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Development of a New Duct Leakage Test: Delta Q

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Introduction

Duct leakage is a key factor in determining energy losses from forced air heating and cooling systems. Several studies (Francisco and Palmiter 1997 and 1999, Andrews et al. 1998, and Siegel et al. 2001) have shown that the duct system efficiency cannot be reliably determined without good estimates of duct leakage. Specifically, for energy calculations, it is the duct leakage air flow to outside at operating conditions that is required. Existing test methods either precisely measure the size of leaks (but not the flow through them at operating conditions), or measure these flows with insufficient accuracy. The DeltaQ duct leakage test method was developed to provide improved estimates of duct leakage during system operation.

In this study we developed the analytical calculation methods and the test procedures used in the DeltaQ test. As part of the development process, we have estimated uncertainties in the test method (both analytically and based on field data) and designed automated test procedures to increase accuracy and reduce the contributions of operator errors in performing field tests. In addition, the test has been evaluated in over 100 houses by several research teams to show that it can be used in a wide range of houses and to aid in finding limits or problems in field applications. The test procedure is currently being considered by ASTM as an update of an existing duct leakage standard.

Background

ASTM has long had a standard on measuring duct leakage (ASTM E1554-94 (1994)). That standard has had two methods in it: duct pressurization and blower door subtraction. Both of these were methods were intended to quantify the leakage of the duct system under fixed experimental conditions.

The blower-door subtraction method has fallen into disuse because the errors associated with this technique have been shown to be quite large both in precision and bias. Duct pressurization methods can provide both more precise and more accurate measurements and are often easier to make. Neither of these methods, however, can measure the air leakage under actual operating conditions. Neither of these methods can easily separate the supply from return leakage and the total leakage from the leakage outside the conditioned space.

Because of the short-comings of the methods listed in the original ASTM standard, researchers have been developing improved or alternative methods of measuring duct leakage. Users have realized that there are several different reasons for wanting to measure duct leakage resulting in different sets of target criteria for the test method. No extant or proposed test method can come close to meeting all of the proposed criteria; thus implying a need for different measurement approaches to achieve different objectives.

Overview of existing duct leakage test methods

The development of each of the following measurement techniques was subject to a different set of priorities and hence compromises. Each one of them measures a different physical quantity (e.g., hole size, envelope pressure changes, etc.), although they all report the same parameter - duct leakage to outside at operating conditions. Detailed step-by-step procedures for these tests are given elsewhere (Walker et al. 1997).

1. Duct Pressurization. Measures the size of holes in the duct system and represents them as a single hole. Leakage air flow is then inferred from assumed pressure differences.

2. House Pressure Test (HPT). Measures the pressure differences across a building envelope caused by leakage imbalance flows in three configurations: air handler on, air handler off and air handler on with the return partially blocked. Leakage air flow is then inferred from the house envelope leakage and a calculation procedure to combine the three test results.

3. Nulling Pressure Test (NPT). Similar to the HPT, in that it uses the pressure differences across the building envelope caused by air handler operation. It replaces the house envelope as a flow meter with a calibrated flow measurement device.

4. Tracer gas. Measures tracer gas concentration flowing into registers, out of registers, in the house, outside and in all duct locations. Changes in gas concentration and the resulting tracer gas mass balances on the house and duct system are used to estimate the air leakage flows.

5. There are two methods currently used in the ASTM E1554 Standard (ASTM 1994). The first is Blower Door Subtraction. It uses the difference between blower door tests with registers covered and blocked to determine duct leakage. It is rarely used by practitioners due to the large fractional uncertainties resulting from determining the difference between two relatively large leakage areas. The second method is similar to the duct pressurization test, but the whole house and the ducts are pressurized simultaneously by a blower door and a flow meter is used to measure flow into the duct system. This second method is also rarely used due to uncertainties in the duct system pressures during testing (including pressure differences between the duct system and the house).

Duct pressurization tests are the most common tests performed on duct systems. They are analogous to pressure testing of building envelopes (ASTM 1999) in that the test measures airflows at specified pressure differences. All the registers in a system are covered and a measured amount of air is blown into the ducts. The resulting duct pressures indicate how leaky the ducts are. These tests measure the size of holes in the duct system, but not the flow to outside through them at operating conditions. To go from hole size to air flow these tests require a duct system operating pressure to be assumed (often based on measured plenum and/or register pressures). This conversion from hole size to air flow has large uncertainties. However, for verifying that ducts have little leakage, these pressurization tests are useful because if we restrict systems to only have small holes, then the flow through them will never be very large. This is why pressurization testing is used as a screening tool in many utility and weatherization programs and is gradually being adopted into codes and standards (e.g., proposed ASHRAE Thermal Distribution Efficiency Standard 152P (ASHRAE 2001), California State Energy code (CEC 1998), EPA Energy Star program (http://infotech.icfconsulting.com/epa/estar/ducts.nsf/homepage)). There are several variations of duct leakage tests with increasing time and equipment requirements (and complexity):

- Total Leakage. This is the simplest test and the most used. Both supply and return ducts are tested at the same time, so the split between supply and return leaks must be assumed. In addition, the fraction of total leakage that leaks to outside must be assumed.

- Leakage to outside. For these tests, the house is pressurized using another fan to the same pressure as the ducts so that any duct leakage is to outside. This test has the additional complication of requiring two fans and extra pressure measurements. In addition, it requires more time because the pressures across the ducts and the building envelope must be balanced.

- Supply/return split. To separate supply and return ducts a physical barrier must be installed, usually inside the air handler cabinet or return plenum. The two sides of the duct system can then be tested separately so that no assumption of the supply/return split is required. The installation of the separating barrier can be difficult and time consuming. If the barrier is not installed correctly the test will overestimate the duct leakage because the barrier leakage will be included in both the supply and return duct measurement.

The HPT measures the pressure changes across the building envelope and duct system due to air handler operation. It uses the house envelope as a flow meter and therefore requires envelope leakage to be measured also. This test can be quick to do if envelope leakage is not measured - although this reduces the accuracy depending on how well the envelope leakage can be estimated. The main problems with this test are the result of being sensitive to wind pressure fluctuations across the building envelope that are the same magnitude as the small pressures measured during the test and the violation of assumptions used in the calculation procedure. In addition, test sensitivity is strongly dependent on envelope leakage. Most studies have found the accuracy of this test to be too poor for the results to be used in energy analyses (Walker et al. 1997, Andrews et al. 1998 and Francisco and Palmiter 1997).

The NPT is similar to the HPT except that a fan assisted flowmeter is used to balance the duct leakage flows instead of using the building envelope. This reduces the uncertainty of the measured flows, however there is still the problem of reliably measuring the small envelope pressures and the added difficulty of controlling a fan to exactly balance the duct leakage flow imbalances. The developers of this technique have developed automated procedures for controlling the flow and taking long time averages of pressures that reduce these uncertainties. The problem with leaky envelopes resulting in small envelope pressure differences that are hard to measure still exists.

The tracer gas tests inject tracer gases into the house and the duct system at various locations. Samples are than taken from the house and duct system (and outside) and the changes and differences in tracer gas concentration are used to calculate duct leakage flows. These tracer gas tests require considerable time and equipment expenditures. In addition, the tests can only be reliably performed by highly skilled technicians with many years of experience in tracer gas testing and analysis. Traditionally, tracer gas studies of air flows in buildings have been the standard against which other diagnostics are evaluated. However, for duct leakage, the poor mixing of gasses in the various duct locations outside conditioned space and the inability to sample correctly at return leaks means that the tracer gas measurements can have large uncertainties and cannot be used as a reference.

For screening of low leakage levels for compliance testing the current duct leakage diagnostic used in most programs is the fan pressurization test of total duct leakage. The reasons for this are:

- Robustness. The fan pressurization test has almost no restrictions on the type of system it can be used on, or the weather conditions during the test.
- Repeatability. Combining the results of several research projects together (Walker et al. 1997 and 1998) with the field experience of other users showed that the repeatability of pressurization testing is very good.
- Precision. The uncertainty in leakage flow will be small if the allowable leakage is set to a low number. The test is good at measuring hole size but not at extrapolating to leakage flows at operating conditions. If we restrict the applications to small hole sizes, even large errors in estimating the pressure difference cross the holes will not result in large leakage flow uncertainties.
- Simplicity. It is easy to interpret the results of fan pressurization without having to perform many (or any – with the appropriate hardware) calculations. This allows the work crew performing the test to evaluate the ducts during the test and also allows the work crew to ensure that the test has been performed properly because they can see if the results make any sense.
- Familiarity. Work crews that have performed envelope leakage tests are familiar with the test method for ducts, because envelope testing uses a similar apparatus and calculation/interpretation methods.

Because the pressurization test is usually implemented to measure the total leakage of the ducts and not just the leakage to outside it will overestimate the leakage required for energy loss estimates. However, from a code compliance testing point of view, this error is in the right direction because it means that the true losses will be less than those indicated by the test. In other words, a system whose total leakage passes a leakage specification is guaranteed to have the leakage to outside be less than the specification.

For energy ratings (using ASHRAE 152P or similar methods) of homes with leaky ducts the simple pressurization test can be poor due to the assumptions about pressures across the duct leaks (Walker et al. 1998 and Palmiter and Francisco 1999). For these leaky systems, the other test methods may give better results because leaky ducts tend to produce a larger pressure signal for the DeltaQ, NPT and HPT methods that reduces their uncertainties.

In addition to the accuracy requirements, different leakage test applications have different time/cost requirements. Previous studies and field experience have shown that the biggest drawback with the pressurization test is the requirement of covering all the registers and attaching the flow and pressurization equipment. In addition, more detailed versions of the test require inserting a blockage to separate the supply and return and using a blower door to match the duct and house pressures – both of which can be time consuming.

Significant advances have been made recently in the use of small and lightweight data acquisition and control systems that can be used in duct leakage testing. These systems are highly recommended for all the tests that measure low pressures: DeltaQ, NPT and HPT. In addition, the ability to control a fan to maintain a set pressure difference or flow (as required by the DeltaQ and NPT) is made much easier with an automated data acquisition and fan speed control system. The pioneers of both tests recommend the use of automated systems. In addition to improving the accuracy and precision of the tests, automation can significantly reduce the time required for the tests and the dependence on an individual operator.

DeltaQ Development

In January of 1999, a Duct Leakage Workshop Subcommittee of ASHRAE SP152P, met at the ASHRAE Winter Meeting in Chicago, to discuss alternatives to existing measurement techniques. Chuck Gaston (Penn State University) presented an idea that would use the difference between house pressurization tests with the air handler fan on and off to determine duct leakage. There were several problems associated with this proposed approach. As envisaged, a complex mathematical investigation would be required to solve the "inverse" problem resulting from knowing the result (the flow differences) without knowing the functional form of the relationships that determined the test result. The experimental procedure proposed relied on a form of blower door subtraction that would have unacceptably large errors from the same sources as the original blower-door subtraction method.

Parallel work by LBNL developed a version of the test that overcame these problems. LBNL used some simplifying assumptions to solve the modeling problem analytically (discussed in detail in this report) and developed a test protocol that would use existing equipment and procedures. This test protocol requires measuring the difference in flows at the same envelope pressure difference, with the air handler fan on and the air handler fan off. The test gets its name from this difference in flows (the common symbol for flows being Q), hence the name DeltaQ. This test represents the next stage in development for blower-door subtraction methods.

The objective of developing the DeltaQ test was to develop faster, better, and cheaper residential duct leakage test procedures. Where: faster=minimize labor hours; better=maximize reproducibility and accuracy; cheaper=require least capital outlay for test equipment.

The DeltaQ test addresses these criteria as follows:

Faster. The DeltaQ test requires little equipment setup – only a blower door and some pressure tubing need to be installed. The NPT can be performed by using a small fan/flowmeter (which takes similar time as a blower door). However, the NPT sometimes requires several configurations of ducting and duct pressurization fan location to be set up depending on the location of the duct system. Lastly – if the envelope leakage is to be measured anyway in a building (as is often the case in weatherization programs, home energy ratings, etc.), then the blower door is already set-up and the only time required for the DeltaQ test is the time for the measurements.

Better. Current duct leakage tests trade off reproducibility and accuracy. Duct pressurization tends to be highly reproducible (Walker et al. 1997 and 1998 and Andrews 1998) but it does not measure duct leakage flows to outside directly, resulting in less accuracy. The other tests that measure envelope pressures should have higher accuracy because they are closer to measuring the duct leakage to outside at operating conditions, but they have very poor reproducibility due to measuring very small pressure differences across building envelopes (Walker et al. 1998 and Andrews 1998) whose pressure fluctuations are of the same magnitude as the pressure signal that the tests are using. The DeltaQ test aims to be more reproducible by measuring at relatively high envelope pressures whilst still concentrating on measuring duct leakage to outside at operating conditions fairly directly.

Cheaper. The DeltaQ test uses apparatus (a blower door) that is widely available and that almost all people interested in duct leakage already have, e.g., weatherization programs. This minimizes the capital cost in preparing to do the tests. Secondly, because the DeltaQ test takes little time, the labor costs are minimized. However, there can be a tradeoff between increased capital costs for automating the test (that requires the use of data acquisition systems and computers to record the data) and the time savings resulting from the automation. In practice, the time saving, record keeping ability, and operator error reductions resulting from automating the test outweigh the higher capital cost of this option.

Derivation of DeltaQ Relationships

The DeltaQ test is based on measuring the change in flow through duct leaks as the pressure across those leaks is changed. The changes in duct leak pressure difference are created by pressurizing and depressurizing the whole house (including the ducts) using a blower door over a range of pressures (including both pressurization and depressurization). The blower door is used to both create and measure the flows occurring through the duct leaks and the building envelope. In the same way as envelope leakage tests, the pressures and flows are measured at several fixed pressure stations, with time averaged pressures and flows recorded at each pressure station. The pressurization (and depressurization) tests are performed twice: once with the air handler on and again with the air handler off. The duct operating pressures used in the calculation procedure are determined by measuring the static pressures in the supply and return plenums relative to the conditioned space. It is assumed that the envelope, supply and return leaks are each represented by power law pressure-flow relationships. In addition, it is assumed that the additional pressures developed by the blower door will be the same everywhere for the envelope and the ducts. This assumption is affected by envelope pressure variations due to wind and stack pressures (as with standard blower door tests of building envelopes). If there are large leaks in the duct system and corresponding large flows, there may also be pressure drops through the duct system – again violating this assumption of uniform pressures. In order to generate significant pressure drops catastrophic leaks are required such as disconnected ducts. However, at this level of leakage, the effects of violating of the assumption of uniform pressures will not be relevant because the leakage test will still indicate that there is catastrophic leakage. With the air handler on the duct system pressures are not assumed to be uniform, but the pressure across the building envelope is assumed to add to the duct system operating pressures. Note that this duct system pressure assumption is not the same as assuming a pressure across leaks for duct pressurization tests. The final result for the DeltaQ test does not scale directly with pressures as in the pressurization test.

In general we have an unknown number and location of supply and return leaks. Each of i supply and j return leaks has its own flow coefficient, C and pressure exponent, n. The sum of the flow through the building envelope and duct leaks is the flow through the blower door. With the air handler fan off at a given envelope pressure difference (ΔP) we have:

$$Q_{off}(\Delta P) = C_{env} \times (\Delta P)^{n_{env}} + \sum_{all\,supply\,leaks} C_{s,i} \times (\Delta P_i)^{n_{s,i}} + \sum_{all\,return\,leaks} C_{r,j} \times (\Delta P_j)^{n_{r,j}} \quad \textbf{(1)}$$

where:

Q_{off}= measured flow through blower door with air handler fan off

ΔP = pressure difference across envelope (in-out)

ΔP_i = pressure difference across supply leak i

ΔP_j = pressure difference across return leak j

C_{env} = flow coefficient for building envelope

$C_{r,i}$ = flow coefficient for supply leak i

$C_{s,j}$ = flow coefficient for return leak j

n_{env} = envelope pressure coefficient

$n_{r,i}$ = supply leak i pressure exponent

$n_{s,j}$= return leak j pressure exponent

For the air handler off tests it is assumed that the pressure across each individual leak is the same as the envelope pressure difference. Because it is not possible in any practical way to know the number, size and location of the duct leaks it is assumed that all the supply leaks can be combined and all the return leaks can be combined such that:

$$C_s = \sum_{all\,supply\,leaks} C_{s,i} \quad \textbf{(2)}$$

$$C_r = \sum_{all\,return\,leaks} C_{r,j} \quad \textbf{(3)}$$

where

C_s = flow coefficient for all of the supply duct leaks
C_r = flow coefficient for all of the return duct leaks

As well as grouping together all the leakage coefficients, the pressures for individual leaks are also reduced to single values. Lastly, it is assumed that a single pressure exponent can also be used. Then Equation 1 can be written as:

$$Q_{off}(\Delta P) = C_{env} \times (\Delta P)^{n_{env}} + C_s \times (\Delta P)^{n_s} + C_r \times (\Delta P)^{n_r} \quad \textbf{(4)}$$

Note that performing air handler off measurements over a range of pressure differences is the same as performing a regular blower door test for envelope leakage. One of the advantages of the DeltaQ test method is that it also provides the leakage of the building envelope.

Using the same model of the house, supply and return ducts, with the air handler fan on we have:

$$Q_{on}(\Delta P) = C_{env} \times (\Delta P)^{n_{env}} + C_s \times (\Delta P + \Delta P_s)^{n_s} + C_r \times (\Delta P - \Delta P_r)^{n_r} \quad \textbf{(5)}$$

where:
Q_{on} = measured flow through blower door with air handler fan on
ΔP_s = pressure difference between supply and house (house as reference).
ΔP_r = pressure difference between house and return (return as reference). Using the return as the reference makes ΔP_r a positive number. When the building is pressurized and the magnitude of return pressure is greater than the imposed blower door envelope pressure the return term in Equation 5 is negative (i.e. flow into house).

Because there is a pressure drop between a plenum and the attached register, the two measured pressures (ΔP_s and ΔP_r) do not necessarily represent pressures across all duct leaks--except in the special case of a single leak in each of the supply and return. More generally, they represent the characteristic pressures that each set of leaks is subject to; in terms of our analysis we can see this as inflection points in the DeltaQ vs. ΔP relationship. Since the leaks that matter most are the ones at or near the plenum pressure, we will assume use those pressures in the analysis and examine the sensitivity of that assumption as we do so.

In future work we will be examining the possibility of determining these pressures by those that give the best fit to the measured data. However, for simplicity and consistency, at the present time we use the plenum pressures. In addition to work by LBNL, John Andrews of Brookhaven National Laboratory (BNL) has performed some example calculations showing that increasing these reference pressures does not necessarily increase the resulting calculated leakage flows (personal communication 11/2000). This is unlike pressurization leakage test methods in which higher system pressures would imply higher leakage flows.

The "DeltaQ" is the difference between the air handler on and air handler off measurements:

$$\Delta Q(\Delta P) = Q_{on}(\Delta P) - Q_{off}(\Delta P) = C_s\left((\Delta P + \Delta P_s)^{n_s} - (\Delta P)^{n_s}\right) + C_r\left((\Delta P - \Delta P_r)^{n_r} - (\Delta P)^{n_r}\right) \quad \textbf{(6)}$$

Defining the supply and return leakage flows:

$$Q_s = C_s(\Delta P_s)^{n_s} \quad ; \quad Q_r = C_r(\Delta P_r)^{n_r} \quad \textbf{(7 and 8)}$$

where:
Q_s = supply leak flow at operating conditions to outside
Q_r = return leak flow at operating conditions to outside
Equations 7 and 8 can be rearranged:

$$C_s = \frac{Q_s}{(\Delta P_s)^{n_s}} \; ; \; C_r = \frac{Q_r}{(\Delta P_r)^{n_r}} \quad \textbf{(9 and 10)}$$

Substituting C_s and C_r into the DeltaQ equation, we get:

$$\Delta Q(\Delta P) = Q_s\left[\left(\frac{\Delta P + \Delta P_s}{\Delta P_s}\right)^{n_s} - \left(\frac{\Delta P}{\Delta P_s}\right)^{n_s}\right] + Q_r\left[\left(\frac{\Delta P - \Delta P_r}{\Delta P_r}\right)^{n_r} - \left(\frac{\Delta P}{\Delta P_r}\right)^{n_r}\right] \quad \textbf{(11)}$$

This equation can be solved for Q_s, Q_r, n_s and n_r given the measured plenum pressures, ΔQ's and ΔP's. However, it is easier (and more robust) if we fix the duct leakage pressure exponents. 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. 2001). This assumption would not be valid for the case of massive duct failure (e.g. a big hole or a disconnected duct). It is not usually too hard to identify such cases and to perform the calculation with a lower exponent. If we fix the value of n=0.6, and do a little algebraic manipulation we get a form that gives DeltaQ in terms of a difference between the supply and return leaks and is a little clearer to interpret (e.g., it is easier to see that when ΔP=0, then ΔQ is the difference between supply and return leaks).

$$\Delta Q(\Delta P) = Q_s\left[\left(1 + \frac{\Delta P}{\Delta P_s}\right)^{0.6} - \left(\frac{\Delta P}{\Delta P_s}\right)^{0.6}\right] - Q_r\left[\left(1 - \frac{\Delta P}{\Delta P_r}\right)^{0.6} + \left(\frac{\Delta P}{\Delta P_r}\right)^{0.6}\right] \quad \textbf{(12)}$$

The DeltaQ can be measured over a range of envelope pressures (both positive and negative). If n is fixed at 0.6 and P_s and P_r are measured at system operating conditions, then we only have two unknowns – the supply and return leakage. This implies that only two pressure stations are required in order to determine the leakage. However, experimental and analytical work has shown that uncertainties are reduced if more than this minimum of two pressure stations are used. Leaks are usually distributed throughout a duct system, with some at high pressure differences at the plenum, some at intermediate pressures at connections in the ducts and other leaks at low pressures at the registers. This range of holes with different pressures means that at some envelope pressure differences some leaks contribute more than others to the resulting leakage flows and therefore to the measured DeltaQ.

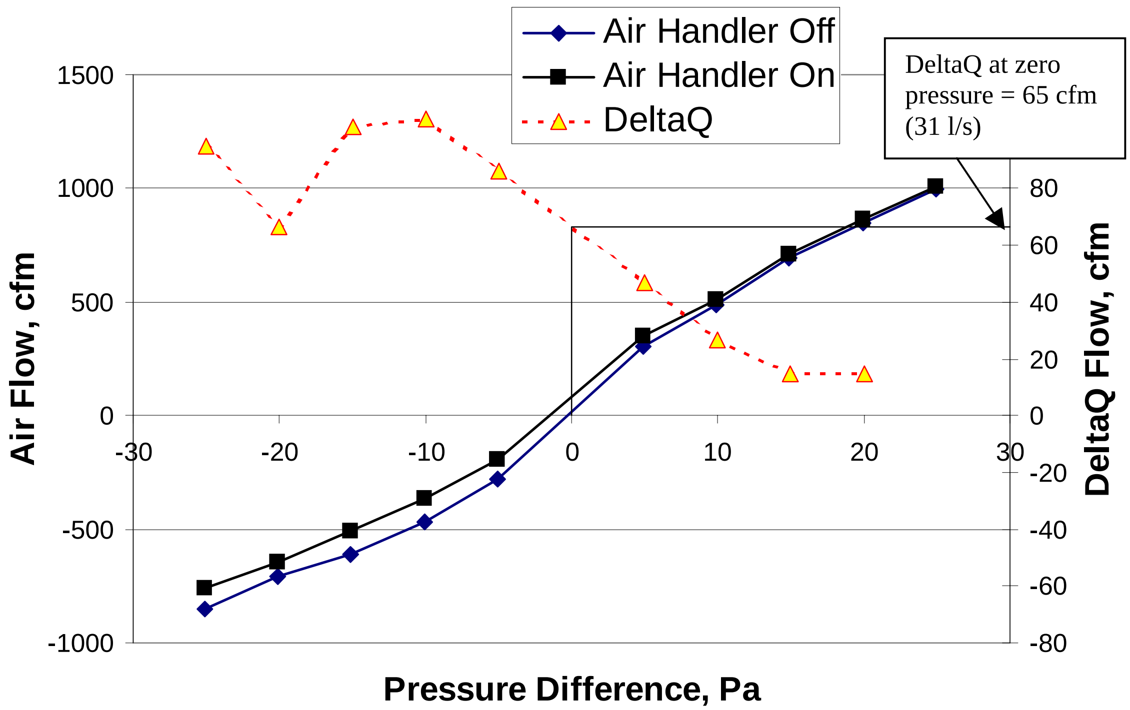

Figure 1. Example DeltaQ test results (l/s = cfm × 0.47)

Figure 1 is an example DeltaQ test showing that the DeltaQ can have multiple maxima and minima, and be non-monotonic and non-linear. To account for this we propose that a wide range of envelope pressures between zero and 25 Pa be used. Also, the house should be both pressurized and depressurized. The final DeltaQ (Equation (12)) is then least squares fitted to all the data points so that the effects of all the leaks are included in the final solution. The interpolated value of the airflow at a zero pressure difference directly gives us the difference between the supply and return leakage under normal operating conditions (in this case 65 cfm (31 l/s)).

Flow Adjustments for Exact Pressure Matching

The most difficult aspect of the DeltaQ test is the requirement that the air handler on and air handler off measurements be performed at identical indoor-outdoor pressure differences. In practice this is not possible due to fluctuations in measured envelope pressures caused primarily by wind pressures and the difficulty in controlling blower doors in such a precise manner. One of the key advantages of the DeltaQ method is that it makes these two measurements close in time; the shorter the time difference between the two measurement the smaller the piece of the wind spectrum that the measurement is subject to. Automatic measurement and control systems can assist in this task by adjusting the blower door fan speed to attempt to maintain the set pressure difference, thus reducing the first order effect. In our field testing experience, this approach has proven to be better than using manual adjustments to the blower door, but there are still residual on-off differences.

Ideally the fan-on and fan-off flow would be measured at exactly the same pressure stations, but noise (e.g. from the wind) often requires that the data be corrected for small differences in the measured pressures. At a given pressure station we have the envelope pressure difference when the system is on (ΔP_{on}), its corresponding flow (Q_{on}), the envelope pressure when the system is off ($\Delta P_{off, measured}$) and its corresponding flow ($Q_{off,measured}$). Assuming a power law relationship between pressure difference and flow, and using the measured envelope pressure exponent, the measured flow with the system off can be corrected to the flow at the same pressure as when the system is on using:

$$Q_{off} = Q_{off,measured}\left(\frac{\Delta P_{on}}{\Delta P_{off,measured}}\right)^{n_{env}} \quad \textbf{(13)}$$

This correction can be used to interpolate the data to give flow estimates for exactly matched pressures. Because the measured P_{off} and P_{on} are close to begin with, any uncertainties in assuming that the pressure flow relationship is a power law and in evaluating the pressure exponent are small. In other words, because the flow corrections will be small anyway, the errors in this interpolation procedure will not be significant. For example, if n_{env} is fixed at 0.67 but is really 0.6, then the error in the flow correction is only about 1% at low pressures (5 to 10 Pa) and about 0.2% at 25Pa.

DeltaQ test protocol

The following step-by-step procedure has been developed in order to take the data required by the DeltaQ test. Note that all envelope pressures are measured relative to outside – i.e. P_{in} –P_{out}, so that pressurization of the house is a positive pressure. Similarly, flows into the house through the blower door are also positive.

1. Connect the blower door assembly to the building envelope using a window or door opening. Seal or tape openings to avoid leakage at these points.
2. Install the envelope pressure difference sensor. The outside pressure measurement location should be sheltered from wind and sunshine. Both the inside and outside pressure measurement locations should be as far away as possible from the localized air flows induced by the air moving apparatus. All the envelope pressures use the outside pressure as the reference.
3. With the blower door opening blocked, blower door off and system off, measure the pressure difference across envelope ΔP_{zero}.
4. With the air handler fan on, measure the supply (ΔP_s) and return (ΔP_r) plenum operating static pressures relative to the conditioned space. Note that both pressures are recorded as positive numbers for use in the analysis, i.e., the return pressure is NOT negative.
5. Turn on the blower door and adjust the flow until there is 5 Pa (0.02 inches of water) envelope pressure difference, with the house at a higher pressure than outside (for pressurization testing). Record the envelope pressure difference (ΔP_{env}) and flow (Q_{on}) through the air-moving device at this pressure station. Only record pressure and flow readings when the pressure reading is within 0.5 Pa (0.002 inches of water) of the 5 Pa (0.02 inches of water) operating point. It is recommended that multiple pressure and flow readings are recorded at each operating point and averaged for use in the calculation procedure. Note that all the blower door flows are positive out of the house and negative if into the house.
6. Repeat step 5, but with the envelope pressure difference, ΔP_{env}, incremented by 5 Pa each time until the envelope pressure difference is 25 Pa. At each ΔP_{env} pressure station the pressure difference must be within 0.5 Pa (0.002 inches of water) of the required operating point. Record the envelope pressure difference with the air handler fan on, ΔP_{on}, for each pressure station. Because the capacity of the air handling equipment, the tightness of the building, and the weather conditions affect leakage measurements, the full range of the higher values may not be achievable. In such cases substitute a partial range encompassing at least five data points, with the size of pressure increments suitably adjusted. At each pressure station, the air handler fan on and off conditions must both have the same target pressure.
7. Turn off the air handler fan and repeat steps 5 and 6, recording Q_{off} and ΔP_{off} at each pressure station.
8. Repeat steps 5, 6 and 7, but with the house depressurized, i.e., for the first point, adjust the flow through the blower door until there is a -5 Pa envelope pressure difference, with the house at a lower pressure than outside. The magnitude of the envelope pressure difference, ΔP_{env}, is then incremented by 5 Pa each until the envelope pressure difference is -25 Pa.
9. With blower door opening blocked, air-moving device fan off and air handler fan off measure pressure difference across envelope with blower door off ΔP_{zero}.
10. Subtract the average of the ΔP_{zero} measurements from each ΔP_{env} to obtain ΔP.
11. Fit the air handler off pressure and flow data to the power law relationship in order to obtain n_{env}.
12. Adjust the flows for correct pressure matching using Equation 13.
13. Calculate ΔQ_i at each pressure station, P_i, by subtracting $Q_{off,i}$ from $Q_{on,i}$.

14. Do a least squares fit of the P and ΔQ pairs to Equation 12 to find supply leakage: Q_s, and return leakage: Q_r.

As experience was gained with the test, this procedure was refined. Initially we attempted to match the air handler on and off pressures consecutively at each pressure station. However, most air handlers incorporate a delay between the switch being activated and the air handler being turned on and the air handler itself should be allowed to run for about 30 seconds to reach steady operation. Many systems have no independent air handler switch and the air handler must be activated through thermostat setpoint manipulation. All of these combine to produce significant time delays between each air handler on and air handler off measurement. The test was streamlined by taking all of the air handler off data followed by all the air handler on data so that there is only a single wait for the air handler to be operating. Given that the air handler on and air handler off pressures are never exactly matched anyway – taking the data further apart in time (between on and off measurements) does not have a significant effect so long as indoor-outdoor temperatures or mean wind speeds to not change greatly (temperature changes greater than 18°F (10°C) or wind speed changes greater than 7 m.p.h. (3 m/s)) during the test. Large changes would result in some biasing of the measured envelope pressures between the air handler on and off tests.

To further reduce the time requirements and to reduce any operator inconsistencies, a computer program has been developed that records all the necessary data and controls the blower door in order to closely match the air handler on and off pressures. This software also performs some simple uncertainty analyses. For example, the air handler off data is taken twice and if the differences between these two tests are above a certain criteria (e.g., if the fitted data yield envelope flow coefficients that differ by more than 2%), then the software tells the operator that the test needs to be repeated. These differences between air handler off tests have several main causes: wind pressure fluctuations on the building envelope, poor placement of indoor and/or outdoor pressure taps, or pressure tubing that is moved during measurements.

The data acquisition system takes 120 data points at each pressure station and the mean values are used in the calculations. The first versions of the software used the standard deviation of these 120 points to determine when the blower door flow and envelope pressures are steady enough to record the reading. A standard deviation of 0.5 Pa was found to give a reasonable compromise between measurement precision and the time taken to do the test. A new software version is currently being tested that uses a 0.1Pa limit of the standard error in the mean of the 120 points. This change has little effect on the operation of the measurement and data acquisition system. The software also checks to see if there was an unusual occurrence (such as individual points many standard deviations from the mean) during a set of 5 pressure points. For each set (air handler on and air handler off) the data are fitted to a power law to determine a flow coefficient, C, and a pressure exponent, n. The software assumes that the measured data are valid if the pressure exponent is between 0.5 and 0.8, and that the correlation coefficient from the least squares fit is better than 0.96. In the future a more appropriate measure of goodness of fit will be used. For example, using 95% confidence intervals for flow coefficient

Uncertainty analyses

Repeatability

Preliminary repeatability testing has been completed using multiple tests in a test building at LBNL. The test building was located in a coastal hillside canyon at LBNL in Berkeley California. The test trailer has a 24 ft (7.3 m) by 50 ft (15.2 m) floorplan, with the long axis aligned with the prevailing winds. Interior floor to ceiling height was 8 ft (2.4 m). There are no interior walls or partitions. The same duct system was tested 20 times over several days. The maximum recorded windspeed during the test was 5 m.p.h. (2 m/s). This is the windspeed measured on site at eaves height and is lower then typically meteorological windspeeds due to the sheltering effects of the canyon walls, trees, and adjacent similarly-sized trailers. The indoor to outdoor temperature differences during the test were typically less than 15°F (8°C). These results showed that the repeatability errors were quite small. Table 1 summarizes the repeatability testing results. Both the standard deviation and 95% confidence interval are given.

Table 1. Repeatability Results For DeltaQ testing					
Average Supply Leakage, cfm (l/s)	Average Return Leakage, cfm (l/s)	Standard deviation of supply leakage, cfm (l/s)	Standard deviation of return leakage, cfm (l/s)	Supply Leak 95% Confidence Interval, cfm (l/s)	Return Leak 95% Confidence Interval, cfm (l/s)
19 (9)	66 (31)	11 (5)	16 (8)	5 (2)	7 (3)

The air handler flow of approximately 1000 cfm (472 l/s) was measured using flow hood and tracer gas measurements. Therefore, the duct leakage and the uncertainty in leakage are small compared to the air handler flow. The repeatability errors were quite small in terms of flow rate, but the small leakage flows lead to large fractional errors. For both uncertainty in energy losses from the duct system and low leakage specification testing, the uncertainty as a fraction of fan flow is the most important factor. In this case the 95% confidence intervals were between 0.5% and 1.0% (for supply and return respectively) of the fan flow – what we would consider to be an excellent result. A similar result (small absolute errors at low leakage) was also found by Andrews (2000). In the future, these tests will be repeated with greater supply and return leakage and changed trailer envelope leakage. If possible tests will be performed at higher windspeeds and temperature differences to increase the potential test to test variability due to changing envelop pressures.

We expect that the fluctuations in envelope pressure during the test (mostly due to fluctuating wind speeds and directions) could lead to increased test result variations. However the repeatability results showed that the test variability does not increase very much with the measured envelope pressure variability (shown in Figure 2). The variability is the standard deviation of the offset pressures measured with the air handler and blower door off. This is a good result, because we would like the test to be relatively insensitive to these pressure fluctuations so that it will give good results in a wide range of weather conditions. Figure 2 also shows the measured equivalent leakage area (ELA) for each test that was calculated from the air handler off data. The ELA values also show no trend with the offset standard deviation that indicates the test procedure is unbiased (for this building) by fluctuations in measured pressures.

John Andrews of BNL (Andrews 2000), has performed the DeltaQ test three times each in two houses. For each house the average leakage and the average absolute difference from the mean were calculated for the three tests. Table 2 shows that the average differences are similar in magnitude to the above LBNL tests, but are proportionally less as a fraction of the duct system leakage because the leakage was much higher in the BNL systems.

Table 2. DeltaQ Repeatability Tests in Two Long Island Houses				
House	Supply Leakage		Return Leakage	
	Average, cfm (l/s)	Average Difference from the mean, cfm (l/s)	Average, cfm (l/s)	Average Difference from the mean, cfm (l/s)
1	214 (101)	8 (4)	46 (22)	14 (7)
2	72 (34)	19 (9)	286 (134)	9 (4)

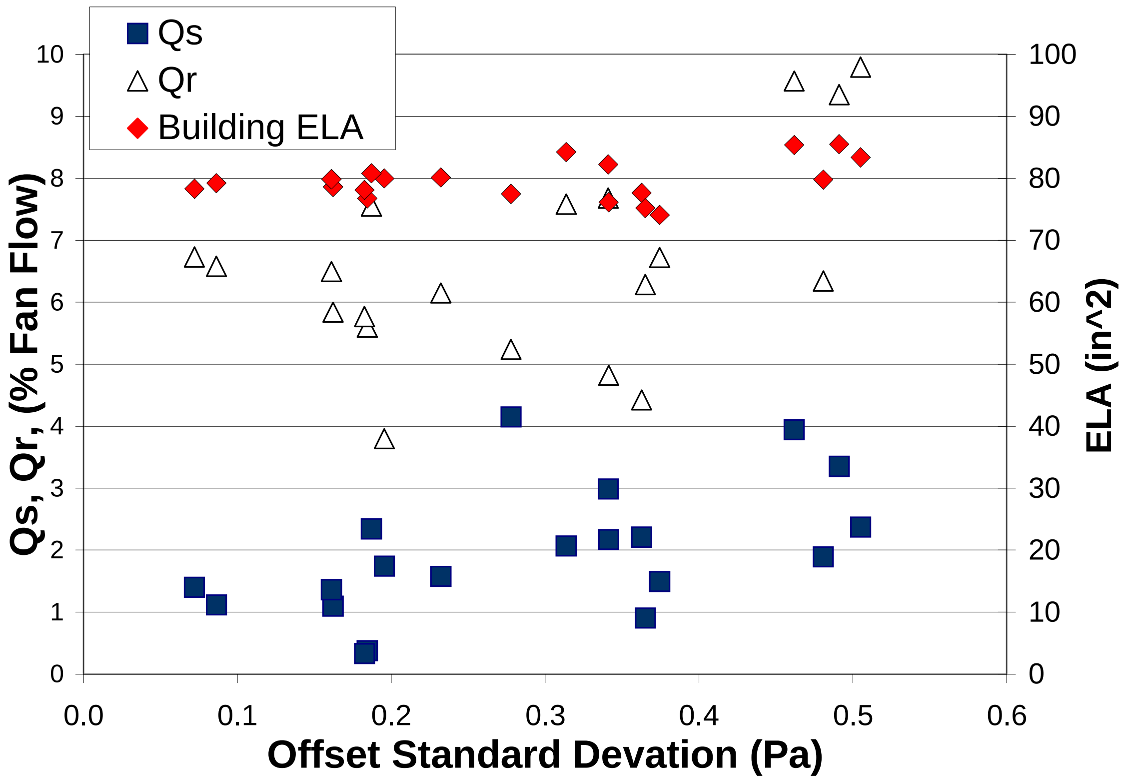

Figure 2: Repeatability Test Results ($cm^2 = in^2 \times 6.5$)

Sensitivity to the pressures used in the DeltaQ calculations

The simplifying assumption that allows all the supply leaks to be represented by a single leak and all the returns to also be represented by a single return leak results in a relationship with a characteristic form (Equation 12). Observations of this relationship over many DeltaQ tests have shown that it has similar characteristics for every test, and that sometimes the individual data pairs (that represent the true sum of all the leakage flows) do not correspond well to this functional form. Figure 3 illustrates how the shape of the derived DeltaQ function is changed by altering the characteristic pressures used in Equation 12.

The standard DeltaQ test uses the plenum pressures as the leak pressures – mostly because they are easy to measure with the least fractional uncertainty and because they are relatively large compared to the other pressures in the system. Changing the pressures to be one half the plenum pressures gives an indication of the sensitivity of the predicted leakage flows to using this pressure. The figure shows that halving the pressure makes only a small change to the DeltaQ function.

A key observation here is that the pressures used are both outside the range of the measured data (±25 Pa). Our observations have shown that the pressures indicate inflection points in the DeltaQ relationship that can be interpreted as pressures at which large individual leaks have the flow through them change direction if there are single dominant leaks. We can use this information to develop "best fit" DeltaQ relationships. The "best fit" pressures were selected to make the DeltaQ relationship fit the measured data closer. In Figure 3, there is a clear jump in the DeltaQ results at around minus 15 Pa. If we use this as one reference pressure and 25 Pa as the other we get the best fit line shown in the figure that reproduces the inflexion point at –15 Pa required to fit the measured results. Note that the inflexion points are only clearly seen for systems with large individual leakage sites where the DeltaQ measured data has large step changes. In many tests this is not the case, and the smooth, non-inflected (over the test pressure range) relationships give very good fits. This is also the case if the pressures across large individual leaks are greater or less than the pressures used in the tests. E.g., when the dominant leaks are at the plenums.

We are currently developing a calculation procedure that extends the fitting procedure to include the reference pressures. This has two clear advantages: the fitted relationship will be closer to the measured data and the test procedure will be quicker because we no longer need to measure plenum pressures.

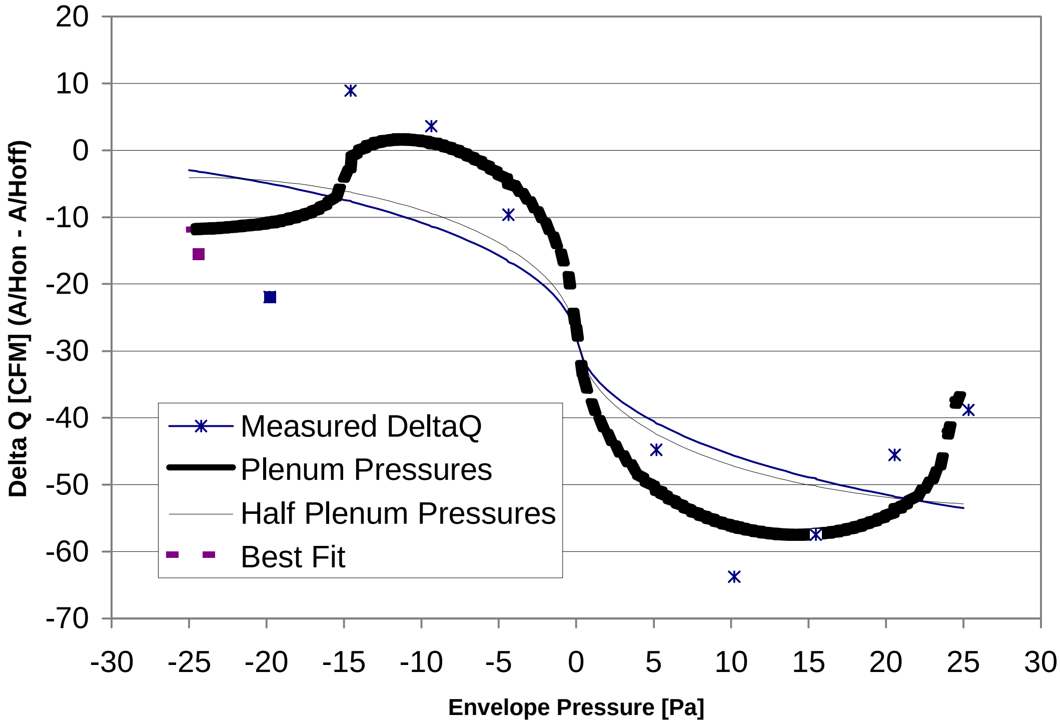

Figure 3. Adjusting the pressures used in the DeltaQ relationship to better fit measured data (l/s = cfm × 0.47)

Unlike duct pressurization tests, the DeltaQ results are not very sensitive to the characteristic pressures as long as the pressures are within a reasonable range, e.g., within a factor of two. Table 3 gives numerical values of supply and return leakage for the data used in Figure 3 based on using different characteristic pressures. Using the standard DeltaQ approach of using the plenum pressures is within one cfm of the "best fit" results. This result is reassuring because it indicates that the assumption of simplifying the DeltaQ procedure by using just the plenum pressures does not introduce large errors. The reason for this is that the functional form of the DeltaQ relationship combines with the least squares fitting method to produce an extremely robust calculation procedure.

Table 3. Sensitivity of DeltaQ results to selecting "best fit" pressures

	Plenum Pressures Ps=63 Pa, Pr=100 Pa	Half Plenum Pressures Ps=31 Pa, Pr=50 Pa	"Best Fit" Pressures Ps=15 Pa, Pr=24 Pa
Q_r, cfm (l/s)	28 (13)	21 (10)	28 (13)
Q_s, cfm (l/s)	56 (26)	49 (23)	55 (26)
R^2	0.881	0.897	0.967

Uncertainty Estimate for exponent and duct pressure assumptions

In addition to the fit of measured data discussed above, the uncertainty associated with fixing the value of n (pressure exponent) and using plenum pressures has been investigated parametrically by using DeltaQ test measurements and varying n and the supply and return pressures. By experimenting with a large number of field tests and analytically examining the functional form of the DeltaQ relationship we found that the results become more sensitive at lower measured system pressures. In the vast majority of cases the supply and return leakage only change by a few cfm with reasonable changes in pressure and exponent. Future work on optimizing the characteristic pressures will look at these changes in more detail.

Andrews (2000) has performed further uncertainty estimates using both analytical techniques and measured field data. He found the theoretical and field-test results to be encouraging for DeltaQ. The following points were found to be most important:

- The predicted results were only weakly dependant on the assumptions about duct operating pressures and duct leakage locations (as we found in our experimental data also).
- A monte-carlo simulation technique that produced variations in the flows and pressures used in the analysis was used to examine four cases: balanced leakage, supply dominant, return dominant and low leakage. 30 Simulations were run for each case and analysis of the results showed that the 3% standard deviation used on the measured data showed how DeltaQ is about four times better at estimating the difference between supply and return leakage than at measuring the sum of supply and return leakage.

Field Experience

Initial Pilot Test

The pilot test of the DeltaQ procedure was performed in a house where we have already made several duct leakage measurements and the duct system characteristics were well known. For this first house the measurements were performed manually, without computer control or data acquisition. The following table summarizes the test results for comparison purposes. The agreement between the NPT, DeltaQ and Tracer gas results indicates the duct pressurization results are overestimating the supply leakage (and underestimating the return) - mostly because of uncertainty in estimating the pressures across the duct leaks. This system had relatively low air handler flow (about 330 cfm (155 l/s)) so the return leakage in this case is a large fraction of the air handler flow.

Table 4. Comparison of duct leakage measurement procedures

	DeltaQ	Duct Pressurization[1]	Duct Pressurization[2]	NPT	Tracer gas
Supply Leakage cfm (l/s)	5 (2)	51 (24)	30 (14)	17 (8)	n/a
Return Leakage cfm (l/s)	181 (85)	116 (55)	95 (45)	151 (71)	160 (75)

1- Converted to operating pressures using pressure pan register pressure measurements
2- Converted to operating pressures using plenum pressures

Initial Field Evaluations

In an effort to determine the practical limits of using the DeltaQ test several researchers have applied the test procedure to some residential houses. Thirteen houses have been tested by LBNL, BNL (Andrews 2000) and Davis Energy Group (DEG). In most cases, pressurization tests and air handler flow tests were also performed. The BNL tests were performed manually but the DEG tests were performed using the software developed by LBNL, and LBNL staff trained DEG staff on how to perform the test. Table 5 shows the results of these tests. These houses cover a range from new to old (zero to 100 years), a large range of sizes (up to about 3700 ft^2 (344 m^2)) and a large range of duct systems, as shown by the range of air handler flows. The system materials include sheet metal, duct board and plastic flex duct. The majority of the ducts in the California and Nevada houses were in the attic, with some systems having ducts in crawlspaces. The Long island houses had the majority of their ducts in unheated/uninsulated basements.

Table 5. Initial Field Evaluations

		DeltaQ Duct Leakage			
House Location	Air Handler Flow, cfm (l/s)	Supply Leakage, cfm (l/s)	Return Leakage, cfm (l/s)	Supply Leakage, % of Air Handler Flow	Return Leakage, % of Air Handler Flow
Long Island, NY	679 (319)	214 (101)	46 (22)	32%	7%
Long Island, NY	912 (423)	72 (34)	286 (134)	8%	31%
Pleasanton, CA	1600 (752)	61 (29)	47 (22)	4%	3%
Walnut Creek, CA	879 (413)	136 (64)	58 (27)	15%	7%
Folsom, CA	1200 (564)	52 (24)	46 (22)	4%	4%
Tracy, CA	1782 (834)	109 (51)	61 (29)	6%	3%
Tracy, CA	1525 (717)	70 (33)	64 (30)	5%	4%
Tracy, CA	2494 (1172)	102 (48)	53 (25)	4%	2%
Las Vegas, NV	1551 (729)	81 (38)	14 (7)	5%	1%
Las Vegas, NV	1900 (893)	18 (9)	23 (11)	1%	1%
Las Vegas, NV	2114 (993)	3 (1)	11 (5)	0%	1%
Alameda, CA	1265 (595)	48 (23)	64 (30)	4%	5%
San Francisco, CA	515 (242)	58 (27)	106 (50)	11%	21%

Pressurization tests were also performed in these houses for leakage to outside. The pressurization calculations used half the plenum pressures as the operating pressure to which the leakage flows were converted. On average, total leakage (supply plus return) for the pressurization tests were 2% of fan flow higher than the DeltaQ tests (about 10% of the measured total). The RMS difference was considerably higher at 9% of fan flow. Figure 4 illustrates these results together with an equality line.

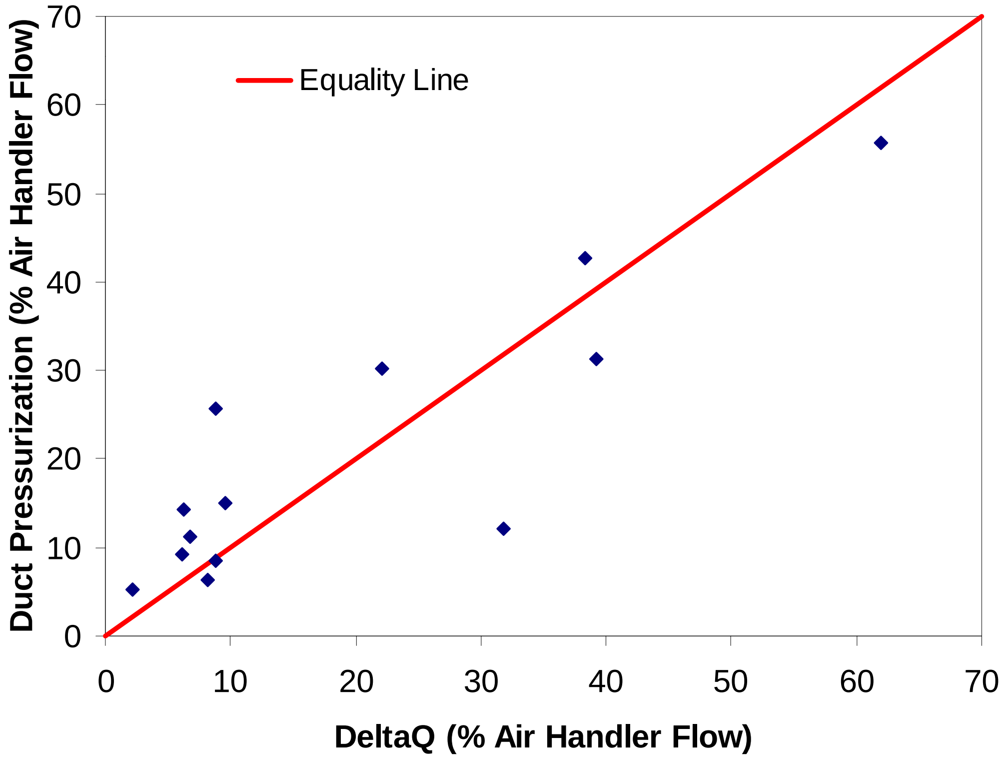

Figure 4. Comparison of DeltaQ to duct pressurization tests for total (supply plus return) leakage. RMS difference = 9% of air handler flow.

Looking at the supply and return leakage results separately shows that the supply leakage averaged 8% for DeltaQ and 12% for duct pressurization. The pressurization supply duct leakage was consistently higher than DeltaQ values, as illustrated in Figure 5, with an RMS difference of 7%. Figure 6 is a similar illustration comparing the return leakage measurements. The return leakage results show a closer agreement between the two tests, with most of the difference occurring in three houses. For the return leaks the average results are the opposite of the supply leaks: the DeltaQ tests averaged 12% and duct pressurization 8%. The RMS difference was 8%, but this is almost entirely driven by the three houses with large differences. Ignoring these houses reduces the RMS difference to 1%.

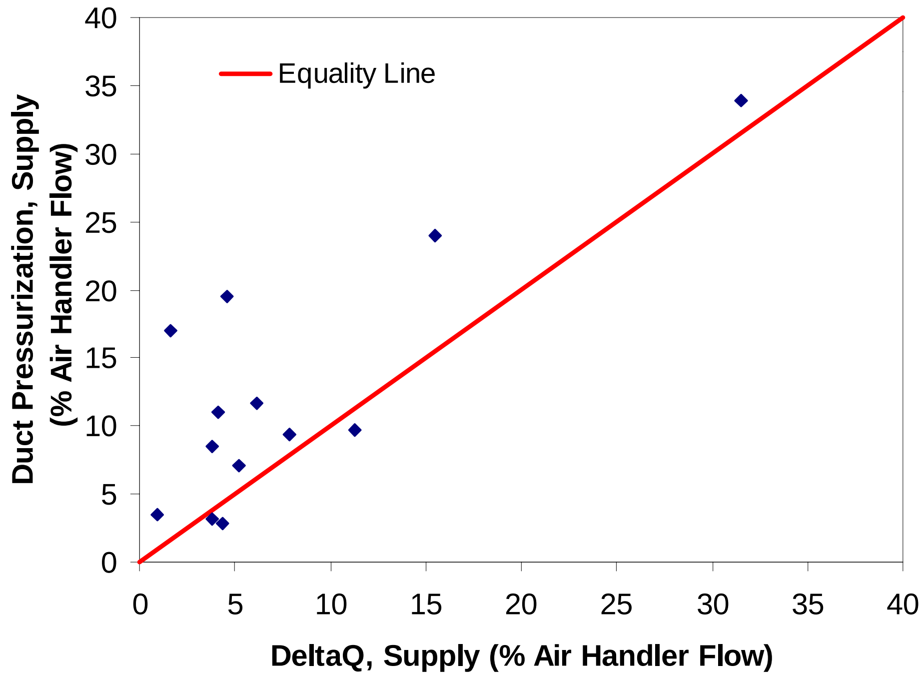

Figure 5. Comparison of DeltaQ to duct pressurization tests for supply leakage. RMS difference = 7% of air handler flow.

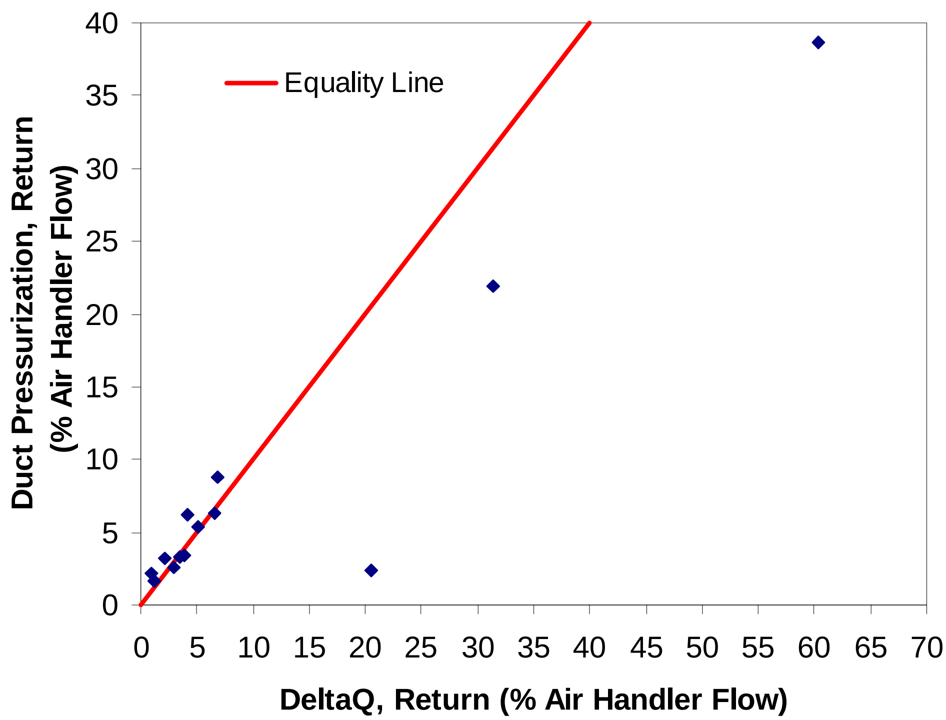

Figure 6. Comparison of DeltaQ to duct pressurization tests for return leakage. RMS difference = 8% of air handler flow.

CSUC/LBNL Field Tests

California State University Chico and LBNL have recently completed a program of field testing over 100 duct systems in California that are between 5 and 20 years old. The field testing includes using the DeltaQ test, duct pressurization and measurement of air handler flows. The DeltaQ field tests used the computer based data acquisition and control program developed by LBNL. The tests were performed by experienced HVAC technicians and undergraduate engineering students. For the DeltaQ test, we found some houses with bad data or bad tests as recorded by the HVAC technicians. Analysis of the continuously monitored envelope pressures showed that our initial assumption that the problems were cased by windy conditions was incorrect. It was thought that windy conditions could produce large envelope pressure fluctuations that the automated control system would not be able to deal with and the fluctuations in measured pressures would propagate into uncertainty in the calculated leakage flows. However, the recorded pressure data showed that the envelope pressures measured when the blower door was not operating were small in magnitude and did not show large fluctuations. The same envelope pressure signal was very noisy during blower door operation and the automated system could not adequately control the blower door in response to this signal. After some analysis, it was concluded that the pressure sensor had been placed near the blower door in the path of the large turbulent airflow from the blower door fan. Thus, when the blower door was operating the indoor pressure tap experienced large fluctuations in pressure. In the future, more explicit instructions regarding pressure sensor placement will be required. In addition, at several houses the pressurization test could not be performed because the house or the ducts were too leaky. For example, more than one house had completely disconnected ducts that could not be pressurized to 25 Pa (It should be noted that these systems would be identified as leaky with either test). These factors reduced the number of systems available for analysis to 87. The DeltaQ test shows that the average leakage for these houses is typical of those seen in previous surveys (Cummings et al. (1990), Downey and Proctor (1994a), Jump et al. (1996a) and Modera and Wilcox (1995)) with 99 cfm (47 l/s or 10% of air handler flow) for supply and 107 cfm (51 l/s or (12% of air handler flow)) for returns. The supply leakage ranged from zero to 330 cfm (156 l/s or 35% of air handler flow). The return leakage ranged from zero to 600 cfm (283 l/s or 73% of air handler flow).

There was a large range of envelope leakage from 760 to 7000 cfm50 (357 to 3300 l/s at 50 Pa). The corresponding 4 Pa ELAs are about 40 to 370 in^2 (260 cm^2 to 2400 cm^2). The average envelope leakage was 2500 cfm50 (1180 l/s at 50 Pa), with a standard deviation of 1100 cfm50 (520 l/s at 50 Pa). Testing over this wide range of envelope leakage is important because the DeltaQ test uses the change in flow through the envelope caused by duct leakage imbalances to calculate the duct leakage. Other tests that use the envelope pressure difference work best only when the envelope is not very leaky. Our field experience with the DeltaQ test has shown that for the houses in this study, the automated DeltaQ test produced reasonable results, even with leaky envelopes. This is because many data pairs are used in the analysis over a range of envelope pressures that greater in magnitude than the weather induced envelope pressure fluctuations. In addition, the automated software used long time averages to reduce weather induced fluctuations and automatically took data until prescribed limits on standard deviation of measured pressures were reached.

Detailed measurement data recorded by the computer program are being used to examine the uncertainties and test results from each individual test. Initial results show that the DeltaQ test procedure is fairly rugged. In windy conditions, or houses with leaky envelopes (when it is expected that the test may have problems), individual test points can show large variation during the test. However, these large variations for individual points do not lead to large variations in the test results. This is an important factor, because previous work (Walker et al. 1997) looking at other test methods that use the pressures measured across the building envelope have shown high sensitivity to wind and envelope conditions. The reason that the DeltaQ test does not have these sensitivities is because it uses multiple pressure stations so that an individual poor measurement does not corrupt the entire test. Also, many of the test pressures are significantly higher than those imposed on the building by the weather, which reduces the sensitivity to weather effects.

To provide guidance for the user of the DeltaQ procedure, an estimate has been made of the envelope pressure difference limits that yield acceptable test results. This envelope pressure difference with the air handler and blower door both turned off was measured at three different times. This included steps 3 and 9 from the Delta Q procedure listed earlier, plus an additional envelope pressure difference between pressurization and depressurization testing. For these DeltaQ tests the envelope pressure differences were measured 600 times over 20 seconds. In addition, the air handler off tests were performed twice by CSUC to provide extra information regarding possible test uncertainties. By looking at tests where there were significant differences between two air handler off envelope leakage tests (e.g., individual points in the repeated air handler off pressurization test or the differences between the fitted results yield envelope flow coefficients that differ by more than about 2%) or the data fit to the DeltaQ equation is poor (e.g., correlation coefficient less than about 0.7) it was possible to select some tests that could be characterized as giving poor results. By examining the differences between the three offset pressures and the standard deviation of each of the three offset pressures it was possible to determine approximate values for these parameters above which the test gave poor results. For the houses tested in this study the limit for a good test was that the standard deviation of each envelope pressure measurement should be less than 1 Pa and the differences between the means of the three tests must be less than 1 Pa. For different averaging times and methods, these values may have to be altered.

By changing the duct pressures and reanalyzing the data it was found that even fairly large changes in duct reference pressure did not change the final result a great deal. Typically, the reference pressure can be changed by a factor of two and only change the supply and return leakage by about 10% to 15%.

When the duct leakage is small the DeltaQ analysis can sometimes yield negative numbers for supply or return leakage. This is a combination of the precision of the test being limited to about 10 to 20 cfm (5 to 10 l/s) and at these low leakage levels, the results become more sensitive to "outliers" in the measured data. The precision is estimated based on the resolution of the envelope pressure measurements (roughly 0.1 Pa, although this can be effectively reduced by taking many data points) and the corresponding envelope flows, combined with the observed magnitude of the small negative numbers generated by the calculation procedure. Generally, when negative numbers result from the test this shows that the duct system is not leaky and the test result should be interpreted to mean that the leakage is less than this precision of the test procedure, i.e. less than 10 to 20 cfm. This implies that the leakage flows are going to be less than about 1% of fan flow and therefore not significant in terms of energy losses or poor distribution. Also, any system with this little leakage is going to pass any of the existing (and probably future) leakage limits found in energy codes (e.g. CEC (1998) gives a 6% of fan flow limit) or voluntary programs (EPA Energy Star ducts have a 10% of fan flow limit). Although these precision errors are not a significant barrier to the use of the DeltaQ test, we hope in future work to use non-Bayesian approaches to incorporate our prior knowledge of non-negativity and thereby improve the analysis.

The only significant problems experienced during the field testing referred to the specific equipment used for the testing. In order to reduce the uncertainty of the measured flows, the test protocol limited the flow range for flow orifice (or "ring") of the blower door, and required the operator to manually change orifices until the flow was within the preset limits for each orifice. In some houses this required iterating between two different orifices several times. This proved to be time consuming and very frustrating for the operators. In future a more relaxed set of criteria will be used for the use of each orifice on the blower door to eliminate this problem at the expense of reduced air flow measurement accuracy. The change in accuracy of the blower door is on the order of a percent or less – so this is not a dramatic change. The effect of this change is further reduced when the air handler on and off data for an individual point are taken with the same ring (at nearly the same flow) so that any biases cancel out when taking the difference between the two flows.

Comparison of DeltaQ and pressurization test results

Because both the DeltaQ and duct pressurization tests were performed in each house, it is possible to compare the test results to look for possible biases and how individual houses compare. In addition, differences in the test results from the point of view of compliance testing will also be evaluated. For another perspective on these results, the Appendix contains a summary of other duct leakage test comparisons. Table 6 summarizes a comparison of the duct pressurization and the DeltaQ results. The supply and return leaks have been combined to look at total leakage only. The duct pressurization results are for duct leakage to outside at 25 Pa. The range of measured duct leakage flows was about 30 to 900 cfm (14 to 425 l/s) for the DeltaQ tests and 30 to 700 cfm (14 to 330 l/s) for the fan pressurization tests. The air handler flows ranged from about 350 cfm to 2000 cfm (165 to 944 l/s). Averaged over all the houses, the two test methods give very close results, with an average difference of only 2% of fan flow (or about 20 cfm (9 l/s)). The average difference for an individual house is estimated by the RMS difference and is about 12% of air handler flow. This is a significant discrepancy: about half of the average leakage. Most of the difference can be attributed to the difficulty in extrapolating from hole size to leakage flow for the duct pressurization tests. Figure 7 shows the comparison for individual houses. In Tables 6 through 8, the % of air handler flow values are based on the % of air handler flows for each individual house. It is **not** the leakage flow divided by the average air handler flow.

Table 6. Comparison of DeltaQ to duct pressurization results in 87 California houses (total leakage to outside)

	Average DeltaQ	Average Duct Pressurization	Average Difference (Pressurization – DeltaQ)	RMS Difference	Air Handler
cfm (l/s)	206 (97)	186 (88)	-20 (9)	110 (52)	996 (470)
Fraction of air handler flow	22%	20%	-2%	12%	-

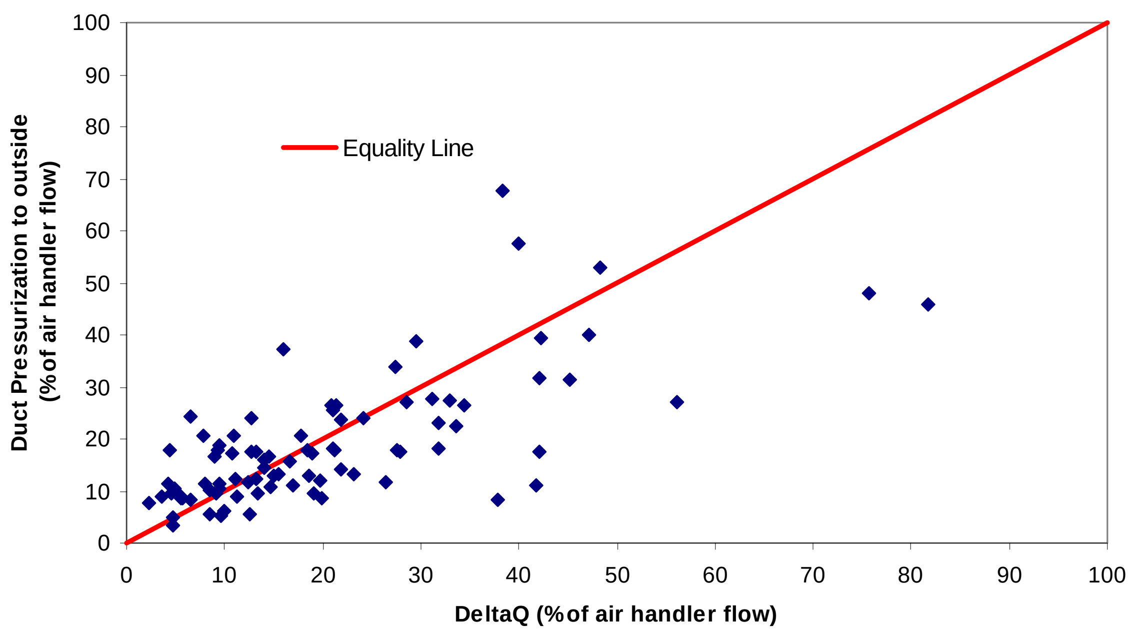

Figure 7. Comparison of DeltaQ total leakage (supply plus return) to duct pressurization leakage to outside at 25 Pa. RMS Difference = 12% of air handler fan flow

The above results looked at the combined supply and return leaks. For many duct systems, supply and return leaks can have significantly different effects on the duct system losses. Table 7 and Figure 8 compare the DeltaQ and duct pressurization results for supplies only, and Table 8 and Figure 9 compare the results for returns only. These results show that the fractional differences between the two tests are greater when the supply and return are looked at individually than when they are combined into the total leakage shown above.

Table 7. Comparison of DeltaQ to duct pressurization supply leakage results in 87 California houses				
	Average DeltaQ	Average Duct Pressurization	Average Difference (Pressurization – DeltaQ)	RMS Difference
cfm (l/s)	97 (46)	103 (49)	6 (3)	67 (32)
Fraction of fan flow, %	10%	11%	1%	7%

Table 8. Comparison of DeltaQ to duct pressurization return leakage results in 87 California houses				
	Average DeltaQ	Average Duct Pressurization	Average Difference (Pressurization – DeltaQ)	RMS Difference
cfm (l/s)	105 (50)	80 (38)	-25 (12)	72 (34)
Fraction of fan flow, %	12%	9%	-3%	8%

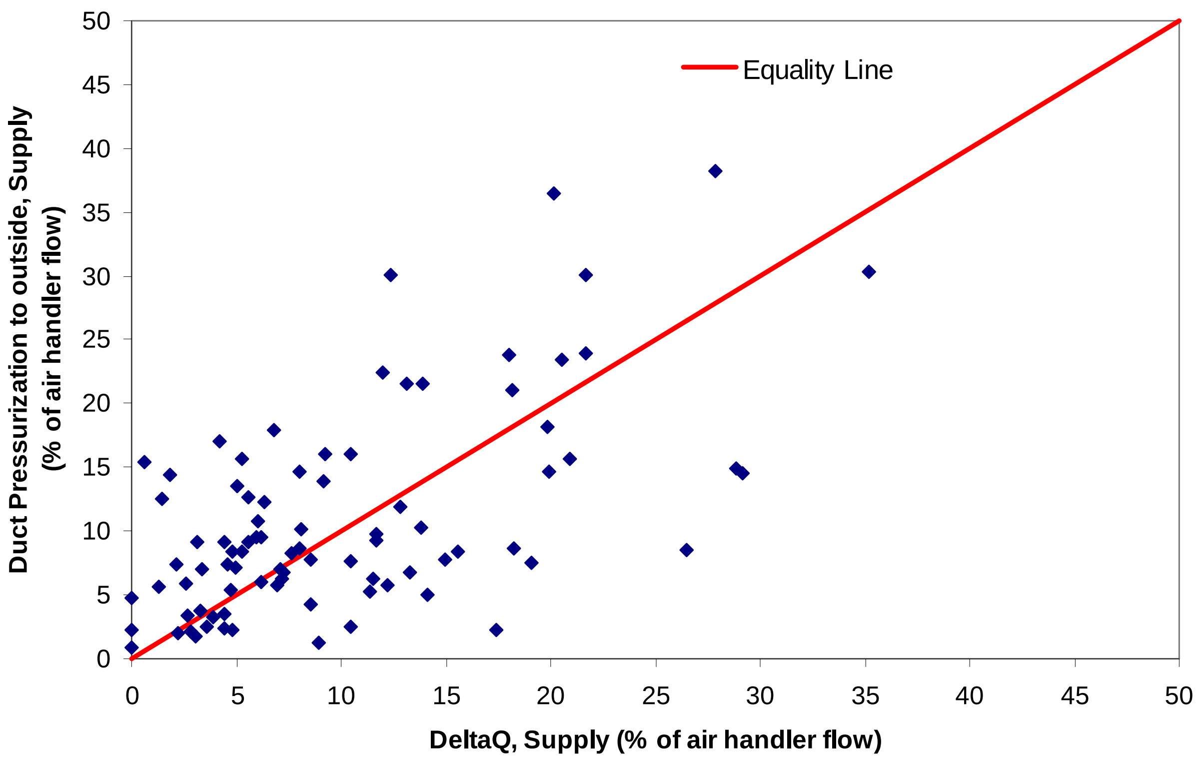

Figure 8. Comparison of DeltaQ supply leakage to duct pressurization supply leakage to outside at 25 Pa. RMS Difference = 7% of air handler fan flow

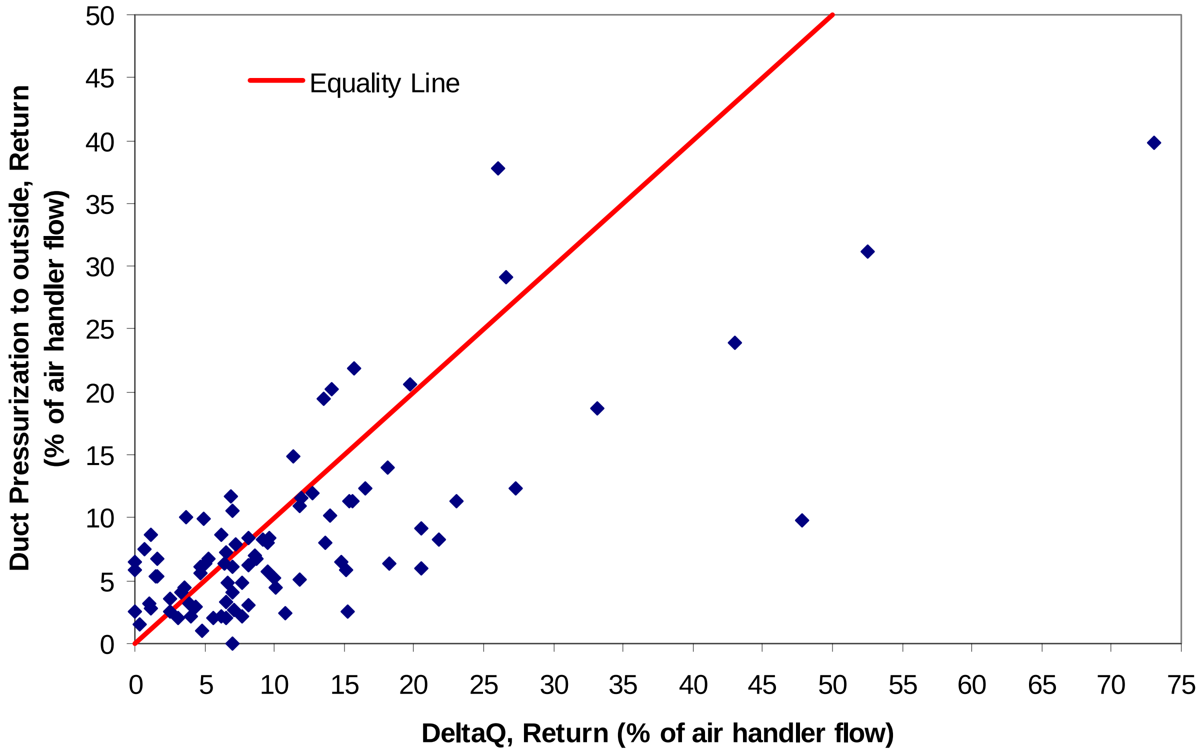

Figure 9. Comparison of DeltaQ return leakage to duct pressurization return leakage to outside at 25 Pa. RMS Difference = 8% of air handler fan flow

Compliance Testing

Given the significant differences between the two test results for individual houses (an RMS difference of 12% of air handler flow), compared to the low leakage limits (between 6% and 10% of air handler flow) set by existing codes and standards, we looked at the decisions that might be made based on the test results for a couple of scenarios. The first is to look at the 6% of air handler flow upper leakage limit set by CA State Energy code for the energy efficient duct credit in the Title 24 Alternative Calculation Manual (CEC (1998)). For this limit we compared the DeltaQ results to the total duct pressurization leakage (Table 9) as well as the leakage to outside comparisons made above (Table 10). We performed these two comparisons because the CA State Energy code uses this total duct pressurization leakage value. The duct pressurization leakage to outside averaged 67% of the total duct pressurization leakage values averaged over all the systems. This is close to the 75% of total duct pressurization to outside found in 44 houses previously studied by LBNL (Jump et al. 1996a, Walker et al. 1997 and Walker et al. 1998).

Because the average leakage for the houses in the current study is much higher than the 6% limit very few houses fall below the 6% level. Table 8 shows that all the systems failed the duct pressurization test, but 11 systems passed using the DeltaQ test. This result implies that the duct pressurization test is conservative, i.e. it over-predicts system leakage. This bias is expected because this pressurization test is for total leakage and not just leakage to outside (as measured by the DeltaQ test and of greater importance for energy losses). In terms of code compliance this is likely an acceptable result because regulators generally do not want a compliance test that passes poor houses. In Table 11, the pressurization tests results are for duct leakage to outside instead. In this case five houses pass the pressurization test, however, the DeltaQ test would fail three of these. It should be noted that at this low leakage level (6%) the vast majority of houses are failed by all three test methods.

Table 9. Number of houses passing or failing the 6% total leakage test, with Duct Pressurization total leakage		
	Duct Pressurization Pass	Duct Pressurization Fail
DeltaQ Pass	0	11
DeltaQ Fail	0	77

Table 10. Number of houses passing or failing the 6% total leakage test, with Duct Pressurization leakage to outside		
	Duct Pressurization Pass	Duct Pressurization Fail
DeltaQ Pass	2	9
DeltaQ Fail	3	74

An alternative scenario is to set the leakage at a higher limit of 10% that is more realistic for older systems and is has been adopted by state weatherization programs (e.g., Oregon), utility programs (e.g., Pacific Gas & Electric in California) and the proposed EPA Energy Star duct program. Table 11 shows that, even at this higher leakage level, only a single house passes using the duct pressurization test of total leakage. Table 12 shows that this is increased to 19 houses if the pressurization test is for leakage to outside. At this 10% level there are a substantial number of houses that are passed by the DeltaQ test, but fail the pressurization test. As with the 6% leakage results, this conservative result for pressurization testing is acceptable because it means that any house that passes the duct pressurization test will certainly have very little leakage to outside resulting in energy losses. The agreement between the two tests is increased if we look at Table 12, where half the tests that passed DeltaQ but failed pressurization testing in Table 11, now also pass the pressurization test. Another result that reinforces the acceptability of pressurization testing for compliance is the small number of houses that pass the pressurization test, but fail under DeltaQ.

Table 11. Number of houses passing or failing the 10% total leakage test, with Duct Pressurization total leakage		
	Duct Pressurization Pass	Duct Pressurization Fail
DeltaQ Pass	1	23
DeltaQ Fail	0	64

Table 12. Number of houses passing or failing the 10% total leakage test, with Duct Pressurization leakage to outside		
	Duct Pressurization Pass	Duct Pressurization Fail
DeltaQ Pass	13	11
DeltaQ Fail	6	58

Time taken to perform the DeltaQ Test

The time required to perform the DeltaQ test was recorded for each house. The average time was 33 minutes with a standard deviation of 14 minutes. The quickest house took only 9 minutes, but the slowest house took about 90 minutes. This large range is mainly because the automated software did not allow a large overlap between use of the blower door orifices, and in some houses this led to the operators having to change orifices multiple times. A secondary factor is that on windier days the automated procedure forces the test to be performed multiple times until the difference between two envelope leakage tests is within a small range. We have since modified the automated procedure to allow greater overlap between blower door orifices and to allow a greater difference between tests. Preliminary evaluation of the test data indicate that these alterations do not significantly degrade the accuracy of the DeltaQ test and will significantly improve its user friendliness and reduce the number of tests that take a long time (>40 minutes). These times do not include set-up or travel times because many other tests were also performed at these houses and it was not possible to separate out the set-up and travel times for an individual test. However, we can estimate the set-up time because the DeltaQ test requires installing a blower door in the house. We estimate that about five minutes should be added to these times to account for the blower-door equipment set-up.

Future Work

Development work is continuing on the DeltaQ test method. This work is concentrated on two fronts: one is the improved automation of the test procedure and the other is in improved analyses. The automation software is being updated to reduce problems with the ring swapping requirements of the blower door when changing flow range. A data analysis procedure is being developed that attempts to optimize the fitting of the DeltaQ equation to the measured data by adjusting the reference pressures P_s and P_r. Initial investigations indicate that the changes in DeltaQ test results are usually small as a result of this process, but some cases where the measured pressures are not representative of duct operating pressures (usually due to difficulties in measuring the duct static pressures) are improved. In addition, if the duct operating pressures are not required to be measured, then the test will be easier and quicker to perform in the field. Lastly, we are also investing a way to use the DeltaQ results to estimate the air handler flow during the test.

Other researchers are also using the DeltaQ test. In particular, ECOTOPE, Inc. is currently performing further field evaluations of the DeltaQ procedure using automated software developed by LBNL.

ASTM Duct Leakage Test Procedure.

As mentioned earlier, the current version of ASTE E-1554 is over 7 years old and contains outmoded or poorly performing procedures. The DeltaQ test is being incorporated into the next version of the test method, as a replacement for the blower-door subtraction method. The results of this study are being used by the ASTM subcommittee in their deliberations.

Summary

The DeltaQ test has been developed in order to provide better estimates of forced air system air leakage for use in energy efficiency calculations and for compliance testing of duct systems. Field and analytical tests have shown the test to be very robust and not very sensitive to fluctuating weather conditions. The use of automated data acquisition and control systems is highly recommended in order to increase the accuracy of the test, reduce operator errors and reduce the time required to perform the tests.

The test can be performed in about 30 minutes because it does not require extensive duct system preparation (e.g., having to tape over all registers for pressurization testing). In terms of time and cost effectiveness, the DeltaQ test also offers the advantage of determining envelope leakage at the same time as duct leakage. A significant amount of analytical and field testing has been performed that shows that the test should not have any significant biases for typical duct systems and the multipoint testing makes the test insensitive to many of the assumptions required in the analysis. Detailed field and analytical studies have shown that the DeltaQ repeatability uncertainties are typically 1% or less of system fan flow.

The DeltaQ test has been performed in more than 100 houses covering a wide range of system types, house types, system size and system leakage. These field tests have shown that the only significant test limitation would be to avoid extremely windy conditions (where the standard deviation of 20 seconds of envelope pressure differences is greater than 1 Pa or the difference between the means of individual offset pressures is greater than 1 Pa), and that our automated test procedure required some refining. The DeltaQ test is less sensitive to fluctuating envelope pressures than other duct leakage tests that use envelope pressure differences (NPT & HPT). The wind speed limitation can be automatically evaluated by looking at the variation in measured pressures and flows, particularly if automated data acquisition and control systems are used. Development of the test is continuing both on an analytical basis (e.g., using "best fit" pressures) and in automating the test procedures and analysis (e.g., automatic uncertainty calculation).

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Appendix. Other comparisons of duct leakage tests

Jump, Walker and Modera (1996a and 1996b) performed field tests in 24 California houses to determine distribution system efficiencies. Part of the test protocol was to measure duct leakage using fan pressurization and the difference between the sum of register flows and the air handler flow. The houses in this study had their duct systems retrofitted to increase insulation levels and reduce duct leakage and were tested before and after retrofitting. This effectively doubled the number of test systems investigated to a total of 48 supply and 44 return duct systems. There are fewer return duct systems because two houses had a return directly into an air handler stand. Figure A1 compares the predicted duct leakage of the two methods and illustrates that there is little correlation between the two methods. The results in Figure A1 are for total duct leakage and not leakage to outside. Averaging all the data in Figure A1 shows that the flow capture hood measurements are 21% higher than the fan pressurization measurements. An estimate of how close the predictions of the two methods are to each other is to average the absolute difference (so that positive and negative differences do not cancel). The RMS difference between the two tests is 125 cfm (59 l/s) and the RMS fraction difference is 250%. Comparing these results to the average measured pressurization result of 120 cfm (57 l/s) shows that there is essentially no agreement between these two tests.

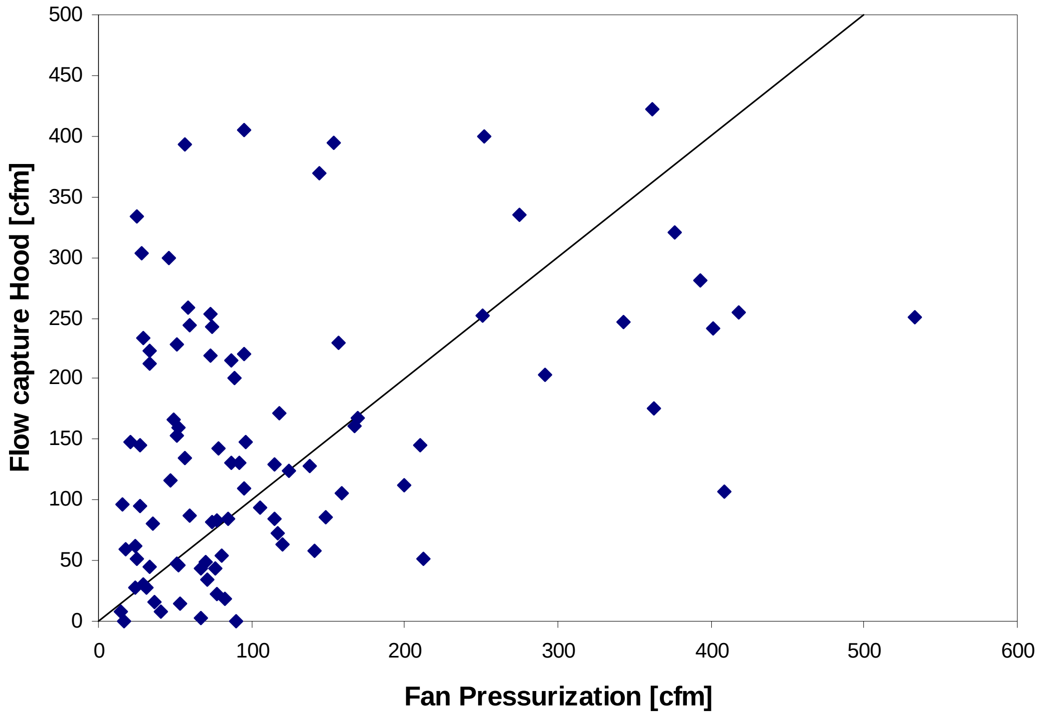

Figure A1. Comparison of total duct leakage predictions using flow capture hood and fan pressurization techniques in single family houses

These large differences between the two tests are the result of both tests having significant sources of error. For the fan pressurization, the most likely source of error is in the estimation of pressure difference across the leaks because the pressures in the duct system can vary by an order of magnitude between plenums and registers. This results in uncertainties of about a factor of two to three in leakage flow. For the flow capture hood method the uncertainty can be estimated based on the individual register flow measurement uncertainties (about ±2% of measured flow using the calibrated powered flow capture hood) and the uncertainty in measured fan flow (about ±5% based on the calibrated fan flow measurement device and extrapolation to operating pressures). For these systems ±5% of fan flow corresponds to about ±50 cfm (±24 l/s) or just under half the average fan pressurization leakage flow.. Note that other flow capture hoods are significantly less accurate (typically errors are in excess of ±20%) and the uncertainty in leakage flows using flow hoods have corresponding large uncertainties. In this case ±20% would be about ±200 cfm (±94 l/s), which is almost double the average leakage flow.

Flow capture hood and fan pressurization tests have also been performed in low-rise apartment buildings in New York as part of an Energy Retrofit Study (Walker, Modera, Tuluca and Graham (1996)). The results of eight of these tests are compared in Figure A2. The mean difference between measurement methods is 83 cfm (39 l/s). This is 31% of the average flow capture hood leakage measurement that was 270 cfm (128 l/s). The flow capture hood measurements are 50 cfm higher (24 l/s) (19% of flow capture hood mean), on average, than the pressurization results.

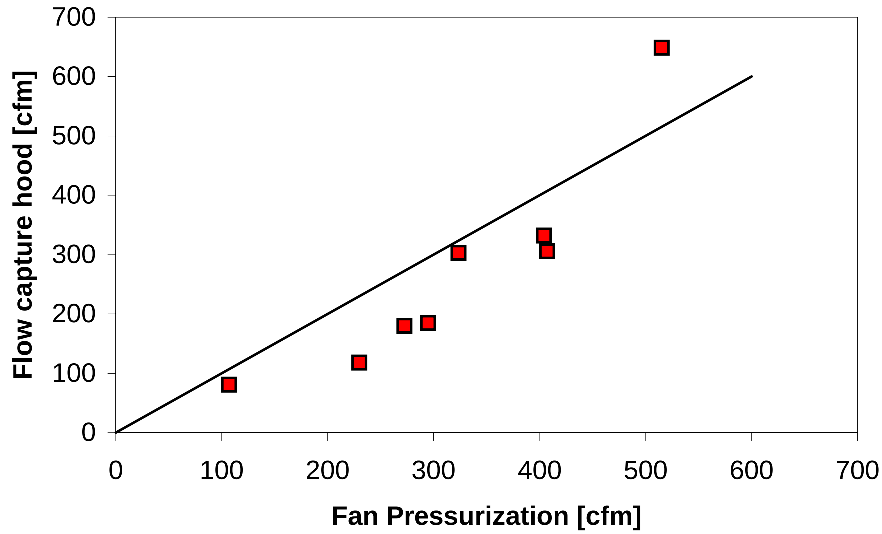

Figure A2. Comparison of duct leakage predictions using flow capture hood and fan pressurization techniques in low rise apartments

Modera and Wilcox (1995) compared fan pressurization measurement test results to house pressure test results (using measured duct system pressures). They used 20 new California homes to perform both types of tests and the results (for return leakage only) are shown in Figure A3. The sum of supply and return duct leakage flow averaged for all the systems was 84 cfm (40 l/s) for both methods. The difference between the leakage averaged over all tests was less than 0.5 cfm (0.25 l/s). The average absolute difference between the two methods was 34 cfm (16 l/s) or 40% of the average leakage flow. There were large differences in individual measurements, but the averages over many tests were close to each other.

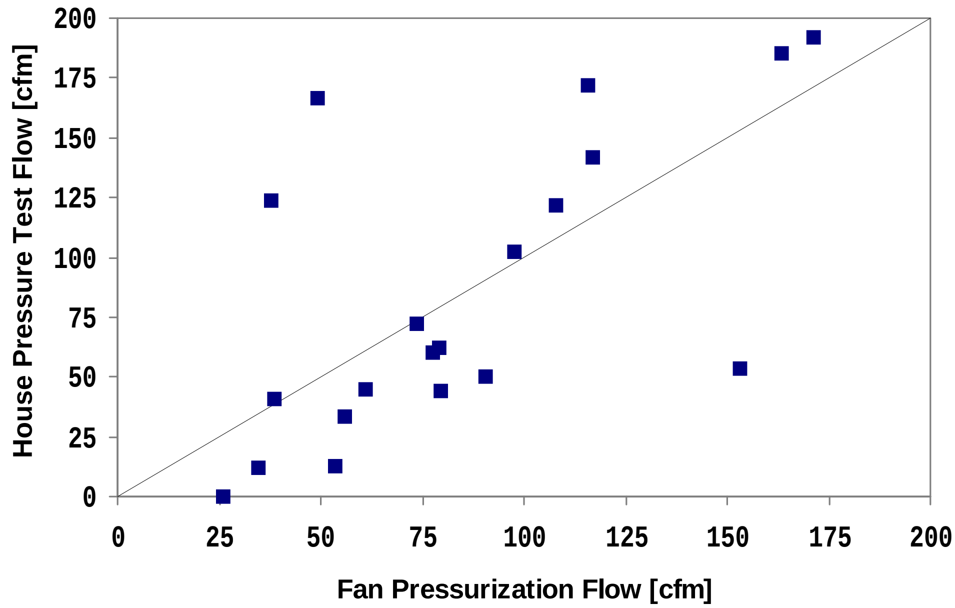

Figure A3. Comparison of Return Leakage Flows using fan pressurization and house pressure test methods (using measured envelope-only leakage and constant 1.35 correction factor for neutral-level shift due to attic duct leakage).

The above comparisons show that there are considerable differences between test methods for individual houses. Similar results were also found by Downey et al. (1994b) in an appendix to Downey and Proctor (1994a). They compared two leakage measurement methods. Both methods determined total leakage at a single fixed pressure rather than leakage at operating conditions. The first method they used was to pressurize the whole house with the registers open and with the registers sealed. The difference was then taken to be the duct system leakage. The second method was to pressurize the whole house with all but one register sealed and to measure the flow onto this one register with a flow hood, and assume that this flow was the leakage flow at the imposed pressure. The average leakage for forty two houses was about the same with both methods, but tests at individual houses typically differed by about 30%.