LBNL 53549

ERNEST ORLANDO LAWRENCE
BERKELEY NATIONAL LABORATORY

Reducing Uncertainty for the DeltaQ Duct Leakage Test

I.S. Walker, M.H. Sherman and D.J. Dickerhoff

Environmental Energy Technologies Division

May 2004

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Program, of the U.S. Department of Energy under contract No. DE-AC03-76SF00098.

Reducing Uncertainty for the DeltaQ Duct Leakage Test

Iain Walker, Ph.D. *Member ASHRAE*
Max Sherman, Ph.D. *Fellow ASHRAE*
Darryl Dickerhoff

ABSTRACT

The thermal distribution system couples the HVAC components to the building envelope, and shares many properties of the buildings envelope including moisture, conduction and most especially air leakage performance. Duct leakage has a strong influence on air flow rates through building envelopes (usually resulting in much greater flows than those due to natural infiltration) because unbalanced duct air flows and leaks result in building pressurization and depressurization. As a tool to estimate this effect, the DeltaQ duct leakage test has been developed over the past several years as an improvement to existing duct pressurization tests. It focuses on measuring the air leakage flows to outside at operating conditions that are required for envelope infiltration impacts and energy loss calculations for duct systems. The DeltaQ test builds on the standard envelope tightness blower door measurement techniques by repeating the tests with the system air handler off and on. The DeltaQ test requires several assumptions to be made about duct leakage and its interaction with the duct system and building envelope in order to convert the blower door results into duct leakage at system operating conditions. This study examined improvements to the DeltaQ test that account for some of these assumptions using a duct system and building envelope in a test laboratory. The laboratory measurements used a purpose-built test chamber coupled to a duct system typical of forced air systems in US homes. Special duct leaks with controlled air-flow were designed and installed into an airtight duct system. This test apparatus allowed the systematic variation of the duct and envelope leakage and accurate measurement of the duct leakage flows for comparison to DeltaQ test results. This paper will discuss the laboratory test apparatus design, construction and operation, the various analysis techniques applied to the calculation procedure and present estimates of uncertainty in measured duct leakage.

INTRODUCTION

The DeltaQ duct leakage test has been developed by LBNL over the past several years as an improved method of measuring duct leakage. It has been incorporated into a draft ASTM Standard (E1554 - 2004) and has been the subject of several previous studies to determine its accuracy and applicability limits. This study aims to improve the test method by addressing issues raised in these previous studies. These improvements include corrections for duct air flow resistance, envelope offset pressures due to duct leakage and the optimization of pressure limits used in the data fitting calculations.

Initial field testing by LBNL (Walker et al. 2001 and 2002) evaluated the same duct system 20 times over several days. These results showed that the repeatability errors were quite reasonable, with a 95% confidence interval of less than one percent of air handler flow. These tests were performed for a relatively sheltered building and it is possible that the differences between tests would increase under windier conditions. This same study also looked at the effect of adding leaks that were carefully instrumented with flow meters to give an indication of true leakage flow. Tests were performed at 6%, 11%, 17% and 36% total leakage (expressed as a fraction of air handler flow). The Root Mean Square (RMS) errors were 1.5% of air handler flow for return leaks and 2.5% of air handler flow for supply leaks. Most of this error was biases: 1.5% of air handler flow for return leaks and 1.5% of air handler flow for supply leaks. The biases were negligible (on the order of 0.1%) for leaks less than 10% of air handler flow and increased at higher leakage flows. The use of fitted pressures (rather than measured plenum pressures, or fixed pressures) was found to slightly improve the DeltaQ results. In addition to these controlled added leak tests, field tests were performed in 87 houses. Because there was no way to measure the true leakage flow in these houses, the results were compared to fan pressurization test results that measure total leakage flow at a fixed pressure, rather than leakage flow to outside at operating conditions. The pressurization test was used for comparison because it is the most commonly used test at present and is used in ASTM (E1554-03) and ASHRAE (Standard 152) standards, and it is useful to know how a new technique compares to current state of the art if one is a potential user of the new technique. The RMS differences were about 10% of air handler flow. Most of these differences can be attributed to the two tests measuring fundamentally different duct system parameters: DeltaQ measures air leakage at operating conditions and the fan pressurization tests give an air flow through the duct leaks at a fixed pressure.

Walker et al. (2002) compared the DeltaQ results obtained by fixing the values of characteristic pressures based on other system measurements and by allowing the characteristic pressures as well as the leakage flows to be fit to the data. In addition, the effect of changing pressure exponents on DeltaQ results was also investigated. Both the characteristic pressure and pressure exponent investigations used the results from eight houses tested by Francisco et al. (2002). These measurements were made with the duct system in the "as-found" condition and with added leaks. The added leakage was mostly accomplished by disconnecting ducts. These cases with a big hole or a disconnected duct (rather than the multiple smaller holes around duct connections typical of most duct systems) will have a pressure exponent for the duct leaks of about 0.5, rather than the 0.6 assumed in the DeltaQ calculation procedure. Using fitted pressures and pressure exponent of 0.5 resulted in an average decrease in supply leakage of 23% and return leakage of 20% compared to using fixed plenum pressures and pressure exponents of 0.6. The majority of this change was due to the change in pressure exponent. This sensitivity to pressure exponent is one of the key reasons for developing duct leaks with pressure exponents near 0.6 for the laboratory testing discussed in the current study. Experiments to characterize the pressure exponent in a wide range of duct configurations have shown that a value of 0.6 is suitable for most duct systems (Walker et al. 1998 and Siegel et al. 2003). Francisco et al. (2002), in their own analysis found that the DeltaQ test tended to over predict the duct leakage compared to other tests. However, the lack of a reference duct leakage flow measurement makes these tests less than definitive and so it was not possible to separate potential biases at high leakage flow in the DeltaQ method from errors in pressure exponent assumptions or in the measurement techniques that DeltaQ was compared to.

Andrews (2000) performed DeltaQ uncertainty estimates using monte-carlo simulation techniques. The simulations showed that the DeltaQ results were only weakly dependant on the assumptions about characteristic pressures and duct leakage locations. However, fitting for the characteristic pressures rather than using fixed plenum pressures can better determine the duct leakage in systems where the duct leakage is far from this plenum pressure (e.g. at register boots). Andrews also demonstrated that the uncertainties in DeltaQ test results are greater for the sum of the supply and return leakage, rather than their difference. This is expected for the DeltaQ test where the primary measurement is caused by this flow difference.

Andrews (2002) evaluated the DeltaQ test using a duct system assembled within a laboratory. A small chamber was used to represent the house envelope. This chamber had a single large opening to represent house envelope leakage with an air flow of 1500 m^3/h (900 cfm) at 25 Pa which corresponds to a relatively tight building envelope typical of new construction (based on the envelope leakage data reported in Sherman and Matson (2002)). The duct system had eight supply branches and a single return. Instrumented duct leaks were added to the system that allowed control over a range of 5% to 60% (combined supply and return) of air handler flow and monitoring of the system air leakage. These added leaks all had pressure exponents of about 0.5. Thirteen different combinations of supply and return leaks were evaluated. The average of the sum of the absolute supply and return DeltaQ leakage errors was 3.4% of air handler flow. It should be noted that Andrews did not fit the characteristic pressures but instead used half of the measured plenum pressure. Andrews also used a standard pressurization test in an iterative procedure to obtain another estimate of characteristic pressures. This was found to significantly improve the accuracy of the DeltaQ test and reduced the average of the sum of the absolute supply and return leakage errors to 1.9% of air handler flow.

Although these studies indicated that the DeltaQ test had reasonable accuracy in many applications, some significant issues were raised regarding potential biases in the DeltaQ test results. For example, the assumption that duct air resistance between the house and the duct leaks is negligible can be particularly poor in some cases, and its effect is most noticeable at high leakage flows where it leads to over prediction of the duct leakage flow. In addition, field applications of the DeltaQ test do not exercise the house envelope and duct system over the whole pressure range seen in residential duct systems. Typically, the maximum pressure achieved across a house envelope is in the range of 25 Pa to 50 Pa (0.1 to 0.2 in. water). The magnitude of pressures in the duct system are often in excess of 100 Pa (0.4 in. water). Normally it is good practice to not extrapolate beyond a measured data range to minimize errors, however, in the case of the DeltaQ test there is significant likelihood of duct leak pressures lying beyond the bounds of the measured field data. Therefore, the pressure limits set for the multivariate fit to the DeltaQ relationship require investigation.

In order to further investigate these issues a series of detailed laboratory tests were undertaken. These tests were intended to precisely measure the actual duct leakage and compare it to the DeltaQ calculated results. The tests were designed to cover a range of duct and building envelope air leakage and pressures. Duct leaks were specifically developed to be similar to those in real buildings, both in magnitude and pressure exponent (i.e., 0.6 rather than 0.5).

LABORATORY TEST APPARATUS

The test chamber

The test chamber was a 9.5 m long × 2.5 m wide × 2.5 m high (32 ft × 8 ft × 8 ft) wood framed structure (see Figure 1). The wood framed walls and ceiling were covered with wallboard or plywood with carefully taped seams and joints to minimize envelope leakage. Additional caulking was used at critical joints to further reduce envelope air leakage. The chamber was mounted above a four-foot high crawl space that contains the supply ducts. There was one weather-stripped door and no windows. The test chamber was built inside a warehouse and is completely sheltered from any outdoor weather. Two blower doors and the return duct were mounted in one end-wall of the chamber. For most of the tests, one blower was mounted so as to pressurize the structure and the other to depressurize it. This eliminated the time and effort required to reverse the blower door every time the testing switched from pressurization to depressurization, and ensured consistent fitting of the blower door each time. This reduced variations in the way the blower door sat in its frame, or how the elasticized weather seal attached to the fan housing. For high envelope leakage tests the blower doors were both mounted with the same orientation because a single blower door was not capable of achieving the higher envelope pressure differences.

Figure 1. Completed test chamber inside warehouse showing the return duct connection and blower door fans, but before supply duct installation.

Test Chamber Leakage

The background leakage of the test chamber was measured using standard fan pressurization techniques, and had a leakage coefficient of 17 m^3/hPa^n (10 cfm/Pa^n) and a pressure exponent of 0.56. This is equivalent to 103 m^3/h (61 cfm) at 25 Pa. Additional pressurization tests were performed with the second blower door carefully sealed with tape that showed about two-thirds of this leakage was through the second blower door and only one-third was through the chamber envelope and duct system. Deliberate holes were added to the test chamber envelope to allow a wide range of envelope leakage. Figure 2 shows an example of these envelope leakage holes. These holes were added to the walls of the test chamber that did not contain the blower doors and return ducting. A total of six holes were used: 2 of 0.28 m (11 in.) diameter, 2 of 0.34 m (13.5 in.) diameter and two of 0.45 m (17.5 in.) diameter. Airtight covers were placed over each hole when they were not in use. Six leakage configurations were used for the DeltaQ testing to cover a wide range of building envelopes from tight (850 m^3/h (500 cfm) at 25 Pa) to leaky (8630 m^3/h (5080 cfm) at 25 Pa).

Figure 2. Test chamber hole number 1 open and hole number 2 with cover in place

The Duct System

The duct system had 10 supply registers and a single return. The supply ducts were made of flexible insulated duct mounted in the crawlspace (as shown in Figure 3). The registers were placed in the floor of the test chamber in the layout illustrated in Figure 4. The flows from each register ranged from about 85 m^3/h to 425 m^3/h (50 cfm to 250 cfm). The air handler flow was measured using a large 16 inch flow nozzle in line with the return duct and ranged from 890 m^3/h (525 cfm) to 1960 m^3/h (1155 cfm), with an average of 1615 m^3/h (950 cfm). The corresponding supply plenum pressures ranged from 17 to 83 Pa (0.07 to 0.33 in. water), with an average of 60 Pa (0.24 in. water). Return plenum pressures ranged from –31 to –55 Pa (-0.12 to –0.22 in. water), with an average of –45 Pa (-0.18 in. water). This large range of flows and pressures was the result of operating the air handler at three different speeds and changes in duct system flow resistance as leaks were added and registers opened and closed. The duct system had two main branches from the supply plenum: one of 12 inches diameter and one of 14 inches diameter. The return duct, air handler and the two main supply branches were located beside the test chamber. The duct system had mastic at all connections, and the register boots were screwed and taped to the floor to minimize duct system leakage.

Figure 3. Ducts in the crawlspace below the test chamber.

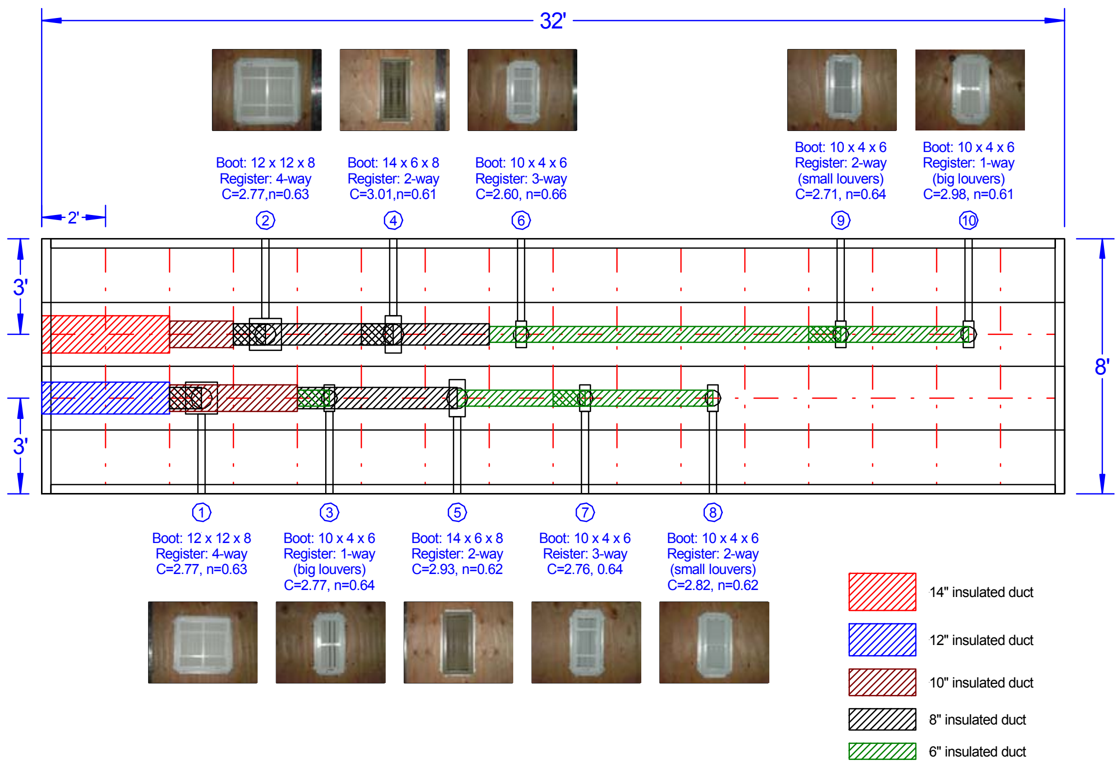


Figure 4. **Floor plan of test chamber showing duct system layout, register location and added boot leakage locations numbered 1-10.**

Supply and Return Boot Leaks

The supply boot leaks were specially designed to have a pressure exponent of about 0.6, that is typical of pressure exponents measured in field studies. A range of example leaks were constructed and calibrated using high accuracy (±0.5%) flow meters. The pressure drop across the leak and the air flow were recorded over a range of flow rates. The pressure exponent and flow rate were controlled by varying the diameter and length of an array of small holes placed inside a pipe. The holes were created using several techniques, such as stuffing straws and small diameter pipe of different lengths and diameters inside the main leakage pipe. The final versions of the calibrated leaks used holes drilled in PVC plugs that were 50 mm (2 in.) long. The holes were 6 mm (0.24 in.) in diameter and there were 55 holes across the cross section of the plug. The use of uniformly milled PVC plugs made the leak construction more consistent than with other methods. The calibrated leaks had a pressure exponent of 0.61 and a flow coefficient of 5.1 m^3/hPa^n (3.0 cfm/Pa^n). This gave a reasonable flow through the leaks, covering a range of about 8.5 to 35 m^3/h (5 to 20 cfm) for each leakage pipe. A total of ten leakage pipes were installed (one for each supply boot) so that the total supply boot leakage could be up to 350 m^3/h (200 cfm). The flows through these boot leaks could be adjusted by changing the register damper settings for the boot. Closing a register damper increased the pressure difference across an individual boot leak, thus increasing the leakage flow. The calibrated leaks were installed at the boots as shown in Figures 5 and 6. These boot leaks were closed for some tests by placing a cap over the end of the pipe, as shown in Figure 6.

The return boot leakage was controlled using a flow meter with three different sized orifice rings with pressure exponents of 0.5. The three rings gave leakage flows ranging from 60 m^3/h(35 cfm) to 350 m^3/h (200 cfm).

Figure 5. End view of calibrated boot leak showing the PVC plug with multiple small holes

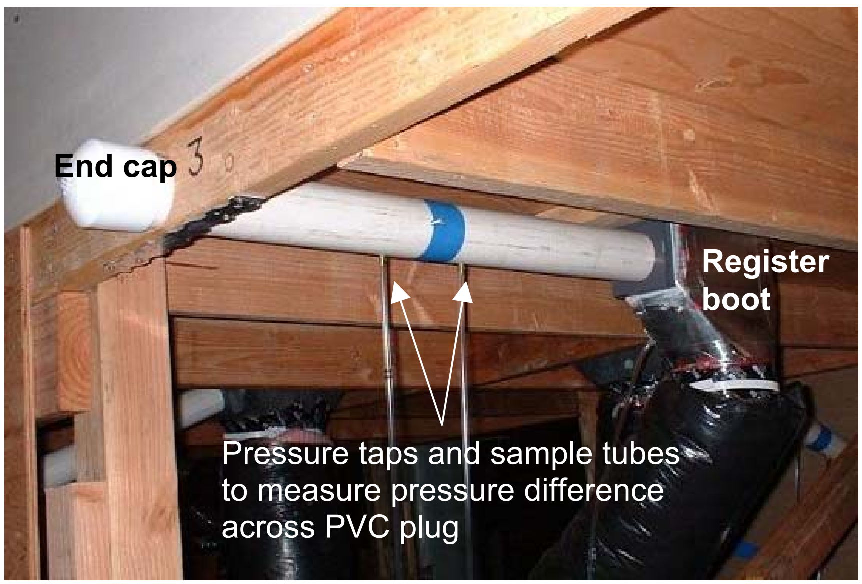


Figure 6. Boot leak showing end cap and attachment to boot.

Supply and Return Plenum Leaks

The supply plenum and the return plenum each had a single added measured leak. The leaks were constructed by connecting a flow meter to each plenum via a piece of flexible duct. The supply plenum leak duct used a 15 cm (six inch) diameter nozzle and the return plenum leak duct used a 10 cm (four inch) diameter orifice. As with the register boot leaks, the leaks could be closed by placing an airtight cap over the end.

EXPERIMENTAL PROCEDURE

A total of 71 duct and envelope leakage combinations were tested. The total duct leakage ranged from zero to about 60% of air handler flow. Different leakage levels were achieved using combinations of return plenum, supply plenum, and boot leakage. In some configurations registers were closed to make the pressures across the boot leaks somewhere in-between the open registers boot pressure and the plenum pressure so that these leaks mimicked leaks at intermediate duct locations. In addition, some test combinations were performed several times as checks on repeatability. Preliminary testing showed that using different blower door rings for air handler on and off tests at a given pressure station added unacceptably large variability to the measured data. In the data presented here, the same ring was used for air handler on and off measurements at each pressure station. This practice should also be used for field testing.

There were several key differences between these laboratory tests and typical field tests:

- An adaptation to improve measurement accuracy was to tape the edges of blower door rings to reduce uncertainties due to air leakage around edges of ring.
- Testing was performed over a range of envelope pressures from –50 Pa to +50Pa (±0.2 in. water). For the high envelope leakage tests multiple blower doors were used.
- A few tests were performed using higher pressure limits (±75 Pa (±0.3 in. water)). This high pressure testing serves a purpose for validation of the DeltaQ method, but is not likely to be used in field testing due to possible damage to house structure and contents and noise issues.

The standard DeltaQ procedure was followed as discussed in detail in previous publications (Walker et al. 2001) and in a soon to be published standard: ASTM E1554-03. The following is a short summary of the procedure:

1. Perform a normal blower door test on the building with the air handler off, recording envelope pressure difference and blower door flow at several pressure stations. Typically the pressure stations are every 5 Pa (0.02 in. water) and cover a range from 5 Pa (0.02 in. water) to 25 Pa (0.1 in. water) or more.

2. Repeat the test with the air handler on recording pressures and flows for the same pressure stations.

3. Perform the air handler off and air handler on tests for both pressurization and depressurization of the building envelope.

4. Calculate the difference between the air handler off and air handler on blower door flows (these are the DeltaQ data: ΔQ) at each envelope pressure station (ΔP).

5. Use a multivariate fitting process to determine the supply (Q_s) and return (Q_r) air leakage flows and corresponding characteristic pressures (ΔP_s and ΔP_r) using the DeltaQ data in the following equation:

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

The use of fitted pressures rather than fixed pressures (e.g., plenum pressures) in the DeltaQ analysis adds significantly to the computational complexity of the non-linear fitting. To examine this issue the DeltaQ analyses were repeated using the measured plenum pressures. The Bias and RMS errors (as a % of air handler flow) for the fitted pressures were –1.3% and 3.7% respectively, compared to 3.9% and 9.1% when using plenum pressures. These results indicate that fitting the pressures gives significantly improved results. Most of the improvement is for cases where the pressures across the leaks are different from the plenum pressures. For the highest leakage cases in this study, the pressures across some of the larger leaks were much lower than plenum pressures. Fitting the pressures allowed the DeltaQ analysis to reflect this, whereas fixing the pressures did not.

At each DeltaQ pressure station the following were recorded: actual duct leakage air flow (all the individual boots plus the return and supply plenum leaks); envelope air flow; boot pressures; plenum pressures; envelope pressures; air handler flow; air handler fan power; air temperature and barometric pressure. These parameters were recorded using five second time averages from computer based data loggers. Pressure and flow readings were allowed to stabilize for about a minute at each pressure station before beginning the averaging.

DELTAQ CORRECTION FACTORS

Examining the flow network and the derivation of the DeltaQ relationship (given in Equation 1) led to the development of a couple of potential corrections to the DeltaQ calculation procedure. Firstly, there is the issue of the flow resistance of the ducts. During the test, any air flow through the duct system from the house to the leak (or visa versa) changes the pressure distribution within the duct system because of the resistance of the ducts to this air flow. When this occurs, the DeltaQ assumption about the duct pressure changes being equal to the house envelope pressure changes is no longer valid. A correction has been developed to account for these changes in duct pressure. To make the correction, the predicted leakage flow is used to calculate the pressure changes in the duct system due to the duct flow resistance. This pressure change is then used to calculate a new leakage flow. An iterative procedure then takes this new leakage flow to re-estimate the pressure changes. This iterative procedure is used for each pressure station. The derivation of this pressure correction is discussed in more detail in Dickerhoff et al. 2004 who showed that this correction factor is greater for high duct leakage, and resulted in an average change in duct leakage flows of about 2% of air handler flow. In the current study, values for this correction factor were slightly higher (due to using higher leakage flows) and were between 2 and 3% of air handler flow.

This flow resistance correction factor depends on the ratio of leakage flow to air handler flow. For this study the air handler flow was measured using the flow meter in the return duct. For cases with return plenum leakage the return duct flow meter was combined with the measured air flow through the return leak to get the total air handler flow. In field testing it may not be practical to always measure air handler flow, in which case an estimate must be made, e.g., based on HVAC system capacity. Fortunately, this pressure correction factor is not very sensitive to the estimate of air handler flow: underestimating the fan flow by about 25% can lead to a change in the estimated leakage flows of about 5%. Overestimation of air handler fan flow has a smaller change. The larger the leakage as a fraction of air handler flow the more sensitive the Qs and Qr are to the air handler flow assumption.

The second correction factor accounts for pressurization or depressurization of the building by unbalanced leakage flows. This changes the building envelope pressure during normal system operation (i.e., when the blower door is off). This correction is much smaller than the duct flow resistance correction: Dickerhoff et al. 2004 showed typical changes of less than 0.5% of duct leakage flow.

Another issue when fitting the DeltaQ relationship to measured data is one common to most multivariate fitting analyses (particularly when they are as non-linear as DeltaQ): i.e., placing limits on the fitted variables. The following limits are based on a combination of experience with analyzing DeltaQ data from many houses and from simple logical and analytical rationales.

- Lower limit for leakage flows. Q_s and Q_r were limited to be greater than zero because the leakage flows are defined to be positive numbers in the DeltaQ analysis. Only cases with little or no leakage ran into this lower limit.
- Upper limit for leakage flows was set to be a number close to typical air handler flows: 1700 m^3/h (1000 cfm). None of the tests ran into this upper limit.
- Lower limit for pressures. The lowest measured pressure station was used, i.e., 5 Pa (0.02 in. water). Although it is theoretically possible to have leaks at lower pressures than this they are unlikely to be of large magnitude. In addition, resolving lower pressures would require more data to be measured at lower pressures below 5 Pa (0.02 in. water).
- Upper limit for pressures. Setting this limit proved to be more of a problem because it was found that several tests had fitted pressures that were close to or at the selected limits. Also, the nature of the DeltaQ equation (Equation 1) is such that allowing the use of high fitted pressures can lead to solutions that fit the data well, but give unrealistic flow results. Several possibilities were investigated for setting upper pressure limits:
    1. Plenum pressures. This is likely to be the highest pressure difference across any leak in the system. However, a key aspect of making the DeltaQ test simple and fast in field applications is that the plenum pressures need not be measured. Also, it is possible for the effective leak pressures to be greater than the plenum static pressures if there are leaks where air flow momentum is significant.
    2. Maximum envelope pressure during the test. This option is appealing as it is generally preferable to limit extrapolations from measured data because this generally leads to increased uncertainty. However, if leaks are at plenums and have higher pressures than the imposed

envelope pressures, then this limit could lead to greater errors in the characteristic pressures than one would expect from allowing extrapolation to more extreme pressures.

3. Set an upper pressure limit based on existing knowledge of duct systems, such that it would be a reasonable upper bound: for example 250 Pa (1.0 in. water). Unfortunately, analysis of experimental data showed that this could lead to unrealistically large fitted pressures. This was because the fit of the DeltaQ relationship to the measured data (up to 50 Pa (0.2 in. water)) became insensitive to the characteristic pressure when the characteristic pressure was greater than two times the measured data limit.

4. Between the maximum envelope pressure achieved during the test and approximately double this maximum pressure. The DeltaQ analysis was performed using the maximum envelope pressure and double the maximum envelope pressure. These two upper pressure limits were applied to the laboratory tests for three cases of maximum envelope pressure: 25 Pa, 50 Pa, and 75 Pa. The decision on using one or two times the highest envelope pressure was studied using the laboratory test data and is discussed in the next section.

LABORATORY TEST RESULTS

In the following test results the bias and RMS errors are reported as fractions of the air handler flow measured for each test. The bias indicates if the DeltaQ test systematically over or underpredicts the air leakage over the range of test conditions. The RMS (Root Mean Square) error represents the error typical of an individual test. If one were surveying a large number of houses and wanted to estimate the errors over all the houses, then the bias is the appropriate error estimate. If an individual house is being tested, for example to determine if it meets a code specification or requires retrofitting, then the RMS error is more appropriate.

Table 1 summarizes the changes in DeltaQ errors for the different characteristic pressure limits discussed above. The entries in bold show which analysis limits gave better results when comparing the test pressure limit to twice this pressure as a limit. The best results were obtained when the pressure limits are set to double the maximum envelope pressure for tests that only go to 25Pa, and set to be the maximum envelope pressure for tests at higher pressures. The 50 Pa (0.2 in. water) envelope pressure limit results are significantly better than the 25 Pa (0.1 in. water) results due to the combination of having double the number of data points (because data were taken every 5 Pa (0.02 in. water) in both cases) and having measured data over a wider range – both of which will generally lead to improved results in this type of analysis. The 75 Pa (0.3 in. water) results do not show any improvement over the 50 Pa limited tests.

For the low (25 Pa (0.1 in. water)) data in Table 1, only 38 tests met the criteria for five pressurization and five depressurization data points. This was mostly due to eliminating data points where blower door rings were changed between air handler on and off tests for the same pressure station. The analysis was repeated with this restraint relaxed to require only four points rather than five. The results were slightly worse, with increased bias and RMS errors averaged over all the test results. The result for setting pressure limits was the same: there was an improvement (0.5% to 1% of air handler flow) in setting the pressure limit to twice the data range for the low envelope pressure limit tests.

Having optimized the pressure limits in the DeltaQ analysis, the results that are corrected for zero envelope pressure offset and duct flow resistance were compared to uncorrected DeltaQ results using the same pressure limits. Table 2 summarizes this comparison and shows the significant improvement in both bias and RMS errors due to the correction factors. Biases are reduced to –1.0% to –0.1% of air handler flow and RMS errors reduced to 2.2% to 1.8% of air handler flow for supply and return, respectively.

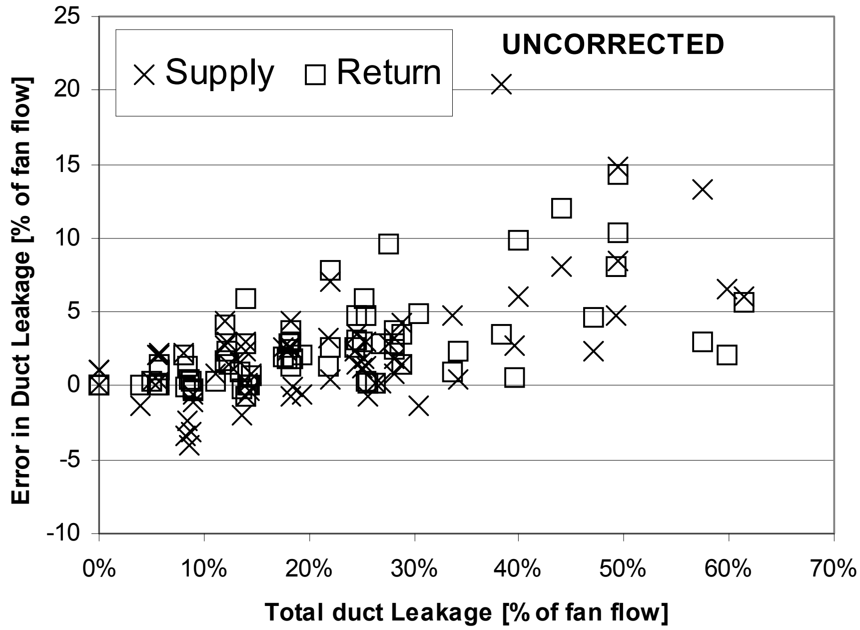
Table 1. Summary of DeltaQ errors for different pressure fitting limits

Analysis Limits on Ps and Pr	Measured pressure limits, Pa (in. water)	Allowed pressure limits for DeltaQ calculations, Pa (in. water)	Supply Leakage		Return Leakage		Total Leakage	
			% of Air Handler Flow					
			RMS	Bias	RMS	Bias	RMS	Bias
Data range	25 (0.1)	25 (0.1)	2.7	-1.5	2.9	-1.3	4.8	-2.8
Data range	50 (0.2)	50 (0.2)	**2.0**	**-0.9**	**1.8**	**-0.1**	**3.1**	**-1.0**
Data range	75 (0.3)	75 (0.3)	**2.5**	-1.3	**2.0**	**0.3**	**3.6**	-1.1
Twice data range	25 (0.1)	50 (0.2)	**2.5**	**-1.2**	**2.6**	**-0.9**	**4.3**	**-2.0**
Twice data range	50 (0.2)	100 (0.4)	2.2	**-0.9**	2.7	-0.2	3.8	-1.1
Twice data range	75 (0.3)	150 (0.6)	**2.5**	**-1.1**	2.1	**0.3**	3.8	**-0.8**

Table 2. Evaluation of DeltaQ Correction Factors

	Supply Leakage		Return Leakage		Total Leakage	
	% of Air Handler Flow					
	RMS	Bias	RMS	Bias	RMS	Bias
Uncorrected	4.5	2.3	4.1	2.7	7.9	5.0
Corrected	2.2	-1.0	1.8	-0.1	3.2	-1.1

Figure 8 shows both the corrected and uncorrected DeltaQ errors for all 71 tests using the pressure limits set above. The figure shows that the corrected data does not have the bias trends at higher leakage flows shown in the uncorrected data.



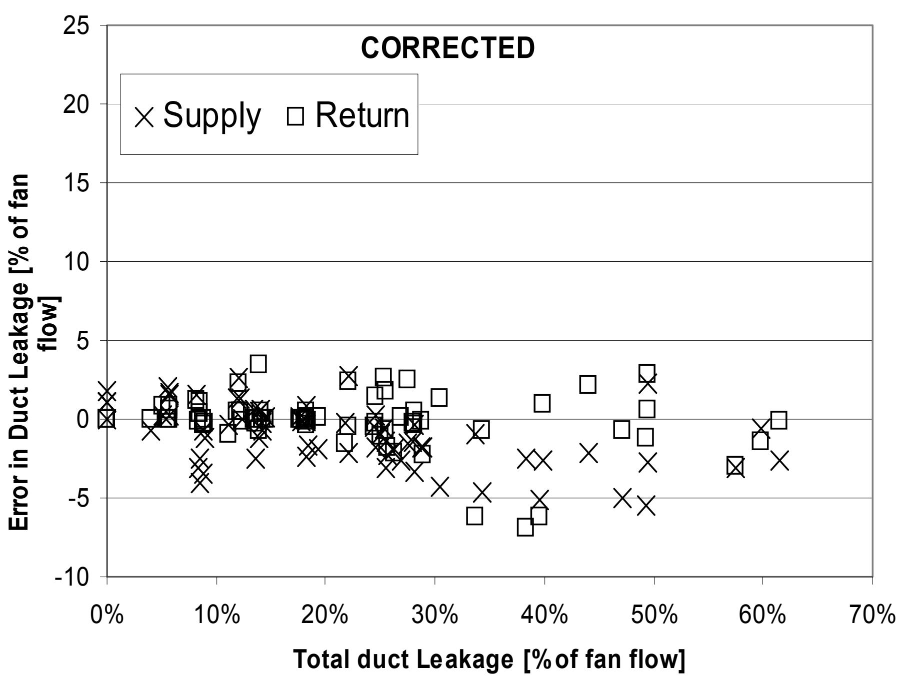
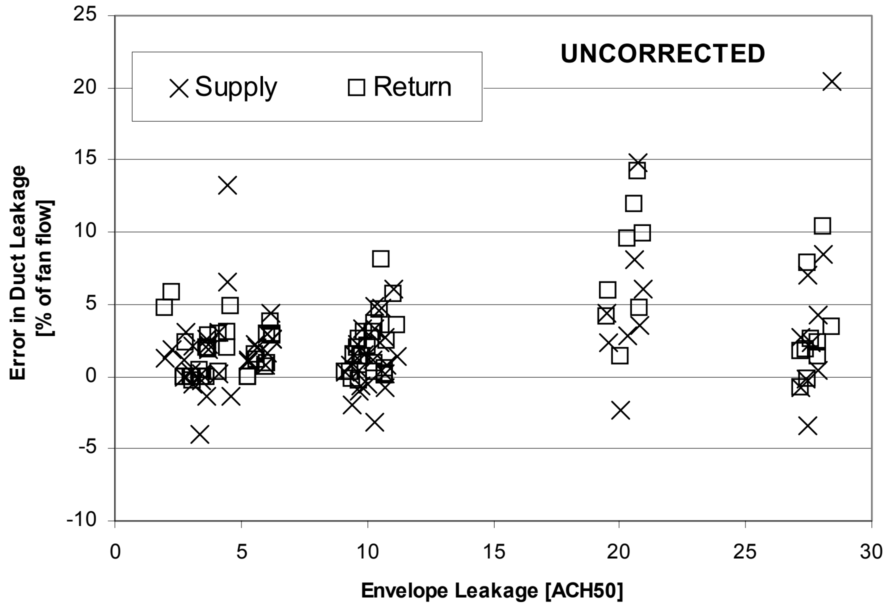


Figure 8. DeltaQ Error Variability with Total Leakage (sum of Supply and Return).

Figure 9 shows how the corrected DeltaQ errors do not have any trends with envelope leakage unlike the increasing trend shown for uncorrected data. The data fall into groups depending on which holes were open in the test chamber. The envelope leakage was determined using the DeltaQ data with the air handler off; therefore it includes the duct leaks as well as the envelope leaks. For this reason, discrete envelope leakage levels are not observed, and the duct leakage variability spreads out the data in the horizontal axis.



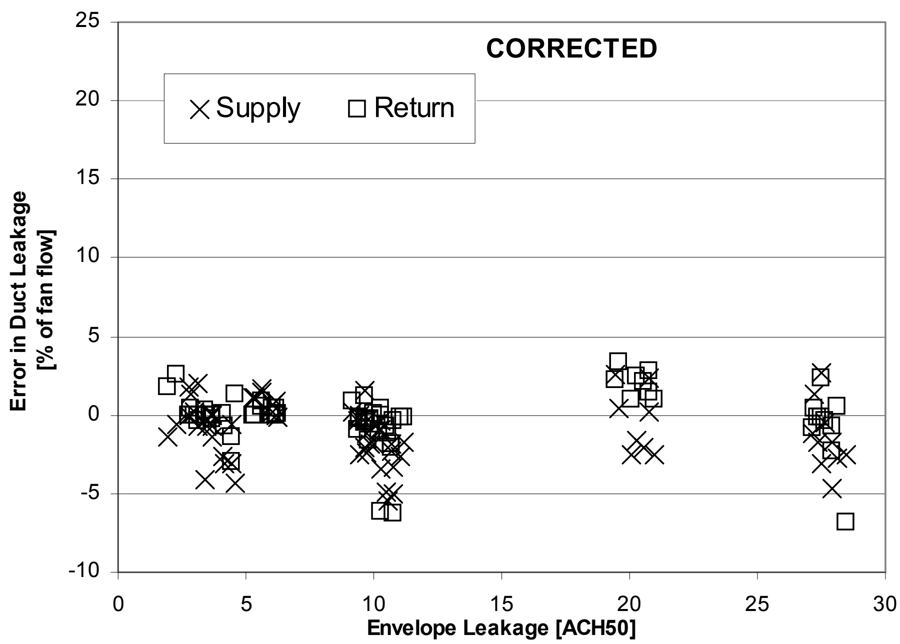


Figure 9. DeltaQ Error Variability with Envelope Leakage.

SUMMARY

The DeltaQ test was evaluated by comparing its predictions of duct system leakage to precisely measured duct leakage flows in a laboratory duct system. The DeltaQ test was evaluated over a wide range of duct leakage (from zero to 60% of air handler flow) and building envelope leakage (from tight (850 m^3/h (500 cfm) at 25 Pa) to leaky (8630 m^3/h (5080 cfm) at 25 Pa)). The test results showed that the DeltaQ test was improved by including corrections that account for duct air flow resistance and whole building pressure offsets due to supply and return leakage imbalances. After applying the correction factors and pressure limit fitting criteria developed in this study, the bias and RMS errors expressed as fractions of air handler flow were –1.0% and 2.2% for supply leaks, and –0.1% and 1.8% for return leaks.

The multivariate least squares analysis required in the DeltaQ calculation procedure requires limits to be placed on the acceptable ranges of flow and pressure. For leakage flows the lower limit was set to zero, and the upper limit to 1700 m^3/h (1000 cfm). The minimum pressure limit is set equal to the lowest imposed envelope pressure (typically 5 Pa (0.02 in. water)). The upper pressure limit that produces the best results depends on the pressures achieved during testing. For a maximum envelope pressure of 25 Pa (0.1 in. water) using an upper limit of twice the maximum measured pressure (i.e. 50 Pa (0.2 in. water) gave improved results. At higher envelope pressure differences (e.g., 50 Pa (0.2 in. water)) the maximum pressure should be set equal to the maximum envelope pressure difference.

CONCLUSIONS

The corrections for the DeltaQ analysis reduced the uncertainty of the test by about a factor of two and removed the biases at high leakage. The corrected DeltaQ results did not show any trends with increasing duct or envelope leakage showing that they can be applied to a wide range of duct and envelope leakage situations. The DeltaQ RMS and bias errors were reduced to less than 2.2% and 1% of air handler flow, respectively, using these corrections. The application of flow and pressure limits developed in this study are required prevent the calculation of unrealistic results in the analysis of DeltaQ data.

ACKNOWLEDGEMENTS

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Program, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. We are grateful for the cooperation and collaboration of John Andrews of Brookhaven National Laboratory, and Douglas Brenner, David Bouly, Jan Coenen, and Chistoph Utz of LBNL.

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.

ASHRAE. 2003. ASHRAE Standard 152 "*Method of test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems.*" American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, GA.

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

CEC. 1998. Low-rise residential Alternative Calculation Method Approval Manual for 1998 Energy Efficiency Standards for Low-Rise Residential Buildings, California Energy Commission, Sacramento, California.

Dickerhoff, D.J., Walker, I.S. and Sherman, M.H. 2004. "Validating and Improving the DeltaQ duct Leakage Test". ASHRAE Transactions (in press). ASHRAE, Atlanta, GA.

Francisco, P., Palmiter. L. and Davis, B. 2002. Field Performance of Two New Residential Duct Leakage Measurement Techniques. ACEEE Summer Study. Pacific Grove. Ca. American Council for an Energy Efficient Economy, 1001 Connecticut Ave. N.W., Suite 335, Washington, D.C. 2002.

Francisco, P., Palmiter, L., Davis, B. 2003. "Insights Into Improved Ways to Measure Residential Duct Leakage". ASHRAE Transactions (in Press). ASHRAE, Atlnata, GA.

Sherman, M.H. and Matson, N.E. 2002. "Air Tightness of New U.S. Houses: A Preliminary Report", Lawrence Berkeley National Laboratory, LBNL-48671. (http://epb.lbl.gov/Publications/lbnl-48671.pdf)

Siegel, J.A., McWilliams, J.A., and Walker, I.S. 2003. "Comparison Between Predicted Duct Effectiveness from Proposed ASHRAE Standard 152P and Measured Field Data for Residential Forced Air Cooling Systems". ASHRAE Trans., Vol. 109., Pt.1. ASHRAE, Atlanta, GA. LBNL 50008.

Walker, I.S., Dickerhoff, D.J. and Sherman, M.H, 2002*, The Delta Q Method of Testing the Air Leakage of Ducts:* ACEEE Summer Study. Pacific Grove. Ca. American Council for an Energy Efficient Economy, 1001 Connecticut Ave. N.W., Suite 335, Washington, D.C. LBNL 49749.

Walker, I.S., Sherman, M.H., Wempen, J., Wang, D. McWilliams, J.A. and Dickerhoff, J.D., 2001, *Development of a new Duct Leakage Test: DeltaQ*. LBNL 47308.

Walker, I, Sherman, M., Siegel, J., Wang, D., Buchanan, C., and Modera, M. 1998. *Leakage Diagnostics, Sealant Longevity, Sizing and Technology Transfer in Residential Thermal Distribution Systems, Part II.* CIEE Residential Thermal Distribution Systems Phase VI Final Report, December 1998, LBNL 42691.