Reducing Measurement Uncertainties in Duct Leakage Testing

J. W. Andrews, Brookhaven National Laboratory

ABSTRACT

Air leakage from residential ducts accounts, typically, for about half of the energy losses in these systems. For this reason, ASHRAE Standard 152P requires that this leakage be measured. A major problem in duct leakage testing is the relatively large uncertainty in the measured values, using currently available methods. This paper presents a general approach to reducing this uncertainty, based on the use of more data than is strictly required to calculate the leakage values. This over-constrains the solution. Where the data are internally consistent, the error bar is reduced. In cases where the data are internally inconsistent (which is not rare) the error bar is not reduced significantly, but the process does produce a result that is more credible than any answer obtained from a lesser data set. In addition to reducing measurement uncertainties, the method can also be used to validate duct leakage test methods that are not over-constrained. The method is applied to published field data from projects whose aim was to validate ASHRAE Standard 152. A new duct leakage test that uses a greatly over-constrained data set is also discussed.

Introduction

One way to reduce uncertainty in scientific measurement is to devise a protocol in which more quantities are measured than are absolutely required to calculate the desired answer. For example, if one wanted to know the volume of a vessel, one could measure its physical dimensions and calculate it that way, and then fill the vessel with water and measure the water's volume by pouring it out into a graduated cylinder. The dimensional measurements and the direct volumetric measurement would then cross-check each other, and one would expect to have greater confidence in an answer that was some kind of average of the two values for the volume than in a result that depended on only one.

One problem that has to be addressed with such a strategy derives from the near certainty that the two calculated values for the desired quantity will not be exactly the same. One then has to decide how much weight to give each of them. Sometimes, instead of two completely separate values for the desired quantity, one has two test protocols whose results, when taken together, add up to more data than is strictly required, but need some disentangling to give two completely independent answers. This will generally be the case in using the data cross-check strategy in duct leakage testing.

The plan of this paper is to illustrate the over-constrained data or data cross-check strategy using components of the two duct leakage tests that are currently in ASHRAE Standard 152P (ASHRAE 1999). Then a new duct leakage test, called the Delta Q test, which uses a greatly over-constrained data set, will be discussed.

Duct Leakage Tests in ASHRAE Standard 152P

Two duct leakage tests currently are specified as options in the draft Standard 152P, Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems, which is being developed by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). One of these tests, called the **fan pressurization test** involves two steps. First, the "operating pressures" in the supply and the return duct systems are measured. The term "operating pressure" is placed in quotation marks because there is no single pressure in a working duct system. Rather, the static pressure is at a maximum (in absolute value) near the plenum and declines to near zero at the registers. The assumption of a single pressure thus is an attempt to select a likely average value representative of the system as a whole. Such an approximation may work well if the leaks are scattered throughout the duct system, but will probably entail significant errors if the leaks are concentrated either at the plenum or the register boots.

The second step in the fan pressurization test is to pressurize (or depressurize) the house with a blower door (an adjustable fan calibrated to measure air flow rate as a function of throat static pressure) to some standard pressure, such as 25 Pa. At the same time, a smaller calibrated fan (duct blower) is used to bring the pressure difference between the house and the supply or return portion of the duct system to zero. The air flow rate through the duct blower is then equal to the duct leakage rate to/from outside at the given pressure. This procedure effectively cancels leaks between the ducts and the conditioned space, leaving only those leaks that are to or from the outside to be measured.

The final step is to convert the leakage at the standard pressure to a value at the "operating pressure" through the use of the relation $Q = C\,\Delta P^n$, where Q is the leakage flow rate, ΔP is the pressure difference between the inside and the outside of the duct, and n is an exponent that in ASHRAE Standard 152P has a default value of 0.6.

An alternative duct leakage test called the **house pressure test** is also available within Standard 152P. In this test, the leakage flow coefficient of the house envelope is measured with a blower door, and this is then used as a standard against which the leakiness of the ducts is compared. The connection is made by means of the response of the pressure within the house (relative to outdoors, typically represented by a well-vented attic) when the system fan is turned on and off. If operating the system fan causes the house pressure to rise, this means that the return leakage from outside exceeds the supply leakage to outside, since a net amount of air is being taken into the duct system from outside and blown into the house. If the house pressure falls when the system fan is turned on, then the supply leakage is greater than the return leakage.

This part of the test, which is often called the **unbalanced duct leakage test**, provides a value for the signed difference between the supply and return leakage rates (i.e., an algebraic sum with supply leakage positive and return leakage negative) but it doesn't give the two values separately. To get a second equation, the house pressure test perturbs the system by partially blocking the return register enough to cause a significant shift in the pressures within the return duct. With the return blocked, the house pressure with the system fan on is again measured, and the extent to which this value is different from what it was with return register unblocked provides a second equation that yields values for supply and return leakage separately. The algorithm that accomplishes this task also requires values for the operating pressures in the supply and return ducts with the return register unblocked and blocked.

Several recent projects (Cummings, Withers, and Moyer1999; Francisco and Palmiter 1999; NAHB/RC 1999; Strunk and Shapiro 1999) have evaluated these tests and variations thereof. Although their results differ in detail, it is possible to summarize their findings as follows:

- The fan pressurization test gives accurate values for the duct leakage rates if the effective leakage pressures are known, but current methods provide only rough approximations of these pressures.
- The house pressure test does not provide repeatable duct leakage values, except possibly under a restricted set of conditions. (ASHRAE Standard 152P restricts the use of the house pressure test to situations where repeatability is expected to be adequate, i.e., there must be only one return register, the filter must be at the grille, and the measured house pressures must meet certain statistical criteria.)

There is reason to think that the part of the house pressure test with blocked return register and the uncertainty in the measured return-duct pressure are most problematic for this test (Andrews 1997). The unbalanced-leakage portion of the house pressure test may be more robust. The thought then naturally occurs: can the accuracy of the fan pressurization test be improved by incorporating the unbalanced leakage test?

Data Cross-Check Strategy in Duct Leakage Testing

In line with the above discussion, the following approach appears promising:

- Perform the <u>fan pressurization test</u> for duct leakage, giving separate values for supply leakage (Q_{sleak}) and return leakage (Q_{rleak}).
- Perform the <u>unbalanced duct leakage</u> portion of the house pressure test, that is, the measurements of the house pressure with unblocked registers and system fan on and off.

The unbalanced leakage test provides a value for the signed difference between the supply and return leakage rates ($Q_{sleak+rleak}$) without requiring any pressure measurements within the ducts themselves. It will add relatively little to the total time and effort required to do the test, but provides a significant cross-check on the result, since in the absence of errors $Q_{sleak+rleak}$ should equal Q_{sleak} - Q_{rleak}. However, because the actual measured values are almost certain to be inconsistent, to a greater or lesser degree, it is necessary to develop a rational method for assigning relative weights to the three measured quantities. Presumably this method will need to take account of the experimental uncertainties (error bars) for each of them.

The objective is to obtain values for the supply and return leakage that will use the information contained in the measured value of $Q_{sleak+rleak}$ to improve on the values of Q_{sleak} and Q_{rleak} that were measured in the fan pressurization test. Let us define the quantities $Q_{s,\,xchk}$ and $Q_{r,\,xchk}$ (the subscript xchk standing for "cross-check") to be those values for supply and return leakage that make optimal use of the available information. To begin, any candidate value for $Q_{s,xchk}$ will be expressed as a linear combination $a_1\, Q_{sleak} + a_2\, Q_{rleak} + a_3\, Q_{sleak+rleak}$, with the a's as coefficients to be determined, with any candidate for $Q_{r,xchk}$ being expressed in a similar manner with coefficients b_1, b_2, and b_3.

On the supply side, the component of return leakage in $Q_{sleak+rleak}$ should, on average, cancel out Q_{rleak} , and this requires that $a_2 = a_3$. Also, if the three measured Q's are free of systematic bias, then $a_1 + a_3 = 1$ if $Q_{s,xchk}$ is to be unbiased. These considerations, and similar ones on the return side, permit us to write:

$$Q_{s,xchk} = a\, Q_{sleak} + (1-a)\,(Q_{rleak} + Q_{sleak+rleak})$$
$$Q_{r,xchk} = b\, Q_{rleak} + (1-b)\,(Q_{sleak} - Q_{sleak+rleak}) \qquad (1)$$

In the ideal case where $Q_{sleak+rleak} = Q_{sleak} - Q_{rleak}$, any values of a and b would give $Q_{s,xchk} = Q_{sleak}$ and $Q_{r,xchk} = Q_{rleak}$, with $Q_{s,xchk} - Q_{r,xchk} = Q_{sleak+rleak}$. In all other cases, a process for selecting a and b is required. We propose to select the values of a and b that will minimize the experimental uncertainties in $Q_{s,xchk}$ and $Q_{r,xchk}$.

The values of a and b will depend on the uncertainties in $Q_{sleak+rleak}$, Q_{sleak}, and Q_{rleak}, so we need to analyze these. In dealing with experimental errors, we are considering uncorrelated random uncertainties only. Although equipment calibration errors may give rise to some correlation of the errors in Q_{sleak}, Q_{rleak}, and, to a lesser extent, $Q_{sleak+rleak}$, the major sources of error (the duct operating pressures in the fan pressurization test and the house pressures in the unbalanced leakage test) are likely to be largely independent of one another.

Let us define the experimental uncertainties as follows:

$errQ_{s,xchk}$	=	Random uncertainty in $Q_{s,xchk}$
$errQ_{r,xchk}$	=	Random uncertainty in $Q_{r,xchk}$
$errQ_s$	=	Random uncertainty in Q_{sleak}
$errQ_r$	=	Random uncertainty in Q_{rleak}
$errQ_{sr}$	=	Random uncertainty in $Q_{sleak+rleak}$

We then may write:

$$errQ_{s,xchk} = \left[a^2(errQ_s)^2 + (1-a)^2(errQ_r)^2 + (1-a)^2(errQ_{sr})^2\right]^{1/2}$$
$$errQ_{r,xchk} = \left[(1-b)^2(errQ_s)^2 + b^2(errQ_r)^2 + (1-b)^2(errQ_{sr})^2\right]^{1/2} \qquad (2)$$

To find the values of a and b that minimize the uncertainties in $Q_{s,xchk}$ and $Q_{r,xchk}$, we take the derivatives of $errQ_{s,xchk}$ and $errQ_{r,xchk}$ with respect to a and b, respectively, and set them equal to zero. This yields Equations 3:

$$a = \frac{(errQ_r)^2 + (errQ_{sr})^2}{(errQ_s)^2 + (errQ_r)^2 + (errQ_{sr})^2}$$
$$b = \frac{(errQ_s)^2 + (errQ_{sr})^2}{(errQ_s)^2 + (errQ_r)^2 + (errQ_{sr})^2} \qquad (3)$$

Inserting these values of a and b into Equation 2 yields--after some algebra--remarkably simple formulas for the uncertainties in $Q_{s,xchk}$ and $Q_{r,xchk}$:

$$errQ_{s,xchk} = \sqrt{a}\ errQ_s$$

$$errQ_{r,xchk} = \sqrt{b}\ errQ_r \qquad (4)$$

In Equations 3 the numerators and denominators are positive numbers (sums of squares), and the numerator is less than the denominator in each case. This implies that a and b are between 0 and 1, and hence the uncertainties in $Q_{s,xchk}$ and $Q_{r,xchk}$ will always be less than the corresponding uncertainties in Q_{sleak} and Q_{rleak}. This is to be expected, given the additional information provided by $Q_{sleak+rleak}$.

Application to Published Field Data

Two of the research projects cited earlier (Cummings, Withers, and Moyer 1999, with follow-on work published as Cummings and Withers 1999; Francisco and Palmiter 1999) undertook to compare measured duct leakage values with "best estimates" obtained using measurements that supplemented those of the Standard 152P protocols. Raw data from these projects were published in the final reports, so they can serve as useful testing grounds to see whether the use of the data cross-check procedure as outlined above improves the agreement between their measured duct leakage values and the "best estimates."

The first of these projects (Francisco and Palmiter 1999) measured duct leakage to/from outside in several single-family houses in the Pacific Northwest. Within each house, duct leakage configurations were varied by intentionally adding leakage area (holes) to the supply duct, the return duct, or both. For each such configuration, a "best estimate" of the actual leakage was determined on the supply side of the duct system by calculating the total leakage as the difference between total air flow through the registers (measured with a flow hood) and flow at the system fan (measured with a duct blower according to Standard 152P), and using that to obtain a refined estimate of the effective operating pressure within the duct. On the return side they used various procedures to arrive at a best estimate because their flow hood was not compatible with the larger return registers and higher flows. In about half the cases, they used data from the fan-pressurization test itself as their "best estimate" on the return side. In the other half, they first determined the unbalanced leakage as measured by the "nulling test," a new test of their invention, and then subtracted this from their "best estimate" of supply leakage.

The second project (Cummings, Withers, and Moyer 1999, Cummings and Withers 1999) studied four houses in Florida. This group obtained their "best estimates" of leakage by directly measuring (with hot-wire anemometer and/or flow hood) the leakage at the locations where holes were added to the ducts for the various leakage configurations. For configurations with added leaks, this meant that the majority of the leakage was directly measured, while the residual leakage (present in the as-found system) was estimated using the fan-pressurization technique. Because this residual leakage was now a small fraction of the total leakage, a large percentage error in the residual leakage results in a much smaller percentage error in their "best estimate."

Assuming that the "best estimate" values for duct leakage in these two projects are, on average, closer to the true values than the results of any single duct leakage test, it should be possible to assess the merit of the data cross-check approach by seeing whether it gives values of duct leakage that are closer to the "best estimate" values than the fan pressurization test alone provides.

Because the full-blown house pressure test is not generally applicable, the approach here has been to use the published fan-pressurization duct leakage results as a baseline, and then to investigate whether the unbalanced-leakage information from the house pressure test would add value to these results.

The next two figures are expressed in terms of "deviations." Here, a deviation is defined as the difference (in absolute value) between a leakage quantity obtained using a given measurement technique and the value for the same quantity using the "best estimate" value. The smaller the deviation, the closer the measurement technique is to the "best estimate."

In Figure 1, the parameter that is plotted is the absolute value of the difference between the unbalanced leakage obtained using the test in question and the unbalanced leakage obtained using the "best estimate" leakage values. That is:

$$X = \left| (Q_{sleak+rleak})_{house\,pressure\,test} - (Q_{sleak} - Q_{rleak})_{best\,estimate} \right|$$

$$Y = \left| (Q_{sleak} - Q_{rleak})_{fan\,pressure\,test} - (Q_{sleak} - Q_{rleak})_{best\,estimate} \right| \qquad (5)$$

Put in a slightly different way, Figure 1 compares the ability of the house pressure test and the fan pressurization test to return accurate values for the unbalanced leakage, i.e., the difference between the supply and return leakage rates. In the house pressure test, this is $Q_{sleak+rleak}$. For the fan pressurization test, it is the difference $Q_{sleak} - Q_{rleak}$. In each case, it is the deviation or absolute value of the difference between this quantity and the "best estimate" value that is plotted. If a point is below and to the right of the 45-degree line, it means that the fan pressurization test was closer to the "best estimate," while if a point is above and to the left of the 45-degree line, it means that the value of $Q_{sleak+rleak}$ from the house pressure test was closer to the "best estimate."

Most of the points in Figure 1 fall within the region bounded by the two dotted lines above and below the 45-degree line. For these, less than 50 cfm separated the two deviations, i.e., they scored fairly closely on being able to return a good value for the unbalanced leakage. However, the points outside this region are overwhelmingly situated in the upper-left region (13 points) rather than the lower-right portion of the chart (3 points). This means that the house pressure test gave better values for the unbalanced leakage than the fan pressurization test, by a 4-to-1 margin, for those cases where one test was significantly better than the other. Even if the unbalanced leakage values from the house pressure test results were only just as good as those from the fan pressurization test, one could still argue that they would add value to the overall result, for the same reason that measuring a given quantity one more time reduces the random uncertainty in the mean value. The fact that the house pressure test values look better is even stronger motivation for including them in some kind of comprehensive calculation procedure.

It should be noted that the $Q_{sleak+rleak}$ values used an envelope leakage flow coefficient that either excluded or corrected for the effect of duct leakage area. The flow coefficients of

Cummings, Withers, and Moyer 1999 were measured with sealed registers. Those of Cummings and Withers 1999 were measured with registers unsealed, but with relatively small duct leakage, because the as-found system (without added leakage) was relatively tight. Francisco and Palmiter measured the envelope flow coefficient with unsealed registers for each individual test, so we applied the correction in ASHRAE Standard 152P, Equation D-11. The neutral-level shift correction of Equation D-9 or D-10 was not applied, because this correction has never been subjected to experimental verification nor has its derivation been published.

Having established the value of a "second opinion" from the unbalanced leakage portion of the house pressure test, it remains to test the data cross-check solutions themselves against the fan- pressurization test results. This comparison is shown in Figure 2. This figure looks very similar to the previous one, so an explanation of the difference is in order. Figure 1 compared the unbalanced leakage rates from each of the two tests in ASHRAE Standard 152P against the unbalanced leakage values obtained using the "best estimates" from the projects in the data base. Figure 2 compares the values of supply and return leakage from the fan-pressurization test with the values obtained using the data cross-check procedure. The parameter that is being compared here is the sum of the absolute value of the difference between the supply leakage value from the test in question and the "best estimate" value, and the absolute value of the difference between the return leakage value from the test in question and the "best estimate" value. That is,

$$X = \left| (Q_{sleak})_{data\,cross\text{-}check} - (Q_{sleak})_{best\,estimate} \right| + \left| (Q_{rleak})_{data\,cross\text{-}check} - (Q_{rleak})_{best\,estimate} \right|$$

$$Y = \left| (Q_{sleak})_{fan\,pressure\,test} - (Q_{sleak})_{best\,estimate} \right| + \left| (Q_{rleak})_{fan\,pressure\,test} - (Q_{rleak})_{best\,estimate} \right| \quad (6)$$

The data cross-check procedure requires that the uncertainties in Q_{sleak}, Q_{rleak}, and $Q_{sleak+rleak}$ be estimated. The following guidelines were used: 30% uncertainty in Q_{sleak} and Q_{rleak}, and 50 cfm - 70 cfm uncertainty in $Q_{sleak+rleak}$ (following Andrews 1998), representing an approximate one-standard deviation probable error.

As in Figure 1, most of the points fall in a narrow band on either side of the 45-degree line, meaning that, in most cases, adding the unbalanced leakage value from the house pressure test did not have a large effect on the goodness of the result. However, in the minority of cases where it did make a significant difference, the instances where the data cross-check procedure improved the result exceeded by an 8-to-1 margin the single case where it made the result worse. The probability of the margin being this lopsided by chance is less than 2% (binomial distribution, one-tailed test).

If the data used in this study are representative of duct systems generally, then the unbalanced leakage portion of the house pressure test appears to be a useful "reality check" that can in many cases significantly improve the results of the fan pressurization test without running much risk of degrading the results in any important way.

The Delta Q Test

Recently, researchers at a 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 by a university researcher (Gaston 1999). This test makes extensive use of the strategy of over-constraining the solution. 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 values of the house pressure (with respect to outside) ranging from -25 Pa to +25 Pa in 5-Pa increments. There are arguments for excluding the zero-pressure point (Andrews 2000), so the number of data sets is either 10 or 11. 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 these ten or 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 mathematical assumptions underlying the Delta Q test lead to the following equation (Walker and Sherman 1999):

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

where ΔQ is the difference between the blower-door air flow rates with the system fan on and the system fan off, with flows into the house considered positive; ΔP is the pressure in the house (induced by the blower door) relative to outside; ΔP_s and ΔP_r are the pressures in the supply and return ducts, respectively, at which the leakage is assumed to occur. (Both ΔP_s and ΔP_r are defined to be positive.) These are all measured quantities, with the exception that ΔP_s and ΔP_r are assumed to equal some representative fraction of the measured pressures at the supply and return plenums under normal operation. The quantities Q_s and Q_r are the supply and return leakage rates to/from outside under normal operation. These being the only two unknowns in the equation, each measurement provides a straight line in the Q_s - Q_r plane. Under ideal conditions, the lines from all the measurements will converge at a single point. Under real test conditions, in which the mathematical assumptions may not hold exactly and in which the blower-door air-flow measurements are subject to experimental error, a least-squares fit is required to obtain the best compromise leakage values.

Tests of the Delta Q procedure were carried out in two houses on Long Island, New York. House 1 is a 1-1/2 story Cape Cod dwelling with a total conditioned floor area of 1115 ft^2. The supply and return duct systems are constructed of uninsulated sheet metal, and most of the ducts are in an uninsulated, unfinished basement. Total duct surface area is 346 ft^2, 80% of which is on the supply side. There are 11 supply registers and two return registers. The house is heated with a gas furnace. No comfort cooling is used at present. The system fan flow rate was measured as 680 cfm. The envelope leakage rate was measured as ~17 ACH50.

House 2 is a 1-story dwelling with a total conditioned floor area of 729 ft^2. The supply and return duct systems are constructed of sheet metal insulated with R-4 duct wrap, and most of the ducts are in an uninsulated, unfinished basement. Total duct surface area is 318 ft^2, 70% of which is on the supply side. There are six supply registers and one return register. The house is heated by a gas furnace and has central air conditioning. The system fan flow rate was measured as 910 cfm. The envelope leakage rate was measured as ~25 ACH50. Both houses thus are fairly small and have leaky envelopes with conventional equipment and simple duct systems.

Delta Q Test Procedure

To perform the Delta Q test, a blower door was set up in an exterior doorway of the house. To mitigate the effects of wind gusts, a manifolded system was used to average outside ambient pressures on the four sides of the house. Three plastic tubes were run from the living space to the vicinity of the air handler, underneath a closed door separating the conditioned space from the basement. One of these was connected to a static 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 outside was left open. The reason for this was so that the mathematical assumptions underlying the equations for the Delta Q test 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 are 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 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 Delta Q test equation 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.

Figures 3A, 3B, and 3C show the three least-squares fits for House 1. The straight lines are the solutions of Equation 7, and they appear as two tightly knit clusters of five lines each, one representing the pressurization tests and the other the tests under depressurization. Figure 3D shows the three least-squares solutions from Figures 3A - 3C, 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 ~40 cfm or ~20% of the measured value. As a percentage of system fan flow the shift is ~6%. The absolute shift for the return leakage, caused by adjusting the duct pressures by a factor of two, is similar to that for the supply leakage, but of course on a percentage basis it is much larger. Distribution efficiency is affected by changes in the leakage as a fraction of system fan flow, not as a fraction of the leakage rate itself, so a large percentage uncertainty in a small leakage rate is not necessarily significant.

Figure 4 shows the same set of data for House 2, and a comparison with Figure 3 is instructive. Immediately obvious is the more scattered appearance of the straight lines to which the least-squares fit is applied, as shown in Figures 4A, 4B, and 4C. 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 door 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. The scatter of Delta Q results and the shift caused by doubling the assumed leakage pressures are similar to what was observed in House 1.

It has been suggested (Nelson 2000) that to improve accuracy the house pressure should be measured at the neutral level, not necessarily at the blower door. The impact of this variable should be explored in future work on the Delta Q test.

Comparison of the Delta Q Test with the Fan Pressurization Test and Data Cross-Check

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. 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 shaded circles in Figure 3D.) 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.

The unbalanced-leakage portion of the house pressure test was also performed (once) on this house. The value of $Q_{sleak+rleak}$ obtained from this test was 110 cfm, reasonably consistent with the average supply and return leakage rates (227 cfm and 60 cfm, respectively) from the fan pressurization test. The data cross-check procedure therefore gave only slightly different values for supply and return leakage from those supplied by the fan pressurization test alone (Figure 3D). The error bars shown for the data cross-check result reflect an estimated 30% uncertainty in the fan-pressurization results and a 50 cfm uncertainty in the value of $Q_{sleak+rleak}$.

The situation in House 2 is quite different. Here the agreement between the Delta Q leakage values and those obtained from fan pressurization is poor (Figure 4D). The Delta Q test has the supply leakage greatly exceeding the return leakage, while the fan pressurization tests gave nearly equal values for the leakage on each side.

Incorporation of the unbalanced leakage portion of the house pressure test via the data cross-check procedure causes a significant modification of these results. The unbalanced leakage test was performed five times, by each of the five testers in the fan pressurization round robin. The values of $Q_{sleak+rleak}$ ranged from -70 cfm to -213 cfm, averaging -157 cfm. The data cross-check values for Q_{sleak} and Q_{rleak} are therefore closer to the Delta Q results, sufficiently so that they can no longer be said to be inconsistent, though not in perfect agreement.

There is one additional reason to mistrust the fan pressurization results in House 2. The pressure-pan readings appeared to be anomalously high, averaging 39 Pa, while the static pressure at the supply plenum ranged from 21 Pa to 24 Pa. Lowering the value of the operating pressure in the supply ducts would, of course, reduce the estimated supply leakage and move the fan-pressurization data points closer to the Delta Q results.

Summary and Conclusions

This paper has explored duct leakage test methods that make use of more data than are strictly required to obtain solutions for supply and return leakage. If the additional data are taken from a procedure (e.g., the unbalanced leakage portion of the house pressure test) that is unrelated to the one used for the basic data set (e.g., the fan-pressurization test), it may provide a robustness in the results that will enhance reliability even in the face of circumstances that can often skew the basic data set. Published field data from two recent projects were used to show that the data cross-check procedure improves some of the measured data and leaves the rest largely unaltered. It thus appears to be a valuable quality-control measure that does not require very much additional time to do.

In the Delta Q test, the procedure used to take the redundant data is the same for all 10 or 11 data sets, but because the degree of over-constraint is so high (10 or 11 equations, 2 unknowns) good repeatability may be expected despite conditions that may significantly skew the data used to obtain any given equation in the set. Field data from two houses on Long Island were used to relate the Delta Q test, the fan-pressurization test, and the data cross-check procedure. In one of these houses, the data from all tests agreed. In the other, although the fan-pressurization and Delta Q results did not agree, the data cross-check procedure removed half of the deviation and moved the results within the error bars of one another. On the basis of these limited results, the Delta Q test appears promising, and further field validation research is recommended.

References

Andrews, J.W. 2000. *Measurement Uncertainties in the Delta Q Test for Duct Leakage.* Brookhaven National Laboratory, Upton, N.Y., draft report in press.

Andrews, J.W. 1998. *Error Reduction in Duct Leakage Testing Through Data Cross-Check.* BNL-66147, Brookhaven National Laboratory, Upton, N.Y.

Andrews, J.W. 1997. *Error Analysis for Duct Leakage Tests in ASHRAE Standard 152P.* BNL-64679, Brookhaven National Laboratory, Upton, N.Y.

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

Cummings, J., C.R. Withers, Jr., and N. Moyer. 1999. *Field Research to Verify Duct Air Leakage Measurements and Distribution Efficiency Computations of ASHRAE Standard 152P.* FSEC-CR-1083-99. Florida Solar Energy Center, Cocoa, Fla.

Cummings, J. and C.R. Withers, Jr. 1999. *Assessment of the Duct Leakage Estimation Procedures of the Standard and Alternative Test Methodologies of ASHRAE 152P.* FSEC-CR-1135-99. Florida Solar Energy Center, Cocoa, Fla.

Francisco, P. W. and L. Palmiter. 1999. *Field Validation of ASHRAE Standard 152.* Final Report, ASHRAE Project 1056-RP. Ecotope, Inc., Seattle, Wash.

Gaston, C. (Pennsylvania State University) 1999. Personal communication to author. February.

NAHBRC. 1999. *Results of Diagnostic and Thermal Duct Testing in Three New Houses.* Final Report. NAHB Research Center, Inc., Upper Marlboro, Md.

Nelson, G. (Energy Conservatory, Inc.). 2000. Personal communication to author. March.

Strunk, P.R. and I.M. Shapiro. 1999. *Standard 152P Validation: Final Technical Report.* SYN-TR-99-522. Synertech Systems Corporation, Syracuse, N.Y.

Walker, I. and M. Sherman (Lawrence Berkeley Laboratory). 1999. Personal communication to author. October.

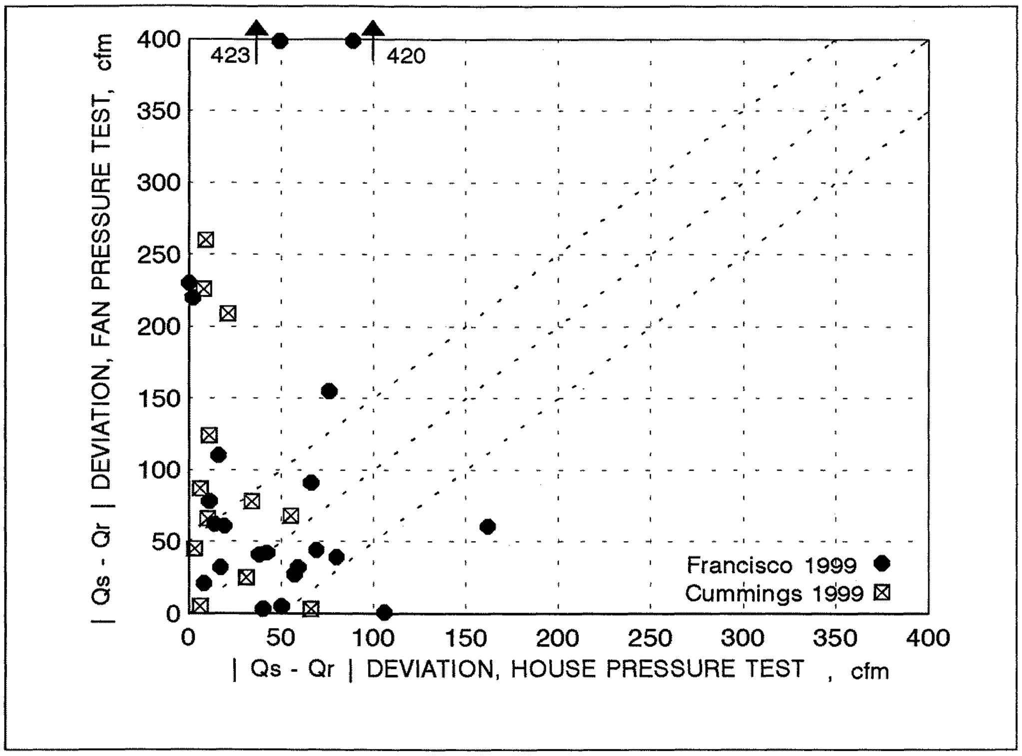

Figure 1. Unbalanced Leakage Deviations from Best Estimates

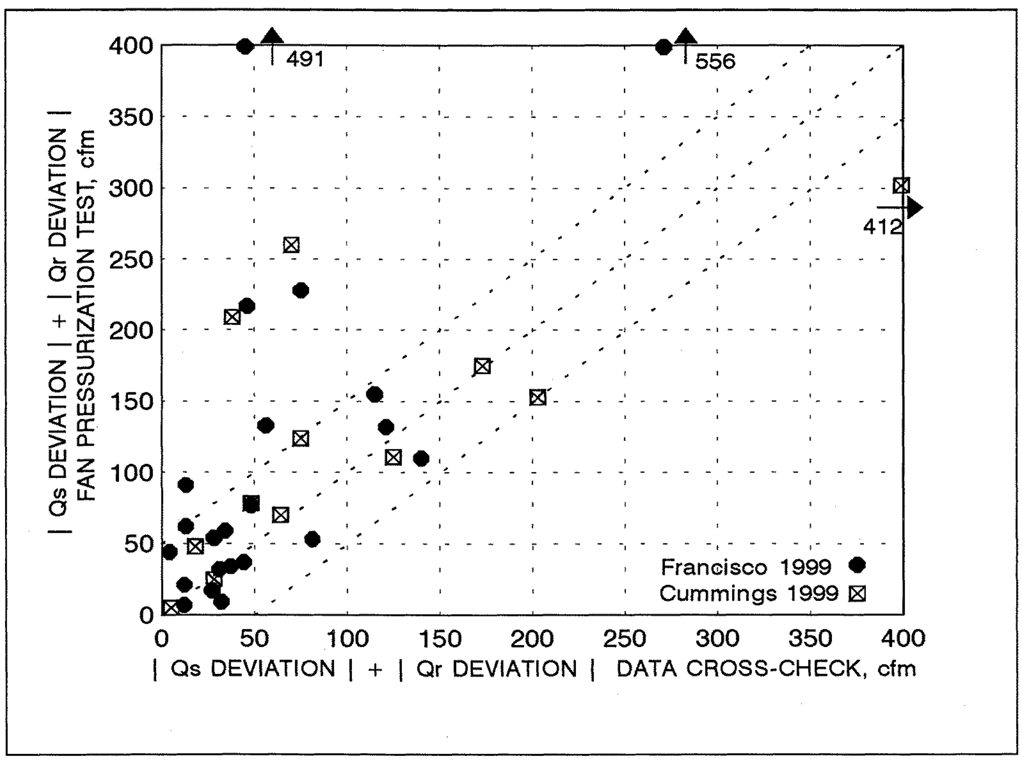

Figure 2. Total Deviations of Supply and Return Leakage from Best Estimates

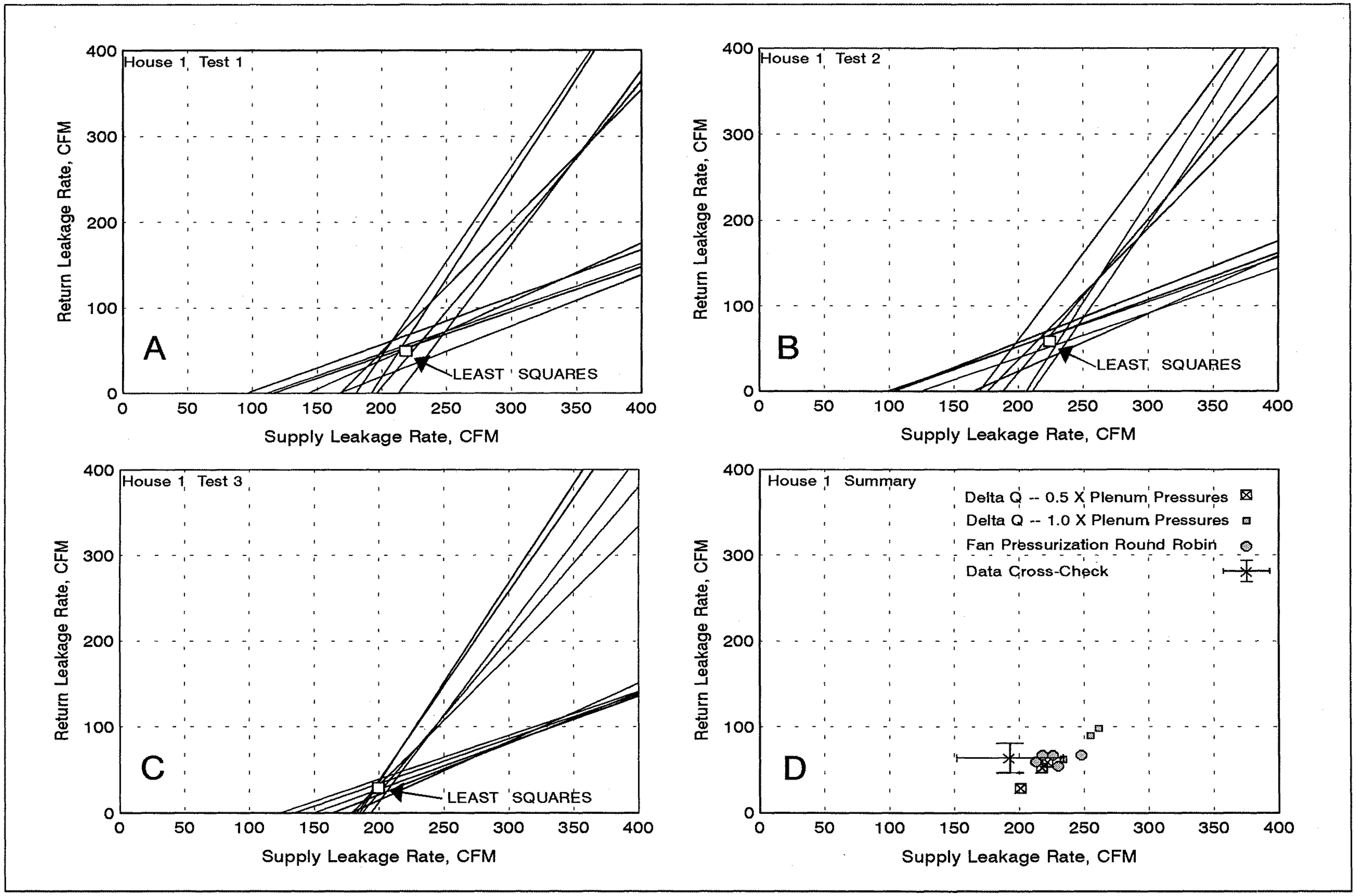

Figure 3. Test Results for House 1 (Long Island, New York)

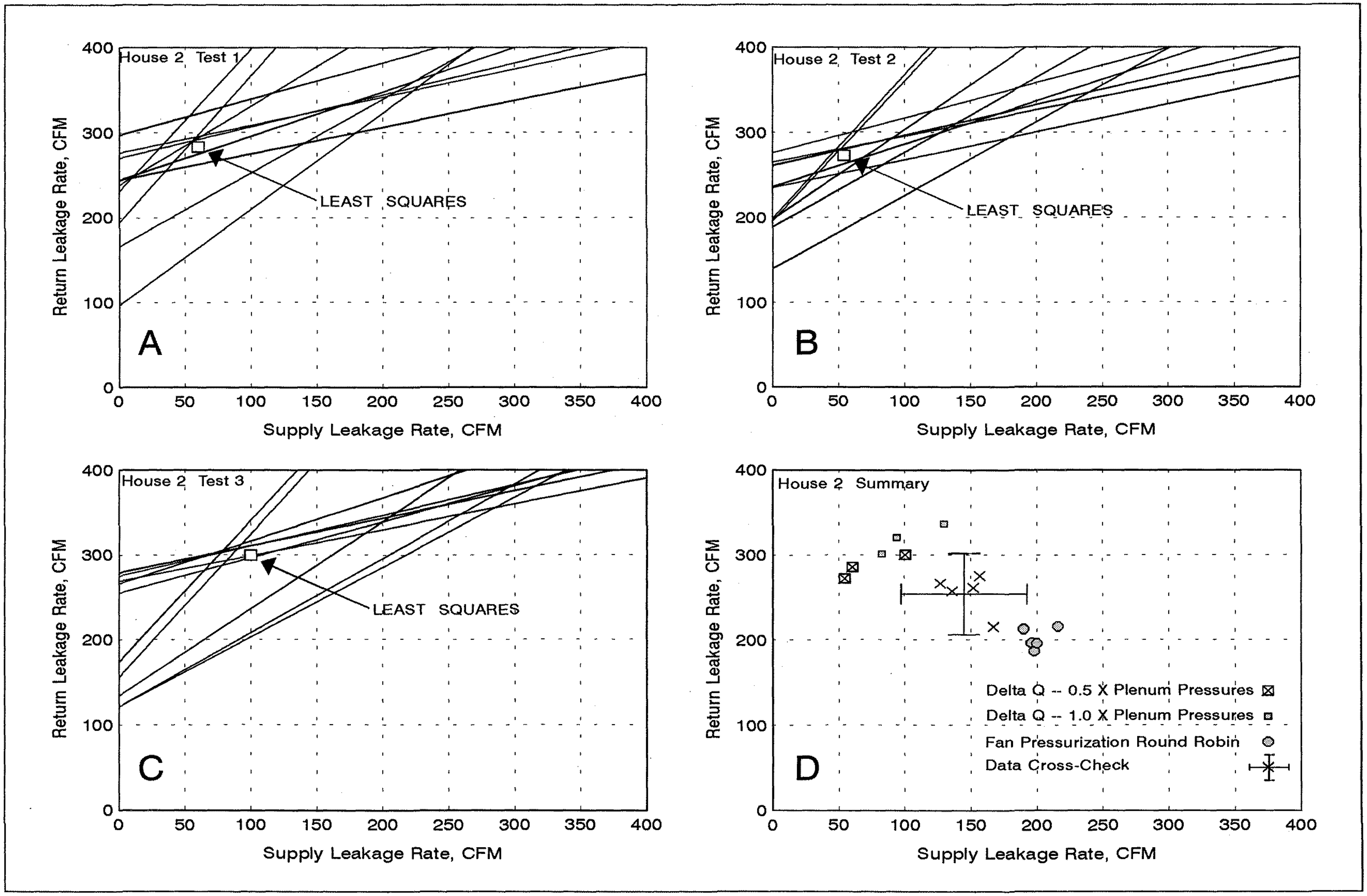

Figure 4. Test Results for House 2 (Long Island, New York)