MEASUREMENT UNCERTAINTIES IN THE DELTA Q TEST FOR DUCT LEAKAGE

JOHN W. ANDREWS

NOVEMBER 2000

**Prepared for:
Office of Building Technologies
State and Community Programs
U.S. Department of Energy
Washington, DC 20585**

Under Contract No. DE-AC02-98CH10886

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MEASUREMENT UNCERTAINTIES IN THE DELTA Q TEST FOR DUCT LEAKAGE

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ABSTRACT

Theoretical and field-test results are reported on a new method for measuring air leakage in residential duct systems. This test, called the Delta Q test by its developers, involves a set of 10 or 11 pairs of measurements using a calibrated fan (blower door). Each pair of measurements is performed with the house pressurized or depressurized to a different pressure with respect to outside. One test in each pair is conducted with the system fan on, the other with it off. Each pair of measurements gives a linear equation in two unknowns, where the unknowns are the air leakage rates (under normal operating conditions) from the supply ducts to outside and into the return ducts from outside. The straight lines represented by these equations rarely intersect at a single point, so a least-squares fit is used to find the best compromise value for the supply and return leakage rates. This report describes a theoretical analysis of errors resulting from mismatches between the assumed and actual operating conditions in the ducts and from uncertainties in the blower-door air flow measurements. It develops a way to estimate the probable errors on a house-specific basis, using the data from a single application of the Delta Q test. Finally, it applies this analysis to field-test results from two houses.

INTRODUCTION

Recently, researchers at Lawrence Berkeley National Laboratory have proposed a new test to measure air leakage from residential duct systems (Walker and Sherman 1999). It was based in part on suggestions made earlier by a researcher at Pennsylvania State University (Gaston 1999). Termed the “Delta Q” test by its developers, it uses a series of blower-door measurements of the air flow required to pressurize or depressurize the house to a target pressure. The measurements are done in pairs, one with the heating/air-conditioning system fan off and the other with it on. These measurements are taken at eleven values of the house pressure (with respect to outside) ranging from -25 Pa to +25 Pa in 5-Pa increments. At each house pressure, the difference between the air flow through the blower door with the system fan on and that with the fan off is termed the delta-Q for that pressure. Each of these pairs of measurements provides an equation where the two unknowns are the air leakage rates (under normal operating conditions) to the outside from the supply ducts and from the outside to the return ducts. Solving the eleven equations in two unknowns using a least-squares fit yields a pair of best values for the supply and return leakage rates.

The test has two major practical advantages: (1) it should be fairly quick and easy to do, especially if an automated blower door capable of holding a given house pressure is used; and (2) it does not require additional test equipment beyond a blower door with a digital pressure gauge. Both of these characteristics are potentially important to the implementation of duct leakage testing by air-conditioning contractors and home weatherization providers.

The essentials of this test were communicated informally to the author of this report. The motivation for the present work was a desire to determine, from as many perspectives as possible, to what extent the usefulness of the delta-Q test might be subject to limitations imposed, first, by the simplifying assumptions made in developing the calculational procedure, and second, by uncertainties in the blower-door measurements.

The first approach was to try a standard type of error analysis based on partial derivatives, similar to ones done previously for other duct leakage tests (Andrews 1997). However, the dependence of the Delta Q test on a least-squares fit has placed roadblocks in this path. Although these may prove tractable in the end, it was desired to obtain useful results immediately. An alternative approach was therefore decided upon, using case studies to examine the sensitivity of the results to deviations of the assumed pressures and leakage distributions from the actual ones, and a Monte Carlo analysis to investigate the effect that measurement errors in the blower-door flow rates would have on the calculated duct leakage rates. These yielded some intriguing insights into the nature of the Delta Q test. Field tests on two houses using the Delta Q method were then compared with earlier measurements on the same houses using conventional duct-leakage assessment techniques, with the objective of assessing, within the limits of what a small number of field tests could reveal, whether the theoretical results appeared to correspond with the behavior of actual data.

The plan of this paper therefore is as follows:

- Derive the fundamental equations for the Delta Q test, following the lead of Walker and Sherman.
- Investigate the effect of deviations in the actual leakage pressures from the assumptions made by Walker and Sherman. A case-study approach using specific examples was used.
- Quantify theoretically the effect that measurement errors in the flow rates through the blower door will have on the supply and return leakage values. Here a Monte Carlo technique was used.
- Evaluate Delta Q test results for two houses that had previously been tested using other leakage measurement protocols.

DERIVATION OF SOLUTION EQUATIONS

This discussion proceeds along lines provided by Walker and Sherman (1999), the major additions being inclusion of the signs of the pressure differences in Equations 1 - 7, and the derivation of formulas for the least-squares fit in Equations 8 - 13.

Equation for One Pair of Measurements at a Given House Pressure

A blower door is installed in an exterior doorway of a house in the usual manner. The main difference between the Delta Q test and ordinary blower-door testing is that the tests are carried out both with the system fan off and with it on. It is important that the fan-off and fan-on tests be carried out at the same house pressure. Since this is not usually possible to do exactly, it is necessary to correct the fan-off air flow to the house pressure of the corresponding fan-on value using the relationship that air flow is proportional to house pressure raised to an exponent, where the value of the exponent is usually in the range 0.55 - 0.75.

If the system fan is off, the air flow through the blower door will be the sum of the air leakage rates through the envelope and through holes in the ducts. Consequently, the air flow Q_{off} through the blower door with the system fan off is given by:

$$Q_{\text{off}} = C_{\text{env}} \text{sign}(\Delta P) |\Delta P|^{n_{\text{env}}} + C_r \text{sign}(\Delta P) |\Delta P|^{n_r} + C_s \text{sign}(\Delta P) |\Delta P|^{n_s} \quad (1)$$

where C_{env} is the envelope leakage flow coefficient, ΔP is the house pressure with respect to outside, n_{env} is the exponent in the envelope $Q=\Delta P^n$ relationship, C_r and C_s are the return and supply duct leakage flow coefficients, respectively, and n_r and n_s are the return and supply duct

leakage exponents. The function "sign(ΔP)" has the value +1 if $\Delta P > 0$, 0 if $\Delta P = 0$, and -1 if $\Delta P < 0$.

The following sign conventions are used: Q_{off} is positive when the blower door is blowing air into the house, and ΔP is positive for pressurization and negative for depressurization..

When the system fan is on, the system is a little more complicated and requires certain assumptions in order for a tractable computation to be carried out. Walker and Sherman have used the assumption that when the house is pressurized or depressurized with respect to outside, the ducts are pressurized or depressurized with respect to outside by the same amount. In other words, the duct system "floats" along with the house. This would appear to be a reasonable assumption if the duct leakage is small. Very leaky systems might depart from this somewhat. Another assumption in their approach is that all the leakage takes place at a single pressure. This might seem overly restrictive, but one may hope that even if the leakage is distributed over portions of the ducts that are at different pressures, it might be possible to represent them as a single "lumped" leakage at a suitable weighted-average pressure. Be these things as they may, under the stated assumption the air flow through blower door with the system fan on is given by:

$$Q_{\text{on}} = C_{\text{dp}} \text{sign}(\Delta P) |\Delta P|^{\varphi_{\text{dp}}} + C_s \text{sign}(\Delta P - \Delta P_r) |\Delta P - \Delta P_r|^{\varphi_s} + C_r \text{sign}(\Delta P + \Delta P_r) |\Delta P + \Delta P_r|^{\varphi_r} \quad (2)$$

where ΔP_s is the leakage pressure in the supply duct and ΔP_r is the leakage pressure in the return duct.

Further sign conventions are defined for Equation 2: ΔP_s and ΔP_r are positive quantities, with the supply duct pressurized with respect to the house and the return duct depressurized. Hence the minus signs in the return term. Also, Q_{on} , like Q_{off} , is positive when the house is pressurized.

Equation 1 is subtracted from Equation 2 get ΔQ :

$$\begin{aligned} \Delta Q &= Q_{\text{on}} - Q_{\text{off}} \\ &= C_s [\text{sign}(\Delta P + \Delta P_r) |\Delta P + \Delta P_r|^{\varphi_s} - \text{sign}(\Delta P) |\Delta P|^{\varphi_s}] \\ &\quad + C_r [\text{sign}(\Delta P - \Delta P_r) |\Delta P - \Delta P_r|^{\varphi_r} - \text{sign}(\Delta P) |\Delta P|^{\varphi_r}] \end{aligned} \quad (3)$$

Now substitute $Q_s = C_s \Delta P_s^{\varphi_s}$ and $Q_r = C_r \Delta P_r^{\varphi_r}$, noting that Q_s and Q_r are both taken as positive:

$$\begin{aligned}\Delta Q = Q_s & \left[\text{sign}(\Delta P + \Delta P_s) \left| \frac{\Delta P + \Delta P_s}{\Delta P_s} \right|^{n_s} - \text{sign}(\Delta P) \left| \frac{\Delta P}{\Delta P_s} \right|^{n_s} \right] \\ & + Q_r \left[\text{sign}(\Delta P - \Delta P_r) \left| \frac{\Delta P - \Delta P_r}{\Delta P_r} \right|^{n_r} - \text{sign}(\Delta P) \left| \frac{\Delta P}{\Delta P_r} \right|^{n_r} \right] \quad (4)\end{aligned}$$

Walker advocates setting the duct exponents equal ($n_s = n_r = n$). In any realistic test method, it is likely that the n 's will be assumed to have a standard value such as 0.6, rather than attempting to measure them, so this does not appear to be a troublesome limitation.

$$\begin{aligned}\Delta Q = Q_s & \left[\text{sign}(\Delta P + \Delta P_s) \left| \frac{\Delta P + \Delta P_s}{\Delta P_s} \right|^n - \text{sign}(\Delta P) \left| \frac{\Delta P}{\Delta P_s} \right|^n \right] \\ & + Q_r \left[\text{sign}(\Delta P - \Delta P_r) \left| \frac{\Delta P - \Delta P_r}{\Delta P_r} \right|^n - \text{sign}(\Delta P) \left| \frac{\Delta P}{\Delta P_r} \right|^n \right] \quad (5)\end{aligned}$$

In a theoretical approach to an error analysis, one would investigate the variation of Q_s and Q_r per unit variation in ΔP_s and ΔP_r . That task would be simplified by making a slight change in the above equation, to make the arguments of the "sign" function the same as what's inside the absolute values. To justify this, we appeal to the fact that ΔP_s and ΔP_r have been defined to be positive, so putting them in the sign functions doesn't change their values:

$$\begin{aligned}\Delta Q = Q_s & \left[\text{sign} \left(\frac{\Delta P + \Delta P_s}{\Delta P_s} \right) \left| \frac{\Delta P + \Delta P_s}{\Delta P_s} \right|^n - \text{sign} \left(\frac{\Delta P}{\Delta P_s} \right) \left| \frac{\Delta P}{\Delta P_s} \right|^n \right] \\ & + Q_r \left[\text{sign} \left(\frac{\Delta P - \Delta P_r}{\Delta P_r} \right) \left| \frac{\Delta P - \Delta P_r}{\Delta P_r} \right|^n - \text{sign} \left(\frac{\Delta P}{\Delta P_r} \right) \left| \frac{\Delta P}{\Delta P_r} \right|^n \right] \quad (6)\end{aligned}$$

and this slightly simplifies to:

$$\Delta Q = Q_s \left[\text{sign} \left(\frac{\Delta P}{\Delta P_s} + 1 \right) \left| \frac{\Delta P}{\Delta P_s} + 1 \right|^p - \text{sign} \left(\frac{\Delta P}{\Delta P_r} \right) \left| \frac{\Delta P}{\Delta P_r} \right|^p \right] \\ + Q_r \left[\text{sign} \left(\frac{\Delta P}{\Delta P_r} - 1 \right) \left| \frac{\Delta P}{\Delta P_r} - 1 \right|^p - \text{sign} \left(\frac{\Delta P}{\Delta P_s} \right) \left| \frac{\Delta P}{\Delta P_s} \right|^p \right] \quad (7a)$$

$$= Q_s \left[\text{sign} \left(1 + \frac{\Delta P}{\Delta P_s} \right) \left| 1 + \frac{\Delta P}{\Delta P_s} \right|^p - \text{sign} \left(\frac{\Delta P}{\Delta P_r} \right) \left| \frac{\Delta P}{\Delta P_r} \right|^p \right] \\ - Q_r \left[\text{sign} \left(1 - \frac{\Delta P}{\Delta P_r} \right) \left| 1 - \frac{\Delta P}{\Delta P_r} \right|^p + \text{sign} \left(\frac{\Delta P}{\Delta P_s} \right) \left| \frac{\Delta P}{\Delta P_s} \right|^p \right] \quad (7b)$$

The form in Equation 7b assures that the signs of the coefficients of Q_s and Q_r are positive for low values of ΔP . Although the last two steps are not essential for the type of analysis that will be undertaken in this paper, the form of the relationship given in Equation 7b may be the most useful starting point for any further analysis of the Delta Q test.

Least Squares Solution for Simultaneous Equations

It is assumed that in the Delta Q Test, a multiplicity of measurements are made over a range of house pressures. Each of these yields an equation like Equation 7. These then have to be merged in some way to get best values for Q_s and Q_r . The least squares approach is probably the best way to handle this "overconstrained" situation.

For the i -th measurement of a set of n such measurements (each at a different house pressure), we rewrite Equation 7 as:

$$\Delta Q_i = Q_s \sigma_i - Q_r \rho_i + \epsilon_i \quad (8)$$

where σ_i and ρ_i are the coefficients of Q_s and Q_r , respectively, that are in square brackets in Equation 7, with the subscript i added to indicate that this is one of a set of equations. The quantity ϵ_i is the "error" in each of these equations, caused by forcing a single pair of Q_s and Q_r values to serve for the entire set of equations.

In line with usual practice, one minimizes the sum of the squares of these epsilons

$$\sum_i \epsilon_i^2 = \sum_i (\Delta Q_i - Q_s \sigma_i + Q_r \rho_i)^2 \quad (9)$$

by setting the partial derivatives with respect to Q_s and Q_r equal to zero:

$$\frac{\partial}{\partial Q_s} \sum_x \epsilon_x^\theta = -2 \sum_x (\Delta Q_x - Q_s \sigma_x + Q_r \rho_x) \sigma_x = 0 \quad (10a)$$

$$\frac{\partial}{\partial Q_r} \sum_x \epsilon_x^\theta = 2 \sum_x (\Delta Q_x - Q_s \sigma_x + Q_r \rho_x) \rho_x = 0 \quad (10b)$$

Rearranging this into the standard form of two equations in two unknowns (Q_s and Q_r) gives:

$$Q_s \sum_x \sigma_x^\theta - Q_r \sum_x \sigma_x \rho_x = \sum_x \Delta Q_x \sigma_x \quad (11a)$$

$$Q_s \sum_x \sigma_x \rho_x - Q_r \sum_x \rho_x^\theta = \sum_x \Delta Q_x \rho_x \quad (11b)$$

The solutions can be expressed as ratios

$$Q_s = \frac{NUMS}{DENOM} \quad (12a)$$

$$Q_r = \frac{NUMR}{DENOM} \quad (12b)$$

where NUMS, NUMR, and DENOM are determinants:

$$DENOM = - \begin{vmatrix} \sum_x \sigma_x^\theta & - \sum_x \sigma_x \rho_x \\ \sum_x \sigma_x \rho_x & - \sum_x \rho_x^\theta \end{vmatrix} = \sum_x \sigma_x^\theta \sum_x \rho_x^\theta - (\sum_x \sigma_x \rho_x)^\theta \quad (13a)$$

$$NUMS = - \begin{vmatrix} \sum_x \Delta Q_x \sigma_x & - \sum_x \sigma_x \rho_x \\ \sum_x \Delta Q_x \rho_x & - \sum_x \rho_x^\theta \end{vmatrix} = \sum_x \Delta Q_x \sigma_x \sum_x \rho_x^\theta - \sum_x \Delta Q_x \rho_x \sum_x \sigma_x \rho_x \quad (13b)$$

$$NUMR = - \begin{vmatrix} \sum_x \sigma_x^\theta & \sum_x \Delta Q_x \sigma_x \\ \sum_x \sigma_x \rho_x & \sum_x \Delta Q_x \rho_x \end{vmatrix} = - \sum_x \Delta Q_x \rho_x \sum_x \sigma_x^\theta + \sum_x \Delta Q_x \sigma_x \sum_x \sigma_x \rho_x \quad (13c)$$

The minus signs in front of the determinants were inserted because of the author's preference to have $DENOM > 0$. They cancel out in the ratios defining Q_s and Q_r .

The values of NUMS and NUMR should usually also be positive, since Q_s and Q_r are defined to be positive quantities. However, a duct with very small leakage on one side or another might yield a negative value of NUMS or NUMR due to experimental error.

Use of these equations in practical calculations was facilitated by incorporating them in a spreadsheet.

DIFFERENCES BETWEEN ASSUMED AND ACTUAL LEAKAGE PROFILES

The preceding derivation made two important simplifying conditions:

- All the leakage from the supply ducts occurs at a single pressure, and all the return leakage also occurs at a (possibly different) single pressure.
- The values for these pressures are known.

It will usually be the case that neither of these assumptions actually holds. The value of the Delta Q test will depend, therefore, on limiting the error in the result that may be caused by the single-leakage pressure assumption and by the imperfect knowledge of the numerical values of the pressures that are actually driving the leakage.

The following approach was taken to investigate these questions. A spreadsheet was developed to calculate the actual supply and return duct leakage that would occur in either of the following situations:

- All duct leakage is concentrated at a single point where the pressure is one-half that at the plenum; and
- Duct leakage occurs at two points with pressures one-fourth and three-fourths of the plenum pressure, and the leakage flow coefficient at each site equal to half that for the single-leakage situation.

Several cases were studied using specific assumptions for the duct and envelope leakage flow coefficients. In line with common practice, the duct exponent was assumed to equal 0.6 and the envelope exponent was set equal to 0.65. The envelope leakage flow coefficient was benchmarked at $200 \text{ cfm/Pa}^{0.65}$, which corresponds to leakage rate of ~2500 cfm at 50 Pa. The duct leakage flow coefficients on the supply and return sides were each set equal to either $10 \text{ cfm/Pa}^{0.6}$ or $40 \text{ cfm/Pa}^{0.6}$, depending on the case.

The duct leakage was assumed to follow one of the following patterns:

1. The leakage was all concentrated at one point, and the static pressure in the duct at that point, relative to the living space, was one-half the plenum pressure; or
2. The leakage was occurred at two sites, one with a static pressure equal to one-fourth of the plenum pressure, the other with a pressure equal to three-fourths of the pressure at the plenum.

The duct pressure assumed in Equation 7 took on one of the following values:

1. One-half the plenum pressure; or
2. The full plenum pressure.

The static pressure at the supply plenum was assumed to equal 40 Pa, while that at the return plenum was set at 60 Pa. In the examples where the duct leakage was split into two sites, the

leakage flow coefficient was equally divided between them. (This of course meant that there would be more leakage at the higher-pressure site.)

The above plan meant that four main cases were constructed, in which the supply and return duct leakage flow coefficients, in $\text{cfm/Pa}^{0.6}$, were (40, 40), (40, 10), (10, 40), and (10, 10). Each of these cases comprised four subcases, in which the supply and return ducts had either one or two leakage sites and the assumed duct pressure was either one-half or one times the plenum pressure. Thus, sixteen examples were considered.

For each of these examples, the calculations had to be done for each of eleven house pressures (from -25 Pa to +25 Pa in 5 Pa increments). First, the air flow through the blower door with the system fan off was calculated using Equation 1. With the fan off, it doesn't matter where the duct leaks are, since the pressure everywhere in the house and in the ducts is the same.

When the system fan is on, however, the situation becomes more complicated. The air flow through the blower door with the system fan on has to be calculated using the actual conditions to be simulated, and these will be compatible with Equation 2 only if there is but one leakage site on each duct. If there are two leakage sites per duct, the duct leakage term for each duct has to be split into two parts, each with its own flow coefficient and leakage pressure.

Once the flows through the blower door were determined for the conditions to be simulated, the predicted supply and return leakage rates were calculated using Equations 7 through 13.

At this point the careful reader might object. Isn't this process circular? After all, we started with assumed supply and return duct leakage rates, calculated blower-door flow rates, and then predicted supply and return leakage rates. However, the first step (leakage rates to blower-door flow rates) is based on the assumed actual conditions, while the second step (blower-door flow rates to predicted leakage rates) is based on the simplifying assumptions (one leakage site per duct, and an assumed leakage pressure) on which the Delta Q test is based. Only if the assumptions in Equations 7-12 match the posited actual conditions will the process lead exactly back to the starting point. In fact, seeing whether it did so was one way to quality-check the spreadsheet. However, if the ducts have more than one leakage site, or if the assumed leakage pressure differs from the actual leakage pressure, one would expect the predicted leakage rates to differ from the starting values. Assessing the magnitude of such differences is the whole point of this exercise.

To recapitulate, then, what was done can be summarized as follows:

1. Set up a theoretical duct system with one or two leakage sites on each duct and a given leakage pressure (relative to the house) at each site.
2. Calculate the actual supply and return duct leakage rates at each of the 11 house pressures.
3. Calculate the actual air flow rates through the blower door for each house pressure, with the system fan off and then with it on.
4. Using the Delta Q algorithm (Equations 7 - 13), calculate the predicted supply and return leakage rates.
5. Compare the predicted leakage rates with the actual leakage rates.

As a visual aid to understanding, the straight lines corresponding to the eleven equations (for house pressures running from -25 Pa to +25 Pa in 5 Pa increments) were plotted on a graph with Q_s as the horizontal variable and Q_r as the vertical one. Even though it is not necessary to construct these plots in order to obtain the least-squares fits, the plots did turn out to be very helpful in gaining insights concerning the effects that varying the parameters in the Delta Q test can have on the results.

Case 1: Balanced Duct Leakage

Figure 1 shows some results for a case where the supply and return leakage flow coefficients were the same. (The leakage rates were somewhat different because the leakage pressures were different.) As explained above, four subcases vary whether there is one effective leakage pressure or two and whether the assumed leakage pressures in Equation 7 are consistent with the actual leakage pressures.

Figure 1A shows what happens when the Delta-Q assumptions match reality perfectly. The supply leakage all occurs at 20 Pa with a flow coefficient of $40 \text{ cfm/Pa}^{0.6}$. The return leakage all occurs at a slightly higher pressure, 30 Pa, but with the same flow coefficient as on the supply side. The leakage flows can be easily calculated: $Q_s = 40 \cdot 20^{0.6} = 241 \text{ cfm}$, while $Q_r = 40 \cdot 30^{0.6} = 308 \text{ cfm}$. These are shown in the summary Table 1. The eleven straight lines all converge at this point on the figure, as one would hope.

Much can be learned from this plot that would be abstruse without it. First, the eleven lines divide naturally into three groups. The five lines resulting from pressurization tests ($\Delta P > 0$ in Equation 7) all have shallow slopes less than one, while the five lines resulting from depressurization tests ($\Delta P < 0$ in Equation 7) all have steep slopes greater than 1. The test conducted at zero house pressure gives a line with slope equal to one.

Table 1. Pressure and Leakage Parameters for Near-Balanced, High Leakage Case.

Flow Coefficients (cfm/Pa ^{0.6}): Cs = 40; Cr = 40					Actual Air Leakage Rates (cfm)		Calculated Air Leakage Rates (cfm)	
Case in Fig. 1	Actual Leakage Pressure(s) (Pa)		Assumed Leakage Pressure (Pa)					
	Supply	Return	Supply	Return	Supply	Return	Supply	Return
1A	20	30	20	30	241	308	241	308
1B	20	30	40	60	241	308	236	321
1C	10, 30	15, 45	20	30	234	298	198	254
1D	10, 30	15, 45	40	60	234	298	204	273

Intuitively, any uncertainty in the location of a best-fit solution in cases where the lines do not all converge on one point is likely to be minimized if there are lines that approach one another at angles as large as possible. Conversely, if all the lines were nearly parallel, one would expect relatively large uncertainties in the least-square fit. From such considerations one concludes that any version of the Delta Q test will need to use points taken under both pressurization and depressurization conditions.

Figure 1B shows the effect of doubling the assumed leakage pressure on both the supply and return sides of the duct system, without changing the real operating conditions in any way. Because the assumed pressures no longer match the actual ones, it is not surprising that the lines no longer meet at one point. A first impression of the lines is that they are quite badly shifted, but nevertheless, the least-squares fit gives a point on the graph that is not far from the one representing the actual conditions. For the best fit, $Q_s = 236$ cfm and $Q_r = 321$ cfm. These values differ from the actual values by 2% and 4%, respectively. For this case at least, only small errors in Q_s and Q_r are introduced by 100% errors in the assumed operating pressures in the ducts. This situation contrasts sharply with that obtaining in the standard test for duct leakage, which uses a smaller version of the blower door (duct blower) to pressurize the ducts. In that test, a 100% overestimate of the operating pressure produces a 52% overestimate of the duct leakage.

Figure 1C shows what happens if the leakage occurs at two pressures that are 25% and 75% of the plenum pressure, with the same flow coefficient as before but divided into two parts, half at each site. The assumed leakage pressure in the Delta Q equations is the same as in Figure 1A, halfway between the true values. Because the leakage function is non-linear, the total actual leakage rates will be ~3% less than in the case represented by Figure 1A, i.e., 234 cfm for Q_s and 298 cfm for Q_r . The calculated leakage values ($Q_s = 198$ cfm and $Q_r = 254$ cfm) are also less than in Figure 1A, but by wider margins. The deviations from the true values are 15% for both supply and return leakage rates.

Figure 1D combines the deviations of Figures 1B and 1C, that is, there are two leakage sites *and* the average leakage pressure is overestimated by 100%. One would think that the deviation of the result from the actual value would increase even more, but the case turns out differently, with the calculated supply leakage at 204 cfm or 13% below the true value and the calculated return leakage at 273 cfm or 8% less than the actual rate.

Case 2: Unbalanced Leakage—Supply Dominant

Figure 2 shows results for a case where the supply leakage rate greatly exceeds the return leakage rate. As in the previous example, four subcases vary the number of leakage sites (one or two) and the assumed operating pressure in the ducts.

Figure 2A shows the subcase where the Delta Q assumptions match reality. The supply leakage is the same as in the previous example; it all occurs at 20 Pa with a flow coefficient of $40 \text{ cfm/Pa}^{0.6}$. Also as before, the return leakage all occurs at a slightly higher pressure, 30 Pa. Now, however, the return leakage flow coefficient is reduced to 25% of its previous value, i.e., to $10 \text{ cfm/Pa}^{0.6}$. The actual leakage flows are $Q_s = 40 \cdot 20^{0.6} = 241 \text{ cfm}$ and $Q_r = 10 \cdot 30^{0.6} = 77 \text{ cfm}$. These are shown in Table 2. The eleven straight lines all converge at this point on Figure 2A.

Table 2. Pressure and Leakage Parameters for Supply-Leak Dominant Case

Flow Coefficients (cfm/Pa ^{0.6}): Cs = 40; Cr=10					Actual Air Leakage Rates (cfm)		Calculated Air Leakage Rates (cfm)	
Case in Fig. 2	Actual Leakage Pressure(s) (Pa)		Assumed Leakage Pressure (Pa)					
	Supply	Return	Supply	Return	Supply	Return	Supply	Return
2A	20	30	20	30	241	77	241	77
2B	20	30	40	60	241	77	214	76
2C	10, 30	15, 45	20	30	234	74	215	57
2D	10, 30	15, 45	40	60	234	74	200	64

Following the same plan as the previous case, Figure 2B shows the effect of doubling the assumed leakage pressure on both the supply and return sides of the duct system, without changing the real operating conditions. As before, the lines no longer meet at one point, but again, the least-squares fit gives a point on the graph that is not far from the one representing the actual conditions. For the best fit, $Q_s = 214 \text{ cfm}$ and $Q_r = 76 \text{ cfm}$. These values differ from the actual values by 11% and 1%, respectively.

Figure 2C shows what happens if the leakage occurs at two pressures that are 25% and 75% of the plenum pressure, with the same flow coefficient as before but divided into two parts, half at

each site. The assumed leakage pressure in the Delta Q equations is the same as that in Figure 1A, halfway between the true values. As in Case 1, this change produces a ~3% drop in the leakage rates, i.e., to 234 cfm for Q_s and 74 cfm for Q_r . The calculated leakage values ($Q_s = 215$ cfm and $Q_r = 57$ cfm) are also less than in Figure 2A, but by wider margins. The deviations from the true values are 8% on the supply side and 23% on the return side. The latter is large in percentage terms, but as an absolute difference it is small, amounting to only 17 cfm.

Figure 2D combines the deviations of Figures 2B and 2C, that is, there are two leakage sites and the average leakage pressure is overestimated by 100%. The calculated supply leakage is 200 cfm or 15% below the true value. The calculated return leakage is 64 cfm, or 14% below the actual rate.

Case 3: Return-Dominant Leakage

The next case studied was a mirror image of the one just discussed. The return leakage rate was fixed at the same high value as in Case 1, but the supply leakage was reduced by a factor of 4. Figure 3 shows results for this case.

Figure 3A shows the subcase where the Delta Q assumptions match reality. The supply leakage all occurs at 20 Pa with a flow coefficient of $10 \text{ cfm/Pa}^{0.6}$. The return leakage all occurs at 30 Pa with a flow coefficient of $40 \text{ cfm/Pa}^{0.6}$. The actual leakage flows are $Q_s = 10 \cdot 20^{0.6} = 60$ cfm and $Q_r = 40 \cdot 30^{0.6} = 308$ cfm. These are shown in Table 3. The eleven straight lines all converge at this point on Figure 3A.

As in the previous cases, the upper-right chart (Figure 3B) shows the effect of doubling the assumed leakage pressure on both the supply and return sides of the duct system, without changing the real operating conditions. Again, the lines no longer meet at one point, but the least-squares fit gives a point on the graph that is not very far from the one representing the actual conditions. For the best fit, $Q_s = 82$ cfm and $Q_r = 326$ cfm. The absolute and percentage differences on the return side are small, 18 cfm and 5%, respectively. On the supply side, the percentage deviation is 37%, but the absolute difference, 22 cfm, although perhaps non-trivial, is still only about 2% of a typical system fan flow in the 900 cfm - 1400 cfm range.

Figure 3C shows the case where the leakage flow coefficient is split evenly between two sites at pressures that are 25% and 75% of the plenum pressure. The assumed leakage pressures in the Delta Q equations are the same as that in Figure 3A, halfway between the true values. As in the previous cases, the total actual leakage rates are slightly smaller than the concentrated-leakage case represented by Figure 3A, i.e., 58 cfm for Q_s and 298 cfm for Q_r . The calculated return leakage of 261 cfm differs from the actual by 12%. The calculated supply leakage rate differs from the true value by 43%. As in Figure 3B, this large percentage deviation is relatively small in absolute (cfm) terms, i.e., only 25 cfm.

Table 3. Pressure and Leakage Parameters for Moderate Leakage Case

Flow Coefficients (cfm/Pa ^{0.6}): Cs = 10; Cr = 40					Actual Air Leakage Rates (cfm)		Calculated Air Leakage Rates (cfm)	
Case in Fig. 3	Actual Leakage Pressure(s) (Pa)		Assumed Leakage Pressure (Pa)					
	Supply	Return	Supply	Return	Supply	Return	Supply	Return
3A	20	30	20	30	60	308	60	308
3B	20	30	40	60	60	308	82	326
3C	10, 30	15, 45	20	30	58	298	33	261
3D	10, 30	15, 45	40	60	58	298	55	278

As in the previous cases, the chart on the lower right (Figure 3D) combines the deviations of the upper-right and lower-left charts. The calculated supply leakage of 55 cfm is 5% away from the true value, differing from it by an insignificant 3 cfm. The calculated return leakage of 278 cfm is within 7% of the actual.

Case 4: Modest Leakage on Both Sides

The last case to be considered here includes moderate amounts of leakage in both the supply and return ducts, driven by flow coefficients one-fourth as great as in Case 1. Figure 4 shows results for this case.

Figure 4A shows the subcase where the Delta Q assumptions match reality. The supply leakage all occurs at 20 Pa with a flow coefficient of 10 cfm/Pa^{0.6}. The return leakage all occurs at 30 Pa with a flow coefficient of 10 cfm/Pa^{0.6}. The actual leakage flows are $Q_s = 10 \cdot 20^{0.6} = 60$ cfm and $Q_r = 10 \cdot 30^{0.6} = 77$ cfm. These are shown in Table 4. The eleven straight lines all converge at this point on Figure 4A.

Table 4. Pressure and Leakage Parameters for Moderate Leakage Case

Flow Coefficients (cfm/Pa ^{0.6}): Cs = 10; Cr = 10					Actual Air Leakage Rates (cfm)		Calculated Air Leakage Rates (cfm)	
Case in Fig. 4	Actual Leakage Pressure(s) (Pa)		Assumed Leakage Pressure (Pa)					
	Supply	Return	Supply	Return	Supply	Return	Supply	Return
4A	20	30	20	30	60	77	60	77
4B	20	30	40	60	60	77	59	80
4C	10, 30	15, 45	20	30	58	74	50	64
4D	10, 30	15, 45	40	60	58	74	51	68

The upper-right chart (Figure 4B) shows the effect of doubling the assumed leakage pressure on both the supply and return sides of the duct system, without changing the real operating conditions. Again, the lines no longer meet at one point, but the least-squares fit gives a point on the graph that is very close to the one representing the actual conditions. For the best fit, $Q_s = 59$ cfm and $Q_r = 80$ cfm. The absolute and percentage differences are very small, 1 cfm (2%) on the supply side and 3 cfm (4%) on the return side.

Figure 4C shows the case where the leakage flow coefficient is split evenly between two sites at pressures that are 25% and 75% of the plenum pressure. The assumed leakage pressure in the Delta Q equations is the same as that in Figure 4A, halfway between the true values. As in the previous cases, the total actual leakage rates are slightly smaller than the concentrated-leakage case represented by Figure 4A, i.e., 58 cfm for Q_s and 74 cfm for Q_r . The calculated return leakage of 50 cfm differs from the actual by 14%, but this is only 8 cfm. The calculated supply leakage rate of 64 cfm also differs from the actual 14%, or 10 cfm in this case.

Finally, the chart on the lower right (Figure 4D) combines the deviations of the upper-right and lower-left charts. The calculated supply leakage of 51 cfm is within 12% or 7 cfm of the true value, while the calculated return leakage of 68 cfm is within 8% or 6 cfm of the actual.

Summary of Leakage-Profile Analysis

In this section of the report, the sensitivity of the calculated supply and return leakage values to differences between the mathematical assumptions and the actual leakage situation was investigated. The two specific variations studied were: 1) two leakage sites at different pressures in the actual system, compared with the assumption of a single leakage pressure; and 2) a doubling of the assumed leakage pressure, relative to the actual one.

For balanced or near-balanced leakage (Cases 1 and 4) the deviations ranged from 2% to 15%, which could be characterized as insignificant to moderate. For unbalanced leakage (Cases 2 and 3) the percentage deviations in the larger leakage were similar to those found in Cases 1 and 4, i.e., 6% to 15%. For the smaller of the two leakage values, the percentage deviations could be quite large. Although the absolute differences were usually small for the cases studied, the possibility exists that for some cases of unbalanced leakage, the deviations in the smaller of the two leakage rates may be uncomfortably large. Similar effects have been observed in other tests that take a holistic approach to measuring supply and return leakage rates together as the output of a single set of equations, as opposed to a test that isolates the two sides of the duct system and measures each independently. It may be that this is something one simply has to live with. On the positive side, thermal distribution efficiencies scale with the leakage rates, so it is absolute differences and not percentage differences that influence the magnitude of the errors. The reader is referred to ASHRAE Standard 152P (ASHRAE 1999) as the primary vehicle for such calculations.

It remains to examine the effect of errors in air-flow measurement, but the results obtained so far are encouraging for a test that, if optimized, should be performable in an hour or less of time, in addition to what would normally be required to do a standard multipoint blower-door test.

ERRORS IN BLOWER-DOOR AIR-FLOW MEASUREMENTS

Up to this point, the analysis has proceeded as if the air flows measured by the blower door were precisely known. Since this will not be the case in real applications of the Delta Q test, it is necessary now to consider the impact of measurement uncertainties in the blower-door data.

Relative Importance of Systematic vs. Random Error

Such measurement errors will normally have both systematic and random components. Systematic error is that error which is the same for all measurements of a given quantity, while random error varies from measurement to measurement. Systematic error might arise, for example, if the blower door or the pressure gauges are miscalibrated. Random error probably stems mainly from variable wind effects on successive measurements of the blower-door air flow, but no doubt there are other causes of random error as well. In their effect on the best-fit values of supply and return leakage in the Delta Q test, a simple argument shows that random error will almost always be of much greater importance than systematic error. To see why this should be so, consider a case where there is systematic error caused by a 3% miscalibration of the blower door, and in addition there are random errors in which the air-flow measurements are normally distributed with a standard deviation of 3%. Examination of Equations 13 shows that each term in NUMS and NUMR is proportional to one of the ΔQ_i 's. Since each ΔQ_i is a difference between a Q_{on} and a Q_{off} , and each of the latter is shifted by 3% due to the systematic error, NUMS and NUMR will also be shifted by 3%. Now, DENOM is not a function of the ΔQ_i 's at all. Therefore, the ratios NUMS/DENOM and NUMR/DENOM will shift by the same 3% that

NUMS and NUMR are. Thus, a 3% calibration error (or any other systematic error) will propagate to the same percentage error in Q_s and Q_r .

Now consider random errors. Suppose that for the i -th test pressure (where i runs from 1 to 11) that the true values are given by $Q_{on} = -800$ cfm and $Q_{off} = -1000$ cfm. Then $\Delta Q_i = +200$ cfm. The 3% random errors in Q_{on} and Q_{off} are 24 cfm and 30 cfm. The RMS error in the difference between these two is obtained by quadrature addition, resulting in a 38 cfm error on a 200 cfm quantity. This is a 19% discrepancy. In general, random errors in the flow rates are magnified by the fact that each ΔQ_i is a difference between two quantities of comparable magnitude. As is well known, such a situation tends to exacerbate the impact of measurement uncertainties in the inputs to the subtraction.

Now it could happen that the systematic-error percentages are typically much greater than the random-error percentages, and were this the case it could overturn the effect of the above analysis and make systematic error the greater threat. Based on admittedly limited experience with the Delta Q test, however, we expect that the two sources of error will likely be of the same order of magnitude. (Further light is shed on this in the discussion of field data.) One blower-door manufacturer quotes an expected uncertainty of 5% in the measurements, and this presumably includes both kinds of error. At the current state of the art in duct leakage tests, we would be very happy to keep errors below 5%, and such small errors would not greatly affect calculated distribution efficiencies in ASHRAE Standard 152, nor would they be likely to influence the desired outcome of decisions to repair or not to repair any given duct system. For these reasons, in the following analysis systematic errors will be ignored.

Approach to the Analysis of Measurement Errors—The Monte Carlo Technique

A straightforward approach to this problem is to take partial derivatives of Q_s and Q_r in Equations 12a and 12b, with respect to the individual Q_{on} and Q_{off} values, using Equations 13, 8, 7, and 3 together with the chain rule to do the calculus. Such an approach was employed successfully in analyzing other duct leakage tests (Andrews 1997). Although some headway has been made on this, the presence of a least-squares fit in the Delta Q test solution represents an analytical roadblock that was not present in the earlier analysis. Ultimately it is hoped that the barrier will be broken, but in the meantime it has seemed expedient to find a way around it. The method chosen to do this is Monte Carlo analysis.

The Monte Carlo method is based on the premise that if one can simulate repeatedly a situation whose outcome is determined in part by random variables, then by looking at the frequency distribution of the the resulting variables of interest, one can obtain a good idea of how the results will be distributed in the corresponding real situation, without having to propagate errors through a complicated thicket of mathematics. “Data” simulated using the Monte Carlo technique will be referred to as “simulated measured values.” This terminology is intended to remind the reader that the Monte Carlo data are simulated, not obtained from real houses, but are intended to mimic what would be obtained including the effects of measurement errors.

In the present case, the spreadsheet that was used to perform the least-squares fits for the solutions in the preceding section was modified to allow random variation in the measured values of Q_{on} and Q_{off} . Using the random number generator embedded in the spreadsheet program, variations in the flow rates were introduced. It was assumed that the measured flow rates would be normally distributed with means equal to the true values and standard deviations equal to a fixed percentage of the true value. For this analysis, a 3% standard deviation was selected. This is somewhat below a manufacturer's quoted error tolerance of 5%, but that includes both systematic and random error. In the following section on field tests, a method for estimating the actual average magnitude of random error in the blower-door measurements is presented, and these results, if typical, indicate that it may be possible to keep the actual standard deviation of blower-door measurements well below this benchmark value.

For the Monte Carlo simulations discussed below, the envelope leakage flow coefficient was set equal to the same $200 \text{ cfm/Pa}^{0.65}$ value that was used in the previous section's analysis. This corresponds to a CFM50 (the measured air flow through the envelope at 50 Pa) of slightly more than 2500 cfm. This was selected to represent a typical level of envelope leakage integrity. It is important to note that errors in the Delta Q test are expected to be approximately proportional to the envelope leakage flow coefficient, because the leakier the envelope, the smaller will be the measured flow differences as fractions of the average measured flow. If the expected random error in blower door measurements is a constant fraction of the measured flow, then everything else being the same, the percentage errors in the Delta Q's will increase as the envelope gets leakier.

Monte Carlo Results for Case 1--Balanced Leakage

A set of 30 separate spreadsheets was prepared for the set of parameters depicted above as Case1D. The assumptions for this case are given in Table 1, but to summarize here, the leakage flow coefficients on both the supply and return sides of the duct system were $40 \text{ cfm/Pa}^{0.6}$. Two leakage sites are assumed on each duct, at pressures equal to one-fourth and three-fourths of the plenum pressure. Also, the full plenum pressures are substituted for ΔP_s and ΔP_r in Equation 7.

Each of the thirty spreadsheets has its 22 air flow values randomized to simulate measurement error, as described above. This randomization produces a scatter of points on the $Q_s - Q_r$ plane, as shown in Figure 5A.

The thirty simulated measured values, shown as triangles in Figure 5A, appear in an elliptical pattern with a major axis of ~200 cfm lying along a line whose approximate slope is equal to one, and a minor axis of ~50 cfm in the perpendicular direction. If the shape and orientation of this ellipse is a general feature of the Delta Q test, it will mean that the test gives a more accurate value of the difference between the leakage rates ($Q_s - Q_r$) than for the sum ($Q_s + Q_r$).

Monte Carlo Results for Case 2--Leakage Supply Dominant

A second set of 30 separate spreadsheets, using a new set of random numbers, was prepared for the set of parameters depicted above as Case2D. Table 2 gives the assumptions for this case. Each of the thirty spreadsheets has its 22 air flow values randomized to simulate measurement error, as described above. This randomization produces a scatter of points on the $Q_s - Q_r$ plane, as shown in Figure 5B. As in the previous cases, the thirty simulated measured values, shown as triangles in the figure, appear in an elliptical pattern of approximately the same size and shape as those of Figure 5A. Figure 5B points up what may be a "fact of life" in duct leakage tests, such as the Delta Q test, that use a single set of measurements to obtain both the supply and the return leakage rates. The absolute uncertainties in the supply leakage and the return leakage appear to be approximately the same. (If the field of points in the scattergram is oriented at 45° to the horizontal, as it appears to be, this statement will be exactly true.) This means that the percentage uncertainty in the smaller of the two leakage rates can be quite large. Here, for example, the simulated measured supply leakage rates range from 150 cfm to 300 cfm, which represents a 33% error bar around the mean value of 225 cfm. The range of return leakage values is zero to ~130 cfm, about the same as the range of supply leakage values. The percentage error bar, however is 100% of the mean. It appears that for highly unbalanced leakage situations, the Delta Q test will not give much information about the smaller of the two leakage values, unless a way can be found to reduce the random errors in flow measurements dramatically below the 3% assumed here.

Monte Carlo Results for Case 3--Leakage Return Dominant

A third set of 30 separate spreadsheets, using another new set of random numbers, was prepared for the set of parameters depicted above as Case3D. Table 3 gives the assumptions for this case. Each of the thirty spreadsheets has its 22 air flow values randomized to simulate measurement error, as described above. This randomization produces a scatter of points on the $Q_s - Q_r$ plane, as shown in Figure 5C. As in the previous cases, the thirty simulated measured values, shown as triangles in the figure, appear in an elliptical pattern of approximately the same size and shape as those of Figures 5A and 5B. This figure shows the same difficulty with percentage uncertainty as the previous one, but here it is the supply leakage that is poorly determined on a percentage basis.

Monte Carlo Results for Case 4—Low Leakage on Both Sides of the Duct System

A fourth set of 30 separate spreadsheets, using still another new set of random numbers, was prepared for the set of parameters depicted above as Case 4D. Table 4 gives the assumptions for this case. Each of the thirty spreadsheets has its 22 air flow values randomized to simulate measurement error, as described above. This randomization produces a scatter of points on the $Q_s - Q_r$ plane, as shown in Figure 5D. As in the previous cases, the thirty simulated measured values, shown as triangles in the figure, appear in an elliptical pattern of approximately the same size and shape as those of Figures 5A - 5C. This figure shows the same difficulty with percentage uncertainty as the previous one, but now both leakage rates are poorly determined.

Uncertainties May Be Greater or Less Than Those Shown So Far

It is expected that two factors will drive the experimental uncertainties in the Delta Q test. One is the envelope leakage flow coefficient. As discussed previously, the Delta Q test should be more precise for houses with “tight” envelopes than for leaky ones. The second factor is the random variability of the blower-door air flow measurements. To the extent that this variability can be reduced, the precision and repeatability of the test will improve. Two figures were generated to illustrate possibilities, using Case 1D as a base. Figure 6A assumes a doubling of the envelope leakage flow coefficient, from 200 to 400 cfm/Pa^{0.65}. There is now a large scattering of points, with simulated measured supply leakage rates ranging from 100 to 350 cfm, with a similar range on the return side. From a chart such as this, one can see that a combination of a leaky envelope and too much variability in the air flow measurements would render the Delta Q test virtually useless.

Figure 6B is more optimistic. Here we are back to an average envelope, not a leaky one, and the standard deviation of the air flow measurements has been halved, from 3% of the central values to 1.5%. This provides a reasonably close-knit set of points. If one could reduce the uncertainties to this level, the Delta Q test would appear quite promising, especially if the time to do the test can be kept within reasonable bounds. Although the potential efficiency of the test is beyond the scope of this report, it's reasonable to hope that automation could reduce both the variability of the data and the time to do the test.

ESTIMATION OF MEASUREMENT UNCERTAINTIES IN FIELD TEST RESULTS

Critical to the usefulness of any test for duct leakage is the ability to quantify the probable errors in the results. The analysis and discussion up to this point were undertaken in an attempt to attain a theoretical understanding of the uncertainties that might be caused, first, by deviations of the actual leakage situation from the mathematical assumptions and, second, by random uncertainties in the blower-door air-flow measurements. It appears that the latter cause may be of greater impact in most cases than the former. Moreover, the impact of air-flow measurement errors depends not only on the size of these errors themselves, but also on the envelope leakage flow coefficient.

A Formula for the Probable Error in Q_s and Q_r

A tentative formula for the measurement uncertainties due to these random errors can be constructed by using as a benchmark the Monte Carlo results for a 3% standard deviation in air-flow measurements and an envelope leakage flow coefficient of 200 cfm/Pa^{0.65}. For this case, a confidence limit of ~97%, i.e., $(1 - 1/30) \times 100$, could be assigned, roughly, to the envelope of the 30 points in the scattergram. In terms of uncertainties in Q_s and Q_r , this envelope extends for a range of ~150 cfm, meaning that the points are all within 75 cfm of the true value. If this benchmark case is combined with the assumption, consistent with Figures 10 and 11, that the uncertainties are directly proportional to the envelope leakage flow coefficient and to the standard deviation of the air-flow measurements, a general formula for probable error can be constructed. Our rough formula, then, can be constructed as follows:

$$\text{probable error in } Q_s \text{ or } Q_r = 12.5 \sigma C_{env} \quad (14)$$

where σ is the standard deviation of the air flow measurements as a fraction of the central value, and C_{env} is the envelope leakage flow coefficient in cfm/Pa^{0.65}. Inserting $\sigma = 0.03$ and $C_{env} = 200$ yields the benchmark value of 75 cfm. As discussed above, the percentage confidence level of this formula should be somewhere in the high 90's. We will take it as a 95% level in what follows, with the understanding that this is a nominal, not a precise, figure.

The elliptical shape of the scatterplots of Figures 5 - 11 shows that the errors in Q_s and Q_r are correlated, with the uncertainty in $Q_s - Q_r$ being only about a fourth as great as that in $Q_s + Q_r$. Therefore, should it be desired to attain greater accuracy by combining the Delta Q test with another test, one should look for a complementary test that measures $Q_s + Q_r$ as accurately as possible, even if it measures $Q_s - Q_r$ poorly.

Can the Delta Q Test Data Predict the Probable Error in Duct Leakage?

One way to estimate random errors is to repeat an experiment several times and study the variability of the results. Such a procedure is appropriate for research, but in practical applications it represents a luxury. Therefore, it would be especially fortunate if the data obtained in one iteration of the Delta Q test could provide a way to estimate the probable error in the result. It is the purpose of this section to show that this ideal situation is probably achievable. The argument is as follows. In order to estimate the probable error, one needs to know the envelope leakage flow coefficient and the standard deviation of the blower-door air-flow measurements. Since a blower door is used in the test, the envelope leakage flow coefficient is easily obtained using the fan-off measurements. Of course, this coefficient will include a portion due to duct leakage, and the question arises whether one should use the coefficient including duct leakage or not including it. At the level of accuracy attained here, it is probably not significant which one is used, unless the ducts are extremely leaky. After all, this only affects our estimate of the error; the measured values of Q_e and Q_r in no way depend on this coefficient. We'll therefore use the raw coefficient, which includes both envelope and duct leaks.

As for the variability of the blower-door air flow measurements, the following is proposed as a way of estimating these. The Delta Q test includes two five-point blower door tests, one pressurizing and the other depressurizing. For each of these two series, do a least-squares fit of the logarithms of the air flows and the house pressures to obtain a best straight line, which provides values for the flow coefficient and exponent in the usual flow equation of the form $Q = C \Delta P^n$. Then determine the amount by which each of the individual measurements deviates from this best-fit equation, and divide by the measured value itself to obtain a fractional deviation. Use the average of the absolute values of these fractional deviations as an estimate of the variability of the measured values from the theoretical central values in a large number of measurements.

Tables 5 and 6 show, for two houses in Long Island, New York¹, on which the Delta Q test was performed, the house pressures, blower-door air flows, predicted flows using logarithmic least-squares fit, and fractional deviations of the measured from predicted flows, for House 1 and House 2, respectively. The average fractional deviation of the predicted flows, using the best-fit curve, from the measured flows was 0.011 for House 1 and 0.017 for House 2.

Tables 7 and 8 show, again for House 1 and House 2, the results of a procedure in which the measured flows, taken at house pressures that were near but not exactly equal to the target

¹Descriptions of these houses are given in the next section.

pressures of 25 Pa, 20 Pa, 15 Pa, etc., were adjusted to what they would have been at the target pressures, using the multiplier

$$\left(\frac{\text{target house pressure}}{\text{measured house pressure}} \right)^{1/n}$$

Next, the mean and standard deviation of each set of three flows measured at that particular house pressure were calculated, and a fractional standard deviation was calculated as the ratio of the standard deviation to the mean.

Finally, the average of the ten fractional standard deviations was calculated and displayed in Table 7 for House 1 and Table 8 for House 2. This average was 0.013 for House 1 and 0.023 for House 2.

For both houses, the average deviation from the ideal curve $Q = C \Delta P^n$ was in the range 75% to 85% of the average standard deviation of the three measured values at a given house pressure.

Tests of additional houses will be needed to determine whether this correspondence was fortuitous or holds up in general. If it proves to have general validity, it will be a tremendous help, since in that case it will be possible to put reliable error bars on the test results.

Using Equation 14, it is now possible to calculate error bars for the tests on House 1 and House 2. The inputs and outputs are as shown below:

House	Envelope Leakage Flow Coefficient (cfm/Pa ⁿ)	Average Fractional Deviation of Flows from $Q = C \Delta P^n$	Probable Error Limit cfm, ~95% confidence
1	212	0.011	±29
2	192	0.017	±41

Now we'll look at the test data. The actual results should fall well within these error limits.

Table 5. House pressures, blower-door flows, predicted flows using logarithmic least-square fit, and fractional deviations of the measured from predicted flows, for House 1.

Pressurization			House 1		Test 1
Phouse	Flow	log10Phou	log10Flow	PredFlow	FracDev
24.85	1588	1.3953	3.2007	1591	0.002
19.70	1395	1.2945	3.1444	1388	0.005
15.50	1203	1.1903	3.0803	1206	0.003
10.25	946	1.0107	2.9761	947	0.000
4.73	602	0.6744	2.7793	601	0.000
flow coef.	242.17	exponent	0.5858	avg.f.dev.	0.002
Depressurization					
5.20	554	0.7160033	2.7433363	565.68	0.021
10.18	902	1.0075344	2.9550411	882.37	0.022
14.88	1177	1.172457	3.0706147	1134.68	0.037
20.18	1358	1.3048135	3.1329024	1388.46	0.022
24.80	1569	1.3944517	3.1956319	1591.84	0.014
flow coef.	189.83	exponent	0.6623	avg.f.dev.	0.023
Pressurization			House 1		Test 2
Phouse	Flow	log10Phou	log10Flow	PredFlow	FracDev
25.25	1638	1.4023	3.2143	1633	0.003
20.50	1426	1.3118	3.1542	1444	0.012
15.48	1216	1.1896	3.0849	1223	0.006
9.98	971	0.9989	2.9872	944	0.028
5.03	622	0.7011	2.7941	630	0.013
flow coef.	243.36	exponent	0.5895	avg.f.dev.	0.012
Depressurization					
5.18	546	0.7139104	2.737539	552.17	0.010
10.33	901	1.0138901	2.9548034	880.14	0.024
14.75	1107	1.168792	3.0442169	1119.71	0.011
19.98	1383	1.3004868	3.1408671	1374.02	0.007
25.08	1588	1.3992409	3.2009447	1601.95	0.008
flow coef.	182.06	exponent	0.6750	avg.f.dev.	0.012
Pressurization			House 1		Test 3
Phouse	Flow	log10Phou	log10Flow	PredFlow	FracDev
24.85	1605	1.3953	3.2055	1601	0.002
20.45	1421	1.3107	3.1525	1420	0.001
15.43	1182	1.1882	3.0726	1192	0.009
9.75	905	0.9890	2.9565	898	0.008
4.75	574	0.6767	2.7592	575	0.002
flow coef.	219.53	exponent	0.6185	avg.f.dev.	0.004
Depressurization					
4.93	550	0.6924062	2.7404567	556.74	0.012
10.08	904	1.0032451	2.9559893	884.78	0.021
15.10	1152	1.1789769	3.0614172	1149.67	0.002
19.98	1374	1.3004868	3.1379482	1377.91	0.003
24.83	1573	1.3948893	3.1967863	1586.06	0.008
flow coef.	198.38	exponent	0.6472	avg.f.dev.	0.009

Table 6. House pressures, blower-door flows, predicted flows using logarithmic least-square fit, and fractional deviations of the measured from predicted flows, for House 2.

Pressurization			House 2		Test 1
Phouse	Flow	log10Phou	log10Flow	PredFlow	FracDev
26.18	1536	1.4179	3.1865	1577	0.026
20.30	1316	1.3075	3.1194	1333	0.012
15.15	1118	1.1804	3.0483	1098	0.018
9.68	869	0.9857	2.9388	816	0.064
4.95	503	0.6946	2.7015	524	0.040
flow coef.	181.80	exponent	0.6617	avg.f.dev.	0.032
Depressurization					
6.13	614	0.7871061	2.7883412	627.34	0.021
10.43	900	1.0180761	2.9540889	882.43	0.020
14.53	1129	1.1621161	3.052592	1091.66	0.034
20.23	1315	1.3058885	3.1189669	1349.96	0.026
25.65	1564	1.4090874	3.1941287	1572.27	0.006
flow coef.	196.13	exponent	0.6415	avg.f.dev.	0.021
Pressurization			House 2		Test 2
Phouse	Flow	log10Phou	log10Flow	PredFlow	FracDev
23.98	1501	1.3798	3.1764	1490	0.007
20.65	1299	1.3149	3.1137	1342	0.032
15.03	1063	1.1768	3.0267	1073	0.009
9.80	846	0.9912	2.9272	794	0.065
4.73	462	0.6744	2.6643	475	0.029
flow coef.	159.35	exponent	0.7037	avg.f.dev.	0.028
Depressurization					
5.18	576	0.7139104	2.7602677	575.23	0.001
10.43	896	1.0180761	2.9524124	896.74	0.001
14.73	1118	1.1680553	3.0483102	1116.21	0.001
19.83	1336	1.2972132	3.1256708	1347.80	0.009
23.73	1522	1.3752062	3.1822892	1510.32	0.007
flow coef.	202.89	exponent	0.6340	avg.f.dev.	0.004
Pressurization			House 2		Test 3
Phouse	Flow	log10Phou	log10Flow	PredFlow	FracDev
24.80	1540	1.3945	3.1874	1523	0.011
20.25	1356	1.3064	3.1323	1337	0.014
15.33	1088	1.1854	3.0366	1118	0.027
9.93	837	0.9967	2.9226	845	0.010
5.18	563	0.7139	2.7504	556	0.012
flow coef.	193.09	exponent	0.6433	avg.f.dev.	0.015
Depressurization					
5.78	645	0.761552	2.8097669	645.21	0.000
9.28	857	0.9673139	2.9330757	860.66	0.004
14.05	1116	1.1476763	3.0477689	1107.93	0.008
19.78	1361	1.2961165	3.1338122	1363.90	0.002
24.78	1562	1.3940137	3.1937169	1564.28	0.001
flow coef.	222.12	exponent	0.6081	avg.f.dev.	0.003

Table 7. Variation of measured flows, corrected to target pressures, over three tests of House 1.

Phouse	Summary Values		Corrected
	Flow		
	Mean	Std.Dev.	Frac. SD
Press			
25	1610.8	14.3	0.009
20	1404.6	2.4	0.002
15	1178.5	13.2	0.011
10	941.4	22.7	0.024
5	611.8	13.4	0.022
Depress			
5	543.0	9.2	0.017
10	890.8	7.1	0.008
15	1150.0	25.9	0.023
20	1369.8	14.4	0.011
25	1581.0	3.2	0.002
Avg. Frac. SD			0.013
At a given pressure			
Avg. Frac. Dev.			0.011
From Curve.			

Table 8. Variation of measured flows, corrected to target pressures, over three tests of House 2.

Phouse	Summary Values		Corrected
	Flow		
	Mean	Std.Dev.	Frac. SD
Press			
25	1528.1	26.6	0.017
20	1306.4	30.6	0.023
15	1081.9	20.6	0.019
10	862.1	19.4	0.022
5	512.4	29.0	0.057
Depress			
5	564.6	21.2	0.038
10	882.1	10.9	0.012
15	1148.2	12.9	0.011
20	1339.7	26.5	0.020
25	1560.6	15.9	0.010
Avg. Frac. SD			0.023
At a given pressure			
Avg. Frac. Dev.			0.017
From Curve.			

FIELD TEST RESULTS

This section of the report discusses the actual field test results for House 1 and House 2. It covers a brief description of the houses, a discussion of the data-taking procedure, and presentation of the results.

House Descriptions

House 1 is a one-and-a-half story Cape Cod dwelling located in a suburban residential area in central Long Island, New York. Its total conditioned floor area is 1115 ft². It is heated by a gas furnace with capacity 76 000 Btu/h. No comfort cooling is used at present. The average measured system fan flow rate is 679 cfm.

The supply duct system is constructed of uninsulated sheet metal. It has a total surface area of 285 ft², of which 82% is in an uninsulated, unfinished basement, 13% is in exterior walls, and the remainder is in the conditioned space. There are 11 supply registers, seven on the first floor and four on the second floor..

The return duct system is also constructed of uninsulated sheet metal. It has a total surface area of 61 ft², of which 62% is in the basement and the remainder is in the conditioned space. There are two return registers, one on each floor.

House 2 is a single-story dwelling located in a village near the north shore of central Long Island, New York. Its total conditioned floor area is 729 ft². It is heated by a gas furnace with capacity 57 000 Btu/h and cooled with a central air conditioner with capacity 27 000 Btu/h. The average measured system fan flow rate is 912 cfm.

The supply duct system is constructed of sheet metal insulated with R-4 duct wrap. It has a total surface area of 215 ft², of which 100% is in an uninsulated, unfinished basement. There are 6 supply registers.

The return duct system is also constructed of sheet metal insulated with R-4 duct wrap. It has a total surface area of 103 ft², of which 83% is in the basement and the remainder is in the conditioned space. There is one return register.

Procedure

A fairly simple procedure was followed. A blower door was set up in an exterior doorway of the house. To mitigate the effects of wind gusts, a “four-wall” apparatus was used as the exterior pressure reference point. This consists of a manifold to which four plastic tubes are connected, with the open ends of the tubes placed near the ground on the four sides of the house. The other side of the manifold is connected to a single tube which passes from the exterior to the interior

and thence to the reference port of a digital manometer. The house pressure is then measured as the pressure difference between the measurement port (which is left open) and the reference port.

Three plastic tubes were run from the living space to the vicinity of the equipment, underneath a closed door separating the conditioned space from the basement. One of these was connected to a pressure tap located in the return plenum. A second was connected to the supply plenum. The third was left open in the basement, to measure the pressure difference between the basement and the living space.

For these tests, a door or window between the basement and the living space was left open. The reason for this was so that the mathematical assumptions underlying Equation 7 would be met. One of these assumptions is that the pressure in the ducts, relative to the pressure in the space surrounding the ducts, rises and falls by the same amount that the house is pressurized or depressurized. This was approximately true if the basement door to outside was open (so that the basement pressure remained close to zero) but not if this door was closed.

This is equivalent to assuming that the basement is not part of the living space. In both houses tested here, the basement was not finished or used as living space, nor were there supply or return registers in the basement. For the purposes of the test, then, the procedure was equivalent to viewing the basement as a well-vented crawl space.

The question may well be asked, whether the results will accurately reflect the actual duct leakage under normal operation, when the basement door to outside is closed. As long as the pressure in the basement shifts by at most a small fraction of the operating pressures in the ducts, the results from an open-door test should be applicable. Such was the case in the houses reported on here.

For each of the target pressures (25, 20, 15, 10, 5, -5, -10, -15, -20, and -25 Pa) the house pressure was brought as close to the target as possible, and then four 5-second average readings were taken, alternately, of the house pressure and the fan-throat pressure of the blower door. The house pressure was then taken as the average of the four measured values, and the air flow was taken as the value corresponding to the average fan-throat pressure, using the calibration curves supplied with the blower door.

With the system fan on, an attempt was made to match as closely as possible the average house pressure actually attained in the fan-off measurement. That is, if the target pressure was 20 Pa and the average house pressure attained in the fan-off part of the test was 19.75 Pa, then in the fan-on part of the test the target was taken as 19.75 Pa, not 20 Pa. Again, the average of the four house pressures was calculated and used as a single data point, and the blower-door fan flow was taken as that corresponding to the average of the four fan-throat pressure measurements. Care was taken to use the same ring on the blower door for the fan-on part of the test (at each target pressure) as for the fan-off part. Generally, Ring A was used at the higher pressures and Ring B at the lower.

Immediately following the fan-on test, the supply plenum, return plenum, and basement pressures, all with respect to the living space, were recorded.

In order that the two flow rates would represent the same house pressure, the fan-off value was corrected to the house pressure at the fan-on value. This was accomplished by multiplying the fan-on value by the 0.65 power of the ratio of the house pressure during the fan-on test to the house pressure during the fan-off test. The fan-off value was corrected to the fan-on house pressure, rather than vice-versa, because the functional form of the blower-door flows with the system fan off is well known, i.e., $Q = C \Delta P^n$, whereas the corresponding flow function for the system-fan-on case is more complicated.

Once the blower-door flow rates at the same house pressure, with the system fan on and with it off, were determined, their difference was set equal to ΔQ and inserted into Equation 7 along with the house pressure (ΔP), supply-duct pressure (Δp_s), and return-duct pressure (Δp_r). The latter two quantities were taken as one half the supply-plenum and return-plenum pressures, respectively.

Measurements were also made at zero pressure. It was found to be difficult to match the fan-on and fan-off pressures very closely. Moreover, the flow rates are extremely sensitive to the indoor-outdoor pressure difference at pressure differences near zero. For example, assuming the envelope leakage flow coefficient equals $200 \text{ cfm/Pa}^{0.65}$, a shift in the house pressure from zero to 0.2 Pa would, theoretically, produce a 70 cfm shift in blower-door air flow, but the same 0.2 Pa shift in house pressure would shift the air flow by no more than 8 cfm at house pressures in the 5 Pa - 25 Pa range. We would argue, therefore, that the zero-pressure point is not worth the trouble required to take it, and the Delta Q test would be improved if testers were instructed to take 10 sets of data at ± 5 through ± 25 Pa and skip the 0 Pa point. Although data were taken at zero pressure during these tests, the results discussed below are based on the 10 non-zero points.

The calculated results for the two houses are given in Table 9. In calculating these results, it was assumed that the operating pressures ΔP_s and ΔP_r in Equation 7 were equal to one-half the static pressures measured at the supply and return plenums, respectively.

For each side of the duct system in each house, the mean value of the three measurements is the best estimate we have of the true leakage. We would expect the maximum deviations from this mean to be less than the probable errors estimated above (since these probable errors are to ~95% confidence, and we have only three values) but nevertheless of the same order of magnitude. In fact, the maximum deviations for House 1 are 13 cfm and 18 cfm, compared with the estimated 95% confidence limit of 29 cfm. For House 2, the maximum deviations are 28 cfm and 14 cfm, compared with the ~95% confidence limit of 41 cfm. Although the data are still too sparse to justify a more sophisticated statistical analysis, we can say that the data we do have are consistent with the proposed methodology for estimating errors.

Table 9. Measured Duct Leakage Rates to Outside

House	Test	Supply Leakage, cfm	Return Leakage, cfm
1	1	218	52
	2	222	59
	3	201	28
	Mean	214	46
	Max. Dev. from Mean	13	18
2	1	61	286
	2	55	272
	3	100	300
	Mean	72	286
	Max. Dev. from Mean	28	14

Figures 7A, 7B, and 7C show the three least-squares fits for House 1. The three sets of straight lines appear to be quite tightly knit, compared with the theoretical cases displayed earlier, e.g., Figure 2. The $Q_s - Q_r$ plot of Figure 7D shows the three solutions from Figures 7A - 7C, which were obtained using half the plenum pressures for ΔP_s and ΔP_r . Also shown are the solutions if the full plenum pressures are used. There is some shift in the values of Q_s and Q_r if this change is made. For the supply leakage the shift is small on both an absolute and a percentage basis. The absolute shift for the return leakage, caused by adjusting the duct pressures a factor of two, is similar to that for the supply leakage, but of course on a percentage basis it is much larger. This needs to be viewed in context. The existing test, which uses a smaller version of the blower door to pressurize a duct system, will exhibit a ~50% increase in reported leakage values if the assumed operating pressure in the duct system is doubled. This is discussed at greater length in the next section.

Figure 8 shows the same set of data for House 2, and a comparison with Figure 7 is instructive. Immediately obvious is the more scattered appearance of the straight lines to which the least-squares fit is applied in Tests 1 - 3. When the House 1 data were taken, the reported wind speeds were in the 5 - 10 mph range. The house was in a somewhat protected location, however, and the winds were not gusty. The reported wind speeds on the day that House 2 was tested were not

very different; however, they were quite gusty and variable, and they blew toward the house up an open street that runs from the waterfront up to the front of the house. Although it was fairly easy to match the actual house pressures to the target values in the tests of House 1 (to within a reasonable tolerance), for House 2 it was a struggle. Sometimes a gust would come up in the middle of taking a set of values. In order to avoid bias, when a sudden wind gust rendered it impossible to take a full set of four readings with the house pressure reasonably close to a particular target value, the entire set of data for that pressure was abandoned and a new set started.

Comparison with the Duct Blower Test of ASHRAE Standard 152P

In addition to the Delta Q results, the supply and return leakage rates in Houses 1 and 2 were also measured using the fan pressurization (duct blower) test, as specified in ASHRAE Standard 152P (ASHRAE 1999). Five tests were performed on the same day by separate testers using the same equipment.

For House 1, the results of this test were very close to the Delta Q results. (See the crosses in Figure 7D.) The supply duct pressure in Standard 152P is obtained by averaging a set of pressure-pan readings at all the supply registers. For House 1, the average pressure-pan reading was 64 Pa, which was very close to one-half of the supply-plenum pressure at zero house pressure (71 Pa, 69 Pa, and 66 Pa in Tests 1, 2, and 3, respectively), which values were used in Equation 7 for the Delta Q test.

A dominant duct leakage test was also performed on this house. In this test, the house pressure with the system fan on is compared with the value of the same quantity with the system fan off. If the fan-on house pressure is greater than the fan-off house pressure, this indicates that the return leakage exceeds the supply leakage, and vice-versa. In the House 1 dominant duct leakage tests, the average fan-on house pressure was 0.38 Pa while the average fan-off house pressure was 1.37 Pa. The one-pascal difference strongly indicates that the supply leakage is dominant, which is in agreement with both the Delta Q and the duct blower results.

The situation in House 2 is quite different. Here the agreement between the Delta Q leakage values and those obtained from the duct blower tests is poor. The Delta Q test has the supply leakage greatly exceeding the return leakage, while the duct blower tests gave nearly equal values for the leakage on each side.

There are at least two reasons to believe that the duct blower results are wrong. First, the pressure-pan readings in House 2 appeared to be anomalously high, averaging 39 Pa, while the static pressure at the supply plenum ranged from 21 Pa to 24 Pa. If one-half the supply plenum pressure is used in calculating the results of the duct blower test, instead of the pressure-pan readings, the results move from the X symbols to the + symbols in Figure 8D. The supply leakage values are now in agreement with the Delta Q results, but the return leakage values still disagree by ~100 cfm. Agreement would be spot-on if most or all of the return leakage happens to occur

at the plenum, as this would increase the calculated return leakage in the duct blower test by 50%. Of course, one cannot assume this, so it has to be considered an open question which test comes closer to the truth.

We can, however, exclude the Standard 152P duct blower results that used the pressure-pan readings. Dominant duct-leakage tests were performed on House 2. In five different tests, the fan-on house pressure exceeded the fan-off house pressure by amounts ranging from 1.01 to 2.12 Pa, with an average difference of 1.70 Pa. This is strongly indicative of dominant return leakage.

CONCLUSIONS

The theoretical and field-test results reported here are very encouraging for the Delta Q test. The following points are singled out as most important:

- The predicted results were not greatly affected by changes in the assumed duct operating pressure or by deviation in the leakage profile from that assumed in the mathematical derivation of Equation 7.
- A method for estimating the impact of measurement errors in the blower-door flow rates was developed using a Monte Carlo technique. Results using a 3% standard deviation as a benchmark gave reason for both optimism and concern.
- In tests on two houses, the average random errors in the measured flow rates ranged from 1% to 2%, well below the 3% value assumed in the benchmark analysis. At these rates, it should be possible to hold measurement errors of the blower-door flow rates to low enough values that the Delta Q test will give useful results in most cases, particularly for diagnosing existing housing, for which duct leakage rates tend to be relatively high. The Delta Q test's greatest limitations occur when duct leakage rates are low and/or when envelope leakage rates are much higher than average.
- A method was developed to estimate the probable error in the results, using only the data from a single application of the Delta Q test. Results from the two test houses were in agreement with the predictions of the method.

REFERENCES

Andrews, J.W. 1997. Error Analysis for Duct Leakage Tests in ASHRAE Standard 152P. BNL-64679, June.

ASHRAE 1999. Standard 152P: Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems. First Public Review Draft, May. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, GA.

Gaston, C. 1999. Pennsylvania State University, York, PA. Discussions at an informal seminar, January.

Walker, I. and M. Sherman 1999. Lawrence Berkeley National Laboratory, Berkeley, CA. Personal communication via Walker, September.

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