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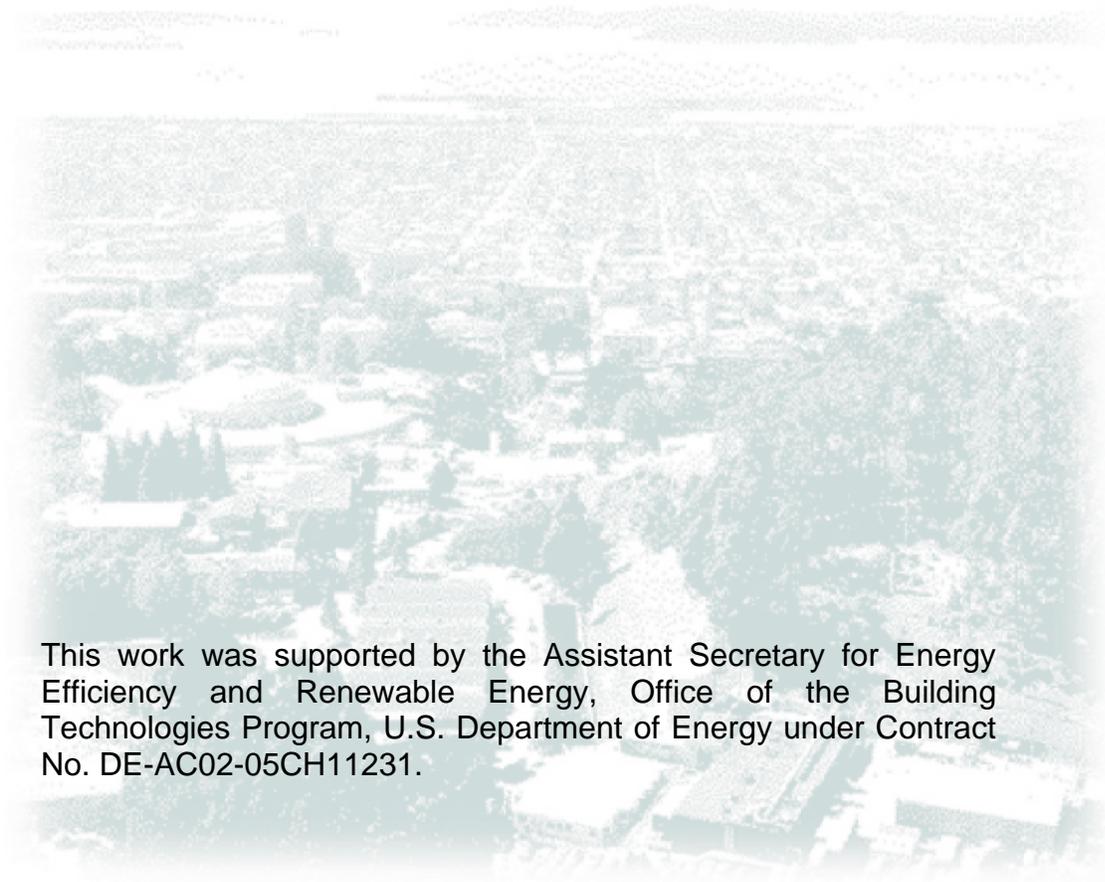
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## **Evaluation of a New Ramping Technique for Duct Leakage Testing**

Iain S. Walker and Darryl Dickerhoff

Environmental Energy Technologies  
Division

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A large, faded aerial photograph of the Berkeley Lab campus, showing various buildings, parking lots, and green spaces.

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# Evaluation of a New ramping Technique for Duct Leakage Testing

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## INTRODUCTION

The DeltaQ duct leakage test has been developed over the past several years as an alternative to duct pressurization testing. Details of the development of the DeltaQ test can be found in Dickerhoff et al. (2004), Walker et al. (2004), and Walker et al. (2002). The DeltaQ test is one of the test methods included in ASTM E1554 “Determining External Air Leakage of Air Distribution Systems by Fan Pressurization” (ASTM 2003).

The DeltaQ test estimates duct leakage to outside under normal operating conditions, and separates supply and return leakage. The DeltaQ test also aims to reduce the time and effort required to leak test ducts. The first time saving is that it does not require all the registers and grilles to be covered. This is a big advantage in homes that have high wall-mounted grilles in two-story rooms that are difficult to access. In occupied houses, access is also limited by furnishings that also hide grilles from view such that they are not noticed by the test crew and therefore are not covered during the test. These uncovered grilles lead to overestimates of leakage. Secondly, if the supply and return sides of the system are to be measured separately, duct pressurization requires separating the return from the supply using internal blocking inside blower cabinetry that is difficult to install and monitor (in case the seal is lost during testing). Thirdly, to determine leakage to outside (this is the value required for energy loss calculations), duct pressurization requires the use of two fans – one to pressurize the ducts and one to pressurize the house, and these fans require synchronization. Finally, the DeltaQ test utilizes a blower door and simultaneously measures envelope and duct leakage. For weatherization programs and other building diagnosticians already measuring envelope leakage, the use of a single fan means that the additional effort to acquire duct leakage information is minimized.

As experience was gained with the DeltaQ test, we looked for ways to make the test faster, simpler and more robust. A couple of key issues have arisen as experience with DeltaQ testing was accumulated. Firstly, the use of distinct pressure stations limited test resolution in the pressure domain and led to the possibility of instability in the multivariate fitting required for the DeltaQ calculations. Secondly, adjusting blower door speeds to achieve the individual pressure stations made the test take longer than desired by potential users such as weatherization crews.

The purpose of this study was to examine an alternative DeltaQ test procedure and several data analysis techniques that would address these issues. The new test procedure does away with specific pressure stations. Instead, the blower door speed is gradually increased and the envelope pressure differences and airflows are continuously recorded. This continuous changing of pressure differences and airflows is referred to as “ramping”. The ramping technique was evaluated using both laboratory and field testing. The laboratory tests were carried out under controlled conditions where the duct leakage was precisely known and there was no influence from wind and thermal pressures. These tests allowed us to separate the modeling errors in DeltaQ from errors arising in field measurements. The controlled laboratory tests also allowed evaluation of different data analysis approaches without the variability introduced by field testing. The field tests where the true duct leakage was unknown were used to examine the reduction in precision due to changing wind and thermal pressures on the envelope as well as experimental errors such as poor pressure tubing placement. The field precision estimates were developed based on repeatability testing in several houses.

## DELTAQ RAMPING TESTING

### 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 current DeltaQ method in ASTM E1554 (ASTM 2003) uses averaged pressure differences and flows (usually averaged for at least 10 seconds) at several envelope pressure difference stations. Typically ten envelope pressure difference stations are used between 5 and 50 Pa. The new ramping technique gradually increases the envelope pressure difference from zero to about 50 Pa over a period of about 90 seconds and then gradually decreases the pressure difference back to zero over the following 90 seconds.

These procedures are 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*

Based on extensive field testing experience by the authors and other users, there are several recommendations for obtaining best results:

- It is important that the same blower door arrangement<sup>1</sup> is used for the forced air system blower on and off measurements to avoid false flow differences being generated by small differences in calibrations between blower door calibrations and arrangements. The automated software used for the ramping tests in this study does this automatically.
- Outside pressure tubing needs to be carefully located. It is best to find a sheltered location as far as possible from the blower door so that the blower door flows do not affect the pressure measurement.
- Indoor pressure tubing also needs to be carefully located to avoid the influence of the blower door flows, especially the turbulence generated by the blower door during pressurization testing. It is recommended that the tubing should be run along the door frame high up and away from the blower door flow.

So that the DeltaQ method can be used by as many people as possible, as soon as possible, we collaborated with a manufacturer of field test equipment to develop automated software to perform the ramping testing. This automated software uses a non-negative least squares (NNLS) fitting technique that allows for multiple characteristic pressures. An Excel spreadsheet developed by LBNL<sup>2</sup> was used to perform the DeltaQ calculations for the ASTM E1554 pressure station testing.

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<sup>1</sup> Most blower door devices use sets of orifices or rings that allow a wide range of flows to be measured using the same basic fan and flow meter device.

<sup>2</sup> Available at [ducts.lbl.gov](http://ducts.lbl.gov)

## DeltaQ analysis

Converting the DeltaQ test data to duct leakage flow requires the use of the DeltaQ model outlined in previous publications (Dickerhoff et al. 2004, Walker et al. 2004, and Walker et al. 2002), and shown in Equation 1, together with fitting routines that determine the model parameters ( $Q_s$ ,  $Q_r$ ,  $\Delta P_s$ ,  $\Delta P_r$ ) that allow the best fit to the measured data ( $\Delta Q$  and  $\Delta P$ ).

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

$\Delta Q$  is the difference between blower door airflows with the system blower on and off at an envelope pressure difference of  $\Delta P$ .  $Q_s$  is the supply leakage flow,  $Q_r$  is the return leakage flow,  $\Delta P_s$  is the characteristic pressure for supply leaks, and  $\Delta P_r$  is the characteristic pressure 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.

Three approaches to simultaneously determining  $Q_s$ ,  $Q_r$ ,  $\Delta P_s$ , and  $\Delta P_r$  have been utilized. One uses fitting routines available in standard statistical packages<sup>3</sup> to perform multivariate least squares fitting to the data and is called “pressure fitting”. The second uses a pressure scanning technique that limits the possible pressures to a fixed set. The third technique fixes the characteristic pressures and then uses a Non-Negative Least Squares (NNLS) technique to determine the duct leakage flows.

In addition to these DeltaQ calculation techniques, two correction factors have also been included (Walker et al. 2004 and Dickerhoff et al. 2004) that account for a couple of assumptions made in the development of Equation 1, namely: 1) changes in building envelope pressure difference due to supply-return leakage imbalances and 2) changes in duct leak pressures due to airflow resistance of the duct system.

When calculating the flow difference between system fan on and off (the DeltaQ) at a given pressure station, it is necessary to have the flows at the same envelope pressure difference. Because there is no guarantee that the measured data will have exactly the same average pressure difference for both system-blower-on and system-blower-off conditions at each pressure station, it is necessary to shift one flow or the other. This is done by adjusting the system fan off data to match the system fan on data. For ASTM E1554 pressure station testing, this shift is achieved by performing a least squares fit to envelope flow and pressure data to determine the envelope leakage coefficient and pressure exponent (as is done in a standard blower door test, such as ASTM E779-03). The envelope pressure exponent was used to shift the system off flows at their average pressure to the system blower off flow that would occur at the system blower on pressure station. To apply this flow shift to the ramping data, the measured data were binned by recorded envelope pressure difference. Bins of 1 Pa in width gave a reasonable balance between having a minimum number of points in each bin and the number of bins used in the analysis. Too few points in each bin leads to noisier data and spurious  $\Delta Q$  and  $\Delta P$  values, whereas more bins allows finer resolution of characteristic pressures. For pressure fitting, the pressure and flow were averaged in each bin. For the NNLS

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<sup>3</sup> In this case STATA.

technique, a least squares analysis was used in each bin to perform a linear fit to the data within the bin. The flow at the center of each bin was calculated from this linear fit.

### **Pressure and Flow Fitting**

Because many more data pairs are analyzed for ramping, it was found that standard least squares routines could take significant time (several hours in some cases) to achieve a solution, particularly when the iterative correction factors were used. To reduce the time requirements, a new pressure scanning technique was developed. This technique applied the DeltaQ equation to fixed supply and return pressure combinations. Combinations of supply and return pressures every 5 Pascals between 5 and 100 Pa were used to make a coarse determination of the characteristic supply and return pressures. Then the pressures at every Pascal  $\pm 4$  Pa about this point were used to determine the characteristic pressures with greater resolution. The changes in leakage flow in between the 5 Pa coarse grid and the 1 Pa sub-grid *averaged over all the tests* was less than 0.2 cfm; the changes were also small for *individual tests*: a standard deviation in the differences between the coarse and fine grid of 1.6 cfm for supplies and 2.4 cfm 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 technique is referred to as “pressure scanning” because all the possible supply and return characteristic pressures are systematically scanned. For each supply and return pressure pair, the least squares error was calculated by comparing the estimated  $\Delta Q$  to the measured  $\Delta Q$ . The supply and return pressure combination that generated the smallest error was the solution to the DeltaQ equation, together with their corresponding airflows. For each combination, the correction factors were applied to the calculated  $Q_s$  and  $Q_r$ . 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. 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 11 Pa). Experience has shown that changing characteristic pressures by 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.

### **Non-negative Least Squares (NNLS)**

This analysis technique only fitted the leakage flows rather than both flows and characteristic pressures. It allowed multiple leakage pressures and flows to be calculated for both supply and return leaks. The characteristic pressures were pre-determined by the user specifying a minimum pressure and a maximum pressure. The intermediate characteristic pressures between this maximum and minimum were spaced logarithmically with more characteristic pressures at lower values. Using too low a pressure (particularly with sparse or no data below the lowest pressure) can lead to numerical instabilities and unrealistic leakage flows. Using too high an upper pressure limit was less problematic, but it was wise to limit the upper pressure to those typical of plenum pressures. For consistency, the same pressure limits and number of pressures were used for every test. For the results presented in this report, the NNLS pressures were:

- Low pressure of 5 Pa
- High pressure of 100 Pa
- Five points spaced logarithmically between these limits

Similar to the scanning technique, the NNLS applied a least squares analysis to the DeltaQ relationship using the measured data. The analysis calculated the leakage flow at each characteristic pressure. The supply leakage was given by the sum of the individual leakage flows at each characteristic supply pressure. Similarly, the return leakage was the sum of the individual leakage flows at each characteristic return pressure. It was often the case that some characteristic pressures have little or no leakage and leakage was concentrated at a single characteristic pressure. This showed that the single pressure assumption used in the DeltaQ relationship in Equation 1 is often a good one. However, some cases show leakage distributed at different pressures throughout the selected range.

For the NNLS analysis, several pressure ranges and numbers of intermediate points were evaluated. For most tests, the number of intermediate points did not change the results by more than a few cfm. The exceptions were for laboratory tests that were known to have a wide range of leak pressures, in which case five or more intermediate pressures allowed leaks to be at these intermediate pressures. Also, if too few intermediate pressures are selected they may be far from the actual leak pressures (unlike pressure scanning that determines a single pressure within 1 Pa).

### Correcting for building envelope pressure changes due to leakage imbalance

$Q_s$  and  $Q_r$  calculated using Equation 1 represent the supply and return air leakage to outside flows when the envelope pressure difference is zero. The normal operating house pressure difference may not be zero because of a combination of large unbalanced leakage and a tight building envelope. To determine the actual leakage flow at operating conditions, the leakage flows must be corrected for the envelope pressure offset during forced air system operation. The pressure offset,  $P_{offset}$ , is calculated using Equation 2:

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

Where  $C_{env}$  is the envelope leakage coefficient and  $n_{env}$  is the envelope pressure exponent.  $C_{env}$  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).

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

The pressure offset is then used to correct the flows (to obtain  $Q_{s,corrected}$  and  $Q_{r,corrected}$ ) using Equations 4 and 5:

$$Q_{s,corrected} = Q_s \left[ 1 + \frac{P_{offset}}{\Delta P_s} \right]^{n_s} \quad (4)$$

$$Q_{r,corrected} = Q_r \left[ 1 - \frac{P_{offset}}{\Delta P_r} \right]^{n_r} \quad (5)$$

Equation 1 and other following equations use a notation system of leading square brackets, “[”, and trailing rounded brackets “)”. This notation 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.

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

This correction process is iterative. The corrected flows are used to re-estimate the pressure offset. For most situations, the pressure offset is small compared to the leak pressures, and this correction is minor and only requires one or two iterations.

### Correcting for duct airflow resistance

The DeltaQ derivation assumed that the pressure difference at the leak rises or falls by the same amount that the envelope pressure difference rises or falls. This assumption ignored the impact of flow resistance in the ducts that may cause a bias. The bias depends on the resistance of the duct system, the airflow that goes through the duct system during the tests, and the relative size and location of the leaks. In the DeltaQ test, the actual pressure at the leak is offset from the nominal one used above because of these

factors. Equation 7 shows how the offsets for pressure differences at the leak are applied to the DeltaQ Equation.

$$\Delta Q(\Delta P) = Q_s \left[ \left[ 1 + \frac{\Delta P - \delta P_s^{on}}{\Delta P_s} \right]^{n_s} - \left[ \frac{\Delta P - \delta P_s^{off}}{\Delta P_s} \right]^{n_s} \right] - Q_r \left[ \left[ 1 - \frac{\Delta P - \delta P_r^{on}}{\Delta P_r} \right]^{n_r} + \left[ \frac{\Delta P - \delta P_r^{off}}{\Delta P_r} \right]^{n_r} \right] \quad (7)$$

The  $\delta P$  terms are the pressure difference offsets in the ducts relative to the house. The superscripts refer to the system blower being on or off. The subscripts refer to supply or return side of the duct system. At each pressure station, a pressure correction is calculated for both the blower on and blower off, and for both supply and return for a total of four pressure correction terms:  $\delta P_s^{on}$ ,  $\delta P_r^{on}$ ,  $\delta P_s^{off}$ , and  $\delta P_r^{off}$ .

### Airflow resistance fan-off analysis

When the system fan is off, but there is an applied pressure in the house, there is a pressure drop between the leak site and the house caused by the resistance in the ducts relative to the resistance in the leak. Since the house pressure can reach the leaks through both supply and return registers, we can generally assume that not much air goes through the air handler when the handler is off. Thus, the flow that goes through the ducts must be the flow that goes through the leaks and we can get a relationship for the pressure offset:

$$\left( 1 - \frac{Q_{r,s}}{Q_e} \right) \left[ \frac{\delta P_{r,s}^{off}}{\Delta P_{r,s}} \right]^{n_{duct}} = \frac{Q_{r,s}}{Q_e} \left[ \frac{\Delta P - \delta P_{r,s}^{off}}{\Delta P_{r,s}} \right]^{n_{r,s}} \quad (8)$$

$n_{duct}$  is the pressure exponent for duct airflow (typically this is about 0.5) and  $Q_e$  is the airflow through the system blower. Because the pressure exponents are generally different for the duct airflow and the leak airflow, Equation 8 requires a numerical solution. This can be simplified to an analytical solution by assuming that the duct and leak pressure exponents are the same. Assigning a value of 0.6 to these exponents and rearranging Equation 8 gives Equations 9 and 10 that are much easier to implement (and have been proposed for a future version of ASTM E1554).

$$\delta P_s^{off} = \frac{P \left( \frac{Q_s}{Q_e} \right)^{\frac{1}{0.6}}}{\left( 1 - \frac{Q_s}{Q_e} \right)^{\frac{1}{0.6}} + \left( \frac{Q_s}{Q_e} \right)^{\frac{1}{0.6}}} \quad (9)$$

$$\delta P_r^{off} = \frac{P \left( \frac{Q_r}{Q_e} \right)^{0.6}}{\left( 1 - \frac{Q_r}{Q_e} \right)^{\frac{1}{0.6}} + \left( \frac{Q_r}{Q_e} \right)^{\frac{1}{0.6}}} \quad (10)$$

### Fan-On Analysis

When the system blower is on, there is still a pressure offset when the house pressure is applied, but it is more complicated because the leak is already under pressure from the system blower. The leakage flow is now equal to the difference between the system blower flow and the flow through the duct, and the defining relationship becomes<sup>4</sup>:

$$1 - \left( 1 - \frac{Q_{r,s}}{Q_e} \right) \left[ 1 \pm \frac{\delta P_{r,s}^{on}}{P_{r,s}} \right]^{1/2} = \frac{Q_{r,s}}{Q_e} \left[ 1 \mp \frac{P - \delta P_{r,s}^{on}}{P_{r,s}} \right]^{n_{r,s}} \quad (11)$$

where the top sign applies to the return and the bottom sign to the supply.

Equation 11 needs to be solved for the pressure correction terms using iterative numerical approaches.

To avoid lengthy, complex and time consuming iterations, Equation 11 can be simplified<sup>5</sup> by assuming that the leak pressure exponent is one half. Equations 12 and 13 can be used to estimate the pressure correction terms at each pressure station.

$$\frac{\delta P_s^{on}}{P_s} = 1 - \left( \frac{\left( 2 - 2 \frac{Q_s}{Q_e} \right) - \left[ \left( 2 \frac{Q_s}{Q_e} - 2 \right)^2 - 4 \left( 1 - 2 \frac{Q_s}{Q_e} \right) \left( 1 - \left( \frac{Q_s}{Q_e} \right)^2 \frac{P}{P_s} \right) \right]^{0.5}}{2 \left( 1 - 2 \frac{Q_s}{Q_e} \right)} \right)^2 \quad (12)$$

$$\frac{\delta P_r^{on}}{P_r} = \left( \frac{\left( 2 - 2 \frac{Q_r}{Q_e} \right) - \left[ \left( 2 \frac{Q_r}{Q_e} - 2 \right)^2 - 4 \left( 1 - 2 \frac{Q_r}{Q_e} \right) \left( 1 + \left( \frac{Q_r}{Q_e} \right)^2 \frac{P}{P_r} \right) \right]^{0.5}}{2 \left( 1 - 2 \frac{Q_r}{Q_e} \right)} \right)^2 - 1 \quad (13)$$

<sup>4</sup> Equation 11 assumes that a supply leak does not affect the flows or pressures on the return side of the duct system and vice versa. Although this assumption has not been rigorously evaluated, Walker (2004) showed that return plenum leakage changed by less than 5% of the leakage flow, when the supply leakage varied from 5 to 25% of the fan flow. So for the experiments discussed here, where the return leaks are also in the return plenum only, the assumption is a good one. However, for more general application, where return leaks are at lower pressures, more work needs to be done to evaluate this assumption.

<sup>5</sup> After considerable algebraic manipulation and rearranging Equation 11 to a quadratic formulation – See Appendix A.

## LABORATORY TESTING

The laboratory tests were carried out in a purpose-built duct leakage test facility shown in Figure 1. This test facility consisted of a test chamber (that represented the house envelope), a duct system and a gas-fired furnace. The test chamber was constructed to be almost air tight and its leakage was controlled by opening and closing calibrated holes of a known size.

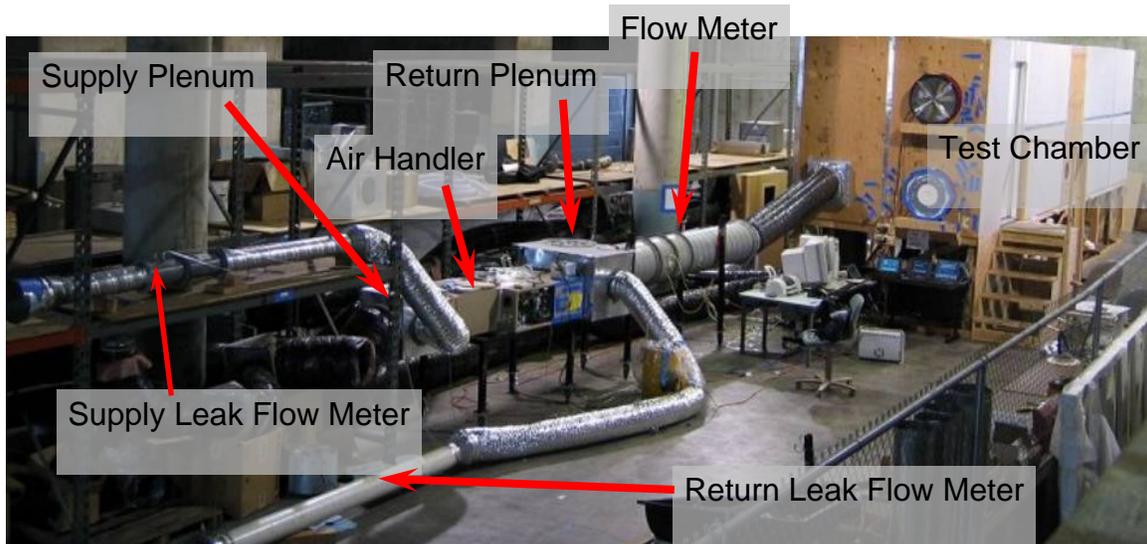
The duct system was fabricated from various diameters of flexible ducting, splitter boxes, wyes and register boots. The system had a total of 11 supply registers and a single return. The duct system was carefully sealed with mastic and foil tape. The total duct leakage measured using 25 Pa pressurization was initially 21 cfm (10 L/s), but was reduced to 14 cfm (7 L/s) about half way through the testing by performing additional sealing. Leakage was added using airflow meters and calibrated leaks such that the actual airflow in and out of the ducts was well known. The uncertainty in the duct leakage was 2 to 3% of the leakage flow depending on which leaks were used. The duct leaks were located at both supply and return plenums and at each register boot. All the airflow for the plenum leaks came through airflow meters. Different orifices were used in the airflow meters to obtain a range of air flow rates. The register boot pressures were varied by changing the position of dampers within each boot. The register boot leaks were specially made to have a pressure exponent of 0.6, while the plenum leaks had pressure exponents of 0.5. This allowed us to test a range of leak pressures and pressure exponents depending on which leaks were used. The furnace was only operated in air circulation mode and no heating was used. The furnace blower was operated at two different speeds. An in-line flow meter was used to measure the total blower airflow.

A total of 46 combinations of envelope leakage, furnace blower flow, leakage flow rate and leak pressures were used. The envelope leakage ranged from 590 cfm<sup>50</sup> to 3760 cfm<sup>50</sup> (275 L/s to 1775 L/s). The furnace blower ranged from 1000 to 1525 cfm (470 to 720 L/s) depending on the leakage configuration tested (that changed the airflow resistance of the duct system) and the blower speed. The maximum supply leakage was 315 cfm (150 L/s) and return leakage was 450 cfm (210 L/s).

The DeltaQ testing used two permanently installed blower doors. One was used for pressurization and the other for depressurization. Two blowers were used for convenience as one of the time consuming aspects of DeltaQ testing is turning the blower doors around when switching between pressurization and depressurization. Also, this reduced uncertainties due to repositioning of the blower door (that can lead to airflow errors – particularly for high flows with no ring mounted in the blower door fan) and installation of the blower door fabric around the circumference of the blower door fan.

In addition to the DeltaQ testing, 25 Pa (0.1 in. water) duct pressurization tests were performed for each leakage combination. Although DeltaQ testing and pressurization testing measure fundamentally different things, it is interesting to compare the two if DeltaQ testing is to become more widespread because pressurization is a popular duct leakage test method used by codes and standards, weatherization and utility programs. In particular, there have been recent debates in the building science research community on the applicability of DeltaQ testing to low leakage systems that are required by codes, and weatherization and utility programs. These pressurization tests were performed by blocking all the register grilles and pressurizing the ducts by attaching a fan and a flow

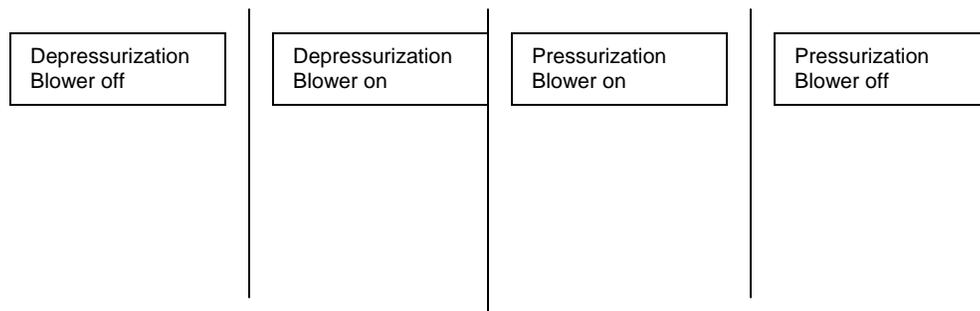
meter to an access panel in the return plenum. In some cases, only return leakage was measured by blocking the return inside the blower cabinet.

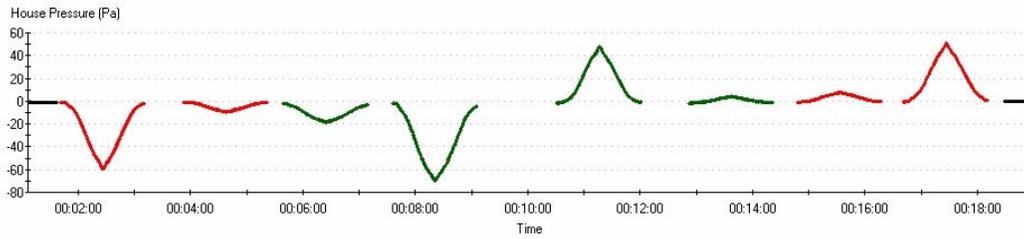


**Figure 1. Illustration of Laboratory Test Facility**

**Ramping Data Example**

Figure 2 is a time line representation of the ramping test data, which shows how the building envelope pressure difference changes during the four parts of the DeltaQ test. The leading and trailing black lines are zero pressure readings used to correct for wind and stack pressures. The first two red lines are depressurization with the blower fan off. The two lines are for two different blower door ranges (rings). Each line ramps up and down over a time period of 90 seconds. The next two green lines are two blower door data ranges for depressurization with the blower on. The following data repeat the testing for pressurization.

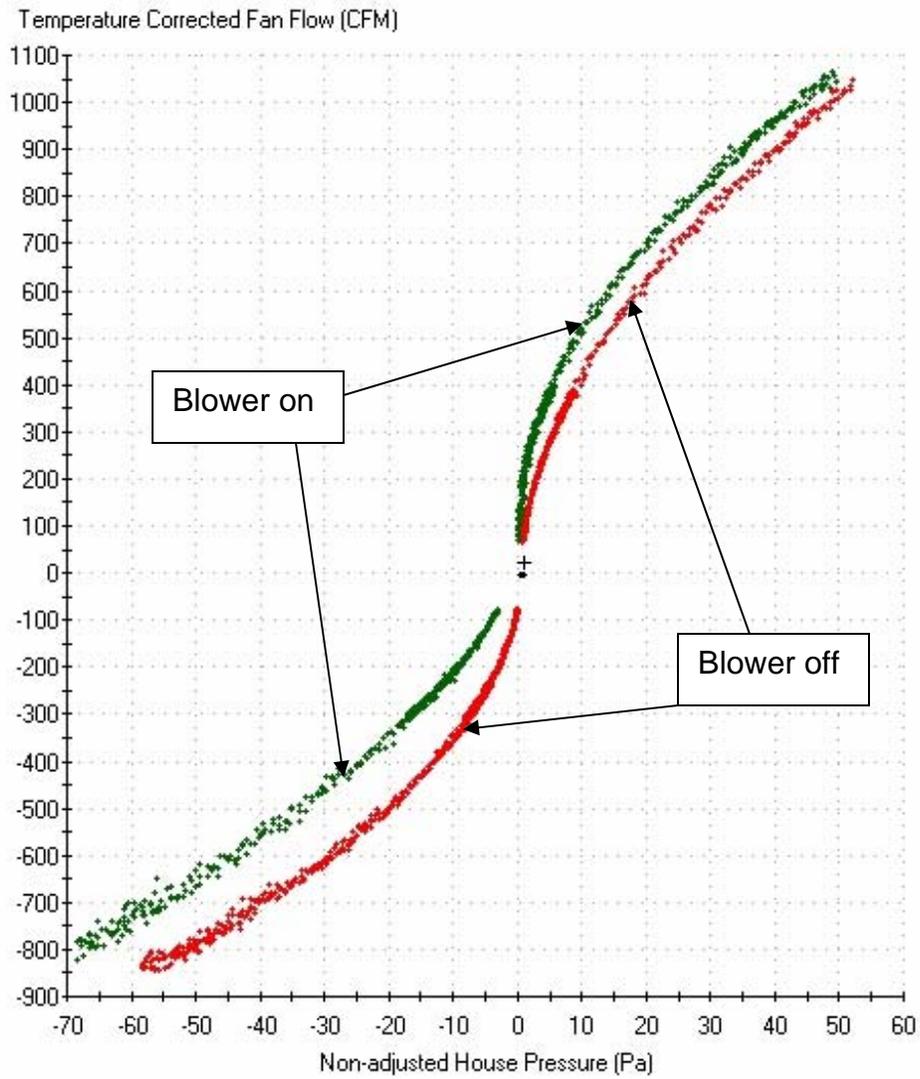




**Figure 2. Timeline of house pressures during the DeltaQ tests**

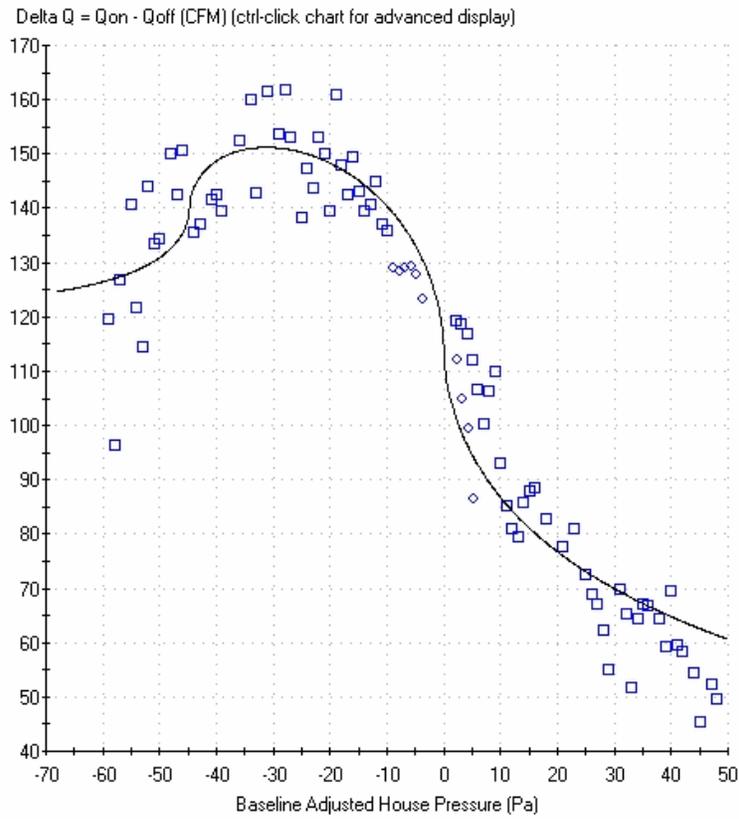
Figure 3 shows the blower door flows together with the corresponding envelope pressures. The difference between the system blower on and off is the DeltaQ information that is the result of the duct leakage.

Figure 4 shows the difference in system blower on and off flows (DeltaQ) as a function of the envelope pressures. The figure also shows the NNLS fitted DeltaQ curve. In this case, the DeltaQ curve fits through the data well and the corresponding leakage estimate is 130 cfm for supply and 17 cfm for return.



**Figure 3. House pressurization data for blower off (red) and blower on (green)**

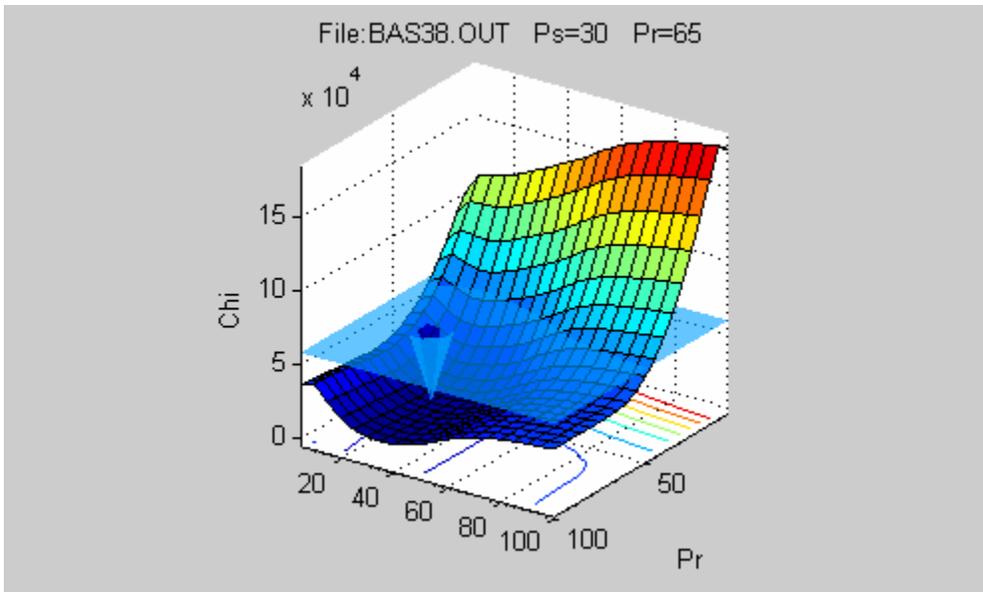
Supply = 130, Return = 17



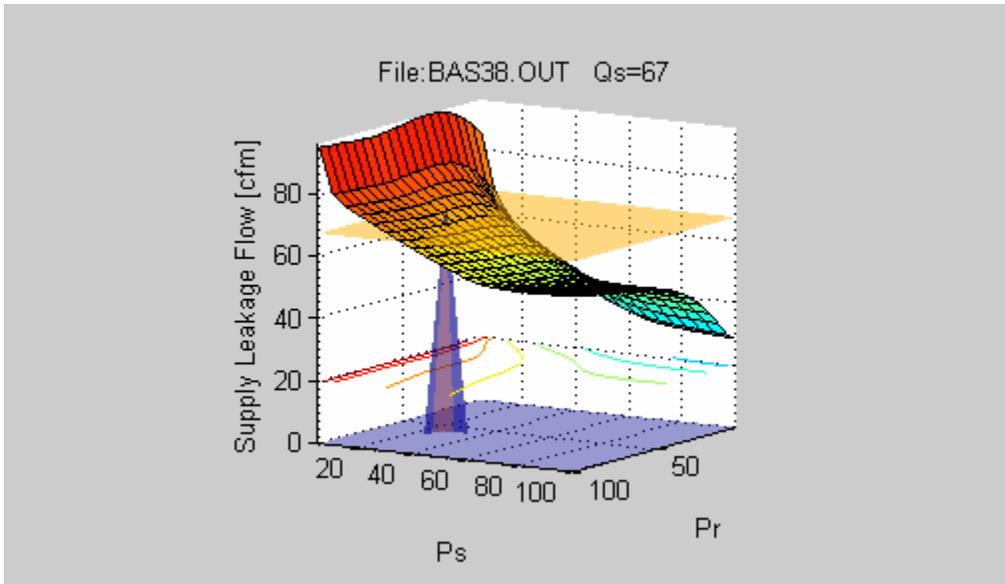
**Figure 4. DeltaQ as a function of house pressure - measured data points and DeltaQ NNLS model line. Small circles are for small blower door ring and squares are for large blower door ring.**

### Example of Pressure Scanning Results

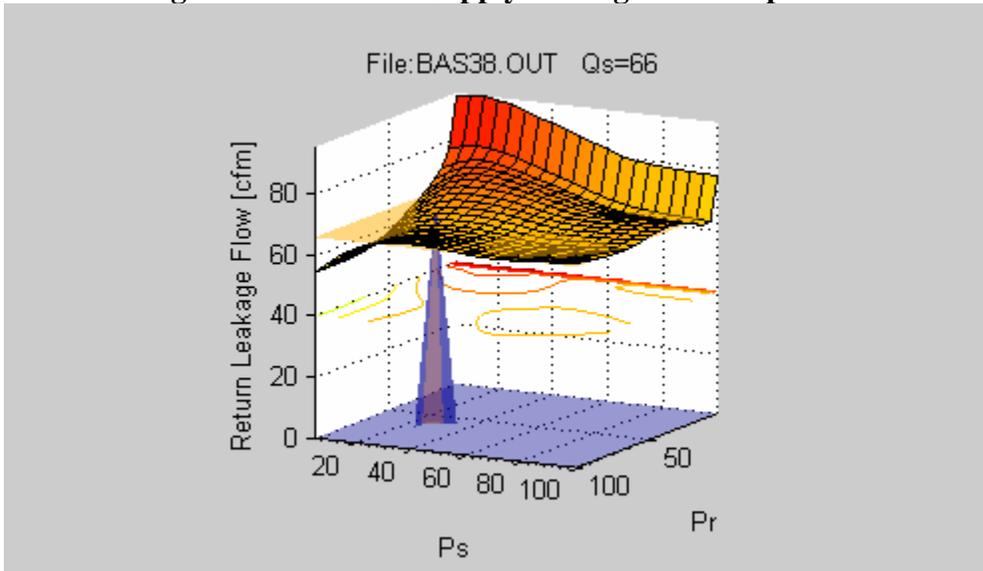
The pressure scanning analysis method generates a leakage flow for both supply and return over a range of supply and return characteristic pressures together with an estimate of error between the data and the DeltaQ model at each characteristic pressure combination. Figure 5 is a 3D plot of this error (labeled “chi” in the plot) as a function of supply and return characteristic pressures. This figure shows the minimum error point indicated by the arrow. This is the supply and return characteristic pressure ( $P_s = 30$  Pa (0.12 in. water) and  $P_r = 65$  Pa (0.26 in. water)) that minimized the error between the measured data and the DeltaQ model. Similar illustrations can be made for the supply and return leaks. Figure 6 is a 3D plot of supply leakage. The arrow corresponds to the error minimizing pressure shown in the error plot of Figure 5. This shows that the corresponding supply leakage flow is 67 cfm (32 L/s). This plot also illustrates that the DeltaQ model results in estimates of the supply leakage from 30 cfm to 90 cfm (15 to 45 L/s) over the full range of pressures. Figure 7 is the same plot but for return leakage. Like the supply plot, this Figure shows that the possible solutions for DeltaQ are limited to a range – in this case even smaller than for supply leakage, with a minimum of 60 cfm and a maximum of 90 cfm.



**Figure 5. 3D Plot of DeltaQ error function for pressure scanning**



**Figure 6. 3D Plot of Supply Leakage flow for pressure scanning**



**Figure 7. 3D Plot of Return Leakage flow for pressure scanning**

## LABORATORY TEST RESULTS

For the laboratory tests, the results were analyzed calculated four ways. This included all three methods discussed earlier as well as pressure fitting without correction factors so that the influence of these corrections could be observed.

1. Pressure scanning including correction factors
2. NNLS that includes the first correction factor for pressure offsets due to leakage imbalance
3. Pressure fitting - no corrections
4. Pressure fitting - with corrections

Figures 8 and 9 compare the actual supply and return leakage to the four ways of estimating DeltaQ leakage. These figures show that, as expected, at high leakage the corrections are significant. The pressure scanning and pressure fitting results are often identical with some occasional small differences. This is due to a combination of the pressure scanning having a resolution of only five Pascal (whereas the pressure fitting is not constrained to integer values of pressure in Pascals) and that the optimization used in the pressure fitting analysis is different from the error minimization used in the pressure scanning. There is no clear trend to over or under predict leakage as the leakage increases – other than for the uncorrected results that tend to over predict at higher leakage.

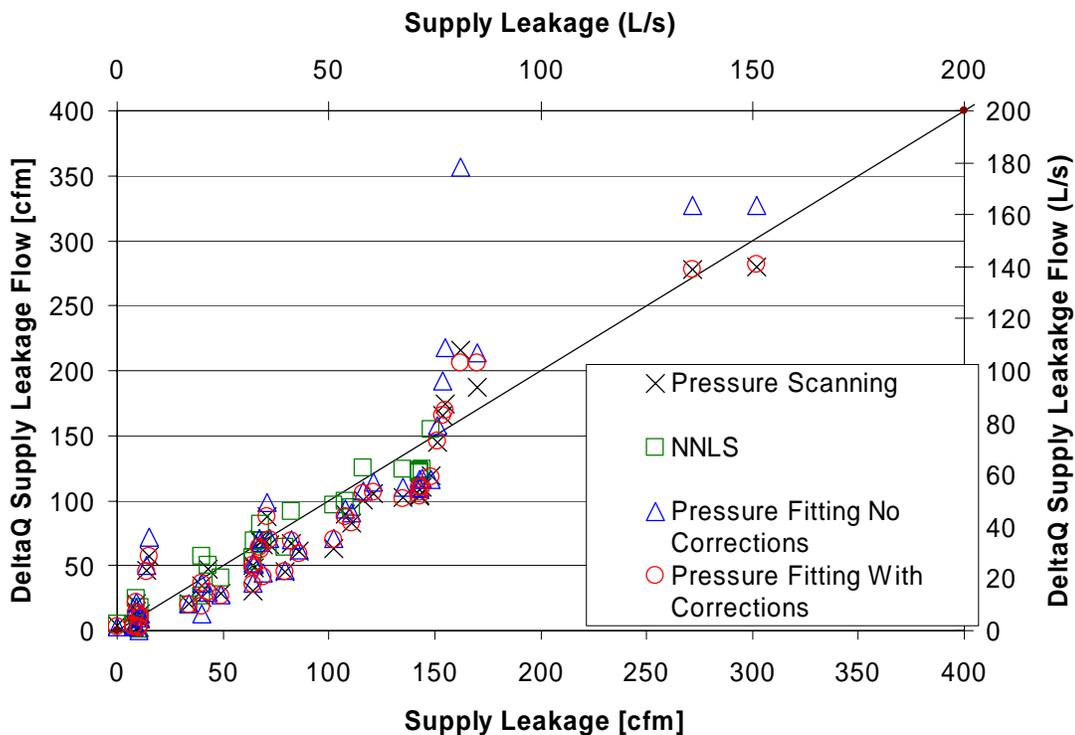


Figure 8. Comparison of DeltaQ analysis technique results to actual supply leakage

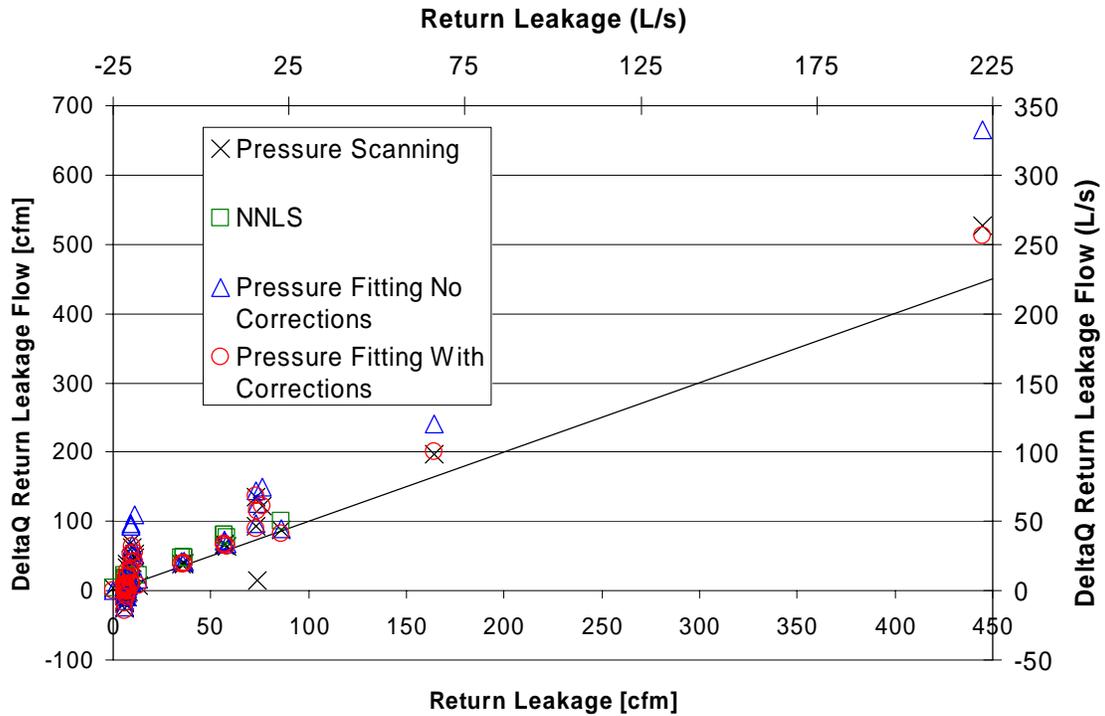


Figure 9. Comparison of DeltaQ analysis technique results to actual return leakage

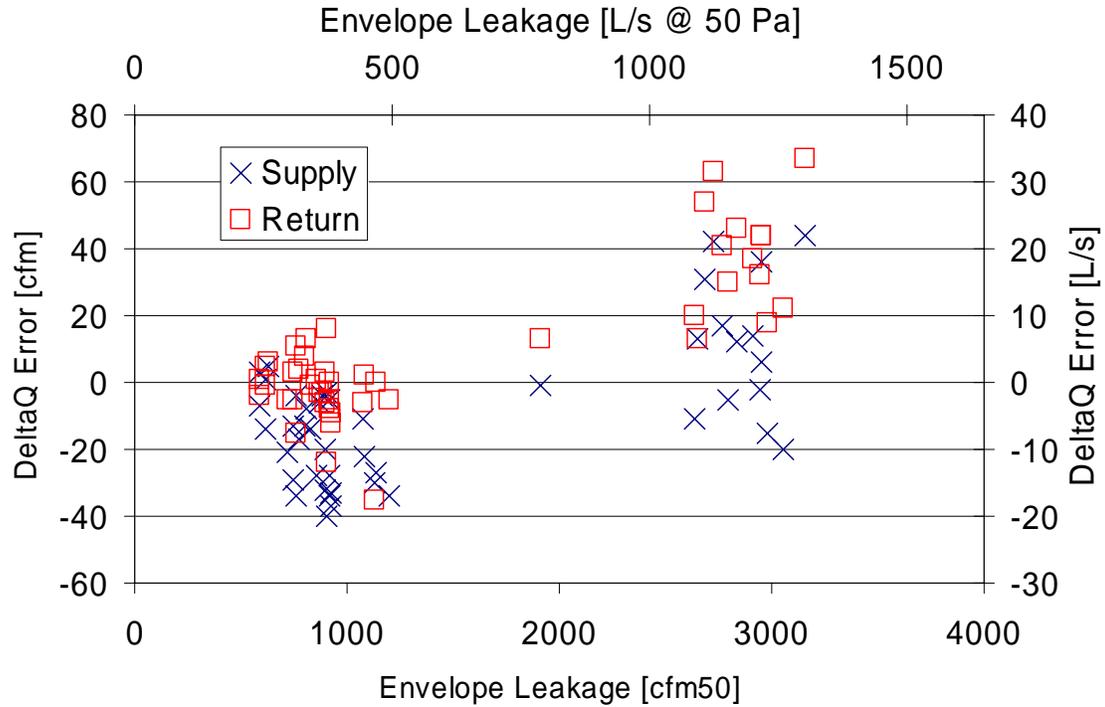
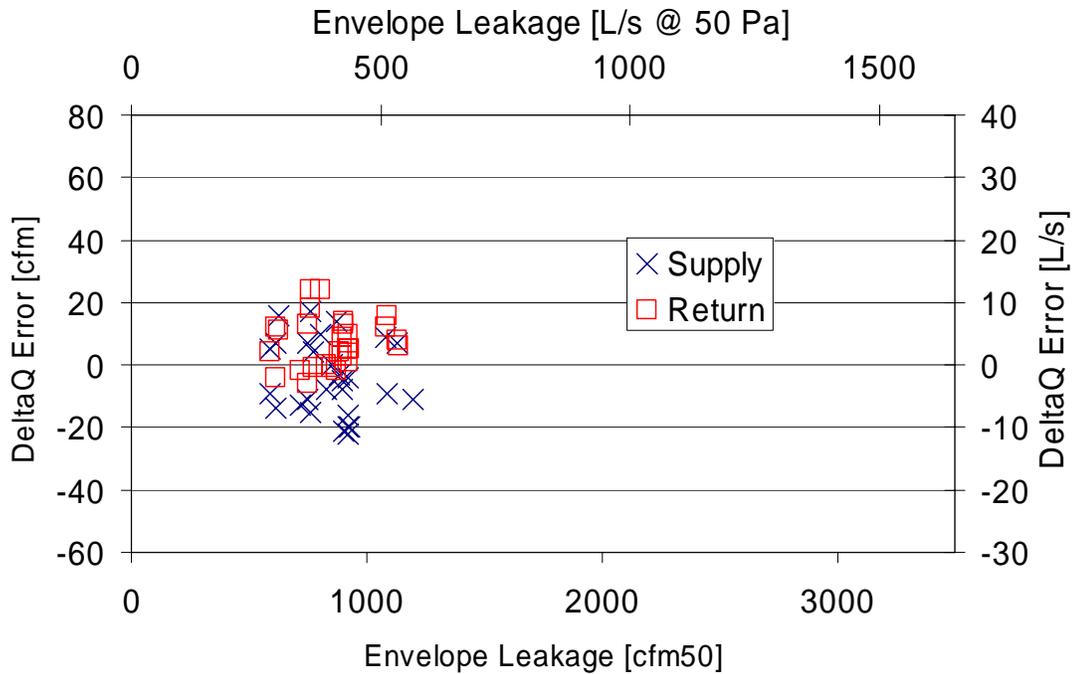


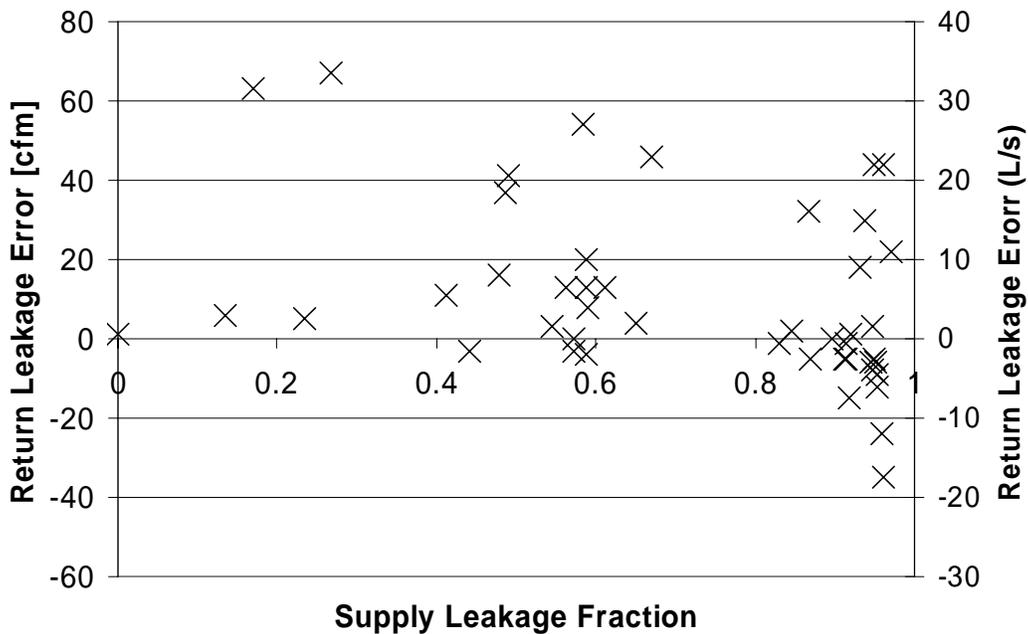
Figure 10. Envelope leakage dependence of DeltaQ errors for corrected pressure scanning

Figure 10 shows that the DeltaQ analysis using pressure scanning tends to over predict all duct leakage more at higher envelope leakage and under predict the supply leakage at lower envelope leakage.



**Figure 11. Envelope leakage dependence of DeltaQ errors for NNLS**

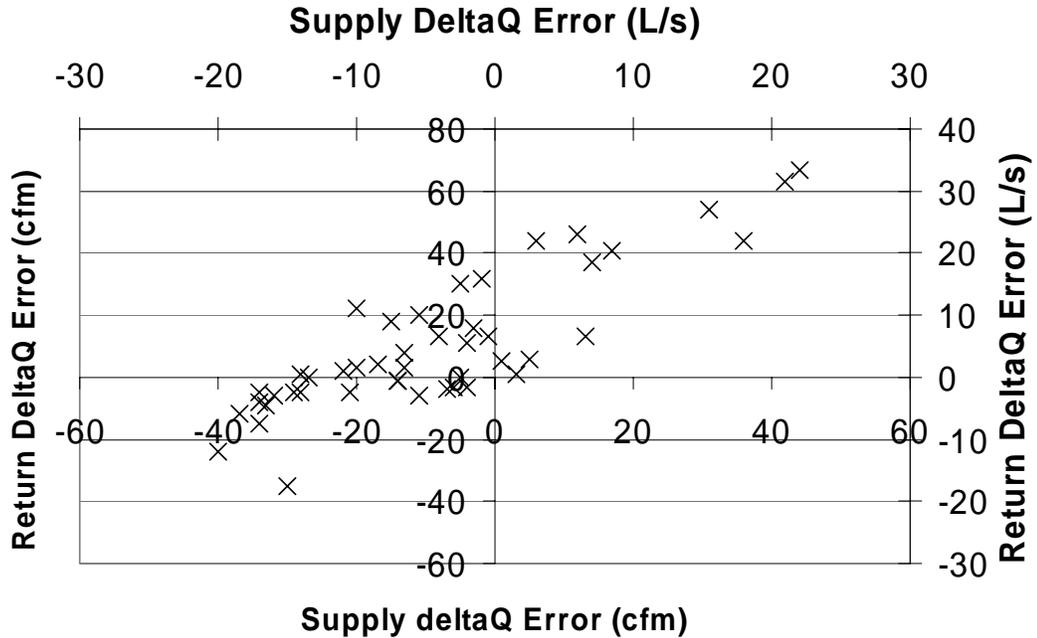
The DeltaQ analysis using NNLS was not performed for the higher envelope leakage cases because we did not have the software during the high leakage testing. So, as Figure 11 shows, it is not possible to tell if there is the same trend of increasing positive bias that the pressure fitting results showed in Figure 10.



**Figure 12. Return leakage error dependence on supply leakage for corrected pressure fitting analysis**

One question that has been raised throughout the development of the DeltaQ test procedure is the degree to which the supply and return leakage are dependant on each other. To investigate this in terms of potential error sources, Figure 12 shows how the error in return leakage changes as the supply leakage changes. This figure shows no clear trends indicating that in terms of uncertainty the magnitude of leakage on one side of the system (the supply) does not significantly affect the error in leakage on the other side (the return).

Another similar question is the possible interdependence of errors – i.e., do large supply errors correlate to large return errors – and does the sign of the error match? Figure 13 indicates that the cases of large supply errors are correlated to cases of large return errors and that if one error is positive the other is likely to be positive also.



**Figure 13. Supply and return leakage error dependence for corrected pressure fitting analysis**

Table 1. Comparison of average ramping DeltaQ results to Actual Leakage for all 46 Laboratory test configurations			
		DeltaQ cfm	Actual cfm
	<b>Analysis Method</b>		
<b>Supply</b>	<b>Pressure Scanning</b>	77	76
	<b>Pressure Fitting, No Corrections</b>	87	76
	<b>Pressure Fitting, With Corrections</b>	76	76
<b>Return</b>	<b>Pressure Scanning</b>	42	26
	<b>Pressure Fitting, No Corrections</b>	56	26
	<b>Pressure Fitting, With Corrections</b>	43	26

Table 1 contains the average results of all 46 laboratory duct and envelope leakage configurations comparing the DeltaQ test results to the actual duct leakage. The bias for supply leaks for pressure scanning and corrected least squares was zero to one cfm (0.5 L/s) or zero to 0.1% of blower flow. The return bias for pressure scanning and corrected least squares was 16 to 17 cfm (8 L/s) or less than 1.5 % of blower flow. For both supply and return, the uncorrected results showed additional positive biases of 10 cfm on average (5 L/s). There was no significant difference between the pressure scanning and corrected pressure fitting techniques.

<b>Table 2. Comparison of average ramping DeltaQ results to Actual Leakage for 28 lower envelope leakage tests</b>			
		<b>DeltaQ cfm</b>	<b>Actual cfm</b>
<b>Analysis Method</b>			
<b>Supply</b>	<b>Pressure Scanning</b>	56	66
	<b>Pressure Fitting, No Corrections</b>	57	66
	<b>Pressure Fitting, With Corrections</b>	54	66
	<b>NNLS</b>	69	66
<b>Return</b>	<b>Pressure Scanning</b>	13	12
	<b>Pressure Fitting, No Corrections</b>	18	12
	<b>Pressure Fitting, With Corrections</b>	14	12
	<b>NNLS</b>	25	12

The NNLS analysis was performed for 28 lower envelope leakage cases only. To compare NNLS to the other techniques, Table 2 shows the average results for these 28 cases only. Because these low *envelope* leakage tests are coincidentally lower *duct* leakage tests, the corrections are not as great as for the results for all cases shown in Table 1. For the pressure scanning and corrected pressure fitting tests, the supply leakage was under predicted by about 10 cfm (5 L/s) or 1% of blower flow. The NNLS over prediction was 3 cfm (1.5 L/s) or 0.3% of blower flow. For the return leaks, the over prediction for pressure scanning and corrected pressure fitting was one to two cfm (0.5 to 1 L/s) or 0.1 to 0.2% of blower flow. The NNLS over predicted by 13 cfm (6L/s) or 1.2% of blower flow. These results indicate that all of these methods introduce only small biases for lower envelope leakage tests.

The mean errors in Tables 1 and 2 are informative if we are interested in any biases in the test procedure over a large population of test houses and duct systems. However, most applications for duct leakage testing refer to an individual house. In that case, the RMS errors summarized in Table 3 are more relevant. The RMS errors were 20 to 30 cfm (10 to 15 L/s) or about 1.5% to 2% of blower flow for pressure scanning a corrected pressure fitting for all 46 tests. This matches the results in previously published work (Walker et al. 2004 and Dickerhoff et al. 2004). For the 28 lower envelope leakage tests, the RMS errors were reduced to 10 to 20 cfm (5 to 10 L/s). This indicates that the precision of estimating the DeltaQ measurement depends, as one might expect, on the envelope leakage. For higher envelope leakage, the absolute uncertainty (as opposed to fractional uncertainty) in the envelope air flow measurement increases, leading to increased uncertainty in the difference between envelope flow measurements with the air handler on and off. The effect of envelope leakage on precision will be further investigated in the field testing results presented later.

<b>Table 3. Summary of RMS errors for alternative DeltaQ analysis techniques</b>			
		<b>For all 46 Tests (cfm)</b>	<b>For 28 lower envelope leakage tests (cfm)</b>
	<b>Analysis Method</b>		
<b>Supply</b>	<b>Pressure Scanning</b>	22	23
	<b>Pressure Fitting, No Corrections</b>	41	15
	<b>Pressure Fitting, With Corrections</b>	22	17
	<b>NNLS</b>	n/a	12
<b>Return</b>	<b>Pressure Scanning</b>	24	10
	<b>Pressure Fitting, No Corrections</b>	52	11
	<b>Pressure Fitting, With Corrections</b>	29	9
	<b>NNLS</b>	n/a	15

For many applications of duct leakage testing, such as meeting minimum leakage levels for code compliance or utility program eligibility, the total leakage is used rather than separate supply and return. Table 4 summarizes the errors in total leakage. The RMS error is 30 to 40 cfm (15 to 20 L/s) for pressure scanning and corrected pressure fitting, or about 2 to 3% of air handler flow, with lower errors for the lower envelope leakage subset. The NNLS result only applies to the lower envelope leakage subset and is slightly lower than the other methods at 25 cfm (12 L/s) or less than 2% of air handler flow. The RMS error is large for the No Corrections case, but it is heavily influenced by a single result. One way of reducing the influence of outliers is to use the average absolute (AA) error rather than RMS. As Table 4 shows, the average absolute error is generally lower than the RMS error, and makes a bigger difference for the “all 46 Tests” results because they include the largest outliers.

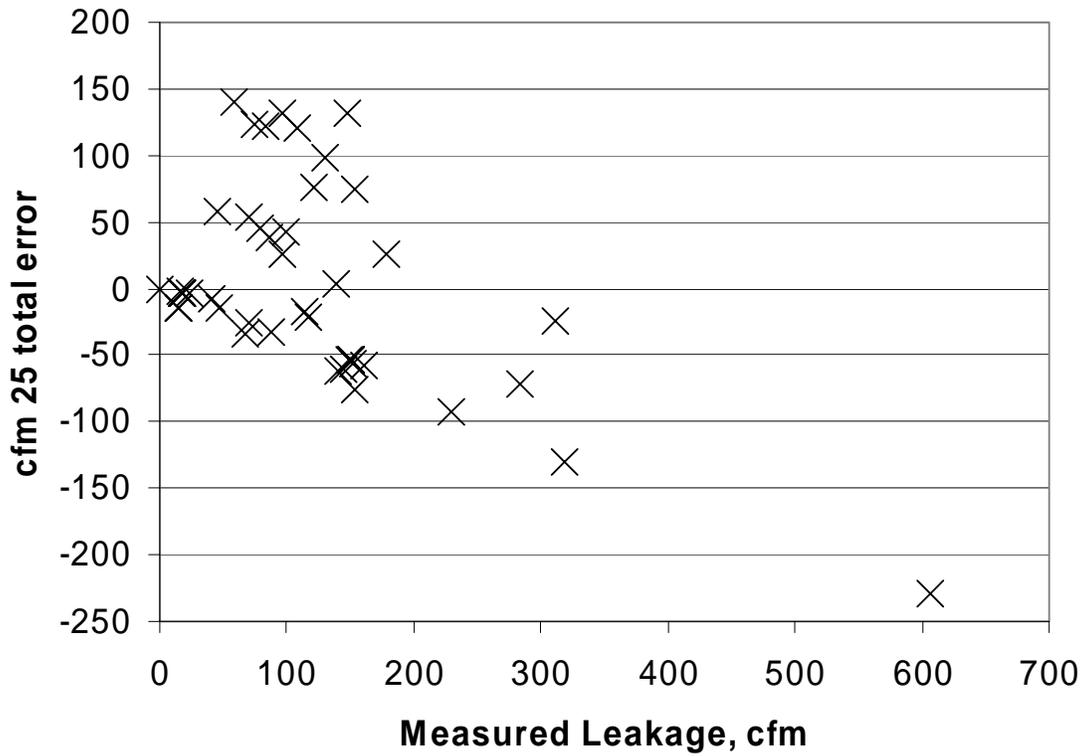
<b>Table 4. Summary of Mean, RMS and Average Absolute (AA) errors in Total Leakage for alternative DeltaQ analysis techniques</b>						
	<b>For all 46 Tests (Mean Leakage Flow = 102 cfm)</b>			<b>For 28 lower envelope leakage tests (Mean Leakage Flow = 78 cfm)</b>		
	<b>Mean</b>	<b>RMS</b>	<b>AA</b>	<b>Mean</b>	<b>RMS</b>	<b>AA</b>
<b>Analysis Method</b>						
<b>Pressure Scanning</b>	2	41	27	-22	30	24
<b>No Corrections</b>	23	83	48	-17	26	20
<b>With Corrections</b>	1	43	32	-22	32	25
<b>NNLS</b>	n/a	n/a	n/a	0	25	18

### 25Pa (0.1 in. water) Pressurization Results

For each leakage configuration, the ducts were pressurized to 25 Pa (0.1 in. water) to determine the air flow at this pressure (cfm25). Although this test does not aim to measure the air leakage under operating conditions, it is used as a surrogate for this parameter in codes and standards, and therefore it is of interest to compare to the true value.

<b>Table 5. Summary of Mean, RMS and Average Absolute (AA) errors for cfm25 measurements</b>						
	<b>For all 46 Tests (Mean Leakage Flow = 102 cfm)</b>			<b>For 28 lower envelope leakage tests (Mean Leakage Flow = 78 cfm)</b>		
	<b>Mean</b>	<b>RMS</b>	<b>AA</b>	<b>Mean</b>	<b>RMS</b>	<b>AA</b>
<b>Test Method</b>						
<b>cfm25 supply</b>	15	63	47	29	67	52
<b>cfm25 return</b>	-13	30	13	-7	14	7
<b>cfm25 total</b>	2	74	55	25	66	52

Table 5 shows that the RMS and AA errors are about one and a half to two times those for DeltaQ testing. This means that the DeltaQ test is better for evaluating individual homes and duct systems. The mean errors show biases close to those for the DeltaQ tests. Field testing (for example, see Francisco et al. 2003a and 2003b) has shown that it is possible for cfm25 pressurization measurements to have large biases for some populations of houses. These results indicate that DeltaQ testing is likely to give more accurate results in field testing.



**Figure 14. CFM25 total leakage error changes with actual leakage**

Figure 14 shows how the cfm25 total leakage changes with the actual leakage. In these laboratory tests, the high leakage tests included large leaks located at plenums at high pressures (about 100 Pa). Conversely, the low leakage airflows were mostly for leaks with less than 25 Pa pressure difference. The trend in Figure 14 is therefore as expected with the low leakage cases that had small leak pressures being over predicted by the cfm25 test and the higher leakage and leak pressure cases being under predicted by the cfm25 test.

## FIELD TESTING

The field tests were performed in order to obtain estimates of test repeatability and to determine if the test procedures have significantly different sensitivity to the wind and stack variations during the test. Four test houses were used with a range of envelope and duct leakage. The testing alternated between ramping and pressure station DeltaQ tests with five of each test being performed over the course of a day. The pressure station testing used 10 second averages at 10 pressure stations for each of the four tests that comprise the DeltaQ procedure, evenly spaced every 5 Pa from 5 to 50 Pa. It took about one minute total time to change fan speed and achieve steady readings at every pressure station.

At sites 1 and 2, the automated software was used to take the ramping data and analyze it using the NNLS technique. For the pressure station data, a spreadsheet was used to perform the DeltaQ calculations that does pressure fitting. At sites 3 and 4, the furnace blower was not activated – thus the actual leakage was not measured. Instead, these tests provided an estimate of what the uncertainty would be for a duct system with no leaks because not activating the furnace means that the DeltaQ at each pressure station should be zero as nothing has changed in the test. At sites 3 and 4, both the ramping and pressure station data were analyzed using both the pressure scanning and NNLS techniques.

The fluctuations in flow and pressure are greater in these field data than the laboratory test data. Detailed observation of the pressure signals showed that these fluctuations are mostly due to changes the airflow signal rather than the envelope pressure difference.

Table 1 summarizes the characteristics of each of the four test houses. All the houses had 2 stories and took similar amounts of time to do the tests: ramping took 20 to 25 minutes and pressure station testing took about 45 minutes. The first two test sites had leaky houses and the second two had tight houses.

Table 1. Summary of House Characteristics for DeltaQ field testing						
Test Site	Floor Area, ft <sup>2</sup> (m <sup>2</sup> )	Location	Wind Conditions	Envelope Leakage at 50 Pa (Q <sub>50</sub> ), cfm (L/s)	Envelope Leakage ACH <sub>50</sub>	Comments
1	1200 (111)	Oakland Hills, CA	Very Windy <sup>6</sup>	3250	20	Wind exposed hilltop site
2	1400 (130)	Berkeley, CA	Calm	4700	25	Ground floor heavily wind sheltered
3	2850 (265)	Minneapolis, MN	Calm	1000	2.5	System Blower OFF
4	2850 (265)	Madison, WI	Calm	700	1.8	System Blower OFF

<sup>6</sup> Local weather data from a weather station at the foot of the Oakland hills in a much more sheltered location showed mean wind speeds of 6 m.p.h. (10 km/h) with gusts up to 20 m.p.h. (32 km/h).

## REPEATABILITY TESTING RESULTS

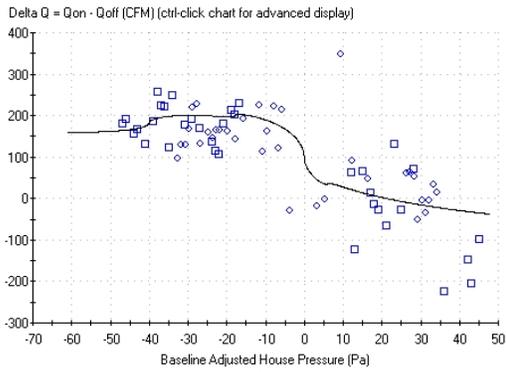
The test results in Table 6 for site 1 show that the Ramping test, analyzed with the NNLS method, resulted in higher leakage flows than the ASTM E1554 style tests. The standard deviations are about 30 cfm (14 L/s). This is about 10 to 15% of the measured leakage flows and about 3% of furnace blower flow. An objective of these field tests is to identify rules of thumb that could be used to assign uncertainty estimates to field test results. For this test site, the standard deviations are close to 1% (33 cfm, 16 L/s) of the 50 Pa envelope leakage ( $Q_{50}$ ). This same estimate will be examined for all four tests sites.

Table 6. DeltaQ repeatability results from Site 1		
Test	Supply Leakage, $Q_s$	Return Leakage, $Q_r$
Ramping #1	279	180
Ramping #2	271	164
Ramping #4 <sup>7</sup>	213	196
Ramping #5	205	128
Ramping #6	262	197
<b>Mean</b>	<b>246</b>	<b>173</b>
<b>Standard Deviation</b>	<b>34</b>	<b>29</b>
E1554 #1	191	158
E1554 #2	190	96
E1554 #3	163	125
E1554 #4	229	129
<b>Mean</b>	<b>193</b>	<b>127</b>
<b>Standard Deviation</b>	<b>27</b>	<b>25</b>

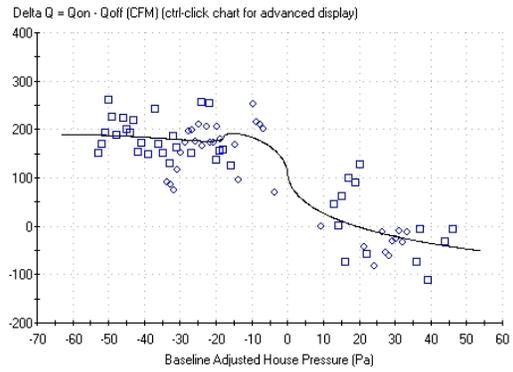
Figure 15 shows the five ramping test DeltaQ results for test site 2, together with the DeltaQ line from the NNLS fit. These results illustrate that, although the wind was calm (resulting in relatively little scatter), the uncertainty in measuring the 5000 cfm (2500 L/s) envelope flows at high envelope pressure differences led to significant shifts in DeltaQ measurements. This is particularly true for the pressurization data that shift by 100 cfm (50 L/s) or more between tests. Comparing to the laboratory data in Figure 4, Figure 15 shows the increased scatter in the data due to testing on a windy day with a leaky building envelope.

<sup>7</sup> Ramping test #3 is not shown due to a fireplace damper opening during the test

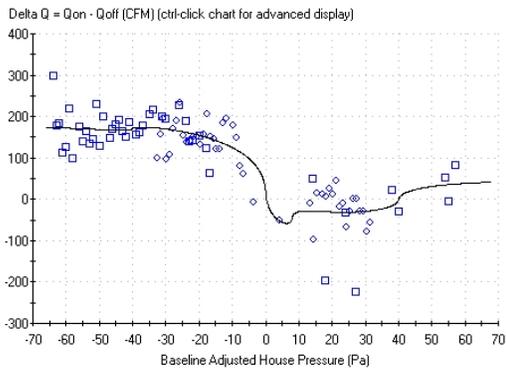
Supply = 279, Return = 180



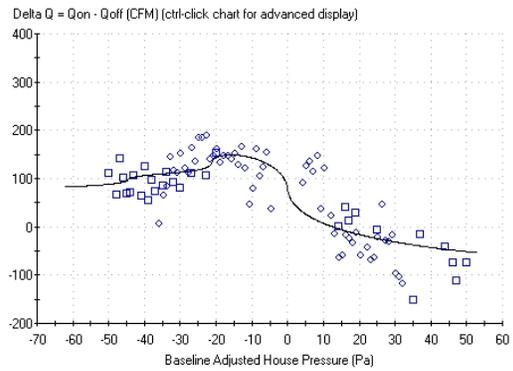
Supply = 271, Return = 164



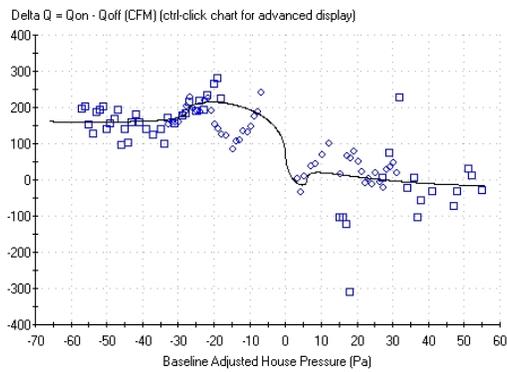
Supply = 213, Return = 196



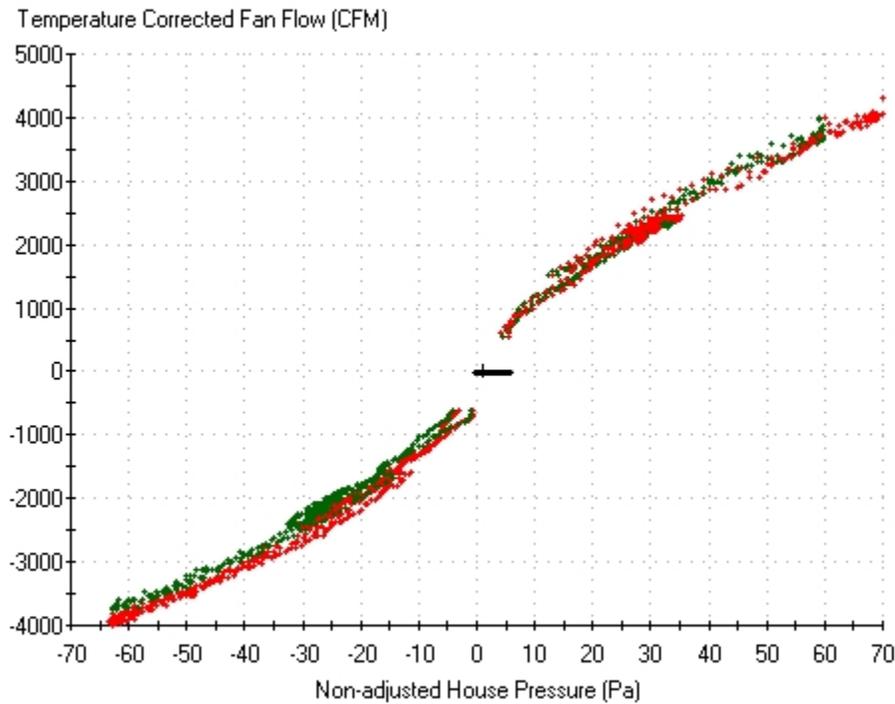
Supply = 205, Return = 128



Supply = 262, Return = 197



**Figure 15. DeltaQ data fits for Site 1 repeatability testing**



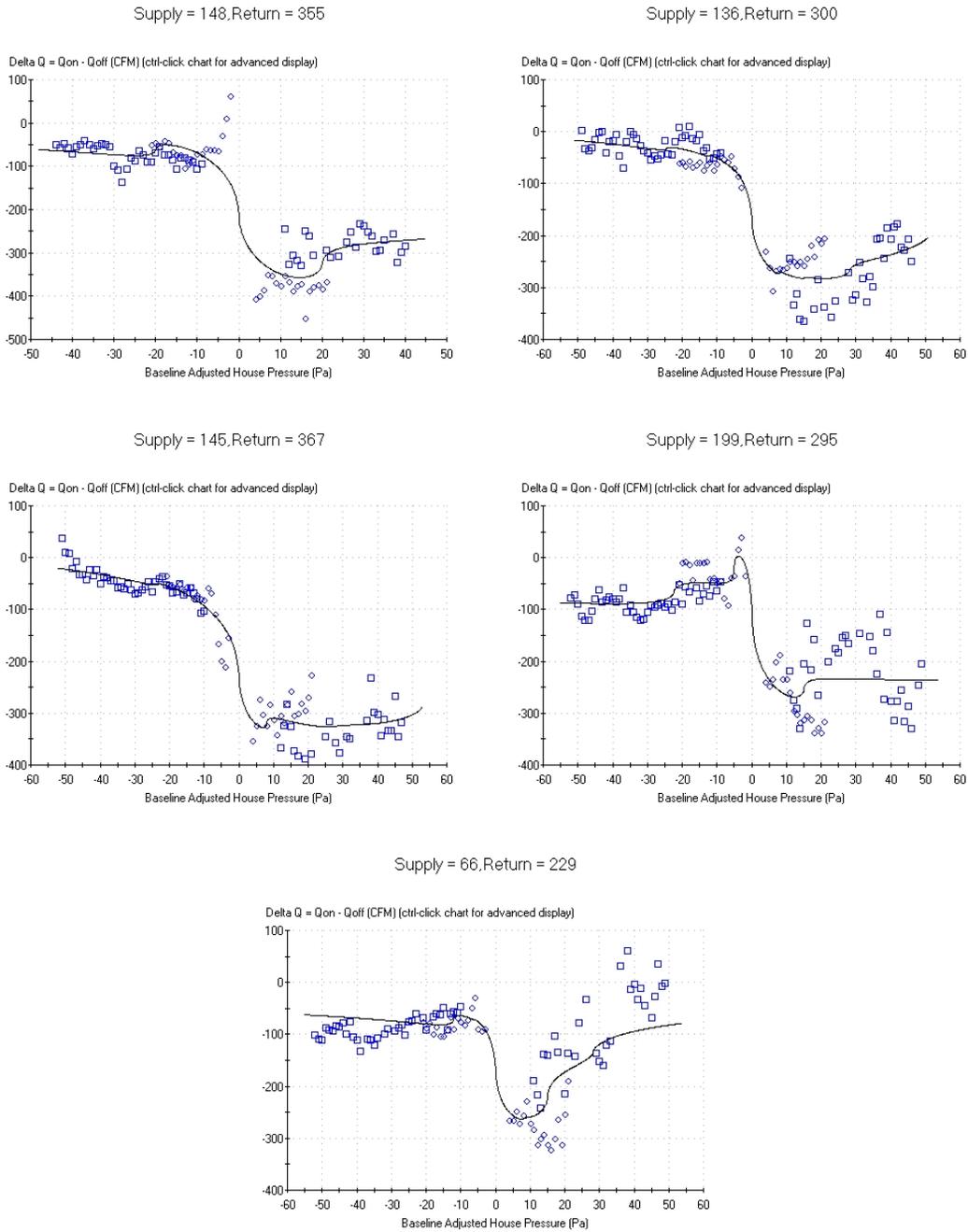
**Figure 16. Airflow and pressure data for Test #2 for Site 1**

Figure 16 is an example of the measured airflow and pressure data for Site 1, Test #2. Comparing this to Figure 3, shows the fluctuations in flow and pressure are greater in these field data than the laboratory test data. These fluctuations are due to changes in envelope pressure and the airflow signal due to a combination of wind pressure fluctuations and blower door airflows moving the pressure sample tubing. This latter effect was found to be significant both in the laboratory and field tests. During the initial part of the tests, considerable care was taken to move the pressure sample tubing to different locations or otherwise shield the tubing from the blower door flow. For the laboratory tests, the apparatus and tubing was deliberately arranged to minimize this problem. In field testing, this is not always so easy – but it is recommended that as much care as possible be taken in pressure tubing placement. Detailed observations have shown that the majority of the fluctuations are in the airflow (or the pressure signal from which airflow was derived) rather than the envelope pressure difference.

The test results in Table 7 for site 2 show that the Ramping test resulted in higher leakage flows. The standard deviations are about 55 cfm. This is about 20 to 50% of the measured leakage flows (2 to 5% of furnace blower flow) and is close to 1% (47 cfm) of envelope  $Q_{50}$ .

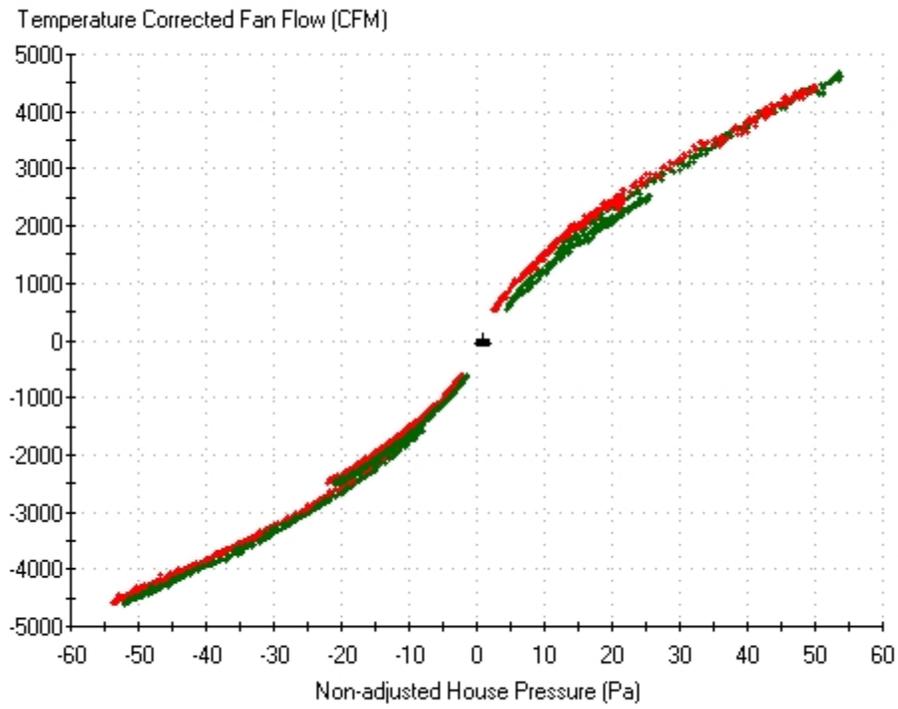
Table 7. DeltaQ repeatability results from Site 2		
Test	Supply Leakage, $Q_s$	Return Leakage, $Q_r$
Ramping #1	148	355
Ramping #2	136	300
Ramping #3	145	367
Ramping #4	199	295
Ramping #5	65	228
<b>Mean</b>	<b>139</b>	<b>309</b>
<b>Standard Deviation</b>	<b>48</b>	<b>55</b>
E1554 #1	36	209
E1554 #2	72	318
E1554 #3	159	325
E1554 #4	141	250
<b>Mean</b>	<b>102</b>	<b>276</b>
<b>Standard Deviation</b>	<b>58</b>	<b>56</b>

Figure 17 shows how the DeltaQ data and the NNLS fits to the data changed for the 5 ramping tests. Because this test was on a day with little wind, the data show less scatter than in Figure 15. However, there is still more scatter than in the Laboratory data in Figure 4. These results illustrate that, although the wind was calm (resulting in relatively little scatter), the uncertainty in measuring the 5000 cfm (2500 L/s) envelope flows at high envelope pressure differences led to significant shifts in DeltaQ measurements. This is particularly true for the pressurization data that shift by 100 cfm (50 L/s) or more between tests. Of particular interest is the final ramping test. The decrease in DeltaQ magnitude at higher positive envelope pressures compared to the other tests led to a much reduced estimate of leakage.



**Figure 17. DeltaQ data fits for Site 2 repeatability testing**

Figure 18 illustrates the measured pressure and flow data for Site 2, Test 5. This illustrates that the calm wind conditions and carefully placed pressure tubing at this site led to pressure and flow data with relatively little scatter. This reinforces the discussion above about the variability in Figure 17 being primarily due to resolution uncertainty at the high envelope flows for this leaky house.



**Figure 18. Measured Envelope Pressures and Airflows for Site 2, Test 5.**

The test results in Table 8 for site 3 are for DeltaQ tests where the system blower is *not* turned on, which mimics a duct system with zero leakage to outside (in this case, the duct leaks simply appear to be envelope leaks). The results show a small (about 5 cfm, 2.5 L/s) positive bias from a true zero measurement for pressure scanning and slightly higher bias for NNLS. The higher bias for NNLS is because it intrinsically cannot have negative results that would tend to offset a positive bias. The standard deviations are about 11 cfm for pressure scanning and are slightly lower at 7 cfm for NNLS. Some of this standard deviation reduction is due to NNLS always reporting a positive result. The standard deviations are close to 1% (10 cfm) of envelope Q<sub>50</sub>.

Table 8. DeltaQ repeatability results from Site 3

Test	Supply Leakage, Qs		Return Leakage, Qr	
	Scanning	NNLS	Scanning	NNLS
Ramping #1	-15	0	-19	0
Ramping #2	-4	6	-6	2
Ramping #3	-8	0	-5	2
Ramping #4	10	10	5	5
Ramping #5	18	20	17	18
<b>Mean</b>	<b>0</b>	<b>7</b>	<b>8</b>	<b>5</b>
<b>Standard Deviation</b>	<b>13</b>	<b>8</b>	<b>10</b>	<b>7</b>
E1554 #1	9	9	18	18
E1554 #2	7	0	8	0
E1554 #3	7	7	7	7
E1554 #4	14	14	17	17
E1554 #5	-7	6	-17	0
<b>Mean</b>	<b>6</b>	<b>7</b>	<b>7</b>	<b>8</b>
<b>Standard Deviation</b>	<b>8</b>	<b>5</b>	<b>14</b>	<b>9</b>

The test results for site 4 in Table 9 are similar to those for site 3 in Table 8. The standard deviations average about 5 cfm. The results show a small (about 5 cfm, 2.5 L/s) positive bias from a true zero measurement for pressure scanning and slightly higher bias (by about 2 cfm, 1 L/s) for NNLS. Again, the higher bias for NNLS is because it cannot have negative results. The standard deviations are about 6 cfm (3 L/s) for pressure scanning and are slightly lower at 4 cfm (2 L/s) for NNLS. Some of this standard deviation reduction is due to NNLS always reporting a positive result. The standard deviations are slightly less than 1% (7 cfm) of envelope Q<sub>50</sub>.

Table 9. DeltaQ repeatability results from Site 4

Test	Supply Leakage, Q <sub>s</sub>		Return Leakage, Q <sub>r</sub>	
	Scanning	NNLS	Scanning	NNLS
Ramping #1	8	9	9	8
Ramping #2	19	8	10	9
Ramping #3	-2	0	1	2
Ramping #4	3	4	4	5
Ramping #5	-2	3	-7	0
<b>Mean</b>	<b>5</b>	<b>5</b>	<b>3</b>	<b>5</b>
<b>Standard Deviation</b>	<b>9</b>	<b>4</b>	<b>7</b>	<b>4</b>
E1554 #1	10	10	7	8
E1554 #2	2	12	4	15
E1554 #3	4	5	3	3
E1554 #4	13	13	7	8
E1554 #5	10	10	7	7
<b>Mean</b>	<b>8</b>	<b>10</b>	<b>6</b>	<b>8</b>
<b>Standard Deviation</b>	<b>5</b>	<b>3</b>	<b>2</b>	<b>4</b>

#### Repeatability Testing Summary

The repeatability tests have shown that the repeatability depends on both the envelope leakage and weather conditions. In general, a leakier building envelope and windier weather can lead to greater uncertainty. For these tests, the building envelope seems to dominate and a reasonable rule of thumb is that the repeatability uncertainty is about 1% of the envelope airflow at 50 Pa (Q<sub>50</sub>). There is no clear repeatability advantage for ramping or pressure stations using the ASTM E1554 approach.

## **OTHER FIELD TESTING ISSUES**

### **When is a leak not a leak?**

One method currently used for mechanically ventilating homes is to introduce air from outside via a duct connected to the return while operating the central forced air system blower. When performing the DeltaQ test, this deliberate leak is accounted for.

If this duct has no damper, then there are two options:

1. The DeltaQ test should proceed as normal, but it should be noted in test results that the return leakage includes airflow through this ventilation duct. This is probably appropriate if the user wants to account for the energy implication of this ventilation system.

2. The duct can be capped off either at its inlet, or more likely where it enters the return plenum. The DeltaQ test is then a measure of duct construction not counting the deliberate ventilation.

If the duct has a damper (usually operated by a timer), then the test should be performed with the damper closed and the duct should be capped off to prevent opening or closing during the DeltaQ test that would invalidate the test. Like option 2 above, the DeltaQ test is then a test of duct air tightness and does not include the ventilation airflow through the duct.

## **SUMMARY AND CONCLUSIONS**

A new DeltaQ ramping method was developed with the objectives of being faster to perform and also to be more robust than the current pressure station technique in ASTM E1554. The experiences from field testing by the authors and other users have shown that ramping is more time efficient and time savings are about 10 to 15 minutes. The potential for additional robustness due to having more individual data points in the DeltaQ analysis was investigated and the low pressure leakage issues that occasionally were found for pressure station testing were reduced so long as the minimum characteristic pressure used in the analysis was double the lowest test pressure.

Several analysis approaches were evaluated. Laboratory testing showed that the pressure scanning, pressure fitting and NNLS approaches all gave results very close to each other such that on average there is no method clearly better or worse than the others. Pressure scanning and pressure fitting utilized correction factors to account for the pressure offset on the building envelope due to leakage imbalances and the change in duct static pressures due to duct leakage. These corrections were found to be effective at reducing high leakage airflow over-predictions by reducing average flows by 10 cfm (5 L/s). The pressure scanning and NNLS techniques are computationally simpler and faster than pressure fitting and therefore lend themselves better to field testing that are time limited.

Laboratory tests have shown that the biases for the ramping test are typically less than 1% of system blower flow, with a range of zero to 1.5% of system blower flow.

Field tests have shown that a reasonable rule of thumb for repeatability uncertainty is 1% of the 50 Pa (0.2 in. water) envelope leakage flow. This combines precision errors for the blower door that increase with increasing airflow rate (and therefore with envelope leakage) with airflow changes due to wind and stack effects. No significant changes in repeatability were found between two leaky houses (one tested on a calm day and the other tested on a windy day) indicating that envelope leakage is more important than wind pressure fluctuations. More houses should be tested to be more definitive about this result. In addition, there was no clear repeatability advantage for ramping or pressure stations or between pressure fitting and the NNLS analysis techniques.

Field tests to determine suitability for confirming zero duct leakage have shown that the limit on measuring zero leakage is the tightness of the building envelope. The above rule of thumb for repeatability uncertainty can also be applied to the estimation of zero duct leakage.

25 Pa (0.1 in. water) pressurization tests have about 2 to 2.5 times the uncertainty bias for an individual test compared to DeltaQ in laboratory testing.

Investigation of correlations between supply and return errors has shown that large errors on one side of the system correspond with large errors on the other side, but not on the magnitude of leakage on the other side.

## **RECOMMENDATIONS**

More houses need to be field tested for repeatability to confirm the finding that envelope leakage dominates over wind induced pressure fluctuations.

Care must be taken on the placement of pressure measuring tubes to insure that the turbulence induced by blower door airflows does not vibrate the pressure tubes. Field experience has shown that locating tubes up off the floor away from the direct blower door flow is effective, as is placing tubing underneath blankets or carpeting if they run on the floor in front of the blower door.

DeltaQ analyses should have pressure limits of double the lowest measured envelope pressure difference or 5 Pa (0.02 in. water) whichever is greater and employ a relaxation factor of 0.5 to the correction factors in order to avoid numerical instabilities and make the calculations more robust.

The ramping technique can be used in place of the pressure station technique in ASTM E1554-03 to save time without introducing additional testing uncertainty.

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## Appendix A. Derivation of Simplified Blower on DeltaQ Correction Factors

We start out with the following relationship that sets the difference in flow through the blower and the ducts (LHS) equal to the duct leakage (RHS).

$$1 - \left(1 - \frac{Q_{r,s}}{Q_e}\right) \left[1 \pm \frac{\delta P_{r,s}^{on}}{P_{r,s}}\right]^{1/2} = \frac{Q_{r,s}}{Q_e} \left[1 \mp \frac{P - \delta P_{r,s}^{on}}{P_{r,s}}\right]^{n_{r,s}} \quad (\text{A1})$$

Assume  $n_{\text{duct}}=n_{r,s}=0.5$ . This is a good assumption for duct flow resistance – but leaks usually have a pressure exponent of about 0.6.

Now let's substitute some variables:

$$\begin{aligned} \phi_s &= \frac{Q_s}{Q_e} & \phi_r &= \frac{Q_r}{Q_e} & a_r &= 1 + \frac{\delta P_{r,on}}{P_r} & a_s &= 1 - \frac{\delta P_{s,on}}{P_s} \\ b_r &= -\frac{P}{P_r} & b_s &= \frac{P}{P_s} \end{aligned}$$

For Return Leaks substituting in Equation A1:

$$1 - (1 - \phi_r) [a_r]^{1/2} = \phi_r [a_r + b_r]^{1/2} \quad (\text{A2})$$

Expanding the LHS:

$$1 - a_r^{1/2} + \phi_r a_r^{1/2} = \phi_r [a_r + b_r]^{1/2} \quad (\text{A3})$$

Squaring both sides:

$$1 - a_r^{1/2} + \phi_r a_r^{1/2} - a_r^{1/2} + a_r - \phi_r a_r + \phi_r a_r^{1/2} - \phi_r a_r + \phi_r^2 a_r = \phi_r^2 a_r + \phi_r^2 b_r \quad (\text{A4})$$

Grouping terms on the LHS

$$1 - 2a_r^{1/2} + 2\phi_r a_r^{1/2} + a_r - 2\phi_r a_r + \phi_r^2 a_r = \phi_r^2 a_r + \phi_r^2 b_r \quad (\text{A5})$$

Eliminating common  $\phi_r^2 a_r$  term

$$1 - 2a_r^{1/2} + 2\phi_r a_r^{1/2} + a_r - 2\phi_r a_r = \phi_r^2 b_r \quad (\text{A6})$$

Grouping  $a_r$  terms and rearranging

$$a_r (1 - 2\phi_r) + a_r^{1/2} (2\phi_r - 2) = \phi_r^2 b_r - 1 \quad (\text{A7})$$

Another change – this time to make it look like a quadratic in  $a_r^{1/2}$

$$a_r (1 - 2\phi_r) + a_r^{1/2} (2\phi_r - 2) + (1 - \phi_r^2 b_r) = 0 \quad (\text{A8})$$

A quadratic has the form:

$$ex^2 + fx + g = 0$$

And has the solution:

$$x = \frac{-f \pm \sqrt{f^2 - 4eg}}{2f}$$

Substitute the following to make Equation A8 a quadratic:

$$x = a_r^{\frac{1}{2}}; e = (1 - 2\phi_r); f = (2\phi_r - 2); g = (1 - \phi_r^2 b_r)$$

$$a_r^{\frac{1}{2}} = \frac{(2 - 2\phi_r) \pm \sqrt{(2\phi_r - 2)^2 - 4(1 - 2\phi_r)(1 - \phi_r^2 b_r)}}{2(1 - 2\phi_r)} \quad (\text{A9})$$

Substitute for  $a_r$  and  $b_r$ :

$$\left(1 + \frac{\delta P_r^{on}}{P_r}\right)^{\frac{1}{2}} = \frac{(2 - 2\phi_r) \pm \sqrt{(2\phi_r - 2)^2 - 4(1 - 2\phi_r) \left(1 + \phi_r^2 \frac{P}{P_r}\right)}}{2(1 - 2\phi_r)} \quad (\text{A10})$$

Squaring both sides, substituting and rearranging (note the use of the [] terminology for addressing negative numbers to non-integer powers  $[x]^n = x(|x|)^{n-1}$ ):

$$\frac{\delta P_r^{on}}{P_r} = \left( \frac{\left( \left( 2 - 2\frac{Q_r}{Q_e} \right) \pm \left[ \left( 2\frac{Q_r}{Q_e} - 2 \right)^2 - 4 \left( 1 - 2\frac{Q_r}{Q_e} \right) \left( 1 + \left( \frac{Q_r}{Q_e} \right)^2 \frac{P}{P_r} \right) \right]^{0.5}}{2 \left( 1 - 2\frac{Q_r}{Q_e} \right)} \right)^2 - 1 \quad (\text{A11})$$

Some example calculations have shown that the negative root is the one we want so the final relationship is:

$$\frac{\delta P_r^{on}}{P_r} = \left( \frac{\left( \left( 2 - 2\frac{Q_r}{Q_e} \right) - \left[ \left( 2\frac{Q_r}{Q_e} - 2 \right)^2 - 4 \left( 1 - 2\frac{Q_r}{Q_e} \right) \left( 1 + \left( \frac{Q_r}{Q_e} \right)^2 \frac{P}{P_r} \right) \right]^{0.5}}{2 \left( 1 - 2\frac{Q_r}{Q_e} \right)} \right)^2 - 1 \quad (\text{A12})$$

Now let's follow the same procedure for supply corrections:  
For supply Leaks substituting in Equation A1:

$$1 - (1 - \phi_s) [a_s]^{1/2} = \phi_s [a_s + b_s]^{1/2} \quad (\text{A13})$$

This is the same as Equation A2 but with “s” for supply instead for “r” for return.  
So the derivation is the same down to Equation A9 that becomes:

$$a_s^{1/2} = \frac{(2 - 2\phi_s) \pm \sqrt{(2\phi_s - 2)^2 - 4(1 - 2\phi_s)(1 - \phi_s^2 b_s)}}{2(1 - 2\phi_s)} \quad (\text{A14})$$

Substitute for  $a_s$  and  $b_s$  using:

$$\phi_s = \frac{Q_s}{Q_e} \quad a_s = 1 - \frac{\delta P_{s,on}}{P_s} \quad b_s = \frac{P}{P_s}$$

$$\left(1 - \frac{\delta P_s^{on}}{P_s}\right)^{1/2} = \frac{(2 - 2\phi_s) \pm \sqrt{(2\phi_s - 2)^2 - 4(1 - 2\phi_s) \left(1 - \phi_s^2 \frac{P}{P_s}\right)}}{2(1 - 2\phi_s)} \quad (\text{A15})$$

Squaring both sides, substituting and rearranging (note the use of the [] terminology for addressing negative numbers to non-integer powers  $[x]^n = x(|x|)^{n-1}$ ):

$$\frac{\delta P_s^{on}}{P_s} = 1 - \left( \frac{\left(2 - 2\frac{Q_s}{Q_e}\right) \pm \left[ \left(2\frac{Q_s}{Q_e} - 2\right)^2 - 4\left(1 - 2\frac{Q_s}{Q_e}\right) \left(1 - \left(\frac{Q_s}{Q_e}\right)^2 \frac{P}{P_s}\right) \right]^{0.5}}{2\left(1 - 2\frac{Q_s}{Q_e}\right)} \right)^2 \quad (\text{A16})$$

Some example calculations have shown that the negative root is the one we want so the final relationship is:

$$\frac{\delta P_s^{on}}{P_s} = 1 - \left( \frac{\left(2 - 2\frac{Q_s}{Q_e}\right) - \left[ \left(2\frac{Q_s}{Q_e} - 2\right)^2 - 4\left(1 - 2\frac{Q_s}{Q_e}\right) \left(1 - \left(\frac{Q_s}{Q_e}\right)^2 \frac{P}{P_s}\right) \right]^{0.5}}{2\left(1 - 2\frac{Q_s}{Q_e}\right)} \right)^2 \quad (\text{A17})$$