# Field Performance of Two New Residential Duct Leakage Measurement Techniques

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## ABSTRACT

Duct leakage is recognized as a major source of energy losses in residential buildings, and one of the most important parameters for estimating duct efficiency. However, quantifying duct leakage has proven to be extremely difficult. Several methods of estimating duct leakage have been used over the past several years, with varying degrees of accuracy. More recently, two new methods have been proposed: the "nulling test" and the "Delta-Q test". The nulling test uses a calibrated fan/flowmeter to counteract the pressure change across the envelope due to duct leakage. The Delta-Q test uses the difference in blower door flows at each of several envelope pressure differences with the air handler on and the air handler off to estimate duct leakage. One of the advantages to both of these methods is that they measure leakage at approximately operating conditions and with the air handler fan running, not at an artificial static pressure. This paper presents a summary of results of a study in which these new duct leakage measurement techniques were compared to the results using the more common and established duct pressurization test and benchmarked against a "best estimate" of leakage using air handler flow and register flows. The project included 73 tests covering 26 duct leakage configurations in 9 homes. In addition to a brief description of the two new tests, the paper includes discussions of both accuracy and repeatability, as well as the ease with which the tests can be performed.

## Introduction

The thermal efficiency of forced-air distribution systems in residential buildings has been the focus of substantial research and many utility programs for more than a decade (see Robison and Lambert 1988; Modera 1989; Parker 1989; Cummings et al 1990; Olson et al 1993; Palmiter, Olson, and Francisco 1995; Jump, Walker, and Modera 1996; Siegel et al 1996; and Davis et al 1997 for a sampling of previous work on this subject). This work has shown that ducts can lose a significant amount of conditioning energy via leakage and heat transfer. Mathematical models have been developed to estimate the thermal efficiency of ducts from several measured parameters. One such mathematical model has become the foundation for the proposed ASHRAE Standard 152P (ASHRAE 2001).

Accurate efficiency estimates from these models require accurate inputs. Two of the most important parameters of duct efficiency are supply duct leakage to and return duct leakage from outside. For supply leakage, the percentage error in the leakage estimate corresponds very closely to the percentage error in the efficiency estimate. Unfortunately, these have also proven to be two of the most difficult inputs to measure accurately. Several methods have been used, with varying degrees of success. The current draft of ASHRAE Standard 152P stipulates that the fan pressurization test be used to measure duct leakage.

The duct pressurization test can be very time-consuming due to the setup requirements, and the results can be extremely poor. The test is run at specified pressures that may not be representative of the operating conditions of the duct system, so it is necessary to estimate an "operating" pressure for use in conjunction with the results of the test. Unfortunately, as there is no rule-of-thumb that routinely works well, any pressure estimate may still be significantly poor at providing an accurate measure of the leakage, sometimes off by a factor of two or more. As a result, there has been a lot of effort put into developing new and better ways to measure duct leakage, both from an accuracy standpoint and in terms of the time required to perform the test.

Two such candidates have recently been developed, both of which purport to measure leakage to outside at actual operating conditions. These two are referred to as the nulling test and the Delta-Q test. The nulling test uses a calibrated fan/flowmeter in the building envelope to counteract any change in building pressure due to turning on the air handler. Since any change is nominally due to unbalanced duct leakage, the flow through the calibrated fan is the unbalanced duct leakage. In order to account for inexact matching of the target pressure, data are collected at three pressures, one at a higher pressure, one at a lower pressure, and one at a pressure close to the target pressure. The higher and lower pressures are typically about 0.5-1.0 Pascals (Pa) different from the target, which is also typically ±2 Pa. House pressure changes due to unbalanced duct leakage are usually less than 2.0 Pa, although in cases of large unbalanced leakage the pressure changes can be larger. The pressure-flow pairs should lie approximately on a straight line, and a regression can be used to estimate the leakage at the target pressure. This test is sensitive to wind, and even modest winds can cause fluctuations in pressures that are significant relative to the pressures being measured. This problem can be largely addressed by using longer sampling times unless wind speeds become very high.

The assumption of a straight line fit will not be exact if the power law function describing the pressure-flow relationship of the home holds to the low pressures measured; however, the small changes in pressure between points allow a straight line fit to make a reasonable approximation of the curve. If the three pressures cover a span of about 1.0 Pa, the error caused by not using an exponent of 0.65 (commonly assumed for houses) will be on the order of 2% for a change in pressure of about 1.0 Pa and on the order of 0.2% for a change in pressure of about 3.0 Pa.

The nulling test is essentially performed twice. The first is with the duct system running normally; the second is with the return ducts isolated through the use of an airtight barrier between the supply and return systems and with a second calibrated fan attached to the air handler cabinet as a surrogate return. The first test gives unbalanced duct leakage, the second test gives supply leakage, and from these two the return leakage can be calculated. This test can be as time-consuming as the fan pressurization test, but does not require any equations or complicated model assumptions other than fan calibrations and a single subtraction. See Francisco and Palmiter (2001) for a more detailed description of this test.

The Delta-Q test uses a blower door to pressurize and depressurize the house at ten different envelope pressure differences, -25 Pa to +25 Pa in 5 Pa increments (skipping 0 Pa) with and without the air handler on. The differences between the flows through the blower door with the air handler off and with the air handler on at each pressure difference are regressed on the pressure differences using a set of equations to produce estimates of the supply and return leakage. This test is simple and fast, but requires complex equations and a set of assumptions about the ducts and house. See Walker et al (2001a) for a more detailed description of this test.

This paper summarizes the results of a research project funded by ASHRAE with cofunding from the United States Department of Energy in which the duct pressurization test, the nulling test, and the Delta-Q test were all tested in the field at several homes (Francisco, Palmiter, and Davis 2002). Accuracy, repeatability, difficulty, and time requirements were all evaluated.

## Methodology

Tests were performed at nine homes. These homes were all single-story and built over a crawl space. In order to get as much information as possible in as few homes as possible, each home was tested with three different levels of duct leakage. These were often as-found, with a supply leak added, and with a return leak added, although in some cases an existing leak was sealed or some other change was made to alter the leakage. Added leaks often took the form of a disconnect at either the boot or at the plenum since these leaks provide a fast way to get a significant change in leakage. While these types of leaks are not found in every home, they are not rare, and represent very common forms of catastrophic leakage. Tests were also repeated three times to assess repeatability.

Data was collected using custom software connected to a pressure datalogger. This datalogger also allowed the measurement of wind speed and several temperatures, including indoor and outdoor temperatures. The software automated much of the testing.

### The “Best Estimate” Reference Method

In order to evaluate the accuracy of the test methods, an independent estimate was made using the difference between air handler flow and the sum of register flows, with a correction made using fan pressurization tests with and without a blower door operating to account for leakage to inside. We do not claim that the predictions using this method are exact. However, in order to assess the accuracy of these proposed methods, an independent method is required that actually estimates leakage at operating conditions. As there is no quick, simple, exact method of evaluating duct leakage in field situations (indeed, if there was there would be no need for these new tests) we are relegated to using an estimate that is the “best” that we believe we can do, and does not have any particular bias.

This method is not a reliable method in general, in part because commercially available flow hoods are not sufficiently accurate on residential supply registers. This is shown in Walker et al (2001b), which describes the sensitivity of flow hoods to flow hood positioning and outlet conditions (e.g. jets, swirl, etc.). However, this same report shows that the flow hood used in this project (labeled in the report as Hood 1 and no longer commercially available) is quite good when centered over a grille with open dampers if the grille does not induce much swirl (see Figure 6 of the report). Having the grille all the way to the edge of the flow hood only made a significant percentage impact at low flows, which results in only a small volumetric flow error. Calibrating the flow hood can improve the results even further. In addition, when used in the field at one house by technicians trying to get as good an estimate as possible, Walker et al (2001b) found that the overall flow errors from this hood were extremely small, on a par with powered flow hoods. There were significant percentage errors on individual registers, but these errors were typically largest for smaller flows, again causing only a small volumetric flow error. The signs of the errors were also mixed, suggesting that much of the error when used in the field is random and will cancel out over a number of registers.

The flow hood was calibrated prior to the project. In addition, the types of floor registers typically found in Pacific Northwest homes do not tend to induce swirl, and we centered the flow hood over the registers as well as we possibly could. We have used this method previously in projects where good duct leakage estimates were required in order to make duct efficiency estimates using a mathematical model, with the resulting agreement with measured duct efficiencies being very good (e.g. Francisco and Palmiter 1999).

## Results

The results are expressed as a fraction of the air handler flow. This was done to normalize the results for more direct comparability across houses. We stress that these results can only be applied to these homes, both because the sample is small and because the nature of the leaks is not random. It is possible that the nature of some of the added leaks represent cases that are difficult for one or more test methods to handle, in which case those methods would look to perform worse in this paper than they do in general. There is no reason that we expected a priori that any particular leakage type would present a specific problem to any test, but that does not eliminate the possibility. If it is the case that some methods are particularly sensitive to some types of leaks, that warrants further study of these methods with a goal of improving the predictions for those situations.

### Supply Leakage Results

Figures 1, 2, and 3 compare the supply leakage fraction estimates from the nulling test, Delta-Q test, and fan pressurization test, respectively, with the best estimate. The line indicates perfect agreement.

**Nulling test**. Figure 1 shows that the nulling test tends to follow the best estimate fairly well, although there is a significant amount of scatter and a small amount of bias, with the nulling test tending to overestimate the leakage by about 1.8% of air handler flow. The root-mean-square (RMS) error, which captures both bias and scatter, was 5.8% of air handler flow relative to the best estimate.

There are also a few negative supply leakage fraction estimates from the nulling test. This can occur for a variety of reasons. One is noise due to wind. Another is instrument uncertainty. There is also the problem that holes in the ducts can impact the neutral level of the building when the air handler is off, thereby changing the pressures across the envelope during the measurement of the reference pressure compared to what it would be with no ducts. If the duct leakage that is being measured is small (such as the negative supply leakages in Figure 1), but there are large holes in the duct system (e.g. around boots or in the return) this effect can cause an error larger than the actual leakage, resulting in a sign error.

Yet another possible cause of negative leakage estimates is a change in stack pressure of the building due to greatly changing temperatures. If temperatures in the building change significantly during the nulling test, matching the pressure at a specific point across the envelope will not match the neutral level, unless the measurement location was at the neutral

**Figure 1. Comparison of Supply Leakage Fraction Estimate from Nulling Test to that from Best Estimate. The Line Indicates Perfect Agreement**

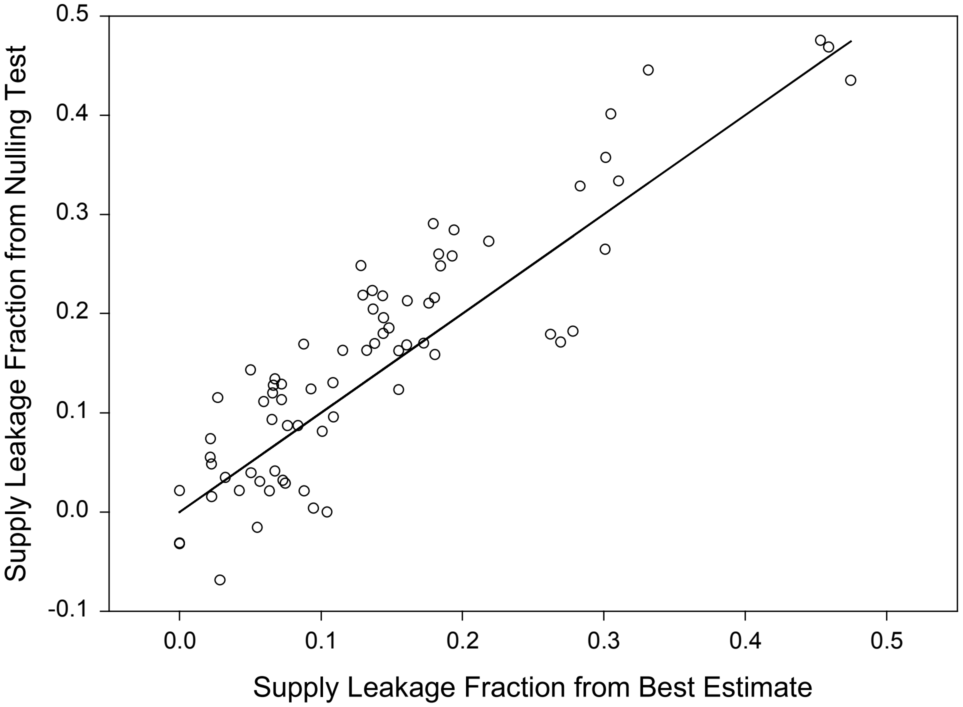


**Figure 2. Comparison of Supply Leakage Fraction Estimate from Delta-Q Test to that from Best Estimate. The Line Indicates Perfect Agreement**

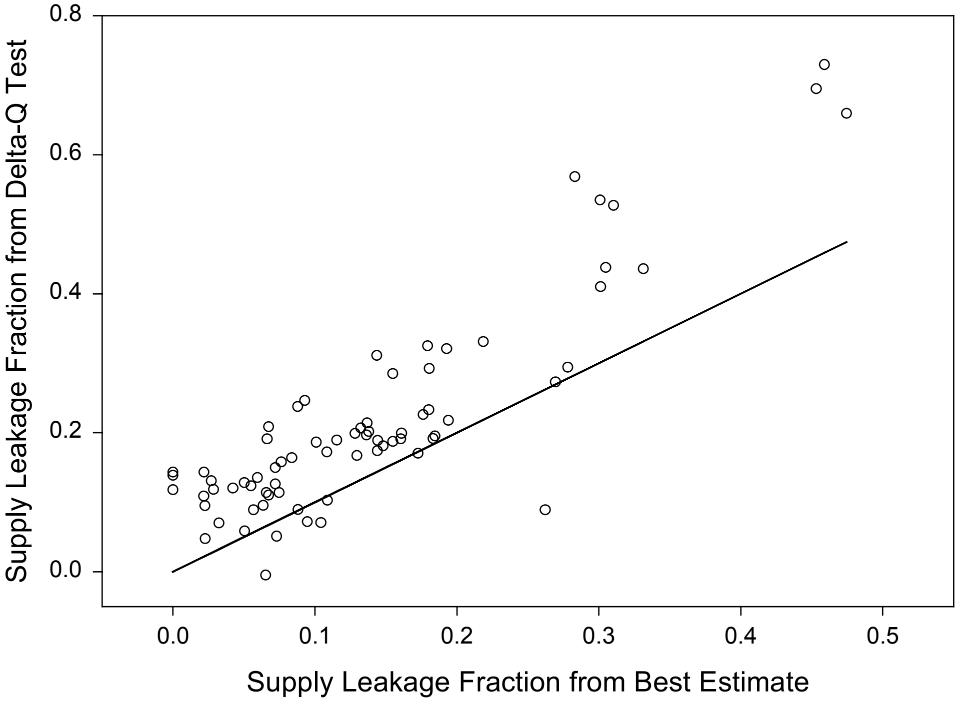
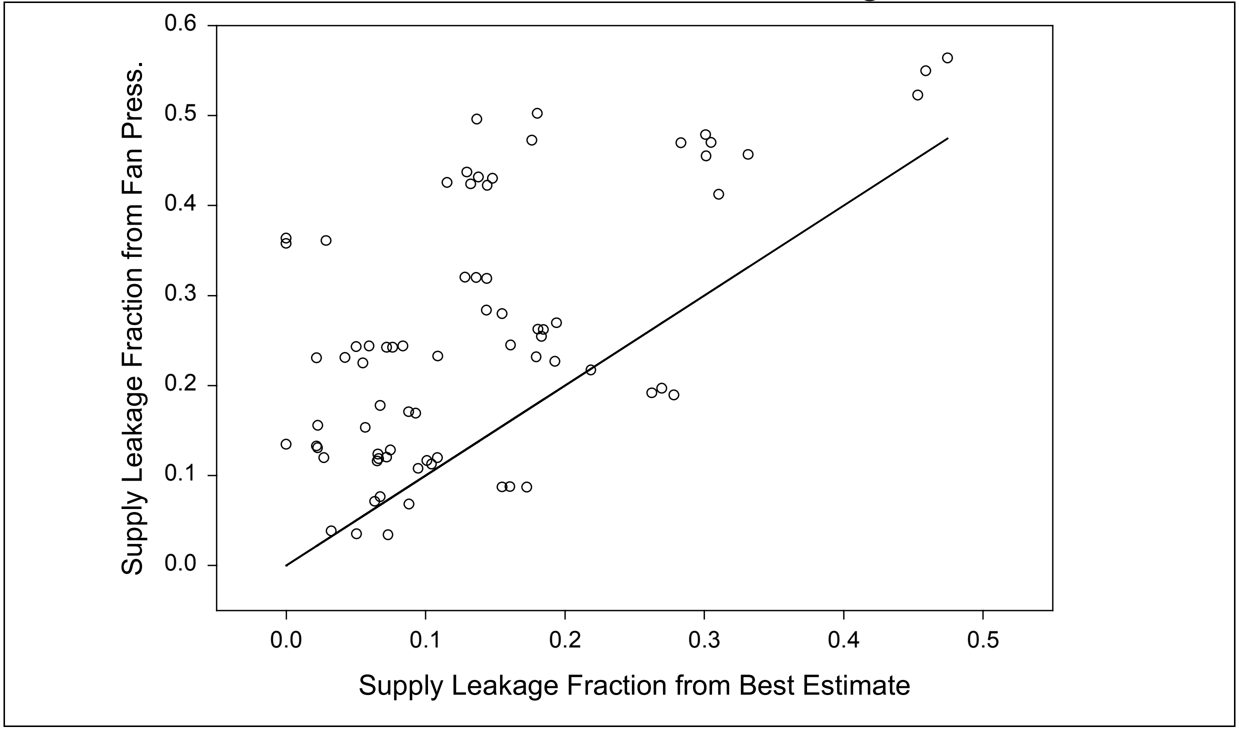


**Figure 3. Comparison of Supply Leakage Fraction Estimate from Fan Pressurization Test to that from Best Estimate. The Line Indicates Perfect Agreement**



level. This means that the pressure distribution will not be what it was when the air handler was not operating, i.e. the building will be pressurized or depressurized rather than returned to its original state. For example, if the stack pressure was 1.0 Pa initially with the neutral level at the middle of the building (making the pressure at the floor –0.5 Pa and the pressure at the ceiling 0.5 Pa when the air handler is off), but due to changing temperatures the stack pressure went up to 1.4 Pa by the end of the test (making the pressure at the floor –0.7 Pa and the pressure at the ceiling 0.7 Pa when the air handler is off), nulling out the pressure change due to running the air handler such that the pressure across the floor is –0.5 Pa does not put the neutral level back to the same location. In this case, the building is still slightly pressurized.

**Delta-Q test**. Figure 2 shows that the Delta-Q test has a much more significant overestimation bias compared to the best estimate, although it does show a strong correlation with the best estimate. The majority of cases that do not show an overprediction are at low leakage levels. The bias is about 7.6% of air handler flow and the RMS error is about 10.6% of air handler flow.

One cause of this bias is the assumption that the pressures in the ducts remain constant relative to the house throughout the range of pressures in the test. This assumption should be true if there is no duct leakage or if the ducts are all inside the house; however, when there is significant duct leakage to outside this assumption breaks down. In some field test cases, the pressure between the ducts and the house changed by more than a factor of two over the range of pressures in the test. Modeling a simplified case using CONTAM confirmed that the pressures between the ducts and the house would exhibit this type of behavior and that the effect would be to overestimate the supply leakage. The exact magnitude of this effect is unknown, but it does warrant further investigation with the possibility of leading to a revision of the analysis technique to address the problem.

Another cause of the bias may be the types of leaks. Added leaks, especially on the supply side, were often made by disconnecting a supply duct. In five homes this was done at the boot, and in four of these the pressure at the leakage site was very low. There were also two disconnects made at the air handler end of the duct at which pressures are high. Further work done on the Delta-Q test has indicated that the analysis technique may break down at low pressures (Walker et al 2001a). It may be, therefore, that the magnitude of overestimation shown in this study is itself biased by the nature of the leaks. Further work will shed additional light on this question.

It has been suggested that an additional flaw in the analysis of the cases with disconnects is the use of 0.6 as an exponent, on the grounds that disconnects have exponents closer to 0.5. While it is true that disconnects behave in this fashion, the argument for changing the analysis technique only holds if this is the only leakage in the system. Especially on the supply side, where the flow through a single disconnected duct may only be 80 cfm (or less), the leakage through the disconnect may be only a fraction of the total leakage and the overall exponent can be significantly higher than 0.6. An investigation of the leakage exponents calculated from fan pressurization tests in the cases where there was a supply disconnect shows that the exponent does go down compared to cases without disconnects, about 0.59 compared to about 0.62 (either expressed as a mean or a median). The minimum for both groups was about 0.535. These results, combined with the fact that the nature of the leaks is not generally known in advance of performing the test, supports the use of the 0.6 exponent assumption for all cases.

**Fan pressurization test**. The fan pressurization test in Fig. 3 also shows a tendency to significantly overestimate the leakage fraction, and it also has much more scatter than either the nulling test or the Delta-Q test. This is because the standard assumption that half of the plenum pressure is approximately the pressure across the leaks under normal operation is usually incorrect but is not incorrect in a uniform manner. The fact that the leakage estimates tend to overpredict the leakage indicates that half of the plenum pressure is typically higher than operating pressures across the leaks. In these homes, the supply plenum pressure averaged about 49 Pa for those cases without an added supply disconnect compared to average estimated operating pressures of about 9 Pa. The half-plenum assumption actually held more closely for those cases with disconnects on average, with plenum pressures averaging about 37 Pa and estimated operating pressures averaging about 15 Pa. This is somewhat deceptive, however, because 3 of the disconnect cases had high pressures at the leaks and 4 had low pressures, so in very few of the cases was the estimated operating pressure actually close to half of the plenum pressure.

## Return Leakage Results

The return leakage results are not presented in graphical detail in this paper due to space limitations, but can be found in the full report. A statistical summary for the return leakage estimates is included in the following section. On the return side, the nulling test and Delta-Q test show similar results as for the supply side. The fan pressurization test, however, performs much better on the return side. This suggests that half of the return plenum pressure is a good surrogate for the return operating pressure in these houses.

## Statistical Summary

The results presented in the previous two sections are quantified in Table 1. Also included in Table 1 are the mean, median, minimum, and maximum measured air handler flows. The first number in each cell of Table 1 indicates the statistic for the overall sample, while the second number indicates the statistic for the tests in which the leakage on the specified side of the duct system was unchanged.

On the supply side, the nulling test was the most accurate on average with respect to the best estimate, with a bias of about 1.8% of air handler flow. This is 5.8 percentage points lower than for the Delta-Q test and about ten percentage points lower than the fan pressurization test. Considered as difference from the best estimate prediction without regard to the sign of the difference (i.e. taken as absolute differences), the nulling test accuracy error is about five percent of air handler flow, which is only about 3.5 percentage points lower than the Delta-Q test. Neither the Delta-Q test nor the fan pressurization test show much change when viewed in absolute terms since they tended to systematically overestimate the leakage. The RMS errors of the test methods with respect to the best estimate show that the fan pressurization test has significantly more discrepancy than the Delta-Q test (16.5% compared to 10.6% of air handler flow), while the nulling test has significantly lower discrepancy, with an RMS error of 5.8% of air handler flow.

**Table 1. Summary of Supply and Return Leakage Fraction Estimates as a Percentage of Air Handler Flow[1]**

| | **Best Estimate** | **Nulling** | **Delta-Q** | **Fan Press.** |
|---|---|---|---|---|
| **Supply (n=73 / 45)** | | | | |
| Mean | 13.9 / 8.4 | 15.7 / 9.3 | 21.5 / 14.3 | 25.6 / 21.7 |
| Median | 11.5 / 7.2 | 15.9 / 8.7 | 18.6 / 14.3 | 23.3 / 21.7 |
| Mean Diff. from Best | -- | 1.8 / 0.9 | 7.6 / 5.9 | 11.7 / 13.3 |
| Median Diff. from Best | -- | 2.8 / 2.1 | 7.2 / 6.4 | 10.2 / 11.1 |
| Mean Absolute Diff. from Best | -- | 5.0 / 4.4 | 8.5 / 6.6 | 13.2 / 13.6 |
| Median Absolute Diff. from Best | -- | 4.2 / 3.7 | 7.4 / 6.9 | 10.2 / 11.0 |
| RMS Error of Diff. from Best | -- | 5.8 / 5.1 | 10.6 / 7.7 | 16.5 / 17.4 |
| | | | | |
| **Return (n=63 / 45)** | | | | |
| Mean | 20.2 / 14.9 | 21.0 / 16.1 | 30.8 / 24.4 | 23.6 / 15.5 |
| Median | 18.4 / 13.0 | 18.0 / 13.6 | 25.8 / 16.4 | 19.3 / 16.6 |
| Mean Diff. from Best | -- | 0.8 / 1.2 | 10.6 / 9.5 | 3.4 / 0.6 |
| Median Diff. from Best | -- | 0.0 / 2.0 | 8.8 / 7.6 | 2.5 / 1.0 |
| Mean Absolute Diff. from Best | -- | 6.0 / 6.3 | 11.7 / 11.0 | 7.8 / 4.9 |
| Median Absolute Diff. from Best | -- | 4.6 / 5.0 | 9.1 / 8.2 | 4.7 / 4.2 |
| RMS Error of Diff. from Best | -- | 7.5 / 7.6 | 14.4 / 14.1 | 13.0 / 5.9 |
| | | | | |
| **Air Handler Flow** | **Mean** | **Median** | **Minimum** | **Maximum** |
| cfm, n=73 | 937 | 900 | 619 | 1220 |

[1] The first number is for the full sample, the second number is for those cases where the leak was not changed on the indicated side of the duct system.

On the supply side, the Delta Q test shows noticeable improvement when those cases of added leakage are removed. The bias goes down to about six percent of air handler flow, with an RMS error of under eight percent of air handler flow. The improvement for the nulling test is more modest, with bias and RMS error dropping to about one and five percent of air handler flow, respectively. The results for the fan pressurization test actually get worse when the cases with modified leaks are removed since many of the cases at which the operating pressure was nearest to half of the plenum pressure were those with added leaks.

On the return side, the nulling test has little bias relative to the best estimate. This suggests that, on average, the error in the unbalanced leakage portion of the nulling test has a similar bias to the supply leakage portion of the test, such that taking the difference of the two gives a good result for the return leakage. The RMS error is larger than for the supply, however, at about 7.5% of air handler flow. The Delta-Q test overestimates the return leakage fraction by about 10.6% of air handler flow on the return side relative to the best estimate. The RMS error is again about twice that of the nulling test, and on the return side is also significantly greater than for the fan pressurization test.

On the return side there is little change due to removing those cases with added leaks except for the fan pressurization test. A single case of large discrepancy is removed with this screening, with the result being that most of the bias and about half of the RMS error are removed.

## Repeatability

One major area of interest for these tests is their repeatability. This was investigated by calculating the internal errors for each test. The internal error is calculated by taking, within a set of three iterations, the average of the absolute values of the differences between each estimate and the average of the three estimates. This can be expressed mathematically as:

$$\varepsilon_{int} = \overline{\left| x - \bar{x} \right|}$$

where $\varepsilon_{int}$ is the internal error

x is the leakage estimate from a particular leakage test method for a particular iteration of the site/duct configuration designation of interest

$\bar{x}$ is the average of the estimates from a particular leakage test methods for all iterations of the site/duct configuration designation of interest

Table 2 shows the internal errors for each leakage test method on each of the supply and return sides. These results suggest that the Delta-Q test and the fan pressurization test are both superior to the nulling test in this respect. The nulling test is about 50% less repeatable than the Delta-Q test, with the fan pressurization test even more repeatable. As expected, the nulling test is less repeatable on the return side than on the supply side, since the return leakage estimates are subject to errors in both the unbalanced and supply portions of the test.

**Table 2. Summary of Internal Errors of Supply and Return Leakage Fraction Estimates as a Percentage of Air Handler Flow**

| | Best Estimate | Nulling | Delta-Q | Fan Press. |
|---|---|---|---|---|
| **Supply (n=69)** | | | | |
| Mean | 1.2 | 1.7 | 1.2 | 0.6 |
| Median | 1.0 | 1.3 | 0.8 | 0.4 |
| Standard Deviation | 0.8 | 1.4 | 0.9 | 0.7 |
| | | | | |
| **Return (n=63)** | | | | |
| Mean | 1.4 | 2.6 | 1.5 | 0.5 |
| Median | 1.0 | 2.3 | 1.4 | 0.3 |
| Standard Deviation | 1.4 | 2.0 | 1.3 | 0.6 |

## Conclusions

1. These results are based on a small sample of homes. As a result, many of the quantitative results cannot be considered representative of homes in general, especially as many of the tests were done with added leaks. While these added leaks were intended to represent the types of leaks that are found in the field, the frequency of their occurrence is not as high in general as it is in this study. Further work on more homes will shed light on the performance of the tests on a more typical distribution of leaks.
2. The leakage test method that compared most favorably with the “best estimate” of duct leakage was the nulling test, with an average overestimation of about 1.8% of the air handler flow on the supply side and 0.8% of the air handler flow on the return side. RMS errors are 5.8% and 7.5% of the air handler flow for the supply and return sides, respectively. The agreement with the “best estimate” is encouraging, since there is no reason to believe that the errors in these tests should be in any way correlated since they do not use the same inputs. It is however less repeatable than other methods. It is also as time-consuming as the fan pressurization test and can be difficult to set up, except for the case of homes without a return system since the supply leakage-only portion of the test is not required.
3. The Delta-Q test was the fastest and easiest of the tests to set up and perform, though the analysis of the data requires a programmed calculator or computer. It was also very repeatable. It was biased significantly more relative to the best estimate than was the nulling test, with an average overestimation of about 7.6% of the air handler flow on the supply side and 10.6% on the return side. RMS errors are 10.6% and 14.4% of the air handler flow for the supply and return sides, respectively. Some of the reasons for the strong bias are the pressure and leakage exponent assumptions used in the analysis and a failure of one of the primary assumptions of the analysis technique. The nature of the added leaks may also contribute to this magnitude of overestimation. On the supply side, the bias relative to the best estimate was reduced to 5.9% of air handler flow with an RMS error of 7.7% of air handler flow when only cases without supply leakage changes were considered. There was little change on the return side when cases with modified return leaks were excluded. It may be possible to make minor modifications to the analysis technique to address these problems and get a better estimate. The bias appears to be proportional, meaning that it is approximately a percentage of the leakage. This causes errors to get larger as the

leakage gets larger. The results did show a strong increasing trend as the best estimate of leakage increased.

4. The nulling test is significantly more sensitive to wind than either the Delta-Q test or the fan pressurization test, though this can be at least partly addressed by sampling for a longer period such as three minutes per pressure station.
5. Automation of the tests using a computer is very useful in performing the nulling test and, even more so, the Delta-Q test.

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