoff et al. 2004, Walker et al. 2004, and Walker et al. 2002), and is shown in Equation 1.

$$\Delta Q(\Delta P) = Q_s\left[\left(\frac{\Delta P + \Delta P_s}{\Delta P_s}\right)^{n_s} - \left(\frac{\Delta P}{\Delta P_s}\right)^{n_s}\right] + Q_r\left[\left(\frac{\Delta P - \Delta P_r}{\Delta P_r}\right)^{n_r} - \left(\frac{\Delta P}{\Delta P_r}\right)^{n_r}\right] \quad \textbf{(1)}$$

ΔQ is the difference between blower door airflows with the system blower on and off at an envelope pressure difference of ΔP. ΔQ and ΔP are the measured data. Q_s is the supply leakage flow, Q_r is the return leakage flow, ΔP_s is the characteristic pressure difference for supply leaks, and ΔP_r is the characteristic pressure difference for return leaks. n_s and n_r are the leak pressure exponents. For numerical stability, n_s and n_r are set to the mean value of those found in previous field measurements: i.e., a value of 0.6.

The fitting of the DeltaQ function to the measured data follows the general outline used in the latest ASTM E1554 (2007) standard and described in more detail in Walker and Dickerhoff (2008). The details of the analysis have significant impacts on the sensitivity of the test to wind pressure fluctuations. Details examined in this study were broken down into two components. The first component includes efforts to eliminate poor data from the analysis or change the analysis technique to make it less sensitive to wind pressure fluctuations. This includes: the size of bin used to average data to create DeltaQ pressure and flow data pairs, the minimum acceptable number of points in each bin, the minimum acceptable envelope pressure, minimum values to restrict the characteristic pressures, and time averaging/filtering. The second component is to find indicators that can flag poor data to alert person doing the

[4] A blower door is a combination of air moving fan and air flow meter used to pressurize or depressurize houses under test.

test of potential problems. This includes: differences between the up and down portion of ramps, mean wind speed, and fluctuations in the baseline pressures. This flagging of poor data is a key feature of DeltaQ testing where if one or more ramp is identified as having poor data only that ramp needs to be retaken rather than redoing the whole test. This ability was built-in to the automated software.

Pressure and Flow Fitting

The flow at the center of each pressure bin was calculated from a linear fit of the measured blower door data , i.e. for a bin 2.5 Pa (0.01 in. water) wide centered on 12.5 Pa (0.05 in. water) the data must be between 11.25 and 13.75 Pa (0.045 and 0.055 in. water). The difference between air flows at the bin center was then used in the DeltaQ analysis.

Correcting for Leakage Flow Imbalance

The correction factors for leakage flow imbalance developed by Walker et al. (2004) and Dickerhoff et al. (2004) were used to account for changes in building envelope pressure difference due to supply-return leakage imbalances. The correction is accounted for by calculating the pressure offset, *P*, using Equation 2:

$$P = \left[\frac{Q_r - Q_s}{C_{env}} \right)^{1/n_{env}} \quad \textbf{(2)}$$

where the subscript "env" refers to the building envelope. C_{env} and n_{env} are determined from a least squares fit to the system blower off envelope flows and pressures using Equation 3 (for example, using the calculation procedures given in ASTM E779-03).

$$Q_{off} = C_{env} \left(P_{off} \right)^{n_{env}} \quad \textbf{(3)}$$

The corrected air flows are given by Equations 4 and 5:

$$Q_s^{actual} = Q_s \left[1 + \frac{P}{P_s} \right)^{n_s} \quad \textbf{(4)}$$

$$Q_r^{actual} = Q_r \left[1 - \frac{P}{P_r} \right)^{n_r} \quad \textbf{(5)}$$

The notation system of leading square brackets, "[", and trailing rounded brackets ")" is used because the terms inside the brackets could be negative numbers raised to non-integer powers. In which case, the sign of the term should be preserved and the absolute value of the term in the brackets is raised to the non-integer power. This is shown algebraically in Equation 6.

$$[x)^n = x(|x|)^{(n-1)} \quad \textbf{(6)}$$

The new values for Q_s and Q_r were used in Equation 2 to re-estimate a new pressure offset. This iterative technique was used until changes in the leakage flows were small. For most situations the pressure offset is small compared to the leak pressures, and this correction is minor and only takes one or two iterations. Occasionally, there were numerical instabilities with the correction factors that resulted in oscillations between two solutions with very slow convergence. It was found that using a relaxation factor of 0.5 when applying the correction factors resulted in much more stable results.

Other correction factors due to airflow resistance of the duct system (Walker et al. (2004) and Dickerhoff et al. (2004)) were not used in this study because the generally small air leakage flows resulting in insignificant corrections (less than 1 cfm).

Two approaches were used to fit the DeltaQ function in Equation 1 to the measured data to determine the unknowns (Q_s, Q_r, ΔP_s, and ΔP_r). The first is pressure scanning and the second is Non-Negative Least Squares (NNLS)[5].

[5] This technique was developed by Collin Olson of The Energy Conservatory.

Pressure Scanning

Pressure Scanning applied the DeltaQ equation at fixed supply and return pressure combinations. Combinations of supply and return pressures every 5 Pascals (0.02 in. water) between 5 and 100 Pascals (0.02 and 0.4 in. water) were used to make a coarse determination of the characteristic supply and return pressures. Thus 400 combinations of P_s and P_r were applied in Equation 1, and for each pair of P_s and P_r , Q_s and Q_r were estimated by least squares linear regression together with the residual least squares error. For each supply and return characteristic pressure pair, the residual least squares error was calculated by comparing the estimated ΔQ to the measured ΔQ. The supply and return pressure combination that generated the smallest error was the solution to the DeltaQ equation, together with their corresponding airflows The pressure scanning technique gave up some precision because only integer values of pressure combinations are used (i.e., there will not be a 10.5 Pa characteristic pressure – it would have to be 10 Pa or 15 Pa) compared to more general least squared fitting methods - but obtained results in significantly less time[6]. Experience has shown that changing characteristic pressures by 0.004 in. water (1 Pa) or less results in changes in leakage flows of 1% or less. This pressure scanning technique is both fast and robust, typically taking 10 seconds or less to complete the calculations.

Additional calculations were performed on some tests to examine a fine subgrid with one Pascal resolution within ±4 Pascals (i.e., a 9×9 subgrid) about the result of the coarse data fit were used to determine the characteristic pressures with greater resolution (i.e., to within 1 Pa). The changes in leakage flow in between the 0.02 in. water (5 Pa) coarse grid and the 0.004 in. water (1 Pa) sub-grid *averaged over all the tests* was less than 0.2 cfm (0.1 L/s); the changes were also small for *individual tests*: a standard deviation in the differences between the coarse and fine grid of 1.6 cfm (0.8 L/s) for supplies and 2.4 cfm (1.1 L/s) for returns (2.5% and 3% of measured flow or 0.1 to 0.2% of system blower flow). The differences were concentrated in a few tests at higher leakage. This implies that the 5 Pa resolution is sufficient and the results reported in the rest of this study used this 5 Pa resolution.

Errors in the measured data can cause over or under-prediction of leakage flows. This means that low leakage systems can have negative leakage flow results. These negative results can be corrected to more physically realistic results. Because the difference between Qs and Qr is known better than the values of Qs and Qr, any negative value is set to zero and its absolute value added to the other duct leakage. If both Qs and Qr are negative both are set to 0. This treatment was applied to all the scanning results in this study.

NNLS

This technique fixed the characteristic pressures and then uses a Non-Negative Least Squares (NNLS) method to determine the leakage flows: Q_s and Q_r. It allowed multiple leakage pressures and flows to be calculated for both supply and return leaks. Any number of characteristic pressures can be selected for the NNLS analysis. In this study the characteristic pressures were spaced logarithmically between a low value and a high value. If too few intermediate pressures are selected they may be far from the actual leak pressures. It was found that increasing the number of characteristic pressures beyond five did not significantly change the results (by less than 2 cfm or typically 2% of leakage flow - whichever is greater) so the number of characteristic pressures was fixed at five for all the NNLS analyses. More details about the role of the number of characteristic pressures in the analysis can be found in Appendix 3. The NNLS routine calculates a leakage air flow at each characteristic pressure so there are five Q_s's and five Q_r's. All five are summed to get the total Q_s and Q_r. The high value or characteristic pressure was set to 100 Pa for all the tests because this is a typical value for a furnace plenum where duct system pressures are highest. A typical low pressure of 5 Pa leads to characteristic pressures of 5, 10.6, 22.4, 47.3, and 100 Pa.

Similar to the scanning technique, the NNLS applied a least squares analysis to the DeltaQ relationship using the measured data. It was often the case that leakage was concentrated at a single characteristic pressure and other characteristic pressures had little or no leakage. This showed that the single pressure assumption used in the DeltaQ relationship in Equation 1 is often a good one. However, some cases had leakage distributed at different pressures throughout the selected range.

---

[6] In previous work by the athors, general least squares routines that also incorporated the iterative leakage imbalance and duct air flow resistance were found to take several minutes to perform the calculations.

As implied by its name, the Qs and Qr values determined by NNLS could not be not allowed to be less than zero. However, NNLS forces a positive result. This can lead to a positive bias in the test results.

Low pressure fitting limits

The low pressure limit for characteristic pressures was limited by the available data. Two factors combine to make this an important issue. The first is that all data fitting schemes can produce unrealistic results if allowed to select solutions beyond the data bounds. Second is that the DeltaQ function is very sensitive to low pressure data. In this study (and in previous work) a limit of two times the lowest measured data was found to be a reasonable low pressure limit for the characteristic pressures, P_s and P_r. Typically this led to a low pressure limit of 5 Pa when 2.5 Pa wide bins are used.

Because the DeltaQ function is particularly sensitive to low pressure data, errors in the measured data at low pressures can cause significant errors in Qs and Qr. These errors characteristically occur due to wind gusts when the low envelope pressure data are being taken. To reduce the influence of low pressure data (particularly erroneous data) a low pressure limit of 20 Pa was also used in the data analysis. This has the advantage of reducing the sensitivity to low pressure measurement errors, but also limits the resolution of the DeltaQ test because low pressure leakage is modeled at higher pressures – even in systems that truly have low pressure leakage. For the NNLS technique this led to fixed characteristic pressure of 20, 29.9, 44.7, 66.9, and 100 Pa.

The loss of low pressure leak modeling accuracy is ameliorated by the fact that it takes very special circumstances for there to be significant (more than 50 cfm) leakage at low pressure leaks. The low pressures occur only at the extremes of the duct system near or at the registers and grilles. At these low pressures the holes need to be large to have significant air flow and are likely to be easily observable. The most likely candidate for large low pressure leaks is a disconnected duct. However, the characteristic pressure (at which the air flow in the leak changes direction) is very unlikely to be low (on the order of 5 to 10 Pa). This is because the characteristic pressure for a disconnect is close to the pressure where the disconnected duct section connects to the rest of the duct system. For an octopus style system where every register or grille has its own duct – this characteristic pressure is the plenum pressure. For a system with a trunk and branches the characteristic pressure is that in the trunk. In both of these cases the characteristic pressures will be high – likely 50 Pa or more. For systems with wye branches the characteristic pressure will be close to the pressure at the first wye the disconnected branch is attached to – working back from the disconnect. This leads to the only case where might be significant low pressure leakage: if a disconnect is very close (within about a meter) of a connection to another duct then the pressure at this connection (and hence the pressure at which the leak flow would change direction) could be down in the 5 to 10 Pa range.

Example Analysis Results

Figure 3 shows the DeltaQ data and NNLS and Scanning results for the measured data shown in Figures 1 and 2. Here the measured data have been sorted into bins 2.5 Pa wide. The Q_s found by NNLS is 13 cfm (6.5 L/s) and by Scanning is 10 cfm (5 L/s); the Q_r found by NNLS is 43 cfm (21.5 L/s) and by Scanning is 42 cfm (21 L/s). While the difference in the leakage flows determined by the two analysis methods is small, the appearance look of the fitted line is strikingly different, particularly at a house pressure of 47.3 Pa, where the NNLS procedure determined significant leakage flow at this one of its five fixed pressures.

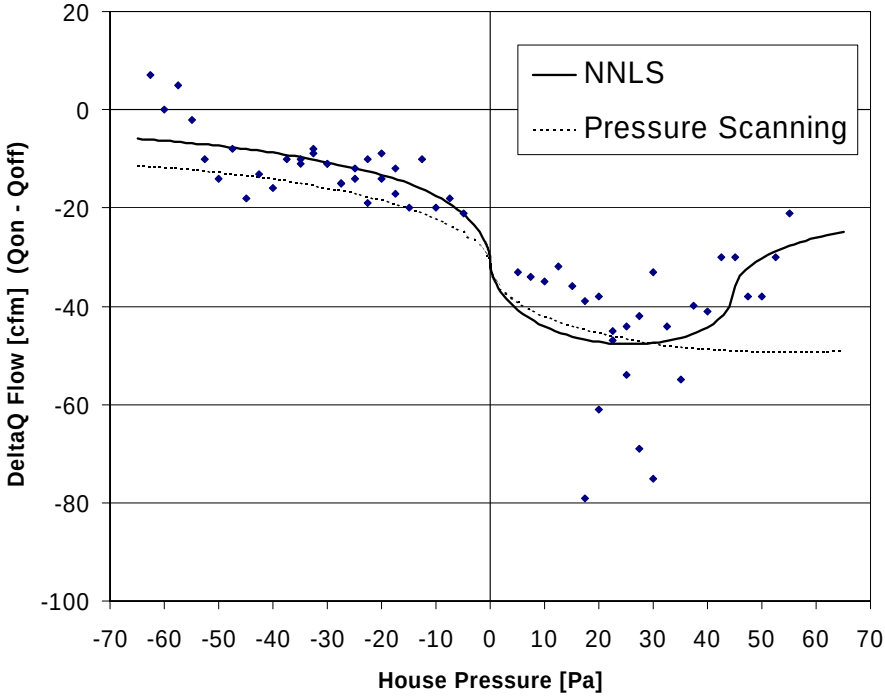


Figure 3: Example DeltaQ fits and results for both NNLS and Scanning analysis methods

Figure 4 shows the results from another test at the same house but with windy conditions. Given the scatter in the rest of the data, the low pressure supply leakage found by NNLS (seen as a spike in the curve fit at -5 Pa) is unlikely to be real. Also leakage at this pressure was not seen in the previous, low wind test. The NNLS result for supply leakage was almost twice the amount determined by Scanning (62 vs. 35 cfm (31 vs. 17.5 L/s)), whereas the return leakage result was about the same (87 and 84 cfm (43.5 and 42 L/s)). This test shows the sensitivity of results to measurement errors at low pressures – particularly if we allow (or force in the case of NNLS) low characteristic pressures.

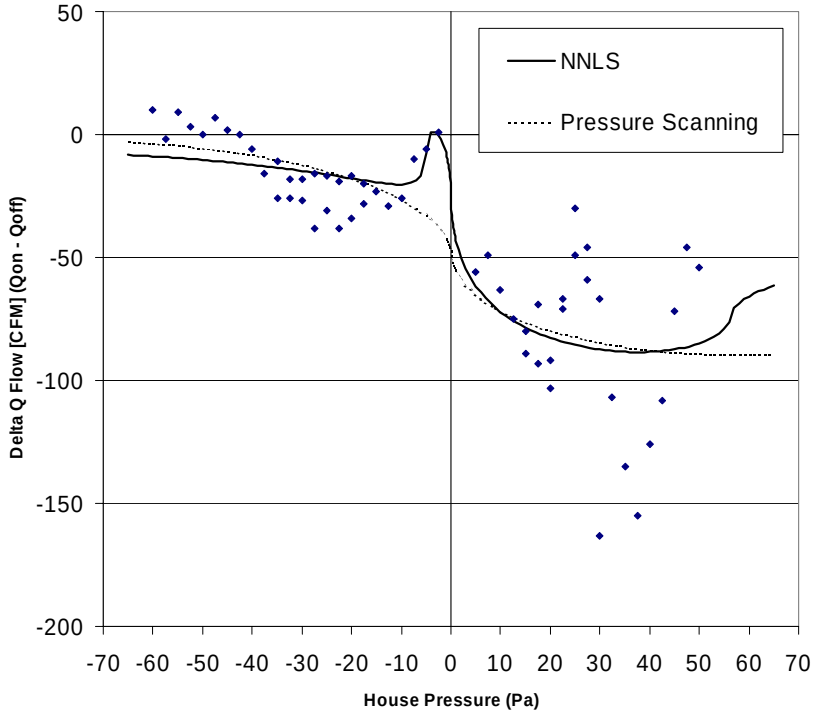


Figure 4: NNLS and Scanning analysis results for a test under windy conditions showing sensitivity to low pressure measurement errors

FIELD REPEATABILITY STUDY

A total of seven houses were used for repeatability testing where the DeltaQ ramping test was performed several times during the course of one day. Two houses were examples of older homes with leaky envelope and duct systems in the San Francisco Bay area and their testing is described in more detail in Walker and Dickerhoff (2008). Five of the houses were new and represent current good construction techniques used in Nevada and inland California. In the new houses, the builders took special care to build tighter than average homes, with tight duct systems, and with the air handler and ducts located within the building envelope for two houses. Characteristics of the test houses are summarized in Table 1.

Wind speed measurements were made on-site at the five new homes. This was measured at a height of about two meters at the least shielded location on the property. The wind speed data was intended to show the wind variation the house experienced during the day of testing. The wind was not measured at the two existing houses but was very high all day at the first of these, and quite low at the second.

The DeltaQ tests were performed multiple times during the course of a day. The two older homes had fewer tests because pressure station DeltaQ tests were also performed at these houses. Walker and Dickerhoff (2006 and 2008) showed that repeatability results were the same for both ramping and pressure station testing at these two houses.

There are several aims for the field testing:

- provide data for estimating test repeatability
- develop in-field guidance on test uncertainty that is useful for the people performing the test
- develop analysis techniques that reduce sensitivity to wind effects
- develop quality control guidance that assist indecisions about retesting and determine flags when there is the potential for increased errors

As well as looking at repeatability results it is instructive to compare cases of high wind and low wind so that we can see where improvements in data acquisition and analysis are needed.

Table 1. Summary of test houses and duct systems

House	Location	Size, ft^2 [m^2]	House characteristic	Number of DeltaQ tests	Envelope Leakage Q50: Air Flow at 50 Pa (0.2 in. water), cfm [L/s]	Duct System	Wind Shelter
Colton	Oakland, CA		About 60 years old - poorly insulated	6	3300 [1560]	In crawlspace and basement	Windward side fully exposed at top of hills
Holly	Berkeley, CA		About 100 years old- poorly insulated	5	4600 [2170]	In crawlspace and interior partitions	Heavy shelter from other close houses and trees
Sparks 1	Sparks (near Reno), NV		New - Building America Home	7	1500 [710]	Designed to be all inside conditioned space	No trees or plants - only shelter is neighboring buildings
Sparks 2	Sparks (near Reno), NV		New - Building America Home	12	1400 [660]	Designed to be all inside conditioned space	No trees or plants - only shelter is neighboring buildings
Rocklin 1	Rocklin (near Sacramento), CA	2168 [202]	New - Building America Home	10	1100 [520]	Furnace and ducts in ventilated attic	No trees or plants - only shelter is neighboring buildings
Rocklin 2	Rocklin (near Sacramento), CA	2577 [240]	New - Building America Home	10	1800 [850]	Furnace and ducts in ventilated attic	No trees or plants - only shelter is neighboring buildings
Vacaville	Vacaville, CA	3714 [345]	New - Building America Home	13	3100 [1460]	Furnace and ducts in ventilated attic	Lightly landscaped, primary shielding is neighboring buildings and fence

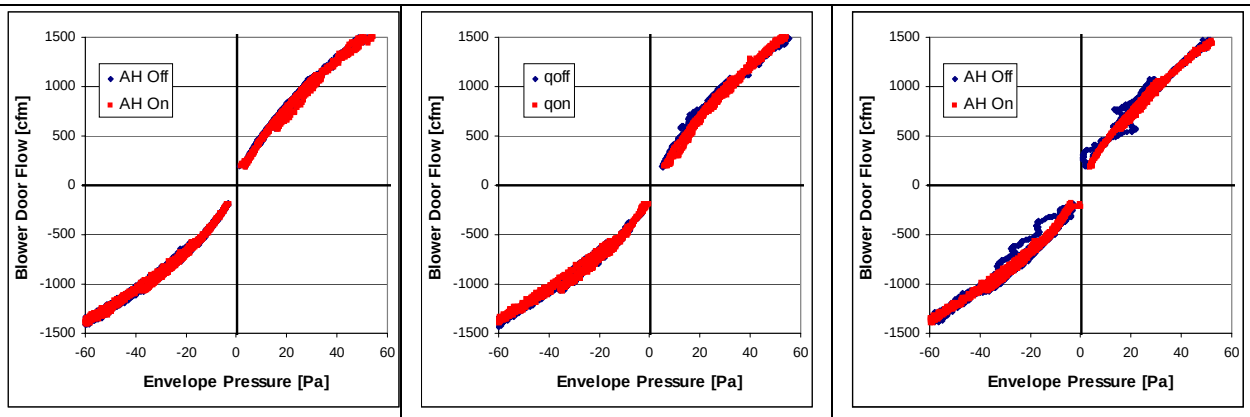
FIELD TESTING RESULTS

All the field testing results for individual tests are in Appendix 1. Because there is no reference measurement of the true air leakage flows, the biases for the different analysis techniques were evaluated relative to the air leakage flows given by the test at lowest windspeed. Generally, this was the test with the best fit to the DeltaQ function and one of the lowest predicted air leakage flows.

Wind Effects

Figures 5a, 5b, and 5c show the raw unbinned data for the Sparks 2 house with little (less than 2.5 mph (1 m/s)) , moderate (about 5 mph (2 m/s)) and very large (greater than 6.25 mph (2.5 m/s)) wind speeds averaged over the test period. The trend to increasing variability in the data can be seen as wind speed increases. At the highest wind speed the excursions are over 200 cfm (100 L/s) even for this tight envelope home at a given envelope pressure, or equivalently, more than 10 Pa (0.04 in. water) in envelope pressure for a given blower door flow. These excursions were of the same magnitude as those expected for a fairly leaky duct system – even though we know this is a low-leakage system based on observations of duct installation, the fact that all the ducts are inside the thermal envelope of the building (if not quite all inside the pressure envelope), and the test results at low wind speeds. These excursions were due to changes in envelope pressure measured by the envelope pressure sensor as well as changes in the blower door flow pressure. When depressurizing, this blower door sensor and reference were both inside and relatively sheltered from wind effects. When pressurizing the blower sensor and its pressure reference were outside exposed to changes in wind pressure.

Field experience has shown that these wind effects can be ameliorated by careful placement of outdoor reference sensors and selection of blower door location. For example in the Colton house the outdoor pressure tubing was terminated inside a large garbage can with the lid slightly open (just enough to allow the pressure tubing to enter). This gave good pressure averaging and reduced the wind effects. Also, the blower door was mounted in a downwind doorway that was fairly well shielded by a small porch and the presence of the garage wall to one side. Unfortunately it is not always possible to select such a favorable location although we recommend that field testers try as hard as possible to carefully place outdoor pressure tubing and select sheltered locations for blower door placement.



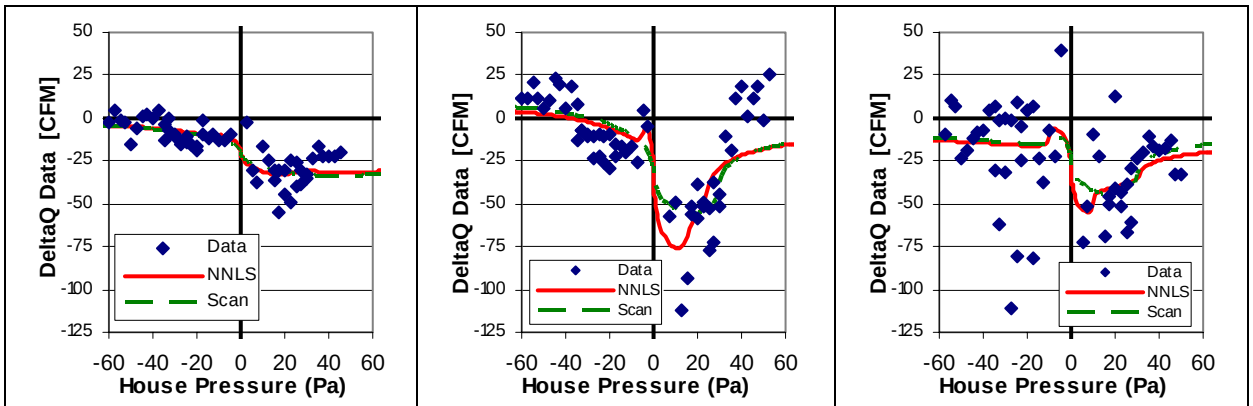
Low wind	Moderate Wind	High Wind
Baseline pressures: Initial: -1.4±0.1 Pa Final: -0.96±0.2 Pa	Baseline pressures: Initial: -1.4±1.3 Pa Final: -0.9±1.5 Pa	Baseline pressures: Initial: -0.2±0.18 Pa Final: 0.45±0.18 Pa

Figure 5a, 5b, and 5c: House pressure curves with the air handler off and on for Sparks 2 at low (less than 1 m/s) , moderate (about 2 m/s) and high (>2.5 m/s) wind speeds averaged over the test period

Figures 6a, 6b, and 6c show the DeltaQ data, NNLS and scanning results for the three tests in Figure 5 using a bin size of 2.5 Pa. Increasing wind generally resulted in an increase in the calculated duct leakage for this house[7]. This

[7] As will be shown later, this trend is not generally the case.

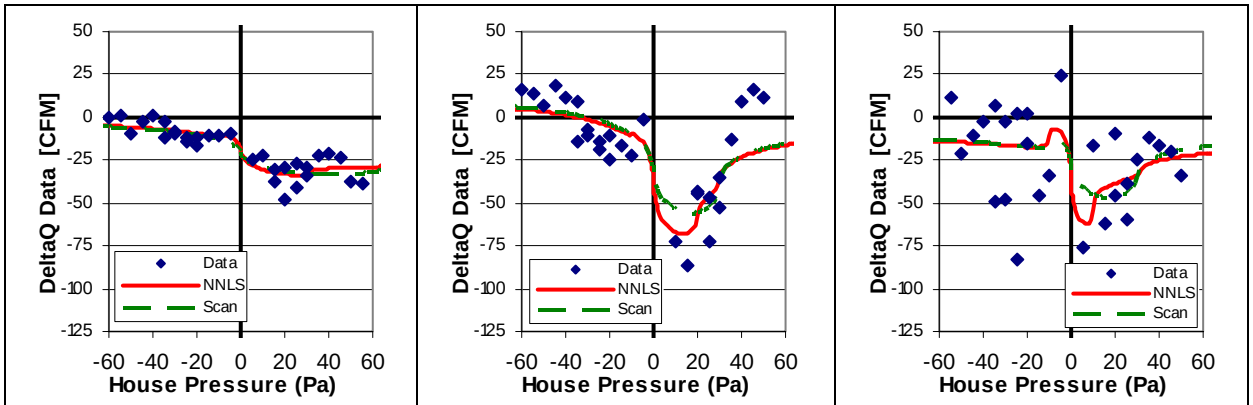
affect was more pronounced for the NNLS analysis than it was for Scanning. The highest flow results were at moderate wind speeds. This illustrates a major point when considering the effect of wind on DeltaQ test results: namely that it is not the variability in wind pressures but instead it is gusts of wind that systematically change wind pressures consistently over a period of several seconds. In these examples, the DeltaQ data are noisier at higher wind speeds but noise is simply averaged out in the DeltaQ function fitting process. It was the consistent deviation for pressurization results at moderate wind speed and low envelope pressures that had the significant influence on the DeltaQ results.



Low Wind	Moderate Wind	High Wind
NNLS: Qs = 14, Qr=34 Scanning: Qs = 9, Qr=30	NNLS: Qs = 44, Qr=78 Scanning: Qs = 22, Qr=55	NNLS: Qs = 23, Qr=53 Scanning: Qs = 13, Qr=38

Figure 6: DeltaQ 2.5 Pa binned measured data, NNLS DeltaQ function and Scanning DeltaQ function at low (less than 1 m/s) , moderate (about 2 m/s) and high (>2.5 m/s) wind speeds averaged over the test period

The analysis was repeated for a bin size of 5 Pa and the results are shown in Figures 7a, 7b, and 7c. Changing the bin size made little difference to the results. This shows that simply widening the bin size to average out wind pressure fluctuations does not change the results very much. This is another illustration of the fact that it is not random variations due to wind that are significant, instead it is the wind pressure changes maintained over several seconds that have major impacts.



Low Wind	Moderate Wind	High Wind
NNLS: Qs = 13, Qr=33 Scanning: Qs = 8, Qr=29	NNLS: Qs = 29, Qr=68 Scanning: Qs = 22, Qr=55	NNLS: Qs = 24, Qr=60 Scanning: Qs = 11, Qr=39

Figure 7: DeltaQ 5 Pa binned measured data, NNLS DeltaQ function and Scanning DeltaQ function at low (less than 1 m/s) , moderate (about 2 m/s) and high (>2.5 m/s) wind speeds averaged over the test period

To further investigate these wind effects Figure 8 shows the measured envelope pressures during a time of high wind. The measured data were taken about twice per second and show large reading to reading fluctuations. More important is the differences in wind pressure between different ramps because it is assumed that the differences between central system blower on and off flows are due to blower operation and do not include these wind effects. To examine the effects of ramp-to-ramp envelope pressure changes, the data were divided into 90 second (1.5 minute) time periods because this is the time taken to obtain a single ramp of data. The average wind pressures in each period are shown in the figure together with a 30 second moving average for illustrative purposes. These data show changes of up to a Pascal in average pressures from ramp-to-ramp. For a leaky house (4000 cfm50 (2000 L/s at 50 Pa)) a 1 Pa shift at low envelope pressures changes the DeltaQ air flow by 500 cfm (250 L/s). Even a relatively tight (1000 cfm50 (500 L/s at 50 Pa)) home will have changes in DeltaQ of over 100 cfm with such a pressure shift. This pressure/flow shift due to wind does not occur over a full ramp because the effect of fixed pressure shift decreases with increasing envelope pressure[8]. However, this gives a guide to the potential magnitudes under very wind conditions.

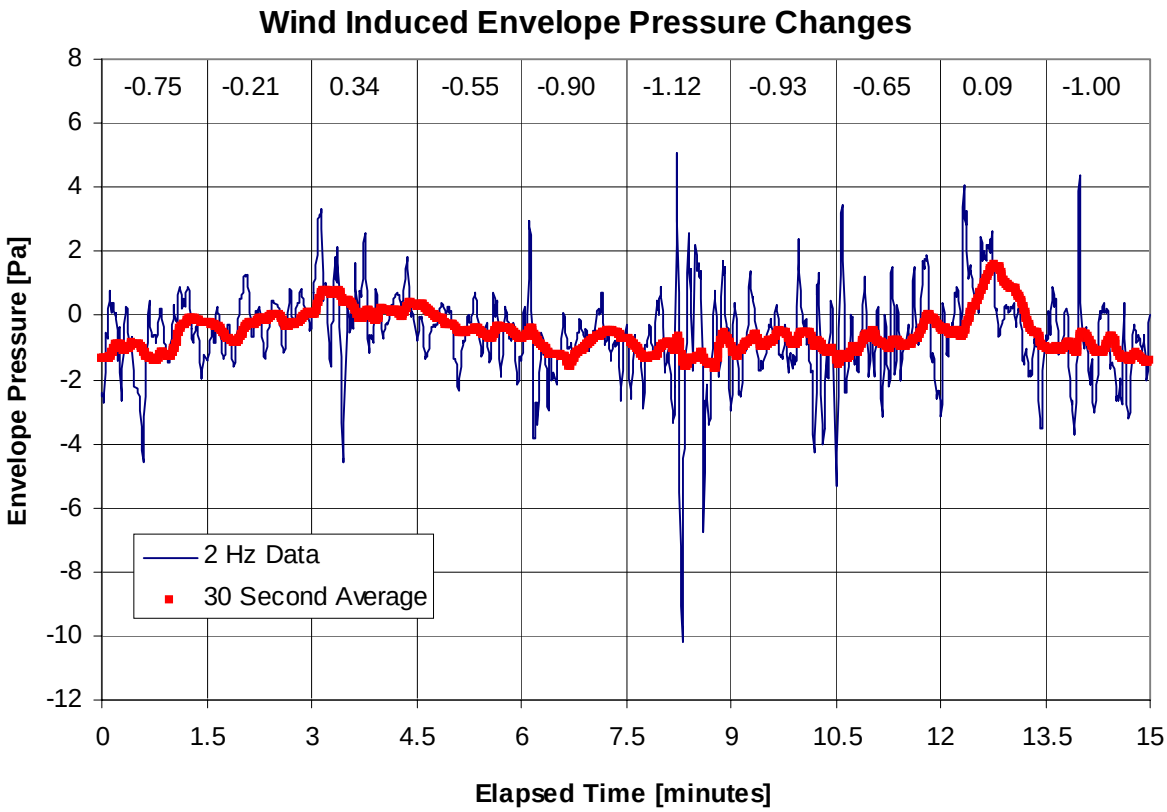


Figure 8. Measured envelope pressures with no DeltaQ testing during a time of high wind. Averages are shown for typical ramping time intervals (90 seconds (1.5 minute)).

[8] Also a simple constant flow shift does not lead to exactly the same change in DeltaQ leakage if occurring at different times in the ramp. In other words, for a fixed flow or pressure change it makes a bigger difference if this occurs at the beginning or end of a ramp where flows and pressures are lower and the DeltaQ function is most sensitive.

IMPROVING DATA ANALYSIS TO REDUCE WIND PRESSURE EFFECTS - IMPROVING DATA QUALITY

Time Filtering

A common way of addressing unwanted fluctuations in measured data is to use time filtering. Several time based filters were applied to the measured data but the test results did not significantly change – even in cases where the effect of wind gusts were clearly observed. This is primarily because the DeltaQ results are not very sensitive to high frequency noise – but instead are influenced by longer term (several seconds in duration) gusts of wind as shown in Figure 8 that are close to the same frequency as the ramping signal. Therefore time filtering is not a useful for improving the data analysis.

Changing bin size and low pressure limits

To limit sensitivity to single erroneous data points, in order for a bin to be considered valid in the analysis, it must have a minimum number of data points. Through trial and error it was found that having at least three individual data points on each side of the mid-point of the bin was a reasonable compromise between too few data points that allow outliers undue influence and too many data points in which case too many bins fail to meet the criteria unless they are made very wide. This selection of a minimum number of points is directly related to the bin size used in the analysis.

.It was found that bins only 1 Pa wide were too sensitive to wind pressure fluctuations producing distinct outliers that led to erroneous air flow estimates particularly if these outliers were at low envelope pressures. Bins greater than 5 Pa wide were too coarse and sometimes missed important changes in the DeltaQ function and therefore increased uncertainty in the resulting air leakage flows. Bin widths of 2.5 Pa and 5 Pa were found to be a reasonable compromise. All the tests were analyzed with bins of 2.5 Pa and 5 Pa and with low pressure limits of twice the lowest data bin and a fixed 20 Pa cutoff. For each house the average leakage was calculated together with the standard deviation of the tests. The standard deviation is an indicator of the wind induced variability, with lower standard deviations indicating lower sensitivity to wind induced pressure changes. Table 2 shows the leakage values and standard deviations averaged over all houses for each bin and pressure limit for both pressure scanning and NNLS. Table 2 averages the results for all the houses, however, examining the results for individual houses showed that the Colton and Holly houses had a large influence on the results – because of their leaky ducts and leaky envelopes compared to the other houses. If the focus of DeltaQ application is for testing tighter ducts and houses then the results in Table 2a are more appropriate where the Colton and Holly results have been removed.

Table 2. Leakage and Standard Deviations averaged over all houses

Lowest allowed Ps and Pr value		Supply Leakage				Return Leakage			
	Analysis Method:	NNLS		Scanning		NNLS		Scanning	
	House Pressure Bin Size (Pa)	2.5	5	2.5	5	2.5	5	2.5	5
Twice data minimum	Average Leakage (cfm)	85	80	64	61	94	90	74	74
	Average Std. deviation (cfm)	37	32	31	25	35	29	29	26
20 Pa	Average Leakage (cfm)	71	73	58	60	84	85	70	72
	Average Std. deviation (cfm)	28	29	24	25	27	27	25	26

Table 2a. Leakage and Standard Deviations without Colton and Holly – i.e., tight houses and tight ducts									
Lowest allowed Ps and Pr value		Supply Leakage				Return Leakage			
	Analysis Method:	NNLS		Scanning		NNLS		Scanning	
	House Pressure Bin Size (Pa)	2.5	5	2.5	5	2.5	5	2.5	5
Twice data minimum	Average Leakage (cfm)	41	40	31	29	43	38	33	31
	Average Std. deviation (cfm)	26	26	26	26	25	22	27	24
20 Pa	Average Leakage (cfm)	64	66	53	55	49	51	39	42
	Average Std. deviation (cfm)	22	26	23	24	21	20	23	22

Several trends are evident from the results for all the houses:

- Pressure scanning consistently produces lower leakage values compared to NNLS by about 15 to 20 cfm (7.5 to 10 L/s) for low leakage at twice the data minimum. Previous laboratory studies (Walker and Dickerhoff (2006 and 2008) have shown similar magnitude positive biases for NNLS compared to pressure scanning).
- Pressure scanning consistently produces lower standard deviations compared to NNLS by about 5 to 10 cfm (2.5 to 5 L/s) for low leakage at twice the data minimum.

These two results are primarily because NNLS does not allow for negative results at low leakage levels resulting in a positive bias and because NNLS is more sensitive to low envelope pressure fluctuations due to pre-selecting low pressures as candidates for the characteristic pressures[9].

- Using 5 Pa bins instead of 2.5 Pa bins reduces the standard deviation when the lowest characteristic pressures are twice the data minimum by about 5 cfm (2 L/s) or about 15%.

The 20 Pa low limit has the effect of reducing the differences between analysis methods:

- The 20 Pa low limit reduces the differences between average leakage for pressure scanning and NNLS to about 10 cfm (5 L/s) and the standard deviations to about 5 cfm (2.5 L/s).
- The 20 Pa low limit essentially removes the differences between 2.5 and 5 Pa bins for both the leakage (within 3 cfm (1.5 L/s)) and standard deviation of leakage values (within 1 cfm (0.5 L/s)).
- The 20 Pa low limit leads to lower leakage flows (for 2.5 Pa bins) by about 12 cfm (6 L/s) for NNLS and 4.5 cfm (2 L/s) for scanning.

For the tighter ducts and houses the trends are similar but the differences are reduced in magnitude:

- Pressure scanning consistently produces lower leakage values compared to NNLS by about 10 cfm (5 L/s) for both low limits for Ps and Pr.
- Pressure scanning and NNLS standard deviations differ by only 1 to 2 cfm (0.5 to 1 L/s).
- Using 5 Pa bins instead of 2.5 Pa bins reduces the standard deviation when the lowest characteristic pressures are twice the data minimum by only a couple of cfm for the twice data limit minimum Ps and Pr. The 20 Pa low limit showed increases in standard deviation for supply leakage.
- The differences between average leakage and standard deviations for pressure scanning and NNLS are the same for both low pressure limits within a couple of cfm.

Selecting a preference here is complicated by the fact that the larger bin widths and higher low pressure limit both limit the ability of DeltaQ to resolve leak pressures and low pressure leakage. Therefore any selection is bound to be a compromise. When applying the test procedure over a wide range of houses (as might be done for a weatherization program) there is a slight preference for a wider 5 Pa bin instead of 2.5 Pa. For low envelope and duct leakage testing (more typical of new construction and code/energy efficiency program compliance testing) the differences are not significant and we recommend using the twice data minimum low pressure criterion for the characteristic pressures Ps and Pr, and the use of 2.5 Pa wide bins because of the potential for increased flexibility in fitting to the measured data without an increase test to test variability.

[9] NNLS is more likely to have the DeltaQ function fit low envelope pressure excursions due to wind effects. This results in high leakage flows and therefore in a positive bias.

The difference between average leakage reported by NNLS and Pressure Scanning is difficult to assess for these field tests where the true leakage is not known. Laboratory tests by Walker and Dickerhoff (2008) where the true duct leakage was known have shown that pressure scanning over-predicted leakage on average (combining supply and return leaks) by 9 cfm (4.5 L/s) and NNLS over-predicted by 16 cfm (8 L/s). This trend of NNLS predicting higher leakage is the same as observed in the field test results in Tables 2 and 2a. For these reasons, it may be preferable to use Pressure Scanning although given the small differences and small datasets this is not an absolute requirement.

Ignoring low pressure (less than 5 Pa) data

The DeltaQ algorithm is more sensitive to low envelope pressure data. Unfortunately, this is where the slope of the pressure-flow relationship for the envelope and ducts is its steepest, resulting in larger flow errors in DeltaQ for a given pressure measurement error (whether wind induced or not). One possibility is to ignore DeltaQ data below a given threshold - for example 5 Pa. This is different from limiting the lowest characteristic pressures used in the fit to the DeltaQ function because it actively eliminates data from the analysis completely rather than restricting fitted parameters. Figure 9 is an example for Sparks 1 - where wind gusts at low envelope pressure led to extreme DeltaQ data for these low pressures. Each figure shows the NNLS and scanning results. Both two times the lowest binned data and 20 Pa low limits for the fitted characteristic leakage pressures are shown to illustrate the effects of imposing these fitted parameter limits in addition to ignoring low pressure data.

Figure 9a shows how the DeltaQ function is strongly influenced by a few low pressure points. Comparing to Figure 9c with the points below 5 Pa removed, the DeltaQ function is changed significantly and the resulting leakage flows are reduced by about 30 % (or 30 cfm (14 L/s)) from almost 100 cfm (47 L/s) to about 70 cfm (33 L/s). In this case we expect from the house construction with the ducts inside that the duct leakage should be low. In addition, low wind speed test results from this house were Qs = 16 cfm (8 L/s) and Qr = 49 cfm (23 L/s) and did not show these low pressure DeltaQ excursions. This shows that removing the erroneous low pressure data resulted in a better result - particularly for the total leakage. For testing of low leakage systems, the difference between 100 cfm (47 L/s) and 70 cfm (33 L/s) is worth pursuing as this would typically be the difference between a house passing or failing a low- leakage test limit.

The 20 Pa low limit for characteristic pressures is also good at effectively ignoring the errors in the low pressure data. Because the 20 Pa low limit can be imposed on the analyzed data the additional restriction of ignoring data below 5 Pa is not required. In the interest of keeping as many data as possible in the analysis we do not recommend ignoring the low pressure data.

Comparing up and down ramps

We attempted to minimize the effects of wind pressures by comparing the up and down sections of each ramp. Differences between the up and down ramps are primarily due to wind effects. Other sources are valving leaks, changes in wind direction, changes in temperature, and hysteresis (See Appendix 2 for an extreme illustration) caused by ramping too quickly. If a gust of wind affected either the up or down ramp then comparing the up and down ramps should reveal this effect. Furthermore, if the difference between up and down ramps for a particular pressure bin exceeds some limit then we can assume that this data point has too large an error and eliminate it from the analysis. Several tests were selected where it was clear that one part (either up or down) of a ramp was strongly affected by wind pressure fluctuations in order to determine an appropriate level of difference between ramps. It was observed that the cutoff for good vs. bad ramps occurred when there was a change of about 20% between an up and down ramp[10].

[10] If the allowable change was lower then too many data were eliminated resulting in too few data pairs for the analysis, conversely, allowing greater than 20% variation meant that too few points were eliminated and there was no effect of comparing the ramps.

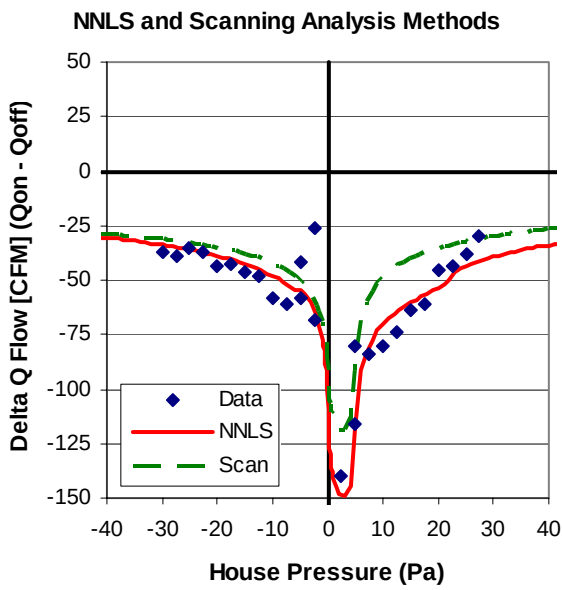


Figure 9a.
All Data
Characteristic Pressure Limit = 2 times lowest data
NNLS: Q_s=12 cfm (6 L/s), Q_r=97 cfm (46 L/s)
Scanning: Q_s=0 , Q_r=92 cfm (43 L/s)

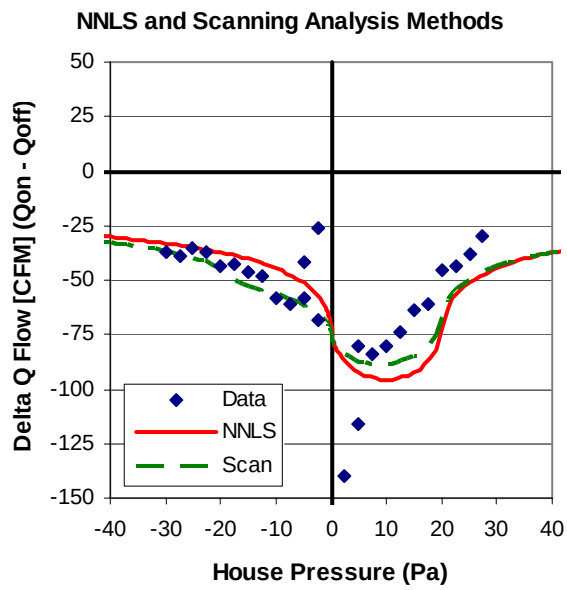


Figure 9b.
All Data
Characteristic Pressure Limit =20 Pa
NNLS: Qs=0, Qr=71 cfm (34 L/s)
Scanning: Qs=0, Qr=75 cfm(35 L/s)

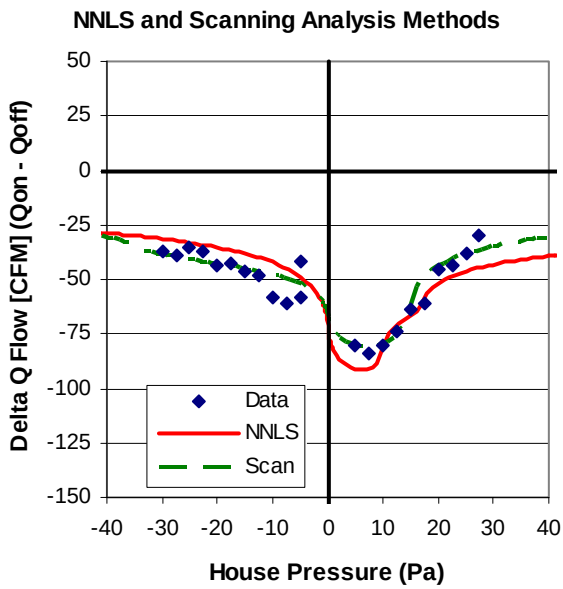


Figure 9c.
No data < 5 Pa
Characteristic Pressure Limit = 2 times lowest data
NNLS: Qs=0, Qr=69 cfm (33 L/s)
Scanning: Qs=0, Qr=67 cfm (32 L/s)

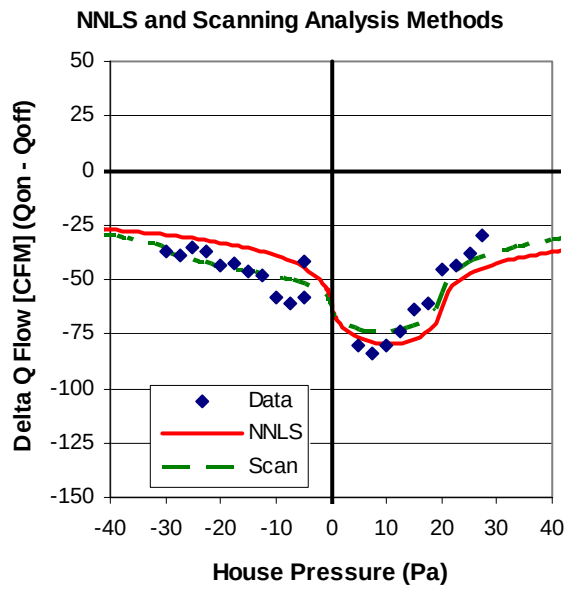


Figure 9d.
No data < 5 Pa
Characteristic Pressure Limit =20 Pa
NNLS: Qs=0, Qr=60 cfm (28 L/s)
Scanning: Qs=0, Qr=62 cfm (29 L/s)

Figure 9. DeltaQ data and fits for Sparks 1 showing the effect of removing low pressure data and imposing different low characteristic pressure limits

Bins where the difference between up and down ramps was greater than 20% were removed from all tests, and the data reanalyzed to determine new leakage flows with these erroneous data removed. All the tests had at least one data point that was changed using this criterion. Table 3 shows the average leakage flows and the average of the standard deviations averaged over all the houses. The analysis was performed for NNLS and scanning, with two low pressure cutoffs: twice the minimum data bin and 20 Pa (0.08 in. water); and two bin sizes: 2.5 Pa and 5 Pa (0.01 and 0.02 in. water). The changes in standard deviation were only significant (greater than about 5 cfm (2.5 L/s)) for a few situations: for 5 Pa (0.02 in. water) bins using a low pressure limit of twice the lowest bin. Other times the removal of data did not significantly change the results. Most tests had insignificant changes (<2 cfm (1 L/s)). Changes concentrated in a few tests where the deviations were significant. Figure 10 shows an example, where there was greater than 20% difference between the up and down ramp in depressurization for the big orifice with the system blower on. The pressurization data in this figure show very little wind induced variability and the single poor ramp stands out clearly. For this example the results changed from Qs = 136 cfm (68 L/s) and Qr = 76 cfm (38 L/s) to Qs = 64 cfm (32 L/s) and Qr = 36 cfm (18 L/s) by eliminating data from the bad ramp. In practice, observing this sort of deviation during the test would indicate that this particular ramp should be redone. From a basic measurement point of view retaking a ramp to get a good ramp will be better than eliminating bad points (i.e., difference between up and down greater than 20%) so the qualitative observation and decision to retake data is very important. This test had a mean windspeed of 3.6 mph (1.6 m/s) that is not particularly high (average for all tests in all houses was 1.9 m/s (4.3 mph)) but the windspeed during the test ranged from 0.25 mph (0.1 m/s) to 13.4 mph (6 m/s) with the higher wind speeds likely responsible for the large up/down ramp difference.

Table 3 . Total Leakage and Standard Deviations averaged over all houses with data points where the difference between up and down ramps was greater than 20% removed.

		Supply Leakage				Return Leakage			
	Analysis Method:	NNLS		Scanning		NNLS		Scanning	
Lowest allowed Ps and Pr value	House Pressure Bin Size (Pa)	2.5	5	2.5	5	2.5	5	2.5	5
twice data minimum	Average Leakage (cfm)	81	76	67	64	91	90	78	79
	Average Std (cfm)	34	24	25	17	31	27	22	21
20 Pa (0.08 in. water)	Average Leakage (cfm)	77	73	65	63	88	88	77	78
	Average Std (cfm)	30	27	22	17	28	26	22	21

In the rest of this report the supply and return leakage values are from Pressure Scanning with 2.5Pa wide pressure bins using twice the data minimum as the lowest characteristic pressure.

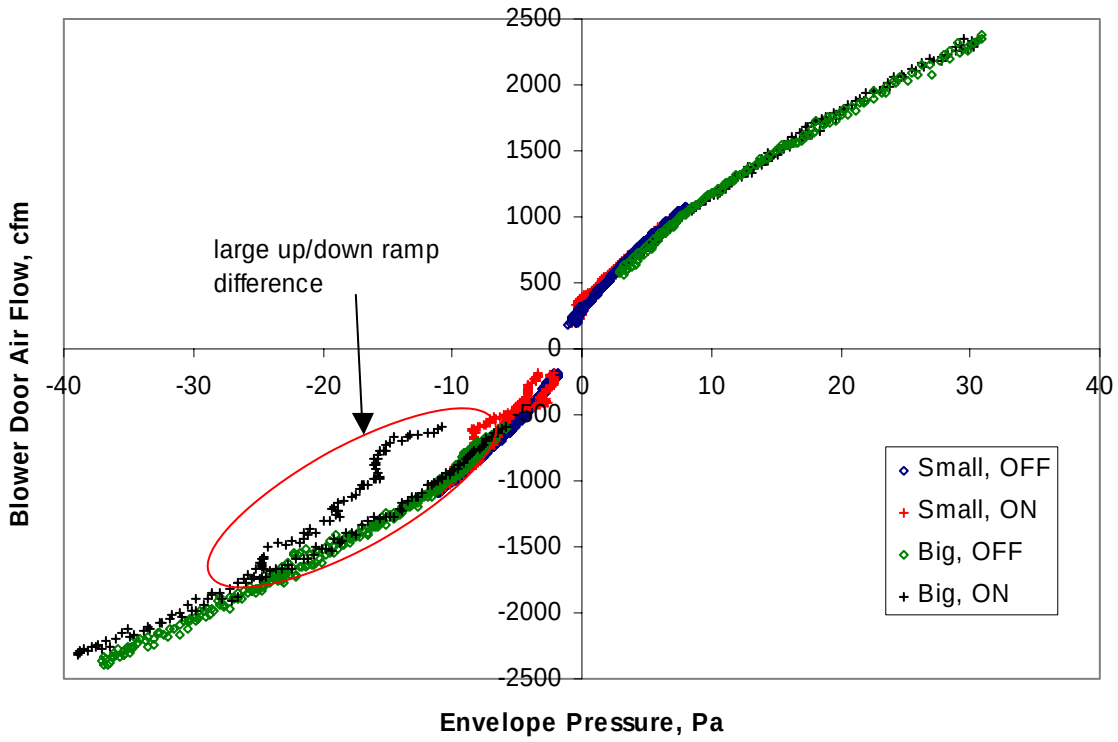


Figure 10. Illustration of ramp with greater than 20% variation between ramping up and ramping down

QUALITY CONTROL: DETECTING PROBLEM TESTS

Because DeltaQ results can be changed by wind, we need to find some sort of quality control indicator for testers that flags potentially poor data. The aim is to provide guidance for users for when it is too windy to do testing or at least when wind will reduce test precision to unacceptable levels. Then either the test (or ramp) can be redone, test results can be reported together with an increased uncertainty, or testing abandoned. There are both qualitative and quantitative approaches. The qualitative approach is to observe the measured data and look for characteristics representative of measurement errors. This requires a combination of experience and guidance. In this study several examples of what to look for in measured data were developed in order to provide background information for guidance. The nature of the ramping test is such that it is often the case that only a single ramp has significant wind induced errors and only this single ramp needs to be repeated rather than the whole test. Because of this, the qualitative approach has proved to be very useful in field testing, i.e., when an operator observes a large deviation in a particular ramp – that particular ramp is repeated and a successful test results. The quantitative approach uses characteristics of the measured data to determine test validity. This can be used as an indicator that some or all of the test needs to be repeated. Combined with the qualitative approach much time can be saved by only repeating the ramps that need to be repeated.

The quantitative indicators investigated here are: wind speed and baseline envelope pressure fluctuations.

In addition to these efforts to flag poor data we have also attempted to use the measured data to estimate the test uncertainty. The method evaluated here is to find an estimate for the standard deviation of the repeated tests and use that as an error estimate that can be provided for an individual house. A method that was found to work well was to base the estimate of repeatability uncertainty on the envelope leakage.

Wind speed

An obvious choice for an on-site quality control indicator is to use on-site measured wind speed, where we might expect to discover a high wind speed limit to testing, beyond which test uncertainty becomes too large. In order to see if there is a bias in the results with increasing wind speed, the leakage results were regressed with wind speed for both NNLS and pressure scanning. Figure 11 shows that the trends are weak for the five houses with measured on-site wind speeds. There was a slight increase in leakage with increasing wind speeds for some cases but not others and the correlation was not strong, with R^2 values typically less than 0.1. Both the NNLS and scanning showed similar weak trends. Although there was considerable variability, the test with the lowest wind speed at each house almost always gave the lowest leakage values. These results indicate that there is no bias resulting from higher wind speed testing. These results also show that variability in test results does not increase systematically with windspeed. This appears surprising at first, but is really just another indicator of the random nature of wind effects and that mean windspeed is not a particularly significant as an indicator of DeltaQ test variability. Rather, it is the ramp-to-ramp variability (particularly between ON and OFF data) and data outliers at low envelope pressures that lead to errors and fluctuations in DeltaQ test results.

Little, if any, field testing will be performed with an on-site weather station to measure windspeed. The results illustrated here show that this lack of on-site wind measurements is not critical. However, we must look elsewhere for useful in-field quality control indicators.

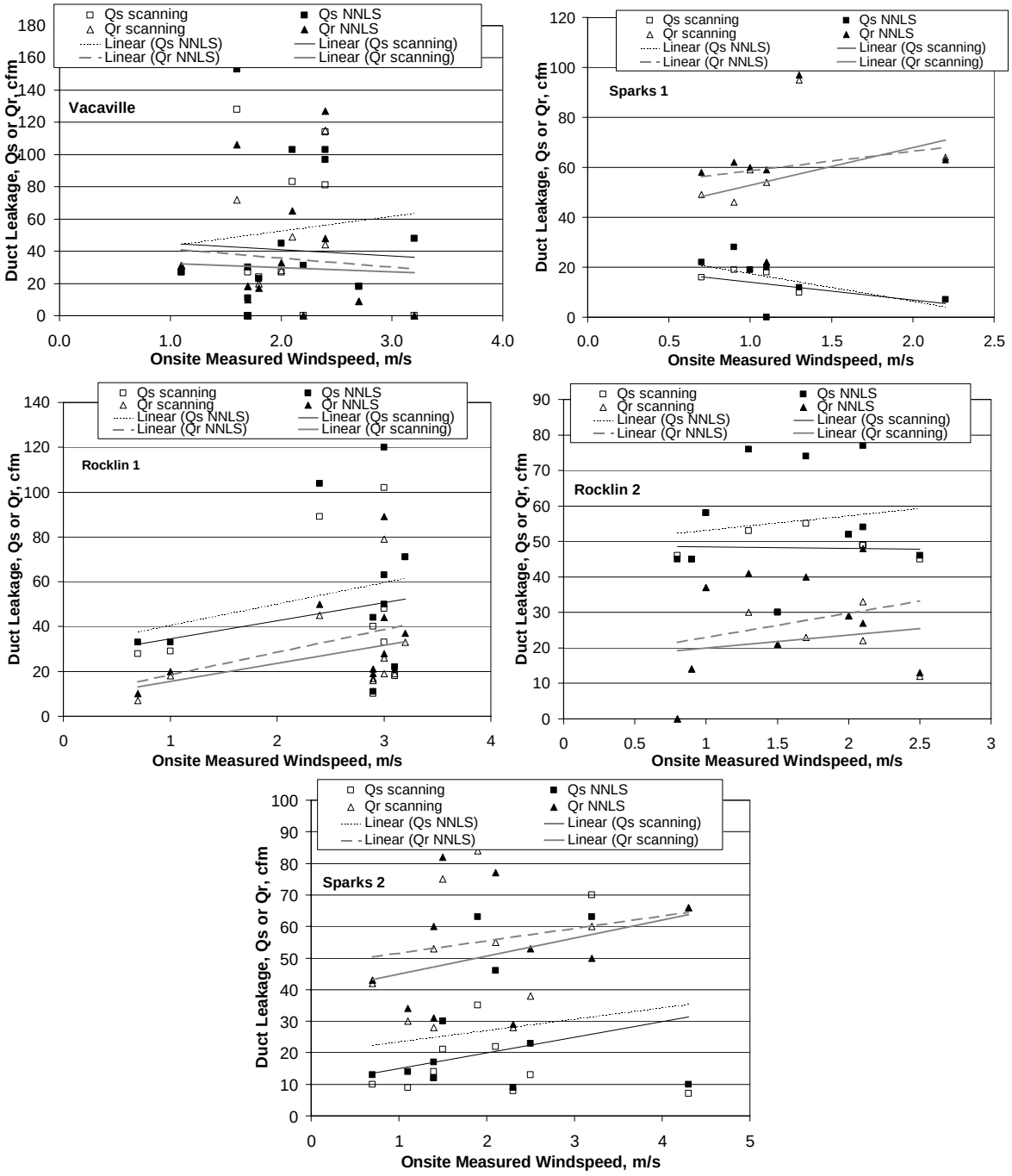


Figure 11. Air leakage trends with wind speed

Baseline Envelope Pressures

One method of determining which tests are valid and which were done during conditions of excessive wind is to evaluate the initial and final "baseline" house pressure measurements. These are measurements of the house pressure with the air handler fan and blower door off and can be used as an indicator of variable wind conditions. Excessive variation of the baseline pressure could be used a flag to warn of poor testing conditions. Data from these times may not reflect the wind during the time in which the DeltaQ data points are determined, so it will be an imperfect indicator, but one that is readily available.

The measured baseline envelope pressures that are already required as part of the test procedure. This has the advantage of not requiring additional equipment, set-up and measurements. The test acceptability is estimated from variability (in this case the standard deviation) of the baseline pressures taken before and after the ramping part of the DeltaQ test. Figure 12 shows how the test results vary with the standard deviation of the baseline pressures. In general, there are no clear trends – just like with the mean wind speeds shown in Figure 11. The exception is Rocklin #1, where above 0.50 Pa (0.002 in. water) the measured leakage values increase sharply.

However, the trends do not tell the full story. Test to test variability (or repeatability) can be characterized by the standard deviation of the tests for each house. The difference in standard deviation with high baseline pressure variation tests eliminated indicates if applying a maximum baseline pressure variation leads to more repeatable results. A reasonable cutoff pressure from the data in Figure 12 is 0.5 Pa (0.002 in. water). This pressure is fairly arbitrary - but it is clear that too low a cutoff (say 0.1 Pa (0.0004 in. water)) would eliminate almost all tests and too high a cutoff (say 1.0 Pa (0.004 in. water)) would not discriminate as almost all tests would meet this criterion.

In some cases the variability in the DeltaQ data is concentrated in a single ramp and retaking this ramp would improve the test results. Each test that had a baseline pressure standard deviation greater than 0.5 Pa (0.002 in. water) was examined to evaluate if redoing a ramp would improve the test. In addition, there are some tests where the baseline pressure variation is small - but strong wind pressure variation was observed in the DeltaQ ramping data. These represent failures of the 0.5 Pa (0.002 in. water) criterion in eliminating bad tests. These results are all summarized in Table 4 for pressure scanning with 2.5 Pa bins using two times the lowest measured pressure as the lowest characteristic pressure. No ramps were redone during the testing at the house except for cases of operator error[11]. The "retaking a ramp" data was simulated by replacing a ramp with data from another test with low wind. Nine of the 26 tests identified as failing the baseline standard deviation criteria were given this treatment. Only tests where replacement of one ramp would "fix" the data were evaluated.

Table 4. Quality control using baseline pressure standard deviation for determining test validity

House	Total tests	Tests with standard deviation of baseline pressure greater than 0.5 Pa	Number of high baseline pressure tests that are salvageable by retaking one ramp	Standard Deviation of Leakage - all tests, cfm [L/s]		Standard Deviation of Leakage - only tests with standard deviation less than 0.5 Pa (0.002 in. water), cfm [L/s]		Standard Deviation of Leakage – with replaced ramps or tests with standard deviation less than 0.5 Pa (0.002 in. water), cfm [L/s]		Number of bad tests*** not captured by baseline pressure limit
				Qs	Qr	Qs	Qr	Qs	Qr	
Sparks 2	11	7*	3	18 [8]	19 [9]	3 [1]	12 [6]	5 [2]	17 [8]	1
Sparks 1	7	1**	1	7 [3	22 [10]	8 [4]	24 11]	Same as all tests	Same as all tests	None
Vacaville	13	6	2	45 [21]	34[16]	14 [7]	14[7]	23 [11]	23 [11]	None
Colton	6	6	None	23 [11]	23 [11]	n/a	n/a	None	None	None
Holly	5	None	n/a	66 [31]	41 [19]	66 [31]	41 [19]	Same as all tests	Same as all tests	1
Rocklin 1	10	5	3	31 [15]	21 [10]	9 [4]	7 [3]	24 [11]	16 [8]	None
Rocklin 2	10	1**	None	8 [4]	11 [5]	8 [4]	12 [6]	Same as all tests	Same as all tests	None

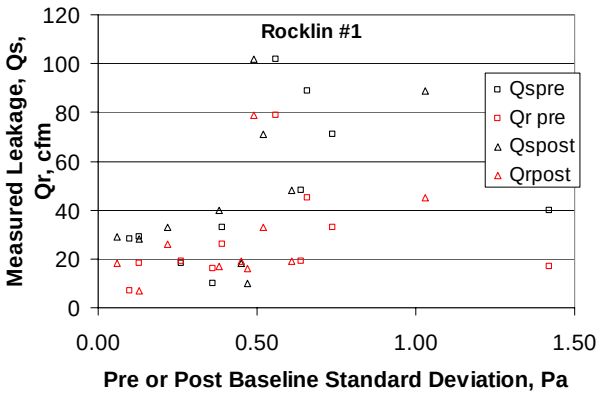
* - three of these 7 tests showed little wind pressure variation effects during the test and the tests were OK.
** - These single occurrences had baseline pressure variation close to the 0.5 Pa limit and the observed DeltaQ data did not have significant wind pressure variation effects and probably did not need even one ramp retaking.
*** - Bad tests in this context had al least one ramp with a significant observable deviation due to wind

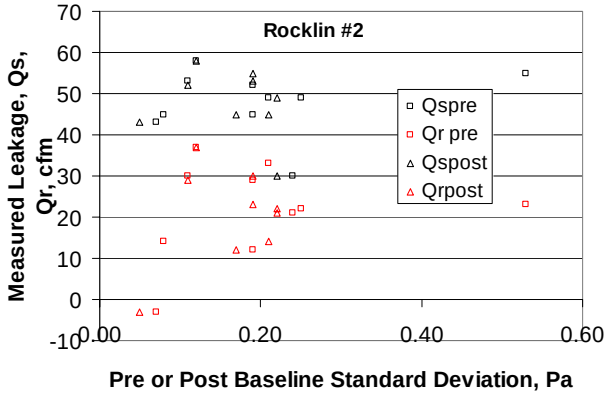
[11] For example, forgetting to use an outside reference for the blower door when pressurizing the house.

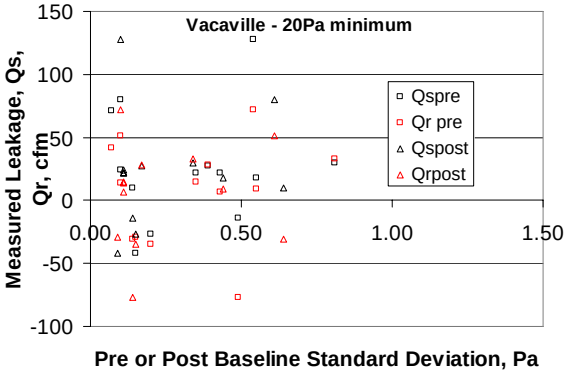
For Sparks 2, Vacaville and Rocklin 1 the test repeatability was improved significantly by applying the 0.5 Pa maximum baseline pressure standard deviation as a criterion for an acceptable test. Only two tests with poor results were not captures by this criterion. One of these tests (Test 1 at Holly) had a single bad low pressure DeltaQ data point (the lowest depressurization data bin). The other test had higher wind induced pressures during the test that were not measured in the baseline data. The combination of improved repeatability together with few missed poor tests indicates that this is a good way of eliminating poor tests. Many of the poor tests could be salvaged by retaking a test ramp so one strategy might be to warn users if the standard deviation of the baseline pressures is high and advise them to retake ramps that show big wind pressure induced variation.

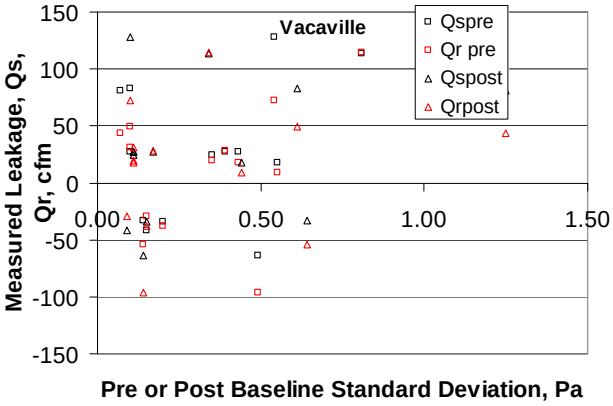
Colton had uniformly high winds and variability for all six tests, however repeatability was among the best (compared to its' envelope leakage). This further illustrates the complexity of wind: it is not just mean windspeed or standard deviation of thirty seconds of wind data that is enough to characterize the wind: if the wind fluctuations are of relatively high frequency compared to the ramping speed then it is averaged out by the binning and DeltaQ function fitting process – as is the case at Colton. The presence of relative long sustained gusts (on the order of 5 to 10 seconds or more) are also required if the DeltaQ results are to be significantly effected. This is essentially impossible to predict. Therefore there will always be some qualitative data observation required and Quality Control issues are reduced to flags for operators to check data.

The 0.5 Pa criterion appears to be conservative because only 2 poor/bad tests (out of 64 total) were not captured but half of the flagged tests were found to be acceptable. However, this criterion is simply being used to flag potentially poor tests that require the user to make decisions about repeating ramps(s) or possibly abandoning testing, rather than categorically state that a test is poor. Therefore the 0.5 Pa criterion is still a very useful Quality Control tool.


Rocklin #1
Measured Leakage, Qs, Qr, cfm
Pre or Post Baseline Standard Deviation, Pa
Qspre
Qr pre
Qspost
Qrpost
120
100
80
60
40
20
0
0.00
0.50
1.00
1.50


Rocklin #2
Measured Leakage, Qs, Qr, cfm
Pre or Post Baseline Standard Deviation, Pa
Qspre
Qr pre
Qspost
Qrpost
70
60
50
40
30
20
10
0
-10
0.00
0.20
0.40
0.60


Vacaville - 20Pa minimum
Measured Leakage, Qs, Qr, cfm
Pre or Post Baseline Standard Deviation, Pa
Qspre
Qr pre
Qspost
Qrpost
150
100
50
0
-50
-100
0.00
0.50
1.00
1.50


Vacaville
Measured Leakage, Qs, Qr, cfm
Pre or Post Baseline Standard Deviation, Pa
Qspre
Qr pre
Qspost
Qrpost
150
100
50
0
-50
-100
-150
0.00
0.50
1.00
1.50

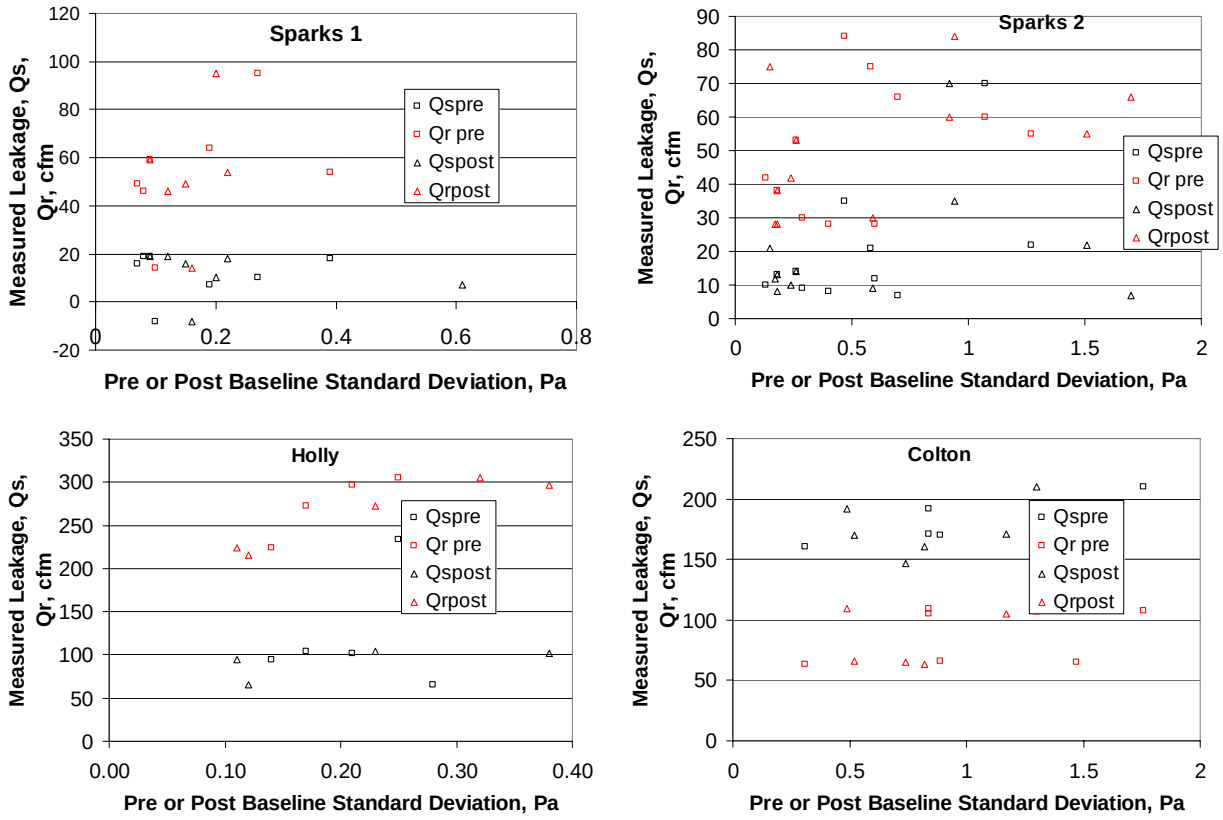


Figure 12. Air Leakage Trends with pre and post baseline pressure variability. (The Qs and Qr values are from one test are plotted twice, once against the pre, and then against the post, baseline pressure standard deviation.

Qualitative approach

The following examples are illustrations of the characteristics of measured data that indicate strong wind pressure change influences on the measured data. There are two primary characteristics to observe that are good indicators of wind induced problems and are cases where repeating a ramp will result in improved measured data.
1. Differences between up and down parts of the same ramp are an excellent indicator of wind-induced problems.
2. "weaving" back and forth during a ramp - in particular if the slope of the data has the wrong sign - e.g., decreasing envelope pressures with increasing air flow.
The illustrative figures are all taken from the Vacaville test house just to show the variability that can be observed for single house.

Figure 10 shows the most dramatic example of large changes between up and down ramps. A difference of this magnitude over such a wide pressure range can significantly change the results - in this case it led to an increase in predicted leakage by about 100 cfm (50 L/s) for supply and 50 cfm (25 L/s) for return leaks compared to the lowest windspeed test. The mean wind speed for the test in Figure 10 was 1.6 m/s (3.6 mph)). Figure 11 shows the DeltaQ calculated from the data in Figure 10, together with the DeltaQ fitted function from the pressure scanning analysis. In this case the wind gust excursion, although far from the other data, did not exert a strong influence on the DeltaQ fitted function.

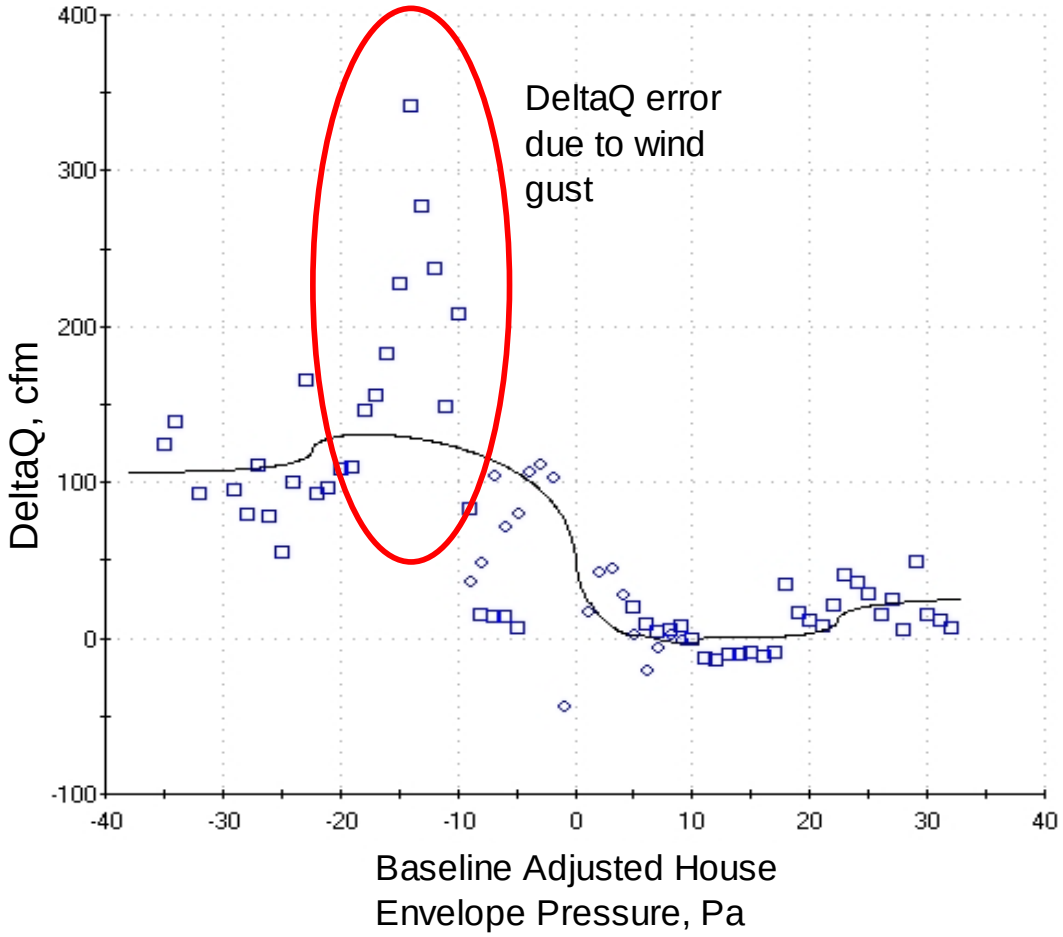


Figure 13. DeltaQ representation of data from Figure 10 showing large excursion in DeltaQ data due to a wind gust.

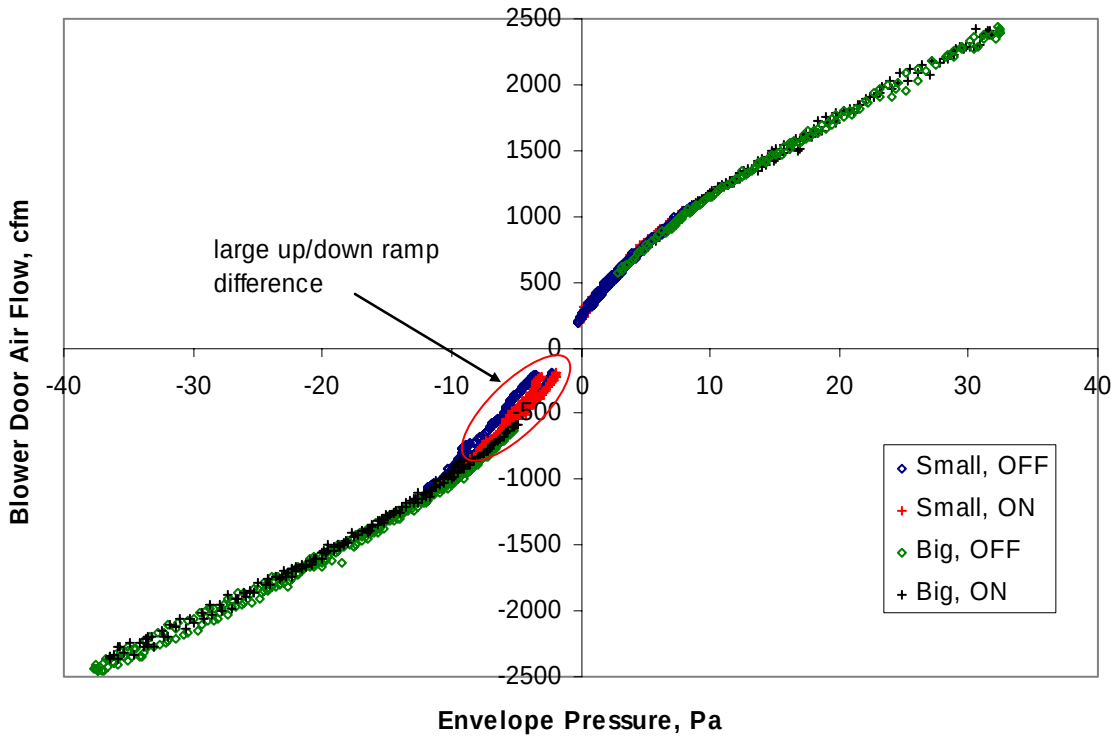


Figure 14. Moderate differences between ramps at lower envelope pressures.

Comparing Figure 10 to Figure 14 shows that it is more difficult to observe the changes in measured air flows and envelope pressure differences when differences between ramps are at lower pressure. However, because the DeltaQ analysis tends to be more sensitive to measurement errors at lower envelope pressures it pays to make careful observation of low pressure measurements. To make this clearer, Figure 15 shows the test data from Figure 14 but for the small orifice, low envelope pressures only. These lower pressure smaller absolute magnitude (but large fractional change) differences between up and down portions of the ramp are slightly harder to observe when looking at all the data on a single plot as in Figure 10. Nevertheless, during testing as the data are plotted by the software the trend is clearly observable and the replotting of low pressure data as in Figure 15 is not necessary. Figure 15 shows how the low pressure depressurization results with the central fan off have big differences (much greater than the 20% criterion used elsewhere to eliminate data from the analysis). The resulting DeltaQ data are shown in Figure 16. This was the lowest windspeed tests for this house and had supply leakage of 27 cfm (13 L/s) and return leakage of 31 cfm (15 L/s).

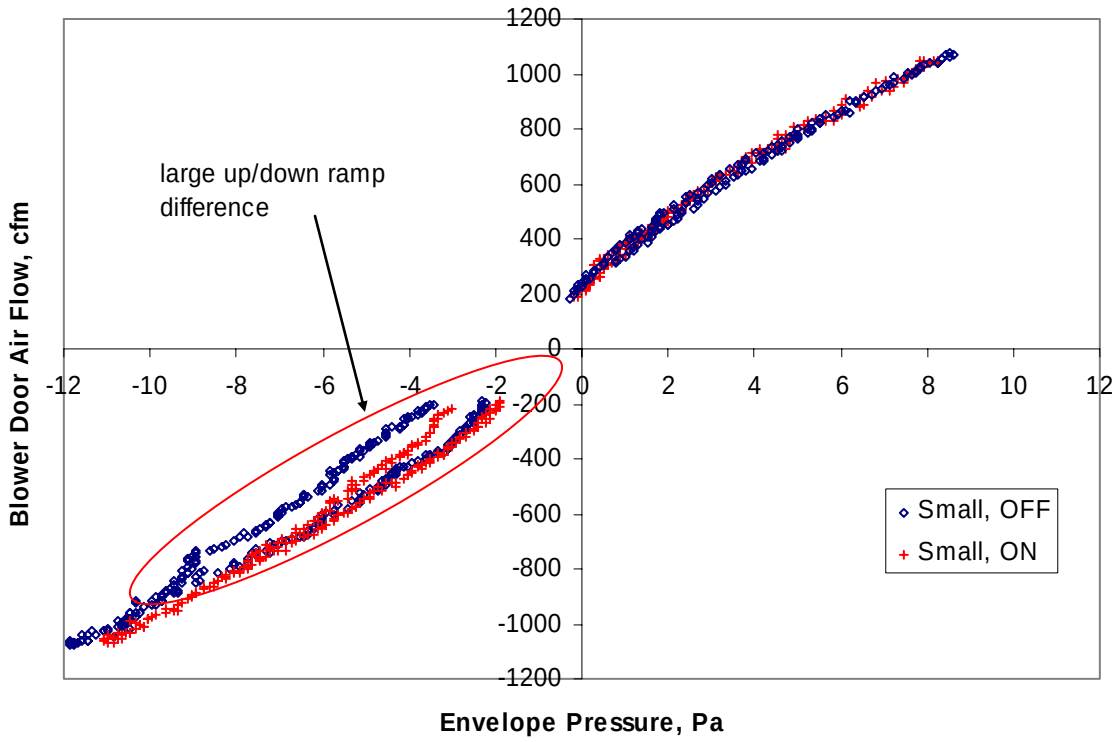


Figure 15. Small orifice, low envelope pressure differences in ramping data for the same test as in Figure 10.

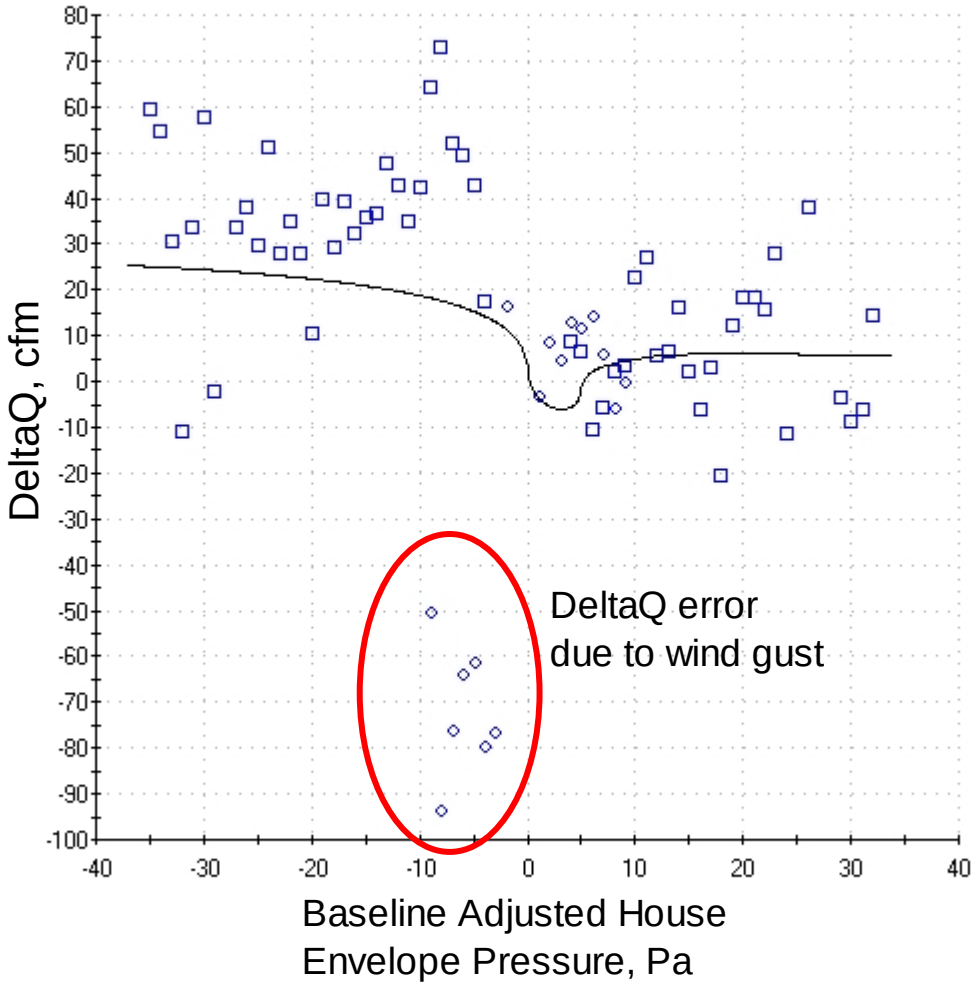


Figure 16. DeltaQ data from the test shown in Figure 14.

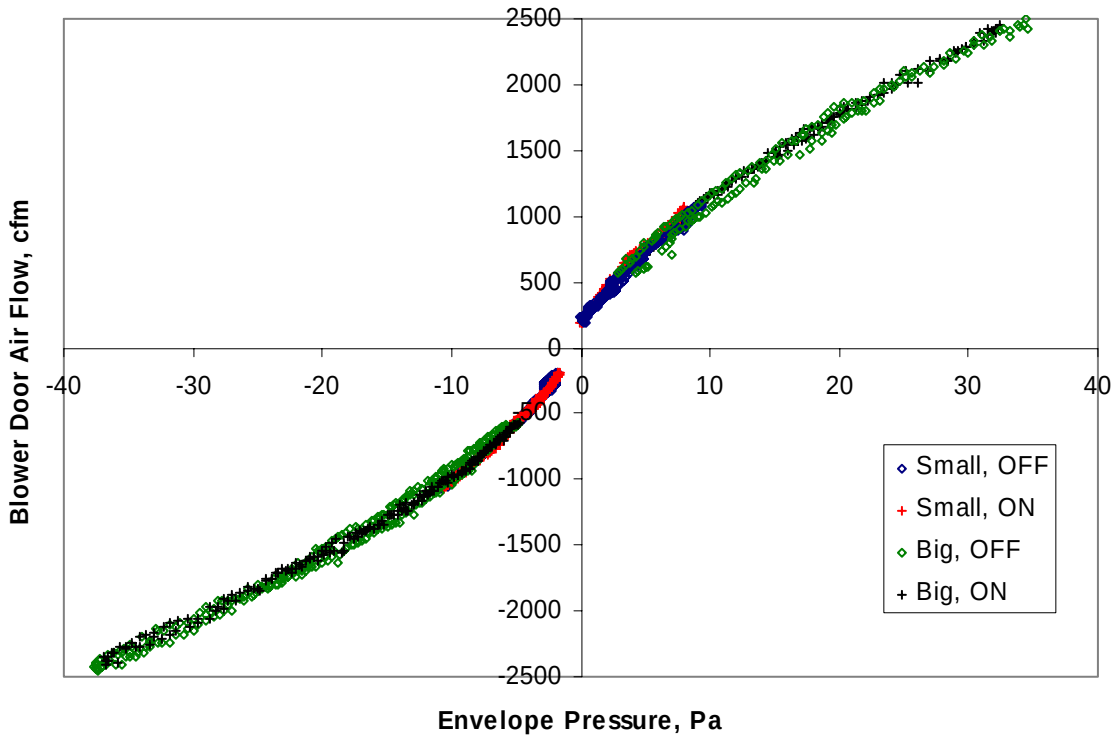


Figure 17. Low wind speed test with consistent up and down parts for each ramp.

Figure 17 illustrates a test with consistent windspeeds for each ramp but with some fairly random pressure and flow variability (due to wind pressure fluctuations). This figure does not exhibit the excursions between up and down ramps seen in Figures 10, and 13 through 16 and no ramps needed to be redone. The mean windspeed is actually higher than for the data in Figure 10 at 1.7 m/s (3.8 mph). Even the maximum windspeed recorded during the test is not particularly low at 4.5 m/s (10.1 mph). What matters most is consistent windspeeds during the test and for the central blower on and off data rather than the magnitude of the wind. Figure 18 shows the DeltaQ data from Figure 17 and illustrates how the variability in DeltaQ is random and does not exhibit the obvious variability shown in Figures 13 and 16. The random DeltaQ data resulted in predicted supply and return leakage flows of zero.

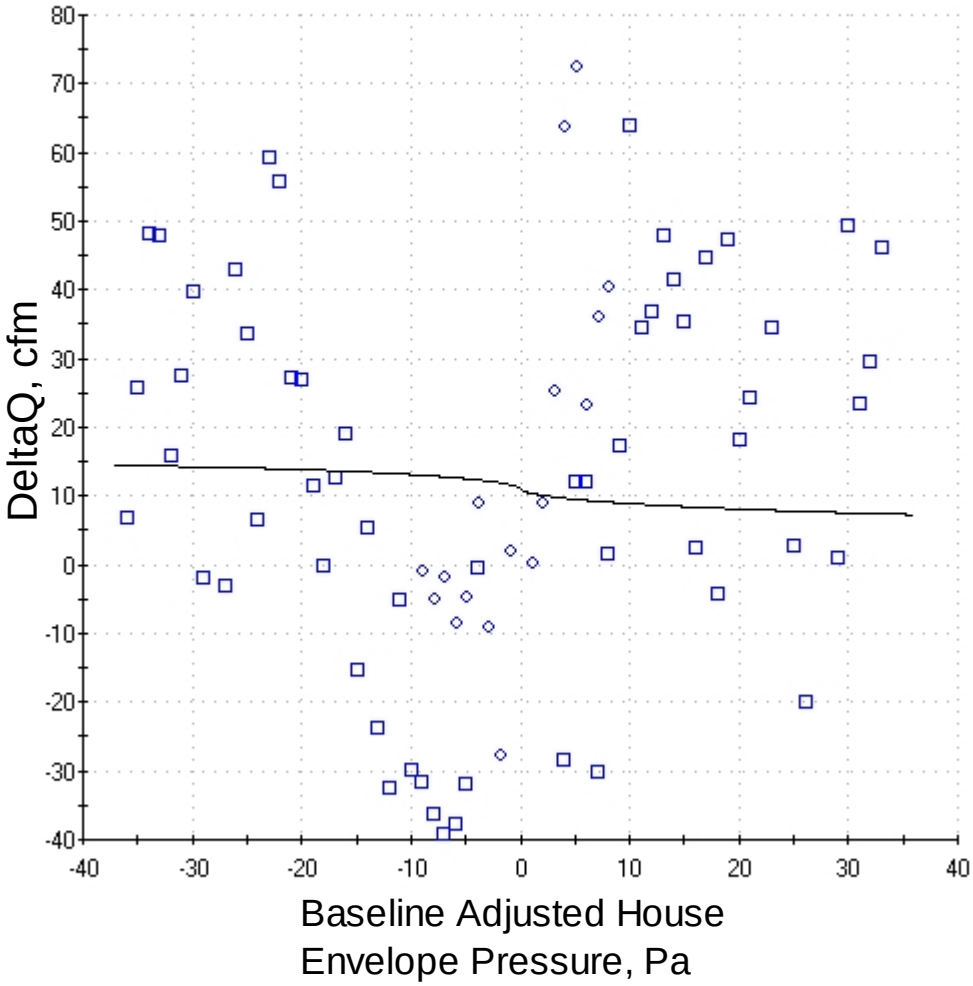


Figure 18. DeltaQ using data from Figure 17 showing random variability and no strong trends, outliers or groups of displaced data due to sustained wind gusts.

Estimating Repeatability Uncertainty Using Envelope Leakage

Because the DeltaQ test is based on air flows through the building envelope it is reasonable to assume that the repeatability uncertainty will scale with envelope leakage because, for any given wind pressure fluctuation, the resulting envelope flows will be larger for a leaky envelope. To examine the relationship between test variability and envelope leakage we examined the ratio of the standard deviation of the tests to the 50 Pa (0.2 in. water) envelope leakage[12]. It averaged 0.77% for supply leaks and 0.97% for return leaks – with high baseline pressure

[12] The envelope leakage used here is taken from the results of a least squares fit to the system blower off data and therefore includes the holes in the duct system that contribute to envelope leakage. This corresponds to the envelope leakage traditionally measured in envelope air tightness testing. It would be possible to subtract the duct contribution but this is not particularly useful or informative.

variation tests not included. This suggests a rule of thumb estimate for leakage uncertainty of 1% of the 50 Pa (0.2 in. water) envelope leakage (Q50) that will be a conservative estimate (i.e., it slightly overestimates the uncertainty). Figure 19 illustrates the standard deviation of the tests as a function of envelope leakage – expressed as 1% of Q50. The trend in the standard deviations clearly correlate with the envelope leakage.

This rule of thumb is still reasonable even if the tests with high baseline fluctuations are included. The ratio of the standard deviation of the tests to the 50 Pa envelope leakage averaged 1.28% for supply leaks and 1.22% for return leaks – and the trend is shown in Figure 20.

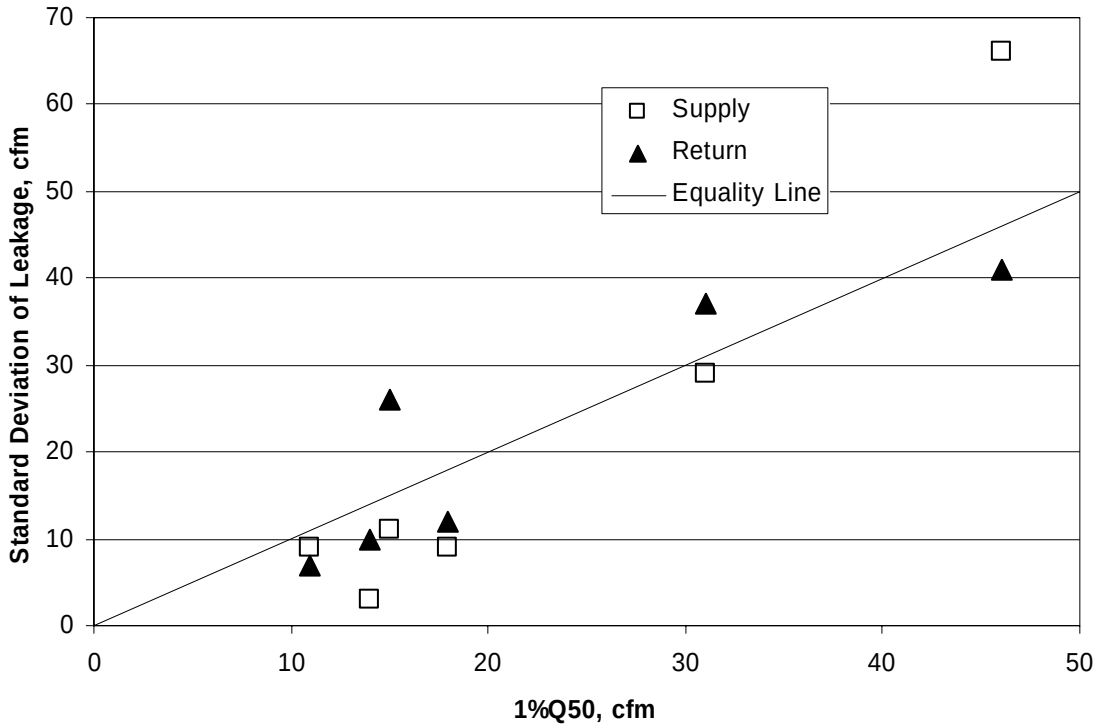


Figure 19. Trend of standard deviation of multiple tests with envelope leakage for tests with high baseline pressure not included

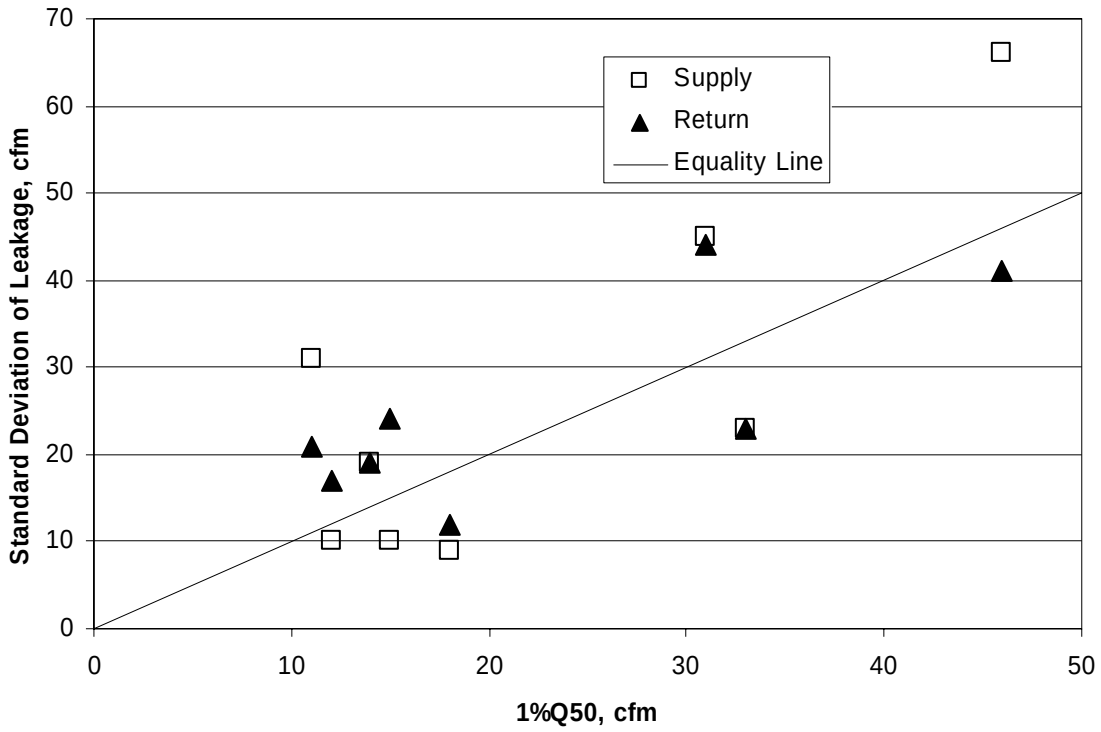


Figure 20. Trend of standard deviation of multiple tests with envelope leakage for all tests

This rule of thumb has also been applied to three additional houses not included in the current study: the two tight houses from Walker and Dickerhoff (2006), an additional test in a Bay Area home. The ratio of the standard deviation of the ramping tests to the 50 Pa envelope leakage averaged 0.74% for supply leaks and 0.97% for return leaks with these additional tests included. Four houses and a trailer at LBNL also had the non-ramping pressure station tests performed multiple times for repeatability – with similar results. The trailer was tested 20 times by Walker et al. (2001) in a single duct leakage configuration and then in a further four duct leakage configurations (with about four tests in each configuration) by Walker et al. (2002). Including these pressure station tests barely changed the ratio of the standard deviation of the tests to the 50 Pa envelope leakage to 0.74% for supply leaks and 0.94% for return leaks. All these results are shown in Figure 21.

A field study by Andrews (2000) performed DeltaQ testing using pressure stations rather than ramping three times in each of two houses. The average difference from the mean was 8 cfm (4 L/s) for supplies and 19 cfm (9 L/s) for returns. Without the envelope leakage we cannot evaluate these results as a fraction of envelope leakage, but they provide another estimate of DeltaQ repeatability.

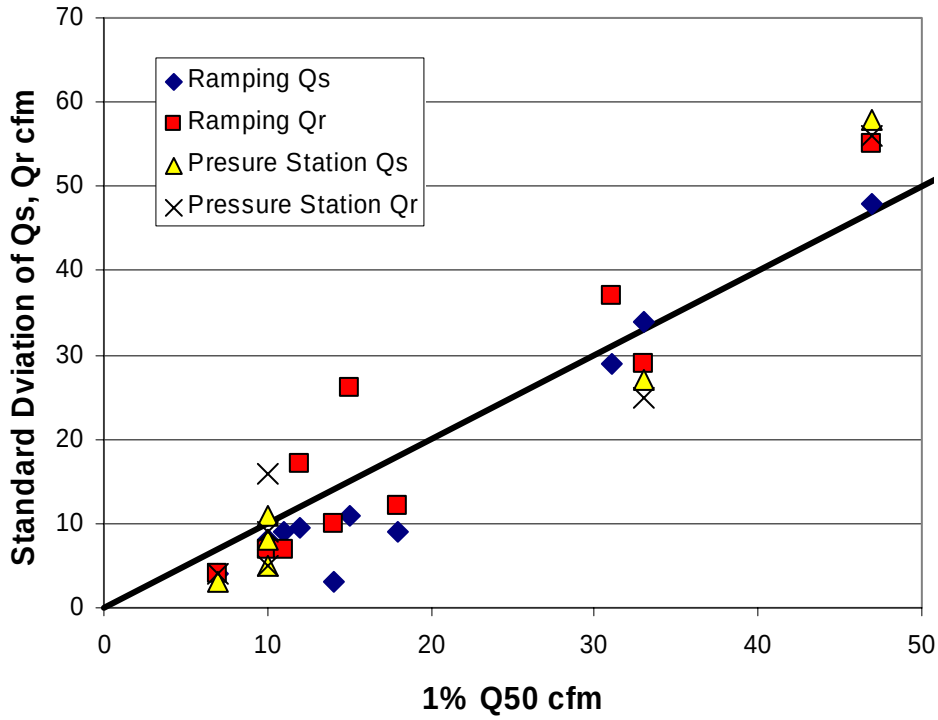


Figure 21. Trend of standard deviation of multiple tests with envelope leakage including houses not tested in this study and using pressure stations instead of ramping for five buildings.

At this point it is informative to compare these estimated uncertainties with those from the test method in common use: duct pressurization[13]. For repeatability only, there is little information available on test-to-test repeatability. A study (Walker et al. 1998) by LBNL and California Energy Commission staff where three tests were performed in each of nine houses showed repeatability uncertainties of ±15 cfm (7.5 L/s). The testers attributed these differences to differences in duct pressure probe placement and pressurization fan installation. These were measurements of total duct leakage, rather than leakage to outside and therefore did not have the complication of trying to match duct and envelope pressure differences. In particular, field experience has shown that trying to maintain a constant envelope and duct pressure to outside on a windy day with fluctuating envelope pressures can be difficult. This can be ameliorated somewhat by taking long time averages but there will be increased uncertainty and repeatability errors for combined envelope and duct testing on windy days. Given these issues it is difficult to compare the repeatability results directly - they can just be used for guidance. For the data presented in this report, the repeatability for duct only pressurization is about in the middle of the repeatability estimates for DeltaQ.

In order to provide more context for these uncertainties, we need to compare the total uncertainty of DeltaQ and pressurization testing. Because pressurization testing measures an air flow at a fixed pressure, the air flow at operating conditions may not be the same as the tested air flow. This issue of not having the same pressure across the leaks during the duct pressurization test as during normal operation is a bigger source of uncertainty than repeatability. Several studies have been performed where the true leakage was known in a laboratory setting: a laboratory study by Walker and Dickerhoff (2008) has shown duct pressurization errors (40 to 60 cfm (20 to 30 L/s)) that were double those of DeltaQ testing (20 to 30 cfm (10 to 15 L/s)). An earlier laboratory study by Andrews (2002) also showed that pressurization errors were double those for DeltaQ testing (using pressure stations rather than ramping). Francisco et al. (2003a) reported similar differences of a factor of two increase in uncertainty for

[13] The results discussed here are for duct pressurization to 25 Pa (0.1 in. water). Some pressurization test protocols specify 50 Pa (0.2 in. water) and these tests would have large biases of 50% compared to the 25Pa test results (and the DeltaQ test results).

pressurization compared to Delta Q in a field study of 51 homes. This study compared DeltaQ testing to a baseline reference. Despite shortcomings with this reference, we can use these results as a guide to the relative applicability of pressurization and DeltaQ testing for low leakage systems. The test results allowed us to evaluate the ability of DeltaQ to correct pass or fail a 6% of system blower flow low leak limit. Eight houses had duct leakage less than 6% of system blower flow. DeltaQ correctly identified seven of these tests. DeltaQ also identified one house as having excess leakage (11% instead of 6%) and two houses as having less than 6% leakage when their baseline reference leakage was 7% and 10%. For fan pressurization, only two of the eight houses with leakage less than 6% were correctly identified. Therefore, six houses were incorrectly identified as being too leaky. In addition, pressurization identified one house with less than 6% leakage when the baseline reference indicated 10% leakage. These results indicate that DeltaQ is at least as good as pressurization at detecting low leakage systems.

Combining these uncertainty estimates indicates that for anything other than a very leaky building (greater than 5000 cfm50) the uncertainties for measuring the duct leakage to outside under normal operating conditions (which is what is needed for energy loss estimates) are smaller for DeltaQ testing than for pressurization. This conclusion applies over the wide range of duct and envelope leakage encompassed by the referenced studies. However, if we want to focus on meeting a tight duct specification, then the results may be different. To answer this question, the 14 tests with actual duct leakage of 6% of fan flow or less from the laboratory tests of Walker and Dickerhoff (2008) were analyzed. They showed an RMS difference of 1.9% of fan flow for DeltaQ and 3.6% of fan flow for pressurization testing. The larger errors for the duct pressurization testing are due to the leak pressures under operating conditions not being equal to 25 Pa (0.1 in. water).

RECOMMENDATIONS

This study focuses on answering two questions:
1. What is the uncertainty associated with changes in weather (primarily wind) conditions during DeltaQ testing?
2. How can these uncertainties be reduced ?

Several techniques for improving the DeltaQ data acquisition and analysis in order to reduce wind sensitivity while retaining a reasonable characteristic pressure resolution have been developed:

- The bin size used in the analysis should be 2.5 Pa (0.01 in. water).
- The minimum number of points per bin is three each size of the bin center.
- Pressure tubing should be positioned to be sheltered from the wind (and blower door flows).
- The blower door should be installed in the most sheltered doorway.
- The minimum characteristic pressure should be at least twice the lowest data bin and could be increased to a fixed value of 20 Pa (0.08 in. water) to make the test more robust under windy conditions for houses with leaky envelopes.
- Under windy conditions, particularly for leaky homes the Pressure Scanning analysis technique is preferable because it is less sensitive to wind pressure changes at low envelope pressures.
- Having a standard deviation of either the pre- or post-test baseline pressures exceed 0.5 Pa is a good flag for the possibility of poor data and indicates that one or more ramps need to be retaken.
- Many tests can be improved by retaking a single ramp.
- A good rule of thumb for repeatability uncertainty is 1% of the whole building air leakage at 50 Pa (0.2 in. water) pressure difference (Q50).

It terms of showing that DeltaQ uncertainties acceptable for testing low leakage systems, the rule of thumb would suggest that typical new homes with 1% of Q50 of 30 cfm (15 L/s) or less will give acceptable results compared to low leakage limits that are typically 6% of air handler flow (a range of about 60 cfm to 120 cfm (30 to 60 L/s) depending on system size).

This study has also developed examples of good and bad test illustrations that can be used by users to further improve quality control.

The uncertainties for DeltaQ testing are lower than those for pressurization testing - particularly at the low leakage levels required for efficient duct systems - therefore DeltaQ testing is recommended for this application.

CONCLUSIONS

The wind induced DeltaQ errors are highly variable and are not amenable to simple correlations with wind speed or even standard deviation of wind induced measured envelope pressure differences. Instead, a rule of thumb has been developed for estimating repeatability uncertainty: 1% of envelope flow at 50 P a (0.2 in. water) .

Variability in baseline envelope pressures can be used successfully to flag potentially poor data. These poor data can be replaced with good data by redoing only part of the test (typically one of the eight ramps).

There are key characteristics that are easily observable during the test that allow the user to recognize poor data.

DeltaQ is an acceptable test at the low leakage levels required for efficient duct systems unless the building envelope is very leaky (greater than about 4000 to 5000 cfm (2000 to 2500 L/s) at 50 Pa (02 In. water)).

REFERENCES:

Andrews, J.W. 2000. *Measurement Uncertainties in the DeltaQ test for Duct Leakage*. Brookhaven National Laboratory report BNL-67894.

Andrews, J.W. 2002. *Laboratory Evaluation of the DeltaQ Test for Duct Leakage*. ACEEE Summer Study. Pacific Grove. Ca. American Council for an Energy Efficient Economy, 1001 Connecticut Ave. N.W., Suite 335, Washington, D.C. 2002.

ASTM (2007) ASTM E1554-07 "Standard Test Methods for Determining External Air Leakage of Air Distribution Systems by Fan Pressurization". American Society for Testing and Materials, West Conshohocken, PA.

ASTM (2003) ASTM E1554-03 "Standard Test Methods for Determining External Air Leakage of Air Distribution Systems by Fan Pressurization". American Society for Testing and Materials, West Conshohocken, PA.

ASTM (2003) ASTM E779-03 "Determining Air Leakage Rate by Fan Pressurization".American Society for Testing and Materials, West Conshohocken, PA.

California Energy Commission. 2005. *Title 24, Part 6, of the California Code of Regulations: California's Energy Efficiency Standards for Residential and Nonresidential Buildings*. California Energy Commission, Sacramento, CA.

Dickerhoff, D.J., Walker, I.S. and Sherman, M.H. (2004), "Validating and Improving the DeltaQ Duct Leakage Test", ASHRAE Transactions Vol. 110, Pt. 2., pp.741-751, ASHRAE, Atlanta, GA. LBNL 53959.

Francisco, P., Palmiter, L. Kruse, E. and Davis, B. 2003a. Field Evaluation of Improved Methods for Measuring the Air Leakage of Duct Systems under Normal Operating Conditions in 51 Homes. National Energy Technology Laboratory Report. Contract # DE-FC26-01NT41257.

Francisco, P., Palmiter, and Davis, B. 2003. Insights Into Improved ways to Measure Residential Duct Leakage". ASHRAE Transactions, Vol. 110, Pt. 2., ASHRAE, Atlanta, GA.

Walker, I., Sherman, M., Modera, M., Siegel, J.(1998). "Leakage Diagnostics, Sealant Longevity, Sizing and Technology Transfer in Residential Thermal Distribution Systems" LBL-41118. http://epb.lbl.gov/publications/lbl-41118.pdf

Walker, I.S., Sherman, M.H., Wempen, J., Wang, D., McWilliams, J.A., and Dickerhoff, D.J. (2001). Development of a New Duct Leakage Test: Delta Q. LBNL-47308. http://epb1.lbl.gov/EPB/Publications/lbnl-47308.pdf

Walker, I.S., Dickerhoff, D.J. and Sherman, M.H. (2002). "The DeltaQ Method of Testing the Air Leakage of Ducts". Proc. ACEEE Summer Study 2002, American Council for an Energy Efficient Economy, Washington, D.C. LBNL 49749. http://epb1.lbl.gov/EPB/Publications/lbnl-49749.pdf

Walker, I.S., Sherman, M.H. and Dickerhoff, D.J. (2004), "Reducing uncertainty for the DeltaQ duct leakage test", Proc. ASHRAE/DOE/BTECC Thermal Performance of the Exterior Envelopes of Buildings IX, ASHRAE, Atlanta, GA. LBNL 53549. http://epb1.lbl.gov/EPB/Publications/lbnl-53549.pdf

Walker, I.S., and Dickerhoff, D.J (2006), "Evaluation of a New Ramping Technique for Duct Leakage Testing", LBNL-61743, http://epb.lbl.gov/publications/lbnl-61743.pdf

Walker, I.S. and Dickerhoff, D.J. (2008). "Field and Laboratory Evaluation of a new ramping technique for duct leakage testing". Accepted for ASHRAE Transactions, January 2008. LBNL 62262.

APPENDIX 1: ANALYSIS RESULTS FOR INDIVIDUAL HOUSES

The tables in this appendix shows the envelope leakage, baseline pressure information, and average wind speed for each test.
The first table shows the results using all the data with the lower limit of Ps and Pr as twice the data minimum.
The second table shows the results where non matching up/down ramp data was removed. (This sometimes resulted in not enough data to allow an analysis of the test.)
The third table shows the test results where Ps and Pr are forced to be at least 20 Pa.

The Table column heading abbreviations are:

BST	Baseline Stability Test, result is Yes or no to flagging for possible errors
N2.5	NNLS with 2.5 Pa bins
N5	NNLS with 5 Pa bins
S2.5	Scanning with 2.5 Pa bins
S5	Scanning with 5 Pa bins
A2.5	Non Negative Adjusted Scanning with 2.5 Pa bins
A5	Non Negative Adjusted Scanning with 5 Pa bins
Avg.	Average
STD	Standard Deviation

Sparks 1

	Envelope Leakage (Includes Duct Leakage) at 50 Pa	Avg. Wind Speed	Initial Baseline House Pressure Measurement		Final Baseline House Pressure Measurement	
Test #	cfm	[m/s]	Average Pressure (Pa)	STD	Average Pressure (Pa)	STD
1	1525	0.7	-1.43	0.07	-0.92	0.15
2	1562	0.9	-1.18	0.08	-0.88	0.12
3	1530	1.0	-1.01	0.09	-0.83	0.09
4	1452	1.1	-0.59	0.10	-0.71	0.16
5	1551	1.3	-0.99	0.27	-0.84	0.20
6	1463	1.1	-1.51	0.39	-0.42	0.22
8	1424	2.2	-1.74	0.19	-0.34	**0.61**

Table A2-1a: Sparks 1 envelope leakage, wind speed, and baseline pressure data. STD values which are in excess of the Baseline Stability Test criteria of 0.5 Pa are in a bold red font.

		Supply Leakage Flow, Qs (cfm)						Return Leakage Flow, Qr (cfm)					
Test #	BST	N2.5	N5	S2.5	S5	A2.5	A5	N2.5	N5	S2.5	S5	A2.5	A5
1	No	22	21	16	16	16	16	58	56	49	49	49	49
2	No	28	24	19	18	19	18	62	59	46	45	46	45
3	No	19	18	19	18	19	18	60	58	59	58	59	58
4	No	0	0	-8	-8	0	0	22	22	14	14	22	22
5	No	12	0	10	-11	10	0	97	84	95	75	95	86
6	No	20	21	18	19	18	19	59	58	54	55	54	55
8	**Yes**	7	0	7	-12	7	0	63	43	64	27	64	39
Avg.		**15**	**12**	**12**	**6**	**13**	**10**	**60**	**54**	**54**	**46**	**56**	**51**
STD		**10**	**11**	**10**	**15**	**7**	**10**	**22**	**19**	**24**	**20**	**22**	**20**
Statistics for tests which pass the BST criteria:													
Avg.		**17**	**14**	**12**	**9**	**14**	**12**	**60**	**56**	**53**	**49**	**54**	**53**
STD		**10**	**11**	**11**	**14**	**8**	**9**	**24**	**20**	**26**	**20**	**24**	**21**

Table A2-1b: DeltaQ analysis results using twice the lowest data as lower limits to Ps and Pr. Note: Test 7 was not done with the ramping method.

		Supply Leakage Flow, Qs (cfm)						Return Leakage Flow, Qr (cfm)					
Test #	BST	N2.5	N5	S2.5	S5	A2.5	A5	N2.5	N5	S2.5	S5	A2.5	A5
1	No	22	19	17	16	17	16	59	49	51	49	51	49
2	No	31	30	21	22	21	22	65	65	48	50	48	50
3	No	18	18	18	16	18	16	59	58	59	57	59	57
4	No	0	0	-7	-8	0	0	22	22	15	14	22	22
5	No	2	0	-8	-9	0	0	88	74	82	68	90	77
6	No	21	22	17	19	17	19	64	62	53	56	53	56
8	**Yes**	2	0	-3	-11	0	0	64	43	58	35	61	46
Avg.		**14**	**13**	**8**	**6**	**10**	**10**	**60**	**53**	**52**	**47**	**55**	**51**
STD		**12**	**12**	**13**	**15**	**10**	**10**	**20**	**17**	**20**	**18**	**20**	**16**
Statistics for tests which pass the BST criteria:													
Avg.		**16**	**15**	**10**	**9**	**12**	**12**	**60**	**55**	**51**	**49**	**54**	**52**
STD		**12**	**12**	**13**	**14**	**10**	**10**	**21**	**18**	**22**	**18**	**22**	**18**

Table A2-1c: DeltaQ analysis where poor data, as determined by differences in the up and down sections of the ramping data collection procedure have been removed. Results using twice the lowest data as lower limits to Ps and Pr.

		Supply Leakage Flow, Qs (cfm)						Return Leakage Flow, Qr (cfm)					
Test #	BST	N2.5	N5	S2.5	S5	A2.5	A5	N2.5	N5	S2.5	S5	A2.5	A5
1	No	18	19	16	16	16	16	49	50	49	49	49	49
2	No	26	25	19	18	19	18	60	58	46	45	46	45
3	No	19	18	19	18	19	18	59	58	59	58	59	58
4	No	0	2	-8	-8	0	0	22	22	14	14	22	22
5	No	0	0	-13	-15	0	0	71	72	60	60	73	75
6	No	20	21	18	19	18	19	57	57	54	55	54	55
8	**Yes**	0	0	-8	-12	0	0	50	43	42	27	50	39
Avg.		**12**	**12**	**6**	**5**	**10**	**10**	**53**	**51**	**46**	**44**	**50**	**49**
STD		**11**	**11**	**15**	**16**	**10**	**10**	**15**	**16**	**16**	**17**	**15**	**17**
Statistics for tests which pass the BST criteria:													
Avg.		**14**	**14**	**9**	**8**	**12**	**12**	**53**	**53**	**47**	**47**	**51**	**51**
STD		**11**	**10**	**15**	**15**	**9**	**9**	**17**	**17**	**17**	**17**	**17**	**17**

Table A2-1d: DeltaQ analysis results 20 Pa as lower limits to Ps and Pr.

Sparks 2

	Envelope Leakage (Includes Duct Leakage) at 50 Pa	Avg. Wind Speed	Initial Baseline House Pressure Measurement		Final Baseline House Pressure Measurement	
Test #	cfm	[m/s]	Average Pressure (Pa)	STD	Average Pressure (Pa)	STD
1	1367	4.3	-0.03	0.70	1.42	1.70
3	1385	2.3	0.25	0.40	0.78	0.18
4	1388	1.4	0.70	0.26	0.32	0.26
5	1383	1.9	-0.18	0.47	0.16	0.94
6	1328	2.5	0.21	0.18	0.25	0.18
8	1325	1.4	0.31	0.60	0.74	0.17
9	1358	1.5	0.06	0.58	0.49	0.15
10	1326	2.1	-1.36	1.27	-0.87	1.51
11	1173	3.2	-1.31	1.07	-0.38	0.92
12	1364	0.7	-1.40	0.13	-0.96	0.24

Table A2-2a: Sparks 2 envelope leakage, wind speed, and baseline pressure data. STD values which are in excess of the Baseline Stability Test criteria of 0.5 Pa are in a bold red font.

		Supply Leakage Flow, Qs (cfm)						Return Leakage Flow, Qr (cfm)					
Test #	BST	N2.5	N5	S2.5	S5	A2.5	A5	N2.5	N5	S2.5	S5	A2.5	A5
1	**Yes**	10	7	7	7	7	7	66	62	66	62	66	62
3	No	9	12	8	10	8	10	29	29	28	29	28	29
4	No	17	18	14	15	14	15	60	57	53	54	53	54
5	**Yes**	63	45	35	27	35	27	87	83	84	80	84	80
6	**Yes***	23	25	13	11	13	11	53	59	38	39	38	39
7	**Yes**	12	15	12	11	12	11	31	28	28	27	28	27
8	**Yes**	30	24	21	20	21	20	82	78	75	73	75	73
9	**Yes**	46	30	22	22	22	22	77	67	55	55	55	55
10	**Yes**	63	78	70	71	70	71	50	52	60	53	60	53
11	No	13	14	10	10	10	10	43	42	42	39	42	39
12	No	14	13	9	8	9	8	34	32	30	29	30	29
Avg.	11 tests	**27**	**26**	**20**	**19**	**20**	**19**	**56**	**54**	**51**	**49**	**51**	**49**
STD		**21**	**20**	**18**	**18**	**18**	**18**	**21**	**19**	**19**	**18**	**19**	**18**
Statistics for tests which pass the BST criteria:													
Avg.	4 tests	**13**	**14**	**10**	**11**	**10**	**11**	**42**	**40**	**38**	**38**	**38**	**38**
STD		**3**	**3**	**3**	**3**	**3**	**3**	**14**	**13**	**12**	**12**	**12**	**12**
Tests with one or more ramps replaced by "good" tests:													
5		34	34	17	18	17	18	75	71	61	61	61	61
7		10	14	10	10	10	10	19	21	18	18	18	18
8		2	0	-13	-25	0	0	21	13	6	-7	19	0
Statistics for tests pass the BST criteria OR were "fixed" by replacing one or more ramps:													
Avg.	7 tests	**14**	**15**	**8**	**7**	**10**	**10**	**40**	**38**	**34**	**32**	**36**	**33**
STD		**10**	**10**	**10**	**14**	**5**	**6**	**21**	**20**	**19**	**23**	**17**	**21**

Table A2-2b: DeltaQ analysis results using twice the lowest data as lower limits to Ps and Pr. Note: Test 2 data file was corrupted; test 6 had low baseline standard deviations, but was clearly influenced by the wind in at least two ramps and is grouped with the "Failed" BST tests.

		Supply Leakage Flow, Qs (cfm)						Return Leakage Flow, Qr (cfm)					
Test #	BST	N2.5	N5	S2.5	S5	A2.5	A5	N2.5	N5	S2.5	S5	A2.5	A5
1	**Yes**	14	8	16	8	16	8	74	69	76	69	76	69
3	No	15	12	15	12	15	12	30	28	29	28	29	28
4	No	16	16	14	15	14	15	59	55	54	54	54	54
5	**Yes**	53	57	35	36	35	36	91	93	86	87	86	87
6	**Yes***	9	11	10	12	10	12	35	40	37	39	37	39
7	**Yes**	13	13	13	13	13	13	32	35	31	35	31	35
8	**Yes**	12	11	12	11	12	11	49	47	49	47	49	47
9	**Yes**	19	14	19	14	19	14	51	37	51	37	51	37
10	**Yes**	44	na	44	na	44	na	18	na	18	na	18	na
11	No	13	14	10	10	10	10	43	44	41	39	41	39
12	No	12	13	9	9	9	9	34	32	29	29	29	29
Avg.	10 tests	**20**	**17**	**18**	**14**	**18**	**14**	**47**	**48**	**46**	**46**	**46**	**46**
STD		**14**	**14**	**11**	**8**	**11**	**8**	**21**	**20**	**21**	**19**	**21**	**19**
Statistics for tests which pass the BST criteria:													
Avg.	5 tests	**14**	**14**	**12**	**12**	**12**	**12**	**42**	**40**	**38**	**38**	**38**	**38**
STD		**2**	**2**	**3**	**3**	**3**	**3**	**13**	**12**	**12**	**12**	**12**	**12**

Table A2-2c: DeltaQ analysis where poor data, as determined by differences in the up and down sections of the ramping data collection procedure have been removed. Results using twice the lowest data as lower limits to Ps and Pr.

		Supply Leakage Flow, Qs (cfm)						Return Leakage Flow, Qr (cfm)					
Test #	BST	N2.5	N5	S2.5	S5	A2.5	A5	N2.5	N5	S2.5	S5	A2.5	A5
1	**Yes**	12	7	7	7	7	7	68	62	66	62	66	62
3	No	10	12	8	10	8	10	30	31	28	29	28	29
4	No	16	18	14	15	14	15	55	56	53	54	53	54
5	**Yes**	37	36	35	27	35	27	85	85	84	80	84	80
6	No	2	1	-3	-4	0	0	33	35	30	30	33	34
7	**Yes**	12	11	12	11	12	11	31	28	28	27	28	27
8	**Yes**	21	20	21	20	21	20	75	73	75	73	75	73
9	**Yes**	23	24	22	22	22	22	62	64	55	55	55	55
10	**Yes**	49	53	49	53	49	53	46	46	46	46	46	46
11	No	12	12	10	10	10	10	42	41	42	39	42	39
12	No	11	10	9	8	9	8	32	32	30	29	30	29
Avg.		**19**	**19**	**17**	**16**	**17**	**17**	**51**	**50**	**49**	**48**	**49**	**48**
STD		**14**	**15**	**15**	**15**	**14**	**14**	**19**	**19**	**20**	**19**	**19**	**18**
Statistics for tests which pass the BST criteria:													
Avg.		**12**	**13**	**10**	**11**	**10**	**11**	**40**	**40**	**38**	**38**	**38**	**38**
STD		**3**	**3**	**3**	**3**	**3**	**3**	**11**	**12**	**12**	**12**	**12**	**12**
Tests with one or more ramps replaced by "good" tests:													
6		23	23	17	18	17	18	73	69	61	61	61	61
7		10	10	10	10	10	10	18	18	18	18	18	18
8		1	0	-13	-17	0	0	14	13	6	3	19	20
Statistics for tests pass the BST criteria OR were "fixed" by replacing one or more ramps:													
Avg.		**12**	**12**	**8**	**8**	**10**	**10**	**38**	**37**	**34**	**33**	**36**	**36**
STD		**7**	**7**	**10**	**11**	**5**	**6**	**21**	**20**	**19**	**20**	**17**	**17**

Table A2-2d: DeltaQ analysis results 20 Pa as lower limits to Ps and Pr.

Rocklin 1

	Envelope Leakage (Includes Duct Leakage) at 50 Pa	Avg. Wind Speed	Initial Baseline House Pressure Measurement		Final Baseline House Pressure Measurement	
Test #	cfm	[m/s]	Average Pressure (Pa)	STD	Average Pressure (Pa)	STD
1	1120	0.7	0.19	0.10	0.00	0.13
2	1109	1.0	0.02	0.13	0.00	0.06
3	1108	2.9	-0.50	**1.42**	0.86	0.38
4	1098	3.1	0.18	0.26	0.04	0.45
5	1096	3.0	0.98	0.39	-0.37	0.22
6	1097	3.2	0.18	**0.74**	-1.20	**0.52**
7	1115	3.0	0.15	**0.64**	0.01	**0.61**
8	1109	3.0	-0.20	**0.56**	-0.29	0.49
9	1148	2.4	-0.07	**0.66**	-0.38	**1.03**
10	1117	2.9	1.75	0.36	0.10	0.47

Table A2-3a: Rocklin #1 envelope leakage, wind speed, and baseline pressure data. STD values which are in excess of the Baseline Stability Test criteria of 0.5 Pa are in a bold red font.

		Supply Leakage Flow, Qs (cfm)						Return Leakage Flow, Qr (cfm)					
Test #	BST	N2.5	N5	S2.5	S5	A2.5	A5	N2.5	N5	S2.5	S5	A2.5	A5
1	No	33	28	28	27	28	27	10	7	7	5	7	5
2	No	33	28	29	25	29	25	20	16	18	14	18	14
3	**Yes**	44	41	40	39	40	39	19	21	17	20	17	20
4	No	22	34	18	25	18	25	21	32	19	30	19	30
5	No	50	51	33	32	33	32	44	39	26	26	26	26
6	**Yes**	71	71	71	71	71	71	37	37	33	37	33	37
7	**Yes**	63	58	48	49	48	49	28	33	19	22	19	22
8	**Yes**	120	109	102	82	102	82	89	80	79	69	79	69
9	**Yes**	104	111	89	100	89	100	50	65	45	55	45	55
10	No	11	17	10	17	10	17	21	28	16	26	16	26
Avg.	10 tests	**55**	**55**	**47**	**47**	**47**	**47**	**34**	**36**	**28**	**30**	**28**	**30**
STD		**35**	**33**	**31**	**28**	**31**	**28**	**23**	**22**	**21**	**19**	**21**	**19**
Statistics for tests which pass the BST criteria:													
Avg.	5 tests	**30**	**32**	**24**	**25**	**24**	**25**	**23**	**24**	**17**	**20**	**17**	**20**
STD		**15**	**12**	**9**	**5**	**9**	**5**	**13**	**13**	**7**	**10**	**7**	**10**
Tests with one or more ramps replaced by "good" tests:													
6		83	80	80	79	80	79	43	42	39	37	39	37
7		42	47	42	46	42	46	20	29	21	21	21	21
8		99	92	65	55	65	55	73	65	58	51	58	51
Statistics for tests pass the BST criteria OR were "fixed" by replacing one or more ramps:													
Avg.	8 tests	**47**	**47**	**38**	**38**	**38**	**38**	**32**	**32**	**26**	**26**	**26**	**26**
STD		**30**	**27**	**24**	**21**	**24**	**21**	**21**	**17**	**16**	**14**	**16**	**14**

Table A2-3b: DeltaQ analysis results using twice the lowest data as lower limits to Ps and Pr.

		Supply Leakage Flow, Qs (cfm)						Return Leakage Flow, Qr (cfm)					
Test #	BST	N2.5	N5	S2.5	S5	A2.5	A5	N2.5	N5	S2.5	S5	A2.5	A5
1	No	37	35	30	29	30	29	14	13	8	8	8	8
2	No	36	36	33	36	33	36	21	19	19	17	19	17
3	**Yes**	29	31	29	31	29	31	13	16	13	16	13	16
4	No	16	23	15	21	15	21	22	36	21	35	21	35
5	No	51	47	39	39	39	39	34	26	28	23	28	23
6	**Yes**	74	68	70	65	70	65	36	31	31	28	31	28
7	**Yes**	66	58	45	48	45	48	28	27	17	21	17	21
8	**Yes**	93	82	84	76	84	76	85	76	74	70	74	70
9	**Yes**	89	89	83	93	83	93	39	51	38	53	38	53
10	No	2	8	-10	8	0	8	6	11	-3	11	0	11
Avg.	10 tests	**49**	**48**	**42**	**45**	**43**	**45**	**30**	**31**	**25**	**28**	**25**	**28**
STD		**31**	**26**	**30**	**26**	**28**	**26**	**22**	**20**	**21**	**20**	**21**	**20**
Statistics for tests which pass the BST criteria:													
Avg.	5 tests	**28**	**30**	**21**	**27**	**23**	**27**	**19**	**21**	**15**	**19**	**15**	**19**
STD		**19**	**15**	**20**	**13**	**16**	**13**	**10**	**10**	**12**	**11**	**11**	**11**

Table A2-3c: DeltaQ analysis where poor data, as determined by differences in the up and down sections of the ramping data collection procedure have been removed. Results using twice the lowest data as lower limits to Ps and Pr.

		Supply Leakage Flow, Qs (cfm)						Return Leakage Flow, Qr (cfm)					
Test #	BST	N2.5	N5	S2.5	S5	A2.5	A5	N2.5	N5	S2.5	S5	A2.5	A5
1	No	32	28	28	27	28	27	9	7	7	5	7	5
2	No	32	28	28	25	28	25	17	13	15	11	15	11
3	**Yes**	39	41	40	39	40	39	18	21	17	20	17	20
4	No	18	28	18	25	18	25	19	31	19	30	19	30
5	No	48	47	33	31	33	31	34	27	26	17	26	17
6	**Yes**	71	71	71	71	71	71	36	37	33	37	33	37
7	**Yes**	55	58	48	49	48	49	22	29	19	22	19	22
8	**Yes**	117	101	102	82	102	82	86	76	79	69	79	69
9	**Yes**	97	111	89	100	89	100	48	65	45	55	45	55
10	No	10	17	10	17	10	17	16	26	16	26	16	26
Avg.		**52**	**53**	**47**	**47**	**47**	**47**	**31**	**33**	**28**	**29**	**28**	**29**
STD		**34**	**32**	**31**	**28**	**31**	**28**	**23**	**22**	**21**	**20**	**21**	**20**
Statistics for tests which pass the BST criteria:													
Avg.		**28**	**30**	**23**	**25**	**23**	**25**	**19**	**21**	**17**	**18**	**17**	**18**
STD		**15**	**11**	**9**	**5**	**9**	**5**	**9**	**10**	**7**	**10**	**7**	**10**
Tests with one or more ramps replaced by "good" tests:													
6		82	80	80	79	80	79	42	42	39	37	39	37
7		43	47	42	46	42	46	20	25	21	21	21	21
8		80	69	65	55	65	55	64	57	58	51	58	51
Statistics for tests pass the BST criteria OR were "fixed" by replacing one or more ramps:													
Avg.		**43**	**43**	**38**	**38**	**38**	**38**	**28**	**29**	**25**	**25**	**25**	**25**
STD		**26**	**22**	**24**	**21**	**24**	**21**	**18**	**16**	**16**	**15**	**16**	**15**

Table A2-3d: DeltaQ analysis results 20 Pa as lower limits to Ps and Pr.

Rocklin 2

	Envelope Leakage (Includes Duct Leakage) at 50 Pa	Avg. Wind Speed	Initial Baseline House Pressure Measurement		Final Baseline House Pressure Measurement	
Test #	cfm	[m/s]	Average Pressure (Pa)	STD	Average Pressure (Pa)	STD
1	1793	0.9	0.25	0.08	-0.15	0.21
2	1788	0.8	0.42	0.07	0.12	0.05
3	1794	1	0.23	0.12	0.89	0.12
4	1789	1.3	1.06	0.11	0.35	0.19
5	1784	1.7	1.28	**0.53**	1.47	0.19
6	1759	1.5	1.10	0.24	1.90	0.22
7	1779	2	1.73	0.19	0.44	0.11
8	1782	2.1	1.31	0.25	1.40	0.22
9	1782	2.1	1.72	0.21	1.21	0.38
10	1779	2.5	1.57	0.19	1.14	0.17

Table A2-4a: Rocklin #2 envelope leakage, wind speed, and baseline pressure data. STD values which are in excess of the Baseline Stability Test criteria of 0.5 Pa are in a bold red font.

		Supply Leakage Flow, Qs (cfm)						Return Leakage Flow, Qr (cfm)					
Test #	BST	N2.5	N5	S2.5	S5	A2.5	A5	N2.5	N5	S2.5	S5	A2.5	A5
1	No	45	49	45	49	45	49	14	16	14	16	14	16
2	No	45	46	43	45	46	47	0	0	-3	-2	0	0
3	No	58	57	58	55	58	55	37	33	37	32	37	32
4	No	76	79	53	52	53	52	41	40	30	28	30	28
5	**Yes**	74	69	55	58	55	58	40	28	23	24	23	24
6	No	30	33	30	33	30	33	21	21	21	21	21	21
7	No	52	47	52	47	52	47	29	25	29	24	29	24
8	No	54	53	49	49	49	49	27	26	22	23	22	23
9	No	77	80	49	54	49	54	48	50	33	28	33	28
10	No	46	46	45	47	45	47	13	13	12	14	12	14
Avg.	10 tests	**56**	**56**	**48**	**49**	**48**	**49**	**27**	**25**	**22**	**21**	**22**	**21**
STD		**16**	**15**	**8**	**7**	**8**	**7**	**15**	**14**	**12**	**10**	**11**	**9**
Statistics for tests which pass the BST criteria:													
Avg.	9 tests	**54**	**54**	**47**	**48**	**47**	**48**	**26**	**25**	**22**	**20**	**22**	**21**
STD		**15**	**16**	**8**	**7**	**8**	**6**	**15**	**15**	**12**	**10**	**12**	**10**
Tests with one or more ramps replaced by "good" tests:													
No replacement ramps were necessary													

Table A2-4b: DeltaQ analysis results using twice the lowest data as lower limits to Ps and Pr.

		Supply Leakage Flow, Qs (cfm)						Return Leakage Flow, Qr (cfm)					
Test #	BST	N2.5	N5	S2.5	S5	A2.5	A5	N2.5	N5	S2.5	S5	A2.5	A5
1	No	44	47	44	47	44	47	14	14	14	14	14	14
2	No	44	44	41	41	45	46	0	0	-4	-5	0	0
3	No	54	57	54	57	54	57	31	34	31	34	31	34
4	No	73	79	53	51	53	51	39	42	28	26	28	26
5	**Yes**	75	74	58	58	58	58	29	29	24	25	24	25
6	No	29	32	29	32	29	32	19	24	19	24	19	24
7	No	53	48	53	48	53	48	29	24	29	24	29	24
8	No	60	53	55	48	55	48	31	27	27	23	27	23
9	No	67	76	48	56	48	56	27	32	19	27	19	27
10	No	46	46	46	46	46	46	14	9	11	10	11	10
Avg.		**55**	**56**	**48**	**48**	**49**	**49**	**23**	**24**	**20**	**20**	**20**	**21**
STD		**15**	**16**	**9**	**8**	**8**	**8**	**11**	**13**	**11**	**11**	**10**	**10**
Statistics for tests which pass the BST criteria:													
Avg.		**52**	**54**	**47**	**47**	**47**	**48**	**23**	**23**	**19**	**20**	**20**	**20**
STD		**13**	**15**	**8**	**8**	**8**	**7**	**12**	**13**	**11**	**12**	**10**	**10**

Table A2-4c: DeltaQ analysis where poor data, as determined by differences in the up and down sections of the ramping data collection procedure have been removed. Results using twice the lowest data as lower limits to Ps and Pr.

		Supply Leakage Flow, Qs (cfm)						Return Leakage Flow, Qr (cfm)					
Test #	BST	N2.5	N5	S2.5	S5	A2.5	A5	N2.5	N5	S2.5	S5	A2.5	A5
1	No	45	49	45	49	45	49	14	16	14	16	14	16
2	No	45	46	43	45	46	47	0	0	-3	-2	0	0
3	No	58	57	58	55	58	55	37	33	37	32	37	32
4	No	61	61	53	52	53	52	35	33	30	28	30	28
5	**Yes**	57	58	55	58	55	58	23	23	23	24	23	24
6	No	27	31	27	31	27	31	11	12	11	12	11	12
7	No	52	47	52	47	52	47	29	24	29	24	29	24
8	No	54	54	49	49	49	49	26	27	22	23	22	23
9	No	52	56	47	54	47	54	23	29	19	28	19	28
10	No	45	46	45	46	45	46	12	12	12	12	12	12
Avg.		**50**	**51**	**47**	**49**	**48**	**49**	**21**	**21**	**19**	**20**	**20**	**20**
STD		**10**	**9**	**9**	**7**	**9**	**7**	**12**	**11**	**12**	**10**	**11**	**10**
Statistics for tests which pass the BST criteria:													
Avg.		**49**	**50**	**47**	**48**	**47**	**48**	**21**	**21**	**19**	**19**	**19**	**19**
STD		**10**	**9**	**9**	**7**	**9**	**7**	**12**	**11**	**12**	**11**	**11**	**10**
Tests with one or more ramps replaced by "good" tests:													
No replacement ramps were necessary													

Table A2-4d: DeltaQ analysis results 20 Pa as lower limits to Ps and Pr.

Vacaville

	Envelope Leakage (Includes Duct Leakage) at 50 Pa	Avg. Wind Speed	Initial Baseline House Pressure Measurement		Final Baseline House Pressure Measurement	
Test #	cfm	[m/s]	Average Pressure (Pa)	STD	Average Pressure (Pa)	STD
1	3018	2.7	-2.88	**0.55**	-2.94	0.44
2	3023	1.6	-2.13	**0.54**	-1.05	0.10
3	3069	1.1	-1.16	0.10	-1.16	0.11
4	3084	1.7	-0.98	0.20	-0.68	0.15
5	3039	1.7	-1.59	0.43	-0.59	0.11
6	3022	1.7	-1.13	0.15	-0.89	0.09
7	3029	2.1	-0.92	0.10	-2.83	**0.61**
8	3038	2.4	-0.40	0.07	2.12	**1.25**
9	2956	3.2	-0.45	0.49	0.40	0.14
10	2998	2.4	0.48	**0.81**	0.56	0.34
11	3153	2.2	0.03	0.14	-0.44	**0.64**
12	3125	1.8	-0.05	0.35	0.33	0.11
13	3215	2.0	0.32	0.39	0.33	0.17

Table A2-5a: Vacaville envelope leakage, wind speed, and baseline pressure data. STD values which are in excess of the Baseline Stability Test criteria of 0.5 Pa are in a bold red font.

		Supply Leakage Flow, Qs (cfm)						Return Leakage Flow, Qr (cfm)					
Test #	BST	N2.5	N5	S2.5	S5	A2.5	A5	N2.5	N5	S2.5	S5	A2.5	A5
1	**Yes**	18	24	18	24	18	24	9	11	9	11	9	11
2	**Yes**	153	166	128	132	128	132	106	108	72	76	72	76
3	No	27	29	27	28	27	28	31	19	31	19	31	19
4	No	11	10	-34	-34	0	0	0	0	-38	-34	0	0
5	No	30	22	27	22	27	22	18	7	18	7	18	7
6	No	0	0	-42	-49	0	0	10	9	-29	-34	0	0
7	**Yes**	103	121	83	101	83	101	65	82	49	65	49	65
8	**Yes**	97	109	81	108	81	108	48	46	44	44	44	44
9	No	48	44	-64	-47	0	0	0	0	-96	-79	0	0
10	**Yes**	103	47	114	38	114	38	127	64	115	59	115	59
11	**Yes**	31	36	-33	-39	0	0	0	0	-54	-60	0	0
12	No	23	28	24	28	24	28	17	24	20	24	20	24
13	No	45	43	27	28	27	28	33	28	28	24	28	24
Avg.	13 tests	**53**	**52**	**27**	**26**	**41**	**39**	**36**	**31**	**13**	**9**	**30**	**25**
STD		**46**	**49**	**61**	**60**	**45**	**45**	**41**	**35**	**56**	**48**	**34**	**27**
Statistics for tests which pass the BST criteria:													
Avg.	7 tests	**26**	**25**	**-5**	**-3**	**15**	**15**	**16**	**12**	**-9**	**-10**	**14**	**11**
STD		**17**	**16**	**40**	**38**	**14**	**14**	**13**	**11**	**47**	**39**	**14**	**11**
Tests with one or more ramps replaced by "good" tests:													
7		69	73	68	72	68	72	75	76	71	76	71	76
11	None	31	36	-33	-39	0	0	0	0	-54	-60	0	0
Statistics for tests pass the BST criteria OR were "fixed" by replacing one or more ramps:													
Avg.	9 tests	**32**	**32**	**0**	**1**	**19**	**20**	**20**	**18**	**-5**	**-6**	**19**	**17**
STD		**21**	**21**	**44**	**44**	**23**	**24**	**24**	**24**	**52**	**49**	**23**	**25**

Table A2-5b: DeltaQ analysis results using twice the lowest data as lower limits to Ps and Pr.

		Supply Leakage Flow, Qs (cfm)						Return Leakage Flow, Qr (cfm)					
Test #	BST	N2.5	N5	S2.5	S5	A2.5	A5	N2.5	N5	S2.5	S5	A2.5	A5
1	**Yes**	31	23	28	22	28	22	35	23	34	23	34	23
2	**Yes**	97	99	96	100	96	100	51	54	50	53	50	53
3	No	29	45	29	40	29	40	17	20	13	16	13	16
4	No	10	10	-35	-38	0	0	0	0	-45	-51	0	0
5	No	36	28	35	28	35	28	27	9	28	9	28	9
6	No	0	0	-40	-45	0	0	8	7	-29	-32	0	0
7	**Yes**	97	89	76	70	76	70	68	72	56	59	56	59
8	**Yes**	90	108	79	107	79	107	45	62	43	61	43	61
9	No	50	54	-45	-4	0	0	0	0	-101	-74	0	0
10	**Yes**	23	14	21	15	25	15	3	5	-4	5	0	5
11	**Yes**	24	30	14	22	31	35	0	0	-17	-13	0	0
12	No	19	20	20	20	20	20	16	17	19	17	19	17
13	No	43	40	36	30	36	30	37	35	32	29	32	29
Avg.	13 tests	**42**	**43**	**24**	**28**	**35**	**36**	**24**	**23**	**6**	**8**	**21**	**21**
STD		**33**	**35**	**44**	**45**	**31**	**36**	**22**	**25**	**45**	**41**	**21**	**23**
Statistics for tests which pass the BST criteria:													
Avg.	7 tests	**27**	**28**	**0**	**4**	**17**	**17**	**15**	**13**	**-12**	**-12**	**13**	**10**
STD		**18**	**19**	**38**	**34**	**17**	**17**	**14**	**13**	**49**	**40**	**14**	**11**

Table A2-5c: DeltaQ analysis where poor data, as determined by differences in the up and down sections of the ramping data collection procedure have been removed. Results using twice the lowest data as lower limits to Ps and Pr.

		Supply Leakage Flow, Qs (cfm)						Return Leakage Flow, Qr (cfm)					
Test #	BST	N2.5	N5	S2.5	S5	A2.5	A5	N2.5	N5	S2.5	S5	A2.5	A5
1	**Yes**	18	24	18	24	18	24	9	11	9	11	9	11
2	**Yes**	150	159	128	132	128	132	90	98	72	76	72	76
3	No	24	28	24	28	24	28	14	15	14	15	14	15
4	No	11	10	-27	-25	0	0	0	0	-35	-31	0	0
5	No	22	16	22	-25	22	0	7	0	7	-31	7	0
6	No	0	0	-42	-49	0	0	10	9	-29	-34	0	0
7	**Yes**	79	99	80	96	80	96	54	73	51	67	51	67
8	**Yes**	71	75	71	75	71	75	42	35	42	35	42	35
9	No	48	44	-14	-21	0	0	0	0	-77	-67	0	0
10	**Yes**	30	29	30	29	30	29	33	36	33	36	33	36
11	**Yes**	31	36	10	-16	41	0	0	0	-31	-53	0	0
12	No	22	26	22	26	22	26	15	16	15	16	15	16
13	No	31	26	27	28	27	28	27	16	28	24	28	24
Avg.	13 tests	**41**	**44**	**27**	**23**	**36**	**34**	**23**	**24**	**8**	**5**	**21**	**22**
STD		**39**	**43**	**45**	**53**	**37**	**42**	**26**	**30**	**41**	**45**	**23**	**26**
Statistics for tests which pass the BST criteria:													
Avg.	7 tests	**23**	**21**	**2**	**-5**	**14**	**12**	**10**	**8**	**-11**	**-15**	**9**	**8**
STD		**15**	**14**	**29**	**32**	**13**	**15**	**9**	**8**	**37**	**34**	**11**	**10**
Tests with one or more ramps replaced by "good" tests:													
7		70	73	68	72	68	72	74	76	71	76	71	76
11	No new ramps	31	36	-33	-39	0	0	0	0	-54	-60	0	0
Statistics for tests pass the BST criteria OR were "fixed" by replacing one or more ramps:													
Avg.	9 tests	**29**	**29**	**5**	**-1**	**18**	**17**	**16**	**15**	**-7**	**-10**	**15**	**15**
STD		**20**	**21**	**36**	**40**	**22**	**24**	**23**	**24**	**46**	**46**	**23**	**25**

Table A2-5d: DeltaQ analysis results 20 Pa as lower limits to Ps and Pr.

Colton

	Envelope Leakage (Includes Duct Leakage) at 50 Pa	Avg. Wind Speed	Initial Baseline House Pressure Measurement		Final Baseline House Pressure Measurement	
Test #	cfm	[m/s]	Average Pressure (Pa)	STD	Average Pressure (Pa)	STD
1	3094	n/a	0.39	0.31	1.39	**0.82**
2	3193	n/a	0.43	**0.84**	0.86	0.49
3	3357	n/a	2.27	**1.76**	1.89	**1.30**
4	3362	n/a	1.08	**0.84**	2.77	**1.17**
5	3323	n/a	2.21	**1.47**	0.32	**0.74**
6	3382	n/a	1.89	**0.89**	0.81	**0.52**

Table A2-6a: Colton envelope leakage, wind speed, and baseline pressure data. STD values which are in excess of the Baseline Stability Test criteria of 0.5 Pa are in a bold red font. Wind speed data was not taken at this house, but was extremely high for all tests.

		Supply Leakage Flow, Qs (cfm)						Return Leakage Flow, Qr (cfm)					
Test #	BST	N2.5	N5	S2.5	S5	A2.5	A5	N2.5	N5	S2.5	S5	A2.5	A5
1	**Yes**	214	217	161	184	161	184	105	104	63	90	63	90
2	**Yes**	270	288	192	221	192	221	160	160	109	128	109	128
3	**Yes**	262	281	210	228	210	228	133	137	108	114	108	114
4	**Yes**	193	179	171	178	171	178	140	127	105	126	105	126
5	**Yes**	165	170	147	161	147	161	81	103	65	93	65	93
6	**Yes**	188	203	170	177	170	177	85	117	66	97	66	97
Avg.	6 tests	**215**	**223**	**175**	**192**	**175**	**192**	**117**	**125**	**86**	**108**	**86**	**108**
STD		**42**	**51**	**23**	**27**	**23**	**27**	**32**	**22**	**23**	**17**	**23**	**17**
Statistics for tests which pass the BST criteria:													
Avg.	none												
STD													

Table A2-6b: DeltaQ analysis results using twice the lowest data as lower limits to Ps and Pr. Note: All tests need many multiple repeat ramps. No test was judged to be fixable.

		Supply Leakage Flow, Qs (cfm)						Return Leakage Flow, Qr (cfm)					
Test #	BST	N2.5	N5	S2.5	S5	A2.5	A5	N2.5	N5	S2.5	S5	A2.5	A5
1	**Yes**	255	220	221	213	221	213	189	162	166	155	166	155
2	**Yes**	261	252	190	207	190	207	148	160	115	132	115	132
3	**Yes**	258	208	199	203	199	203	118	96	83	91	83	91
4	**Yes**	177	197	169	174	169	174	96	146	92	124	92	124
5	**Yes**	167	191	151	189	151	189	89	118	71	104	71	104
6	**Yes**	188	201	175	180	175	180	84	108	69	81	69	81
Avg.		**218**	**212**	**184**	**194**	**184**	**194**	**121**	**132**	**99**	**115**	**99**	**115**
STD		**45**	**22**	**25**	**16**	**25**	**16**	**41**	**28**	**37**	**28**	**37**	**28**
Statistics for tests which pass the BST criteria:													
Avg.	none												
STD													

Table A2-6c: DeltaQ analysis where poor data, as determined by differences in the up and down sections of the ramping data collection procedure have been removed. Results using twice the lowest data as lower limits to Ps and Pr.

		Supply Leakage Flow, Qs (cfm)						Return Leakage Flow, Qr (cfm)					
Test #	BST	N2.5	N5	S2.5	S5	A2.5	A5	N2.5	N5	S2.5	S5	A2.5	A5
1	**Yes**	212	203	161	184	161	184	105	101	63	90	63	90
2	**Yes**	248	268	192	221	192	221	152	155	109	128	109	128
3	**Yes**	264	281	210	228	210	228	138	137	108	114	108	114
4	**Yes**	177	181	171	178	171	178	114	127	105	126	105	126
5	**Yes**	162	173	147	161	147	161	80	105	65	93	65	93
6	**Yes**	192	201	170	177	170	177	85	116	66	97	66	97
Avg.		**209**	**218**	**175**	**192**	**175**	**192**	**112**	**124**	**86**	**108**	**86**	**108**
STD		**40**	**46**	**23**	**27**	**23**	**27**	**29**	**20**	**23**	**17**	**23**	**17**
Statistics for tests which pass the BST criteria:													
Avg.	none												
STD													

Table A2-6d: DeltaQ analysis results 20 Pa as lower limits to Ps and Pr.

Holly

	Envelope Leakage (Includes Duct Leakage) at 50 Pa	Avg. Wind Speed	Initial Baseline House Pressure Measurement		Final Baseline House Pressure Measurement	
Test #	cfm	[m/s]	Average Pressure (Pa)	STD	Average Pressure (Pa)	STD
1	4715	n/a	0.17	0.25	0.59	0.32
2	4660	n/a	0.38	0.17	0.06	0.23
3	4742	n/a	0.46	0.21	1.08	0.38
4	4645	n/a	0.49	0.14	-0.06	0.11
5	4418	n/a	0.86	0.28	-0.05	0.12

Table A2-7a: Holly envelope leakage, wind speed, and baseline pressure data. STD values which are in excess of the Baseline Stability Test criteria of 0.5 Pa are in a bold red font. Wind speed data was not taken at this house, but was very low for all tests.

		Supply Leakage Flow, Qs (cfm)						Return Leakage Flow, Qr (cfm)					
Test #	BST	N2.5	N5	S2.5	S5	A2.5	A5	N2.5	N5	S2.5	S5	A2.5	A5
1	Pass	314	187	234	98	234	98	449	394	305	292	305	292
2	Pass	140	143	104	100	104	100	295	298	273	261	273	261
3	Pass	153	155	102	111	102	111	369	370	297	309	297	309
4	Pass	198	142	94	88	94	88	295	275	224	219	224	219
5	Pass	67	70	65	57	65	57	227	234	215	206	215	206
Avg.	5 tests	**174**	**139**	**120**	**91**	**120**	**91**	**327**	**314**	**263**	**257**	**263**	**257**
STD		**91**	**43**	**66**	**21**	**66**	**21**	**85**	**67**	**41**	**45**	**41**	**45**
Statistics for tests which pass the BST criteria:													
Avg.	all												
STD													

Table A2-7b: DeltaQ analysis results using twice the lowest data as lower limits to Ps and Pr..

		Supply Leakage Flow, Qs (cfm)						Return Leakage Flow, Qr (cfm)					
Test #	BST	N2.5	N5	S2.5	S5	A2.5	A5	N2.5	N5	S2.5	S5	A2.5	A5
1	Pass	315	191	234	88	234	88	447	399	306	288	306	288
2	Pass	137	134	104	100	104	100	290	286	272	260	272	260
3	Pass	154	155	99	106	99	106	370	380	296	309	296	309
4	Pass	153	161	122	115	122	115	301	295	276	255	276	255
5	Pass	84	81	83	75	83	75	253	242	240	227	240	227
Avg.		**169**	**144**	**128**	**97**	**128**	**97**	**332**	**320**	**278**	**268**	**278**	**268**
STD		**87**	**41**	**61**	**16**	**61**	**16**	**77**	**67**	**25**	**32**	**25**	**32**
Statistics for tests which pass the BST criteria:													
Avg.	All												
STD													

Table A2-7c: DeltaQ analysis where poor data, as determined by differences in the up and down sections of the ramping data collection procedure have been removed. Results using twice the lowest data as lower limits to Ps and Pr.

		Supply Leakage Flow, Qs (cfm)						Return Leakage Flow, Qr (cfm)					
Test #	BST	N2.5	N5	S2.5	S5	A2.5	A5	N2.5	N5	S2.5	S5	A2.5	A5
1	Pass	156	152	112	98	112	98	361	367	293	292	293	292
2	Pass	127	129	104	100	104	100	289	288	273	261	273	261
3	Pass	135	129	102	111	102	111	334	332	297	309	297	309
4	Pass	127	117	94	88	94	88	274	263	224	219	224	219
5	Pass	36	33	36	33	36	33	206	197	206	197	206	197
Avg.		**116**	**112**	**90**	**86**	**90**	**86**	**293**	**289**	**259**	**256**	**259**	**256**
STD		**46**	**46**	**31**	**31**	**31**	**31**	**60**	**65**	**41**	**47**	**41**	**47**
Statistics for tests which pass the BST criteria:													
Avg.	all												
STD													

Table A2-7d: DeltaQ analysis results 20 Pa as lower limits to Ps and Pr.

Appendix 2. Hysteresis effects

In an effort to speed up the testing faster ramps were used to find out how fast ramping could be performed without any observable hysteresis. The 90 seconds used in this study was found to be a reasonable ramping time that did not show any hysteresis. If ramping times are significantly reduced from 90 seconds to 15 seconds then the hysteresis effects become clear. The following data are from Sparks 1 with 15 second ramps and three ramps used in each of the four parts of the DeltaQ test (for a total of 45 seconds of data - about half of the data quantity taken in a 90 second ramp. Another reason for taking the multiple fast ramps approach is to see if this avoids some of the wind effects by spreading out individual up or down ramps in time and spreading wind gusts out over a wider envelope pressure range such that they are averaged in with more data over a wider range instead of being concentrated at a given pressure. Hystersis of this magnitude may lead to additional test uncertainty - although this is not clear from this testing in a house with little duct leakage where the fast ramping test results were Qs = 11 cfm (5.5. L/s) and Qr = 13 cfm (6.5 L/s). The hysteresis effects were consistent, with the measured flow being larger (at the same indicated envelope pressure) with increasing blower door air flow and envelope pressures - indicating that the blower door flow leads the envelope pressure signal.

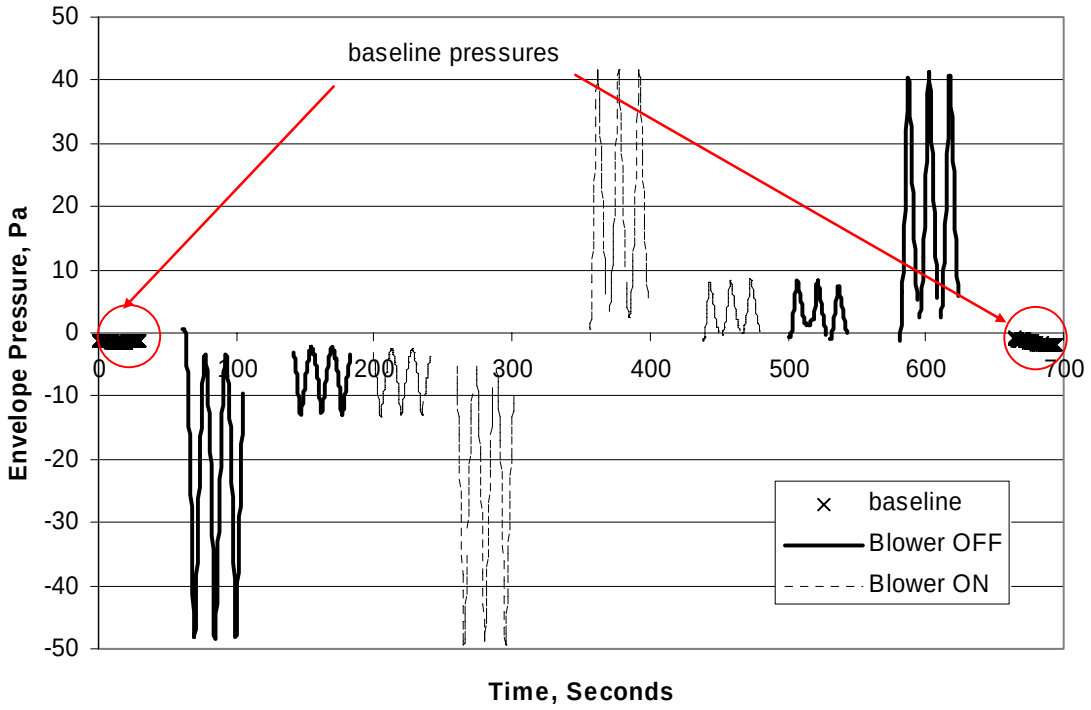


Figure A.2.1 Fast ramping data from Sparks 1 showing three fast (15 second) ramps for each stage of DeltaQ.

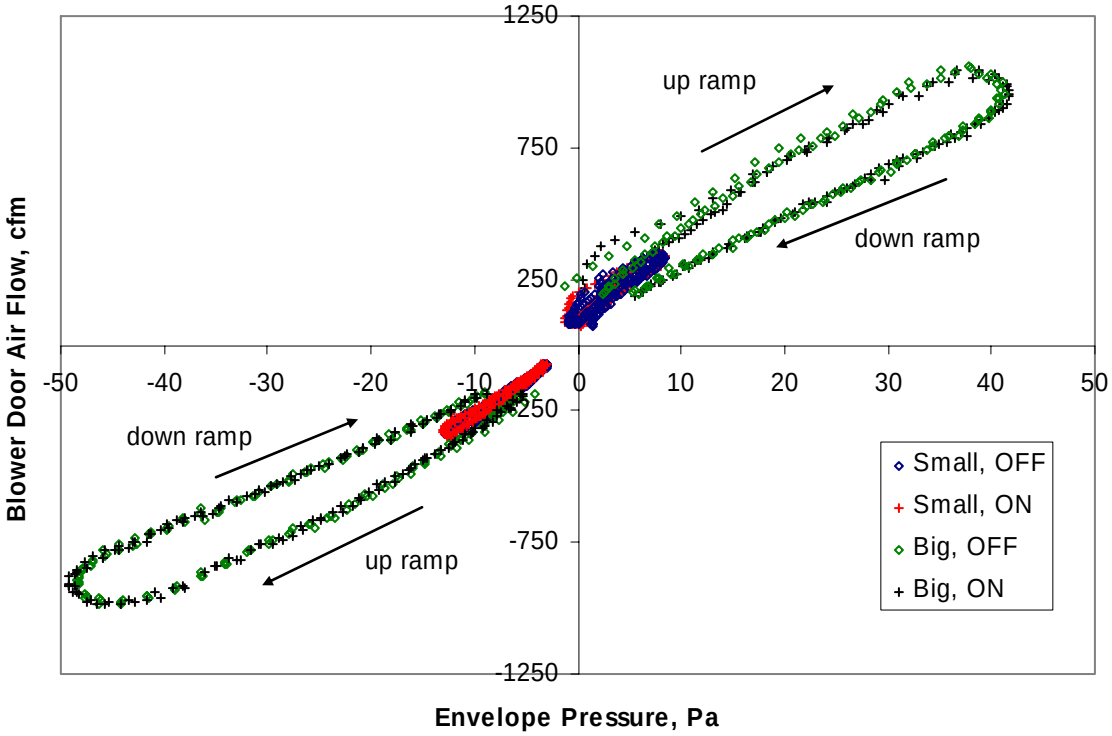


Figure A2.2 Hysteresis effects on up and down portions of ramps for 15 second ramps at Sparks 1.

Appendix 3. Number of leak pressures assumed in the NNLS analysis

The NNLS analysis assigns leakage to pre-determined pressures. The selected pressures are log normally spaced between the low and high limits. In this study the high limit was always set to 100 Pa. The low limit has been either set by the ASHRAE suggested limit (no lower than twice the lowest data) or a fixed value of 20 Pa. With a bin size of 2.5 Pa the lowest limit would be 5 Pa but most tests did not have enough data to make a bin at 2.5 Pa and their first bins were then at 5 Pa or higher. Thus the ASHRAE limit for most tests was 10 Pa.

The number of pressures between the low and high limits can be selected in the NNLS analysis. If two pressures are selected then the leakage is assigned to be at these two pressures. As it is unlikely that the real leakage is at these two pressures more pressures are usually allowed. In this study five leakage pressures were allowed for supply leakage, and another five for return leakage. Five pressures were selected based on observations performed on a limited set of tests, many from other data sets, that the resulting leakage flows were not dependent on the number of leakage pressures as long as at least four or five pressures were allowed.

Table A3 shows how the number of points allowed in the analysis influences the leakage results for a few typical, low wind, tests.

Number of Pressures used in Analysis	Holly test 2				Rocklin #2, test 5				Sparks #2, test 11			
	Lower Pressure Limit of 5 Pa		Lower Pressure Limit 20 Pa		Lower Pressure Limit of 10 Pa		Lower Pressure Limit 20 Pa		Lower Pressure Limit of 10 Pa		Lower Pressure Limit of 20 Pa	
	Qs	Qr	Qs	Qr	Qs	Qr	Qs	Qr	Qs	Qr	Qs	Qr
2	188	358	155	320	66	24	57	22	13	43	14	45
3	159	314	122	284	69	27	57	23	15	46	12	42
4	136	296	138	299	68	25	57	24	13	43	12	43
5	132	289	127	289	69	27	57	23	13	43	12	42
6	140	298	131	291	69	27	57	23	14	44	11	43
7	133	290	139	301	69	26	57	23	13	43	12	43
8	146	303	133	294	69	27	57	23	13	43	12	43
9	138	295	135	296	69	26	57	23	13	43	11	43
10	147	304	138	300	69	26	58	23	14	44	12	43

Table A3:

In the tests shown, the number of pressures used did not vary the leakage determined by more than a few cfm for tight duct systems as long as at least four pressures were selected. However houses with leakier duct systems seem to have less stable results.

Appendix 4. DeltaQ and Fan Pressurization