

# Improved Ways to Measure Residential Duct Leakage

Final Report

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# EXECUTIVE SUMMARY

## Overview

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 conduction. 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 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. 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. Previous versions included a second method, called the house pressure test; this method has subsequently been dropped due to poor quantitative performance in several field studies (Francisco and Palmiter 1999, 2000; Cummings, Withers and Moyer 1999; Strunk and Shapiro 1999).

Despite the superior performance of the fan pressurization test relative to the house pressure test, there are still a number of problems and concerns with the test. The test can be very time-consuming, and the results can be extremely poor in many cases. The test is run at specified pressures that may or 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. 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 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 that is required to remove the change in pressure is the unbalanced duct leakage. The nulling test is essentially performed twice. The first is with the duct system running normally; the second is with the return ducts isolated 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 time-consuming, but it does not require any equations or complicated model assumptions.

The Delta-Q test uses a blower door to pressurize and depressurize the house at ten different pressure stations, -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 at each pressure station are regressed on the pressures 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.

This report details 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. Accuracy, repeatability, difficulty, and time requirements were all evaluated.

In addition, sources of error and possible improvements were investigated. For the nulling test, corrections for changes in neutral level and stack pressure due to factors such as infiltration through duct leaks with the air handler off and changing temperatures in the house were evaluated. For the Delta-Q test, sensitivity to assumed operating pressures and leakage exponents was investigated. Also, the validity of one of the underlying assumptions, that the pressure between the ducts and the house remains constant throughout the portion of the test with the air handler on, was evaluated in detail.

In an add-on to the project, two additional tests were performed. These tests, called the add-a-hole test and the modified blower door subtraction test, do not measure leakage at operating conditions, but were evaluated for their ability to get comparable results to the fan pressurization test at specific pressures in less time.

In the “add-a-hole” test the blower door is set to pressurize the house. Again two tests are done. The first is with all registers and grilles sealed. The second is with a hole of known size added to each the return and supply sides of the ducts. The hole typically needs to be small enough to provide a significant pressure difference between the ducts and the house, but large enough to be substantially different than the test with all registers and grilles sealed. By measuring the pressures in each of the supply and return ducts with respect to the house in each of these tests, and by knowing the flow through the hole, an estimate of the size of the leaks in the ducts can be made, which leads to estimated leakage at specific pressures.

The modified blower door subtraction test uses the difference in flow through a blower door with and without all registers and grilles sealed, with the pressures between the house and the zones in which the ducts are located used to make an adjustment for duct leakage to inside. As done in this study, the modified blower door subtraction test does not separate the supply leakage from the return leakage. The test could be done to separate the supply and return leakage if a barrier was placed between the two sides of the system and if the sealing of registers and grilles was done separately for each side, i.e. first seal off one side, then unseal that side and seal the other side.

## Comparison Method

In order to judge the accuracy of the nulling test and Delta-Q test, an independent method of estimating the leakage was necessary. The method developed, referred to as the “best estimate”, uses the difference between the air handler flow and total flow through the registers or grilles. This is the total duct leakage for the supply or return, including leakage to inside. To correct for leakage to inside, the leakage at 25 Pa was calculated both from a fan pressurization test for total leakage (i.e. a fan pressurization test that does not use a blower door to eliminate flow to inside) and from the fan pressurization test for leakage to outside, which does use a blower door. The ratio of the leakage to outside to the total leakage was multiplied by the total leakage from air handler flow and register flow measurements, with the result being the best estimate of leakage to outside. On the supply side, the flow through the registers was measured using a propeller-type flow hood that was calibrated in-office just prior to beginning the field testing. For the return flows, a large, recently-calibrated commercial flow capture hood was used. This type of flow capture hood has been found to not work well on residential supply registers, hence the different flow measurement devices. In order to make the comparisons of various flows in this project as fair as possible, measured flows were corrected to a standard temperature of 68 F.

This method of obtaining an independent estimate of leakage has raised some question regarding its reliability. This is for two primary reasons. The first reason is that the leakage estimate is based on taking the difference of two large numbers (air handler flow and register flow) to get a smaller one, and small errors in the large numbers could be large errors in the smaller one.

The second reason that this method has been questioned is the poor accuracy of flow hoods to measure residential flows, primarily on the supply side. Testing has been performed on several flow hoods with regard to their ability to measure residential supply flows, and the results were not encouraging (Walker et al. 2001b).

However, there are a number of reasons why we believe that this is not a significant problem for the houses tested in this project. For one, the flow hood that was used is the propeller type hood, which was found to be the best of the existing flow hoods measured in the above study. This is in part because the propeller covers the entire cross-section (other than a very small area at the edge, rather than hoping that pressure taps in a few locations will accurately represent the flow.

Further, the testing done by Walker et al. used supply registers that induce a significant amount of swirl, which does cause problems for this flow hood, whereas the registers found in the houses tested were of a type that does not cause this type of swirl. This type of floor register is the most common type found in the Pacific Northwest region.

Another contributing factor to the conclusions of the Walker et al. study was the dependence on the degree to which the flow hood is centered on the register. Calibrations of the propeller flow hood done by the authors agree with that conclusion. In the study presented in this report, the flow hood was centered as best as possible to minimize this potential source of error. The extent to which the flow hood was ever not centered was small, and the resulting error would also be small.

Another reason that this method should work well in this study is that the errors in the flow hood readings tend to be more random than bias. As such, over all of the registers in the home, errors should largely cancel out. In fact, in the Walker et al. study they tested this type of flow hood in a home and found that, while the errors on a single register could be significant, the overall error was about 1%.

Some amount of circumstantial evidence has also led to trust in this method for these types of systems and registers. In a previous project for ASHRAE (Francisco and Palmiter 1999), this method was used as one of several methods of estimating leakage for input into a model to predict the thermal efficiency of duct systems. These results were compared to the efficiency measured using the short-term coheat method. Over 26 different tests, this method of estimating leakage consistently produced efficiency estimates that were in close agreement with the measured results. Also, this method has agreed well with the nulling test, a completely independent method. Finally, the direction of the errors between this method and the Delta-Q test is the same as is predicted using computer simulation. These last two points will be shown in detail in the results section of this report.

Our experience with this method in these homes suggests that typical errors are probably on the order of 20 cfm. This corresponds to about 15% of the average leakage measured by this method on the supply side in this project.

## **Results**

### *Overall*

These findings and conclusions are based on the unmodified leakage tests, i.e. the leakage tests as described by their developers. Modifications are discussed in the sections devoted to the individual tests.

- 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 artificial duct configurations. The duct leakage that was added was intended to represent the types of leaks that are found in the field, but the frequency of their occurrence is not as high in general as it is in this study. Further work on more homes is warranted.
- The most accurate of the leakage test methods was the nulling test, with an average overestimation of about 13% of the best estimate of duct leakage on the supply side and 4% of the best estimate of duct leakage on the return side. It is, however, as time-consuming as the fan pressurization test and can be difficult to set up. It is also somewhat less repeatable than other methods.
- For homes without return ducts, such as manufactured homes, the nulling test is both the fastest and most accurate. This is because the supply leakage-only portion of the test is not required, and it is this portion of the test that requires the majority of the setup. The unbalanced leakage portion of the nulling test provides the supply leakage in these homes because there is no return leakage.

- The Delta-Q test was the fastest and easiest of the tests to perform, though the analysis of the data requires a programmed calculator or computer. It was also very repeatable. It was strongly biased, with an average overestimation of about 70% of the best estimate of duct leakage on the supply side and 61% on the return side. 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 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. Despite the poor agreement with the best estimate, the results did show a strong increasing trend as the best estimate of leakage increased.
- The fan pressurization test performed better than expected on the return side, with results that were nearly as good as from the nulling test, both in terms of bias and the degree to which the estimates show a strong increasing trend with increasing leakage from the best estimate. This indicates that the assumption that the operating pressure is half of the plenum pressure tends to be a good one. The test was also extremely repeatable, even more repeatable than the Delta-Q test. There are only a couple of cases, with disconnected main return trunk ducts, where the fan pressurization test failed. It seems likely that over a larger sample of homes this test would continue to perform well on the return side, on average, using the half plenum pressure assumption.
- On the supply side, the fan pressurization test performed very poorly, with an average overestimation of about 84% of the best estimate of duct leakage, though repeatability was still high. The results on the supply side also did not show a particularly strong trend of increasing leakage estimate as the best estimate of leakage increased, although there were very few cases where the fan pressurization test underestimated the leakage. It can be stated that this test did not produce much in the way of false negatives on the supply side, where there was significant leakage but the test indicated that leakage was small. However, there were a number of cases where the test indicated large supply leakage when this was not actually the case. This was largely because of a combination of an overestimation of operating pressures and the effects of the momentum of air during operating conditions. The momentum of air takes the air past certain holes in ducts when the registers are not sealed that air is forced to go out of with the registers sealed during the fan pressurization test.
- In addition to the poor performance in estimating supply leakage, the fan pressurization is also time-consuming and can be difficult to set up. In some cases it may not be possible to perform this test due to inaccessible registers and grilles, which must all be sealed.

### *Nulling Test*

- Despite the potential for holes in ducts to cause the target pressure in the house to be affected, the methods of adjusting for this are time-consuming and the results showed very little improvement from implementing them. As a result, it does not seem worthwhile to make these adjustments.
- It is also not usually worth adjusting the results for changes in stack pressure unless interior conditions changed drastically, such as from having a furnace running with the heat on for an extended period of time during the test. It is preferable to run the nulling test with the air handler running in fan-only mode.
- The nulling test is very sensitive to wind, but the effects of wind can be mitigated with longer sample intervals such as three minutes per pressure station.

- It is important to measure the flows at least at three different pressures that bracket the target pressure. This allows for interpolation to the exact target in the event that the target was not matched exactly.
- Automated data collection software is very important for simplifying and troubleshooting the test. This type of software can give immediate feedback as to whether the data falls on a nearly straight line; if it does not, a problem is indicated and the test can be redone.

### *Delta-Q Test*

- Changing the pressure assumption from full plenum pressures to either half plenum pressures or quarter plenum pressures did not greatly improve the results. Using half of the plenum pressure reduced the bias to about 55% of the best estimate of duct leakage on the supply side and 52% on the return side. Using one quarter of the plenum pressure actually increased the bias. This non-monotonic behavior, whereby a decrease in pressure may not correspond to a decrease in leakage, is counterintuitive but is one of the features of the equations used to analyze the Delta-Q test results.
- Changing the leakage exponent assumption can also have a significant impact on the results, but as with the pressure assumption there is not a set of reasonable exponents that results in a good leakage prediction. Reducing the exponents to 0.55 from 0.6 reduces the bias to about 45% on the supply side and 43% on the return side. The leakage estimates do change monotonically with exponent, so the exponent would have to be reduced significantly further to provide good agreement with the best estimate. However, the theoretical lower limit on the exponent is 0.5.
- The problems with the pressure and exponent assumptions mean that, in these houses, there is not a set of reasonable pressures and exponents that can provide satisfactory agreement with the best estimate.
- One of the major problems with this test is the failure of the assumption that the pressure difference between the ducts and the house remains constant throughout the portion of the Delta-Q test with the air handler on. This pressure difference can vary by more than a factor of two for leaky systems across the range of pressure stations in the test. The failure of this assumption leads to an overestimation of leakage estimates, which was confirmed by computer simulations using CONTAM. These simulations were done with all other assumptions satisfied, including having known duct pressures and leakage exponents. This problem warrants further investigation for possible remedies. One possibility is to measure the actual pressures between the ducts and the house at each station, and to use these in place of the constant duct pressure in the Delta-Q analysis. This requires a third pressure measurement tap, in addition to the taps for house pressure and fan pressure.
- Another assumption of the Delta-Q test that will not always hold true is that the pressure across the envelope is the same as the pressure across the duct leaks when the air handler is off. If the space in which the ducts are located is significantly connected to the conditioned space, with regard to pressures, the duct zones will change pressure differently than the house when the blower door operates. This will occur when the duct zone is not well ventilated. The impact of this assumption was not evaluated in this study.
- There can be a significant amount of crosstalk between the supply and return sides in this test, meaning that a large leak on one side can cause the test to also estimate a large leak on

the other side, even if the leakage is not large. This can lead to incorrect and time-wasting decisions as to whether it is worth fixing duct leakage.

- Automation is important to make the test user-friendly and less prone to user error. It is absolutely critical that the analysis of the data to provide leakage estimates be automated, as the equations for performing this analysis are difficult and complex.

#### *Fan Pressurization Test*

- As has been found in many previous studies, the biggest technical problem with the fan pressurization test is estimating the effective operating pressures at the leaks. At these houses the standard assumption that the effective operating pressure is half of the plenum pressure is poor on the supply side. This assumption overestimates the effective supply operating pressures by about a factor of two, on average. This results in greatly overestimated leakage. One of the primary reasons for this is that many leaks occur downstream of several bends that occur after the plenum, each of which causes a substantial pressure drop. Another reason is that many holes in ducts occur in locations which get largely bypassed by the air during normal operation because of momentum, but in the fan pressurization test the air is forced out of these holes since the registers are sealed.
- On the return side the standard assumption for operating pressure of half the plenum pressure worked well unless there was a major disconnect in main trunk. The return ducts typically consisted of only a very few large, straight sections, so the pressure drop was not as large between the main portion of the ducts and the plenum. The momentum of air is also less of a problem on the return side because the ducts are pulling air in through the leaks instead of pushing air out.

#### *Blower Door Subtraction/Add-a-Hole Test*

- Both the add-hole and modified subtraction methods show promise where the goal is to measure duct leakage to outside at a given reference pressure. They share the drawback of the fan pressurization method of requiring an estimate of an appropriate "effective" duct-to-outside pressure difference in order to get an estimate of leakage at operating conditions.
- The add-a-hole method as performed here has the advantage of producing values separately for the return and supply ducts. This is important, because in most conditions, the thermal losses associated with supply leaks are significantly larger than those associated with return leaks of the same size.
- The modified blower door subtraction test could be extended to provide separate supply and return leakage by taping off one side and then the other and performing a blower door test under each configuration.
- Both the modified blower door subtraction and add-a-hole tests are faster and easier than the fan pressurization test, and require less equipment.



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## 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 conduction. 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 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. 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. Previous versions included a second method, called the house pressure test; this method has subsequently been dropped due to poor quantitative performance in several field studies (Francisco and Palmiter 1999, 2000; Cummings, Withers and Moyer 1999; Strunk and Shapiro 1999).

Despite the superior performance of the duct pressurization test relative to the house pressure test, there are still a number of problems and concerns with the test. The test can be very time-consuming, and the results can be extremely poor in many cases. The test is run at specified pressures that may or 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. 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. These two are referred to as the nulling test and the Delta-Q test. This report details 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. Accuracy, repeatability, difficulty, and time requirements were all evaluated. In addition, sources of error and possible improvements were investigated.

In an add-on to the project, two additional tests were performed. These tests, called the add-a-hole test and the modified blower door subtraction test, do not measure leakage at operating conditions, but were evaluated for their ability to get comparable results to the fan pressurization test at specific pressures in less time.

## LEAKAGE TEST METHODS

There were three primary leakage tests that were to be evaluated in this project: the fan pressurization test, the nulling test, and the Delta-Q test. An add-on to the project provided the opportunity to evaluate two other leakage test methods, the modified blower door subtraction method and the “add-a-hole” method. In order to make evaluations of accuracy, an independent best estimate of leakage at operating conditions was required. This was done by taking the difference of air handler flow and register flows at each house, with an adjustment for leakage to or from inside based on the fan pressurization test results. All of these methods are described in more detail in this section.

### Fan Pressurization

The fan pressurization test uses a calibrated duct pressurization fan to measure the duct leakage. To estimate the supply and return leakage separately, a barrier is placed between the supply and return sides of the system, and the supply and return ducts are tested individually. This barrier is usually placed in the filter slot on the return side of the air handler. The duct pressurization fan is attached to the duct system, usually at the air handler for supply tests and at a return grille for return tests. All supply registers and return grilles are sealed during this test except for any that have the duct pressurization fan attached to them (maximum of one on each side). To estimate leakage to or from outside only, a blower door is run simultaneously to zero out the pressure difference between the ducts and the house, thereby eliminating leakage to inside.

Tests are typically done at one or two selected pressure stations (frequently 25 and 50 Pa). The flow through the duct pressurization fan and the pressure between the ducts and either the duct zone or the outside are measured. The standard assumption is that duct leakage follows a power law, so the logarithms of the measured pressures and flows are regressed on each other. The resulting duct leakage curve has the form  $Q = C\Delta P^n$ , where  $Q$  is the flow,  $C$  is the leakage coefficient,  $\Delta P$  is the pressure difference across leaks, and  $n$  is the leakage exponent. If the fan pressurization test is performed at only a single location, an exponent of 0.6 is typically assumed. This is based on typical values from many tests. For a specific duct system, however, the exponent can vary from 0.5 to about 0.75.

This test can be very time-consuming because all of the registers and grilles need to be sealed, placing a barrier in the filter slot can be difficult (especially making sure that there is a good seal around the perimeter), and firmly attaching the duct pressurization fan to the duct system can be difficult. In some cases, one or more registers and/or grilles cannot be sealed easily due to furniture or location high on a wall. Another register type that causes sealing problems is the toe kick, which commonly has a hole under a cabinet through which the supply air enters the house, and a register on the front face of the bottom of the cabinet. There may be significant leakage in the cabinet, and in some cases the “register” is actually just a long slot the length of the cabinet.

The fan pressurization test also has the major drawback that the measurement is done at an artificial pressure or pressures that may not be representative of that existing at the leakage sites in the ductwork. To correct the results to operating conditions, estimates are made of the average operating pressure at these leakage sites. This estimated operating pressure is then inserted into

the power law equation describing the duct leakage to obtain duct leakage at operating conditions.

## **Nulling Test**

The nulling test was developed by the authors (Francisco and Palmiter 2001). It consists of two parts: measurement of unbalanced duct leakage and separation into supply and return components. The test is predicated on the assumption that any change in the pressures across the building envelope due to turning on the air handler is due to unbalanced duct leakage. Unbalanced duct leakage can be viewed as analogous to either a supply fan (return-dominated leakage) or an exhaust fan (supply-dominated leakage). As with ventilation fans, if another fan of the same flow but opposite direction is installed, there will be no net change in the pressures across the building envelope. A calibrated fan, referred to as a nulling fan, is then used to zero out the pressure change due to duct leakage, and the flow through the nulling fan is the unbalanced leakage. One concern is the ability to exactly match the target pressure. This was addressed prior to any field testing being performed by modifying the test method to measure at three different envelope pressures: one below the target by a small amount, usually 0.5 Pa; one at approximately the target pressure; and one above the target pressure by a small amount, usually 0.5 Pa. This should result in a straight line, and linear regression and interpolation provides a result at the target pressure. Because of the small pressure differences being induced, it is highly desirable to have a calibrated fan with the capability to be adjusted precisely.

The nulling test has the advantage that the leakage estimate is at operating conditions. Another major advantage is that it is model-independent, meaning that no assumptions are required about the house leakage distribution or the leakage location in the ducts. In addition, no equations are required. The test is subject to errors due to noise from gusty winds and the impact of holes in the ducts changing the neutral level during periods when the air handler is off. Preliminary tests using this method showed significant promise for both the accuracy and time requirements for this test (Francisco and Palmiter 1999, 2000).

### *Measurement of Unbalanced Leakage*

The first step in measuring the unbalanced duct leakage is to measure the pressure across the building envelope with and without the air handler fan operating. All doors and windows should be closed during these measurements. The location of this pressure measurement is arbitrary, other than that measuring the building pressure with respect to a buffer space in which ducts are located should be avoided. This is because duct leakage can also change the pressure in the buffer space in which the ducts are located, which can compromise the measurement. Buffer spaces without ducts can be good candidates as references for the pressure measurement because they will frequently reduce noise from wind. Buffer spaces with ducts can be used if it is first determined that the buffer space is sufficiently connected to outdoors that duct leakage does not change the pressure of the buffer space.

The second step in the nulling test is to place the calibrated nulling fan, such as a Duct Blaster or blower door, into a door or window of the building. If the pressure measurements across the envelope with the air handler off and on indicate that the building is being depressurized due to

unbalanced duct leakage (meaning return-dominated leakage), the nulling fan is installed to pressurize the building. If the pressures indicate that the building is being pressurized due to unbalanced duct leakage (meaning supply-dominated leakage), the nulling fan is installed to depressurize the building. Figure 1 depicts this setup. The setup shown is a typical duct system with the air handler in a garage. The bold arrow indicates the return, while the thin lines and arrows out of the air handler indicate the supply system. The top schematic (a) is for return dominated leakage, while the bottom schematic (b) is for supply-dominated leakage.

Next, with the nulling fan sealed off, the pressure across the building envelope with the air handler off is measured again. Then the air handler is turned on along with the uncovered nulling fan. The nulling fan is adjusted until the pressure across the building envelope is the same as was measured with the air handler off. The flow through the nulling fan when this pressure has been reached is then an estimate of the unbalanced duct leakage.

Figure 1 shows a schematic of the unbalanced leakage portion of the nulling test.

One caution regarding this test is to avoid having the air handler operating in either heating or cooling mode for more than a few minutes. Changes in the building temperature result in changes in the stack pressures, and can bias the results. If the air handler has a fan-only setting, that can be used to mitigate this problem.

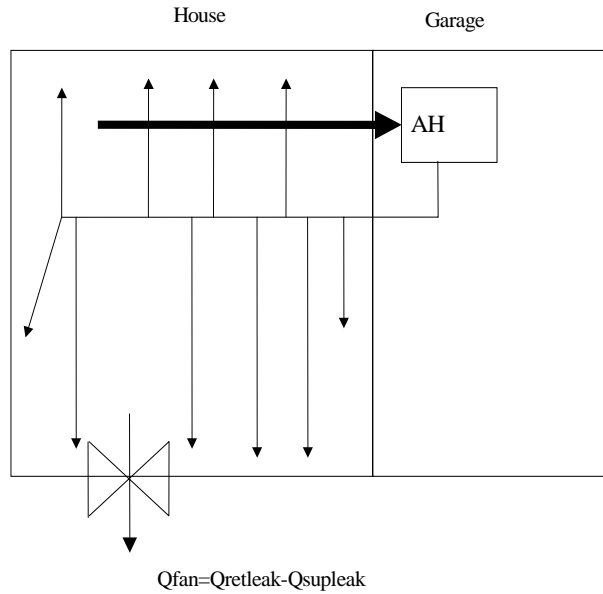
#### *Separation of Duct Leakage Into Supply and Return Components*

Estimating the supply and return leakage separately involves a similar test procedure, only with the return ducts eliminated from the system and substituted with another fan, which is adjusted to assist the air handler fan until the supply plenum pressure from normal operating conditions is matched. If this second fan is a calibrated fan, this is essentially a combination of the nulling test for unbalanced leakage described above with the method of estimating air handler flow using a calibrated fan, as described in ASHRAE Standard 152P (ASHRAE 2001). Note that, if the air handler is in the conditioned space, it is not essential that a second fan be used; one could simply open the air handler fan access cover, and then close it off until the supply plenum pressure is back to its normal operating mode level. The use of the second fan, however, does provide an estimate of the air handler flow.

The first step is to measure the pressure in the supply plenum relative to the conditioned space. Then a barrier is placed between the supply and return ducts, typically at the filter slot, to isolate the return system. A calibrated fan is then mounted to the front of the blower access door of the air handler cabinet. There are two options for setting up this fan. The first, and most preferable one, is in such a way that the air going through the fan will be taken from the house. The other option is to draw the air from another space.

The setup at the air handler is the same setup that was required to measure air handler flow in previous drafts of Standard 152P, and thus the nulling test would not have required significant additional setup time over what was already required to implement Standard 152P. However, the current draft allows use of the recently-developed flow plate technology, and the setup time

(a) Nulling test: Unbalanced return-dominated leakage



(b) Nulling test: Unbalanced supply-dominated leakage

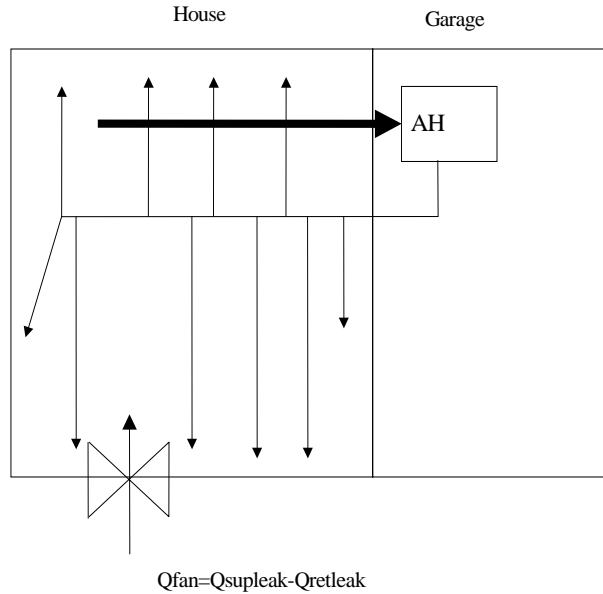


Fig. 1a-b. Schematics detailing the unbalanced leakage portion of the nulling test. The top picture (a) is for return-dominated leakage; the bottom picture (b) is for supply-dominated leakage

required for the nulling test is a considerable increase over what would be required for Standard 152P if the flow plates are used to measure air handler flow.

### Air Drawn from the Conditioned Space

If the air handler is located in the conditioned space, it is simple to set up the fan attached to the air handler such that it will draw air from the conditioned space. If the air handler is outside the conditioned space, such as in an attached garage or basement, the fan can be attached to the air handler via a flexible duct and installed in the doorway between the conditioned space and the space in which the air handler is located. This installation is similar to the installation of a blower door in an exterior doorway. Figure 2 details this setup.

The fan and any flexible duct attachment act as the return system, but in this case the return system is airtight. Therefore, any change in building envelope pressure when the air handler is turned on is due to supply leakage. Since supply-dominated leakage always depressurizes the house, the nulling fan is installed to pressurize the building. The test described above for measuring unbalanced duct leakage is performed, with the flow through the nulling fan being an estimate of the supply duct leakage.

The return duct leakage is then obtained by combining the supply duct leakage and the unbalanced duct leakage measurements. If the unbalanced duct leakage is supply-dominated, the return duct leakage is the unbalanced duct leakage subtracted from the supply duct leakage. If the unbalanced duct leakage is return-dominated, the return duct leakage is the unbalanced duct leakage added to the supply duct leakage.

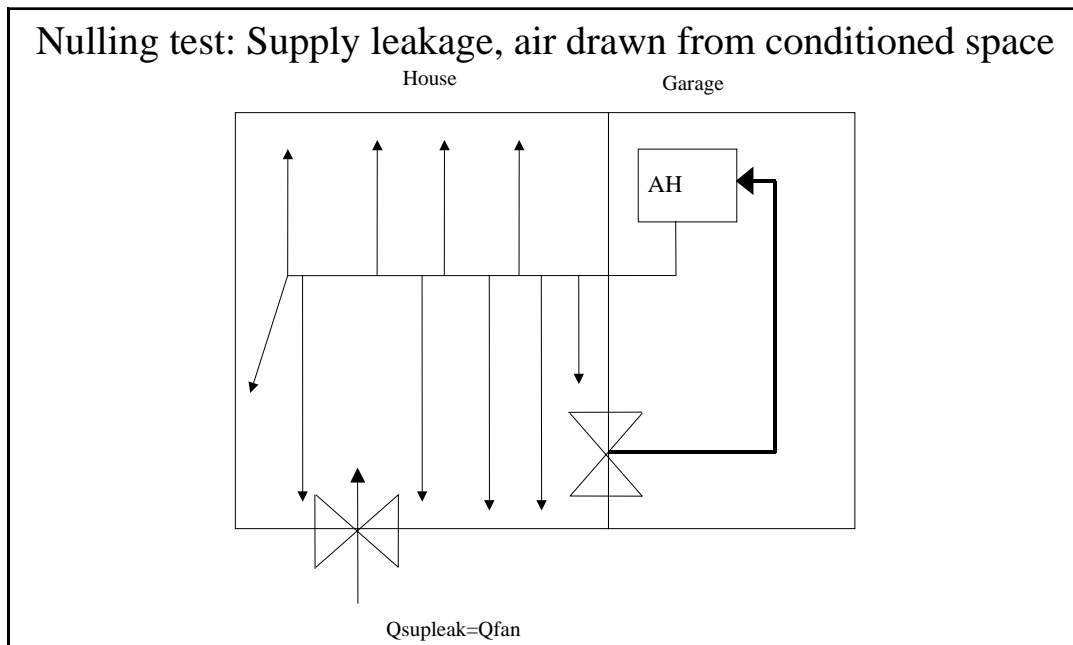


Fig. 2. Schematic detailing the supply leakage portion of the nulling test for the situation where the air is drawn from the conditioned space.

## Air Drawn from an Unconditioned Space

In some cases, it may not be possible to set up the fan attached to the air handler such that the air is drawn from the conditioned space. This is especially true in cases where the air handler is located in an attic or crawlspace, though it may still be possible to set up a frame in the access for these spaces in which to set up the fan.

If the air through the air handler is drawn from outside the conditioned space, the change in pressures across the building envelope are due to the supply air that comes into the building rather than due to the supply duct leakage. This is because no return air comes from the building. In this case, the nulling fan is set up to depressurize the house. The test described above for measuring unbalanced duct leakage is performed, with the flow through the nulling fan being an estimate of the flow into the building via the supply ducts. This flow can be subtracted from the flow through the fan that is attached to the air handler to get an estimate of the supply leakage, which can then be combined with the unbalanced duct leakage to get the return leakage. Figure 3 details this setup.

Taking the air from outside of the conditioned space is less desirable for two reasons. First, subtracting two large numbers to get a small number, as would be the case unless there is catastrophic supply duct leakage, can lead to higher errors in the estimates. Second, this method

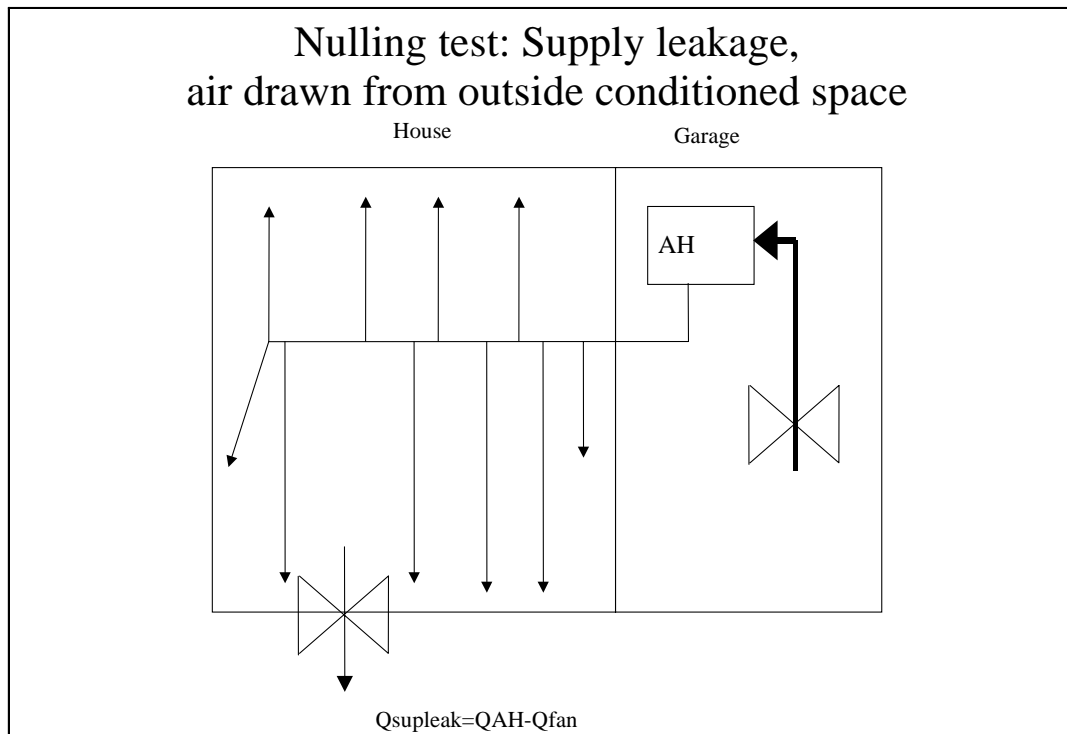


Fig. 3. Schematic detailing the supply leakage portion of the nulling test for the situation where the air is drawn from outside the conditioned space.

uses measured flow rates from two different fans that were not calibrated to each other. Since even calibrated fans have some uncertainty associated with them, the errors will potentially be very large. For example, the uncertainty for each fan may be  $\pm 3\%$ . If one is high and one is low, the errors due to combining results from them may be large regardless of the level of uncertainty inherent in field measurement.

### *Time Requirements*

Prior to the invention of the flow plate technology for measuring air handler flow and the subsequent incorporation into Standard 152P, the additional setup required to perform this test over what was required for other diagnostic tests needed to estimate duct efficiency was minimal. No sealing of registers and grilles is required. The nulling test requires attachment of a fan to the air handler and the isolation of the return system, but this was required already for estimating air handler flow in previous drafts of ASHRAE Standard 152P. Also, while ASHRAE Standard 152P does not require the measurement of the building infiltration rate with a blower door, this is fast and easy to set up and is commonly used in weatherization work. If flow plates are used to measure air handler flow, the nulling test does require significant additional setup time over what is already required in Standard 152P, and the test takes a similar amount of time as the fan pressurization test.

The exception to this is homes that do not have a ducted return system, such as manufactured homes. In these homes only the unbalanced leakage test is required, since by definition this is the supply leakage and there is no return leakage. The nulling test is the fastest and simplest test to perform in this type of home.

### *Nulling Test Problems*

As with all leakage tests, the nulling test is not without imperfections. High wind speeds can be a serious problem, as the change in pressures across the building envelope due to high winds can be more than the signal from the duct leakage. Other leakage test methods are also subject to noise from wind, but the nulling test, with the low pressures and small number of data points being measured, is more sensitive than other methods. Longer-term averaging during windy times (on the order of three minutes per pressure station) can significantly improve the results.

Another source of problems is the effect that leaks in the ducts have on the neutral level during the times when the air handler is off. Holes in ducts provide pathways for greater infiltration than would exist without the ducts being installed, and this can have an effect on the neutral level. When the air handler is switched on, these leaks are shut off. If these leaks could be shut off during the air handler off times, the neutral level may change, and it is this neutral level that one would most like to adjust to. This effect will be most pronounced when all of the duct leakage is either high or low. Holes in ducts both high and low will tend to counteract each other somewhat, and the discrepancy in the nulling test result will be only a fraction of the additional infiltration due to the ducts.

The preceding problem can be best illustrated with an example. Consider a house with airtight walls and a floor and ceiling that are equally leaky. Without duct leakage (and with no effect

from wind), the neutral level for this house will be at the midheight of the house. If supply and return ducts are added in the crawl space, with a leakage area equal to that of the floor, the neutral level with the air handler off will be brought down to one-third of the house height (two-thirds of the holes are in the floor, one-third in the ceiling). When the pressure is measured across the envelope at the beginning of the unbalanced leakage portion of the nulling test, it will reflect the pressures based on the neutral level at one-third of the height. However, when the air handler is turned on, the duct leaks are shut off from the point of view of infiltration. If the duct leakage is balanced, the neutral level would be at the midheight with the air handler on. However, to match the original pressure, the nulling fan would be turned on until the pressure matched that with the neutral level at one-third of the building height, and would imply unbalanced leakage.

Another potential problem with the nulling test is the impact of changes in stack pressure due to changing indoor temperatures. These changes can occur either by having the heating or cooling active instead of just operating the air handler fan during the test, or by having large amounts of air from outdoors enter the house during the test. If the stack pressure changes during the test, then the pressures everywhere across the envelope will not be what they were with the air handler off when the pressure change at the measurement location is nulled out. It is actually the neutral level that one would most like to match, but this is impractical.

Stack pressure changes due to running the conditioning equipment can be mitigated by using a fan-only setting, if available, but in many cases this option is not installed. Stack pressure changes due to bringing in large quantities of outdoor air can be mitigated by performing the test in a fairly short amount of time. However, problems will arise on occasion, whether it is an error in the setup of the test, a hose coming loose, or some other error, so one cannot expect that this problem will always be avoided. This problem will be larger for larger leakage, since the nulling fan will be moving a greater volume of air through the house.

## **Delta-Q Test**

The other of the recently developed tests is the Delta-Q test (Walker, Sherman, and Siegel 1999), which is based on a measurement technique first conceived by Dr. Charles A. Gaston of Penn State University. In this test, blower door tests are performed at several pressures (such as -25 Pa to +25 Pa in 5 Pa increments) both with and without the air handler running. The differences between the blower door flow measurements at each pressure station, known as “delta-Qs”, are subjected to a least-squares analysis to obtain estimates of the supply and return leakage.

### *Derivation of Delta-Q Analysis Equations*

The derivation of the Delta-Q analysis technique, as provided by the developers (Walker et al. 2001a), is presented here.

With the air handler off, the flows through the blower door at each pressure station are:

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

where  $Q_{\text{off}}(\Delta P)$  is the flow through the blower door with a pressure difference of  $\Delta P$  across the envelope and the duct leaks with the air handler off.

$C_{\text{env}}$  is the leakage coefficient of the building

$C_s$  is the leakage coefficient of the supply ducts

$C_r$  is the leakage coefficient of the return ducts

$n_{\text{env}}$  is the leakage exponent of the building

$n_s$  is the leakage exponent of the supply ducts

$n_r$  is the leakage exponent of the return ducts

Note that eq. (1) assumes that the pressure across the building envelope and the pressure across the duct leaks are the same. This may not be the case for at least two reasons. The first reason is that the zone in which the ducts are located may be somewhat connected to inside, in which case the duct zone will be pressurized (or depressurized) by the blower door, but by a different amount than the house. The pressures across the leaks would then be less than the pressure across the house.

The second reason that the pressure across the building envelope and the pressure across the duct leaks may be different with the blower door on and the air handler off is that, if there is flow in the ducts, there will be a pressure drop across the registers and grilles. There will be flow in the ducts when the blower door is on any time there are duct leaks, with larger holes in the ducts providing larger flows due to operation of the blower door. The fact that there is a pressure drop across the grilles and registers implies that the pressures in the ducts and in the house are different.

With the air handler on, the flows through the blower door at each pressure station are:

$$Q_{\text{on}}(\Delta P) = C_{\text{env}}\Delta P^{n_{\text{env}}} + C_s(\Delta P + \Delta P_s)^{n_s} + C_r(\Delta P - \Delta P_r)^{n_r} \quad (2)$$

where  $Q_{\text{on}}(\Delta P)$  is the flow through the blower door with a pressure difference of  $\Delta P$  across the envelope and the air handler on.

$\Delta P_s$  is the pressure difference between the supply ducts and house (house as reference).

$\Delta P_r$  is the pressure difference between the return ducts and house (return as reference).

Using the return as the reference makes  $\Delta P_r$  a positive number. When the building is pressurized and the magnitude of return pressure is greater than the imposed blower door envelope pressure the return term in Equation 5 is negative (i.e. flow into house).

In practice, the pressures in the ducts are measured at the plenums.

Note that eq. (2) requires the assumption that the pressure difference between the ducts and the house remains constant throughout the range of pressures in the Delta-Q test. It does not, however, require that the pressure everywhere in the ducts be the same.

Equation (2) also suffers from the same problems as discussed for eq. (1) in that the pressure difference induced by the blower door on the house may be different than the pressure induced on the ducts, such that applying the same  $\Delta P$  to both house and ducts may not be appropriate.

The “Delta-Q” is the difference between the air handler on and air handler off measurements:

$$\Delta Q(\Delta P) = Q_{\text{on}}(\Delta P) - Q_{\text{off}}(\Delta P) = C_s \left[ (\Delta P + \Delta P_s)^{n_s} - \Delta P^{n_s} \right] + C_r \left[ (\Delta P - \Delta P_r)^{n_r} - \Delta P^{n_r} \right] \quad (3)$$

The supply and return leakage flows, respectively, can be defined as:

$$Q_s = C_s \Delta P_s^{n_s} \quad Q_r = C_r \Delta P_r^{n_r} \quad (4 \text{ and } 5)$$

where  $Q_s$  is the supply leak flow at operating conditions to outside  
 $Q_r$  is the return leak flow at operating conditions to outside

Equations (4) and (5) can be rearranged as

$$C_s = \frac{Q_s}{\Delta P_s^{n_s}} \quad C_r = \frac{Q_r}{\Delta P_r^{n_r}} \quad (6 \text{ and } 7)$$

Substituting  $C_s$  and  $C_r$  into the equation (3) gives

$$\Delta Q(\Delta P) = Q_s \left[ \left( \frac{\Delta P + \Delta P_s}{\Delta P_s} \right)^{n_s} - \left( \frac{\Delta P}{\Delta P_s} \right)^{n_s} \right] + Q_r \left[ \left( \frac{\Delta P - \Delta P_r}{\Delta P_r} \right)^{n_r} - \left( \frac{\Delta P}{\Delta P_r} \right)^{n_r} \right] \quad (8)$$

For simplicity and robustness, the developers of this technique fix the duct leakage pressure exponents to 0.6, which field results suggest is suitable, on average, for most duct systems (Walker et al. 1998 and Siegel et al. 2001). With this assumption and some algebraic rearrangement, the final DeltaQ equation can be written as

$$\Delta Q(\Delta P) = Q_s \left[ \left( 1 + \frac{\Delta P}{\Delta P_s} \right)^{0.6} - \left( \frac{\Delta P}{\Delta P_s} \right)^{0.6} \right] - Q_r \left[ \left( 1 - \frac{\Delta P}{\Delta P_r} \right)^{0.6} + \left( \frac{\Delta P}{\Delta P_r} \right)^{0.6} \right] \quad (9)$$

The measured Delta-Qs are fitted with equation (9) using least-squares to provide the supply and return leakages.

### *Delta-Q Test Advantages and Problems*

As with the nulling test, the leakage estimates from the Delta-Q test are also at operating conditions. It has the added advantage of only requiring one calibrated fan (a blower door) instead of two. Further, there is no need to place a barrier between the supply and return portions

of the ductwork or to seal off the registers. The test is also relatively fast; it can be completed in about 30 minutes.

Two drawbacks of the test are the complexity of the equations, and that the simplifying assumptions about the duct leakage characteristics may not always be valid. Further, this method requires an assumption about the duct operating pressures, similar to the fan pressurization test, although the sensitivity to pressure assumption is usually not as great as it is for the fan pressurization test. It also assumes that the pressures in the ducts will remain constant with respect to the house as the blower door pressurizes and depressurizes the house. Though this assumption is correct if there are no leaks, it can fail when there is duct leakage to outside. The test can be sensitive to noise from gusty winds, though it does not appear to be as sensitive to wind noise as the nulling test. This is because the pressures being tested at are much larger than those for the nulling test, such that the noise due to the wind does not typically overwhelm the signal, and also because more pressure stations are measured, so that an error due to wind in one station can be mitigated by the regression over all stations.

Another issue for this test is that, because the delta-Qs are differences of two large numbers, the blower door that is used needs to have a high level of precision.

### **Modified Blower Door Subtraction**

Blower door subtraction was one of the first leakage tests invented. This test involves performing a blower door test twice, one with all the registers and grilles sealed and one with all of them open. Tests are usually done in depressurization mode at either one or two pressure differences between the house and outside: one or both of -25 Pa and -50 Pa. The difference in flow through the blower door between the two tests was supposed to be an estimate of duct leakage at that pressure.

Unfortunately, this test was fraught with problems. One problem is that it relied on subtracting two very large numbers to obtain a number that was often very small. Hence a small percentage error in one or both of the large numbers could have a major impact on the quality of the leakage estimate. In addition, it was not at operating conditions, nor did it separate supply and return leakage. It also did not account for communication between the duct zone and the house (i.e. leakage to or from inside), which resulted in duct leakage at the reference pressure being underestimated.

The development of software to automate the blower door testing process in conjunction with a pressure datalogger that allows the recording of pressures between the ducts and the house and between the duct zones and the house warrant a rethinking of the utility of the blower door subtraction idea. The automation reduces the uncertainties of the test results. The test is referred to as the “modified” blower door subtraction test because of the use of the interzonal pressures to make adjustments for communication between the home and the duct zone. This test can also be done using a sufficiently precise hand-held manometer, especially if long-term averaging is used.

The modified blower door subtraction test still does not separate the supply leakage from the return leakage, and it is still at artificial pressures that may not represent operating conditions.

As such, it cannot be considered to be more accurate than the fan pressurization test (hence its original exclusion from the scope of this project). However, it is of interest because it may be a fast way to qualitatively ascertain whether the ducts are very tight, with the argument that if the ducts are very tight that the actual numerical leakage value may not be of particular interest.

The test could be done in such a way as to separate the supply and return leakage if a barrier was placed between the two sides of the system and if the sealing of registers and grilles was done separately for each side, i.e. first seal off one side, then unseal that side and seal the other side.

### **“Add-A-Hole” Test**

In the “add-a-hole” test the blower door is set to pressurize the house. Again two tests are done. The first is with all registers and grilles sealed. The second is with a hole of known size added to each the return and supply sides of the ducts. The hole needs to be small enough to provide a significant pressure difference between the ducts and the house, but large enough to be substantially different than the test with all registers and grilles sealed. By measuring the pressures in each of the supply and return ducts with respect to the house in each of these tests, and by knowing the flow through the hole, an estimate of the size of the leaks in the ducts can be made, which leads to estimated leakage at specific pressures.

As with the modified blower door subtraction test, the results are not at operating conditions. However, this test does separate supply and return leakage estimates, and these results can be compared directly with those from the fan pressurization test. The test cannot be considered more accurate than the fan pressurization test. The interest here is a possible faster way to get about the same information as from the fan pressurization test without having to set up the pressurization fans on each of the supply and return duct systems.

### **Best Estimate**

The supply and return leakages that were deemed to be the “best” estimates were calculated as follows: first, the total flow through the registers or grilles was subtracted from the air handler flow. This is the total duct leakage for the supply or return, including leakage to inside. To correct for leakage to inside, the leakage at 25 Pa was calculated both from a fan pressurization test for total leakage (i.e. a fan pressurization test that does not use a blower door to eliminate flow to inside) and from the fan pressurization test as described above. The ratio of the leakage to outside to the total leakage was multiplied by the total leakage from air handler flow and register flow measurements, with the result being the best estimate of leakage to outside. On the supply side, the flow through the registers was measured using a propeller-type flow hood that was calibrated in-office just prior to beginning the field testing. For the return flows, a large, recently-calibrated commercial flow capture hood was used. This type of flow capture hood has been found to not work well on residential supply registers, hence the different flow measurement devices. In order to make the comparisons of various flows in this project as fair as possible, measured flows were corrected to a standard temperature of 68 F.

This method of obtaining an independent estimate of leakage has raised some question regarding its reliability. This is for two primary reasons. The first reason is that the leakage estimate is

based on taking the difference of two large numbers (air handler flow and register flow) to get a smaller one, and small errors in the large numbers could be large errors in the smaller one.

The second reason that this method has been questioned is the poor accuracy of flow hoods to measure residential flows, primarily on the supply side. Testing has been performed on several flow hoods with regard to their ability to measure residential supply flows, and the results were not encouraging (Walker et al. 2001b).

However, there are a number of reasons why we believe that this is not a significant problem for the houses tested in this project. For one, the flow hood that was used is the propeller type hood, which was found to be the best of the existing flow hoods measured in the above study. This is in part because the propeller covers the entire cross-section (other than a very small area at the edge, rather than hoping that pressure taps in a few locations will accurately represent the flow.

Further, the testing done by Walker et al. used supply registers that induce a significant amount of swirl, which does cause problems for this flow hood, whereas the registers found in the houses tested were of a type that does not cause this type of swirl. This type of floor register is the most common type found in the Pacific Northwest region.

Another contributing factor to the conclusions of the Walker et al. study was the dependence on the degree to which the flow hood is centered on the register. Calibrations of the propeller flow hood done by the authors agree with that conclusion. In the study presented in this report, the flow hood was centered as best as possible to minimize this potential source of error. The extent to which the flow hood was ever not centered was small, and the resulting error would also be small.

Another reason that this method should work well in this study is that the errors in the flow hood readings tend to be more random than bias. As such, over all of the registers in the home, errors should largely cancel out. In fact, in the Walker et al. study they tested this type of flow hood in a home and found that, while the errors on a single register could be significant, the overall error was about 1%.

Some amount of circumstantial evidence has also led to trust in this method for these types of systems and registers. In a previous project for ASHRAE (Francisco and Palmiter 1999), this method was used as one of several methods of estimating leakage for input into a model to predict the thermal efficiency of duct systems. These results were compared to the efficiency measured using the short-term coheat method. Over 26 different tests, this method of estimating leakage consistently produced efficiency estimates that were in close agreement with the measured results. Also, this method has agreed well with the nulling test, a completely independent method. Finally, the direction of the errors between this method and the Delta-Q test is the same as is predicted using computer simulation. These last two points will be shown in detail in the results section of this report.

Our experience with this method in these homes suggests that typical errors are probably on the order of 20 cfm. This corresponds to about 15% of the average leakage measured by this method on the supply side in this project.

This method of determining a best estimate is only clearly applicable in homes with all ducts outside the conditioned space because duct leakage in internal spaces typically occurs at different pressures than the operating pressure for leakage to outside, and hence the correction method for leakage to inside would not be appropriate. For this reason homes were restricted to single-story homes with all ducts outside the conditioned space. There were two houses, however, that had crawl spaces with little enough venting that they were significantly connected to the house regarding pressures. This should not cause a problem with the correction to the best estimate for leakage to outside because all of the ducts were still in the same zone. This method may also work for multi-story homes, especially if all runs are fully ducted, but no research has been done to date to investigate this.

## FIELD SAMPLE CHARACTERISTICS

Nine homes were tested in this project. The project originally called for only eight homes to be tested; however, due to homeowner problems and a power outage at Site L02, we were unable to complete the full testing at that house. As a result, we added a ninth house, which was a manufactured home and is designated as Site L07.

All of the homes in this study were single story homes, in an attempt to mitigate uncertainty about duct leakage to inside. All homes were located in the Puget Sound region. With the exception of Site L07, which had a heat pump, all of the homes had gas furnaces.

Table 1 details some of the more pertinent characteristics of each house.

**Table 1. House Characteristics.**

Site	Air Handler Location	Foundation Type	Attic Detail	Floor Area (ft <sup>2</sup> )	Volume (ft <sup>3</sup> )
L01	Garage	Crawl Space	Single	1360	10777
L02	Garage	Crawl Space	Single	-- <sup>1</sup>	-- <sup>1</sup>
L03	Garage	Crawl Space	Dual/Split	1677	12826
L04	Crawl	Crawl Space	Single	973	7709
L05	Interior	Crawl Space	Single	1428	11425
L06	Crawl	Crawl Space	Single	758	5558
L07	Interior	Crawl Space	None	2635	23050
L08	Garage	Crawl Space	Single	1353	10379
L09	Crawl	Crawl Space	None	989	7741

<sup>1</sup> Floor area measurements were not taken at Site L02 due to time restrictions.

Tables 2 and 3 show important characteristics of the supply and return ducts, respectively, for each home. The majority of homes have trunk-and-branch supply systems, meaning that there is ductwork going from the supply plenum down the length of the house with ducts branching off of this main trunk to each register. Two of the homes have radial systems, meaning that instead of a main trunk they have ducts that go directly from the supply plenum to the registers. In one home, L08, there is a perimeter supply duct system, in which there are four trunks leaving the plenum that then travel down the length of the house in parallel, with branches at register locations, and then meet up again at the opposite end of the house, such that the duct system makes a full loop. With the exception of flex duct branches at Site L02, the supply ducts are all made of sheet metal.

Seven of the eight return duct systems (the manufactured home does not have a return system) were also made of metal, with Site L02 the exception. Most of the return systems were central systems, with either one or two grilles leading to large ducts that met up near the air handler. Site L08 has three return grilles, one large one in the living room and a smaller one in each of the two bedrooms. These each lead to a duct that meets up with the others in a junction box above the plenum. Site L05 has zoned returns, resulting in seven grilles that lead to a radial system.

**Table 2. Supply Duct Characteristics**

Site	Supply System Type	Supply Duct Material	Supply Zone	Number of Registers
L01	Trunk & Branch	Metal	Crawl	10
L02	Trunk & Branch	Metal/Flex	Crawl	12
L03	Trunk & Branch	Metal	Crawl	13
L04	Trunk & Branch	Metal	Crawl	8
L05	Trunk & Branch	Metal	Attic	10
L06	Radial	Metal	Crawl	5
L07	Trunk & Branch	Metal	Belly Space/Crawl	14
L08	Perimeter	Metal	Crawl	6
L09	Radial	Metal	Crawl	5

**Table 3. Return Duct Characteristics**

Site	Return System Type	Return Duct Material	Return Zone	Return Filter Type	Number of Grilles
L01	Trunk	Metal	Attic	Elec. Air Cleaner	1
L02	Trunk	Flex	Attic	Fiberglass	2
L03	Trunk	Metal	Attic	Elec. Air Cleaner	2
L04	Trunk	Metal	Crawl	Metal washable	1
L05	Radial	Metal	Crawl	Elec. Air Cleaner	7
L06	Trunk	Metal	Crawl	Elec. Air Cleaner	1
L07	--	--	--	Fiberglass	--
L08	Trunk	Metal	Attic	Elec. Air Cleaner	3
L09	Trunk	Metal	Crawl	Plastic washable	1

Five homes had electronic air cleaners. Two, including the manufactured home, had standard 1-inch fiberglass filters. The remaining two had washable permanent filters: the one at Site L04 was metal and the one at L09 was plastic.

At each house the ducts were modified in one or more ways to provide a variety of leakage levels at each house. In the results portions of this report, many of the results are broken down by a “Site/Configuration Designation”. This designation consists of two digits. The first digit is the site number (1-9) and the second is the duct configuration number (1-3). The duct configuration number specifies whether the leakage is approximately balanced, supply-dominated, or return-dominated. It is not consistent across all sites, but rather reflects the order in which they were done in the field. The following table provides a key to the designations, with as-found duct configurations indicated. Any modifications made to the duct system are indicated.

**Table 4. Site/Configuration Designation Key**

Site/Configuration Designation	Description
11 (as-found)	Supply-dominated
12	Balanced, supply leak sealed
13	Return-dominated, return hole opened, supply leak sealed
21 (as-found)	Supply-dominated
22	Balanced, return hole opened
23	Return-dominated, return hole opened, supply leak sealed
31 (as-found)	Balanced
32	Return-dominated, return duct disconnected
33	Supply-dominated, supply duct disconnected
41 (as-found)	Balanced
42	Return-dominated, return hole opened
43	Supply-dominated, supply duct disconnected
51	Supply-dominated, supply duct disconnected
52	Return-dominated, return duct disconnected
53 (as-found)	Balanced
61 (as-found)	Balanced
62	Supply-dominated, supply duct disconnected
63	Return-dominated, return hole opened
71	Supply-dominated, supply hole opened
72 (as-found)	Balanced
81 (as-found)	Return-dominated
82	Balanced, supply duct disconnected
83	Supply-dominated, supply duct disconnected, 2 registers sealed
91 (as-found)	Balanced
92	Supply-dominated, supply duct disconnected
93	Return-dominated, return hole opened

## TESTING METHODOLOGY

The field testing methodology was designed to look at both accuracy and repeatability of the leakage tests. In order to look at accuracy over a wide range of duct leakage levels, temporary changes were made to the duct leakage at each house such that three different leakage levels were tested. The goal was to have tests at each house with one duct configuration providing supply-dominated leakage, one with approximately balanced leakage, and one with return-dominated leakage. In most houses, one configuration was with the ducts in their as-found condition. Changes were then made from this baseline level of leakage. In many cases the as-found leakage was approximately balanced, and one modification was made on each the supply and return ducts to increase the leakage on one side or the other. It was not always possible to get the leakage well-balanced in a reasonable amount of time, so in some houses there are two sets of tests where the leakage is dominated on either the supply or return side in two configurations, one with moderate dominant leakage and one with more extreme dominant leakage.

To evaluate the repeatability of the leakage test methods, testing was repeated over a period of three days except at Sites L02 and L07, with a full set of tests on each duct configuration being performed each day. At L02 testing was only done on two days due to a power outage, and on the two days during which testing was done the testing was incomplete due to homeowner issues. At L07 testing was only done on two days because the lack of return system reduced the number of tests and duct configurations that were required.

A customized data collection system was provided by The Energy Conservatory, and was designed to communicate with two of their APT dataloggers simultaneously, one with 8 pressure channels and one with two. This allowed us to control two calibrated fans simultaneously and record up to ten pressures. Pressures were measured both high and low across an exterior door to get a measure of the stack pressure, across another exterior surface to get a pressure to outside on another building face (to allow for one side of the building having more stable pressures in the event of significant wind), to each buffer space (up to three: crawl space, attic, and garage), and to each the supply and return plenum. The remaining two pressure channels were allocated for the fan pressures of the calibrated fans.

The software allowed for any sampling period desired at each testing station, which allowed for investigation into the possibility that long-term averaging could overcome the impacts of wind, especially for the nulling test, which is the most sensitive test to wind. It also provided immediate feedback regarding the quality of the results. In the case of the Delta-Q test, it showed whether the curve of Delta-Qs vs. pressures had the correct shape. In the case of the nulling test, it provided feedback on whether the three pressure measurement stations did in fact result in an approximate straight line; when it did not, we were able to immediately resample one or more pressure stations to provide the desirable straight line. Detailed results were not evaluated at the house so as to not bias the following days' repeatability testing. Any automated system for doing these tests should provide these immediate checks so as to allow for the immediate discard and replacement of spurious results.

## LEAKAGE AT OPERATING CONDITIONS

### Unmodified Leakage Test Results

The first set of results compares the best estimate to the leakage estimates for the nulling test, Delta-Q test, and fan pressurization test as described previously. These estimates are expressed as a fraction of the air handler flow. This was done for two reasons. The first is to normalize the results for more direct comparability across houses. The second reason is that the thermal efficiency of a duct system depends on this fraction, not on the quantity of leakage itself. Later results will include adjustments to the nulling test and sensitivities of the Delta-Q test.

#### *Air Handler Flow*

The air handler flow measurements that are used in the calculations and summaries from this work are all based on the flow through a calibrated fan that is attached to the front of the air handler cabinet, with the return ducts isolated from the air handler via an airtight barrier. The fan is used to assist the air handler fan to provide the same supply plenum pressure as was measured under normal air handler operation, with the resulting flow being an estimate of air handler flow.

When performing the air handler flow tests, the air handler cabinet and any return duct downstream of the airtight barrier were sealed as well as possible to minimize the amount of air that could leak into the cabinet and not be counted by the calibrated fan. This was done by taping off seams, knockouts, and any leaks that were found. During testing we also felt around the air handler cabinet for air flows, and sealed any that were discovered.

In order to assess the adequacy of the airtight barrier, the return pressure was monitored during the measurement of the air handler flow. As this pressure tap was installed upstream of the barrier, the pressure difference between the return and outside should not change when the air handler and calibrated fan are turned on (and should be zero other than small stack or wind effects). If the return pressure changed while performing the test the barrier was checked and resealed until the return pressure did not change by performing the test.

#### *Supply Leakage Results*

Figures 4, 5, and 6 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.

Figure 4 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.

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 described previously of the impact that holes in the ducts can have on the neutral level of the building, 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 supply leakage in Figure 4), but there are large holes in the ducts (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 leakage estimates with the wrong sign 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 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.

Regarding these sources of error, it is interesting to note that all of the negative supply leakage fraction estimates from the nulling test in Fig. 4 are from one house, Site L06. This house, which had all of the ducts in the crawl space, had two fairly large holes in the return duct while there was little as-found leakage on the supply side. In addition, it was the only house at which we were unable to run the furnace in fan-only mode, and the temperatures in the house did change by large amounts during testing. Both of these factors may contribute to the sign error of the supply leakage fraction estimates.

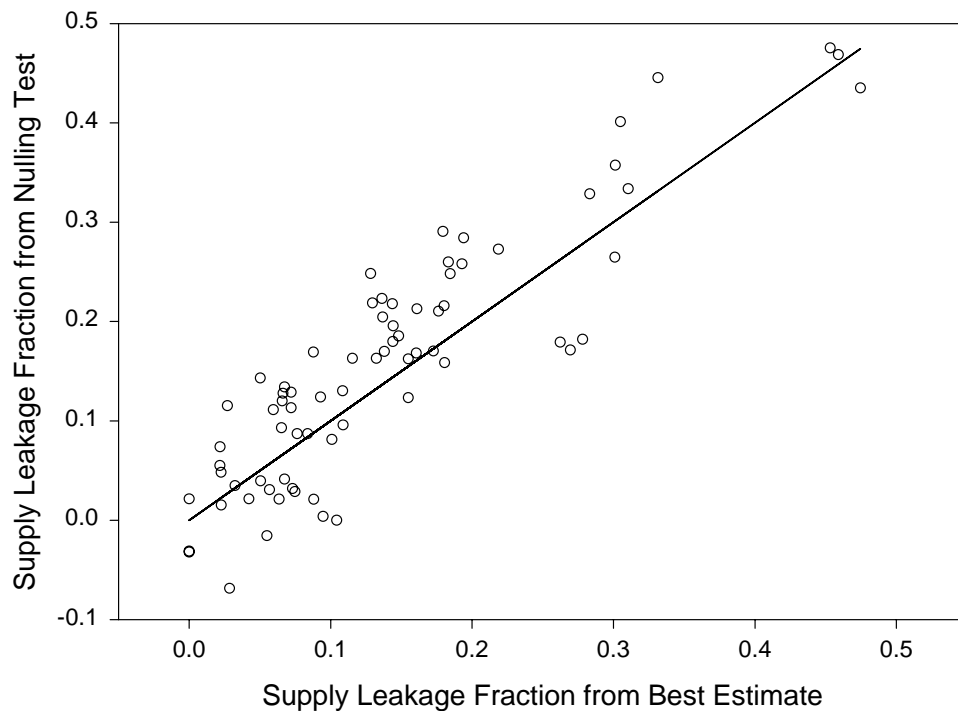


Figure 4. Comparison of supply leakage fraction estimate from nulling test to that from best estimate. The line indicates perfect agreement.

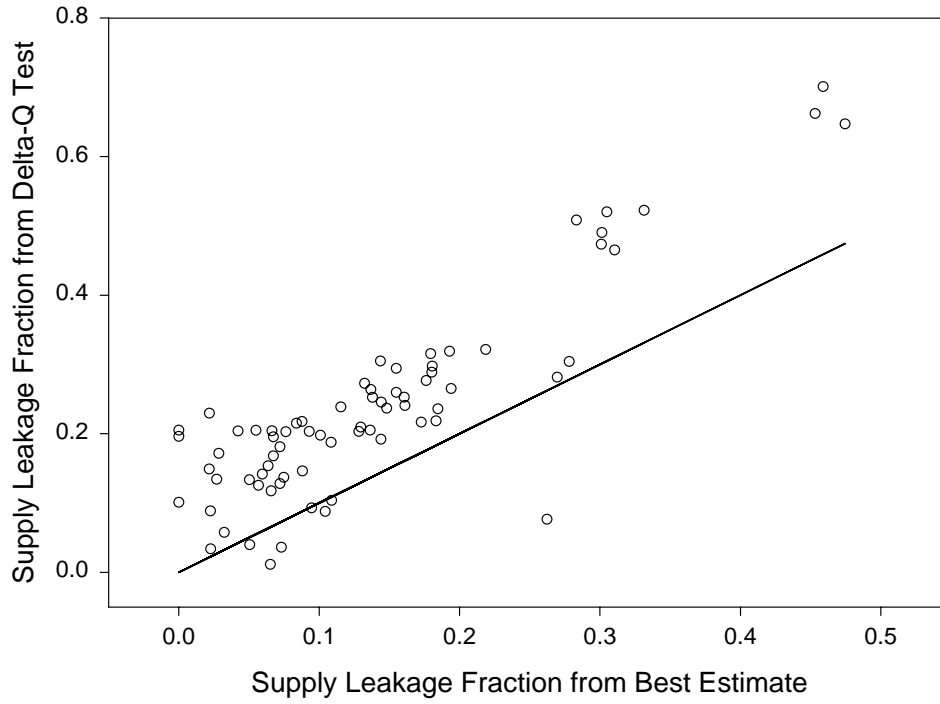


Figure 5. Comparison of supply leakage fraction estimate from Delta-Q test to that from best estimate. The line indicates perfect agreement.

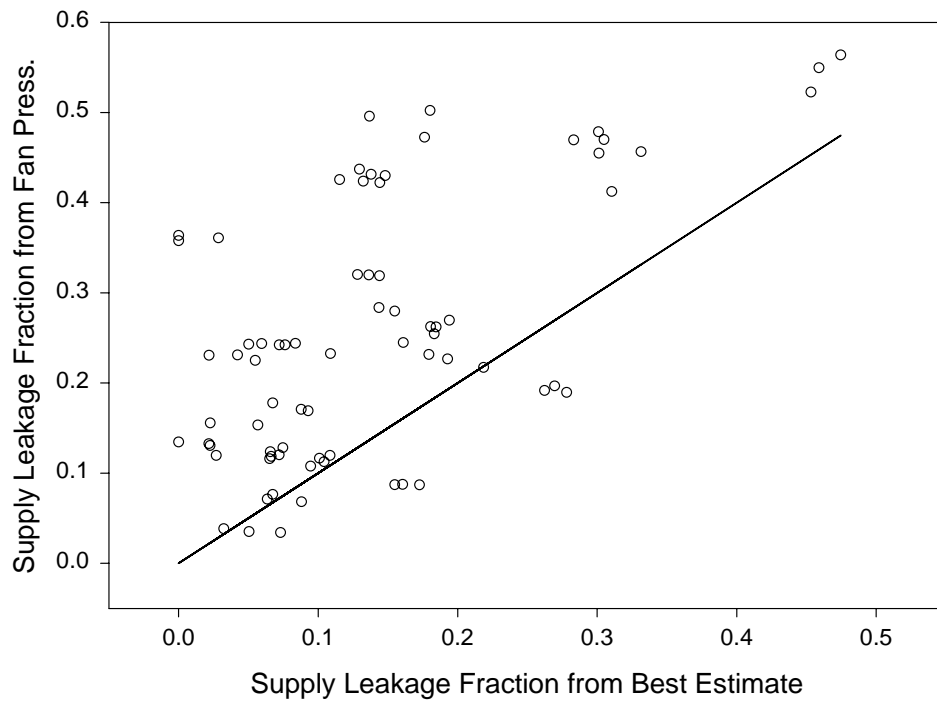


Figure 6. Comparison of supply leakage fraction estimate from fan pressurization test to that from best estimate. The line indicates perfect agreement.

Figure 5 shows that the Delta-Q test, while showing a similar slope to the best estimate, has a much more significant overestimation bias. Nearly all predictions overestimate the leakage fraction; the vast majority of cases that do not show an overprediction are at low leakage levels.

One of the primary causes of this bias has been identified as 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 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. The problems associated with this assumption will be analyzed and discussed in more detail in a later section of this report.

The fan pressurization test in Fig. 6 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.

Figure 7 compares the supply leakage fraction estimates by site and configuration, and overall for all houses and configurations. The bars represent averages for all iterations done at the site with the designated configuration.

With the exception of designations 21, 22, and 33, the nulling test provides a lower average estimate of supply leakage than the Delta-Q test in all cases. Of the three leakage test methods being evaluated, the fan pressurization test provides the highest average estimates of supply leakage in five of nine houses (across all leakage configurations), the lowest in two (L05 and L07), and the middle in two (L08 and L09).

One interesting issue that can be seen in Fig. 7 is that the Delta-Q test estimate of supply leakage can be greatly affected by the addition of a large return leak. This can be most easily seen by comparing designation 31 to 32, and also by comparing designations 91 to 93. In each of these pairs, no change has been made to the supply side of the ducts. However, in 32 and 93 a large leak was made in the return duct. The best estimates and nulling tests do not show a significant change in supply leakage due to adding the return leak, but the Delta-Q estimates increase by a sizeable amount. In fact, at Site L03, the supply leakage estimate from the Delta-Q test with the added return leak is about the same as the supply leakage estimate from the Delta-Q test with the added supply leak (designation 33).

This “crosstalk”, whereby large leakage on one side of the duct system also manifests itself as an increased leakage on the other side is of some concern regarding the usability of the test. At Site L03, with the large return leak (case 32), a contractor would have gotten the message that there was a large amount of supply duct leakage and could likely have spent a lot of time in the crawl space looking for leakage that was not really there. Fixing only the leakiest side first to try to mitigate this impact could help, but will not always be practical. In many cases, a retrofit team will want to work in parallel instead of in series, and taking the time to fix only one side, then

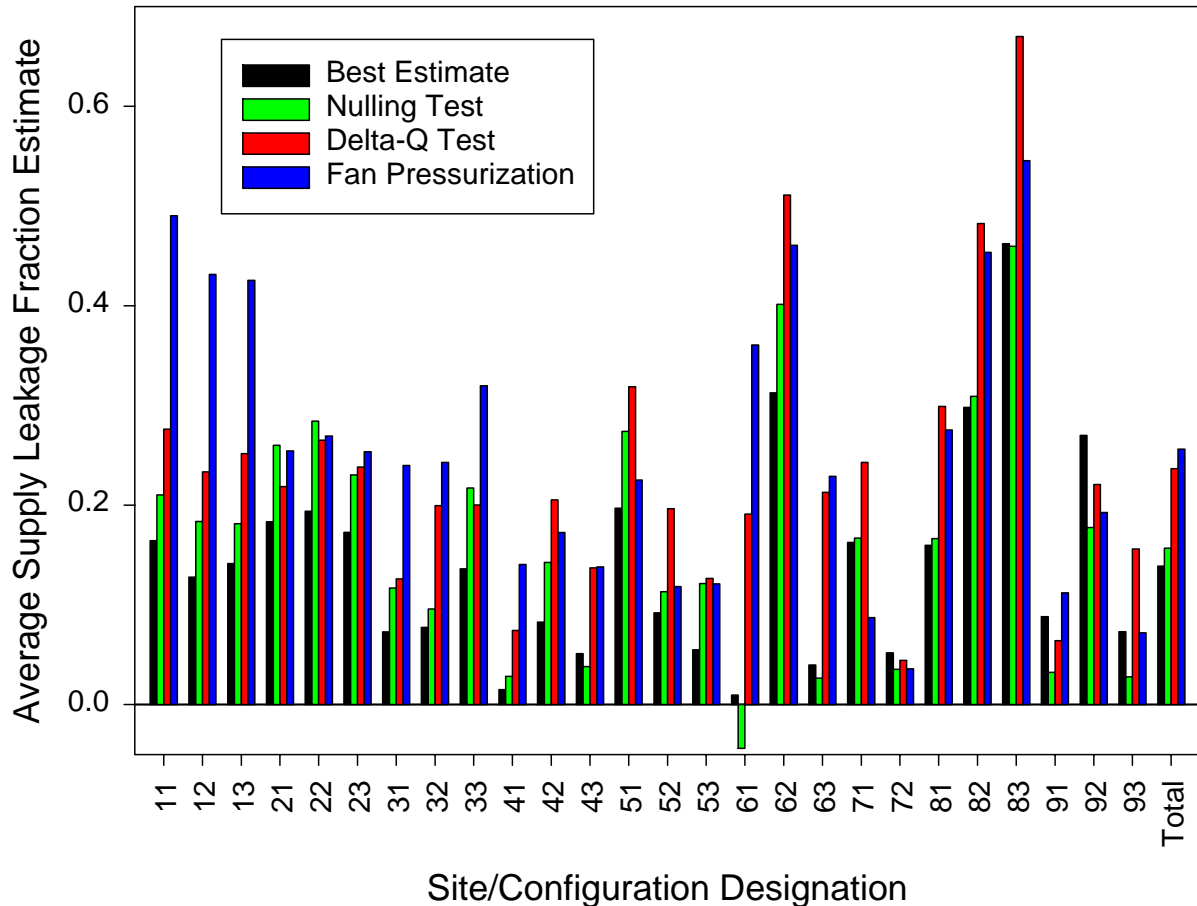


Figure 7. Comparison of supply leakage fraction estimates from all unmodified tests to those from best estimate. The Site/Configuration Designation key is in Table 4.

retest, and then fix the other side (if necessary) will take a lot longer than is desired. Also, since in most cases return leakage has a lesser impact than supply leakage, the time spent first fixing a return system that is somewhat leakier than the supply system, in order to mitigate the crosstalk problem, may not be the most cost-effective use of time and resources.

### Return Leakage Results

Figures 8, 9, and 10 compare the return leakage fraction estimates from the nulling test, Delta-Q test, and fan pressurization test, respectively, with the best estimate. The line indicates perfect agreement. Figures 8 and 9 show that the return estimates from the nulling test and Delta-Q test have similar trends to the supply estimates in Figs. 4 and 5, respectively. The nulling test has significant scatter but does not show a large bias with respect to the best estimate. The Delta-Q test provides return estimates that tend to systematically overestimate the leakage fraction from the best estimate.

The return estimates from the fan pressurization test, however, do show much better agreement than the corresponding supply leakage fraction estimates. There are three points in the upper

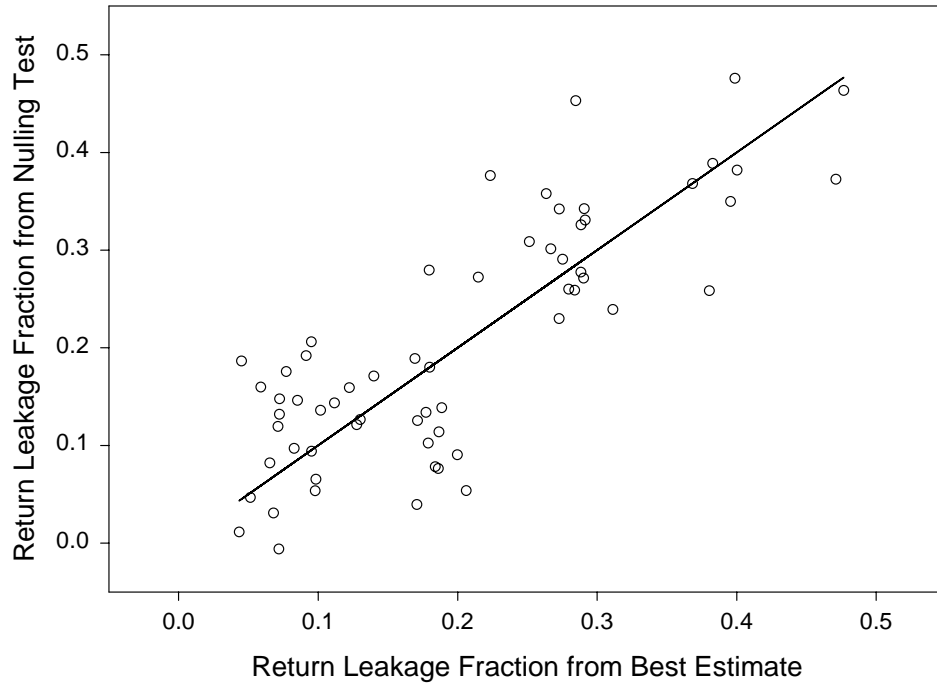


Figure 8. Comparison of return leakage fraction estimate from nulling test to that from best estimate. The line indicates perfect agreement.

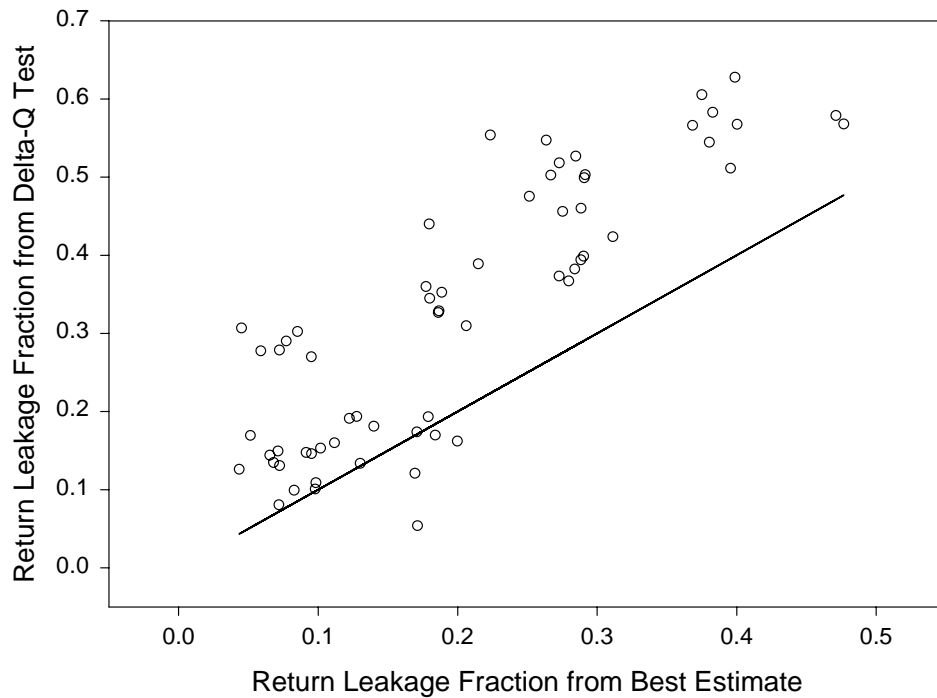


Figure 9. Comparison of return leakage fraction estimate from Delta-Q test to that from best estimate. The line indicates perfect agreement.

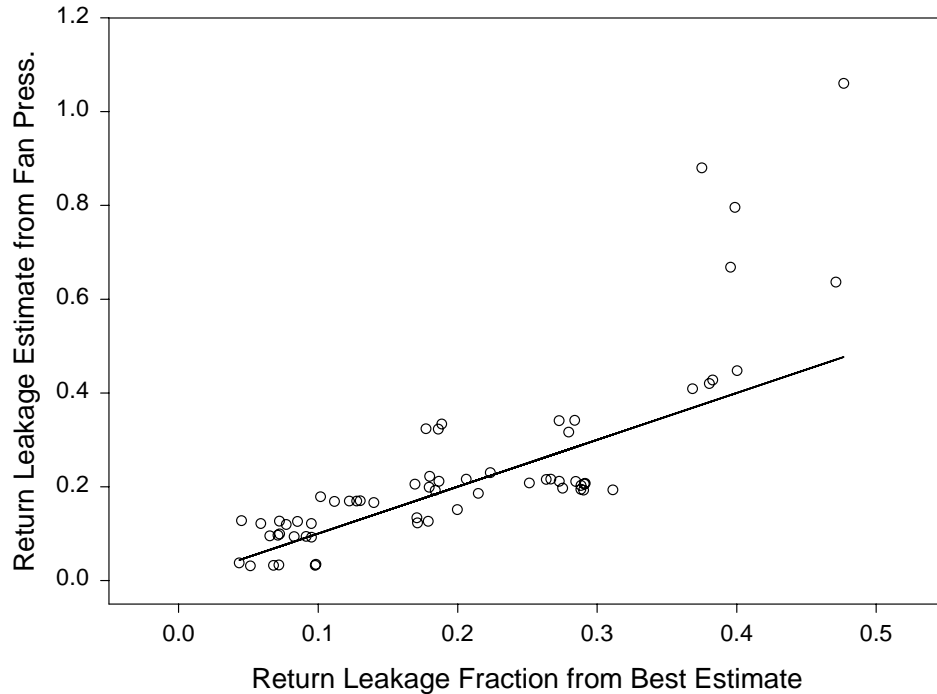


Figure 10. Comparison of return leakage fraction estimate from fan pressurization test to that from best estimate. The line indicates perfect agreement.

right corner that all show very poor agreement, but it should be noted that these three points represent the three repeated tests of the same configuration at the same house, so they only truly represent one outlying case. This case had one of two return trunks mostly disconnected, and the calibrated fan was only able to pressurize the return ducts to about 10 Pa. At low pressures such as this, noise becomes a large fraction of the signal, and extrapolation to half of the plenum pressure (16 Pa in this case) is problematic. While there was not any user error in performing this test in this case, one must conclude that the fan pressurization test is simply not applicable in a case such as this. Other than this case, Fig. 10 suggests that, for the return side in particular in these houses, half of the plenum pressure is a good surrogate for the operating pressure in the fan pressurization test.

All of the leakage test methods overestimate the return leakage fraction with respect to the best estimate on average over the entire sample. The nulling test overestimates by the smallest amount, with the Delta-Q test and the fan pressurization test both significantly higher, although the Delta-Q test not as high as the fan pressurization test.

Figure 11 compares the return leakage fraction estimates by site and configuration, and overall for all houses and configurations. Site L02 is not presented in this graph because an equipment problem caused us to not be able to get return grille flows during the four sets of tests that we were able to do at this house. Site L07 is not included because it does not have a return duct system. The bars represent averages for all iterations done at the site with the designated configuration.

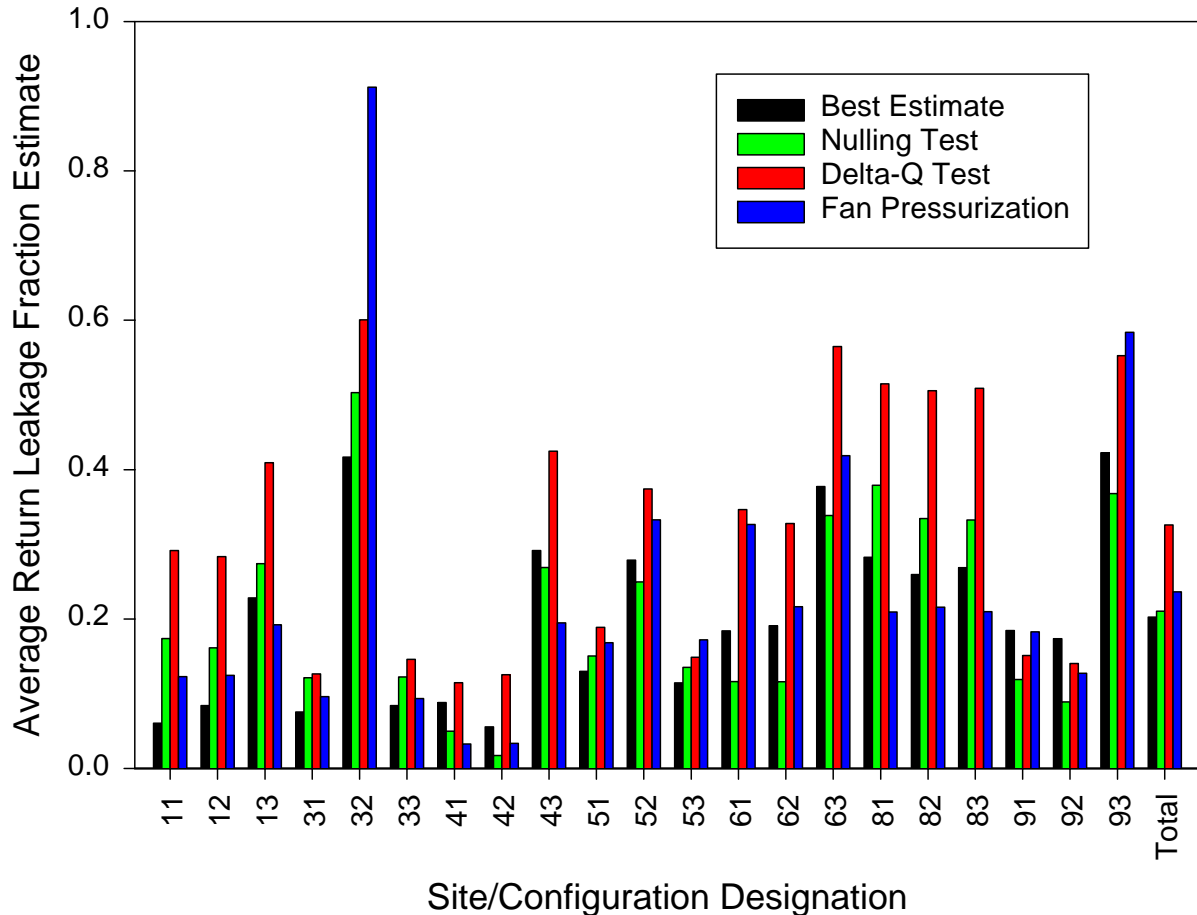


Figure 11. Comparison of return leakage fraction estimates from all unmodified tests to those from best estimate. The Site/Configuration Designation key is in Table 4.

On the return side, the nulling test provides lower average estimates than the Delta-Q test in all houses. The fan pressurization test provides the lowest average return leakage fraction estimates in three of seven houses, the highest in two (L03 and L09), and the middle in two (L05 and L06). Over all seven houses, the nulling test and fan pressurization test do about equally well, with the average estimates being slightly higher than the best estimates. The Delta-Q test averages a much higher estimate than any other method.

### Statistical Summary

The results presented in the previous two sections are quantified in Table 5a. For a point of reference, the results are also presented in cfm in Table 5b, so that the reader can get a feel for what amount of leakage corresponds to these estimates. Also included in Table 5b are the mean, median, minimum, and maximum measured air handler flows that correspond to the supply leakage estimates (the full sample) and the subset of cases with return leakage estimates (63 of 73 cases). It should be noted that, for comparisons to the best estimate, any error in the best estimate will be included in the summary results since whatever errors are in the best estimate are not separable from the differences.

For the sample as a whole on the supply side, the nulling test was the most accurate with respect to the best estimate, with a bias of about 1.8% of air handler flow, which is eight percentage points lower than for the Delta-Q test and about ten percentage points lower than the fan pressurization test. When viewed as distance from the best estimate prediction (i.e. taken as absolute differences), the nulling test accuracy error increases to about five percent of air handler flow, which is only about five 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 root mean squared error of the test methods with respect to the best estimate do show that the fan pressurization test has significantly more discrepancy than the Delta-Q test, including both bias and scatter. This can also be seen by comparing Figs. 5 and 6.

It is especially important to note that the Delta-Q test averages a supply leakage fraction prediction that is about 70% higher than the best estimate, which corresponds roughly to an average 70% overprediction on the impact of the supply leakage on energy loss. The fan pressurization test is even higher, at 84% greater leakage fraction than the best estimate. The nulling test overestimates the supply leakage fraction by an average of about 13%.

On the return side, the nulling test has extremely little bias. 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 absolute differences, however, show that there is a similar amount of error as for the supply leakage estimates.

**Table 5a. Summary of Supply and Return Leakage Fraction Estimates as a Percentage of Air Handler Flow**

	Best Estimate	Nulling	Delta-Q	Fan Press.
<b>Supply (n=73)</b>				
Mean	13.9	15.7	23.7	25.6
Median	11.5	15.9	20.5	23.3
Mean Diff. from Best	--	1.8	9.8	11.7
Median Diff. from Best	--	2.8	10.1	10.2
Mean Absolute Diff. from Best	--	5.0	10.6	13.2
Median Absolute Diff. from Best	--	4.2	10.3	10.2
RMS Error of Diff. from Best	--	5.8	12.1	16.5
<b>Return (n=63)</b>				
Mean	20.2	21.0	32.6	23.6
Median	18.4	18.0	32.7	19.3
Mean Diff. from Best	--	0.8	12.3	3.4
Median Diff. from Best	--	0.0	11.2	2.5
Mean Absolute Diff. from Best	--	6.0	13.0	7.8
Median Absolute Diff. from Best	--	4.6	11.6	4.7
RMS Error of Diff. from Best	--	7.5	15.4	13.0

**Table 5b. Summary of Supply and Return Leakage Estimates, in cfm**

	Best Estimate	Nulling	Delta-Q	Fan Press.
<b>Supply (n=73)</b>				
Mean	133	153	224	240
Median	118	143	221	270
Mean Diff. from Best	--	20	91	108
Median Diff. from Best	--	22	92	88
Mean Absolute Diff. from Best	--	47	98	121
Median Absolute Diff. from Best	--	41	93	88
RMS Error of Diff. from Best	--	56	112	149
<b>Return (n=63)</b>				
Mean	188	200	302	226
Median	148	166	267	177
Mean Diff. from Best	--	12	114	38
Median Diff. from Best	--	0	107	23
Mean Absolute Diff. from Best	--	54	120	75
Median Absolute Diff. from Best	--	44	107	43
RMS Error of Diff. from Best	--	70	143	139
<b>Air Handler Flow (cfm)</b>	Mean	Median	Minimum	Maximum
Supply cases (n=73)	937	900	619	1220
Return cases (n=60)	921	883	619	1220

The Delta-Q test has a similar amount of overestimation on the return side as it does on the supply side, at about 61% greater than the return leakage fraction from the best estimate. The mean absolute difference from the best estimate is again about twice that of the nulling test, and on the return side is also significantly greater than for the fan pressurization test.

The fan pressurization test shows surprisingly good agreement with the best estimate on the return side. The bias is not much larger than for the nulling test, nor is the mean absolute difference. It is of interest to note that, excluding the set of three tests that showed extremely poor agreement between the return fan pressurization test and the return best estimate, the fan pressurization test shows extremely good agreement, on average, with the best estimate. For these 60 tests, the fan pressurization test has a mean absolute difference from best estimate of 5.7% of air handler flow, which is slightly better than the nulling test for these cases at 5.8%. The Delta-Q test has a mean absolute difference of 12.8% of air handler flow for these 60 tests.

### *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 of each estimate and the average of the three estimates. This can be expressed mathematically as:

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

where  $\varepsilon_{\text{int}}$  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 6 shows the internal errors for each leakage test method on each the supply and return sides. These results are presented graphically in Figs. 13 and 14 for the supply and return leakage fraction estimates, respectively.

Figures 12 and 13 show the average internal error for each configuration at each site. Both of these graphs show what appear to be anomalous internal errors for the Delta-Q test at Site 9. Indeed, in two of the three configurations (designated 91 and 92), there was a single Delta-Q test that provided very different results than for the other two iterations. An investigation of the data does not indicate any problem with the data collection; therefore, they have not been dropped from the sample and should be considered the sort of spurious result one might expect to get occasionally over a large number of tests. However, we do not consider these results to accurately reflect the precision of the Delta-Q test. If Site 9 was dropped from the summary in Table 6, the Delta-Q test internal errors on the supply side would drop to an average of 1.2% of

**Table 6. Summary of Internal Errors of Supply and Return Leakage Fraction Estimates as a Percentage of Air Handler Flow**

	Best Estimate	Nulling	Delta-Q <sup>1</sup>	Fan Press. <sup>2</sup>
<b>Supply (n=69)</b>				
Mean	1.2	1.7	1.6	0.6
Median	1.0	1.3	1.1	0.4
Standard Deviation	0.8	1.4	2.1	0.7
<b>Return (n=63)</b>				
Mean	1.4	2.6	1.8	1.3
Median	1.0	2.3	1.5	0.3
Standard Deviation	1.4	2.0	1.6	3.0

1 If Site 9 results were dropped to eliminate the two anomalous Delta-Q tests, the supply-side internal errors for this test would drop to an average of 1.2%, a median of 0.8%, and a standard deviation of 0.9% of air handler flow. On the return side, the internal errors would drop to an average of 1.5%, a median of 1.4%, and a standard deviation of 1.3% of air handler flow.

2 If designations 32 and 93 were dropped to eliminate the anomalous fan pressurization tests, the return-side internal errors for this test would drop to an average of 0.5%, a median of 0.3%, and a standard deviation of 0.6% of air handler flow.

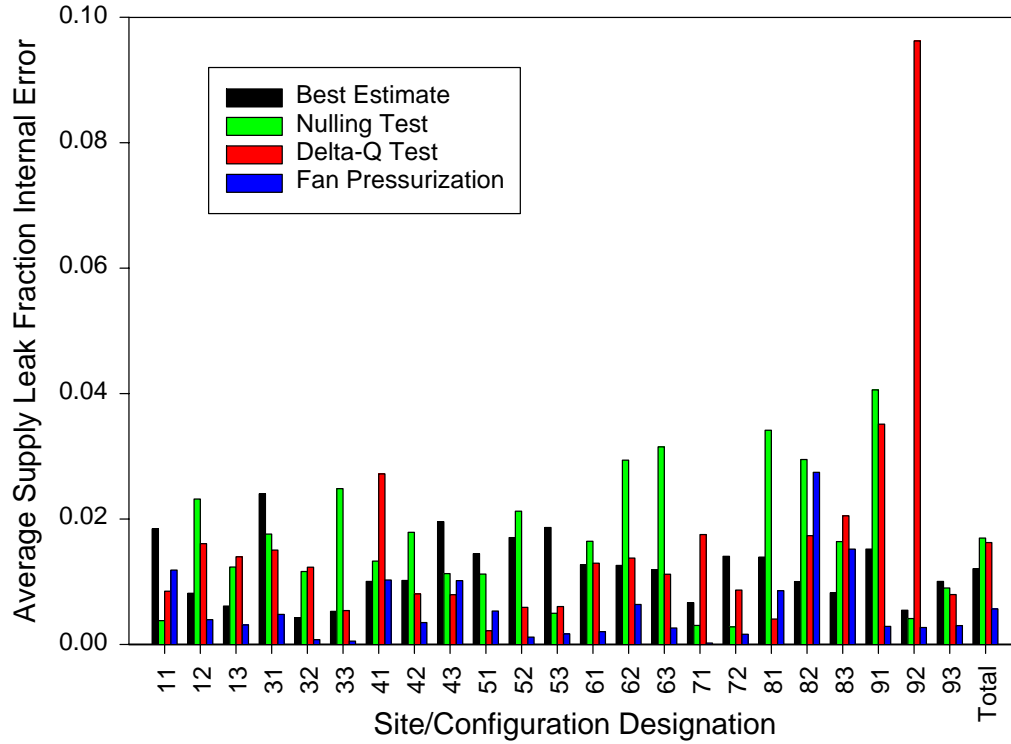


Figure 12. Supply leakage fraction internal errors (repeatability) from best estimate and all unmodified tests. The Site/Configuration Designation key is in Table 4.

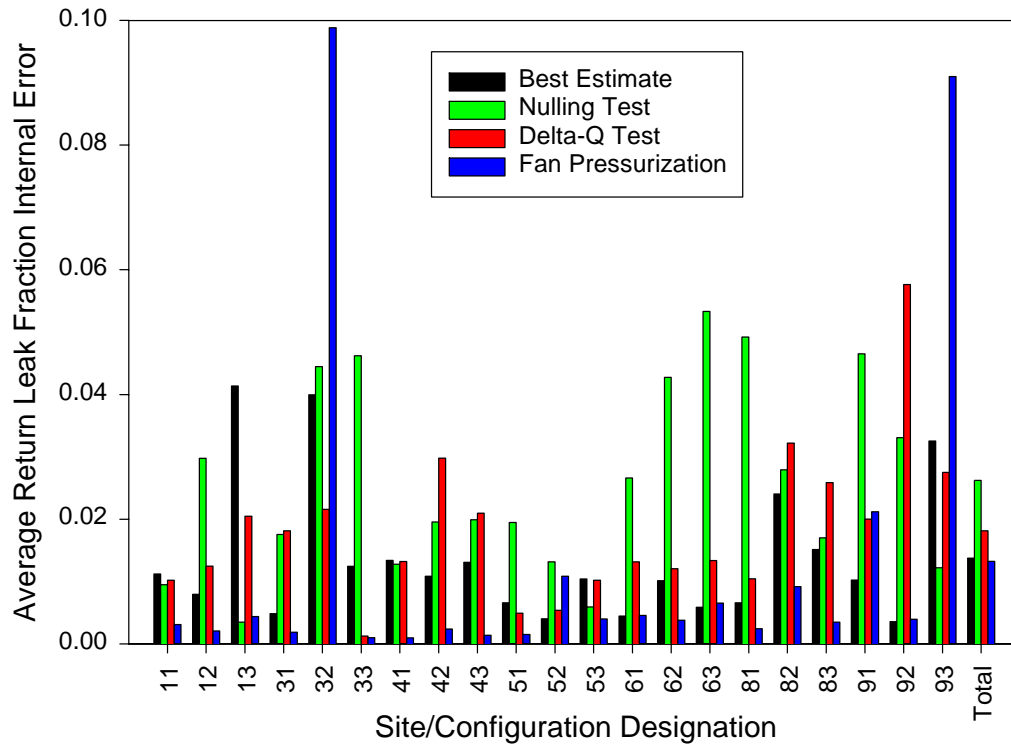


Figure 13. Return leakage fraction internal errors (repeatability) from best estimate and all unmodified tests. The Site/Configuration Designation key is in Table 4.

air handler flow with a standard deviation of 0.8% of air handler flow. The median would be 0.9% of air handler flow. The statistics for the other tests do not change significantly with this additional restriction.

There are also anomalous large errors for the fan pressurization test in two site/configuration combinations. The first one, designation 32, is the case discussed previously with a large disconnect in one of the two main trunks. We were unable to pressurize this duct to more than about 12 Pa, and the large extrapolation to half of the plenum pressure caused very different results in each of the three repetitions. This result is more of an indication that the fan pressurization test is not applicable to this situation than that there was any mistake done in performing the test.

The other anomalous repeatability error for the fan pressurization test on the return side is in designation 93. An investigation of the data shows that the leakage curve exponent is extremely low, at about 0.42 for one case. This indicates a mistake in the actual execution of the test, and not a problem with the test method itself. However, as the problem was not noticed by the experienced crew even with the automated software, it can be considered to be the sort of error that can and will be made on occasion. If designations 32 and 93 were removed from the repeatability analysis, the fan pressurization test on the return side would have a mean internal error of 0.5% of air handler flow with a standard deviation of 0.6%. The median would remain at 0.3% of air handler flow.

The repeatability 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.

## Issues Regarding the Nulling Test

As discussed in the “Leakage Test Methods” section, the nulling test is subject to errors due to the effect of holes in the ducts on the neutral level and the impacts of indoor temperature changes on the stack pressure. The nulling test is also somewhat more sensitive to noise from high wind speeds than other tests due to the size of the pressures being measured. This section discusses our investigations into ways to address these issues.

### *Modified Nulling Test Results*

At five of the houses (Sites L04-L08) we collected additional data so that we were able to make corrections for the effect of holes in the ducts on the neutral level and the impacts of indoor temperature changes on the total stack pressure. The total stack pressure is the pressure difference measured across the building envelope at the top of the building minus the pressure difference measured across the building envelope at the bottom of the building.

To account for the effect of duct leaks on the neutral level, we measured the neutral level with the air handler off and all registers and grilles sealed as well as with all registers and grilles open. Comparison of these neutral levels provides an indication of the amount of change from the duct leaks and the amount of correction required. Applying the regression line from the nulling tests to the adjusted neutral levels provides an estimate of the corrected duct leakage.

We made two different types of adjustments to account for possible changes in total stack pressure due to changing indoor temperatures. The first was to make a direct adjustment to the total stack pressure by comparing the total stack pressure measured with the air handler off and the total stack pressure measured with the air handler on. The second was to use the change in temperature difference between indoors and outdoors from the period when the air handler was off to the periods with the air handler on. In both cases, corrections were made to each data point within the periods with the air handler on. These corrections were applied using the corrected neutral level described above, not the unmodified nulling test result.

The general equations for correcting the nulling test for a change in total stack pressure are as follows:

Nomenclature:

- $\Delta P_{s,0}$  average total stack pressure (i.e. pressure at the top of the building minus pressure at the bottom of the building) with air handler off (baseline) **[from data]**
- $\Delta P_{s,j}$  total stack pressure with air handler on at jth data point **[from data]**
- $\Delta P_0$  average pressure across ceiling with air handler off (baseline) **[from data]**
- $\Delta P_j$  pressure across ceiling with air handler and nulling fan on, with total stack pressure measured with air handler on, at jth data point **[from data]**
- $\Delta P_{j,0}$  pressure across ceiling with air handler and nulling fan on, with total stack pressure measured with air handler off, at jth data point **[this is what we want, needs to be calculated]**
- $\Delta P_f$  pressure change induced by nulling fan **[to be calculated]**

A	stack adjustment factor [ <b>to be calculated</b> ]
T <sub>out,0</sub>	average outdoor temperature with air handler off [ <b>from data</b> ]
T <sub>in,0</sub>	average indoor temperature with air handler off [ <b>from data</b> ]
T <sub>out,j</sub>	average outdoor temperature with air handler on at jth data point [ <b>from data</b> ]
T <sub>in,j</sub>	average indoor temperature with air handler on at jth data point [ <b>from data</b> ]

Equations:

$$\Delta P_{s,j} = A\Delta P_{s,0} \quad (10)$$

$$\Delta P_j = A\Delta P_0 + \Delta P_f \quad (11)$$

$$\Delta P_{j,0} = \Delta P_0 + \Delta P_f \quad (12)$$

Rearranging (11),

$$\Delta P_f = \Delta P_j - A\Delta P_0 \quad (13)$$

Substituting into (12),

$$\Delta P_{j,0} = \Delta P_0 + \Delta P_j - A\Delta P_0 \quad (14)$$

Rearranging (14),

$$\Delta P_{j,0} = (1 - A)\Delta P_0 + \Delta P_j \quad (15)$$

The only piece that we need to calculate at this point is A, which can take one of two forms.

To correct directly from measured stack pressures:

$$A = \frac{\Delta P_{s,j}}{\Delta P_{s,0}} \quad (16)$$

To correct based on temperature difference between indoors and outdoors:

$$A = \frac{(1/T_{out,j} - 1/T_{in,j})}{(1/T_{out,0} - 1/T_{in,0})} \quad (17)$$

### Supply Leakage Results

Figure 14 compares the average supply leakage fraction estimates, by site and configuration designation, from the unmodified nulling test and the three modified versions of the nulling test with the best estimate.

This graph shows that, while making the adjustment for neutral level can have a beneficial impact (such as at Site L04), the effect is typically small and in some cases provides a worse

answer. Overall, the average neutral level-corrected supply leakage fraction estimates from the nulling test is about one percentage point greater than the best estimate (15.2% vs. 14.2%), whereas the unmodified estimates average about 1.7 percentage points above the best estimate for these cases (16.0%).

As for corrections for stack pressure, there is also typically little impact. The only notable case where the stack pressure correction appears to be significant is at Site L06. At this site, which is the site where we had no fan-only setting available to us, correcting for stack pressure changes largely eliminates the negative leakage fraction estimates in configuration 1 and improves the estimates noticeably for configuration 3. In configuration 2 there was no notable impact of the stack pressure correction.

Overall, the average supply leakage fraction estimates with both neutral level and stack pressure corrections incorporated do not differ significantly from the unmodified test. Both of the stack pressure-corrected versions have averages that fall in between the unmodified test and the test with only the neutral level correction made.

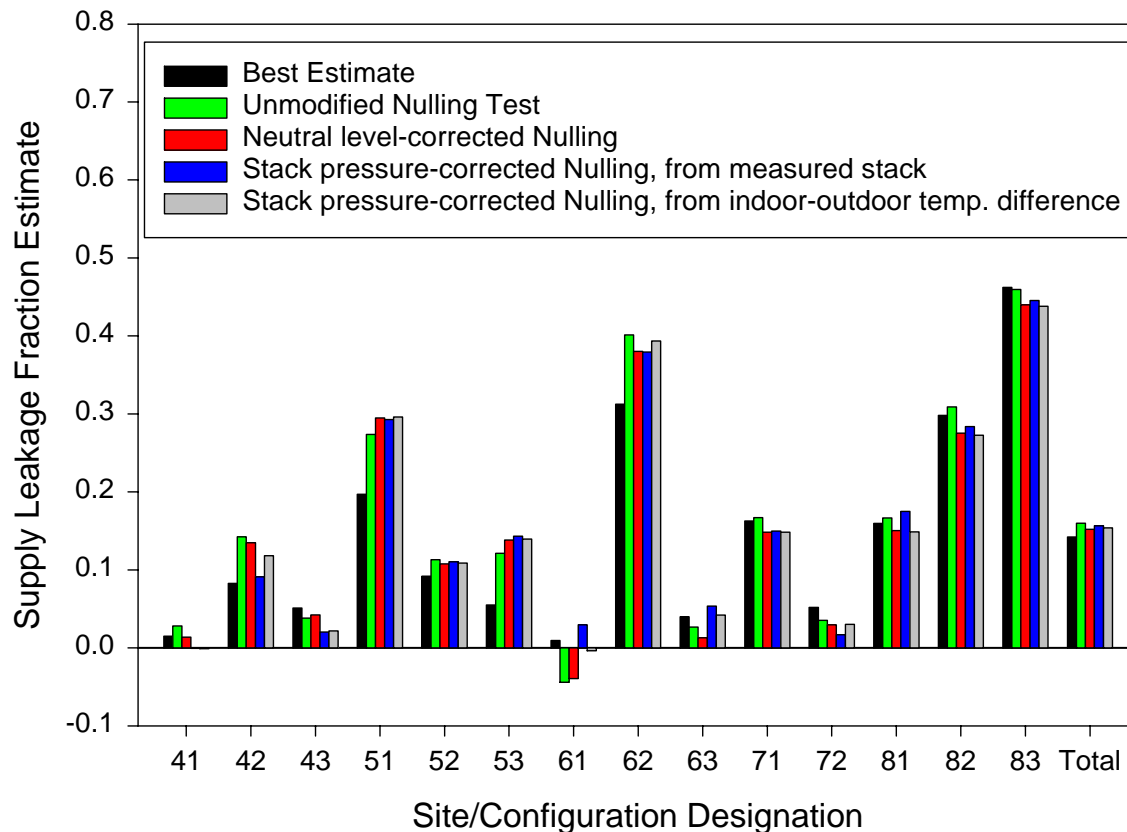


Figure 14. Supply leakage fraction estimates from best estimate, unmodified nulling test, and nulling tests corrected for neutral level and stack pressure changes. The Site/Configuration Designation key is in Table 4.

## Return Leakage Results

Figure 15 compares the average return leakage fraction estimates, by site and configuration designation, from the unmodified nulling test and the three modified versions of the nulling test with the best estimate.

This graph largely reinforces the conclusions from the supply leakage fraction estimates, in that there is typically not a lot of impact of making the corrections and that the corrections may not always improve the estimates. At Site L06, the results do show marked improvement, as they did on the supply side.

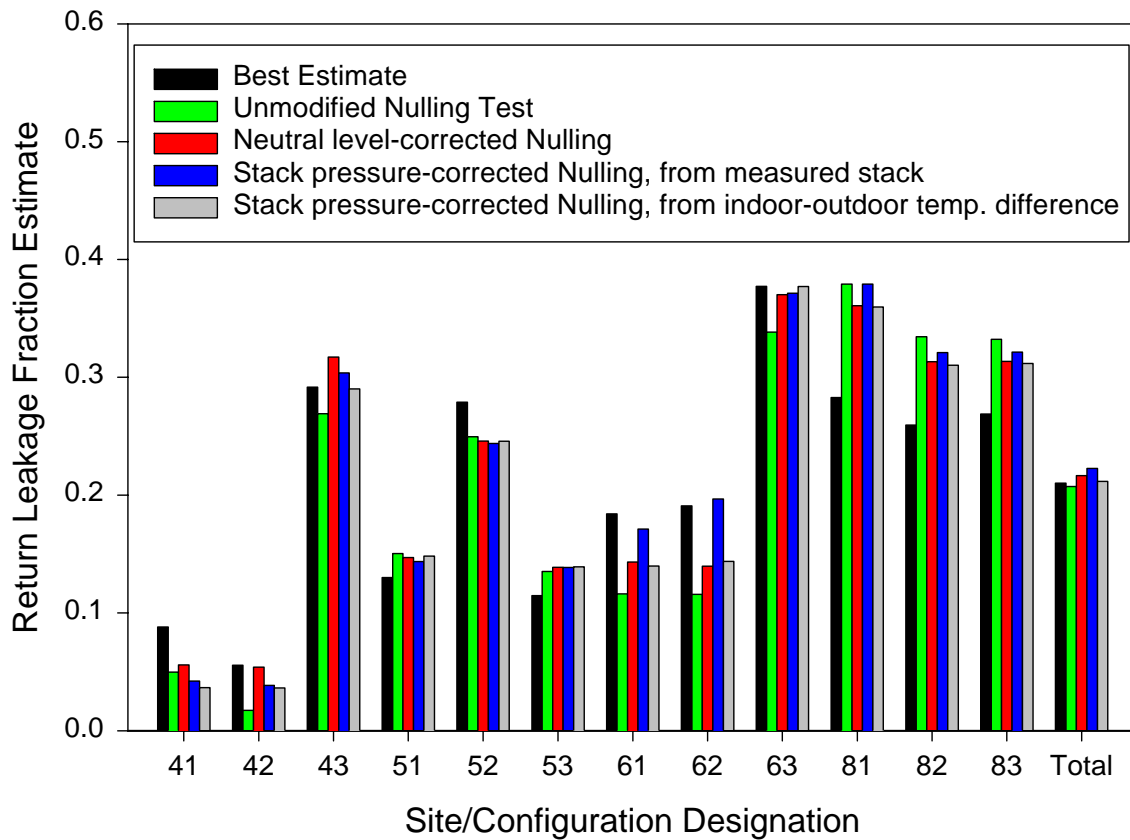


Figure 15. Return leakage fraction estimates from best estimate, unmodified nulling test, and nulling tests corrected for neutral level and stack pressure changes. The Site/Configuration Designation key is in Table 4.

## Conclusion

These results suggest that, except for houses at which the fan cannot be operated without also operating the heating or cooling equipment, there is little to be gained by going to the additional effort of gathering the information required to make these adjustments. It may be that an adjustment would be warranted in tall houses on cold days, but this project did not gather any information suitable for addressing this situation. It is likely that one of the primary reasons for the lack of improvement from these corrections is that the changes in pressures that are being corrected are small and within the noise level of the measurements.

### *Impact of Wind*

At Sites L04 and L09 some nulling tests were performed during periods of high winds. At Site L04 this occurred on the second day. At Site L09 both of the first two days had high winds. When attempting to perform the tests under windy conditions and without increasing the sample time, we found that the noise from the wind was much larger than the signal, and we were unable to get any reasonable results. To dampen the impacts of the wind on the nulling test results, we increased the sampling time for each pressure station during the test, from 20-30 seconds to 120-180 seconds. Also, rather than trying to match specified pressures, we simply set the nulling fan to each of three distinct flow rates, and used the regression line to correct to the target pressure.

Table 7 shows the results of increasing the sample time. At Site L04 we did not have a working anemometer. By Site L09 we had a three-cup anemometer. As a result, Table 7 only includes maximum wind speeds for Site L09. In the table, the letters (A, B, C) indicate the first, second, or third day, respectively; the numbers (1, 2, 3) indicate the configuration.

**Table 7. Impact of Increased Sampling Time on Nulling Test Results During Windy Days**

	Sampling Time (s)	Supply Leakage Fraction (%)	Return Leakage Fraction (%)	Max. Wind Speed (mph)	Air Handler Flow (cfm)
<b>Site L04</b>					
A1	20	4.8	6.5	--	643
B1	180	1.5	5.3	--	655
C1	20	2.1	3.1	--	654
A2	20	13.4	1.1	--	619
B2	180	12.4	-0.6	--	645
C2	20	16.9	4.7	--	644
A3	20	2.9	23.9	--	694
B3	180	3.1	27.7	--	685
C3	20	5.5	29.1	--	671
<b>Site L09</b>					
A1	120	0.0	9.0	6.8	808
B1	120	9.3	18.9	10.4	794
C1	30	0.4	7.8	0	807
A2	120	17.9	12.5	5.9	798
B2	120	17.1	3.9	10.4	788
C2	30	18.2	10.2	0	802
A3	120	2.1	38.2	7.1	807
B3	120	4.1	35.0	11.9	798
C3	30	2.1	37.2	0	800

This table shows that, in most cases, the results for the tests performed under windy conditions are comparable to the tests done with little wind. The largest discrepancy at Site L04 is about 5% of air handler flow, which corresponds to only about 32 cfm. There are some results from Site L09 which do show a marked difference from the others. For configuration 1 on the second day both the supply and return are about 9% of air handler flow higher than the other tests, corresponding to about 72 cfm. The fact that both supply and return results are high by about the same amount indicates that the unbalanced leakage test was in line with the tests from the other days. The other test that shows a marked discrepancy is on the second day in configuration 2. The return leakage is about 8% of air handler flow lower than the other tests, which is about 64 cfm. Because the supply does not show this behavior, the error is in the unbalanced leakage test.

Overall, the results in Table 7 suggest that increasing the sampling time will often mitigate the effects of wind on the nulling test.

## Issues Regarding the Delta-Q Test

This section discusses several issues about the Delta-Q test that we have investigated. One issue is the sensitivity of the equations to the inputs of duct pressure and leakage exponent. A second issue is the applicability of the test to homes without return systems, such as manufactured homes. The third issue discussed in this section is the validity of the assumption that the duct pressure changes by the same amount as the house pressure throughout the test, such that the pressure between the ducts and the house remains constant. Finally, the possible impact of envelope pressure changes from unbalanced leakage on the test is discussed. There are other questions that have been raised about the Delta-Q test, including some mentioned in the description of this test earlier in this report, that were not investigated in this project.

### *Sensitivity to Pressure and Exponent Assumptions*

The Delta-Q test requires assumptions for duct pressures and leakage exponents. The developers of the analysis methodology stipulate that the pressures measured at the supply and return plenums be used for the duct pressures, and that a leakage exponent of 0.6 be used. These are the assumptions that produced the results in the “Unmodified Leakage Test Results” section. In this section we present results for other pressure and exponent assumptions.

### Pressures

Originally, the developers of the Delta-Q test analysis technique suggested that, instead of using the full plenum pressure for the duct pressure, half of the plenum pressure should be used. Later work by Andrews (2000) suggested that using the full plenum pressure would reduce the bias of the Delta-Q test when compared to analytic solutions. Partially as a result of this work, the recommendation was changed to be the full plenum pressure.

To investigate the sensitivity of the Delta-Q leakage estimates to the pressure assumptions, we also performed the analysis with pressure assumptions of one-half and one-quarter of the plenum pressures. The same fractional assumption was used for both the supply and return for all cases, because any final test recommendation would almost certainly propose a single fractional pressure assumption for both sides. While the one-quarter plenum pressure assumption has not been suggested by anyone as a possible standard assumption, we included it for a variety of reasons, including evaluation of the sensitivity over a wider range, evaluation of this pressure assumption as a possible improvement over the other two options, and investigation of the shape of the sensitivity curve. The standard default exponent of 0.6 was used for all runs.

Figure 16 shows the supply leakage fraction estimates resulting from the different pressure assumptions. This graph illustrates a number of interesting findings. One finding is that, counter to what intuition would suggest, the leakage estimates do not increase with increasing pressure assumptions. In some cases, such as at Sites L04 and L05 (designations 41, 42, 43, 51, 52, and 53), the one-quarter plenum pressure assumption results in the highest supply leakage prediction.

Figure 16 also shows that, not only do the results not increase with increasing pressure assumption, but that the trend is not always monotonic. Designations 43 and 52 are two examples of this. At each of these (and in others as well), the half-plenum pressure assumption provides a lower estimate than either the full plenum pressure or the quarter-plenum pressure. This corroborates a finding by Andrews (2000).

The extremely large leakage estimate seen in Fig. 16 for designation 71 using one quarter of the plenum pressure is due to the instability of the equation when very small pressures are input into the Delta-Q equations. In this case, which had no return duct, the return pressure that was used was one quarter of the pressure measured in the air handler closet. The result was a pressure that was low enough to cause the equation to “blow up”, with a large amount of “crosstalk” causing the supply leakage estimate to be extremely large.

These behaviors do not by themselves constitute a serious practical problem with using the test and a specific pressure assumption. If the results do not vary a lot between pressure assumptions, or if one pressure assumption systematically gives the best result, then this issue can be considered minor. However, this does not prove to be the case. On average, the half-plenum pressure assumption gives the best result and the quarter-plenum pressure assumption gives the worst, although all pressure assumptions significantly overestimate the leakage. In individual cases, however, the quarter-plenum pressure assumption is sometimes the best. Also, if the three sets of assumptions are compared within a designation, there are frequently two pressure assumptions that provide similar answers and one that appears to be an outlier. Which one is the outlier varies from case to case. The largest discrepancies over the entire sample do tend to be with the quarter-plenum assumption. It is also of interest to note that, in cases where the leakage estimates either monotonically increase or decrease with increasing pressure assumption, it is the pressure assumption that provides the largest amount of leakage that is most different from the other estimates.

Figure 17 shows the corresponding results for the return leakage estimates. As in the section on unmodified results, Sites L02 and L07 are not included in the return leakage graph. The return leakage results reinforce the findings from the supply leakage estimates.

Table 8 presents the statistical results for this analysis. This table shows that the half-plenum pressure assumption tends to perform better in all respects than the full plenum assumption, although the discrepancy relative to the best estimate is still large. The quarter-plenum assumption results suggest that a few large errors dominate the average. This can be seen by comparing the means of the supply estimates, which show a better result with the full plenum pressures, to the medians, where the quarter-plenum pressure assumption is nearly as good as the half-plenum assumption and better than the full plenum.

These results suggest that the quarter-plenum assumption is too prone to spurious results to be a viable candidate. They also suggest that, despite the suggestions of prior work, the full plenum assumption is not as good as the half-plenum pressure assumption. However, the half-plenum pressure assumption still shows enough bias (about 55% greater, on average, than the best estimate) that changing back to this recommendation is not sufficient to consider the Delta-Q test to be an accurate test.

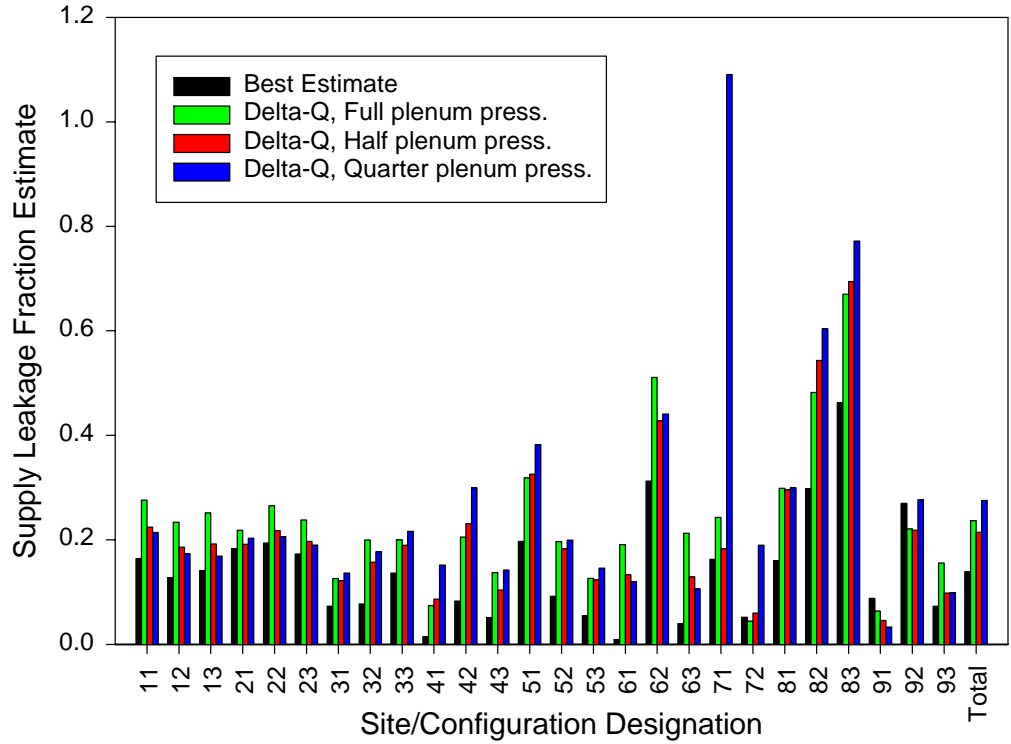


Figure 16. Supply leakage fraction estimates from best estimate and Delta-Q test with three pressure assumptions: full plenum (unmodified), half plenum, and quarter plenum. The Site/Configuration Designation key is in Table 4.

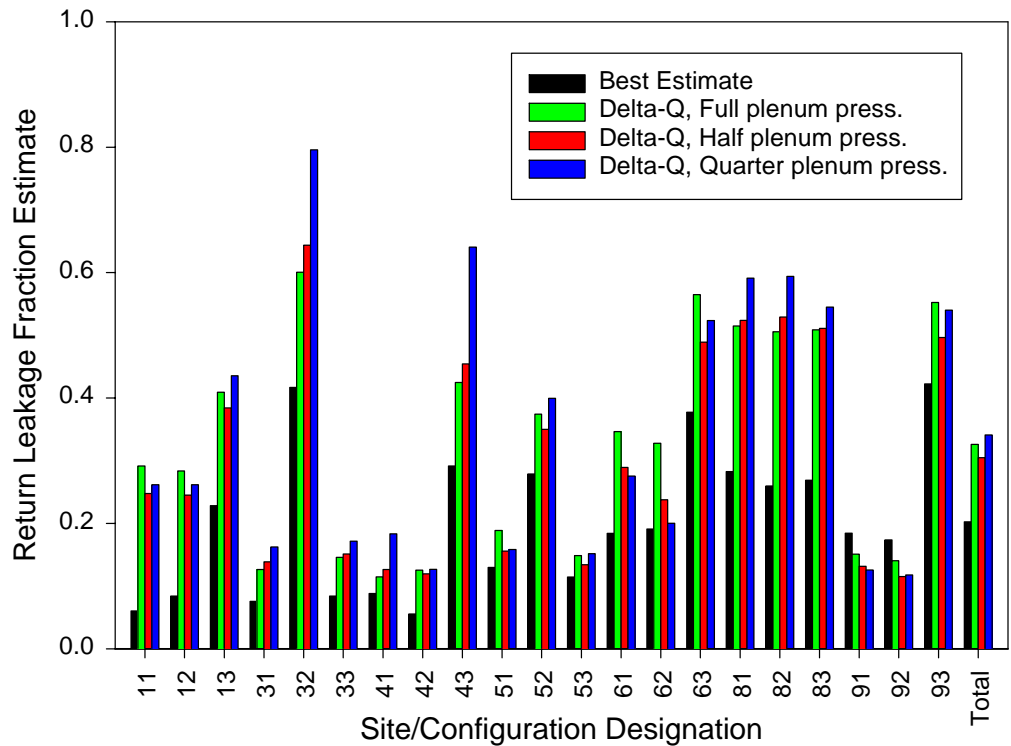


Figure 17. Return leakage fraction estimates from best estimate and Delta-Q test with three pressure assumptions: full plenum (unmodified), half plenum, and quarter plenum. The Site/Configuration Designation key is in Table 4.

**Table 8. Summary of Supply and Return Leakage Fraction Estimates as a Percentage of Air Handler Flow for Different Pressure Assumptions in Delta-Q Test**

	Best Estimate	Delta-Q		
		Full Plenum	½- Plenum	¼- Plenum
<b>Supply (n=73)</b>				
Mean	13.9	23.7	21.5	27.5
Median	11.5	20.5	18.6	19.2
Mean Diff. from Best	--	9.8	7.6	13.6
Median Diff. from Best	--	10.1	7.2	9.4
Mean Absolute Diff. from Best	--	10.6	8.5	14.6
Median Absolute Diff. from Best	--	10.3	7.4	9.6
RMS Error of Diff. from Best	--	12.1	10.6	23.8
<b>Return (n=63)</b>				
Mean	20.2	32.6	30.8	34.6
Median	18.4	32.7	25.8	26.6
Mean Diff. from Best	--	12.3	10.6	14.3
Median Diff. from Best	--	11.2	8.8	11.8
Mean Absolute Diff. from Best	--	13.0	11.7	16.0
Median Absolute Diff. from Best	--	11.6	9.1	12.6
RMS Error of Diff. from Best	--	15.4	14.4	20.4

Table 8 also shows that the errors are larger for the return side than the supply side, though as a fraction of the best estimate the errors are fairly similar. This suggests that the errors may be percentage errors (i.e. multiplicative) rather than offset errors (i.e. additive).

### Exponents

To evaluate the sensitivity of the Delta-Q results to the assumption of leakage exponent, we performed Delta-Q analyses with three additional sets of exponents. These are 0.55 for both supply and return, 0.65 for both supply and return, and the supply and return exponents from the duct pressurization test. As with the pressure assumptions, no mixing of these exponent assumptions was done because any final analysis method would most likely stipulate the same exponent for each side. The exponents from the duct pressurization test are not intended to represent a possible suggestion for a standardized Delta-Q test, because the time required to perform both the Delta-Q test and the duct pressurization test would be prohibitive in anything but a research setting. However, it is of interest to determine whether the use of measured exponents improves the results. All of the exponent-sensitivity runs were done with the full plenum pressure.

Figures 18 and 19 show the results of this analysis for the supply and return leakage, respectively. Unlike the pressure-sensitivity results, these results show that the leakage estimates monotonically increase with increasing exponent. On average, however, all of the exponent sets still provide leakage estimates that are significantly higher than the best estimate. The exponent

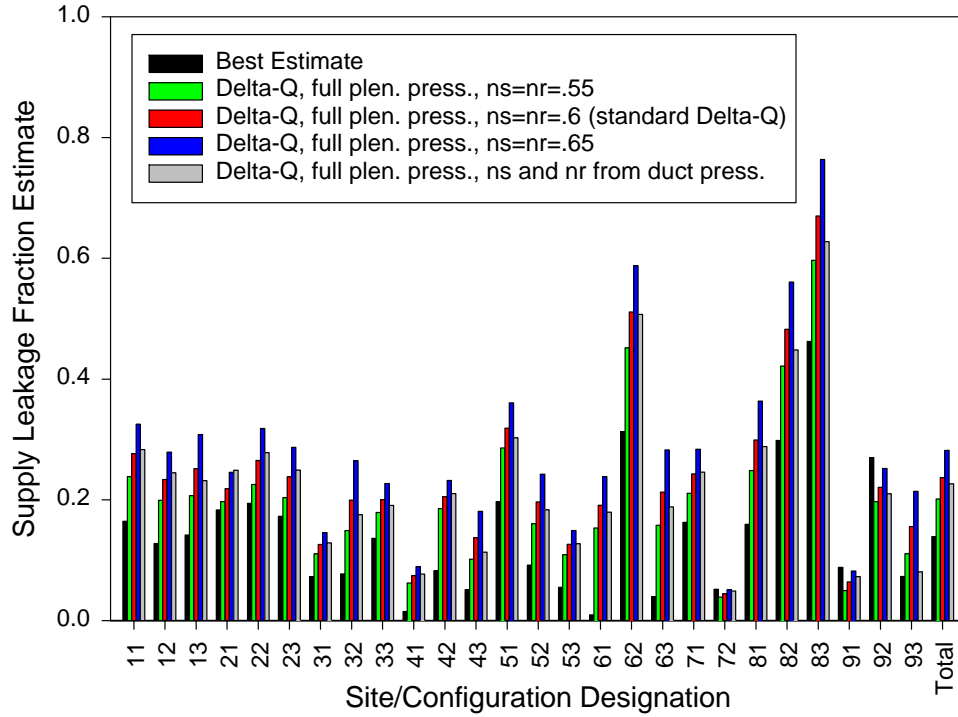


Figure 18. Supply leakage fraction estimates from best estimate and Delta-Q test with four exponent assumptions: 0.55, 0.6 (unmodified), 0.65, and those measured with the fan pressurization test. The Site/Configuration Designation key is in Table 4.

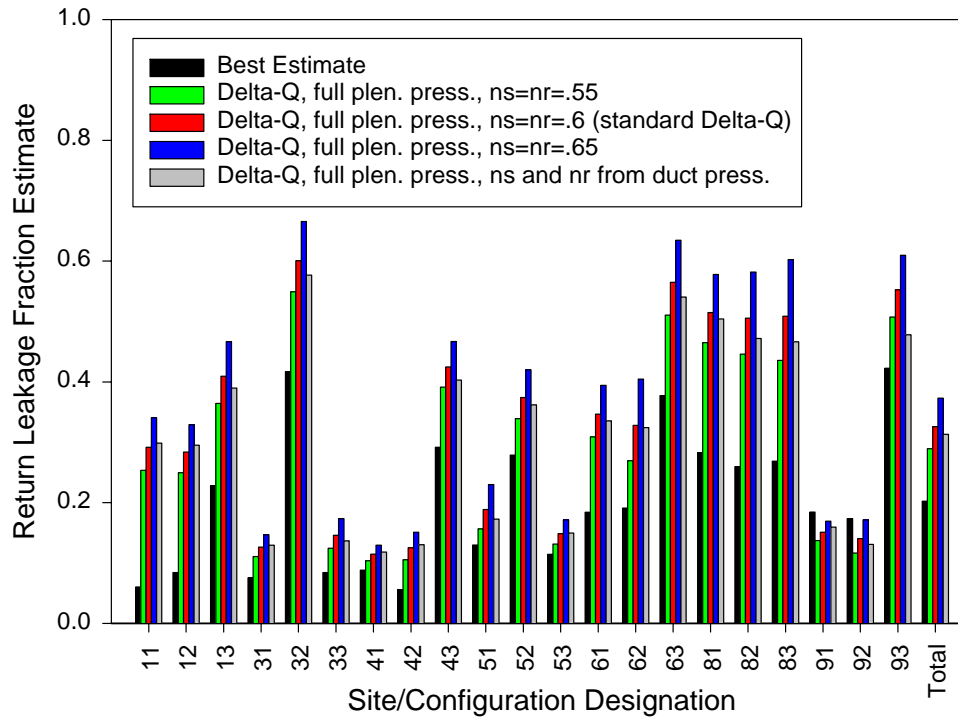


Figure 19. Return leakage fraction estimates from best estimate and Delta-Q test with four exponent assumptions: 0.55, 0.6 (unmodified), 0.65, and those measured with the fan pressurization test. The Site/Configuration Designation key is in Table 4.

set which provides the smallest overestimation, which is the assumption of exponents equal to 0.55, overestimates the supply leakage by an average of 45% and the return leakage by an average of 43%. Using the exponents from the duct pressurization tests does not make much of an improvement compared to the unmodified results (exponents of 0.6) implying that, on average, the duct leakage exponents did not vary much from the default.

Table 9 presents the statistical results for the exponent sensitivity analysis. This table shows the monotonically changing behavior displayed in Figs. 18 and 19. These results suggest that there may be an exponent assumption that would provide unbiased results, but the trend suggests that the exponents that would be required would be significantly below 0.5. This is problematic, because theory stipulates that the exponent can not be lower than 0.5.

Table 9 also reinforces the findings of Table 6 that the errors are likely percentage errors (i.e. multiplicative) rather than offset errors (i.e. additive).

**Table 9. Summary of Supply and Return Leakage Fraction Estimates as a Percentage of Air Handler Flow for Different Exponent Assumptions in Delta-Q Test**

	Best Estimate	Delta-Q			
		n=0.55	n=0.6	n=0.65	meas. n
<b>Supply (n=73)</b>					
Mean	13.9	20.1	23.7	28.2	22.6
Median	11.5	17.6	20.5	25.2	21.0
Mean Diff. from Best	--	6.2	9.8	14.3	8.7
Median Diff. from Best	--	6.7	10.1	14.9	9.6
Mean Absolute Diff. from Best	--	7.4	10.6	15.0	9.7
Median Absolute Diff. from Best	--	6.7	10.3	14.9	9.9
RMS Error of Diff. from Best	--	8.6	12.1	16.9	11.2
<b>Return (n=63)</b>					
Mean	20.2	28.9	32.6	37.3	31.3
Median	18.4	27.0	32.7	38.3	33.0
Mean Diff. from Best	--	8.7	12.3	17.1	11.1
Median Diff. from Best	--	7.5	11.2	16.6	9.7
Mean Absolute Diff. from Best	--	9.8	13.0	17.6	11.7
Median Absolute Diff. from Best	--	7.9	11.6	16.6	11.2
RMS Error of Diff. from Best	--	11.8	15.4	20.3	14.0

*Applicability of the Delta-Q Test to Homes without Return Systems*

One question that arose regarding the Delta-Q test was whether it could be used in homes that did not have a ducted return system, such as manufactured homes, and if it could, how would one do the analysis. This question came up because the analysis equations require a return duct pressure, which is an undefined quantity when there is no return duct system, and because the output of the equations includes a return leakage, which should be zero in this type of home but is not guaranteed to be zero by anything in the Delta-Q analysis equation.

Following the problems at Site L02 (homeowner problems and a power outage), we added a manufactured home to the study. In many respects, this home required a lower level of effort due to the lack of a return duct system, but it also provided us with an opportunity to investigate this question.

The actual execution of the Delta-Q test protocol is straightforward in a manufactured home, in that there is no problem with measuring envelope fan flows and envelope pressures with and without the air handler on and through the full range of pressures specified in the Delta-Q test. The testing problem is in the duct pressure measurement.

On the supply side, the measurement problem is that there is typically not an accessible plenum. The typical way that pressures are measured in the supply ducts in a manufactured home are to measure at the closest register, frequently by removing the register and pushing the pressure tap as far towards the plenum as possible. The home that we tested was already instrumented for pressure measurement, so we had the luxury of having a pressure tap placed in the supply plenum. However, the actual location of this tap within the supply plenum was close to the inside of a right-angle bend, such that the measured pressure was about half of the actual plenum pressure and not dissimilar from the pressures that one typically measures in a manufactured home supply duct.

On the return side, the question is where to measure any pressure. One possibility is to measure the pressure between the closet in which the air handler is located and the remainder of the house. This will usually result in a very small number. Another possibility is to measure the pressure across the filter; however, it is unclear why the pressure drop across the filter would have anything to do with duct leakage. Our primary approach was to measure the pressure difference between the air handler closet and the remainder of the house, as that is what we figured would be the most likely result of a contractor trying to apply this test. We also obtained a one-time measurement of the pressure across the filter.

Table 10 shows the Delta-Q results using the pressure difference between the air handler closet and the house for each of the three iterations of each duct configuration. The first configuration (labeled “A”) is with a large supply leak located at the plenum. The second (labeled “B”) is as-found, with little supply leakage. The pressures recorded between the air handler closet and the house were typically less than 1 Pascal. The leakage exponents were assumed to be 0.6.

This table shows some clear problems with what is likely the most straightforward method of performing the Delta-Q test at this house. While the supply leakage estimates with the full plenum and half-plenum pressure assumptions are comparable in accuracy to the leakage estimates in other houses, the return leakage estimates are not only far from zero, but in many of the cases with the large added supply leak they are physically impossible. While one might be tempted to simply ignore the return estimates and use the supply estimates, it is unclear how much the return side of the analysis might influence the results, and how much better the results might be with other analyses.

**Table 10. Supply and Return Leak Fraction Estimates, as Percentage of Air Handler Flow, for Site L07 - Delta-Q Test Using Return Pressure Between Air Handler Closet and House**

	Air Handler Flow (cfm)	Best Estimate	Full plenum		½ - plenum		¼ - plenum	
			Supply	Return	Supply	Return	Supply	Return
A1	1034	17.3	21.7	23.7	17.0	-76.0	89.0	433.1
A2	1005	16.1	25.3	76.9	19.1	-69.2	121.3	858.4
A3	1010	15.5	25.9	64.3	18.7	-68.5	116.7	698.9
B1	942	7.3	3.6	10.2	5.1	14.9	17.0	51.2
B2	908	5.0	4.0	9.0	5.8	14.1	16.4	46.4
B3	889	3.2	5.7	18.4	7.0	22.4	23.5	74.4

Table 11 shows a similar table, but with the return pressure set to 15 Pa, which is about the pressure drop across the filter. This table shows a significant improvement over the results in Table 10, with most return leakage estimates much closer to zero and no physically impossible results. Using the full plenum pressure, the supply results are also better than those from Table 10 for the leaky supply case, though this is not the case using half of the plenum pressure. For the configuration without the added leak there are some iterations for which the results in Table 10 are better than from Table 11, and there are other iterations where the opposite is true.

One possible method of dealing with the return leakage estimates that has been used in other tests in the past is to set the return leakage to zero and add the change to the supply leakage. This can be done by subtracting the return leakage estimate from the supply leakage estimate. This does improve the comparison with the best estimate in Table 11, but neither this tactic nor the use of the pressure drop across the filter can be justified as having anything to do with the actual leakage.

An inspection of the Delta-Q analysis equations sheds some light into why the results can be so spurious, especially on the return side, in Table 10. Equation (9) shows that the return duct pressure is in the denominator, so when this number is close to zero the resulting leakage estimate can get extremely large and be of uncertain sign. Following this inspection, we felt that a reasonable attempt at getting the return leakage estimates to be zero would be to input an

**Table 11. Supply and Return Leak Fraction Estimates, as Percentage of Air Handler Flow, for Site L07 - Delta-Q Test Using Return Pressure of 15 Pa.**

	Air Handler Flow (cfm)	Best Estimate	Full plenum		½ - plenum		¼ - plenum	
			Supply	Return	Supply	Return	Supply	Return
A1	1034	17.3	21.0	2.0	24.4	0.2	66.9	28.6
A2	1005	16.1	23.2	4.6	26.9	2.7	83.6	45.3
A3	1010	15.5	24.0	4.7	26.6	2.1	84.3	46.0
B1	942	7.3	2.5	1.8	3.4	2.4	10.9	10.1
B2	908	5.0	3.1	1.6	4.2	2.2	11.2	9.0
B3	889	3.2	3.8	3.3	4.4	3.6	13.6	12.9

**Table 12. Supply and Return Leak Fraction Estimates, as Percentage of Air Handler Flow, for Site L07 - Delta-Q Test Using Return Pressure of 10000 Pa.**

	Air Handler Flow (cfm)	Best Estimate	Full plenum		½ - plenum		¼ - plenum	
			Supply	Return	Supply	Return	Supply	Return
A1	1034	17.3	17.2	-2.1	14.5	-7.0	33.1	-2.3
A2	1005	16.1	19.4	-0.1	15.4	-6.3	36.8	-0.6
A3	1010	15.5	19.1	-0.8	15.5	-6.3	37.3	-0.7
B1	942	7.3	3.4	2.1	3.6	1.5	7.0	2.2
B2	908	5.0	4.0	2.0	4.2	1.3	7.8	2.1
B3	889	3.2	5.4	3.8	4.7	2.3	9.2	3.3

extremely large number into eq. (9) for the return pressure. Table 12 shows the results of this analysis, with the return pressure set to 10000 Pa.

Overall, these results show better performance than either of the two previous sets. The quarter-plenum pressure assumption no longer gives extremely high estimates for the configuration with the added supply leak. However, many of the return leakage estimates are now negative, and while some of these estimates are extremely small, and could be considered within the error band of the test, this is not always the case. Negative leakage estimates of 6-7% of the air handler flow, as can be seen for the half-plenum pressure assumption, likely can not be ignored. Also, the tactic of setting the return leakage to zero and adding the change to the supply leakage will worsen the agreement with the best estimate.

We tried one final method of analyzing the Delta-Q data at this house. This method was to reformulate the Delta-Q analysis equations, removing the return from the beginning. This method will cause the return leakage to be defined as zero, as should be the case. The final equation from this reformulation is simply eq. (9) with the return term dropped, i.e.

$$\Delta Q(\Delta P) = Q_s \left[ \left( 1 + \frac{\Delta P}{\Delta P_s} \right)^{0.6} - \left( \frac{\Delta P}{\Delta P_s} \right)^{0.6} \right] \quad (18)$$

Table 13 shows the results from analyzing the Delta-Q data using eq. (18).

Overall, these results are better than any of the other sets except for possibly the set with the return pressure set to 10000 Pa. For the configuration with very low leakage, the reformulated Delta-Q test actually underestimates the leakage. For the configuration with the added leak, the results are not as good as the set with the 10000 Pa return pressure; however, the overestimation is commensurate with that seen in other houses, so it may be that a refinement to the analysis technique for all houses would apply equally well here, and make the set in Table 11 worse. The reformulation is also significantly more defensible than any attempt to input a false return pressure.

**Table 13. Supply Leak Fraction Estimates as a Percentage of Air Handler Flow for Site L07 from Reformulated Delta-Q Test with the Return Removed from the Analysis.**

	Air Handler Flow (cfm)	Best Estimate	Full plenum		½ - plenum		¼ - plenum	
			Supply	Return	Supply	Return	Supply	Return
A1	1034	17.3	19.4	--	24.2	--	38.3	--
A2	1005	16.1	19.5	--	24.6	--	38.3	--
A3	1010	15.5	20.0	--	24.9	--	38.9	--
B1	942	7.3	1.2	--	1.6	--	2.1	--
B2	908	5.0	1.9	--	2.4	--	3.3	--
B3	889	3.2	1.3	--	1.5	--	1.9	--

This analysis shows that, while the Delta-Q test methodology can be implemented in houses without return duct systems, the analysis of the data needs to be changed. It should be noted, however, that it is these houses at which the nulling test is most simple and fast, and is the preferred method of estimating the duct leakage.

*Validity of the Constant Duct-House Pressure Assumption*

One of the primary assumptions in the development of the Delta-Q test analysis technique was that, as the house was pressurized or depressurized, the pressure in the ducts changed by the same amount, such that the pressure difference between the ducts and the house remained constant throughout the test. This does not imply that the ducts are at a uniform pressure along the length, only that the pressure at any single location remains constant relative to the house.

Measured Pressures

This assumption was found to fail in many cases. Whereas the assumption should be correct if there is no leakage to outside, as leakage to outside increases the assumption will become less and less valid. Figures 20-22 show examples of this behavior. In each of these graphs the return plenum pressure is displayed as a positive number so that the scale will allow the trends to be more visible. This is the same as referring to the return data as house with respect to return plenum. The supply plenum pressures are expressed as supply plenum with respect to house. The external static is the supply plenum with respect to the return plenum, which corresponds to adding the two lines on each graph.

Figure 20 shows the duct pressures for one iteration of Site L04 with the ducts in their as-found condition (designation 41). This was the case that had the smallest combined supply and return leakage in the entire study, implying that the assumption made regarding the behavior of the duct pressures during the Delta-Q test should be most accurate in this case. The graph shows that the return pressure changed by about 7 Pa (out of about 31 Pa average) throughout the test. The supply pressure changed by about 9 Pa (out of about 54 Pa average). These changes are noticeable but not catastrophic. Because the two pressures are changing by similar amounts with

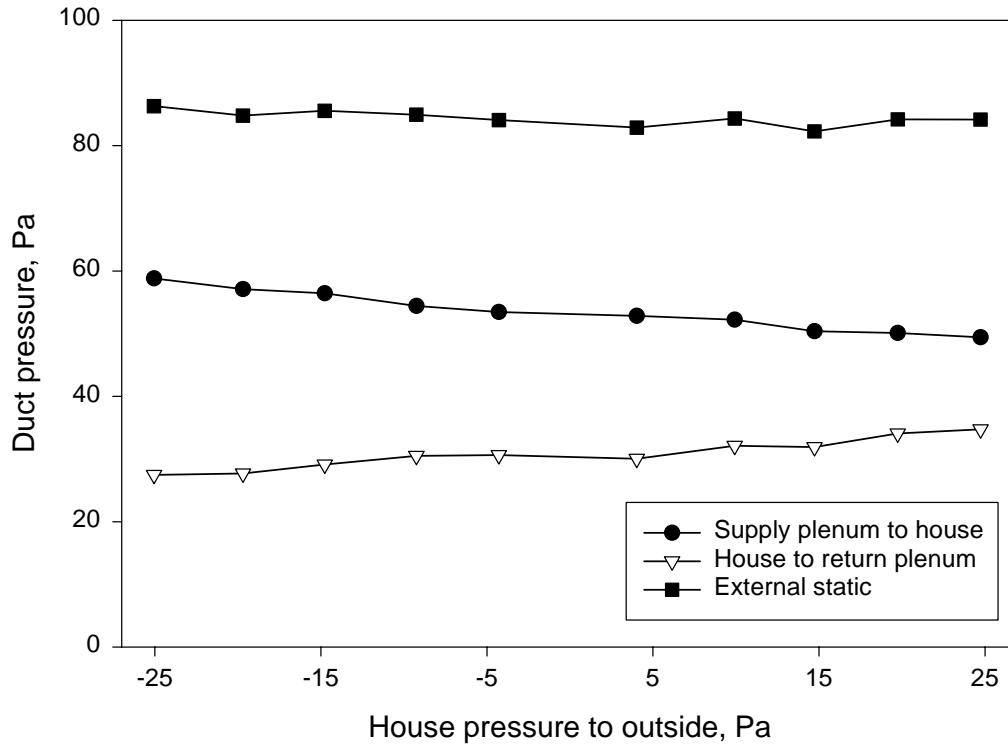


Figure 20. Duct pressures during Delta-Q test for third iteration of designation 41 (as-found leakage).

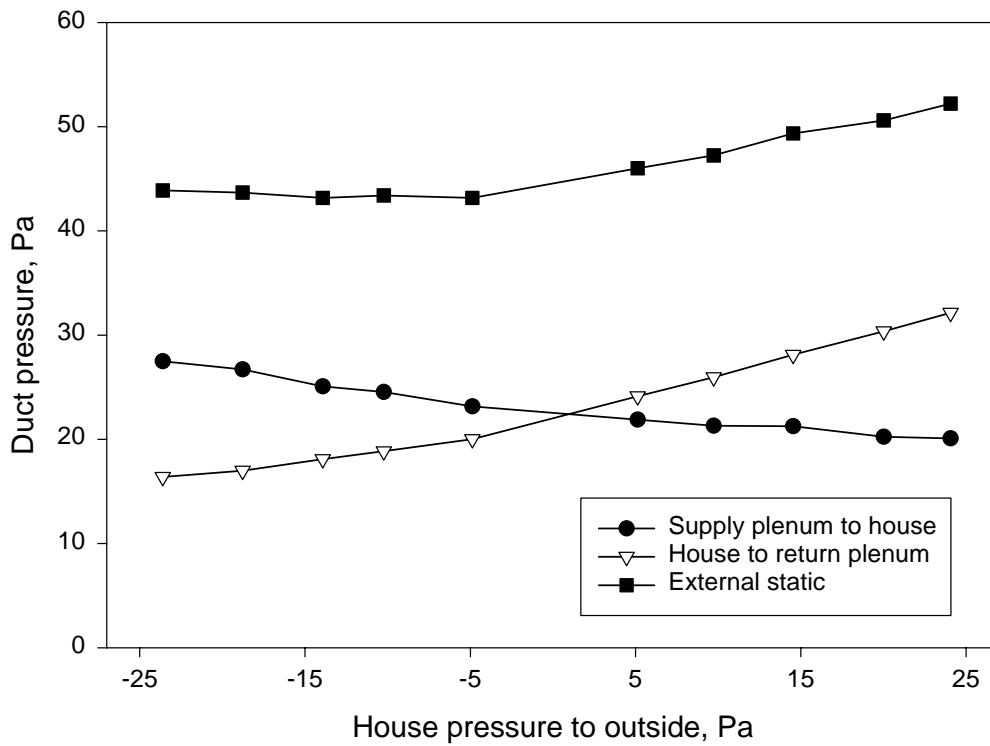


Figure 21. Duct pressures during Delta-Q test for first iteration of designation 43 (added return leakage).

respect to the house, the external static does in fact remain fairly constant. The Delta-Q test results from this designation are fairly close to the best estimate results.

Figure 21 shows the duct pressures for the same house but with a large return leak added. This leak represented about 20% of the air handler flow. This graph shows that all pressures are smaller than with no added leaks. The supply pressure changes by only about 7.5 Pa, similar to Fig. 20. However, the return pressure about doubles throughout the test. Further, the return pressure changes more quickly during the pressurization portion of the test, such that the external static, which was about constant during the depressurization portion of the test, increases significantly during the pressurization portion. Comparing the best estimate to the Delta-Q results for this designation shows that the Delta-Q test overpredicts the return leakage by about 40% for this case.

Figure 22 shows the results for Site L05 in the configuration with a large added supply leak. This leak was created by disconnecting one of the highest flow registers at the boot. The return pressure changes by only about 8 Pa (out of about 60), but the supply pressure changes by about 15 Pa out of about 32 Pa. The external static reflects this larger decrease in the supply pressure. The added leak represented about 13% of the air handler flow, and the Delta-Q test overestimated the supply leakage by about 68% in this case. It is fair to note, however, that the Delta-Q test overpredicts the leakage in this house by a similar amount even without the added leak.

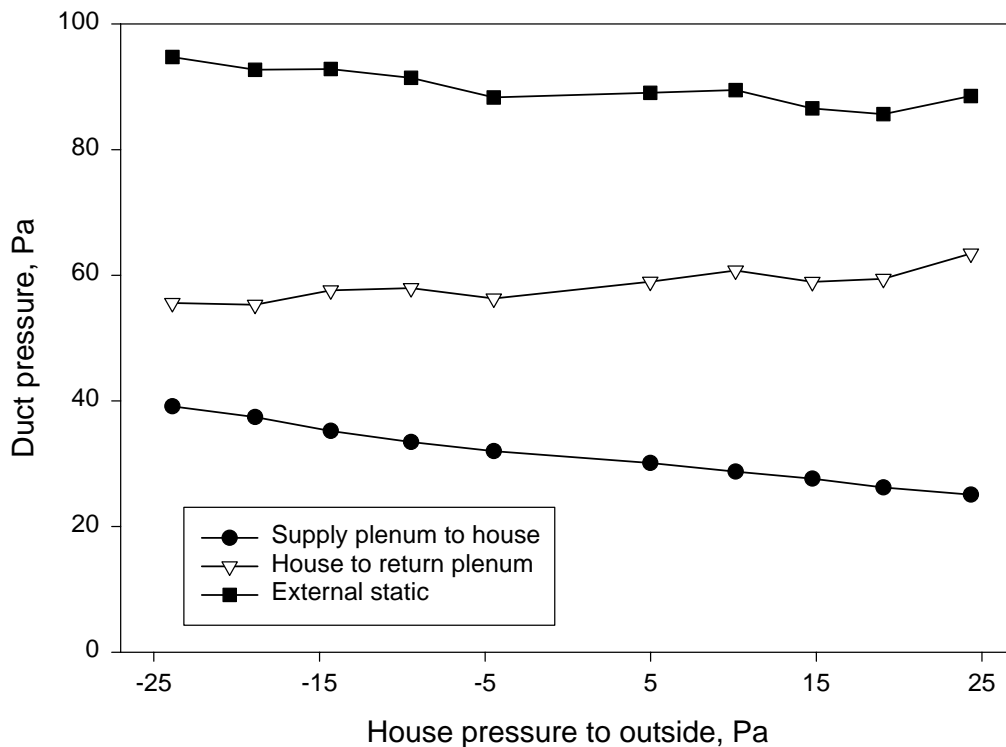


Figure 22. Duct pressures during Delta-Q test for first iteration of designation 51 (added supply leakage).

## CONTAM Computer Simulations

After finding that the duct pressures can change significantly with respect to the house during the Delta-Q test, we performed two computer simulations using CONTAM to verify this behavior. The first was with extremely low duct leakage in order to verify that the Delta-Q analysis would agree with CONTAM when there was not much leakage. The second was with significant, though not excessive, duct leakage on both the supply and return sides.

In both simulations the duct leakage exponent was set to be exactly 0.6, thereby eliminating the leakage exponent as a source of error. Further, the ducts were set to have no pressure drop along their length other than due to leakage, thereby eliminating uncertainty as to what the pressure is at the leakage site. As a result, in both simulations all of the assumptions in the Delta-Q test were met with the exception of the assumption that the duct pressures are constant relative to the house. In addition, stack and wind effects were ignored.

The simulations were done as follows: the supply and return ducts were set to be in different zones. The air handler was set to deliver 1000 cfm at 100 Pa total external static (e.g. 50 Pa on each side), and the return grille and supply register were each set to deliver 1000 cfm at 50 Pa. The house was set to a leakage of 2000 cfm at 50 Pa with a leakage exponent of 0.65. An envelope fan was set to change the house pressure through all of the pressures in the Delta-Q test, once through with the air handler off and once through with the air handler on. This provided envelope fan flow, supply and return duct pressures, and duct leakages. Doing a run with the air handler on and the envelope fan off also provided the actual duct pressures and leakages at operating conditions. These actual duct pressures are the ones that get input as the supply and return duct pressures in the Delta-Q analysis.

The pertinent data from the low-leakage simulation are shown in Table 14. Leakage characteristics for both the supply and return ducts were set to 10 cfm at 50 Pa. This table shows that, as expected for very low leakage, the duct pressures do not change much throughout the Delta-Q test. Because the leakage is balanced, there is no change in house pressure due to the duct leakage. Entering this data into the Delta-Q equation, with both supply and return duct pressures entered as 49.024, gives an estimate of 10.0 cfm on each side. If the duct pressures are reduced by half, the result is 9.2 cfm. CONTAM predicts duct leakage of 9.9 cfm on each side. The small discrepancy can be explained by roundoff error.

Table 15 shows the data from the simulation with significant duct leakage. On the supply side, the leakage is 300 cfm at 50 Pa; on the return side it is 150 cfm at 50 Pa.

CONTAM predicts that the leakage at operating conditions for this configuration will be 221 cfm on the supply side and 128 cfm on the return side. However, the Delta-Q analysis provides estimates of 255 cfm on the supply side and 155 cfm on the return side, which is 15% high for the supply side and 21% high for the return. If different assumptions are made for leakage operating pressures (e.g. half-plenum) the results get worse for the supply and better for the return. It is important to remember that this level of disagreement is with all other assumptions met and without environmental driving forces complicating the matter. In the field, of course, the other assumptions will usually not be exactly correct and stack and wind can be a problem.

**Table 14. CONTAM Simulation Data for Delta-Q Test with Low Leakage.**

	Air Handler Off	Air Handler On		
	Envelope Flow (cfm)	Envelope Flow (cfm)	Supply-House Pressure (Pa)	Return-House Pressure (Pa)
-25	-1288	-1281	49.4	-48.8
-20	-1114	-1107	49.3	-48.8
-15	-924	-918	49.2	-48.9
-10	-710	-705	49.1	-48.9
-5	-453	-449	49.1	-49.0
5	453	449	49.0	-49.1
10	710	705	48.9	-49.1
15	924	918	48.9	-49.2
20	1114	1107	48.8	-49.3
25	1288	1281	48.8	-49.4
0 (operating conditions)		0	49.0	-49.0

This table also confirms that, at reasonable levels of leakage similar to those found in the field, the duct pressures with respect to the house will change significantly, by an amount consistent with that seen in the field.

These findings cast doubt on the adequacy of the Delta-Q analysis technique as it currently exists to provide suitable leakage estimates. Further work needs to be done to investigate possible improvements to the technique to make this test widely useful with a reasonable degree of reliability. One possibility is to measure the actual pressures between the ducts and the house at each station, and to use these in place of the constant duct pressure in the Delta-Q analysis. This requires a third pressure measurement tap, in addition to the taps for house pressure and fan pressure.

**Table 15. CONTAM Simulation Data for Delta-Q Test with Significant Leakage.**

	Air Handler Off	Air Handler On		
	Envelope Flow (cfm)	Envelope Flow (cfm)	Supply-House Pressure (Pa)	Return-House Pressure (Pa)
-25	-1562	-1310	37.7	-34.7
-20	-1354	-1110	36.0	-35.3
-15	-1126	-896	34.4	-36.0
-10	-869	-658	33.0	-36.7
-5	-558	-378	31.6	-37.4
5	558	567	29.0	-38.8
10	869	847	27.8	-39.6
15	1126	1083	26.7	-40.5
20	1354	1296	25.6	-41.4
25	1562	1494	24.6	-42.4
-0.4 (operating conditions)		0	30.4	-38.0

## Issues Regarding the Fan Pressurization Test

There are two primary problems with the fan pressurization test. The first is the amount of time it takes to set up and perform the test. In many cases installing the airtight barrier between the supply and return systems can be difficult, as can installing the pressurization fan to the duct system. Also, sealing registers is time-consuming, may involve moving around ladders and furniture, and in some cases it may not be possible to get to all of the registers.

The other primary problem with the fan pressurization test is the need to assume an operating pressure. Many efforts have been made to provide a better, simple way to estimate this pressure, with little practical success.

Figures 23 and 24 show the degree to which the assumption of half the plenum pressure is suitable as an operating pressure for the fan pressurization test for the supply and return, respectively. The effective operating pressures were obtained by combining the best estimate of leakage to outside with the leakage coefficient and exponent from fan pressurization test, and solving for the operating pressure.

Figure 23 shows that there is frequently a very large difference between the effective operating pressure and half of the plenum pressure. For these houses, the effective operating pressure was frequently below 10 Pa, though half the plenum pressure was typically in the 20-30 Pa range, and never dropped below 10 Pa. This is due largely to the fact that supply duct systems frequently

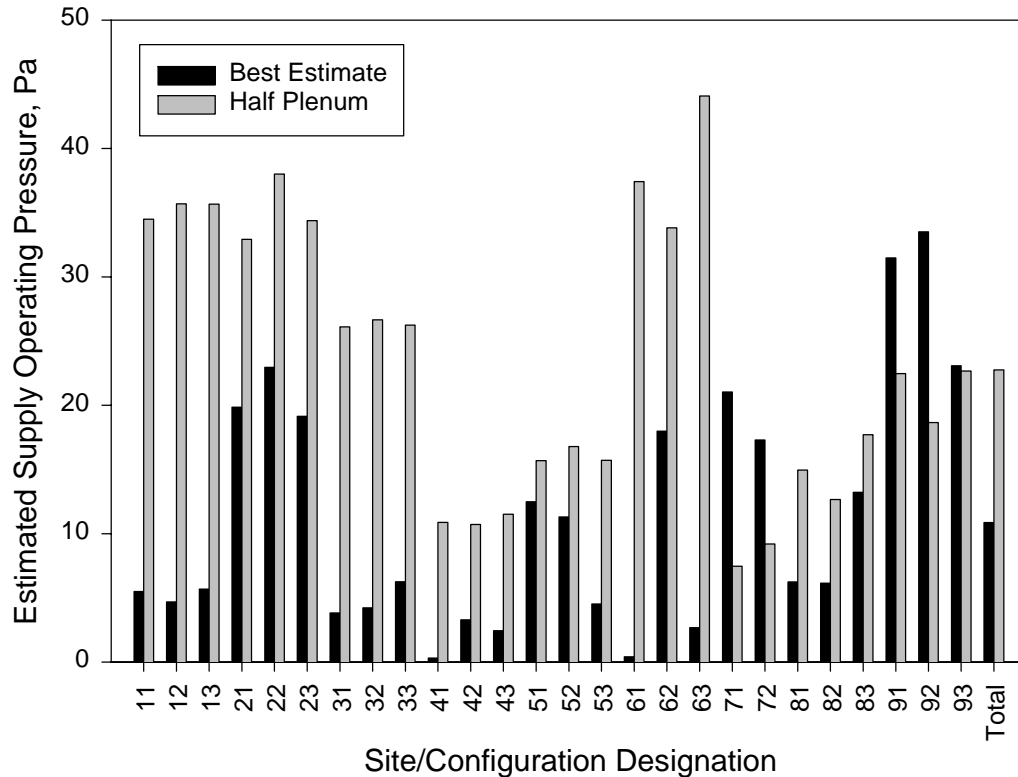


Figure 23. Supply operating pressures. The Site/Configuration Designation key is in Table 4.

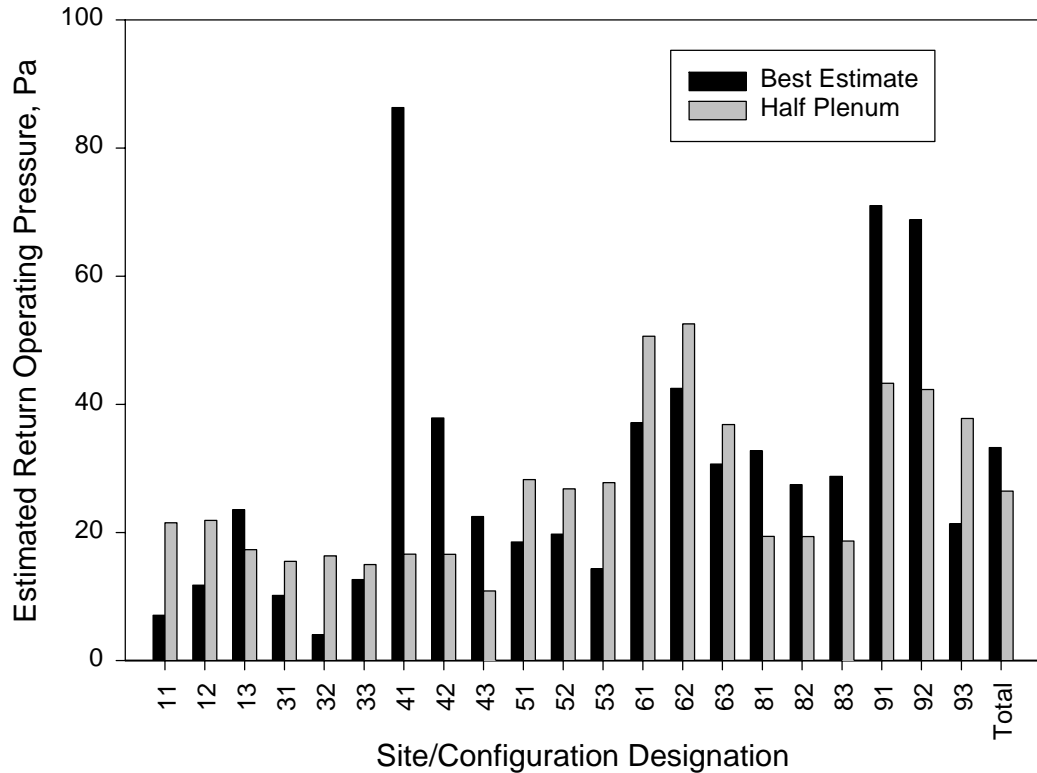


Figure 24. Return operating pressures. The Site/Configuration Designation key is in Table 4.

have one or more bends immediately after the plenum. Each bend causes a substantial pressure drop, so that by the time the air gets to the leakage sites downstream of the plenum the pressure is much lower than half of the plenum pressure. In some cases the low effective pressures are due in part to the location of the added supply leak; if the supply leak is added at the register end the pressure will be lower than if the leak was added at the plenum end. However, even in those cases without an added supply leak the effective operating pressure is usually much smaller than half of the plenum pressure, and often less than 10 Pa.

Statistically, the effective operating supply pressures averaged about 10.9 Pa, with a median of about 6.3 Pa. Half of the plenum pressures averaged about 22.8 Pa with a median of about 21.9 Pa. Based on means, therefore, the effective operating supply pressures were about 48% of the assumed pressures for the fan pressurization test, and about 24% of the plenum pressure. Based on medians the effective supply pressures were about 28% of the assumed pressures.

The half-plenum assumption worked much better on the return side in these houses. Most of the systems have only a few long, straight runs, so there will be fewer of the large, discrete pressure drops along the ducts. On average, the effective return operating pressures are about 26% higher than the half plenum assumption, but this is heavily weighted by one case, designation 41. This case had extremely low leakage, so small changes in the leakage coefficient and exponent can have big impacts on the pressure. Based on medians, the effective operating pressures for the return are only about 12% higher than the half plenum assumption. It is likely that the half plenum assumption will work well in many houses due to the simple nature of return duct systems.

## Time and Material Requirements

Table 16 provides estimates of the amount of time required for the nulling and Delta-Q tests, as well as the equipment required. These are based on our experience, and may vary.

This table shows that the nulling test is faster to run once setup is complete, but that the setup can be time-consuming. The most difficult part of the setup is placing the barrier between the supply and return, and installing the second calibrated fan to the air handler cabinet for the supply-only portion of the test. If this is being done anyway in order to measure air handler flow (one of the primary methods for making this measurement requires this) then the additional time is comparable to that for setting up the Delta-Q test. The nulling test also requires an additional calibrated fan than does the Delta-Q test.

**Table 16. Time and Material Requirements for the Nulling and Delta-Q Tests**

Test	Setup Time	Test Time	Equipment
Nulling	45-75 minutes, depending on the ease of placing the barrier between supply and return. <i>If the method used for measuring air handler flow requires placing this barrier, the additional time is about 15-30 minutes (installation of pressure hoses and a calibrated fan in the envelope).</i>	15 minutes (longer in windy conditions)	<ul style="list-style-type: none"> <li>• 2 calibrated fans that can run at low pressures and flows</li> <li>• Pressure gauge, preferably one that can connect to a computer</li> <li>• Laptop preferable</li> </ul>
Delta-Q	15-30 minutes (installation of pressure hoses and a calibrated fan in the envelope)	30 minutes	<ul style="list-style-type: none"> <li>• 1 calibrated fan</li> <li>• Pressure gauge, preferably one that can connect to a computer</li> <li>• Laptop preferable</li> </ul>

## STATIC TESTS – LEAKAGE AT A FIXED PRESSURE CONDITION

In addition to the tests already described in detail, we also performed two simpler tests: the add-a-hole test and the modified blower-door subtraction test. Both of these methods require only the use of a blower door. Both of these are modifications of methods proposed by Michael Blasnik (1989). However, the actual details of the tests we performed differ sufficiently from those proposed by Blasnik, that a new derivation is required. First we present a common nomenclature for the two test methods.

Nomenclature for derivations and schematics

$Q_f$	flow through house pressurization fan
$Q_h$	flow through house envelope not including ducts
$Q_i$	flow through internal leakage from house to ducts
$Q_d$	flow through duct leaks to outside
$Q_{hole}$	measured flow through added hole
$Q_{reg}$	flow through open registers
$P_h$	pressure difference: house to outside
$P_i$	pressure difference: house to duct
$P_d$	pressure difference: duct to outside
$C_d$	flow coefficient: duct to outside
$C_h$	flow coefficient: house to outside
$C_i$	flow coefficient: house to duct
$nd$	assumed flow exponent: duct to outside = 0.6
$nh$	measured flow exponent: house to outside
$ni$	assumed flow exponent: house to duct = $nh$
$s, u$	indicate whether hole/registers sealed or unsealed

For all tests we have the following identity

$$P_h = P_i + P_d \quad (19)$$

### Derivation of Methods

The test setup for the add-a-hole and modified subtraction methods are shown schematically in Figs. 25 and 26, respectively.

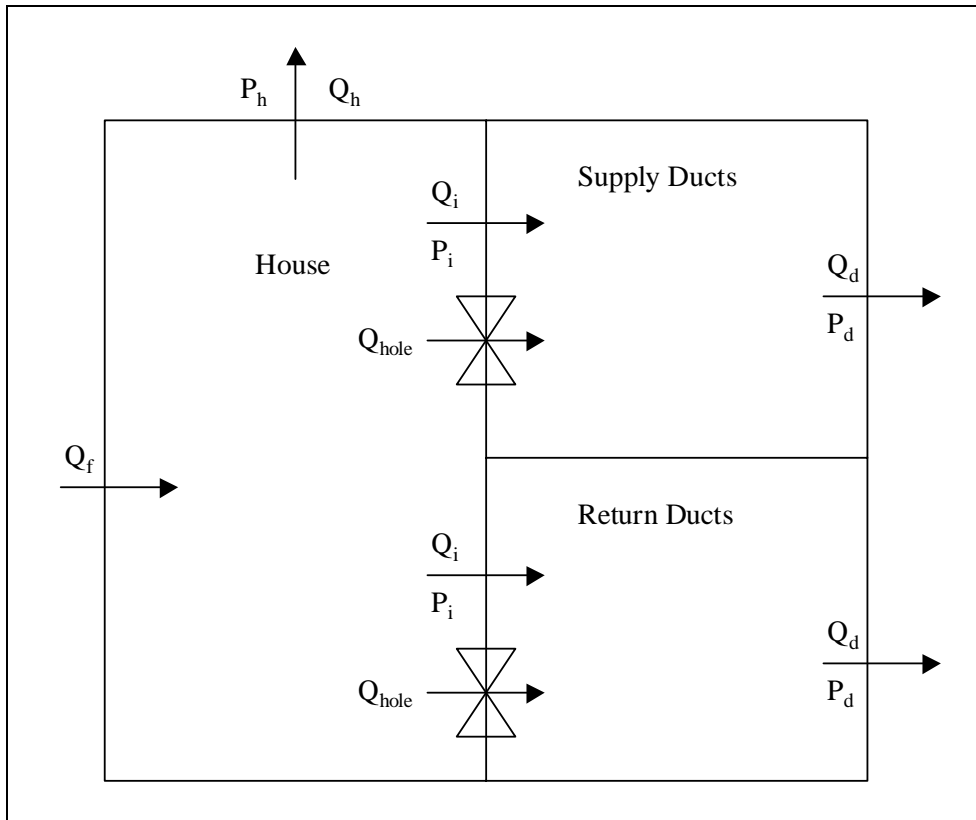


Figure 25. Schematic of the add-a-hole test setup.

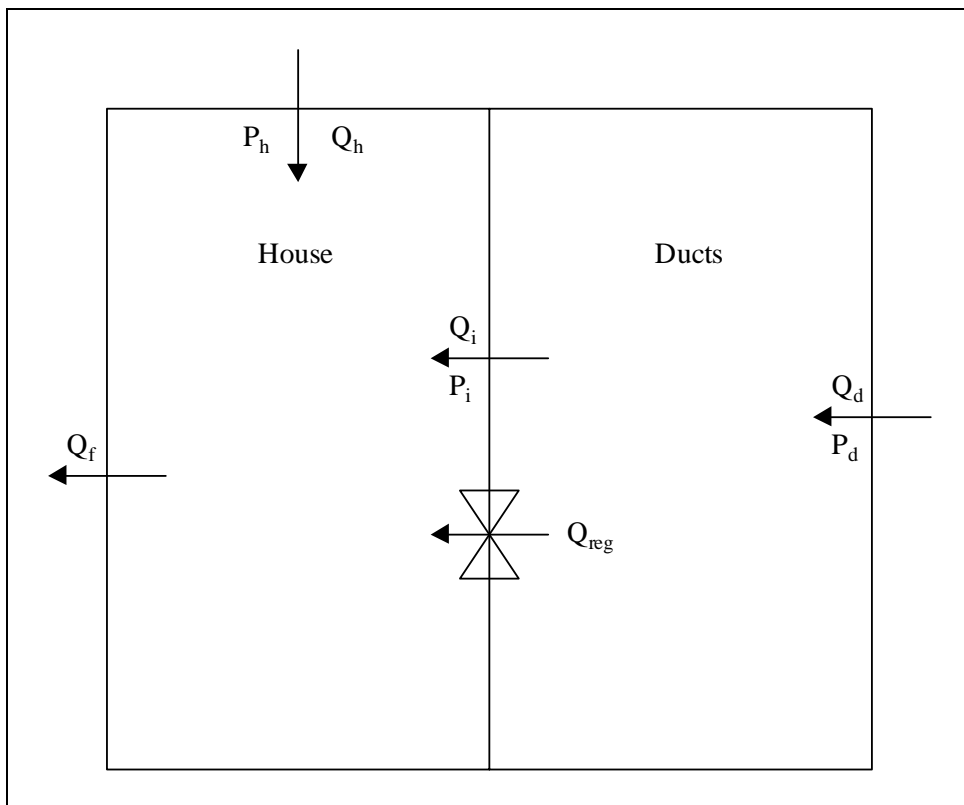


Figure 26. Schematic of the modified blower door subtraction test setup.

### *Derivation of Add-a-Hole Method*

As indicated in Fig 25, this method allows the simultaneous measurement of leakage on the supply and return sides of the duct system. Pressures are measured from the house to outside and from the house to the duct system (all results presented here used the supply plenum and return plenums for the house-to-duct pressures. The supply and return ducts are separated by an airtight seal at the location of the filter slot in the return box. We use the same nomenclature for the supply side and the return side because they are calculated separately, one at a time.

For the first step in this method, the registers are all sealed. The blower door is run to pressurize the house to a target pressure of 50 Pa and also 25 Pa. We used this test get the value of  $nh$ . The pressure differences  $P_h$  and  $P_i$  were measured.

In the second step, two calibrated holes are added, one for the supply ducts and one for the return ducts. In our case, we used two duct blasters attached to either registers or by a snorkel to the return side of the air handler, but in general a box with a hole of known area would work just as well. The blower door is again used to pressurize the house to target pressures of 50 and 25 Pa, and the house-to-outside and house-to-duct pressures are measured. In addition, the fan pressures of the two duct blasters are recorded so the flow through the holes can be calculated.

With this information we can calculate the duct leakage to outside and to inside. The equations are the same for the supply side and the return side, so only one set is provided. The flow through the hole and the pressure from house to ducts are the only quantities that differ for the return and supply calculations. Notice that the flows through the blower door are not used in estimating the leakage, only the flows through the added holes. The flow exponent for internal leakage  $ni$  was assumed to be the same as that for the house.

With the hole sealed we have

$$Q_{i,s} = Q_{d,s} \quad (20)$$

so that

$$C_i P_{i,s}^{ni} = C_d P_{d,s}^{nd} \quad (21)$$

$$C_i = C_d \frac{P_{d,s}^{nd}}{P_{i,s}^{ni}} \quad (22)$$

With the hole unsealed we have

$$Q_{hole} = Q_{d,u} - Q_{i,u} \quad (23)$$

so that

$$Q_{hole} = C_d P_{d,u}^{nd} - C_i P_{i,u}^{ni} \quad (24)$$

Combining eqs. (22) and (24) we can solve for  $C_d$

$$C_d = \frac{Q_{hole}}{P_{d,u}^{nd} - P_{d,s}^{nd} \left( \frac{P_{i,u}^{ni}}{P_{i,s}^{ni}} \right)} \quad (25)$$

from which we can calculate the duct leakage to outside as

$$Q_{d,25} = C_d 25^{nd} \quad (26)$$

and the duct leakage to inside as

$$Q_{i,25} = C_i 25^{ni} \quad (27)$$

#### *Derivation of Modified Subtraction Method*

The main problem with the unmodified blower door subtraction method is that it does not properly account for internal leakage between the ducts and the house. The unsealed test gives correct results, but the sealed test does not because there is still flow through the internal leakage to the ducts and then to outside. As a result, the flow measured when the registers are sealed is biased high, and when we subtract it from the unsealed result to get the duct leakage, the value will be biased low, and the greater the internal leakage, the greater the bias. The modified subtraction method is a procedure for using an additional measured pressure to correct the bias.

The set-up for this method is shown in Fig. 26. In the first step, all registers are sealed and measurements are made exactly as for the previous method, except that the blower door is set to depressurize the house and the flow through the blower door will be used in the calculation. In step two, the blower door is run again but with the registers unsealed, and the blower door flow and pressures to ducts and outside are recorded. The duct leakage to inside and outside can then be calculated as follows.

For the sealed test we have

$$Q_{f,s} = Q_{h,s} + Q_{d,s} \quad (28)$$

$$Q_{f,s} = C_h P_{h,s}^{nh} + C_d P_{d,s}^{nd} \quad (29)$$

$$C_h = \frac{Q_{f,s} - C_d P_{d,s}^{nd}}{P_{h,s}^{nh}} \quad (30)$$

and for the duct leakage to inside we have

$$Q_{i,s} = Q_{d,s} \quad (31)$$

$$C_i P_{i,s}^{ni} = C_d P_{d,s}^{nd} \quad (32)$$

so that

$$C_i = C_d \frac{P_{d,s}^{nd}}{P_{i,s}^{ni}} \quad (33)$$

For the unsealed test we have

$$Q_{f,u} = Q_{h,u} + Q_{d,u} \quad (34)$$

$$Q_{f,u} = C_h P_{h,u}^{nh} + C_d P_{d,u}^{nd} \quad (35)$$

$$C_h = \frac{Q_{f,u} - C_d P_{d,u}^{nd}}{P_{h,u}^{nh}} \quad (36)$$

Equating the two expressions for  $C_h$  in eqs. (30) and (36), we can solve for  $C_d$  in terms of the other quantities:

$$C_d = \frac{P_{h,u}^{nh} Q_{f,s} - P_{h,s}^{nh} Q_{f,u}}{P_{h,u}^{nh} P_{d,s}^{nd} - P_{h,s}^{nh} P_{d,u}^{nd}} \quad (37)$$

Notice that if the sealed and unsealed house-to-outside pressures are exactly the same, the equation simplifies to

$$C_d = \frac{Q_{f,s} - Q_{f,u}}{P_{d,s}^{nd} - P_{d,u}^{nd}} \quad (38)$$

where the numerator is just the negative of the blower door subtraction result and the denominator is the correction factor.

Now, we can calculate the leakage from ducts to outside at 25 Pa as

$$Q_{d,25} = C_d 25^{nd} \quad (39)$$

and the leakage from the ducts to inside at 25 Pa as

$$Q_{i,25} = C_i 25^{ni} \quad (40)$$

## Results

The combined supply and return duct leakage to outside at 25 Pa was calculated for the add-a-hole, unmodified blower door subtraction and modified blower door subtraction methods. The test results are shown in Fig. 27. For comparison purposes, the graph also shows the total duct leakage to outside at 25 Pa from the fan pressurization tests, which are presumably the most accurate values.

As can be seen from the graph, the add-a-hole and modified subtraction methods both produce results fairly close to those from the fan pressurization tests. The unmodified blower door subtraction method underpredicts as expected.

It is also useful to express the results in terms of percentage error relative to the fan pressurization tests. The median percentage error for the unmodified blower door subtraction method was -17.8%, for the modified blower door subtraction method it was 2.5% and for the add-a-hole method it was 5.2%. This shows that, on a percentage basis, both the modified subtraction and the add-a-hole method provide a significant improvement over the unmodified blower door subtraction method. As mentioned earlier, one of the criteria for selecting these test homes was low internal leakage (e.g., we excluded two-story homes which tend to have large portions of the duct system in the joist space separating the floors). As a result one would expect that the benefit of correcting the bias due to subtraction would be even greater in the general case than for the homes tested in this project.

Figure 28 is a scatter plot with a one-one line that plots the unmodified blower door subtraction method results versus the fan pressurization results. There is a fairly consistent percentage bias apparent.

Figure 29 shows a scatter plot of the add-a-hole test results for total leakage versus the fan pressurization results. The agreement is fairly good over the whole range of data.

Figure 30 shows a scatter plot of the modified blower door subtraction method versus the fan pressurization results. Again there is fairly good agreement.

The add-a-hole method produces separate values for the return and supply ducts, so it is of interest to compare those separately with the results from the duct blaster tests. Figure 31 shows a bar chart of the add-a-hole duct leakage to outside for the supply ducts only with the fan pressurization results for comparison. There is fairly good agreement with the exception of Site L08, where the add-a-hole method is noticeably high. This one site contributes significantly to the small bias exhibited by the averages shown at the far right.

Figure 32 shows a bar chart of the add-a-hole method and the fan pressurization method for the return ducts only. There is a large discrepancy for Configuration 2 at Site L05. The cause of this is not known.

In summary, both the add-hole and modified subtraction methods show promise where the goal is to measure duct leakage to outside at a given reference pressure. They share the drawback of the fan pressurization method in requiring an estimate of an appropriate "effective" duct-to-outside pressure difference. The add-a-hole method as performed here has the advantage of producing values separately for the return and supply ducts. This is important, because in most conditions, the thermal losses associated with supply leaks are significantly larger than those associated with return leaks of the same size.

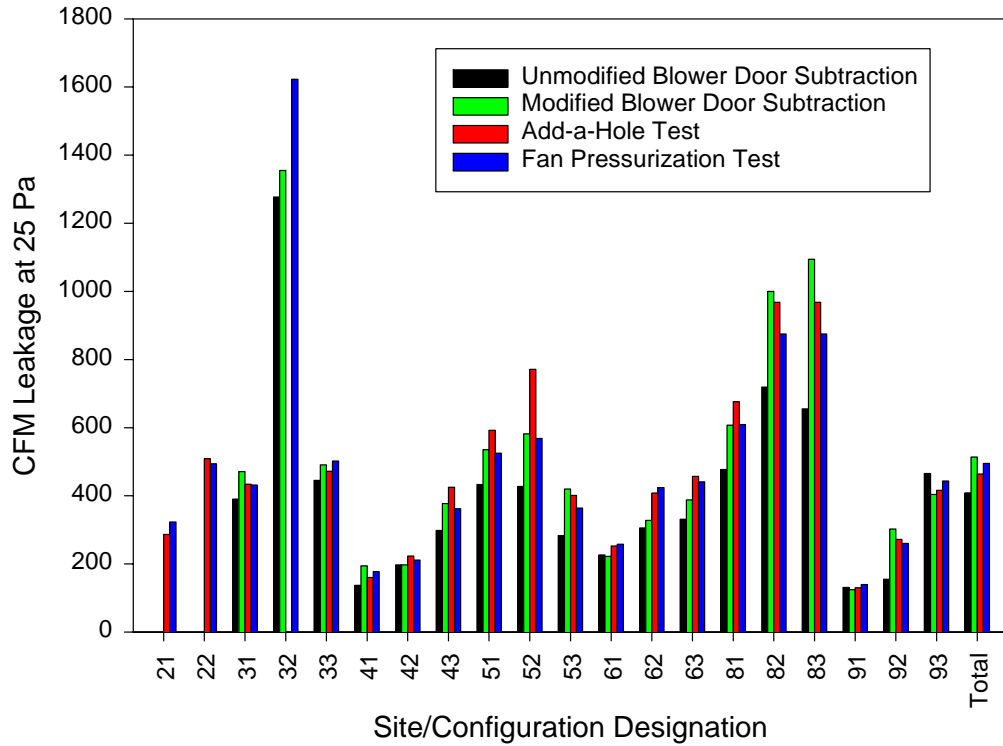


Figure 27. Comparison of unmodified blower door subtraction, modified blower door subtraction, add-a-hole test, and fan pressurization test predictions of combined supply and return duct leakage to outside at 25 Pa. The Site/Configuration Designation key is in Table 4.

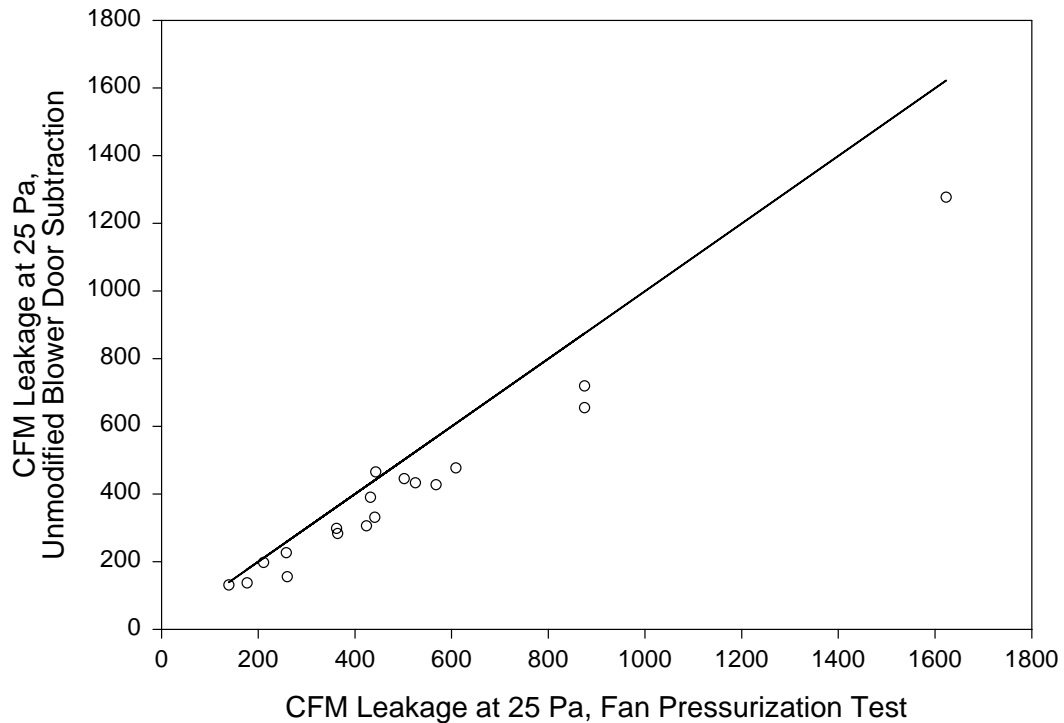


Figure 28. Comparison of unmodified blower door subtraction and fan pressurization test predictions of combined supply and return duct leakage to outside at 25 Pa.

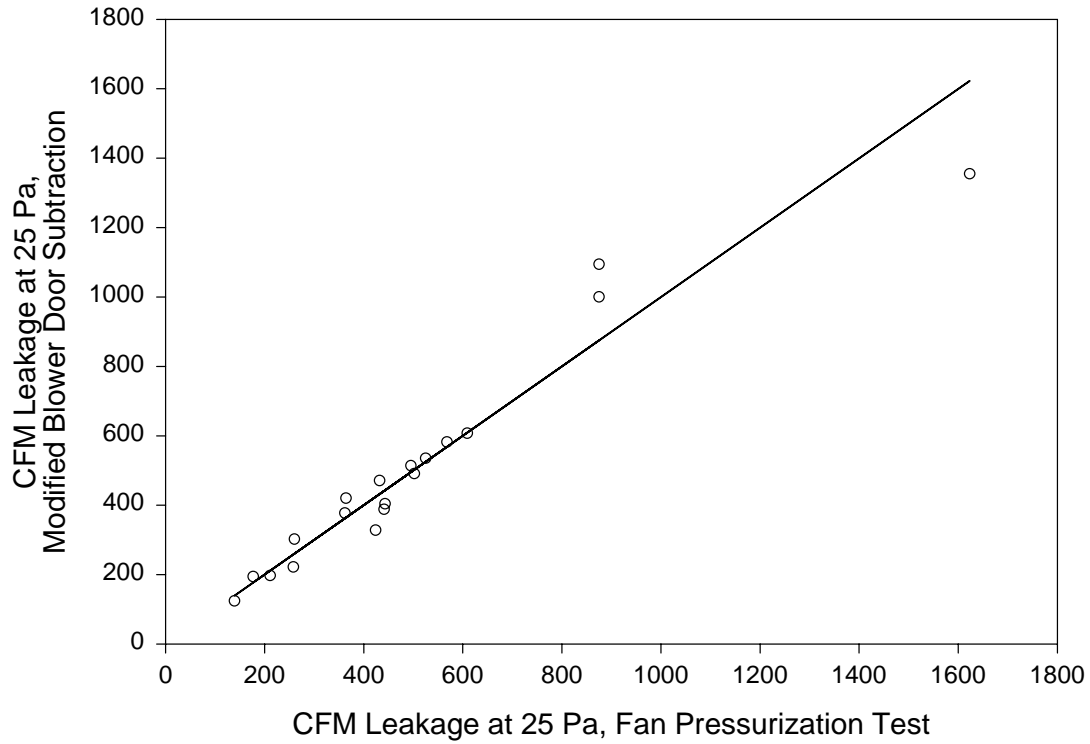


Figure 29. Comparison of modified blower door subtraction and fan pressurization test predictions of combined supply and return duct leakage to outside at 25 Pa.

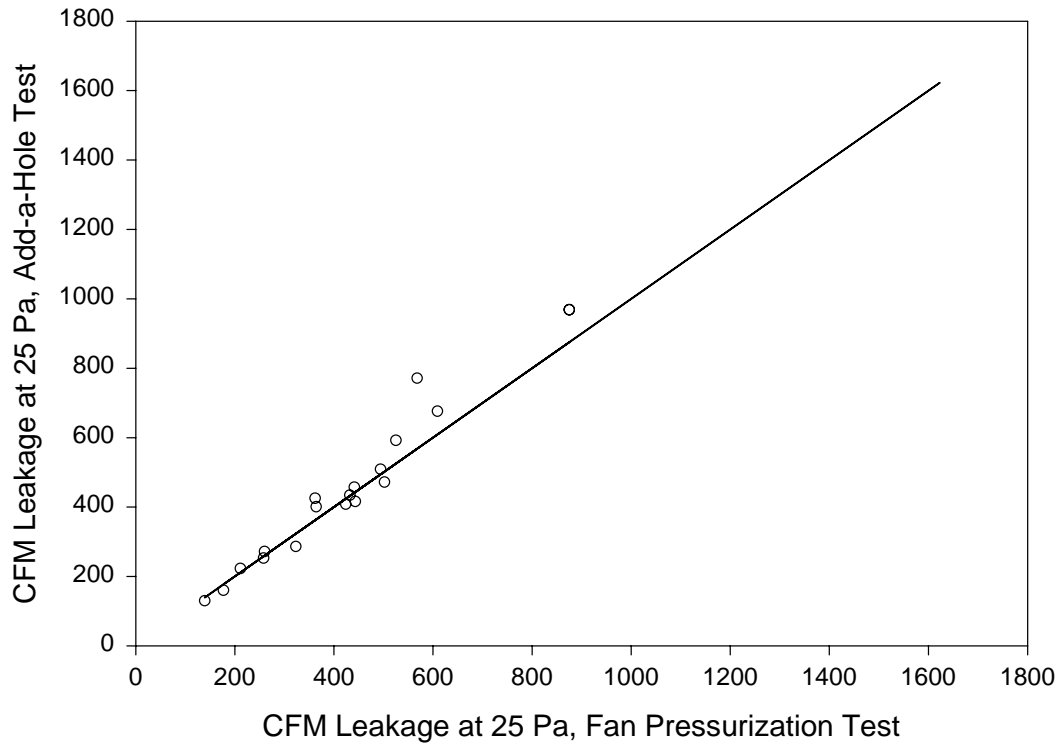


Figure 30. Comparison of add-a-hole test and fan pressurization test predictions of combined supply and return duct leakage to outside at 25 Pa.

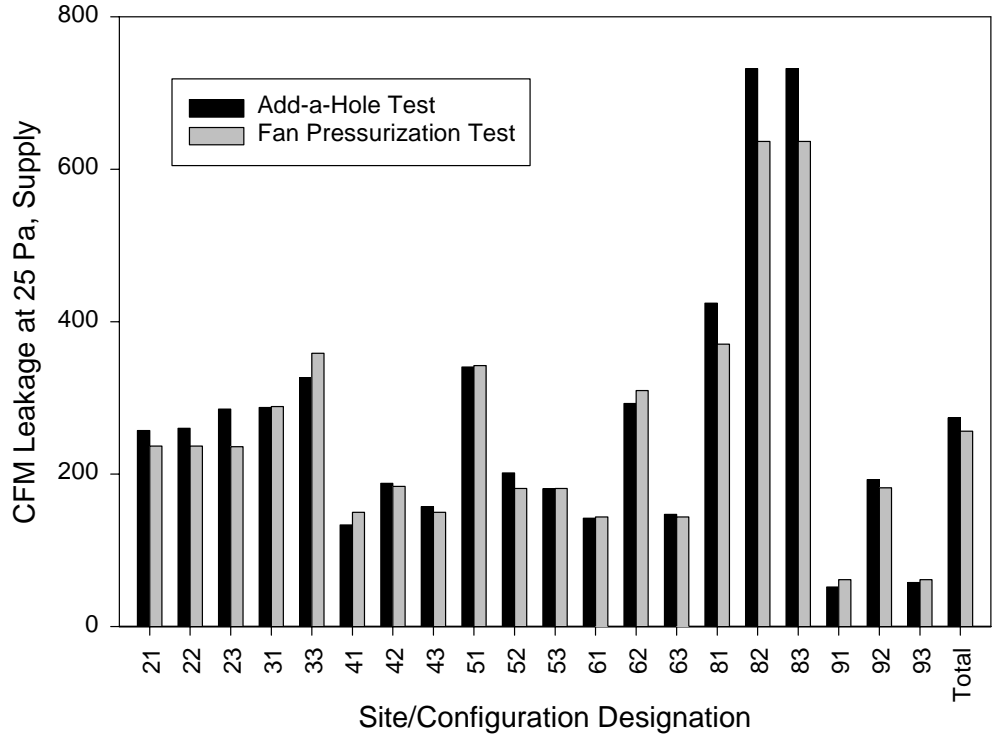


Figure 31. Comparison of add-a-hole test and fan pressurization test predictions of supply duct leakage to outside at 25 Pa. The Site/Configuration Designation key is in Table 4.

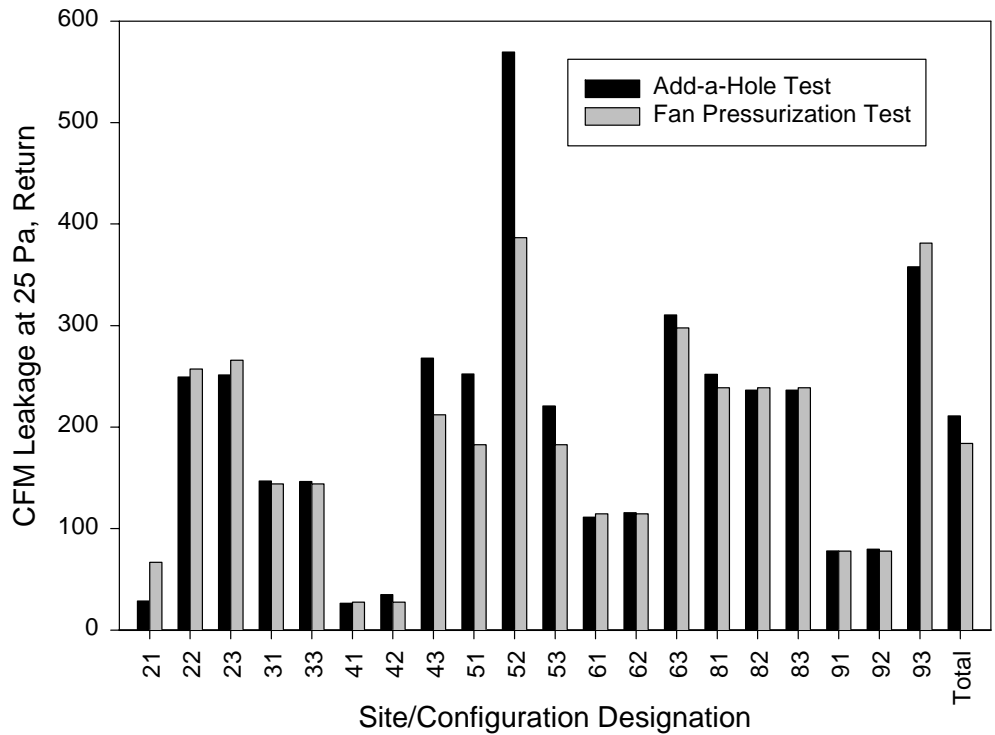


Figure 32. Comparison of add-a-hole test and fan pressurization test predictions of return duct leakage to outside at 25 Pa. The Site/Configuration Designation key is in Table 4.

## FINDINGS AND CONCLUSIONS

This section is broken down similarly to the results sections of the report. The “Overall” findings and conclusions are based on the comparisons across leakage test methods. After the “Overall” section are sections dedicated to findings and conclusions about each leakage test method individually.

### Overall

These findings and conclusions are based on the unmodified leakage tests. Modifications are discussed in the sections devoted to the individual tests.

- 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 artificial duct configurations. The duct leakage that was added was intended to represent the types of leaks that are found in the field, but the frequency of their occurrence is not as high in general as it is in this study. Further work on more homes is warranted.
- The most accurate of the leakage test methods was the nulling test, with an average overestimation of about 13% of the best estimate of duct leakage on the supply side and 4% of the best estimate of duct leakage on the return side. It is, however, as time-consuming as the fan pressurization test and can be difficult to set up. It is also somewhat less repeatable than other methods.
- For homes without return ducts, such as manufactured homes, the nulling test is both the fastest and most accurate. This is because the supply leakage-only portion of the test is not required, and it is this portion of the test that requires the majority of the setup. The unbalanced leakage portion of the nulling test provides the supply leakage in these homes because there is no return leakage.
- The Delta-Q test was the fastest and easiest of the tests to perform, though the analysis of the data requires a programmed calculator or computer. It was also very repeatable. It was strongly biased, with an average overestimation of about 70% of the best estimate of duct leakage on the supply side and 61% on the return side. 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 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. Despite the poor agreement with the best estimate, the results did show a strong increasing trend as the best estimate of leakage increased.
- The fan pressurization test performed better than expected on the return side, with results that were nearly as good as from the nulling test, both in terms of bias and the degree to which the estimates show a strong increasing trend with increasing leakage from the best estimate. This indicates that the assumption that the operating pressure is half of the plenum pressure tends to be a good one. The test was also extremely repeatable, even more repeatable than the Delta-Q test. There are only a couple of cases, with disconnected main return trunk ducts, where the fan pressurization test failed. It seems likely that over a larger sample of

homes this test would continue to perform well on the return side, on average, using the half plenum pressure assumption.

- On the supply side, the fan pressurization test performed very poorly, with an average overestimation of about 84% of the best estimate of duct leakage, though repeatability was still high. The results on the supply side also did not show a particularly strong trend of increasing leakage estimate as the best estimate of leakage increased, although there were very few cases where the fan pressurization test underestimated the leakage. It can be stated that this test did not produce much in the way of false negatives on the supply side, where there was significant leakage but the test indicated that leakage was small. However, there were a number of cases where the test indicated large supply leakage when this was not actually the case. This was largely because of a combination of an overestimation of operating pressures and the effects of the momentum of air during operating conditions. The momentum of air takes the air past certain holes in ducts when the registers are not sealed that air is forced to go out of with the registers sealed during the fan pressurization test.
- In addition to the poor performance in estimating supply leakage, the fan pressurization is also time-consuming and can be difficult to set up. In some cases it may not be possible to perform this test due to inaccessible registers and grilles, which must all be sealed.

### **Nulling Test**

- Despite the potential for holes in ducts to cause the target pressure in the house to be affected, the methods of adjusting for this are time-consuming and the results showed very little improvement from implementing them. As a result, it does not seem worthwhile to make these adjustments.
- It is also not usually worth adjusting the results for changes in stack pressure unless interior conditions changed drastically, such as from having a furnace running with the heat on for an extended period of time during the test. It is preferable to run the nulling test with the air handler running in fan-only mode.
- The nulling test is very sensitive to wind, but the effects of wind can be mitigated with longer sample intervals such as three minutes per pressure station.
- It is important to measure the flows at least at three different pressures that bracket the target pressure. This allows for interpolation to the exact target in the event that the target was not matched exactly.
- Automated data collection software is very important for simplifying and troubleshooting the test. This type of software can give immediate feedback as to whether the data falls on a nearly straight line; if it does not, a problem is indicated and the test can be redone.

### **Delta-Q Test**

- Changing the pressure assumption from full plenum pressures to either half plenum pressures or quarter plenum pressures did not greatly improve the results. Using half of the plenum pressure reduced the bias to about 55% on the supply side and 52% on the return side. Using one quarter of the plenum pressure actually increased the bias. This non-monotonic behavior, whereby a decrease in pressure may not correspond to a decrease in leakage, is

counterintuitive but is one of the features of the equations used to analyze the Delta-Q test results.

- Changing the leakage exponent assumption can also have a significant impact on the results, but as with the pressure assumption there is not a set of reasonable exponents that results in a good leakage prediction. Reducing the exponents to 0.55 from 0.6 reduces the bias to about 45% on the supply side and 43% on the return side. The leakage estimates do change monotonically with exponent, so the exponent would have to be reduced significantly further to provide good agreement with the best estimate. However, the theoretical lower limit on the exponent is 0.5.
- The problems with the pressure and exponent assumptions mean that, in these houses, there is not a set of reasonable pressures and exponents that can provide satisfactory agreement with the best estimate.
- One of the major problems with this test is the failure of the assumption that the pressure difference between the ducts and the house remains constant throughout the Delta-Q test. This pressure difference can vary by more than a factor of two for leaky systems across the range of pressure stations in the test. The failure of this assumption leads to an overestimation of leakage estimates, which was confirmed by computer simulations using CONTAM. These simulations were done with all other assumptions satisfied, including having known duct pressures and leakage exponents. This problem warrants further investigation for possible remedies. One possibility is to measure the actual pressures between the ducts and the house at each station, and to use these in place of the constant duct pressure in the Delta-Q analysis. This requires a third pressure measurement tap, in addition to the taps for house pressure and fan pressure.
- Another assumption of the Delta-Q test that will not always hold true is that the pressure across the envelope is the same as the pressure across the duct leaks when the air handler is off. If the space in which the ducts are located is significantly connected to the conditioned space, with regard to pressures, the duct zones will change pressure differently than the house when the blower door operates. This will occur when the duct zone is not well ventilated. The impact of this assumption was not evaluated in this study.
- There can be a significant amount of crosstalk between the supply and return sides in this test, meaning that a large leak on one side can cause the test to also estimate a large leak on the other side, even if the leakage is not large. This can lead to incorrect and time-wasting decisions as to whether it is worth fixing duct leakage.
- Automation is important to make the test user-friendly and less prone to user error. It is absolutely critical that the analysis of the data to provide leakage estimates be automated, as the equations for performing this analysis are difficult and complex.

### **Fan Pressurization Test**

- As has been found in many previous studies, the biggest technical problem with the fan pressurization test is estimating the operating pressures at the leaks. At these houses the standard assumption that the operating pressure is half of the plenum pressure is poor on the supply side. This assumption overestimates the supply operating pressures by about a factor of two, on average. This results in greatly overestimated leakage. One of the primary reasons for this is that many leaks occur downstream of several bends that occur after the plenum, each of which causes a substantial pressure drop. Another reason is that many holes

in ducts occur in locations which get largely bypassed by the air during normal operation because of momentum, but in the fan pressurization test the air is forced out of these holes since the registers are sealed.

- On the return side the standard assumption for operating pressure of half the plenum pressure worked well unless there was a major disconnect in main trunk. The return ducts typically consisted of only a very few large, straight sections, so the pressure drop was not as large between the main portion of the ducts and the plenum. The momentum of air is also less of a problem on the return side because the ducts are pulling air in through the leaks instead of pushing air out.

### **Blower Door Subtraction/Add-a-Hole Test**

- Both the add-hole and modified subtraction methods show promise where the goal is to measure duct leakage to outside at a given reference pressure. They share the drawback of the fan pressurization method of requiring an estimate of an appropriate "effective" duct-to-outside pressure difference in order to get an estimate of leakage at operating conditions.
- The add-a-hole method as performed here has the advantage of producing values separately for the return and supply ducts. This is important, because in most conditions, the thermal losses associated with supply leaks are significantly larger than those associated with return leaks of the same size.
- The modified blower door subtraction test could be extended to provide separate supply and return leakage by taping off one side and then the other and performing a blower door test under each configuration.
- Both the modified blower door subtraction and add-a-hole tests are faster and easier than the fan pressurization test, and require less equipment.

### **Future Work**

- These results are based on only a few houses with only a few types of leaks. It is important that more houses be tested, including houses of different housing types (e.g. multi-story), foundation types (e.g. slabs), and construction types (e.g. brick, cement block) and in different regions. Only a larger sample could show whether some of the results and problems found in this study are truly systematic or whether they were particular to these houses.
- It is also extremely important to investigate possible changes to the Delta-Q analysis technique to remedy the problems discovered, including a change of the assumption regarding the pressure difference between the ducts and the house, the estimate of operating pressures and leakage exponents, and the degree to which large leaks on one side of the duct system influence the estimates on the other side. Unless these problems are addressed the Delta-Q test does not appear to be accurate enough for widespread use.

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## APPENDIX A – DETAILED RESULTS FOR SITE L01

Figure A1 shows the front of Site L01. This house has a floor area of 1360 ft<sup>2</sup>.

This house has a downflow gas furnace in the garage (see Fig. A2), with supply ducts in the crawl space and return ducts in the attic. There is a single central return and ten supply registers. There was a large supply leak on the inside of an elbow near the furnace (see Fig. A3). As a result, we considered the as-found leakage to be our supply-dominated case, and we sealed this leak off for our approximately balanced case. We cut a large hole in the return plenum to create our return-dominated case (see Fig. A4), which provided a leak of about 15% of air handler flow.

The analysis showed that, despite the proximity of the large supply leak to the furnace, the leakage through this hole was quite small (only about 4% of air handler flow). This was because it was on the inside of a bend and because there were two other bends between the furnace and this leak, causing the pressure to actually be a lot lower at the leak than plenum pressure. As a result, there is not much difference between the “supply-dominated” supply leakage and the “balanced” supply leakage.

The as-found leakage levels were about 17% for the supply and about 7-8% on the return side.



Figure A1. Front view of Site L01.



Figure A2. Downflow gas furnace in garage.



Figure A3. As-found leak in supply trunk.



Figure A4. Added return leak at plenum.

Table A1 shows the supply leakage estimates from the best estimate, the nulling test, the Delta-Q test based on the full plenum pressures, and the fan pressurization test using half of the plenum pressure. These estimates are expressed both in terms of actual cfm and as a percentage of air handler flow. This table shows that both the nulling test and the Delta-Q test give results that are a lot closer to the best estimate than the fan pressurization test, with the nulling test being the closest in all but one case. All predictions are greater than the best estimate, regardless of test.

Figure A5 shows the supply results graphically, expressed as a fraction of air handler flow.

Table A2 shows the return leakage estimates from the best estimate, the nulling test, the Delta-Q test based on the full plenum pressures, and the fan pressurization test using half of the plenum pressure. As for the supply leakage estimates, these estimates are expressed both in terms of actual cfm and as a percentage of air handler flow. For the return, the fan pressurization test provides the best estimates, with the nulling test and Delta-Q test estimating significantly higher leakage. The reason for the poor performance of the nulling and Delta-Q tests is not known. The nulling test again provides estimates that are closer to the best estimate than does the Delta-Q test.

Figure A6 shows the return results graphically, expressed as a fraction of air handler flow.

**Table A1. Site L01 Supply Leakage and Leakage Fraction Estimates**

	Best Estimate		Nulling Test		Delta-Q Test		Fan Pressurization	
	cfm	%	cfm	%	cfm	%	cfm	%
<b>Supply-dominated (as-found)</b>								
A1	118	13.7	177	20.5	228	26.4	429	49.6
B1	159	18.0	190	21.6	254	28.9	442	50.2
C1	157	17.6	187	21.0	246	27.7	420	47.2
<b>Approximately Balanced</b>								
A2	101	11.5	142	16.3	211	23.9	371	42.5
B2	122	13.8	150	17.0	223	25.3	381	43.1
C2	113	13.0	191	21.9	183	20.9	382	43.7
<b>Return-dominated</b>								
A3	115	13.2	141	16.3	235	27.3	367	42.4
B3	130	14.4	176	19.6	221	24.6	380	42.2
C3	133	14.8	167	18.6	213	23.7	387	43.0

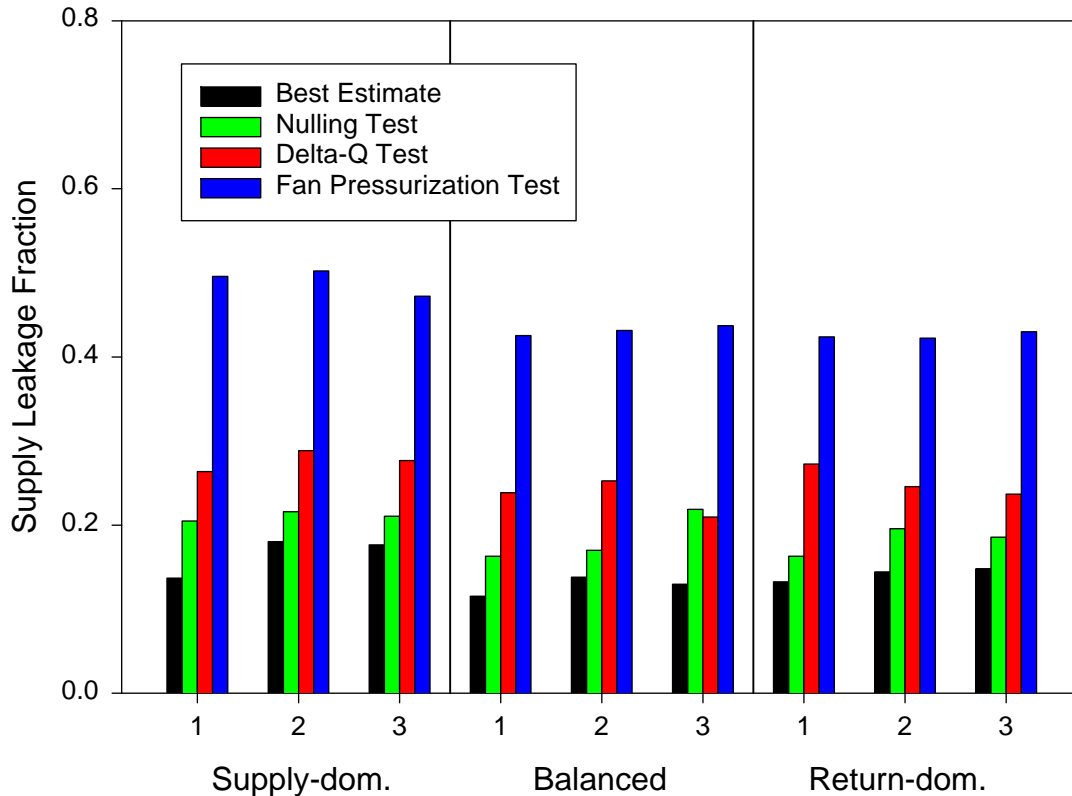


Figure A5. Supply leakage fraction results for Site L01.

**Table A2. Site L01 Return Leakage and Leakage Fraction Estimates**

	Best Estimate		Nulling Test		Delta-Q Test		Fan Pressurization	
	cfm	%	cfm	%	cfm	%	cfm	%
Supply-dominated (as-found)								
A1	51	5.9	138	16.0	240	27.7	105	12.1
B1	40	4.5	164	18.6	270	30.7	112	12.7
C1	69	7.7	156	17.5	258	29.0	106	11.9
Approximately Balanced								
A2	63	7.2	115	13.2	245	27.9	110	12.6
B2	75	8.5	129	14.6	267	30.2	111	12.6
C2	83	9.5	180	20.6	236	27.0	106	12.1
Return-dominated								
A3	156	18.0	242	27.9	380	44.0	172	19.9
B3	261	29.0	244	27.1	359	39.9	173	19.2
C3	193	21.5	245	27.2	350	38.9	167	18.6

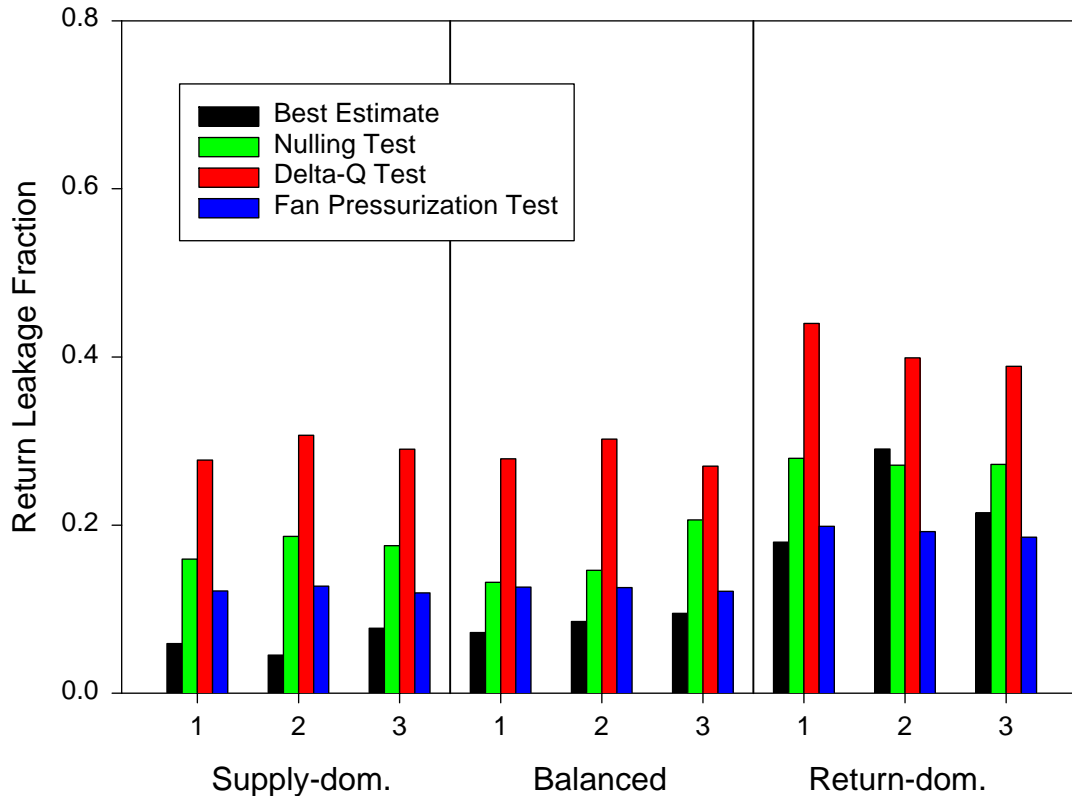


Figure A6. Return leakage fraction results for Site L01.



## **APPENDIX B – DETAILED RESULTS FOR SITE L02**

Site L02 has a downflow gas furnace in the garage, with supply ducts in the crawl space and return ducts in the attic. There are two return grilles and twelve supply registers. There was a supply leak in an elbow near the furnace. As a result, we considered the as-found leakage to be our supply-dominated case. We added a large hole in the return plenum to create our approximately balanced case. We sealed the supply leak while leaving the large hole in the return plenum to create our return-dominated case.

Despite the fact that the large supply leak was not on the inside of a bend, as it was at Site L01, the analysis still showed that there was not a lot of air coming out of the leak under normal operating conditions because of the momentum of the air.

Table B1 shows the supply leakage estimates from the best estimate, the nulling test, the Delta-Q test based on the full plenum pressures, and the fan pressurization test using half of the plenum pressure. These estimates are expressed both in terms of actual cfm and as a percentage of air handler flow. This table shows that all of the tests perform similarly, with all predictions greater than the best estimate.

Figure B1 shows the supply results graphically, expressed as a fraction of air handler flow.

Table B2 shows the return leakage estimates from the nulling test, the Delta-Q test based on the full plenum pressures, and the fan pressurization test using half of the plenum pressure. Due to an equipment problem we were unable to get a best estimate of the return leakage at this house. As with the supply leakage estimates, these estimates are expressed both in terms of actual cfm and as a percentage of air handler flow. The nulling and Delta-Q tests provide similar estimates, with the Delta-Q being a bit higher with the added return leak. The fan pressurization test provides lower estimates for all cases.

Figure B2 shows the return results graphically, expressed as a fraction of air handler flow.

**Table B1. Site L02 Supply Leakage and Leakage Fraction Estimates**

	Best Estimate		Nulling Test		Delta-Q Test		Fan Pressurization	
	cfm	%	cfm	%	cfm	%	cfm	%
Supply-dominated (as-found)								
A1	204	18.3	289	26.0	243	21.9	283	25.4
Approximately Balanced								
A2	224	19.4	328	28.4	306	26.5	311	26.9
Return-dominated								
A3	186	16.1	246	21.3	278	24.0	283	24.5
B3	210	18.5	282	24.8	268	23.6	298	26.2

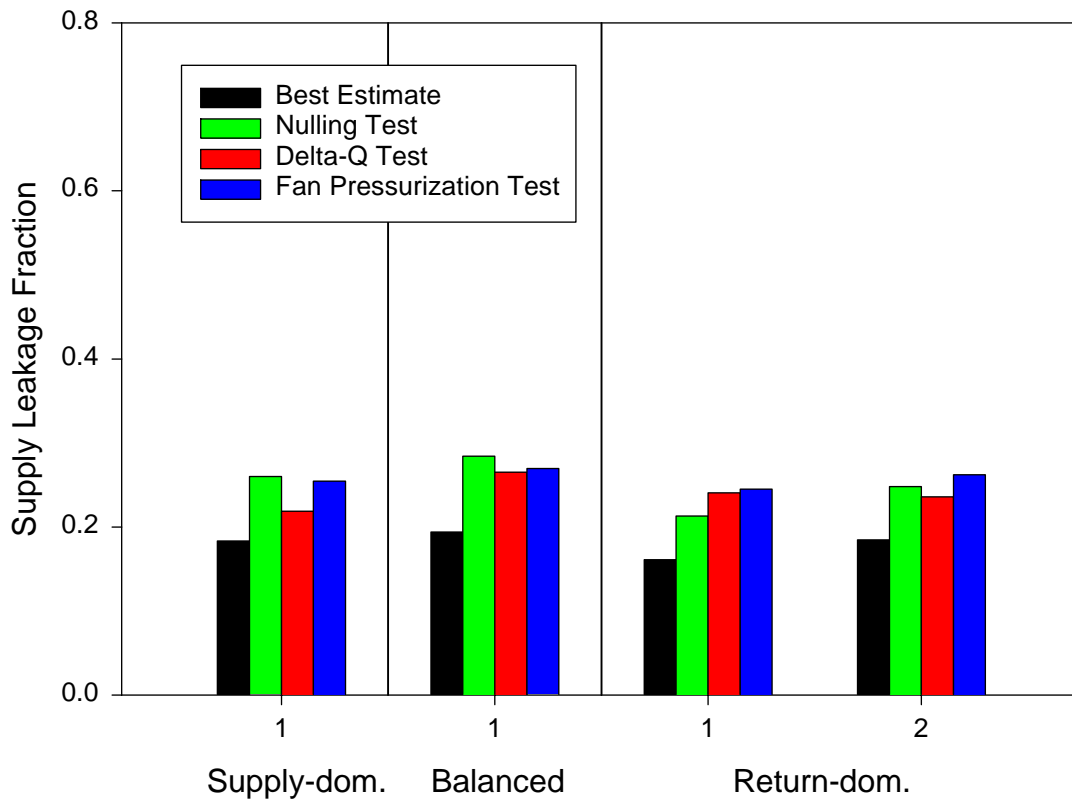


Figure B1. Supply leakage fraction results for Site L02.

**Table B2. Site L02 Return Leakage and Leakage Fraction Estimates**

	Best Estimate		Nulling Test		Delta-Q Test		Fan Pressurization	
	cfm	%	cfm	%	cfm	%	cfm	%
Supply-dominated (as-found)								
A1	--	--	113	10.2	114	10.3	72	6.5
Approximately Balanced								
A2	--	--	373	23.3	407	35.3	236	20.5
Return-dominated								
A3	--	--	305	26.4	364	31.5	234	20.2
B3	--	--	323	28.4	356	31.3	251	22.1

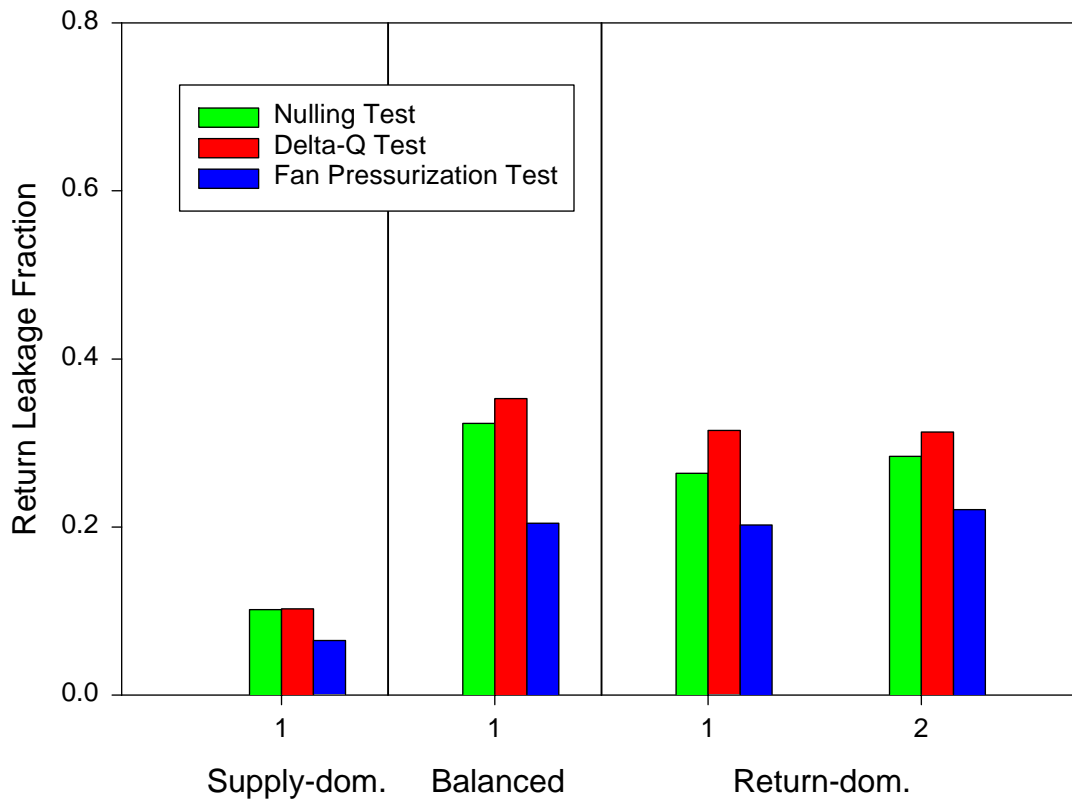


Figure B2. Return leakage fraction results for Site L02.



## APPENDIX C – DETAILED RESULTS FOR SITE L03

Figure C1 shows the front of Site L03. This house has a floor area of 1677 ft<sup>2</sup>.

This house has a downflow gas furnace in the garage (see Fig. C2), with supply ducts in the crawl space and return ducts in the attic. There are two return grilles and thirteen supply registers. The as-found duct leakage was used for the balanced case. We disconnected a supply duct at the boot to create our supply-dominated case (see Fig. C3). This disconnect provided a leak of about 7-8% of air handler flow. We separated two segments of one of the two return ducts to create our return-dominated case (see Fig. C4). This disconnect provided a leak of about 30% of air handler flow. No more than one of the added leaks was present at any one time.



Figure C1. Front view of Site L03.



Figure C2. Downflow gas furnace in garage.



Figure C3. Added supply leak at register boot.



Figure C4. Added leak in return duct.

Table C1 shows the supply leakage estimates from the best estimate, the nulling test, the Delta-Q test based on the full plenum pressures, and the fan pressurization test using half of the plenum pressure. These estimates are expressed both in terms of actual cfm and as a percentage of air handler flow. This table shows that both the nulling test and the Delta-Q test give results that are closer to the best estimate than the fan pressurization test. The nulling test is usually closer to the best estimate than the Delta-Q test. The Delta-Q test also shows a significant increase in supply leakage when the only change is the added return leak, indicating that the supply leakage prediction is sensitive to the amount of return leakage.

Figure C5 shows the supply results graphically, expressed as a fraction of air handler flow.

Table C2 shows the return leakage estimates from the best estimate, the nulling test, the Delta-Q test based on the full plenum pressures, and the fan pressurization test using half of the plenum pressure. As with the supply leakage estimates, these estimates are expressed both in terms of actual cfm and as a percentage of air handler flow. For the return, the fan pressurization test provides the best estimates for the cases without the large return leak. The poor performance of this test with the big return leak is because the leak was a disconnect of half of the system, and the pressures that the ducts could be pressurized to were quite low. The nulling test was inconsistent, usually performing reasonably well but with some individual bad test, such as for case C3. The Delta-Q test was much more consistent, but provided very high estimates for the case with the leaky return and typically overestimated the leakage by a substantial amount in the other cases.

Figure C6 shows the return results graphically, expressed as a fraction of air handler flow.

**Table C1. Site L03 Supply Leakage and Leakage Fraction Estimates**

	Best Estimate		Nulling Test		Delta-Q Test		Fan Pressurization	
	cfm	%	cfm	%	cfm	%	cfm	%
Approximately Balanced (as-found)								
A1	57	5.0	162	14.3	151	13.3	275	24.3
B1	128	10.9	113	9.6	122	10.4	274	23.3
C1	67	6.0	125	11.1	159	14.1	274	24.4
Return-dominated								
A2	88	7.6	101	8.7	235	20.3	281	24.2
B2	96	8.4	100	8.7	247	21.5	280	24.4
C2	83	7.2	130	11.3	208	18.1	278	24.2
Supply-dominated								
A3	148	12.8	286	24.8	234	20.3	369	32.0
B3	158	13.6	259	22.3	238	20.5	371	32.0
C3	166	14.4	207	18.0	221	19.2	367	31.9

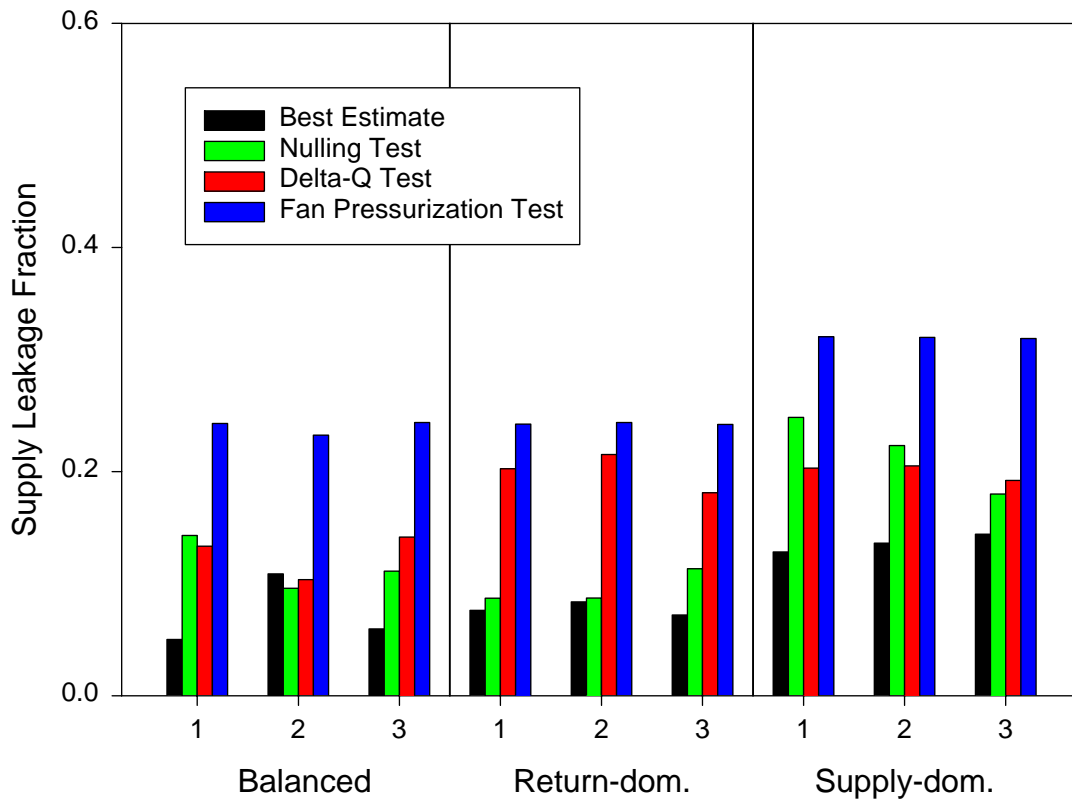


Figure C5. Supply leakage fraction results for Site L03.

**Table C2. Site L03 Return Leakage and Leakage Fraction Estimates**

	Best Estimate		Nulling Test		Delta-Q Test		Fan Pressurization	
	cfm	%	cfm	%	cfm	%	cfm	%
Approximately Balanced (as-found)								
A1	82	7.2	167	14.8	148	13.1	112	9.9
B1	97	8.3	114	9.7	117	9.9	110	9.3
C1	80	7.1	134	11.9	168	14.9	108	9.6
Return-dominated								
A2	463	39.9	552	47.6	728	62.8	923	79.6
B2	547	47.7	532	46.3	652	56.8	1217	106.0
C2	430	37.5	654	57.0	695	60.5	1010	88.0
Supply-dominated								
A3	105	9.1	221	19.2	170	14.8	108	9.4
B3	76	6.5	95	8.2	167	14.4	110	9.5
C3	110	9.5	108	9.4	168	14.6	106	9.2

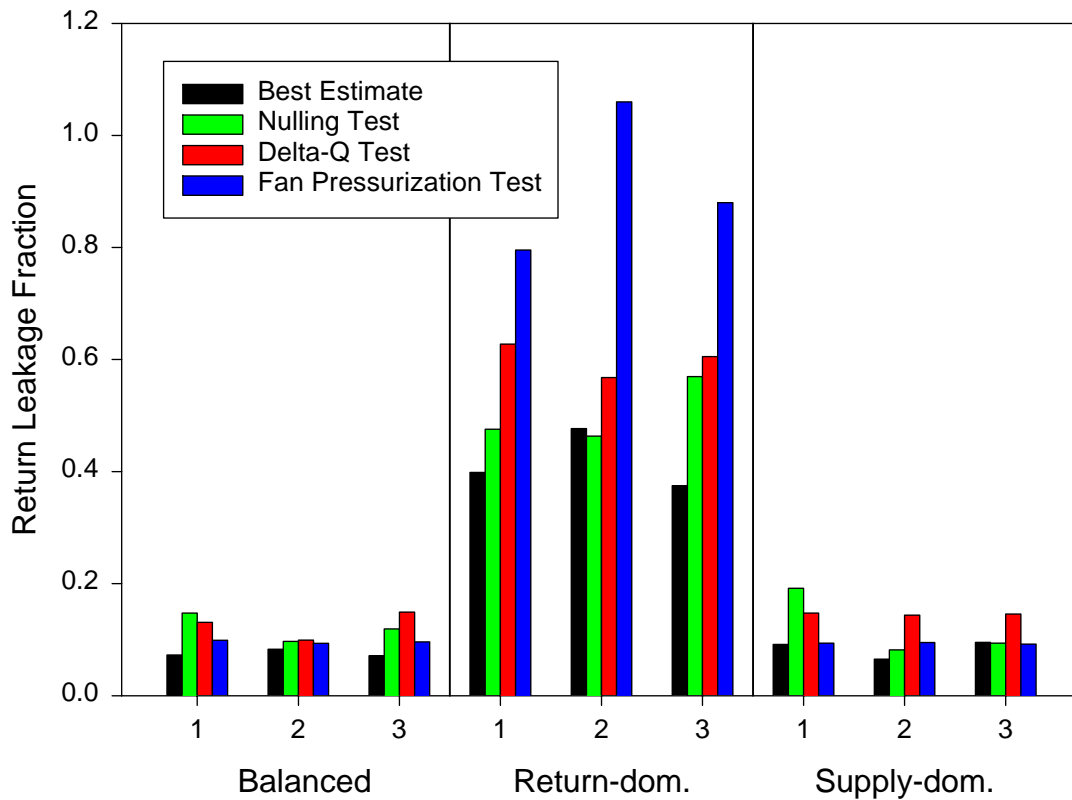


Figure C6. Return leakage fraction results for Site L03.



## APPENDIX D – DETAILED RESULTS FOR SITE L04

Figure D1 shows the front of Site L04. This house has a floor area of 973 ft<sup>2</sup>.

This house has a horizontal gas furnace in the crawl space, with all supply and return ducts also in the crawl space. There is a single central return and eight supply registers. The as-found leakage was used as the balanced leakage case. We disconnected one supply duct at the register boot to create our supply-dominated leakage case (see Fig. D2). We cut a large hole in the return plenum to create our return-dominated case (see Fig. D3). No more than one of the added leaks was present at any time.

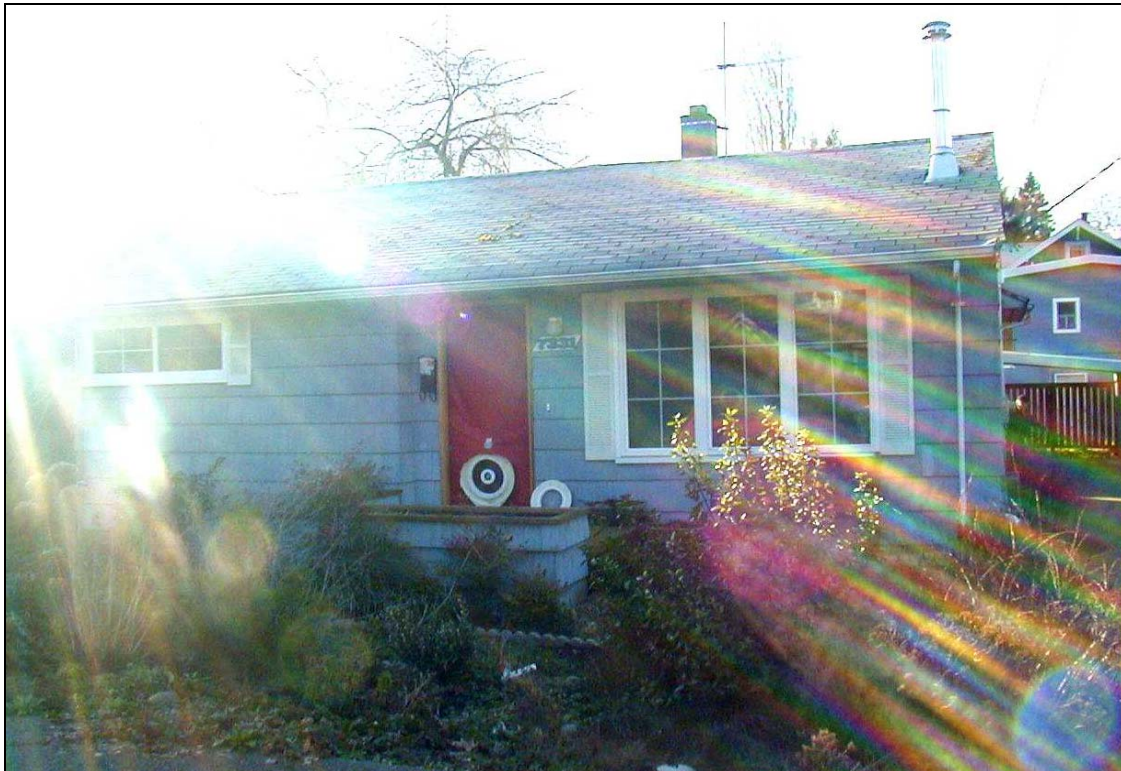


Figure D1. Front view of Site L04.



Figure D2. Added supply leak at register boot.



Figure D3. Added return leak at plenum.

Table D1 shows the supply leakage estimates from the best estimate, the nulling test, the Delta-Q test based on the full plenum pressures, and the fan pressurization test using half of the plenum pressure. These estimates are expressed both in terms of actual cfm and as a percentage of air handler flow. This table shows that the nulling test performs better than either of the other two tests on the supply side at this house. The nulling test predicts much smaller leakage than the other two tests for the two cases without the added leak. Even with the added leak the nulling test does not overpredict by as much as the other methods. In this house, the Delta-Q test and the fan pressurization test give similar results for supply leakage.

Figure D4 shows the supply results graphically, expressed as a fraction of air handler flow.

Table D2 shows the return leakage estimates from the best estimate, the nulling test, the Delta-Q test based on the full plenum pressures, and the fan pressurization test using half of the plenum pressure. As for the supply leakage estimates, these estimates are expressed both in terms of actual cfm and as a percentage of air handler flow. For the return, the fan pressurization test underpredicts the leakage in all cases. The nulling test performs better than the Delta-Q test for the case of the added return leak. For the other cases neither the nulling test nor the Delta-Q consistently provide the best results.

Figure D5 shows the return results graphically, expressed as a fraction of air handler flow.

**Table D1. Site L04 Supply Leakage and Leakage Fraction Estimates**

	Best Estimate		Nulling Test		Delta-Q Test		Fan Pressurization	
	cfm	%	cfm	%	cfm	%	cfm	%
Approximately Balanced (as-found)								
A1	15	2.3	31	4.8	57	8.9	84	13.1
B1	15	2.3	10	1.5	22	3.4	102	15.6
C1	0	0.0	14	2.1	66	10.1	88	13.5
Supply-dominated								
A2	42	6.7	83	13.4	121	19.5	110	17.8
B2	60	9.3	80	12.4	131	20.3	109	16.9
C2	57	8.8	109	16.9	140	21.7	110	17.1
Return-dominated								
A3	52	7.5	20	2.9	95	13.7	89	12.8
B3	39	5.7	21	3.1	86	12.6	105	15.3
C3	15	2.2	37	5.5	100	14.9	89	13.3

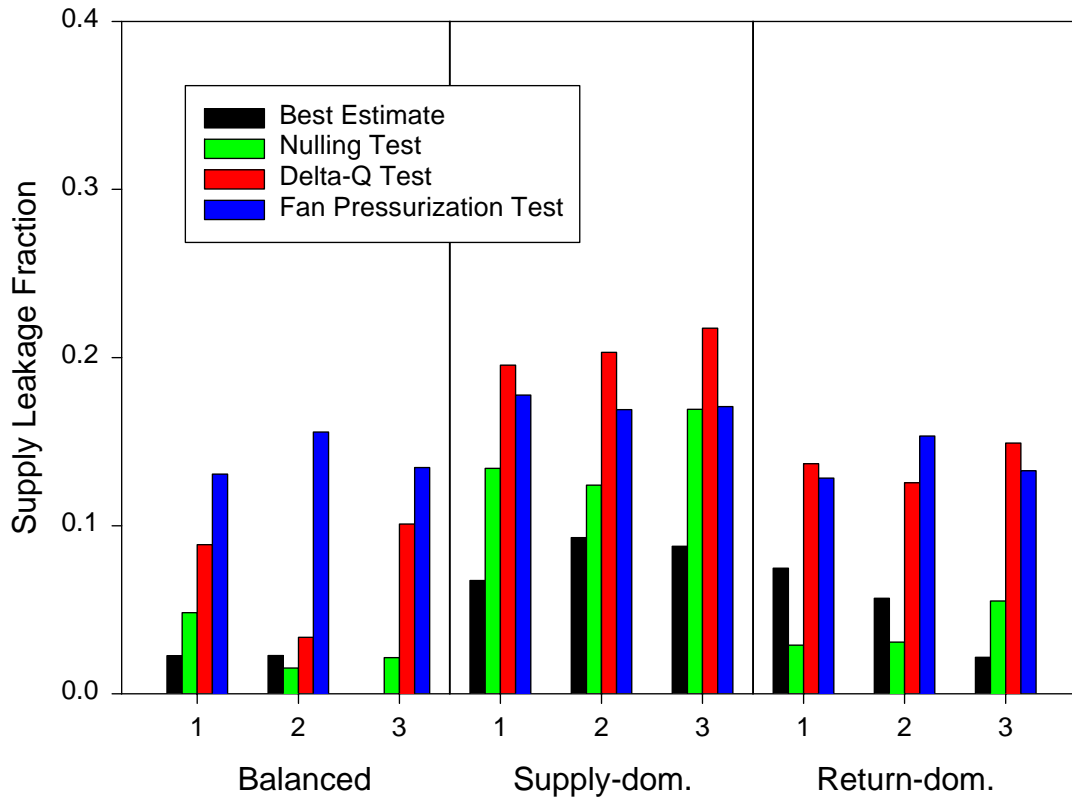


Figure D4. Supply leakage fraction results for Site L04.

**Table D2. Site L04 Return Leakage and Leakage Fraction Estimates**

	Best Estimate		Nulling Test		Delta-Q Test		Fan Pressurization	
	cfm	%	cfm	%	cfm	%	cfm	%
Approximately Balanced (as-found)								
A1	63	9.8	42	6.5	70	10.9	22	3.4
B1	64	9.8	35	5.3	66	10.1	21	3.2
C1	44	6.8	20	3.1	88	13.5	21	3.2
Supply-dominated								
A2	27	4.3	7	1.1	78	12.6	23	3.7
B2	46	7.2	-4	-0.6	52	8.1	21	3.3
C2	33	5.1	30	4.7	109	16.9	20	3.1
Return-dominated								
A3	216	31.1	166	23.9	294	42.4	134	19.3
B3	198	28.8	190	27.7	270	39.4	133	19.4
C3	185	27.5	195	29.1	306	45.6	132	19.7

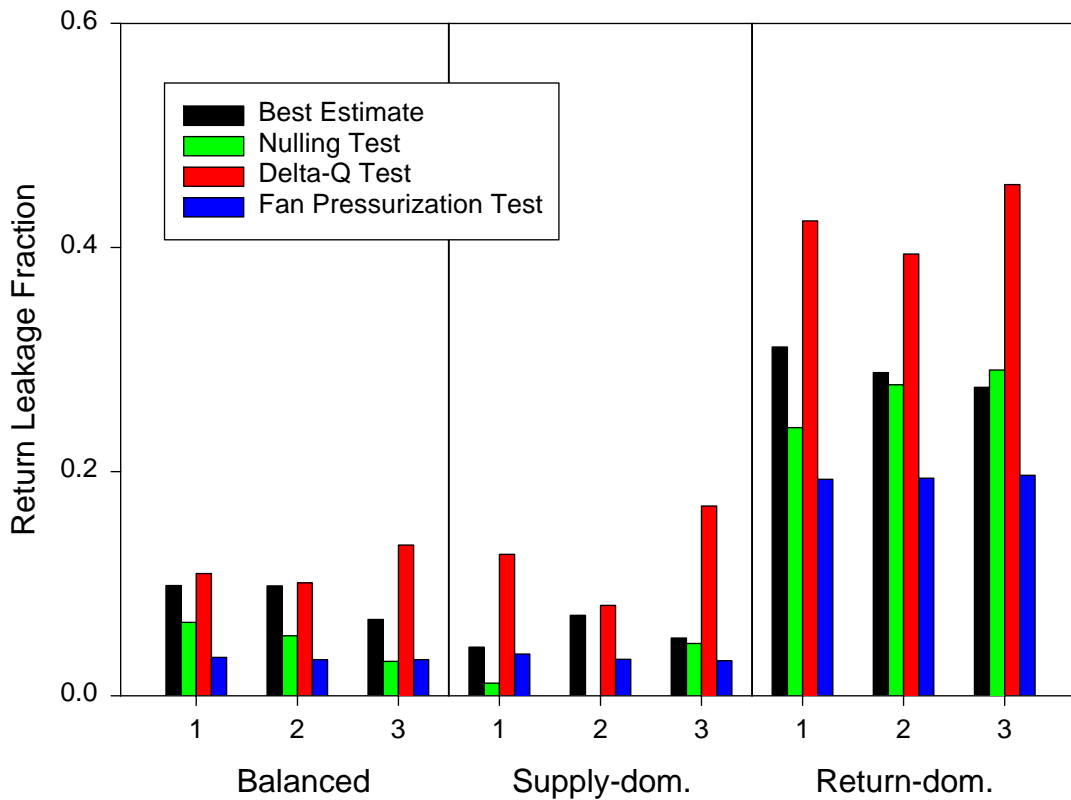


Figure D5. Return leakage fraction results for Site L04.



## APPENDIX E – DETAILED RESULTS FOR SITE L05

Figure E1 shows the front of Site L05. This house has a floor area of 1428 ft<sup>2</sup>.

This house has a downflow gas furnace within the conditioned space (see Fig. E2), with supply ducts in the attic and return ducts in the crawl space. The supply duct system was trunk-and-branch; the return duct system was radial. The crawl space was not well vented, such that the crawl space was partially connected to the house. There are seven return registers and ten supply grilles. The as-found leakage was used as the balanced leakage case. We disconnected one supply duct at the register boot to create our supply-dominated leakage case (see Fig. E3). This disconnect resulted in a leak of about 12% of air handler flow. We disconnected one of the seven radial return ducts about midway down its length to create our return-dominated case (see Fig. E4). This disconnect resulted in a leak of about 14% of air handler flow. No more than one of the added leaks was present at any time. The actual initial leakage was about 7% on the supply side and 11% on the return side.



Figure E1. Front view of Site L05.



Figure E2. Upflow gas furnace in closet.



Figure E3. Added supply leak at register boot.



Figure E4. Added return leak in return duct.

Table E1 shows the supply leakage estimates from the best estimate, the nulling test, the Delta-Q test based on the full plenum pressures, and the fan pressurization test using half of the plenum pressure. These estimates are expressed both in terms of actual cfm and as a percentage of air handler flow. This table shows that the fan pressurization test is similar to the nulling test for the cases without the added supply leak and better than the nulling test for the case with the added supply leak. For the cases where there are no added leaks the Delta-Q test also performs well. When either the supply leak or the return leak is added the Delta-Q test provides the highest estimates of supply leakage. All methods tend to overestimate the supply leakage at this house.

Figure E5 shows the supply results graphically, expressed as a fraction of air handler flow.

Table E2 shows the return leakage estimates from the best estimate, the nulling test, the Delta-Q test based on the full plenum pressures, and the fan pressurization test using half of the plenum pressure. As for the supply leakage estimates, these estimates are expressed both in terms of actual cfm and as a percentage of air handler flow. For the return, the nulling test does a good job at estimating the leakage. The fan pressurization test tends to be high. As with the supply leakage estimates, the Delta-Q test does a good job of estimating return leakage at this site when there are no added leaks, but overestimates the return leakage significantly when either the supply or return leak is added.

Figure E6 shows the return results graphically, expressed as a fraction of air handler flow.

**Table E1. Site L05 Supply Leakage and Leakage Fraction Estimates**

	Best Estimate		Nulling Test		Delta-Q Test		Fan Pressurization	
	cfm	%	cfm	%	cfm	%	cfm	%
<b>Supply-dominated</b>								
A1	210	17.9	340	29.1	369	31.5	271	23.2
B1	260	21.9	324	27.3	382	32.2	258	21.7
C1	221	19.3	296	25.8	366	31.9	260	22.7
<b>Return-dominated</b>								
A2	79	6.6	152	12.8	243	20.1	141	11.8
B2	123	10.1	99	8.1	241	19.8	142	11.6
C2	132	10.8	159	13.0	229	18.8	146	12.0
<b>Approximately Balanced (as-found)</b>								
A3	74	6.6	135	12.0	132	11.7	139	12.4
B3	30	2.7	128	11.5	149	13.4	133	12.0
C3	83	7.2	149	12.9	148	13.0	139	12.0

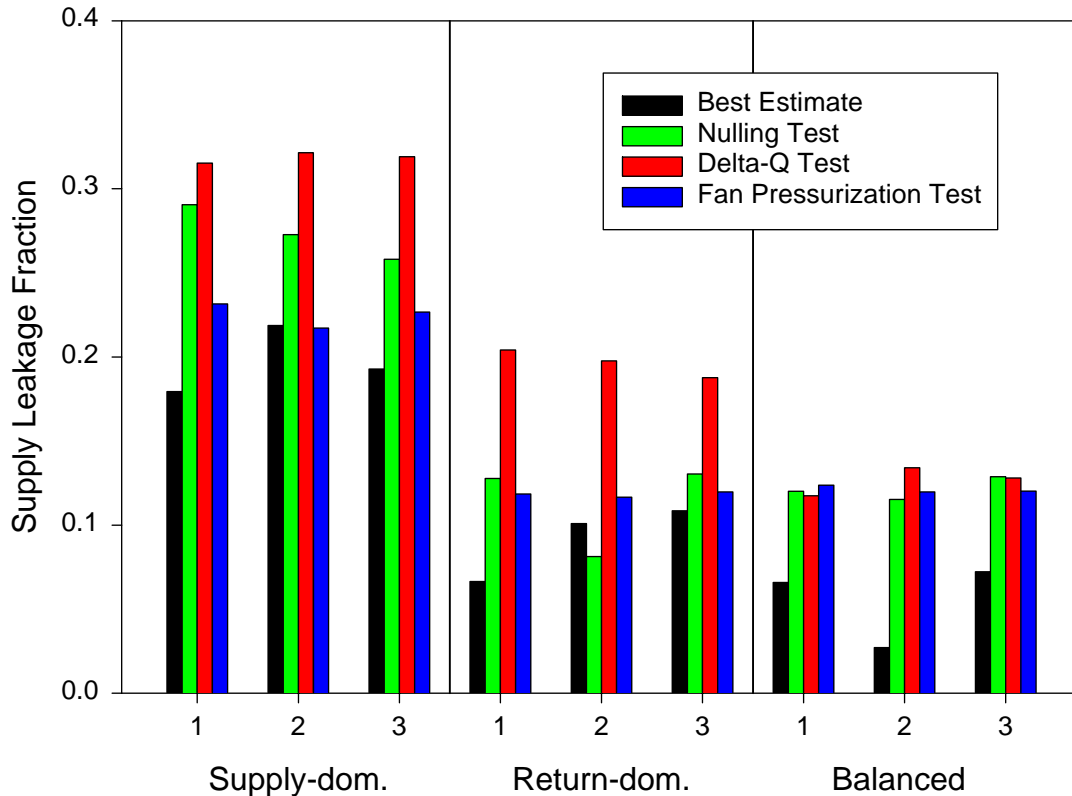


Figure E5. Supply leakage fraction results for Site L05.

**Table E2. Site L05 Return Leakage and Leakage Fraction Estimates**

	Best Estimate		Nulling Test		Delta-Q Test		Fan Pressurization	
	cfm	%	cfm	%	cfm	%	cfm	%
<b>Supply-dominated</b>								
A1	164	14.0	200	17.1	212	18.1	194	16.6
B1	145	12.2	189	15.9	227	19.1	201	16.9
C1	146	12.8	139	12.1	222	19.4	194	16.9
<b>Return-dominated</b>								
A2	338	28.4	308	25.9	455	38.2	406	34.1
B2	332	27.3	280	23.0	455	37.3	415	34.0
C2	341	28.0	317	26.0	448	36.7	386	31.6
<b>Approximately Balanced (as-found)</b>								
A3	146	13.0	142	12.6	150	13.3	191	17.0
B3	113	10.2	151	13.6	170	15.3	198	17.8
C3	129	11.2	166	14.3	185	16.0	195	16.9

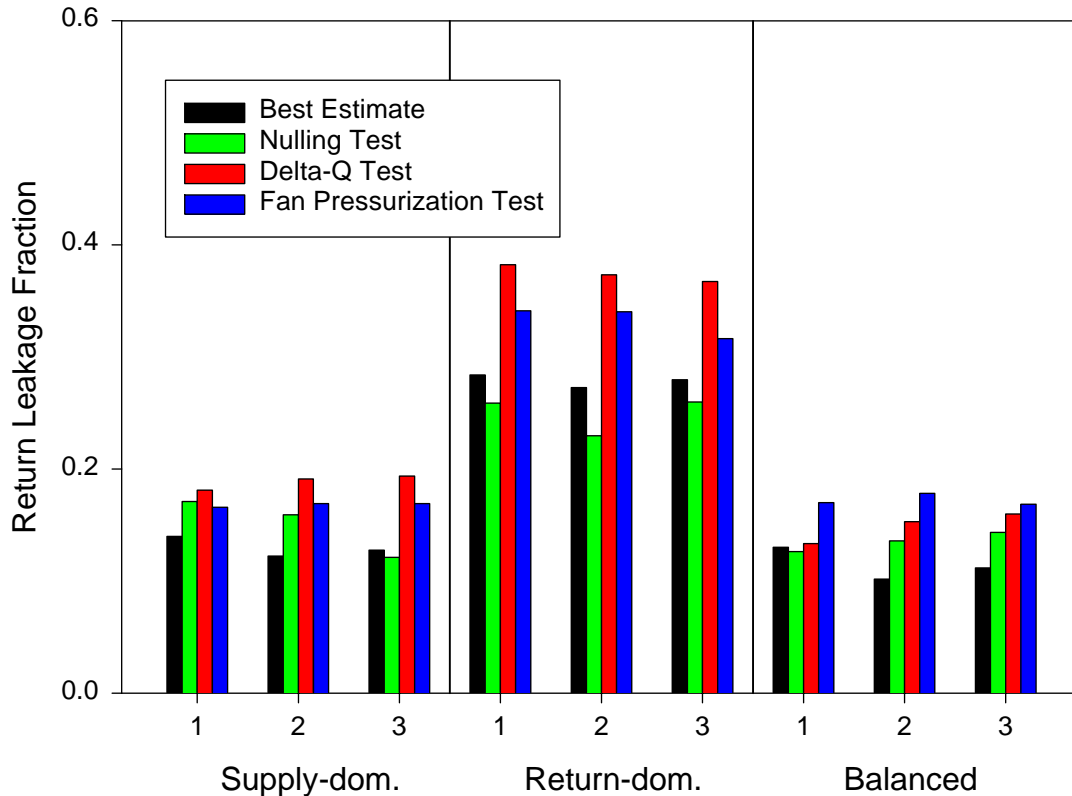


Figure E6. Return leakage fraction results for Site L05.



## APPENDIX F – DETAILED RESULTS FOR SITE L06

Figure F1 shows the front of Site L06. This house has a floor area of 758 ft<sup>2</sup>.

This house has a horizontal gas furnace in the crawl space (see Fig. F2), with supply ducts and return ducts also all in the crawl space. There is a single central return and five supply registers. The supply duct system was a radial system. This house had an outdoor air intake attached to the return plenum, which we disconnected for all tests. The as-found leakage, with the outdoor air intake disconnected, was used as the balanced leakage case. We disconnected one supply duct at the plenum to create our supply-dominated leakage case (see Fig. F3). This hole resulted in a leak of about 30% of air handler flow. We removed the cap that was placed on the attachment hole for the outdoor air intake to create our return-dominated leakage case (see Fig. F4). This hole resulted in a leak of about 18% of air handler flow. No more than one of the added leaks was present at any time.

The analysis showed that the supply side was initially very tight (leakage of about 3% of air handler flow), but that the return was somewhat leaky, about 18% of air handler flow. Further investigation of the return duct uncovered some poorly attached duct segments, causing gaps between lengths, and some leaky finger joints. These were sealed following testing. Because of these leaks, there was not a truly “balanced” leakage case.



Figure F1. Front view of Site L06.



Figure F2. Horizontal gas furnace in crawl space.



Figure F3. Added supply leak at plenum.



Figure F4. Added return leak at plenum.

Table F1 shows the supply leakage estimates from the best estimate, the nulling test, the Delta-Q test based on the full plenum pressures, and the fan pressurization test using half of the plenum pressure. These estimates are expressed both in terms of actual cfm and as a percentage of air handler flow. This table shows that only the nulling test correctly estimates that the as-found supply leakage is small, though the nulling test does frequently estimate a negative number for this as-found supply leakage. These negative values are likely at least partially due to the changing stack pressure in the home caused by not having a fan-only switch, thereby requiring the heat to be on for the duration of the testing. For the case of the added supply leak the nulling test overpredicts the leakage, but is the closest of the three tests.

The Delta-Q test substantially overpredicts the leakage in all cases, and in the case of the low, as-found leakage, it predicts about 20% leakage. This result would suggest to a contractor that a leakage retrofit would likely be in order, though there is very little leakage to seal.

The fan pressurization test provides extremely high estimates of the leakage in all cases. The difference between the two groups of results without the added supply leak is because of a change in plenum pressure due to the added return leak.

Figure F5 shows the supply results graphically, expressed as a fraction of air handler flow.

Table F2 shows the return leakage estimates from the best estimate, the nulling test, the Delta-Q test based on the full plenum pressures, and the fan pressurization test using half of the plenum pressure. As for the supply leakage estimates, these estimates are expressed both in terms of actual cfm and as a percentage of air handler flow. For the return, the nulling test and fan

pressurization test both perform fairly well, except in the case of the added supply leak where the changed plenum pressure causes the fan pressurization test to overestimate the results. The nulling test does have two tests from the third day which show substantially worse agreement than on other days. The Delta-Q test greatly overestimates the leakage in all cases.

Figure F6 shows the return results graphically, expressed as a fraction of air handler flow.

**Table F1. Site L06 Supply Leakage and Leakage Fraction Estimates**

	Best Estimate		Nulling Test		Delta-Q Test		Fan Pressurization	
	cfm	%	cfm	%	cfm	%	cfm	%
Approximately Balanced (as-found)								
A1	0	0.0	-24	-3.1	158	20.5	271	36.4
B1	0	0.0	-25	-3.2	153	19.6	279	35.8
C1	22	2.9	-54	-6.9	135	17.2	284	36.1
Supply-dominated								
A2	244	30.5	321	40.1	416	52.0	376	47.0
B2	267	33.1	359	44.5	421	52.2	368	45.7
C2	247	30.1	293	35.7	402	49.0	373	45.5
Return-dominated								
A3	37	4.2	19	2.2	180	20.4	204	23.1
B3	19	2.2	65	7.4	202	23.0	203	23.1
C3	49	5.5	-14	-1.6	184	20.5	202	22.5

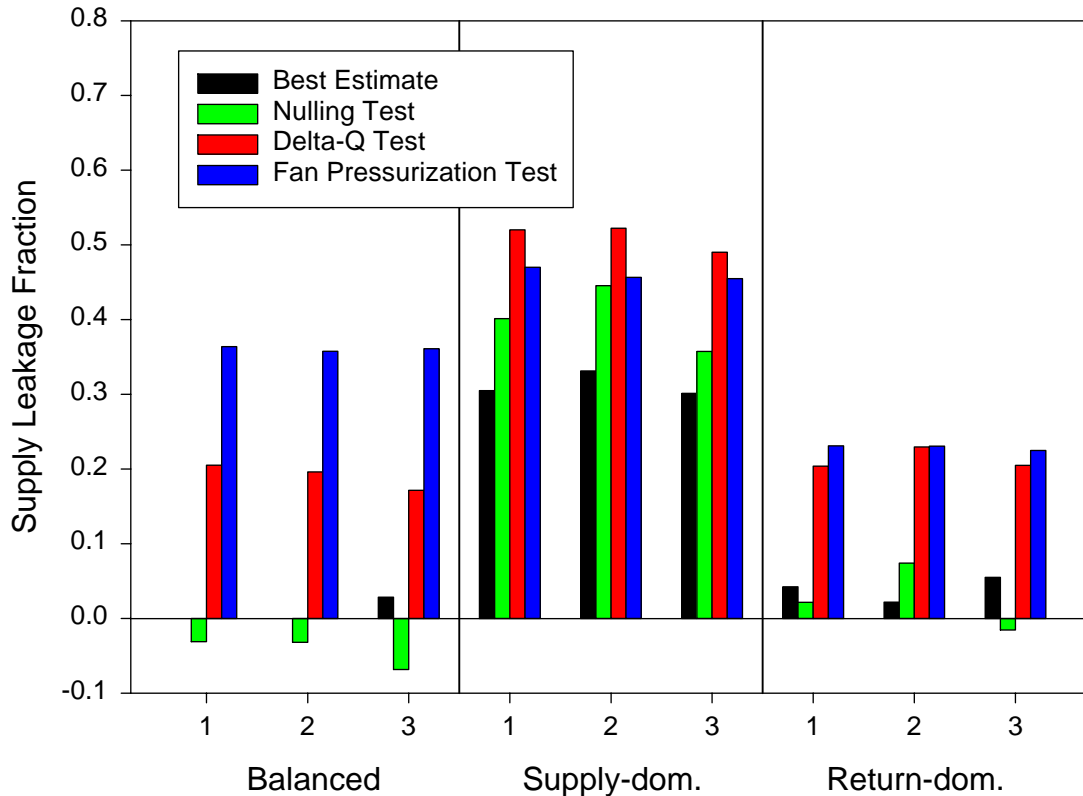


Figure F5. Supply leakage fraction results for Site L06.

**Table F2. Site L06 Return Leakage and Leakage Fraction Estimates**

	Best Estimate		Nulling Test		Delta-Q Test		Fan Pressurization	
	cfm	%	cfm	%	cfm	%	cfm	%
Approximately Balanced (as-found)								
A1	137	17.7	103	13.4	277	36.0	249	32.3
B1	147	18.9	108	13.8	275	35.3	260	33.3
C1	146	18.6	60	7.6	257	32.7	254	32.3
Supply-dominated								
A2	149	18.7	91	11.4	263	32.9	169	21.1
B2	145	18.0	145	18.0	278	34.5	179	22.2
C2	169	20.6	44	5.4	254	31.0	177	21.6
Return-dominated								
A3	325	36.8	325	36.8	500	56.6	361	40.9
B3	337	38.3	342	38.9	513	58.3	376	42.7
C3	342	38.0	232	25.8	489	54.5	377	42.0

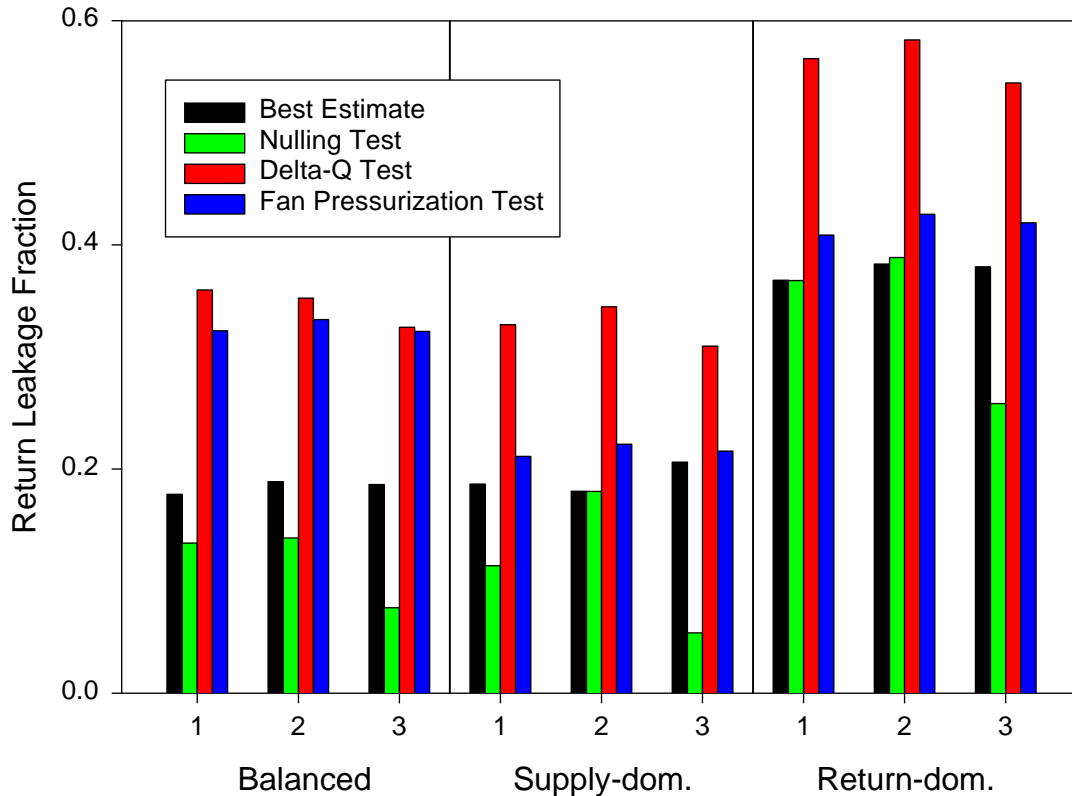


Figure F6. Return leakage fraction results for Site L06.

## APPENDIX G – DETAILED RESULTS FOR SITE L07

Figure G1 shows the front of Site L07. This house has a floor area of 2635 ft<sup>2</sup>.

This triple-wide manufactured home has a downflow heat pump in a closet in the conditioned space (see Fig. G2) with supply ducts in the crawl space. There are no return ducts since it is a manufactured home. There are fourteen supply registers. The heat pump is located in the middle section of the home. Below the heat pump is a splitter box that leads to two crossover ducts, one to each of the outside sections of the home. Each of the crossover ducts leads to the main trunk run for that section.

Since there was no return system we performed only two sets of tests on the home. There was very little leakage in the ducts, so the as-found was one configuration. The other configuration had a large hole cut into the side of the splitter box in the crawl space.

The analysis suggested that the as-found leakage was about half to inside the house, though the low level of leakage makes it impossible to draw any firm conclusions about the degree to which the belly or crawl space is connected to the house. Pressure measurements indicated that the belly and the crawl space were well-connected to outdoors and to each other, though it is common in manufactured homes for half of the leakage to go inside the home. It may be at this house that the half of the leakage that went to inside was at the boots.



Figure G1. Front view of Site L07.



Figure G2. Downflow heat pump in closet in conditioned space.

Table G1 shows the supply leakage estimates from the best estimate, the nulling test, the Delta-Q test based on the full plenum pressures, and the fan pressurization test using half of the plenum pressure. These estimates are expressed both in terms of actual cfm and as a percentage of air handler flow. This table shows that both the nulling test performs very well in this house. The Delta-Q test and fan pressurization test also perform well when there is no hole added. The Delta-Q overestimates by more than half and the fan pressurization underestimates by about half for the case with the large added leak.

Figure G3 shows the supply results graphically, expressed as a fraction of air handler flow.

**Table G1. Site L07 Supply Leakage and Leakage Fraction Estimates**

	Best Estimate		Nulling Test		Delta-Q Test		Fan Pressurization	
	cfm	%	cfm	%	cfm	%	cfm	%
<b>Supply-dominated</b>								
A1	178	17.3	176	17.0	224	21.7	90	8.7
B1	161	16.1	169	16.8	254	25.3	88	8.8
C1	156	15.5	164	16.2	262	25.9	88	8.7
<b>Approximately Balanced (as-found)</b>								
A2	69	7.3	30	3.2	34	3.6	32	3.4
B2	46	5.0	36	4.0	36	4.0	32	3.5
C2	29	3.2	31	3.5	51	5.7	34	3.8

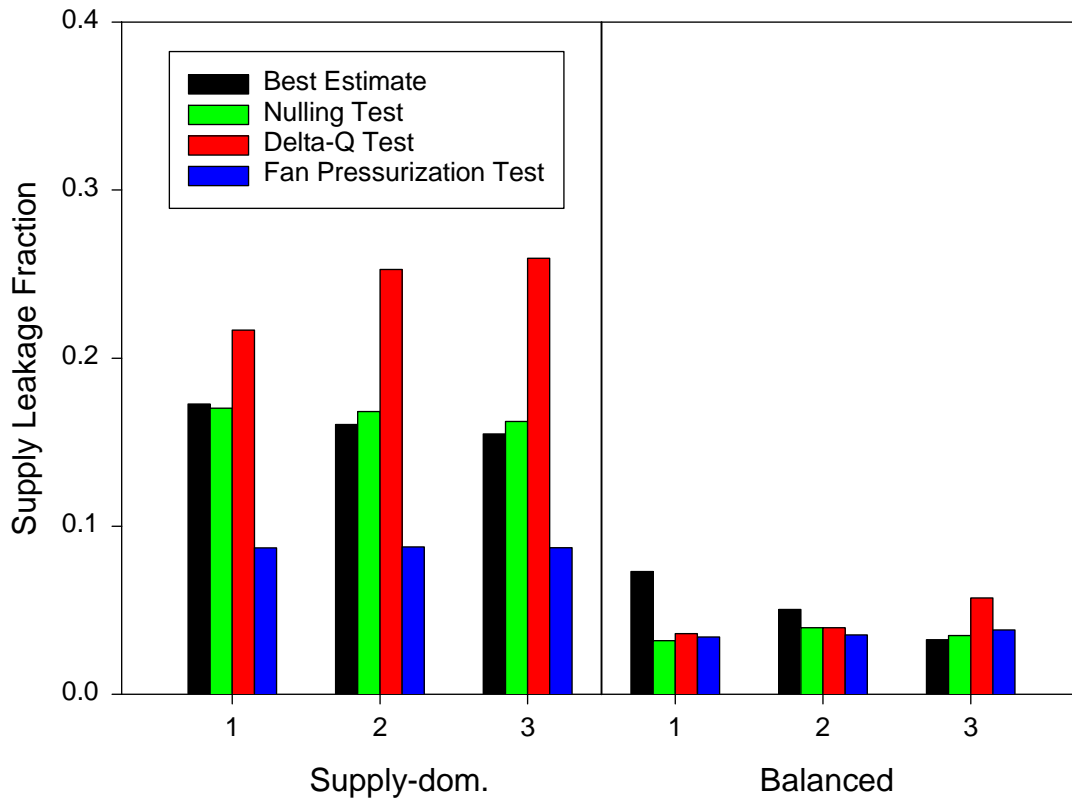


Figure G3. Supply leakage fraction results for Site L07.



## APPENDIX H – DETAILED RESULTS FOR SITE L08

Figure H1 shows the front of Site L08. This house has a floor area of 1353 ft<sup>2</sup>.

This house has a downflow gas furnace in the garage (see Fig. H2), with supply ducts in the crawl space and return ducts in the attic. The crawl space was not well vented, such that the crawl space was partially connected to the house. There are three central returns and six supply registers. This house had a perimeter supply duct system, with four trunks taking off from the plenum, running parallel, and joining up at the other end of the house. There was a large supply leak in one of these trunks where the trunk had collapsed (see Fig. H3). There was evidence that someone had tried to prop it up, but had been unsuccessful. This collapse resulted in some of the subfloor being ripped away. The return ducts also had large leaks at a junction box above the plenum. There had initially been filters at the junction box, but these had been removed when the new furnace was installed. The attempt to seal off these filter slots had not been entirely successful (see Fig. H4). As a result, the as-found condition had return-dominated leakage and was used for this case. We added an additional disconnect in one of the other trunk runs in the supply system to create our balanced case (see Fig. H5). This leak resulted in an increase of supply leakage of about 15% of air handler flow. At this point, adding additional leaks on the supply side was found to be problematic, so we taped off two registers to increase the pressures within the system and thereby increase the leakage. This became our supply-dominated case, which had about an additional leakage of 15% as a fraction of air handler flow. The as-found leakage levels were about 15% on the supply side and about 28% on the return side.



Figure H1. Front view of Site L08.



Figure H2. Downflow gas furnace in garage.



Figure H3. As-found leak in supply trunk (dirtier insulation indicates larger leakage).



Figure H4. One of the as-found return leaks at junction box (note fingers).



Figure H5. Added supply leak in trunk.

Table H1 shows the supply leakage estimates from the best estimate, the nulling test, the Delta-Q test based on the full plenum pressures, and the fan pressurization test using half of the plenum pressure. These estimates are expressed both in terms of actual cfm and as a percentage of air handler flow. This table shows that the nulling test performs fairly well in most cases. Both the Delta-Q test and the fan pressurization test greatly overpredict the supply leakage at this house, with the fan pressurization being slightly closer to the best estimate than the Delta-Q test.

Figure H6 shows the supply results graphically, expressed as a fraction of air handler flow.

Table H2 shows the return leakage estimates from the best estimate, the nulling test, the Delta-Q test based on the full plenum pressures, and the fan pressurization test using half of the plenum pressure. As for the supply leakage estimates, these estimates are expressed both in terms of actual cfm and as a percentage of air handler flow. For the return, the fan pressurization test tends to underestimate the leakage and the nulling test tends to overestimate the leakage by similar amounts, usually about 5-10 percentage points. The Delta-Q test, as with supply estimates, greatly overestimates the return leakage, usually predicting in excess of 50% leakage though the leakage is actually 25-30%.

Figure H7 shows the return results graphically, expressed as a fraction of air handler flow.

**Table H1. Site L08 Supply Leakage and Leakage Fraction Estimates**

	Best Estimate		Nulling Test		Delta-Q Test		Fan Pressurization	
	cfm	%	cfm	%	cfm	%	cfm	%
<b>Return -dominated (as-found)</b>								
A1	149	15.5	119	12.3	284	29.4	270	28.0
B1	142	14.4	215	21.8	301	30.5	280	28.4
C1	181	18.1	159	15.9	298	29.7	263	26.2
<b>Approximately Balanced</b>								
A2	255	28.3	296	32.9	458	50.8	423	46.9
B2	290	30.1	255	26.5	456	47.4	461	47.9
C2	312	31.0	335	33.4	467	46.5	414	41.2
<b>Supply -dominated</b>								
A3	431	45.9	440	46.9	658	70.1	516	55.0
B3	468	47.5	429	43.5	638	64.7	556	56.4
C3	432	45.3	453	47.5	631	66.2	498	52.3

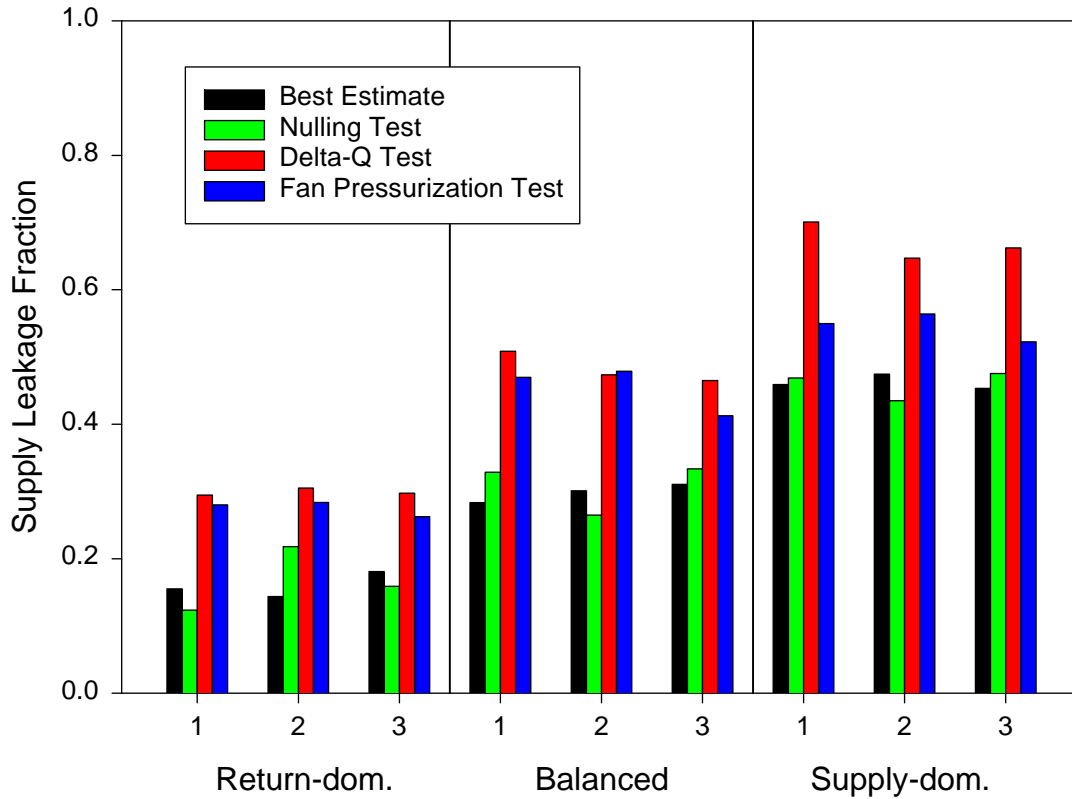


Figure H6. Supply leakage fraction results for Site L08.

**Table H2. Site L08 Return Leakage and Leakage Fraction Estimates**

	Best Estimate		Nulling Test		Delta-Q Test		Fan Pressurization	
	cfm	%	cfm	%	cfm	%	cfm	%
<b>Return -dominated (as-found)</b>								
A1	263	27.3	330	31.2	500	51.8	204	21.1
B1	281	28.5	447	45.3	520	52.7	208	21.1
C1	291	29.1	343	34.2	500	49.9	206	20.6
<b>Approximately Balanced</b>								
A2	201	22.3	339	37.6	499	55.4	207	23.0
B2	257	26.7	290	30.1	484	50.3	208	21.6
C2	290	28.8	327	32.6	462	46.0	203	20.2
<b>Supply -dominated</b>								
A3	247	26.4	336	35.8	514	54.7	202	21.5
B3	287	29.2	326	33.1	496	50.3	204	20.7
C3	240	25.1	294	30.8	453	47.5	198	20.8

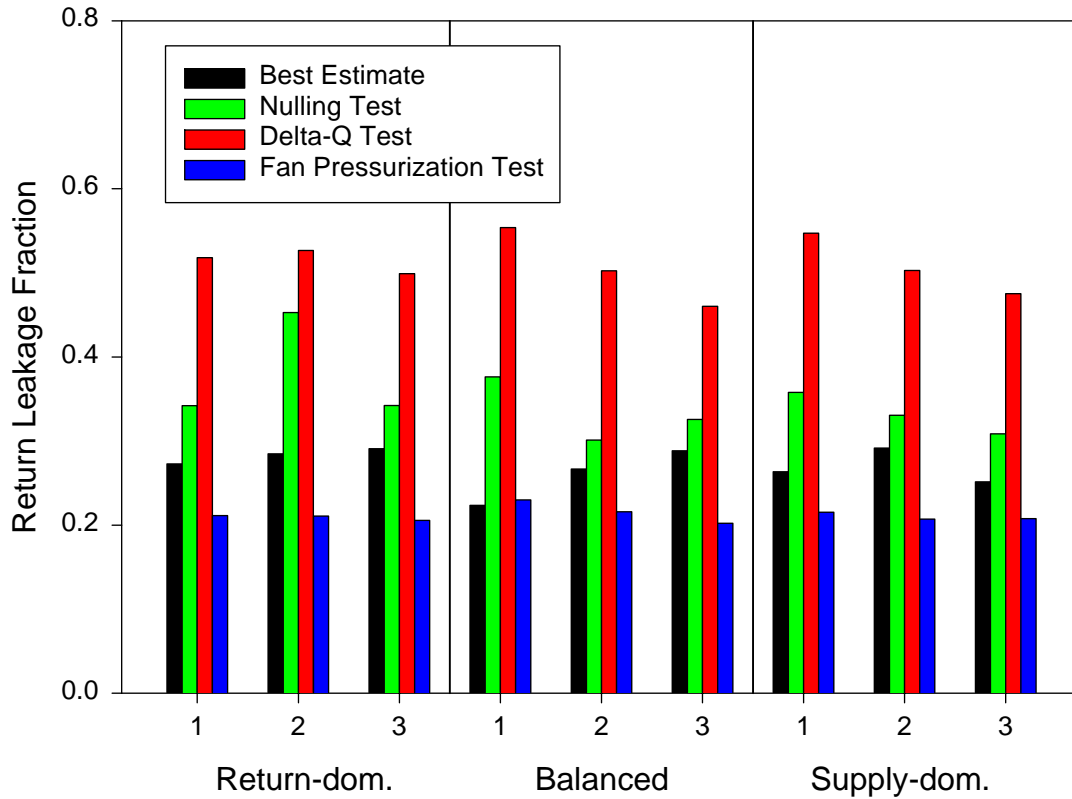


Figure H7. Return leakage fraction results for Site L08.



## APPENDIX I – DETAILED RESULTS FOR SITE L09

Figure I1 shows the front of Site L09. This house has a floor area of 989 ft<sup>2</sup>.

This house has a horizontal gas furnace in the crawl space (see Fig. I2), with supply and return ducts all in the crawl space. There is a single central return and five supply registers. The as-found leakage was used as the balanced leakage case. We disconnected one supply duct at the register boot to create our supply-dominated leakage case (see Fig. I3). This hole resulted in a leak of about 20% of air handler flow. We pulled open one of the return panned joists to create our return-dominated leakage case (see Fig. I4). This opening resulted in a leak of about 23% of air handler flow. No more than one of the added leaks was present at any time. The as-found leakage was about 7% on the supply side and about 17% on the return side.



Figure I1. Front view of Site L09.



Figure I2. Horizontal gas furnace in crawl space.



Figure I3. Added supply leak at register boot.



Figure I4. Added return leak at panned joist at grille.

Table I1 shows the supply leakage estimates from the best estimate, the nulling test, the Delta-Q test based on the full plenum pressures, and the fan pressurization test using half of the plenum pressure. These estimates are expressed both in terms of actual cfm and as a percentage of air handler flow. This table shows that the Delta-Q test give provides the best overall results for supply leakage at this site, with the exception of two tests at which some problem appears to have occurred. An investigation of the data does not indicate the source of the problem during these tests. The nulling test tends to underestimate the supply leakage by a significant amount at this site. The fan pressurization test performs well for the low-leakage cases but underestimates the supply leakage for the case with the added leak.

Figure I5 shows the supply results graphically, expressed as a fraction of air handler flow.

Table I2 shows the return leakage estimates from the best estimate, the nulling test, the Delta-Q test based on the full plenum pressures, and the fan pressurization test using half of the plenum pressure. As for the supply leakage estimates, these estimates are expressed both in terms of actual cfm and as a percentage of air handler flow. For the return, Delta-Q test again does the best job of estimating the leakage except for the case with the added return leak. For this case, the Delta-Q overestimates the leakage significantly and the nulling test provides better estimates. The fan pressurization test performs reasonably well for the low-leakage cases but overpredicts the leakage by a substantial amount for the case with the added return leak since the leak is at the register end of the return system.

Figure I6 shows the return results graphically, expressed as a fraction of air handler flow.

**Table I1. Site L09 Supply Leakage and Leakage Fraction Estimates**

	Best Estimate		Nulling Test		Delta-Q Test		Fan Pressurization	
	cfm	%	cfm	%	cfm	%	cfm	%
Approximately Balanced (as-found)								
A1	94	10.4	0	0.0	71	8.8	91	11.3
B1	52	6.5	74	9.3	9	1.1	92	11.6
C1	76	9.5	3	0.4	75	9.3	87	10.8
Supply-dominated								
A2	209	26.2	143	17.9	61	7.6	153	19.1
B2	212	27.0	135	17.1	222	28.1	155	19.7
C2	223	27.8	146	18.2	244	30.4	152	19.0
Return-dominated								
A3	71	8.8	17	2.1	118	14.6	55	6.8
B3	54	6.7	33	4.1	134	16.8	61	7.6
C3	51	6.4	17	2.1	123	15.4	57	7.1

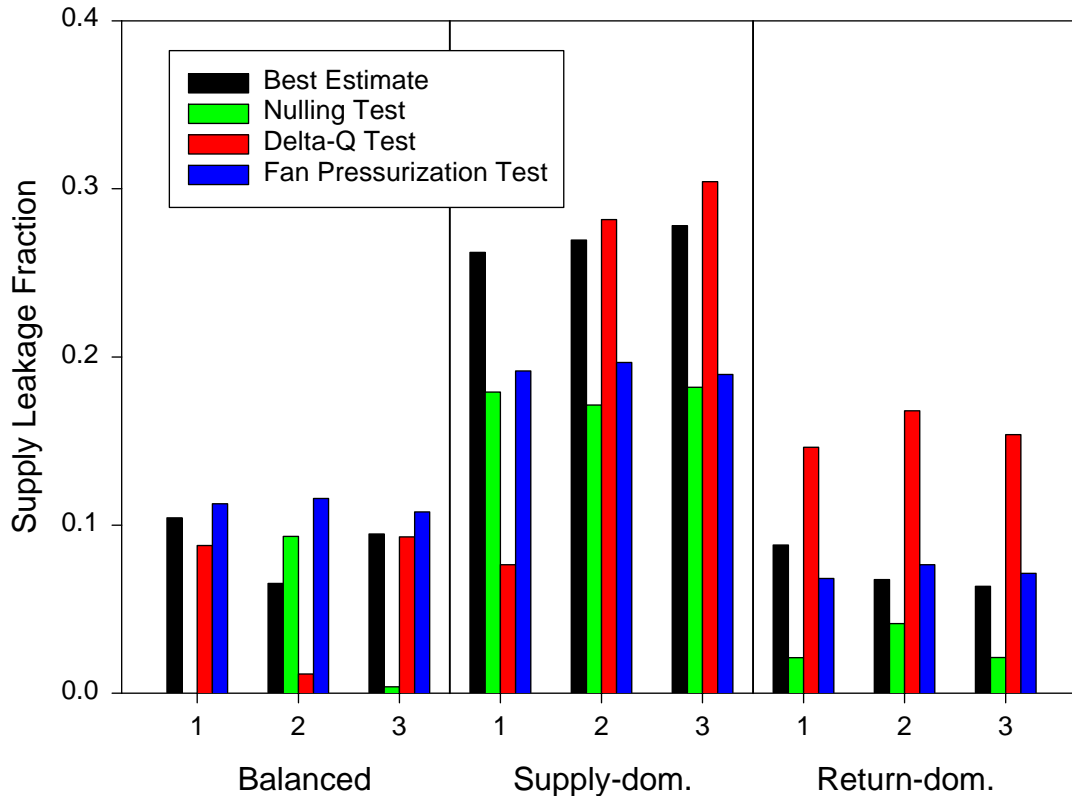


Figure 15. Supply leakage fraction results for Site L09.

**Table I2. Site L09 Return Leakage and Leakage Fraction Estimates**

	Best Estimate		Nulling Test		Delta-Q Test		Fan Pressurization	
	cfm	%	cfm	%	cfm	%	cfm	%
Approximately Balanced (as-found)								
A1	161	20.0	73	9.0	131	16.2	122	15.1
B1	135	16.9	150	18.9	96	12.1	163	20.5
C1	148	18.4	63	7.8	137	17.0	155	19.2
Supply-dominated								
A2	137	17.1	100	12.5	43	5.4	98	12.3
B2	135	17.1	31	3.9	137	17.4	105	13.3
C2	144	17.9	82	10.2	155	19.3	101	12.6
Return-dominated								
A3	323	40.0	308	38.1	458	56.8	361	44.7
B3	316	39.6	279	35.0	408	51.1	533	66.8
C3	377	47.1	298	37.2	463	57.9	509	63.6

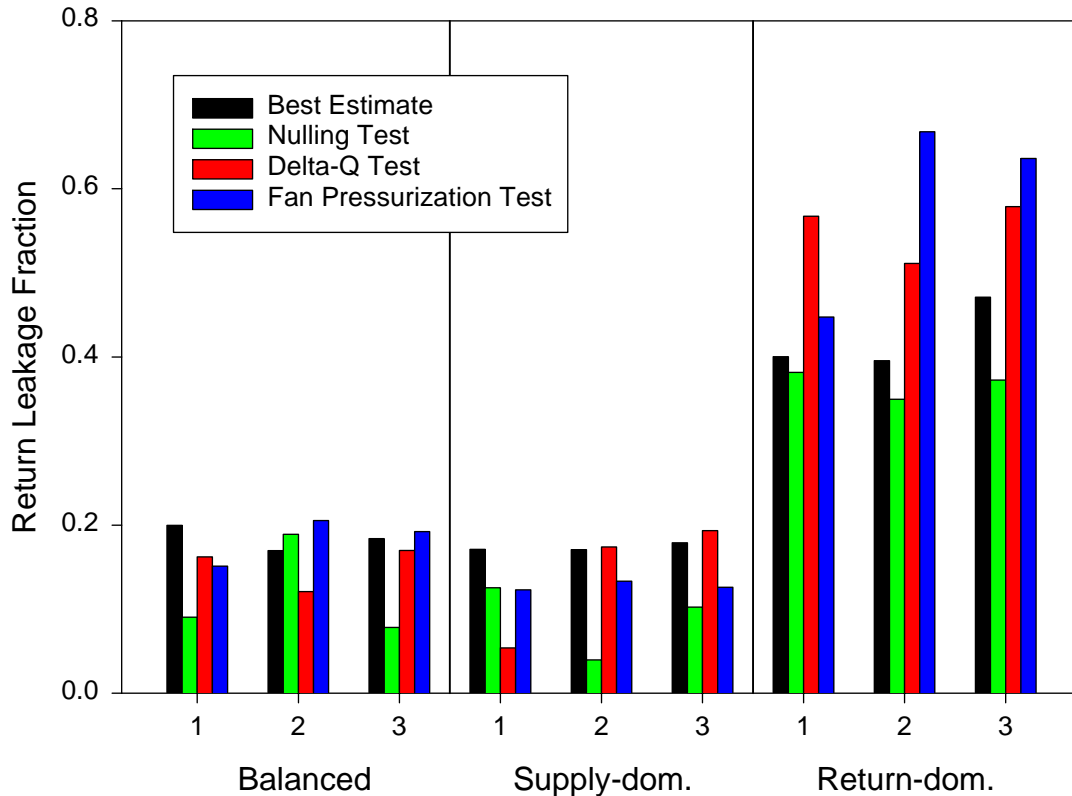


Figure I6. Return leakage fraction results for Site L09.