# FIELD EVALUATION OF IMPROVED METHODS FOR MEASURING THE AIR LEAKAGE OF DUCT SYSTEMS UNDER NORMAL OPERATING CONDITIONS IN 51 HOMES

**Final Report**

**Paul W. Francisco**
**Larry Palmiter**
**Erin Kruse**
**Bob Davis**

**October 18, 2003**

**Prepared for the National Energy Technology Laboratory**
**under contract DE-FC26-01NT41257**

**Ecotope, Inc.**
**4056 9th Ave. NE**
**Seattle, WA 98105**

## Disclaimer

# ABSTRACT

Duct leakage in forced-air distribution systems has been recognized for years as a major source of energy losses in residential buildings. Unfortunately, the distribution of leakage across homes is far from uniform, and measuring duct leakage under normal operating conditions has proven to be difficult. Recently, two new methods for estimating duct leakage at normal operating conditions have been devised. These are called the nulling test and the Delta-Q test. Small exploratory studies have been done to evaluate these tests, but previously no large-scale study on a broad variety of homes has been performed to determine the accuracy of these new methods in the field against an independent benchmark of leakage. This sort of study is important because it is difficult in a laboratory setting to replicate the range of leakage types found in real homes.

This report presents the results of a study on 51 homes to evaluate these new methods relative to an independent benchmark and a method that is currently used. An evaluation of the benchmark procedure found that it worked very well for supply-side leakage measurements, but not as well on the return side. The nulling test was found to perform well, as long as wind effects were minimal. Unfortunately, the time and difficulty of setup can be prohibitive, and it is likely that this method will not be practical for general use by contractors except in homes with no return ducts.

The Delta-Q test was found to have a bias resulting in overprediction of the leakage, which qualitatively confirms the results of previous laboratory, simulation, and small-scale field studies. On average the bias was only a few percent of the air handler flow, but in about 20% of the homes the bias was large. A primary flaw with the Delta-Q test is the assumption that the pressure between the ducts and the house remain constant during the test, as this assumption does not hold true.

Various modifications to the Delta-Q method were evaluated as possible improvements. Only one of these modifications provided improved results. This modification requires measuring the duct pressure relative to the house at either every pressure station within the Delta-Q test or at the extremes of the house pressure range involved in the Delta-Q test. If the pressures are only measured at the extremes, then calculated pressures at the other pressure stations are obtained via interpolation. Using these pressures reduced the bias in the Delta-Q test by about one-third.

# EXECUTIVE SUMMARY

Duct leakage in forced-air distribution systems has been recognized for years as a major source of energy losses in residential buildings (see Robison and Lambert 1988; Modera 1989; Parker 1989; Cummings et al. 1990; Andrews and Modera 1991; Olson et al. 1993; Palmiter, Olson, and Francisco 1995; Jump, Walker, and Modera 1996; Siegel et al. 1996; Davis et al. 1997; Walker et al. 1998a; Siegel et al. 2003; and Francisco et al. 2002a, 2002b, 2003 for a sampling of previous work on this subject). Duct leakage can have a variety of impacts. It causes the thermal efficiency of the distribution system to be lower. For heat pumps and air conditioners, return leakage can greatly affect the conditions of the air flowing over the coil, thereby reducing its performance. For heat pumps in heating mode, duct leakage can cause the backup heating to be used more, reducing the efficiency benefits of having a compressor. Further, large or concentrated duct leakage can cause homes to have localized areas that are uncomfortable.

It has also been found through many of the above-referenced studies that duct leakage is not uniform across houses. Most houses have some duct leakage, but if the duct system is installed properly, the duct leakage is likely to be a small percentage (<10%) of the overall system flow, and that it is distributed throughout the duct system, located primarily at seams and connections. It is often not cost-effective to repair duct leakage in these homes. It is important to note that the leakage of interest, when energy concerns are primary, are leaks to or from outside; leaks to and from inside are still considered to be contributing to the overall desired conditioning of the home. Leaks to inside may affect comfort in specific regions of the house, but they do not severely impact the energy use.

There are enough houses with larger leakage, however, to continue to attract the attention of a wide variety of agencies, including governmental agencies such as the US Department of Energy and the Environmental Protection Agency, code-making and regulatory bodies, and utilities. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) is in the final stages of passing a standard for measuring thermal duct efficiency. These concerns are brought about by national energy concerns, consumer protection, and load management, and will likely only increase as energy prices continue to rise.

Because of the concentration of large leakage in a relatively small percentage of houses, it is desirable to have a measurement technique with sufficient accuracy to focus repair resources on the right houses, while also being simple enough for widespread proper use. This type of test is also desirable when commissioning new buildings; a test with insufficient accuracy can inadvertently penalize contractors who installed a duct system well, while letting some leaky systems through.

A test with this combination of simplicity and accuracy has been elusive, however. Tracer gas tests are expensive, difficult, and time-consuming. Other than tracer gas tests, duct leakage tests for years were done under artificial conditions, with the air handler off and the ducts pressurized or depressurized.

This type of test is problematic when trying to assess the actual duct leakage because the pressure is usually essentially uniform throughout the ducts, and is typically set to approximately the same for all houses. This differs from normal operation of the duct system, where the pressures at the plenums can range from 10 Pascals (Pa) to 200 Pa, and the pressures change drastically as one gets closer to the registers and grilles (pressures get closer to zero near the register and grille end). If the majority of the duct leaks are at high pressure locations, such as plenums, static tests may underrepresent the actual leakage. If the duct leaks tend to be at lower pressure locations such as registers, the static tests may overrepresent the leakage. Static tests actually measure the effective cumulative area of the holes (airtightness), not the pressure at the holes that is causing the leakage.

In the late 1990s, two new tests were developed that purported to measure duct leakage to outside at actual operating conditions. The first of these, called the nulling test, was developed by the authors of the current study (Francisco and Palmiter 2001; Francisco et al. 2002a, 2002b, 2003). The second, called the Delta-Q test, was developed by Lawrence Berkeley Laboratory (Walker et al. 1998b; Walker et al. 2001a) based on an idea by Dr. Chuck Gaston of the Pennsylvania State University, York campus (Gaston 1999).

The nulling test, which does not contain a mathematical model, has previously been evaluated in only a few homes. These include four homes in a study evaluating ASHRAE Standard 152P (Francisco and Palmiter 1999, 2000), one home in a study initially evaluating the Delta-Q test (Walker et al. 1999), five homes in another study evaluating Standard 152P (Cummings and Withers 1999), and nine homes in the previous study evaluating these new methods (Francisco et al. 2002a, 2002b, 2003).

The only previous Delta-Q tests performed in the field against an independent benchmark that assesses the leakage under actual operation was performed by the authors in the previous study evaluating these new methods in nine homes (Francisco et al. 2002a, 2002b, 2003). This study found that the Delta-Q test overestimated the leakage by an average of 55%, or 7.6% of air handler flow. However, this project included changing the leakage in each house, often by adding individual large holes. While the data do not suggest that these types of leaks caused an increase in bias, the sample of tests was both small and non-representative, so it also can not be considered conclusive of the performance of the Delta-Q test.

This report presents the results of a study, funded by the National Energy Technology Laboratory, in which 51 homes located in the Puget Sound region were tested. Five of the homes were tested multiple times, with and without added leaks, to evaluate the accuracy of the benchmark estimate technique. Three sites were manufactured homes, which are evaluated separately. The remaining 48 homes were nearly evenly split between single-story and multi-story homes.

The results of this project include estimates from each leakage test method as described by the developers at the time the project began. In addition, for the Delta-Q test, several modifications were evaluated as possible improvements.

## Benchmark Estimate

One of the most surprising results of the study relates to the benchmark estimate, which combines air handler flow with register and grille flows, with an adjustment made to account for leakage to inside. Many researchers have considered this method to be reasonable on the return side, but several of these same researchers believed the results on the supply side would be highly questionable due to the perceived lack of accuracy of flow hood measurements on residential supply systems. This may be true in many cases, such as where the flow hood has not been calibrated, where the registers provide adverse flow conditions such as swirl, the flow hood is not used carefully, or the flow hood was not really designed for supply-side use.

However, the benchmark estimate validation tests found that it was on the return side that this method of estimating leakage fell short. Much of the reason for this may be the lack of cancellation of errors across return grilles in a single home, since many homes have only one return grille, and rarely more than three. There is also evidence that the flow hood used for return grille flows, though calibrated, did not perform well in the field.

On the supply side, however, the benchmark estimate was shown to be more accurate than expected in those houses in which validation testing was performed. When comparing the benchmark estimate results on the supply side to the added known leak, the maximum error was less than 7 cfm, and no error in these houses was greater than 1% of the air handler flow.

There is evidence in the supply-side benchmark estimate results that the correction for leakage to inside was not as good as was desired for homes with a significant amount of ducts in the conditioned space, primarily multi-story homes. The correction procedure contains an implicit assumption that leaks to inside are at the same effective pressure as the leaks to outside. This may be a reasonable assumption in some cases, but it does not always hold true. As a result, for these types of homes, the nulling test may actually be the best estimate of the methods tested.

## Nulling Test

The nulling test was found to work very well in most houses. For single-story homes, where the benchmark estimate is the most accurate on the supply side, the nulling test showed very little bias relative to the benchmark estimate. The mean absolute error was less than 2% of air handler flow, and the RMS error was 2.4% of air handler flow. There was also little tendency for the nulling test to overestimate the flow by a large amount. This was a concern because many applications for duct leakage testing have a low tolerance for false positives, i.e. estimating excessive leakage when the leakage is actually within allowable limits.

Because the nulling test does not perceive leakage to inside as different from airflow through registers, there is no conceptual reason to believe that the performance should be worse for multi-story homes. Therefore, though there is larger disagreement between the nulling test and the benchmark estimate for multi-story homes, it is likely the benchmark estimate that is causing the problem more than the nulling test.

The benchmark estimate validation tests showed little difference in the accuracy of the nulling test estimates on the return side compared to those on the supply side. This is counter to the expectation that the return results would be worse because the return estimates are based on combining two tests, the unbalanced leakage test and the supply-only test. The small sample size of these validation homes prevents a firm conclusion from being drawn, but these results are encouraging.

As determined in previous studies, the primary source of error for the nulling test appears to be noise due to wind. The test is done at a few small pressures, so significant wind can make accurate pressure measurements nearly impossible. One method for dealing with the wind noise is to do the nulling test at three distinct flows rather than pressures, and sample for an extended period of time. While this does often allow for obtaining reasonable looking data, there is still much greater uncertainty as to the accuracy of the results.

Other than wind noise, the primary drawback to the nulling test is the time-consuming nature of the setup for the supply-only measurement. The difficult and time-consuming part of the setup is the same as is done for measuring air handler flow using a calibrated fan, so if this test of air handler flow is also being done then the nulling test requires little additional setup and time. Other than homes where this testing is being done, however, the nulling test is probably only practical for use by contractors in homes without ducted return systems since at these homes only the unbalanced leakage portion of the test is required. This portion of the nulling test is fast and requires little setup. Examples of houses for which this would be appropriate are many manufactured homes and homes with platform returns.

**Delta-Q Test**

Qualitatively, the results confirmed previous findings on the performance of the unmodified Delta-Q test. This test, which uses envelope pressures to ±25 Pa, and assumes a leak pressure of half the plenum pressure, showed the same tendency to overestimate the leakage as in other studies, both by the authors and by other researchers. The magnitude of the overestimation was not as great in this study as it was in the previous study by the authors. The larger bias in the previous study can at least partially be explained by the results of two houses in a sample size of only nine homes.

In this study, the unmodified Delta-Q test had a bias of about 2% of air handler flow relative to the benchmark estimate of supply leakage in the single-story homes, with an RMS error of nearly 5% of air handler flow. The bias was smaller for multi-story homes, even when compared to the nulling test, which is probably the best estimate available for that set of homes.

As seen in previous studies and in theoretical modeling of the Delta-Q test, one of the most major problems is the failure of the assumption that the pressure difference between the ducts and the house remains constant throughout the test. The Delta-Q equations implicitly require this to be true, but these pressures can actually change by 20% or more in practice. The result tends to be an overprediction of the flow, which is in agreement with both lab and field studies.

It is this assumption that is a likely cause of the improved agreement by the nulling test in multi-story homes. There tend to be more registers as well as increased leaks to inside in multi-story homes. Since the ducts are then better connected to the house, they can be more easily pressurized or depressurized along with the house, and the assumption will often be closer to true. This agrees with simulation results, which have found that the Delta-Q test works better when the ducts become more connected to the house.

Due to the symmetry of the Delta-Q test, there is no reason to believe that the results would be substantially different on the return side compared to the supply side. When compared to the nulling test, which is likely the best estimate available on the return side, this holds true. On average, the Delta-Q test is 2.5% of air handler flow higher than the nulling test on the supply side and 2.9% higher than the nulling test on the return side.

Because of the tendency of the Delta-Q test to overpredict the leakage, sometimes by large amounts, caution needs to be taken when deciding whether to use the test for a specific application. If there is low tolerance for false positives, the Delta-Q test may not be an acceptable alternative.

The modifications to Delta-Q contained a mix of surprising results and confirmations of previous findings.

The use of envelope pressures to ±50 Pa was first considered because it would cover a broader range of leakage pressures. This was considered to be likely to reduce the errors of Delta-Q when leaks were at these larger pressures. However, the results show that the overall performance of the Delta-Q test is worse when this change is made. Part of the reason for this is that, in order to avoid increasing the time required to perform the test substantially, some of the lower envelope pressures are dropped.

It appears that the coarser spacing between pressures at the lower end of the range causes the results to become worse more than the increased range might improve the results. Further evaluation shows that the Delta-Q test has its largest errors at lower pressures, and that the majority of the leaks are at lower pressures. This suggests that focusing efforts at the lower end of the pressure range is more important than expanding the range.

The use of the full plenum pressure instead of half the plenum pressure as the assumed leak pressure was first proposed because theoretical work suggested that this choice would have a smaller bias and uncertainty. However, as was found in previous work, the use of the full plenum pressure also reduces the accuracy of the test, on average. The disagreement with the theoretical work suggests that the nature of leakage in real duct systems is sufficiently different from theoretical and lab conditions in a way that causes the half plenum pressure to be a better choice for the leak pressure surrogate.

Perhaps the most surprising result regarding Delta-Q test modifications is the finding that the two worst options of the modifications evaluated are those that attempt to apply a more accurate estimate of the leakage pressure. These modifications are the pressure fitting technique and the use of the estimated actual leakage pressures as based on other tests.

It has been assumed that, if the true leakage pressure is used, the results will be improved. Not only was this not the case in these homes, but on average the results from these modifications were more than twice as far away from the unmodified Delta-Q result as any other modification investigated. These results show that attempts to improve the estimation of the leakage pressure are not the appropriate means to improve the Delta-Q test.

A primary reason for this is that the pressures across the leaks change as the test is being done. One of the physical effects that the Delta-Q test is looking for is a reversal of flow across a leak, which would manifest itself as an inflection point in the data. However, this reversal will occur at a different pressure than occurs across the leak under normal operation, and fitting the Delta-Q curve to determine a leak pressure is finding the wrong pressure. This problem is similar to the problem of the assumption that the pressure between the ducts and the house remains constant throughout the Delta-Q test.

A related finding to the failure of the use of “improved” leak pressures to increase the accuracy of the result is that the pressures obtained from the pressure fitting tend to be significantly higher than the estimated leak pressures using other tests. This was also found in theoretical work on the Delta-Q test. Another finding in the theoretical work that was also seen in the data was the tendency for the pressures resulting from the fitting technique to fall on pressures used as envelope pressure stations. This finding suggests that the choice of pressure stations has as much or more to do with the “leak” pressure obtained from fitting than the actual pressures at the leaks. The theoretical work found that the cause of this phenomenon is that the envelope pressure stations cause local minima in the fitting curve, such that the fitting process can get “stuck” at these pressures.

The modification that used leakage exponents as estimated from fan pressurization tests instead of the assumed exponents of 0.6 also did not improve the results. This result was surprising, but it suggests that assuming an exponent of 0.6 is not a bad assumption. It may be that the failure of actual exponents to improve results is for reasons similar to the failure of leakage pressures to improve the results, in that the process of the Delta-Q test may actually change the apparent exponents at the leaks. It is not possible to determine this from the data collected in this study, however. This method is also not practical from a general use standpoint, because the additional time required to estimate the exponents is significant.

The only modifications that were evaluated that showed any improvement to the results of the Delta-Q test were those that attempted to address the fundamental flaw in the assumption of the constant duct-to-house pressure. The primary modification that was made to address this was to measure the plenum pressure at each envelope pressure station, and use these pressures in the Delta-Q analysis. In this study we performed the Delta-Q analysis using half of these pressures, consistent with the unmodified test. The result of using these pressures was to reduce the average bias by about a third, and based on medians reduce the bias by about half. This improvement is significant, although there are still homes with large overestimates of leakage.

The primary drawback with measuring the plenum pressure at each envelope pressure station is that additional pressure measurement equipment is required. The most common pressure measurement meters for this type of work have two channels, which are required for the blower door fan flow and for the envelope pressure. Measuring the plenum pressures at each station would require a second meter.

As a result, a variant to this modification was analyzed, whereby the plenum pressures were only measured additionally at the maximum envelope pressure stations (25 Pa and –25 Pa). Pressures for each station were then estimated by interpolating between these pressures and the plenum pressures measured with the blower door off. Pressures were interpolated separately for the pressurization and depressurization portions of the test, because the slopes can be very different between these two sides.

The result of this simplification was that the estimates were virtually unchanged, on average, compared to using the measured pressures at each station.

The failure to find a modification to Delta-Q that more completely corrected the errors was disappointing. This suggests that the only way to make the Delta-Q test as accurate as desired over a broad range of leakage conditions is to reformulate the basic underlying model. In the absence of that, the interpolation of duct pressures from pressures measured at the maximum envelope pressures and the duct pressures measured with the blower door off is a simple method of improving the results. This change should be incorporated in further use of the Delta-Q as based on the current derivation.

Another conclusion about the Delta-Q test that has also been stated in previous studies is that there needs to be a separate equation for homes without a return duct system. The equations as they are currently written require a return duct pressure to be entered, and when there is no return duct it is not clear what one should do.

**Fan Pressurization**

As has been noted in many projects, the fan pressurization test can often provide leakage estimates that are greatly different than the actual leakage. This is because this test is not designed to measure leakage at operating conditions. This test is accurate when estimating the effective leakage area of the holes in the ducts, but it does not address the pressures across the leaks. As has been seen in previous work, the estimates from the return side are much better than the estimates on the supply side, primarily because the return side is often a single, long duct instead of a complex system of many ducts.

**Overall Duct Leakage**

One of the primary findings of interest when looking at the sample as a whole is that the average leakage in these homes tends to be about 12% of air handler flow on each the supply and return sides. For each side of the duct system approximately 15% of the total sample has leakage greater than 20% of air handler flow and an additional 10% has leakage greater than 15% of the air handler flow. In many cases, the homes with large leakage on one side do not have large leakage on the other side. Approximately a quarter of the sample has leakage on either the return or supply side greater than 25%, with an additional 15% with leakage greater than 15% of air handler flow on either the supply or return side.

**Final Summary**

One of the primary recommendations from this work is to make the modification to the Delta-Q test that interpolates duct pressures between those measured at maximum envelope pressures and those measured with the blower door off, with the results used at each envelope pressure station for the Delta-Q analysis.  This improves the results over any other Delta-Q variant evaluated.

Possible reformulation of the Delta-Q test model should be considered, with a focus being to account for the changes in the pressure between the ducts and the house as the test is performed.

The nulling test is most appropriate when there is no return duct system, but care must be taken to minimize the effects of wind.

The benchmark estimate method did not meet expectations on the return side, and also was subject to greater errors on the supply side in houses with multiple stories.  This can be a useful technique in careful research, but is not a candidate for general use.

Despite the size of the sample tested, there were not enough homes with large leakage to allow a thorough investigation of the causes of errors in the Delta-Q test when large leakage is present. These homes often cause the Delta-Q test to perform poorly, and it is these same cases that are of most interest to individuals and organizations attempting to target duct leakage sealing efforts. As a result, it is desirable to test an additional sample of homes to more fully understand the failure modes of the leakage tests.

# TABLE OF CONTENTS

# TABLE OF TABLES

# TABLE OF FIGURES

# 1
# INTRODUCTION AND BACKGROUND

Duct leakage in forced-air distribution systems has been recognized for years as a major source of energy losses in residential buildings (see Robison and Lambert 1988; Modera 1989; Parker 1989; Cummings et al. 1990; Andrews and Modera 1991; Olson et al. 1993; Palmiter, Olson, and Francisco 1995; Jump, Walker, and Modera 1996; Siegel et al. 1996; Davis et al. 1997; Walker et al. 1998a; Siegel et al. 2003; and Francisco et al. 2002a, 2002b, 2003 for a sampling of previous work on this subject). Duct leakage can have a variety of impacts. It causes the thermal efficiency of the distribution system to be lower. For heat pumps and air conditioners, return leakage can greatly affect the conditions of the air flowing over the coil, thereby reducing its performance. For heat pumps in heating mode, duct leakage can cause the backup heating to be used more, reducing the efficiency benefits of having a compressor. Further, large or concentrated duct leakage can cause homes to have localized areas that are uncomfortable.

It has also been found through many of the above-referenced studies that duct leakage is not uniform across houses. Most houses have some duct leakage, but if the duct system is installed properly, the duct leakage is likely to be a small percentage (<10%) of the overall system flow, and that it is distributed throughout the duct system, located primarily at seams and connections. It is often not cost-effective to repair duct leakage in these homes. It is important to note that the leakage of interest, when energy concerns are primary, are leaks to or from outside; leaks to and from inside are still considered to be contributing to the overall desired conditioning of the home. Leaks to inside may affect comfort in specific regions of the house, but they do not severely impact the energy use.

There are enough houses with larger leakage, however, to continue to attract the attention of a wide variety of agencies, including governmental agencies such as the US Department of Energy and the Environmental Protection Agency, code-making and regulatory bodies, and utilities. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) is in the final stages of passing a standard for measuring thermal duct efficiency. These concerns are brought about by national energy concerns, consumer protection, and load management, and will likely only increase as energy prices continue to rise.

Because of the concentration of large leakage in a relatively small percentage of houses, it is desirable to have a measurement technique with sufficient accuracy to focus repair resources on the right houses, while also being simple enough for widespread proper use. This type of test is also desirable when commissioning new buildings; a test with insufficient accuracy can inadvertently penalize contractors who installed a duct system well, while letting some leaky systems through.

A test with this combination of simplicity and accuracy has been elusive, however. Tracer gas tests are expensive, difficult, and time-consuming. Other than tracer gas tests, duct leakage tests for years were done under artificial conditions, with the air handler off and the ducts pressurized or depressurized.

This type of test is problematic when trying to assess the actual duct leakage because the pressure is usually essentially uniform throughout the ducts, and is typically set to approximately the same for all houses. This differs from normal operation of the duct system, where the pressures at the plenums can range from 10 Pascals (Pa) to 200 Pa, and the pressures change drastically as one gets closer to the registers and grilles (pressures get closer to zero near the register and grille end). If the majority of the duct leaks are at high pressure locations, such as plenums, static tests may underrepresent the actual leakage. If the duct leaks tend to be at lower pressure locations such as registers, the static tests may overrepresent the leakage. Static tests actually measure the effective cumulative area of the holes (airtightness), not the pressure at the holes that is causing the leakage.

The first of the tests based on fan-induced artificial pressures was the blower door subtraction test. A blower door test is a test where a large, calibrated fan is placed in a door or a window of the house, and the flow is adjusted until the pressure in the house relative to outside reaches a certain level, usually 25 or 50 Pa. The flow through the fan, which is called a blower door, is the leakage through the house at that pressure. During this test, all exterior doors and windows are closed, and all interior doors are open.

The blower door subtraction test combined the results of two blower door tests, one with all heating system registers and grilles unsealed and the other with them sealed off. The difference between the two was said to be a measure of the duct leakage at the pressure to which the house was put. This test, however, was flawed in at least three ways. The first was that two large numbers were being subtracted to get a smaller one, and the measurement instruments were not good enough at the time to provide satisfactory accuracy. The second problem was that leakage to inside biased the results. Leaks to inside can be viewed as unintended registers, so the ducts were not isolated from the house as much as would have been desired. This resulted in systematic underestimation of duct leakage. The final problem with this test is that it is at an artificial, static condition, instead of at the conditions found throughout the ducts when the system is running in normal mode.

A modification to the blower door subtraction test addressed the second problem, which is the bias caused by leaks to and from inside. One of these, called the modified blower door subtraction method, used the pressure between the house and the ducts during the blower door test with the registers and grilles sealed to make a correction for leakage to inside. Though this was largely successful at addressing this problem, it still had the other two problems: two large numbers were being subtracted to get a small one, and the tests were done under artificial conditions. Measurement instruments have advanced enough that today, with computer-automation software and sufficient averaging, the first of these problems has been greatly reduced to the point where these tests may rival other tests done at static conditions (Francisco et al. 2002a; Palmiter and Francisco 2002), but that was not the case in the early 1990s.

The next test to be developed for measuring duct leakage came along about 1992 with the invention of a calibrated fan sized for duct systems instead of houses. With the registers and grilles sealed, this fan could pressurize the ducts directly to estimate the duct leakage, including duct leakage to and from inside. With the simultaneous use of a blower door to cause the pressure difference between the house and the ducts to be zero, an estimate could be made of the duct leakage to outside only. This test, known as the fan pressurization test, removes the need to subtract two large numbers to get a smaller one, and also addresses the effect of leakage to inside. It has also been found to be highly repeatable. However, it still does not address the problems that the leakage is not under operating conditions.

In an attempt to assign a pressure to this test for the purpose of attaining a leakage value, two methods are common. The first is to simply assume a pressure of 25 Pa. This has the advantage of comparing the airtightness of all duct systems directly, but it is commonly thought that this pressure systematically overestimates the leakage. The other method is to use half of the plenum pressure. This instills some amount of system dependency that is based on the actual operating pressures, but it still may not represent the pressures at the leaks. This method, though perhaps better than simply using 25 Pa when trying to estimate actual leakage, is also thought to tend to overestimate the leakage.

In the late 1990s, two new tests were developed that purported to measure duct leakage to outside at actual operating conditions. The first of these, called the nulling test, was developed by the authors of the current study (Francisco and Palmiter 2001; Francisco et al. 2002a, 2002b, 2003). The second, called the Delta-Q test, was developed by Lawrence Berkeley Laboratory (Walker et al. 1998b; Walker et al. 2001a) based on an idea by Dr. Chuck Gaston of the Pennsylvania State University, York campus (Gaston 1999). These two tests will be described fully in a later section of this report.

The nulling test, which does not contain a mathematical model, has previously been evaluated in only a few homes. These include four homes in a study evaluating ASHRAE Standard 152P (Francisco and Palmiter 1999, 2000), one home in a study initially evaluating the Delta-Q test (Walker et al. 1999), five homes in another study evaluating Standard 152P (Cummings and Withers 1999), and nine homes in the previous study evaluating these new methods (Francisco et al. 2002a, 2002b, 2003).

To date, the majority of the evaluation of the Delta-Q test has been either using computer simulation (e.g. Andrews 2000a; Palmiter et al. 2003) or laboratory evaluation (Walker et al. 2001a; Walker et al. 2002; Andrews 2002). These are extremely valuable, because they allow for the control and accurate measurement (or, in the case of computer simulation, assignment) of leaks. This then allows for some level of investigation into the accuracy of the methods under known conditions, as well as sensitivity to changes to the leakage magnitudes and locations.

However, there has been little field evaluation of the Delta-Q test with comparison to an independent, benchmark estimate. For this type of test, which is highly dependent on the model assumptions, it is imperative to perform evaluation in the field, since the leaks found in the field are often of a type that does not lend itself to exact measurement in the lab setting. One of the most common types of leaks in the field is distributed leakage, where there are small leaks at nearly every seam and connection. There may be larger holes as well, often in locations such as bends and with odd shapes that also do not lend themselves to easy, measurable replication in the lab.

There have been three field studies done using the Delta Q test previously. The first of these studies included thirteen homes tested by researchers at Lawrence Berkeley National Laboratory, Brookhaven National Laboratory (Andrews 2000a), and Davis Energy Group. The results of these tests can be found in Walker et al. (2001a). In this study, the only comparison was made to the fan pressurization test with an assumed pressure of half of the plenum pressure. Agreement was good when comparing total (supply plus return) leakage to outside, with the discrepancy being only about 2% of air handler flow. There was significant disagreement on individual houses, with an RMS error of 9%, and the differences were also greater when the leakage was split into supply and return leakage separately.

The second study, which provided Delta-Q tests on 87 homes, was performed by California State University – Chico in conjunction with Lawrence Berkeley National Laboratory (Walker et al. 2001a). Again, the only comparison was made to the fan pressurization test, this time with an assumed pressure of 25 Pa. Again, agreement was found to be within 2% of air handler flow, though again there was significant disagreement on a house-to-house basis.

These results are important in showing how different static tests can be from tests done with the system operating. However, because these two studies only compared the Delta-Q test to the fan pressurization test, which is considered unreliable and probably tends to be biased high, these studies can not be considered as validation of the Delta-Q test. This is especially true since the two studies used different assumed leakage pressures for the fan pressurization test.

The only previous tests performed in the field against an independent benchmark that assesses the leakage under actual operation was performed by the authors in the previous study evaluating these new methods in nine homes (Francisco et al. 2002a, 2002b, 2003). This study found that the Delta-Q test overestimated the leakage by an average of 55%, or 7.6% of air handler flow. However, this project included changing the leakage in each house, often by adding individual large holes. While the data do not suggest that these types of leaks caused an increase in bias, the sample of tests was both small and non-representative, so it also can not be considered conclusive of the performance of the Delta-Q test.

Despite the small sample size, the previous study contained several important findings. The nulling test continued to show a high level of promise relating to accuracy, but it could have a significant problem with wind and it took a long time to set up for the part of the test that estimated supply leakage only. The nulling test showed additional promise for homes without a ducted return system, such as manufactured homes and homes with platform returns (a single grille through a platform within the conditioned space on top of which sits the air handler), since the supply-only portion of the test is not required.

For the Delta-Q test, one of the most critical findings of the study by Francisco et al. was that the pressure between the ducts and the house did not stay constant throughout the test. This is one of the primary assumptions implicit in the Delta-Q test. Further analyses of the impact of the failure of this assumption, both in the Francisco et al. study and further modeling work by Palmiter et al. (2003) have shown it to be perhaps the most major source of error in the Delta-Q test.

Another finding was that there was a tendency for the Delta-Q test to exhibit “cross-talk”, whereby a large leak on either the return or the supply side would artificially inflate the leakage estimate on the other side. This effect was most obvious when a leak was added on only one side of the duct system, yet the estimate from the Delta-Q test would increase for the other side of the system as well.

There was also evidence that the Delta-Q test had problems estimating the leakage when the pressures at the leaks were small, as is common for leaks well downstream of the air handler.

Despite these problems, the size and nature of the sample tested did not lessen the general optimism that the Delta-Q test could be made to work, perhaps with modifications. The continuing need for a more accurate and simple test also fueled the desire for additional investigation of the method, as well as further evaluation of the nulling test. Therefore, a more extensive study of the test methods in homes was required. In order to best assess the actual general performance of the test methods, these tests should be done in a wider variety of homes and with the ducts tested primarily in their as-found condition. In addition to allowing an evaluation of the overall performance of the test methods, this larger sample would also allow for a better investigation of the conditions in which the tests exhibited the worst performance, and potentially identify improvements.

This report presents the results of such a study, which was funded by the National Energy Technology Laboratory. In this study, 51 homes located in the Puget Sound region were tested. Five of the homes were tested multiple times, with and without added leaks, to evaluate the accuracy of the benchmark estimate technique. Three sites were manufactured homes, which are evaluated separately. The remaining 48 homes were nearly evenly split between single-story and multi-story homes.

The results of this project include estimates from each leakage test method as described by the developers at the time the project began. In addition, for the Delta-Q test, several modifications are evaluated as possible improvements.

# 2
# TEST DESCRIPTIONS

The tests performed in this project fall into three categories: duct leakage tests, house leakage tests, and air handler flow tests. This section details each test.

## DUCT LEAKAGE TESTS

### Nulling Test

The nulling test is predicated on the idea that, when the air handler is turned on, any change in house pressure is due to unbalanced duct leakage. When there is more supply leakage than return duct leakage, the effect is analogous to an exhaust fan, and the house is depressurized. If the return leakage is greater, the unbalanced duct leakage is like a supply fan, and the house is pressurized. Using a calibrated fan to counter the change in pressure can provide an estimate of duct leakage.

Two of the most appealing features of the nulling test are that it directly measures leakage to outside at operating conditions and it is not based on an underlying model, and so has no equations. The primary drawbacks are the setup required for a portion of the test and sensitivity to wind.

The nulling test only accounts for an overall flow balance in the home, meaning that there is no distinction between leaks to inside and flow through registers and grilles. It does not matter where the envelope or duct leaks are, so there are no modeling assumptions related to the leakage characteristics of the ducts or house. Because the test accounts for an overall flow balance, the leakage that is estimated is leakage to or from outside only, which is the leakage of interest when assessing energy penalties.

The nulling test consists of two parts. The first part is the unbalanced duct leakage test, which is done with the air handler and duct system in their normal operating mode. The setup is shown as a schematic in Fig. 2-1, and an example is shown in Fig. 2-2. In Fig. 2-1, the air handler is in the garage, there is a single return duct (the thicker line), and a trunk-and-branch supply duct system (thinner lines). This portion of the test has actually been used for more than 10 years for measuring exhaust and supply fan flows.

At the beginning of the unbalanced duct leakage test, all interior doors are open and all exterior doors and windows are closed. The pressure between the house and outside is measured, with the result being the target baseline. If a buffer space is sufficiently vented to outside, and is not pressurized or depressurized by duct leakage, the buffer space can be used as the outside reference for this measurement, and can also afford some protection from measurement noise due to wind.

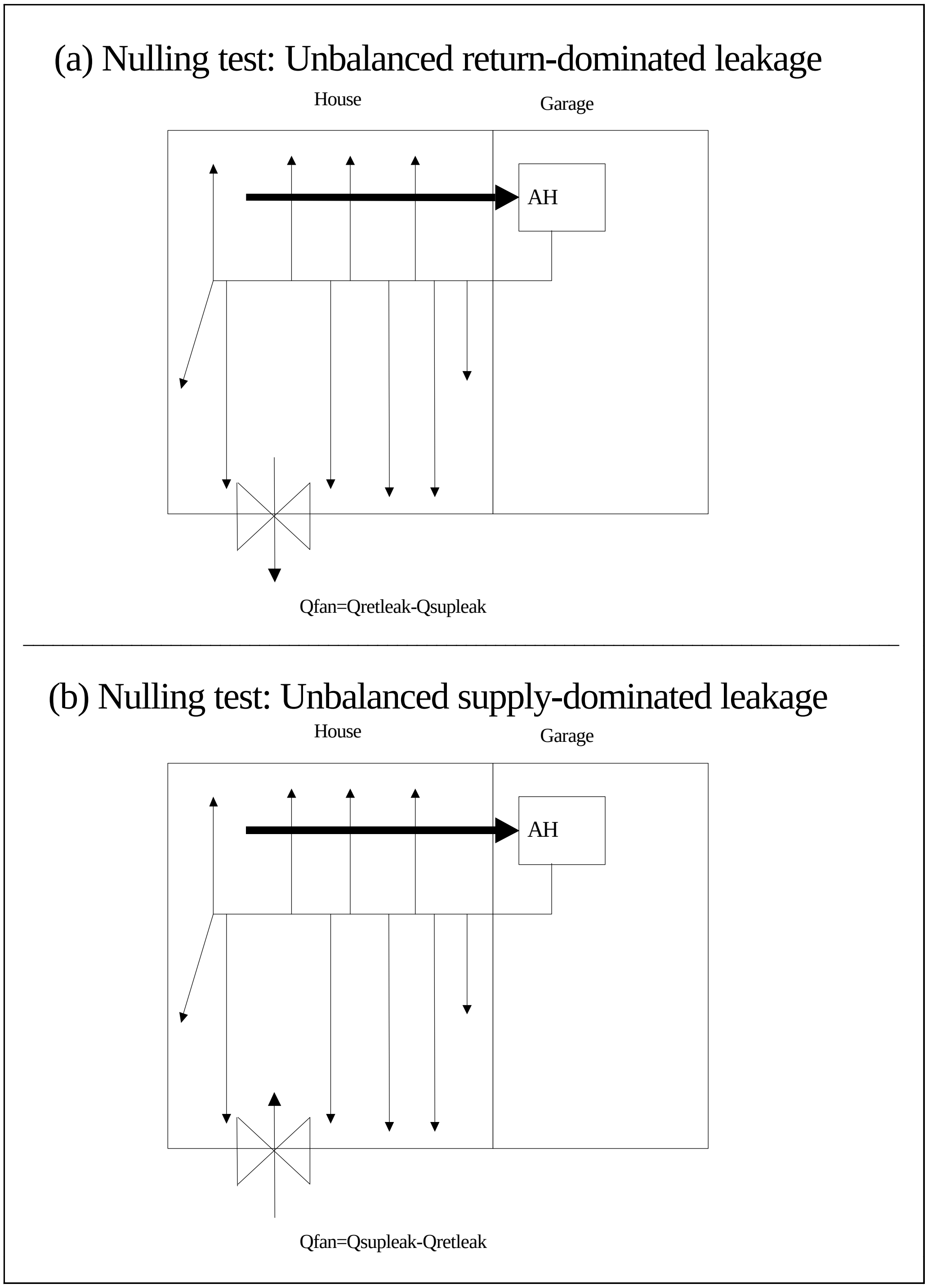



Figure 2-1. Schematic of the setup for the unbalanced leakage portion of the nulling test.

Figure 2-2.  Calibrated fan installed for nulling test.

After the pressure between the house and outside is measured, the air handler is turned on to determine whether the house is pressurized or depressurized due to air handler operation.  A calibrated fan is installed in an exterior door or window, set to counteract the pressure difference. For example, if the house is depressurized when the air handler is turned on, the calibrated fan is set to pressurize the home.

The basic idea of the nulling test is to adjust the calibrated fan until it has counteracted, or "nulled out", the pressure change due to turning on the air handler, such that the pressure between the house and outside is returned to the target baseline.  It is best to do this with the air handler fan operating without any heating or cooling active to avoid large changes in house temperature.  The flow through the calibrated fan when the target baseline has been matched is the nulling test estimate of the unbalanced duct leakage.

Because it is difficult to adjust the calibrated fan so precisely that the target baseline is matched exactly, three measurements are taken.  In addition to one measurement taken as close to the target baseline as possible, measurements are taken at a higher pressure and at a lower pressure than the target baseline.  Often, the difference between the pressure stations is about 0.5 Pascals

(Pa), though this can be modified to suit the house and conditions.  This sometimes requires turning the calibrated fan around to make one of the measurements.  In addition, readings with the air handler off are taken both before and after the three measurements with the air handler on are made.

In some cases, when there is enough wind to cause pressures to fluctuate widely, it is necessary to sample for longer periods of time (e.g. 1-3 minutes) at each station, and to adjust the calibrated fan to provide different flows instead of specific pressures.

Once all of the data have been collected, a linear regression is applied to the flow vs. pressure data with the air handler on, and the average of the two measurements with the air handler off is applied to the resulting equation to get the unbalanced duct leakage estimate.  It may not be exactly correct to use a straight-line fit, because house leakage exponents are typically about 0.65 rather than 1.  However, it is not known what the house leakage exponents really are at such low pressures (the exponents are typically determined at house pressures of 25 and 50 Pa relative to outside).  Also, because the pressure stations are so close together, approximating any curvature with a straight line will result in only small errors, typically no more than 2%.

Use of software that provides a graphical representation of the data can assist in assuring a good test by showing the extent to which the data falls on a straight line.

The second portion of the nulling test, referred to as the supply-only portion, is performed to allow for the separate estimation of supply and return leakage.  The basic idea is to isolate the return duct system from the air handler and supply ducts by placing an airtight barrier between the air handler and the return ducts, often at a filter slot.  A second calibrated fan is attached to the front of the air handler in place of the air handler cabinet cover.

There are two setup options for the supply-only portion of the nulling test.  The first, and most preferable, is shown in Fig. 2-3 as a schematic and in Fig. 2-4 for examples of air handlers within and outside the conditioned space.  In this case, the second calibrated fan is attached such that the air that is supplied to the air handler is brought from the house.  If necessary, this includes setting up the second calibrated fan in a doorway between the house and the space containing the air handler, with a duct running between the fan and the air handler, as shown in the right panel of Fig. 2-4.  The second, which is to be avoided when possible, is to attach the second calibrated fan such that the air is supplied from outside the home.  This is shown in Fig. 2-5.

Prior to setup the pressure between the supply plenum and the house is measured with the air handler running in normal operating mode.  Once the setup is complete and a target baseline has been obtained, the air handler is turned on, and the second calibrated fan is adjusted until the normal operating supply plenum pressure is matched.

Once this has been done, the same measurement procedure as was used for estimating the unbalanced duct leakage is performed.  Any discrepancy between the supply plenum pressure relative to the house during this test relative to the pressure under normal operating conditions can be corrected for by applying a square root correction to the flows through both calibrated fans.  The equation is as follows:

$$Q_{corr} = Q_{meas} \sqrt{\frac{\Delta P_{s,nom}}{\Delta P_{s,meas}}} \qquad \textbf{(2-1)}$$

where $Q_{corr}$ is the corrected flow
$Q_{meas}$ is the measured flow
$\Delta P_{s,nom}$ is the pressure between the supply plenum and the house under normal operation
$\Delta P_{s,meas}$ is the pressure between the supply plenum and the house during the nulling test

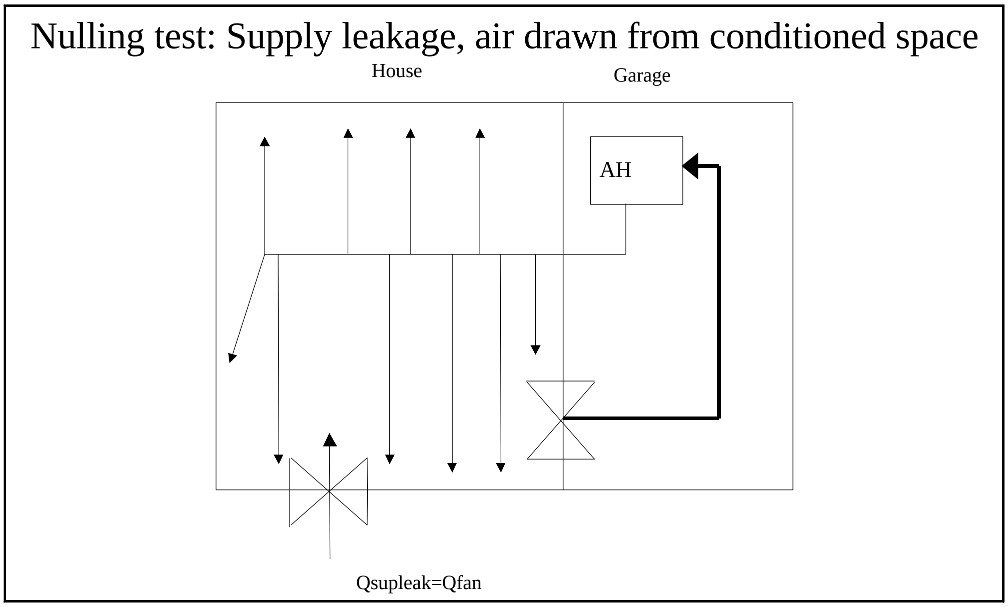



Figure 2-3. Schematic of the setup for the supply leakage only portion of the nulling test, with air taken from within the conditioned space.

Figure 2-4. Calibrated fan attached to air handler within the conditioned space (left) and outside the conditioned space (right), such that air comes from house.

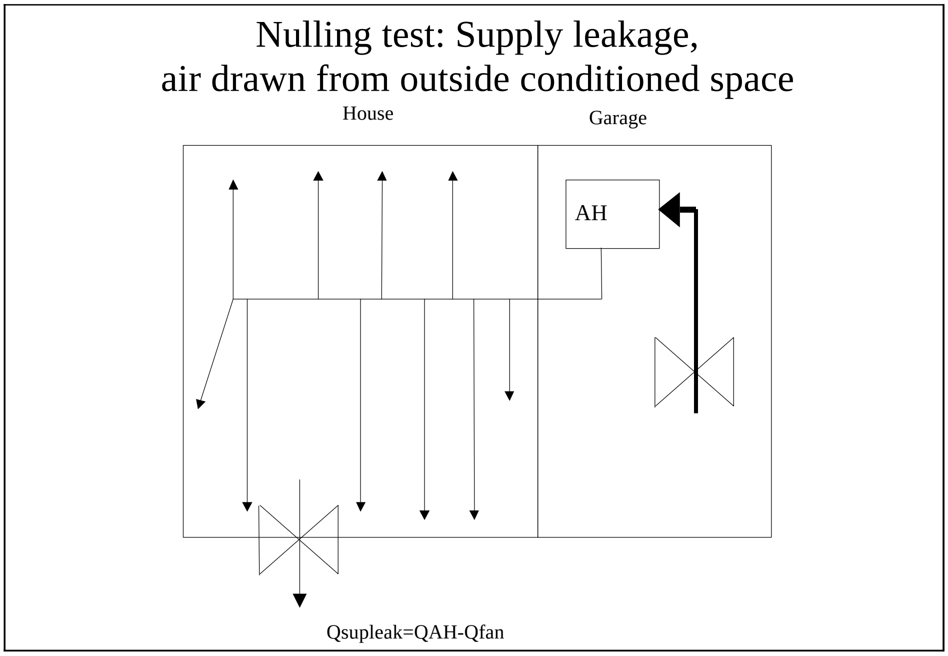



Figure 2-5. Schematic of the setup for the supply leakage only portion of the nulling test, with air taken from outside the conditioned space.

If the second calibrated fan is set up to bring air from the house, the first calibrated fan is set to pressurize the house and the flow through the first fan is a direct measurement of the supply leakage. In addition, the flow through the second fan is a measurement of the air handler flow. This method of measuring the air handler flow is one of two approved ways in ASHRAE Standard 152P (ASHRAE 2003).

If the second calibrated fan is set up to take air from outside the home, the first calibrated fan is set to depressurize the house and the flow through the first fan is a measure of the supply flow into the house. In order to estimate the supply leakage with this setup, the flow through the first fan must be subtracted from the air handler flow, which is measured through the second fan. It is this required subtraction that makes this setup less desirable. Subtracting two large numbers (air handler flow and supply flow) to get a smaller one (supply leakage) can result in a large percentage error in the smaller one. In addition, the use of two separate pieces of equipment, each of which has some inherent error, can result in a systematic bias in the result from subtracting the two flows.

After both the supply leakage and unbalanced leakage have been estimated, the unbalanced leakage can be subtracted from the supply leakage to estimate the return leakage. It is worth noting that, for homes without return ducts outside the conditioned space, the supply leakage only portion of the nulling test, which requires the most setup, does not need to be done since the unbalanced duct leakage is the supply leakage. Manufactured homes often have no return ducts, and there are also many homes that have a platform return, where the air handler sits atop a platform that contains a grille to bring in air from the room. Platform returns are especially common in regions that have many homes built on slabs, such as the southeast and the southwest. The nulling test may be particularly useful in these cases.

There are two physical phenomena, other than pressure fluctuations due to wind, that are known to cause errors in the nulling test. Both of these relate to the target baseline pressure between the house and outside. Other than wind, the pressure across the building envelope is a result of the stack effect, which is the pressure difference between indoors and outdoors due to temperature differences between indoors and outdoors. The magnitude of the stack pressure, which is the change in indoor-outdoor pressure difference from the floor to the ceiling, is a result of the temperature difference. The exact pressure at any height on the wall is also a function of the distribution of holes within the house.

Changes in temperature in the home can affect the pressure measured at any height on the wall except for at the neutral level, which is where the pressure difference across the wall is zero. It is for this reason that the air handler should be run without heating or cooling during the nulling test. There can still be some change in indoor temperature due to the operation of the calibrated fans, but this amount is usually much smaller than the changes due to long running times of the heating or cooling.

When the air handler is off, the holes in the ducts can adjust the pressures along the height of the wall relative to what the distribution would be if there were no holes in the ducts, because these holes act somewhat like additional holes in the envelope. However, when the air handler is turned on, it effectively shuts off these leaks as additional holes in the envelope. The true desired target baseline pressure should be the pressure across the envelope with all holes in the ducts sealed. This is difficult to accomplish, however. It is possible to seal all of the registers and grilles, but this can be time-consuming. In addition, sealing the registers and grilles does nothing about communication between the ducts and the house through other, unintentional paths, as are common in multi-story homes.

Examples of the impact of the indoor-outdoor temperature difference on the stack pressure are shown by comparing Figs. 2-6 and 2-7. These figures show that, for a single-story house with half of the leakage in the walls and the other half split evenly between the ceiling and floor, the pressure across the ceiling and floor will be about 1.5 Pa when the indoor-outdoor temperature difference is 48 F. If the indoor-outdoor temperature difference is reduced to 25 F, the pressures at the floor and ceiling are also cut in half. These examples show the indoor temperature being constant and the outdoor temperature changing, but the same holds true if the indoor temperature changes and the outdoor temperature stays the same, as would happen if the heat was left on for an extended period of time.

The impact of the distribution of holes within the envelope is shown by comparing Figs. 2-6 and 2-8. In Fig. 2-8, the holes in the floor have been removed, as will approximately be the case for homes with a slab foundation. These figures show that, while the total stack pressure stays the same (about 3 Pa, the difference is due to rounding), when there are more holes in the ceiling than in the floor the neutral level shifts closer to the ceiling and the pressure near the floor gets larger. This is similar to what happens when holes in ducts are effectively “shut off” to infiltration by the operation of the air handler. For duct leaks, the impact depends on the cumulative size of holes in the ducts that are high relative to the holes that are low.

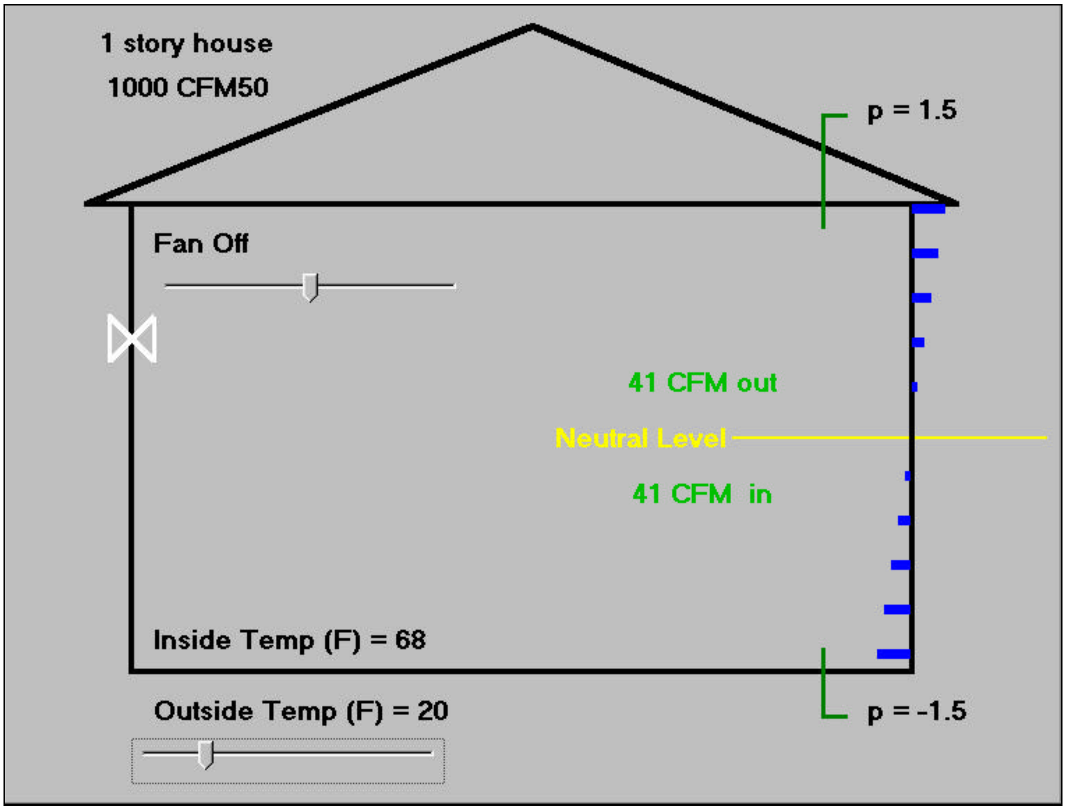



Figure 2-6. Pressures across the envelope due to stack effect, temperature difference of 48 F.

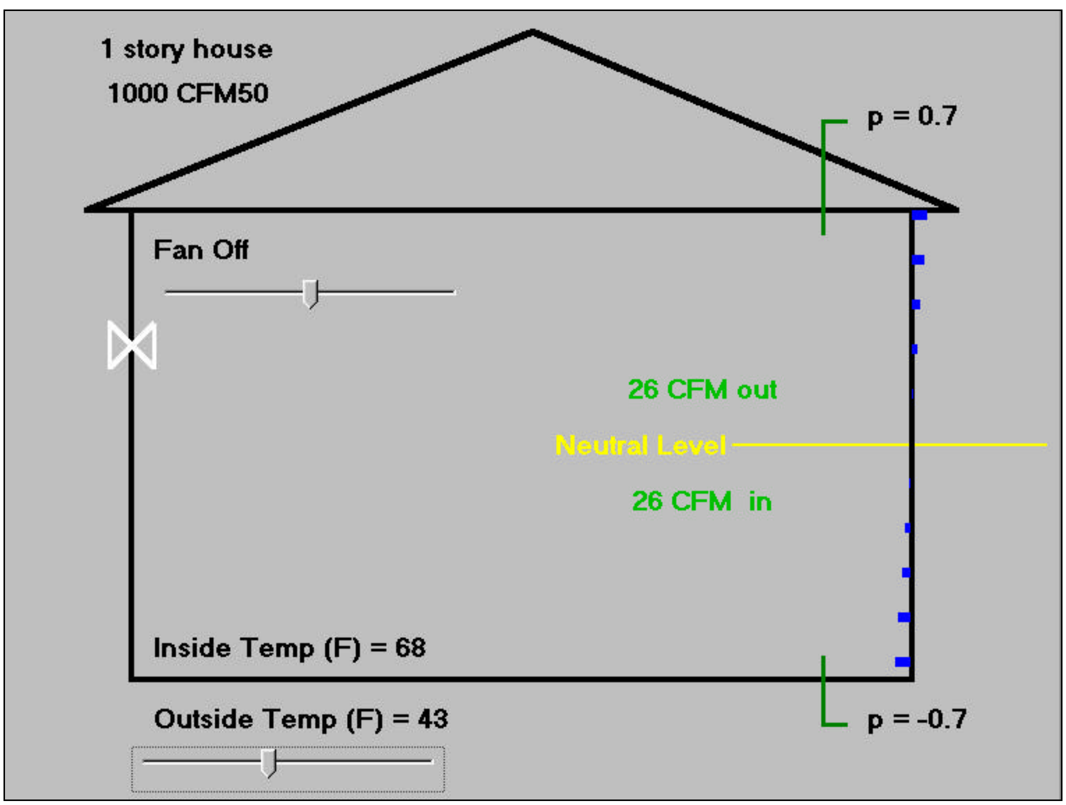



Figure 2-7. Pressures across the envelope due to stack effect, temperature difference of 25 F.

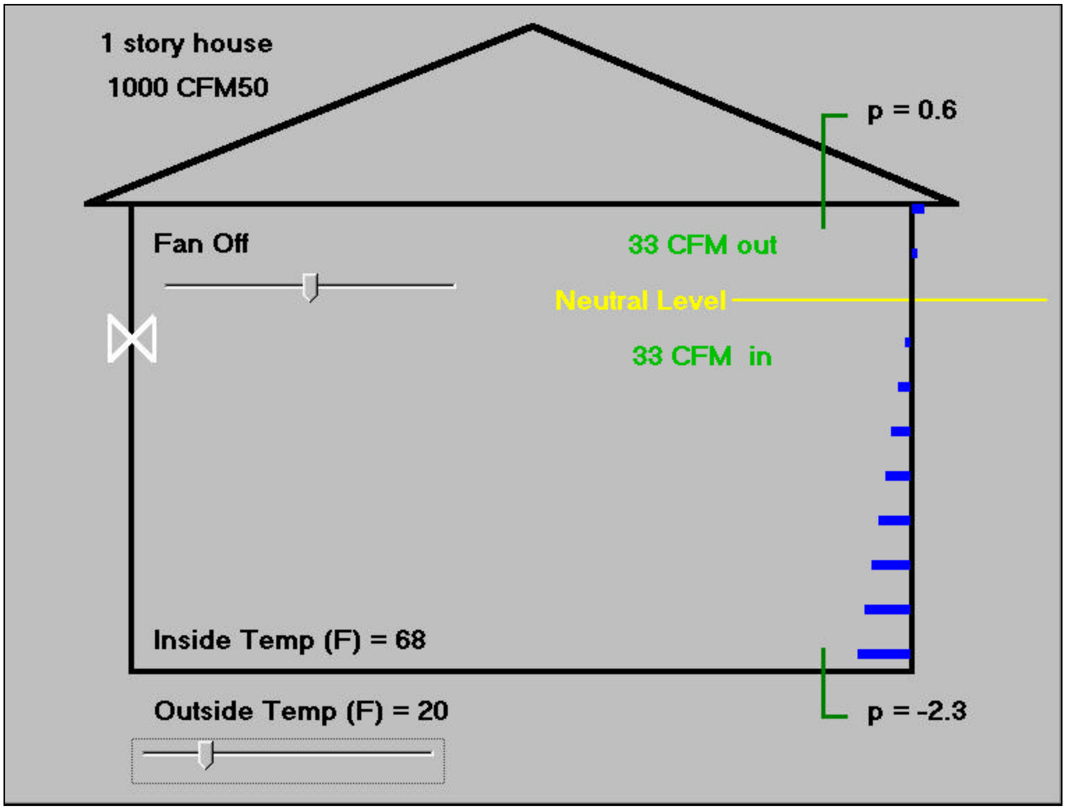



Figure 2-8. Pressures across the envelope due to stack effect, temperature difference of 48 F and no holes in the floor, half in the ceiling, and half in the walls.

An evaluation of techniques to address these two affects on the target baseline pressure was done in a previous project (Francisco et al. 2002a). No systematic improvement was found from attempts to eliminate the effect of the holes in the ducts on the pressure distribution along the height of the wall. The only case where adjustments for changing indoor temperature had a clear benefit was the case where the air handler could not be run without the heat.

The general equations for correcting the nulling test for a change in total stack pressure due to changing indoor temperature are as follows:

Nomenclature:

- $\Delta P_{s,0}$ average total stack pressure (i.e. pressure difference at the top of the building minus pressure difference 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 nulling test pressure station **[from data]**
- $\Delta P_0$ average pressure across envelope with air handler off (baseline) **[from data]**
- $\Delta P_j$ pressure across envelope with air handler and nulling fan on, with total stack pressure measured with air handler on, at jth nulling test pressure station **[from data]**

$\Delta P_{j,0}$ pressure across envelope with air handler and nulling fan on, with total stack pressure measured with air handler off, at jth nulling test pressure station **[this is what is being sought, needs to be calculated]**

$\Delta P_f$ pressure change induced by nulling fan **[to be calculated]**

$A$ stack adjustment factor **[to be calculated]**

$T_{out,0}$ average outdoor temperature with air handler off **[from data]**

$T_{in,0}$ average indoor temperature with air handler off **[from data]**

$T_{out,j}$ average outdoor temperature with air handler on at jth nulling test pressure station **[from data]**

$T_{in,j}$ average indoor temperature with air handler on at jth nulling test pressure station **[from data]**

Equations:

$$\Delta P_{s,j} = A\Delta P_{s,0} \quad \textbf{(2-2)}$$

$$\Delta P_j = A\Delta P_0 + \Delta P_f \quad \textbf{(2-3)}$$

$$\Delta P_{j,0} = \Delta P_0 + \Delta P_f \quad \textbf{(2-4)}$$

Rearranging **(2-3)**,

$$\Delta P_f = \Delta P_j - A\Delta P_0 \quad \textbf{(2-5)}$$

Substituting into **(2-4)**,

$$\Delta P_{j,0} = \Delta P_0 + \Delta P_j - A\Delta P_0 \quad \textbf{(2-6)}$$

Rearranging **(2-6)**,

$$\Delta P_{j,0} = (1-A)\Delta P_0 + \Delta P_j \quad \textbf{(2-7)}$$

The only piece that needs to be calculated at this point is *A*, which can take one of two forms.

To correct directly from measured stack pressures:

$$A = \frac{\Delta P_{s,j}}{\Delta P_{s,0}} \quad \textbf{(2-8)}$$

To correct based on temperature difference between indoors and outdoors:

$$A = \frac{\left(1/T_{out,j} - 1/T_{in,j}\right)}{\left(1/T_{out,0} - 1/T_{in,0}\right)} \quad \textbf{(2-9)}$$

In this study, all houses were tested with the air handler running without any heating or cooling, so these adjustments were not required. However, the equations are provided as part of the overall test description.

**Delta-Q Test**

The Delta-Q test is most appealing because it can be done relatively quickly and with little setup. It also requires only one major piece of equipment, which is a blower door. It is also done with the air handler and ducts operating normally. It does depend on modeling assumptions and complex equations, so the results are best obtained with a computer and are subject to the accuracy of the assumptions in the model.

The Delta-Q test method utilizes four multi-point blower door tests. Two of these are tests that pressurize the house, and the other two depressurize the house. For each of these pairs of blower door tests, one test is with the air handler off and the other is with the air handler on.

Each test is done at several different pressure differences between the house and outside. There are any number of choices that could be made as to what these pressure "stations" are, but at the time that this project started the recommended stations were from 5-25 Pa in 5 Pa increments for each of the four blower door tests. Another recommendation that has been made is to measure at 5 Pa and then from 10-50 Pa in 10 Pa increments for each blower door test. This set of stations has been considered because of the concern that many leaks may be at pressures greater than 25 Pa, and that using a wider range of pressures may improve the results.

Because of duct leakage to outside, the flow through the blower door required to achieve a certain pressure difference between the house and outside is different with the air handler on than it is with the air handler off. The difference between these flows at each pressure station is called the "delta-Q" for that station. The basic idea of the Delta-Q test is to regress the set of delta-Qs that are obtained from the test on the pressure stations, using equations for a model derived by Walker et al. (1999, 2001a). The model assumptions and derivation follow.

*Derivation of the Equations for the Delta-Q Test*

In order to understand the derivation of the Delta-Q model equations, it is useful to understand that air leakage in buildings and ducts are typically represented as a power law relationship between flow and pressure difference between the zone and outside. This relationship can be expressed as

$$Q = C\Delta P^{n} \tag{2-10}$$

where $Q$ is the flow (leakage) to outside at a pressure difference to outside of $\Delta P$
$C$ is the leakage coefficient
$n$ is the leakage exponent

The house, supply ducts, and return ducts will each be represented by their own equation. The leakage coefficient and exponent can be obtained through pressurization testing at a minimum of two different pressures. If measurements are only taken at one pressure, then the exponent needs to be assumed and the coefficient can be calculated using the assumed exponent.

With the air handler off, the Delta-Q model represents the flows through the blower door at each pressure station as:

$$Q_{off}(\Delta P) = C_{env}\Delta P^{n_{env}} + C_s\Delta P^{n_s} + C_r\Delta P^{n_r} \qquad \textbf{(2-11)}$$

where $Q_{off}(\Delta P)$ 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.
$C_{env}$ 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
$n_{env}$ 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

In this equation, the first term on the right-hand side is the leakage through holes in the building envelope, the second term is the leakage from the supply ducts to outside, and the third term is the leakage from the return ducts to outside. Leakage through the ducts is due only to pressurization or depressurization by the blower door.

Note that eq. **(2-11)** assumes that a single pressure can be applied to the duct terms as well as the house term. This assumption may not be correct 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:

$$Q_{on}(\Delta P) = C_{env}\Delta P^{n_{env}} + C_s(\Delta P + \Delta P_s)^{n_s} + C_r(\Delta P - \Delta P_r)^{n_r} \qquad \textbf{(2-12)}$$

where $Q_{on}(\Delta P)$ 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) with the air handler on and the blower door off.
$\Delta P_r$ is the pressure difference between the return ducts and house (return as reference) with the air handler on and the blower door off.
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 eq. **(2-15)** is negative (i.e. flow into house).

In practice, the pressures in the ducts are measured at the plenums.  At the time that this project began, the recommendation was to use half of this measured value in the Delta-Q equations, though at times the recommendation has been to use the full plenum pressure.  The pressure differences between the ducts and the house are measured with the blower door off, i.e. under normal operating conditions.

In eq. (**2-12**), the duct leakage is now based on a pressure that is the superposition of the pressure across the envelope and the pressure between the ducts and house when the air handler is on (and the blower door is off).  Equation (**2-12**) makes two assumptions about the pressures in the ducts. One is the same as for the air handler off case, which is that the building envelope pressure can also be applied to the ducts.

The second assumption about the pressures in the ducts in eq. (**2-12**) is that the pressures between the ducts and the house remain constant throughout the Delta-Q test.  This can be seen by noting that these pressures are not measured concurrently with the house pressure at each pressure station, but are based on the duct pressures when the blower door is off.  This should be true when there is no duct leakage or when the ducts are all inside the house.  However, when the ducts are outside the conditioned space and have leaks, such that they are somewhat connected to a space that is not being affected by the blower door in the same way as the house, this assumption will not be true.

Equation (**2-12**) does not require that the pressure everywhere in the ducts be the same.

The “Delta-Q” is the difference between the air handler on and air handler off measurements. When this subtraction is made, the leakage through the building envelope drops out, and the equation can be expressed as

$$\Delta Q(\Delta P) = Q_{on}(\Delta P) - Q_{off}(\Delta P) = C_s\left[(\Delta P + \Delta P_s)^{n_s} - \Delta P^{n_s}\right] + C_r\left[(\Delta P - \Delta P_r)^{n_r} - \Delta P^{n_r}\right] \quad \textbf{(2-13)}$$

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

$$Q_s = C_s \Delta P_s^{\,n_s} \qquad Q_r = C_r \Delta P_r^{\,n_r} \qquad \textbf{(2-14 and 2-15)}$$

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 **(2-14)** and **(2-15)** can be rearranged as

$$C_s = \frac{Q_s}{\Delta P_s^{\,n_s}} \qquad C_r = \frac{Q_r}{\Delta P_r^{\,n_r}} \qquad \textbf{(2-16 and 2-17)}$$

Substituting $C_s$ and $C_r$ into eq. **(2-13)** gives

$$\Delta Q(\Delta P) = Q_s\left[\left(\frac{\Delta P + \Delta P_s}{\Delta P_s}\right)^{n_s} - \left(\frac{\Delta P}{\Delta P_s}\right)^{n_s}\right] + Q_r\left[\left(\frac{\Delta P - \Delta P_r}{\Delta P_r}\right)^{n_r} - \left(\frac{\Delta P}{\Delta P_r}\right)^{n_r}\right] \quad \textbf{(2-18)}$$

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. 1998b and Siegel et al. 2001). With this assumption and some algebraic rearrangement, the final Delta-Q equation can be written as

$$\Delta Q(\Delta P) = Q_s\left[\left(1 + \frac{\Delta P}{\Delta P_s}\right)^{0.6} - \left(\frac{\Delta P}{\Delta P_s}\right)^{0.6}\right] - Q_r\left[\left(1 - \frac{\Delta P}{\Delta P_r}\right)^{0.6} + \left(\frac{\Delta P}{\Delta P_r}\right)^{0.6}\right] \quad \textbf{(2-19)}$$

The measured Delta-Qs are fitted with eq. **(2-19)** using least-squares to provide the supply and return leakage estimates. Figure 2-9 shows an example of a typical Delta-Q curve. In this example, the house leakage coefficient is set to 100 cfm/Pa$^n$, the duct leakage coefficients are each set to 30 cfm/Pa$^n$, and the duct pressures are set to 50 Pa.

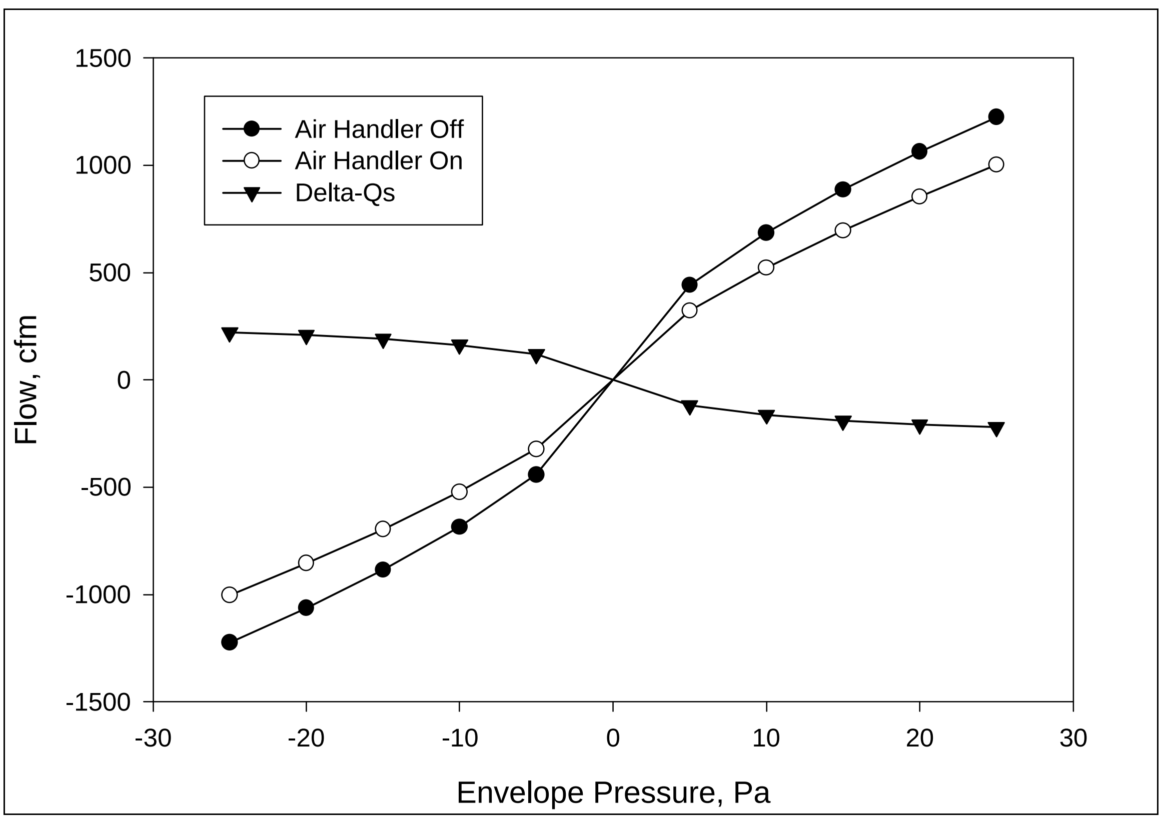



Figure 2-9. Example of Delta-Q test data.

Due to the power law behavior of the leaks, large Delta-Qs on the pressurization side correspond more to large return leaks than supply leaks, and large Delta-Qs on the depressurization side correspond more to large supply leaks than return leaks. Changes in direction of the Delta-Q curve, or a sharp jump at an individual pressure station followed by a return to the normal curve may indicate that the blower door has caused the flow through a leak to reverse.

*Delta-Q Test Protocol*

Figure 2-10 shows a blower door installed for the Delta-Q test. As for the nulling test, all of the interior doors should be open for the Delta-Q test and all of the exterior doors and windows should be closed. The protocol for performing the Delta-Q test is as follows.

First, with the blower door off, measure the pressure difference between each the supply and return plenums and the house. Then, turn the air handler off.

Figure 2-10. Blower door installed for Delta-Q test.

With the air handler off and the blower door sealed, measure the pressure difference between the house and outside. This pressure is the baseline house pressure. Next, depressurize the house by approximately 5 Pa relative to the baseline house pressure, and record the actual house pressure relative to outside and the flow through the blower door. Repeat this process for depressurizations of approximately 10, 15, 20, and 25 Pa relative to the baseline house pressure.

Next, turn on the air handler. For each pressure station, use the blower door to match as nearly as possible the actual house pressure. Record the actual house pressure and flow through the blower door.

Repeat this process for symmetric pressurization stations. Because pressures will not be exactly matched between air handler off and air handler on cases, use the correction equation shown in the nulling test description, eq. **(2-1)**, to adjust the air handler off data to be consistent with the pressures at each station with the air handler on. Subtract the baseline house pressure from all resulting pressures.

The resulting Delta-Qs can then be regressed on the pressures to provide estimates of supply and return leakage. A computer or programmable calculator will be required to perform this calculation.

**Fan Pressurization Test**

The fan pressurization test has been around for more than 10 years. It is a simple test to perform, though setup can be time-consuming. All registers and grilles need to be sealed in order to do the fan pressurization test. The basic principle is that a calibrated fan pressurizes the ducts to a certain pressure, and because all of the intentional openings (the registers and grilles) have been sealed, the flow through the calibrated fan must be going through the leaks in the ducts. Because the registers and grilles have all been sealed, the pressure throughout the duct system is approximately uniform, though large leaks can cause this assumption to fail.

If leakage to outside only is desired, then a blower door is required in addition to the calibrated fan that pressurizes the ducts. The blower door pressurizes the house to the same level that the ducts are pressurized, such that the pressure between the ducts and the house is zero. Then there is no leakage between the ducts and the house, and all of the measured flow through the fan pressurizing the ducts is through leakage to outside.

If it is desired to estimate supply and return leakage separately, an airtight barrier must be placed between the supply and return duct systems, and the test must be done on each portion of the ducts separately. The airtight barrier is typically placed at the filter slot. If the air handler is outside the conditioned space, it is also important to seal up as many air handler cabinet leaks as possible to avoid having those leaks, which are actually return leaks, from being present in the supply leakage estimate. This sealing will, however, result in underestimating the return leakage at the assumed pressure.

In addition to the potentially lengthy setup process, this test has the major drawback that the test is performed at artificial static pressures with the air handler off, and hence it is difficult to estimate leakage under normal operating conditions. It has become common to express the leakage either at an assumed pressure of 25 Pa, or at half of the plenum pressure.

The use of 25 Pa for all houses makes the actual airtightness of the ducts directly comparable across houses. The airtightness refers to how large the cumulative hole area in the ducts is, without regard to the pressures across the various holes. It is this characteristic of the ducts that the fan pressurization test is good at measuring, and for which it was originally designed.

The use of half of the plenum pressure is an attempt to account for differences between systems. This is the assumption used in ASHRAE Standard 152P (ASHRAE 2003). The assumption is that the leakage is rarely all at the plenum or all at the registers, so a reasonable compromise is half of the plenum pressure. Because duct leaks can be anywhere, this assumption often produces results that are incorrect by large amounts.

The basic procedure for performing these tests, after all of the registers and grilles have been sealed, is to attach the calibrated fan to either the air handler cabinet (for supply leakage) or a return grille (for return leakage). For the return leakage, the grille to be used should be sealed only around the fan. The setup of the calibrated fan for the supply leakage measurement is the same as for the measurement of air handler flow during the portion of the nulling test in which only supply leakage is measured; see Fig. 2-4 in the nulling test description section for examples. Figure 2-11 shows an example of the calibrated fan attached to a return grille.

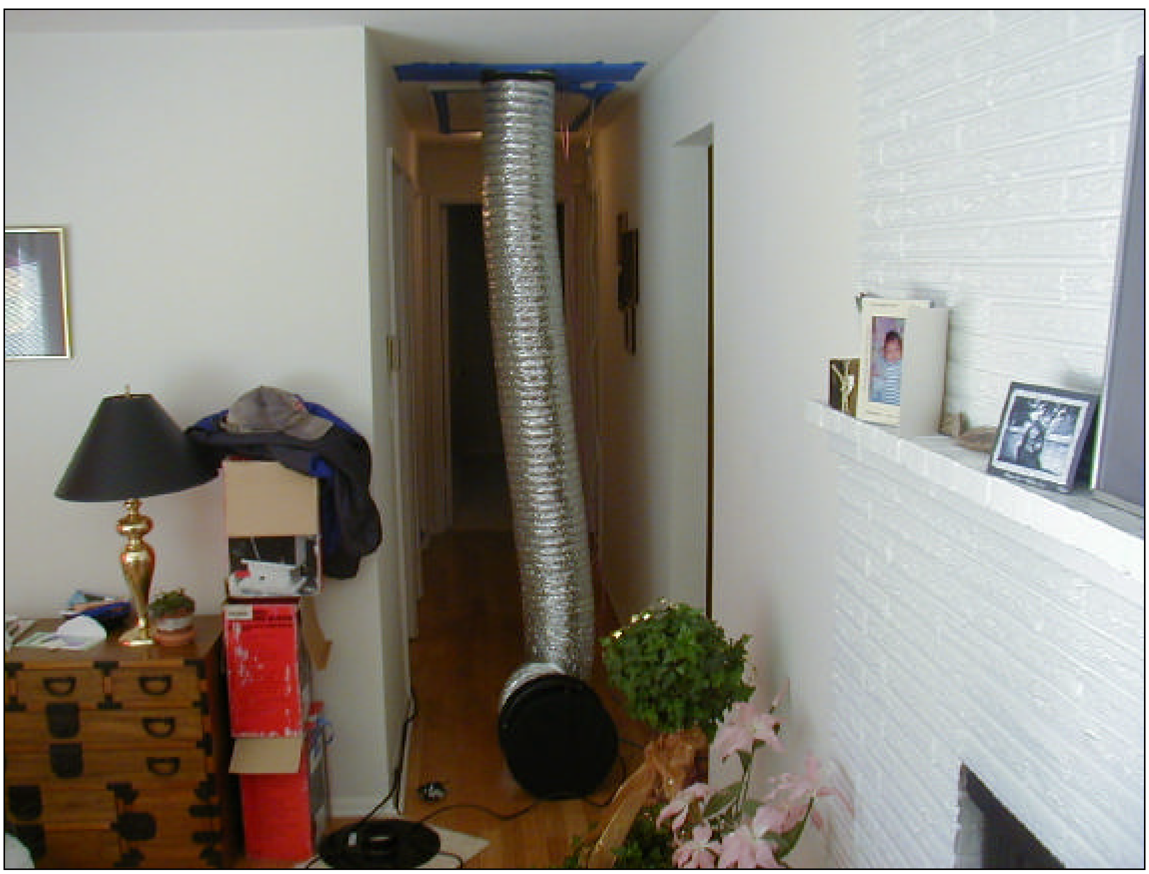


Figure 2-11. Calibrated fan attached to a return grille.

It is possible to use other locations for the attachment of the fan, such as a supply register for the supply leakage test, but the locations stated have multiple advantages.  One is that they are typically large enough to make it simple to inject large amounts of air into the ducts.  Also, these locations cause the air to go through the ducts in the same direction as under normal operation, although this will not be the case for additional return branches other than the one going from the grille to which the fan is attached to the plenum.

The calibrated fan is adjusted until the pressure in the ducts reaches the desired pressure.  If duct leakage to or from outside only is desired, the blower door is turned on concurrently.  Once the pressure between the house and ducts has reached zero, the pressure between the ducts and outside is recorded along with the flow through the fan pressurizing the ducts.  If the test is repeated at a second pressure, the leakage exponent can be calculated instead of assumed.  This additional point typically only takes a few extra minutes.  The equation for duct leakage is the same as eq. **(2-10)** shown in the Delta-Q derivation section,

$$Q = C\Delta P^n \qquad \textbf{(2-10)}$$

**Benchmark Estimate**

The benchmark estimate used in this study for comparisons of the other methods uses the combination of air handler flow measurements and measured flow through the registers and grilles.  The air handler flow was measured during the portion of the nulling test that measures only supply leakage.

Supply register flows were measured with a propeller-based flow hood designed for measuring residential supply register flows.  Figure 2-12 shows an example of a measurement using this flow hood.  It is no longer commercially available, but it has been found to work better than pressure-drop based flow hoods that were designed more for either larger flows (such as those found in commercial buildings or residential central returns) or high velocity jets such as are commonly found in Europe.  This hood was calibrated in-house at the beginning and end of the project.  This flow hood is sensitive to high-velocity jets and swirl, so homes with registers than caused these flow patterns were avoided.  Typical floor registers, as is common in the Puget Sound region and shown in Fig. 2-13, do not tend to produce these flow patterns.

Return grille flows were measured using a commercially available flow hood sized for residential returns.  This flow hood was calibrated by the manufacturer at the beginning and end of the project, as well as in-house at the conclusion of the field testing.  Figure 2-14 shows an example of a measurement using this flow hood.

The basic idea of the benchmark estimate test is that the difference between the air handler flow and the sum of the flows measured through the registers is the duct leakage.  This duct leakage, however, includes any leakage to inside.  As a result, this simple subtraction is not comparable to the other leakage tests whenever there is leakage to inside, as is common in multi-story homes.

Figure 2-12.  Measurement of supply register flow.

Figure 2-13.  Typical floor register.


Figure 2-14. Measurement of return grille flow.

In order to address this problem, a correction procedure was devised to adjust the result of the subtraction to be leakage to outside only. This correction uses two fan pressurization tests. The first is the test described previously, where the blower door is used to zero out the pressure difference between the house and the ducts in order to provide leakage to outside only. The second fan pressurization test used in the adjustment of the benchmark estimate did not use the blower door, so the leakage estimated includes the leakage to inside.

For each of these fan pressurization tests, leakage flows were calculated at 25 Pa. The ratio of the resulting leakage to outside to the resulting leakage including that to inside is the adjustment factor, and is multiplied by the difference between air handler flow and register flows to get the benchmark estimate of leakage to outside. This process can be expressed as

$$Q_{be} = \left(Q_{AH} - \sum Q_{reg}\right)\frac{Q_{ext25}}{Q_{tot25}} \qquad \textbf{(2-20)}$$

where $Q_{be}$ is the benchmark estimate of leakage to outside
$Q_{AH}$ is the air handler flow
$\Sigma Q_{reg}$ is the sum of the flows through the registers
$Q_{ext25}$ is the duct leakage to outside at 25 Pa
$Q_{tot25}$ is the duct leakage at 25 Pa including both leaks to inside and outside

This adjustment process makes the implicit assumption that the leaks to inside are at the same effective pressure as the leaks to outside. This assumption is likely to be frequently incorrect; as a result, it is expected that homes with significant leakage to inside, such as multi-story homes, will have greater errors in the benchmark estimate than homes without leaks to inside, such as most single-story homes.

It is possible to do the correction procedure for leakage to inside at any pressure. Another option that was considered was to use the leakage equation from the fan pressurization test that included leakage to inside to calculate the leakage pressure, and then to use that pressure in the equation for leakage to outside. This process is as follows:

The difference between air handler flow and the sum of register flows is the total leakage, including leakage to inside. Therefore, set this difference equal to the leakage equation for total leakage on the side of interest, supply or return:

$$Q_{AH} - \sum Q_{reg} = C_{tot} \Delta P^{n_{tot}} \tag{2-21}$$

where $C_{tot}$ is the leakage coefficient from the fan pressurization test that includes leakage to inside

$n_{tot}$ is the leakage exponent from the fan pressurization test that includes leakage to inside

This can be rearranged to solve for the only unknown, $\Delta P$:

$$\Delta P = \left( \frac{Q_{AH} - \sum Q_{reg}}{C_{tot}} \right)^{1/n_{tot}} \tag{2-22}$$

This pressure is an estimate of the effective leakage pressure for all of the leaks, including those to inside. With this available, it can be used in the equation for leakage to outside only to obtain an estimate of the leakage to outside at operating conditions.

In a large majority of cases, this method gave nearly identical answers as the method described in eq. **(2-20)** for the benchmark estimate. However, when leakage pressures are small, it is necessary to extrapolate well beyond the range of data taken for the fan pressurization tests (which are done at 25 and 50 Pa), and an error in the estimate of the leakage exponent can cause large errors in the leakage flows at these lower pressures. Because the leakage flows at 25 Pa are within the range of data, the process described in eq. **(2-20)** is more robust, so for consistency across homes that method was chosen for use in the benchmark estimate procedure.

However, this same idea can be used as an estimate of the apparent leakage pressure for the leaks to outside. Once the correction procedure for leaks to inside has been applied, the resulting benchmark estimate leakage can be applied to the equation from the fan pressurization test for leakage to outside:

$$Q_{be} = C_{out} \Delta P_l^{n_{out}} \qquad \textbf{(2-23)}$$

where $C_{out}$ is the leakage coefficient from the fan pressurization test for leakage to outside
$n_{out}$ is the leakage exponent from the fan pressurization test for leakage to outside
$\Delta P_l$ is the estimated leak pressure

Solving for $\Delta P_l$:

$$\Delta P_l = \left( \frac{Q_{be}}{C_{out}} \right)^{1/n_{out}} \qquad \textbf{(2-24)}$$

In this study, the pressure resulting from this equation was considered the estimated leakage pressure, sometimes referred to as the benchmark estimate of leakage pressure.

When measuring flows through registers and grilles, every effort was made to center the flow hood over the opening as exact as possible, and to wait to record the reading until the flow hood reading had stabilized.

Despite the use of this method in this study as the benchmark to which other methods were compared, the benchmark estimate method is not recommended for general use as a duct leakage diagnostic method for a number of reasons. One is that the accuracy of commercially-available equipment is unsatisfactory for applicability to a wide variety of registers. A primary reason that this method was suitable in this project was the specific nature of the registers tested and the use of a flow hood that is no longer available for purchase.

Another reason that this method is not recommended is the need for the additional fan pressurization tests to account for leakage to inside. These additional tests cause the time and setup requirements to be prohibitive except in a research setting.

In general, the care that must be taken to get accurate measurements of all of the components involved in the benchmark estimate is significant, even if conditions such as register types are good. Therefore, it is considered by the authors to not be plausible except in a research setting, where the time and care can be taken to obtain good results.

**OTHER TESTS**

In addition to the leakage tests, three other airflow measurements were made in this project. One is the measurement of air handler flow using a calibrated fan attached to the air handler, as described in the nulling test description. This test was also used in determining the benchmark estimate of duct leakage.

One of the other two tests was a second measurement of air handler flow using a calibrated plate designed to replace the furnace filter. This test was not done in all houses due to filter slot access limitations. The other test performed was a blower door test with all registers and grilles sealed.

This test, which was done at all houses, provides data regarding the airtightness of the houses excluding duct leakage.

### Air Handler Flow Using Calibrated Plate

The second method of measuring air handler flow is very simple. The pressure in the supply plenum is measured relative to the house with the filter still in place and the system running normally. Then, the filter is removed and the calibrated plate inserted in its place, as shown in Fig. 2-15. The calibrated plate has spacers to allow systems with a wide variety of common filter slot sizes to be measured, and also includes weatherstripping on all sides to provide a good seal around the plate. It is desirable to avoid leaks either around the plate or between the filter slot and the air handler fan because only air that passes through the plate is measured.

The pressure drop across the plate with the air handler fan running is then measured. The upstream total pressure and the downstream static pressure are each measured using a pressure manifold. The resulting pressure drop is applied to the calibration equation to get the uncorrected flow reading. This flow is then adjusted for any change in supply plenum pressure relative to the pressure with the filter in place by using the same procedure as is used to correct readings in the nulling and Delta-Q tests, described by eq. **(2-1)**.

This method, though simple, was not used as the main technique for estimating air handler flow. This is because it is more sensitive to the inlet geometry of the ducts than the method using a calibrated fan attached to the air handler.

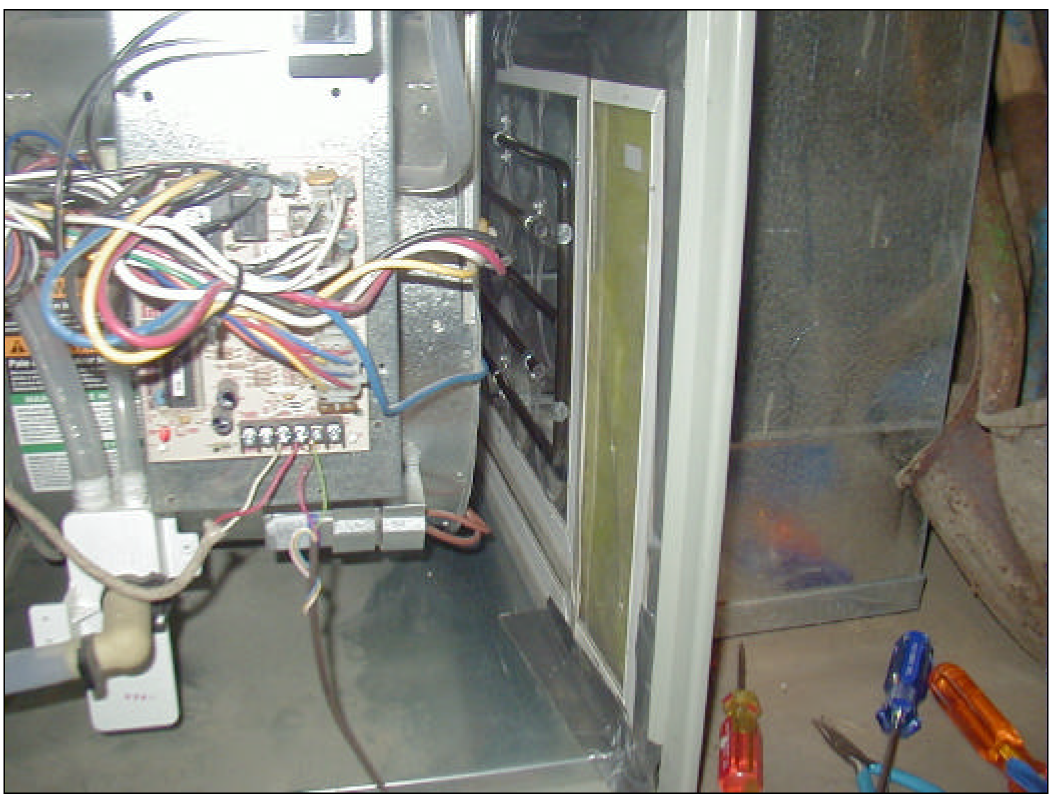


Figure 2-15. Calibrated plate for measuring air handler flow.

### Blower Door Test with Registers Sealed

Other than the actual sealing of the registers and grilles, the blower door test with registers sealed is the same as the standard blower door test. All interior doors are open, and all exterior doors and windows are closed. The blower door is then turned on and adjusted until the house is depressurized to 50 Pa, and then 25 Pa. By measuring at two points, a leakage exponent for the house can be estimated instead of assumed. Figure 2-10 in the Delta-Q discussion section shows an installed blower door.

# 3
# SAMPLE SELECTION

## SELECTION PROCESS

Screening of homes for participation in the study was set up primarily to create a sample of convenience. Other than due to a few critical criteria, such as the ability to complete the testing in a reasonable amount of time and the ability to perform all of the tests, no homes were turned away. A standard test day, including setup and breakdown, was from eight to twelve hours inside the home. The desire to limit the time in the home was as much a consideration of the homeowner as for the crew performing the tests. The additional time required for a few unexpected, small problems was anticipated and accounted for in this estimate. The screening process helped prevent the number of issues from escalating to something that, in sum, extended the time in the home considerably. The selection of homes was also unbiased, in that homes were not screened for particular leakage levels or style of home. Any remaining bias in the sample is unintended and primarily attributable to regional construction practices, such as the widespread use of crawl spaces.

Identification of valid test homes was a multi-part process. First, contacts at Puget Sound Energy and the Seattle Chapter of the Northwest EcoBuilding Guild broadcast our solicitations to employees and members through their mailing lists. Homeowners whose homes fit a brief description were invited to contact Ecotope if interested in participating in the study. This portion of the selection process mainly identified houses which posed insurmountable time constraint problems; homes which were too far away, too large to test in one day, or with conditioning equipment with restrictive access were declined. Additionally, homes were requested which had a considerable percentage of the ducts running outside the conditioned space.

Homeowners with homes fitting this initial description were then given a screening questionnaire (included in Appendix B) to further gauge the suitability of the home for testing. At this stage, it was determined if there were smaller details which could complicate the testing. Homeowners were asked about such things as the accessibility of the registers and grilles, the style of filter (e.g. electronic air cleaner, double ”V”-style filter, etc.), the existence of a “Fan Only” switch, and the accessibility to the buffer spaces containing the ductwork. Finally, upon arrival at each home, the test team made an inspection of the house and the conditioning equipment before proceeding with the test setup.

Homes with the majority of ducts within the conditioned space were undesirable because the test methods are being compared on the basis of measuring leakage to outside the home. However, some exceptions were made to this rule. A few manufactured homes (with no return ductwork and supply ducts running within the space between the floor and an insulated, membrane that restricted airflow) were included in the study to demonstrate the effect this would have on the Delta-Q test method, which requires a return pressure be entered into the equations. Split-level and tri-level homes were also included in the sample. Even though the majority of the ductwork runs inside the conditioned space, there was typically enough outside to make the testing worthwhile.  Also, one home with ducts contained within a conditioned basement was included in the study, despite the known dearth of leakage to outside these homes exhibit, to address the concerns of regions more populated with basements.

A few characteristics tended to automatically eliminate a house from consideration.  Homes with a large fraction of undesirable registers were not tested.  Undesirable registers include those which, by the design of their diffusers, create flow patterns that are difficult to measure accurately with available flow capture hoods.  Examples of registers that produce problematic flow patterns are four-way registers which create a large amount of swirl and those with older, more-decorative, less-diffusing registers that produce a jet of air.  In addition, registers without the clearance necessary to use the flow measurement instruments, such as under-cabinet toe-kicks and those that were under or behind large pieces of furniture, created measurement difficulties.

Usually, in homes with only a few of these situations, these registers were sealed with tape for the entire day.  However, houses with a high percentage of the total number of registers (greater than about 20%) needing to be sealed were screened out due to the large effect this can have on the operating pressure throughout the system.  Although an attempt was made to foresee and avoid these homes, if the registers were found to be problematic only after arriving at a house, testing would typically continue.  Only about 2-3 homes that were tested were likely to have been screened out had the situation been known in advance.  Complications due to inhospitable diffusers are thought to be a source of error in the flow hood measurements in at least one home.

Homes with air handlers installed in the crawl space or attic were also eliminated from consideration.  In addition to being inconvenient and difficult to work with, these were also problematic for the tests that required the return system to be isolated from the air handler and supply ducts.  For these tests a surrogate return is attached, which normally is set up to draw air from inside the house but in this case would likely have to draw outside air.  Although compensations can be made for this, it was desired to avoid this complication.

Dual filters arranged in a “V”- or “A”- orientation, as well as the position of the flue in some furnaces, present problems with installing a barrier at the air handler to isolate the return ducts. This barrier is required by the nulling test to estimate the supply and return leakage separately, and is also necessary for fan pressurization tests.  The problem with the filters arises due to the lack of a single filter slot that is typically used for supporting the barrier.  Additionally, with many downflow gas furnaces the flues must be removed to insert the split.

Initially, conditioning equipment thought to have these difficulties was avoided.  Often homeowners are not fully aware of what they have, however, and many were encountered once on-site.  Eventually, after experience with the filter slots showed that there was often a feature that could be used for support, and the disassembly became somewhat less time-consuming, it was decided that these homes should not be immediately screened out.  The willingness to accommodate certain features also grew as the initial recruitment resources were being exhausted and the possibility of wading through the multitude of responses resulting from other recruitment strategies, such as a large-scale newspaper advertisement, became real.

Occasionally homeowners contacting Ecotope had homes that did not completely fit the requirements, but were still able to be tested. For instance, several homes with basements were able to be tested by converting the basement into a simulated crawl space. The ability to do this was established in the screening process by exploring the possibilities of sealing doors between the first floor and basement and opening the basement to outdoors. If the necessary doors and windows were present, the house was able to be tested. As mentioned above, one house was included in the sample which had a basement that was not converted in this manner and was tested as a true basement.

## SAMPLE CHARACTERISTICS

The screening process produced a sample of 51 different houses with the characteristics summarized in the following tables. All homes had central return systems except for one zoned return system. In addition, all homes had supply ducts in unconditioned spaces below the house (e.g. crawl space or basement) except for one home with all supply ducts in the attic and the one home with the fully conditioned basement.

Table 3-1. House Characteristics.

| | Stories | | Foundation Type | | | Construction Type | |
|---|---|---|---|---|---|---|---|
| | Single | Multi | Crawl | Basement | Slab | Site-Built | Manufactured |
| Number of Houses | 28 | 23 | 49 | 1 | 1 | 48 | 3 |

Table 3-2. Air Handler Characteristics.

| | Filter Style[1] | | Orientation | | Equipment Type | | | Equipment Location | |
|---|---|---|---|---|---|---|---|---|---|
| | EAC | "V" | downflow | upflow | Gas Furnace | Electric Furnace | Heat Pump | Inside Cond. Space | Outside Cond. Space |
| Number of Houses | 11 | 14 | 39 | 12 | 45 | 5 | 1 | 19 | 32 |

1 All other filters were of a traditional single piece, made from any of a variety of materials.

Table 3-3. Characteristics of Site-Built Homes.

| | Floor Area ($ft^2$) | Volume ($ft^3$) | Supply Registers | | Return Grilles | | % Supply Duct Location | | % Return Duct Location | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Total | Sealed[2] | Total | Sealed[2] | Inside | Outside | Inside | Outside |
| Mean | 1647 | 13753 | 10.1 | 0.8 | 1.97 | 0.04 | 27.2 | 72.8 | 34.5 | 64.5 |
| Median | 1668 | 13592 | 10 | 1 | 2 | 0 | 20 | 80 | 7.5 | 92.5 |
| Min | 707 | 5036 | 3 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| Max | 2683 | 27549 | 16 | 3 | 7 | 1 | 100 | 100 | 100 | 100 |

2 Number of registers taped off for testing.

Table 3-4. Characteristics of Manufactured Homes.

| Site Number | Floor Area ($ft^2$) | Volume ($ft^3$) | Supply Registers | | % Supply Duct Location[3] | |
|---|---|---|---|---|---|---|
| | | | Total | Sealed | Inside | Outside |
| N-41 | 1458 | 12241 | 8 | 3 | 0 | 100 |
| N-45 | 1443 | 12023 | 7 | 3 | 0 | 100 |
| N-49 | 1458 | 12241 | 11 | 0 | 0 | 100 |

3 All manufactured homes tested were double-wide, with two main trunks between the floor and belly blanket and a crossover duct outside the belly blanket in the crawl space.

# 4
# METHODOLOGY

The following section includes discussions on the field testing process and the custom software used throughout the study. Specific details on each leakage test method can be found in Chapter 2, Test Descriptions.

## THE TESTS PERFORMED

The primary tests performed at each house were the benchmark estimate, the Delta-Q test, the nulling test, and the fan pressurization tests. Air handler flow was determined with two methods approved by ASHRAE Standard 152P (ASHRAE 2003), the results of which are discussed in Chapter 6. In all homes the air handler flow was measured with a pressure matching technique using a Duct Blaster®. Flow plates were used to provide an additional measure when a suitable filter slot was available to permit installation.

To characterize the house envelope leakage, a blower door test with all of the registers and grilles sealed was performed. Duct leakage, especially to inside, can cause these estimates to be higher than they should be for measuring the leakage through the building materials only, but there is no way to easily remove this bias. It is this connection that made the unmodified blower door subtraction test systematically biased low as a measurement technique for duct leakage. Sealing the registers removes much of the connection between the house and the ducts, thereby improving the result as much as possible.

Where possible, a map was made of the supply ducts, including duct lengths, sizes, and insulation values, in order to calculate conduction losses. Characteristics of the home, such as floor area and volume, and nameplate information on the conditioning equipment were also recorded. In homes with a gas furnace, a combustion analysis was also performed to provide sample characteristics as well as feedback for the homeowner.

## SETUP

The data acquisition system used in this study included a laptop connected to two Energy Conservatory dataloggers with sampling frequencies of just over 1 sample per second (higher frequency when fewer channels were used). Each datalogger had eight analog channels and either two or eight pressure channels, and the ability to remotely control one fan apiece.

Although some data was collected manually, a large percentage was acquired through the pressure and analog channels on the dataloggers. Using the two dataloggers, a maximum of ten pressures could be measured at each house. The specific location of the pressure taps varied from house to house, but in general pressures between the house and outside, attic, and crawl space were measured, and return and supply plenums were measured with respect to the house. Fan pressures were measured for use in the calibration equations to calculate flow through the fan.

Pressures were measured from the house directly to outside in multiple locations to allow for investigation of the effect of wind. On windier days, placement of taps on the leeward and windward sides of house helped to gauge the pressure differentials being caused by the wind and avoid sampling when these were largest. Occasionally, pressure taps were placed in low and high penetrations in a wall in order to observe the stack effect.

The analog ports on the dataloggers were used to measure temperatures and wind speed. Temperatures were typically measured inside and outside the house and at the inlet to each fan. A three-cup anemometer was placed on the lot in a location selected to capture the maximum wind speeds.

Certain attention to detail and minor alterations to the house during the setup process facilitated collection of the highest quality data. Ventilation fans were sealed to both reduce the leakage of the house, thereby enhancing the signal, and to prevent dampers from opening and closing mid-test. Along the same lines, openings to fireplaces were also sealed. Having the ventilation fans and fireplaces sealed during testing actually means that the envelope leakage tests will not include these leaks, but if the dampers work properly and close tightly this effect should be small. In addition, these holes through the envelope are intentional, and it is often the intent of an envelope leakage test to evaluate the unintentional leakiness of the building.

All windows and exterior doors were closed throughout testing, and all interior doors were required to remain open. Care was taken to keep pressure hoses out of the sun and to keep people from inadvertently crushing them.

The homes tested in this study did not have active attic fans, but rather were passively ventilated. Measurements indicated that most of the attics were well connected to outdoors. If there had been attic fans, it would have been advisable to disable them for the duration of testing to prevent them from coming on mid-test and changing the pressures in the attic.

## TEST PROCEDURE

The majority of the leakage tests require measurements of the pressure across the envelope. Therefore, a single location at each house was necessary to serve as this “reference” pressure. Prior to recording any data, the suitability of the pressure tap locations for use as the reference pressure was checked by running a variety of pressure tests. The attic was typically used as the reference to outside in order to dampen wind noise. However, if the attic was not sufficiently vented to reflect the outdoor pressure, or showed changes in pressure with pressurization of the house or due to duct leakage in the attic, alternatives were available. The crawl space was the next option, but if it too was not suitable, a shed or other unconditioned shelter on the property was sought. On the rare occasion when all of these possibilities were exhausted, an outdoor location sheltered from direct wind was used. In all cases, the attic and crawl space pressures continued to be measured even when not chosen as the reference to outside.

Pressures were also used later in the day to check the integrity of the barrier between the return ducts and the rest of the duct system during the supply-only portion of the nulling test and the fan pressurization tests. If the barrier is sufficiently airtight, the return plenum should remain at or very near zero, relative to the house, when the supply ducts are pressurized.

The first test that was done was with the air handler running normally, with all exterior doors and windows closed, and all interior doors open to get normal operating plenum pressures and the house pressure offset due to turning on the air handler. The standard deviation on this data point was also used to evaluate the sample period. Typically, 40 seconds was adequate in the nulling test (the test most affected by wind) to keep the standard deviations of the pressures at or below ±0.2 Pa. On windy days, the number of samples was increased, often doubled, to mitigate the pressure fluctuations across the house envelope.

The test sequence was optimized to make use of common setup requirements as much as possible. For instance, the air handler flow estimate that is based on pressure matching was done concurrently with the supply-only nulling test. The following is an outline of all the tests, in the order in which they were performed.

1. Unbalanced nulling test
2. Supply–only nulling test (including air handler flow estimate)
3. Fan pressurization tests
    a) Supply leakage to outside
    b) Total supply leakage
    c) Return leakage to outside
    d) Total return leakage
4. Sealed blower door test
5. Delta-Q test
6. Flow plate air handler flow estimate (when possible)
7. Flow hood measurement of register and grille flows for use in benchmark estimate
8. Manual measurements:
    a) House area and volume
    b) Duct map (when possible)
    c) Combustion analysis

**SOFTWARE**

Custom data acquisition software was written specifically for this project by The Energy Conservatory. Following the initial setup, the software provided considerable time savings by automating many of the tests to the point of only requiring user determination of when to begin each sample. Custom calibrations for each fan were programmed into the software, as well as the ability to perform immediate density corrections based on temperature measurements. The software also provided the user with the ability to select a sampling period, which allowed for longer periods to be chosen for windier conditions.

Portions of the software are shown in Figs. 4-1 through 4-6 below. The page used during the set-up process to select the pressure and analog channels to be used is seen in Fig. 4-1. Pressure channels one and two were always in use on both dataloggers, and use of the remaining channels was determined at each individual house. If a channel was not used, it could be switched off on this page, reducing the amount of data recorded and increasing the sampling rate. The pressure

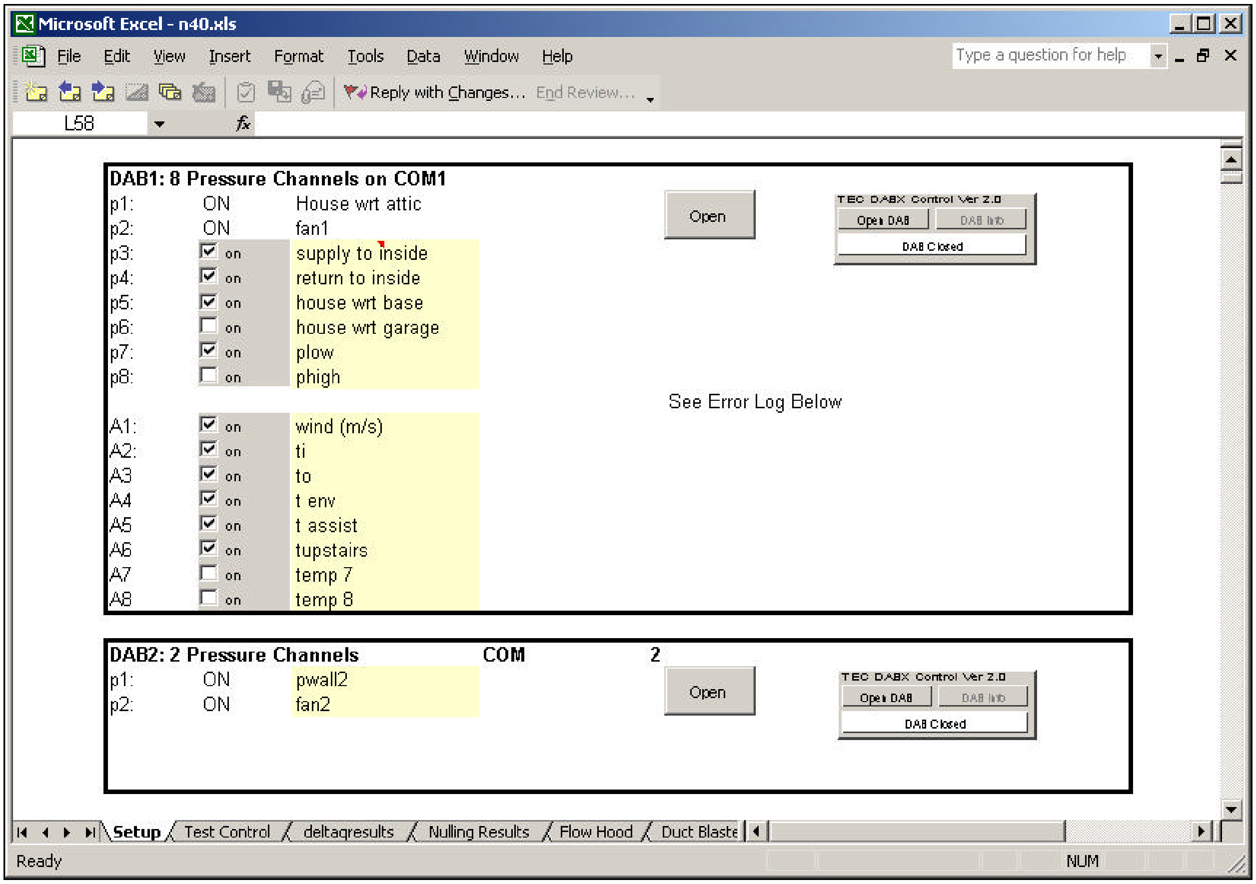



Figure 4-1. "Setup" page in test software.

channels are relabeled at each home to reflect the particular location of each pressure tap, but the software looked to certain channels for specific types of pressures. For instance, pressure channels three and four on the eight channel datalogger were always the supply and return plenums respectively.

Figure 4-2 shows the test control page. This is the main graphical user interface used throughout the testing. From here the user can control the fans, select which test to run, set the sample period, and begin recording each sampling. Pull-down menus allow the user to specify which fans are being used and which ring is in place; the software then automatically applies the appropriate calibration to the raw data. Also found on this page are the toggle switches indicating whether the fans in use are positioned to pressurize or depressurize, and whether the air-handler fan is on or off. Sliders near the top of the page are moved with the mouse to control the speed of the selected fan when setting this manually.

One of the automation features built into the software also allows the fan speed to be continually adjusted by the computer to maintain a user-specified pressure being measured on a different channel. This feature is utilized in the fan pressurization tests, for instance, when the house pressure and/or the plenum pressure is maintained at 25 and 50 Pa. The automation is taken one step further with the Delta-Q test where the software automatically moves on to the next required

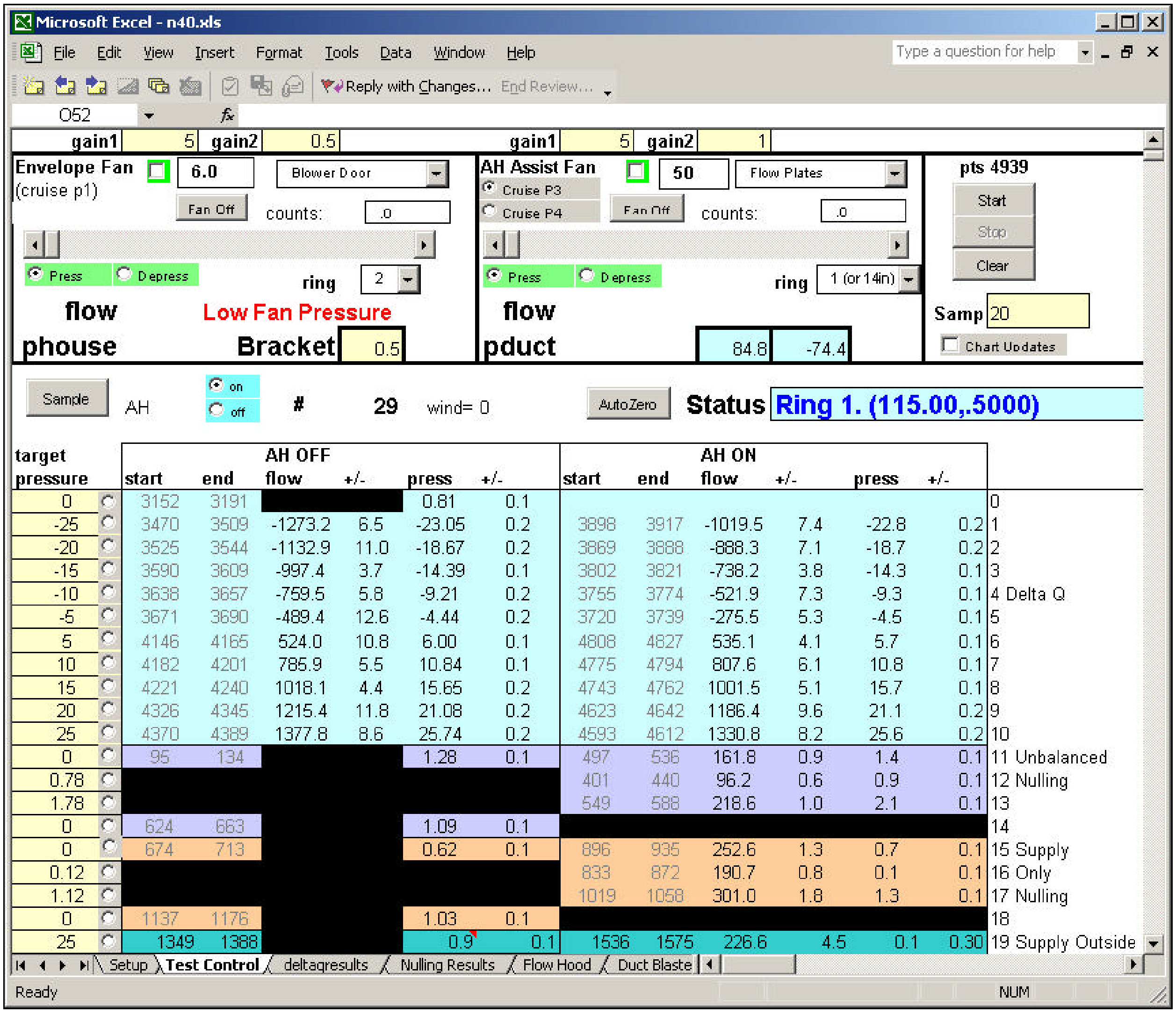


Figure 4-2.  “Test Control” page in test software.

pressure station.  Sampling begins only after the user determines that the pressures have stabilized and clicks the ‘Sample’ button.

Figure 4-2 also displays some of the features built into the software that provided instant feedback on the success of each test.  Access to per-sample standard deviations helped to generate immediate awareness of problems such as gusty winds or a person stepping on a pressure hose.

Instant access to the test results at the completion of each test also helped to determine if the test had been performed satisfactorily.  If it had not, the immediate feedback meant the test could be repeated with minimal repeat set-up.  For instance, as seen in Figs. 4-3 and 4-4, automatically generated plots of the lines being fit to the data points taken in Delta-Q and each part of the nulling test allowed qualitative evaluation of the goodness of fit.  In addition, the error estimate from the regression used to calculate the leakage in the Delta-Q test is also shown in Fig. 4-3.

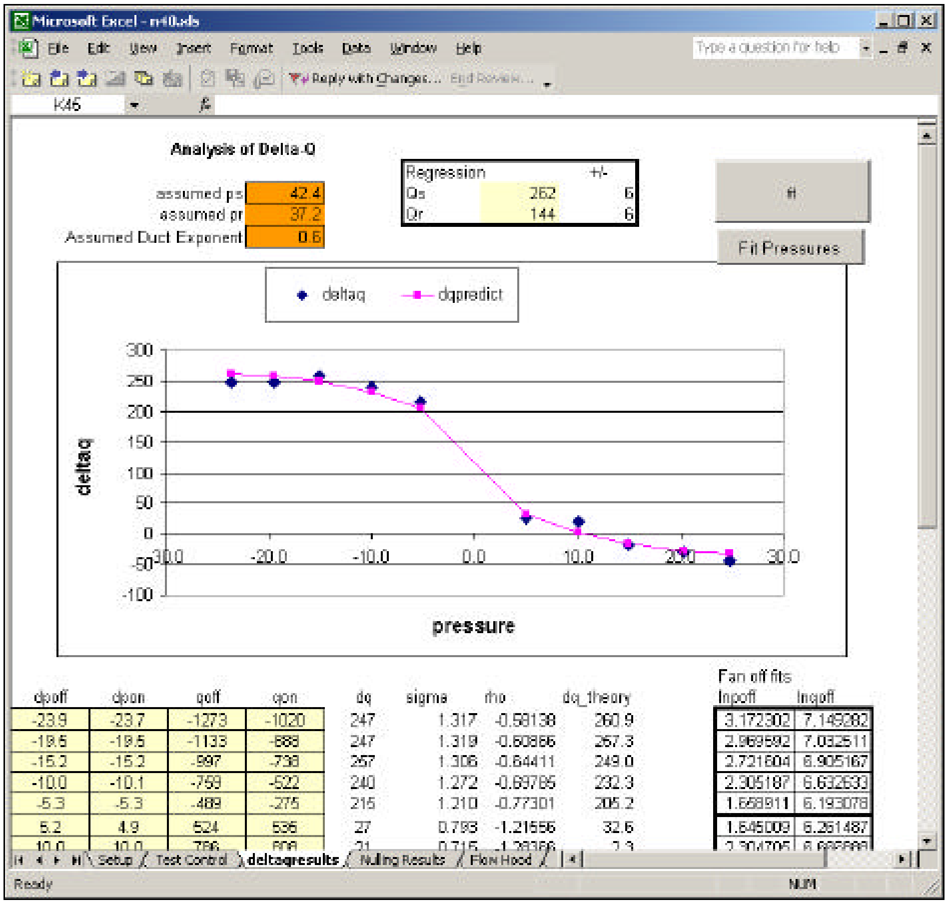


Figure 4-3. “Delta-Q Results” page in test software.

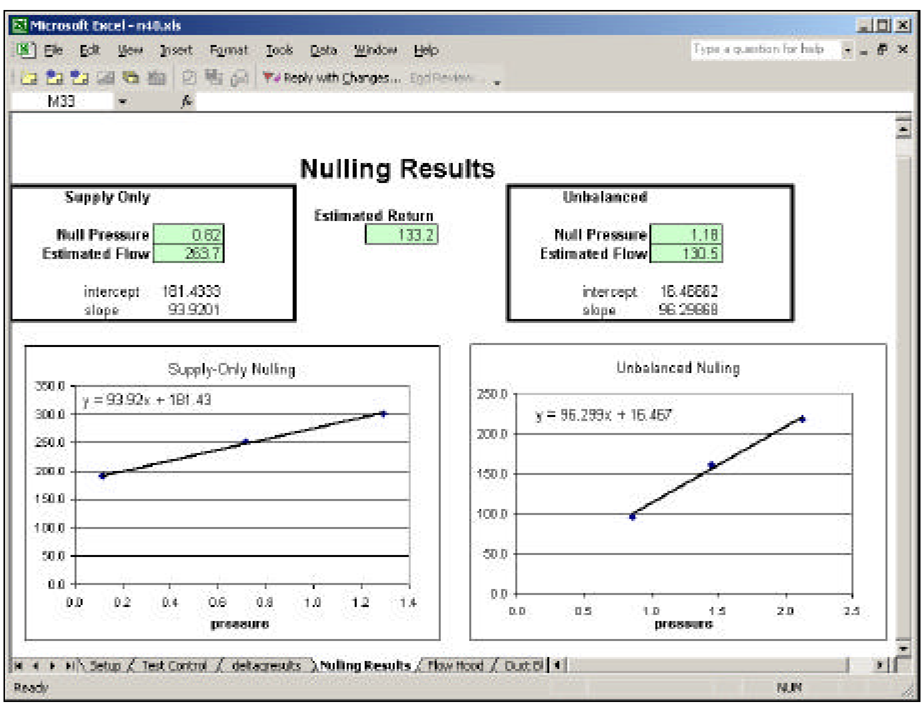
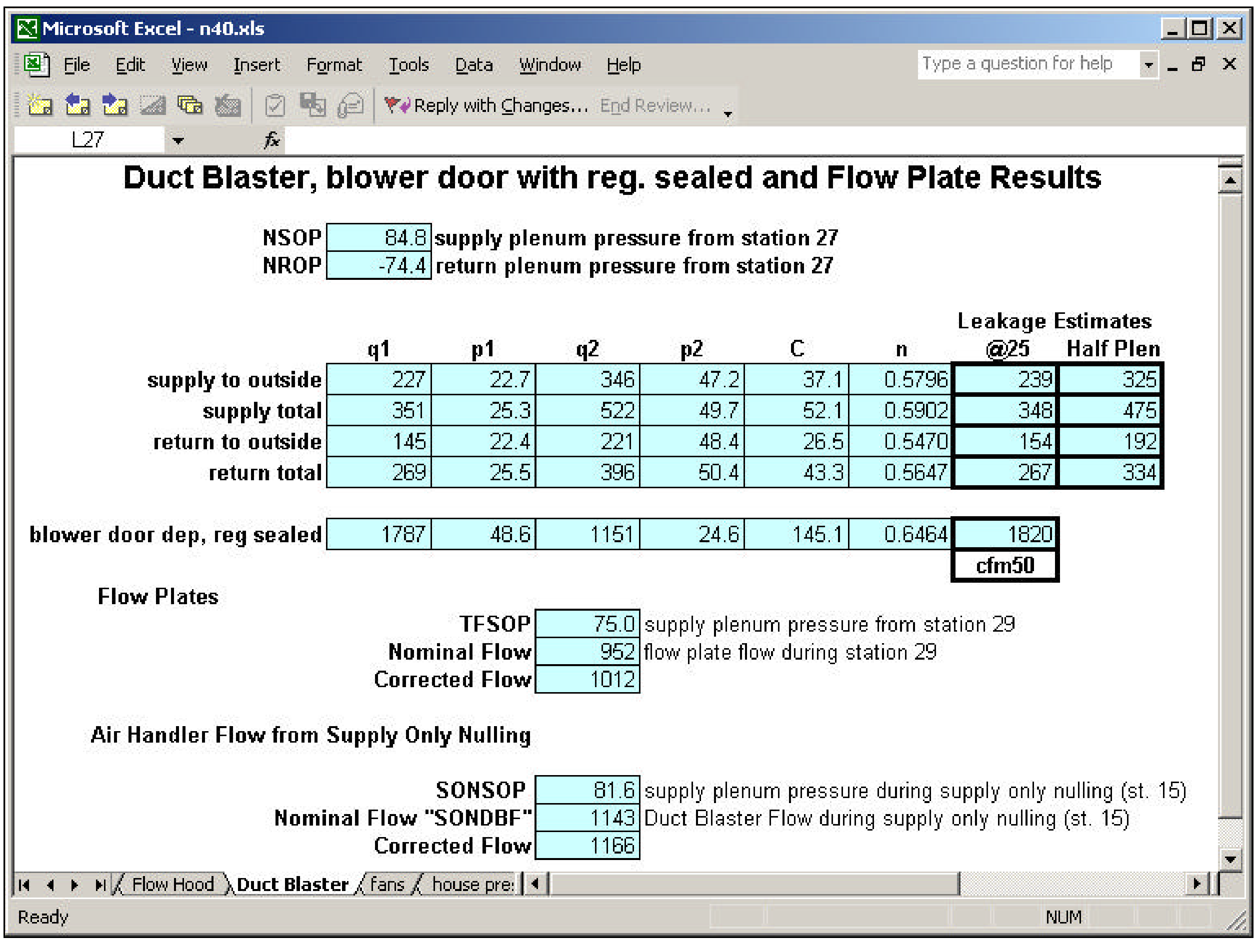


Figure 4-4. “Nulling Results” page in test software.

Examination of the leakage exponents produced by the fan pressurization tests, shown in Fig. 4-5, also easily elucidated bad data.

Figure 4-5 shows the results of the fan pressurization tests, including the estimated leak flow coefficients and exponents. The leakage estimate is displayed in terms of both a duct pressure of 25 Pa and at half of the plenum pressure. The plenum pressures, which are measured under normal operating conditions early in the day, are transferred automatically from the "Test Control" page to the cells at the top of this page for use in this form of the fan pressurization leakage estimates.

Also displayed on this page are the air handler flow estimate results from the flow plates and using the Duct Blaster®. This also shows the corrections used by each method. The flow plates adjust the raw flow estimate to reflect any change in plenum pressure caused by replacing the filter with the flow plates. When using the Duct Blaster® to measure the air handler flow, an attempt is made to maintain the supply plenum pressure at the previously measured operating condition pressure. The adjustment seen here adjusts for any difference that may occur between




**Duct Blaster, blower door with reg. sealed and Flow Plate Results**

| | | |
|---|---|---|
| NSOP | 84.8 | supply plenum pressure from station 27 |
| NROP | -74.4 | return plenum pressure from station 27 |

| | q1 | p1 | q2 | p2 | C | n | Leakage Estimates @25 | Half Plen |
|---|---|---|---|---|---|---|---|---|
| supply to outside | 227 | 22.7 | 346 | 47.2 | 37.1 | 0.5796 | 239 | 325 |
| supply total | 351 | 25.3 | 522 | 49.7 | 52.1 | 0.5902 | 348 | 475 |
| return to outside | 145 | 22.4 | 221 | 48.4 | 26.5 | 0.5470 | 154 | 192 |
| return total | 269 | 25.5 | 396 | 50.4 | 43.3 | 0.5647 | 267 | 334 |
| blower door dep, reg sealed | 1787 | 48.6 | 1151 | 24.6 | 145.1 | 0.6464 | 1820 cfm50 | |

Flow Plates

| | | |
|---|---|---|
| TFSOP | 75.0 | supply plenum pressure from station 29 |
| Nominal Flow | 952 | flow plate flow during station 29 |
| Corrected Flow | 1012 | |

Air Handler Flow from Supply Only Nulling

| | | |
|---|---|---|
| SONSOP | 81.6 | supply plenum pressure during supply only nulling (st. 15) |
| Nominal Flow "SONDBF" | 1143 | Duct Blaster Flow during supply only nulling (st. 15) |
| Corrected Flow | 1166 | |

Figure 4-5. "Duct Blaster" page in test software, showing results of the fan pressurization test and the air handler flow as measured by the flow plates and using the Duct Blaster®.

the actual average pressure maintained across the sample period, and the normal operating supply plenum pressure measured previously.

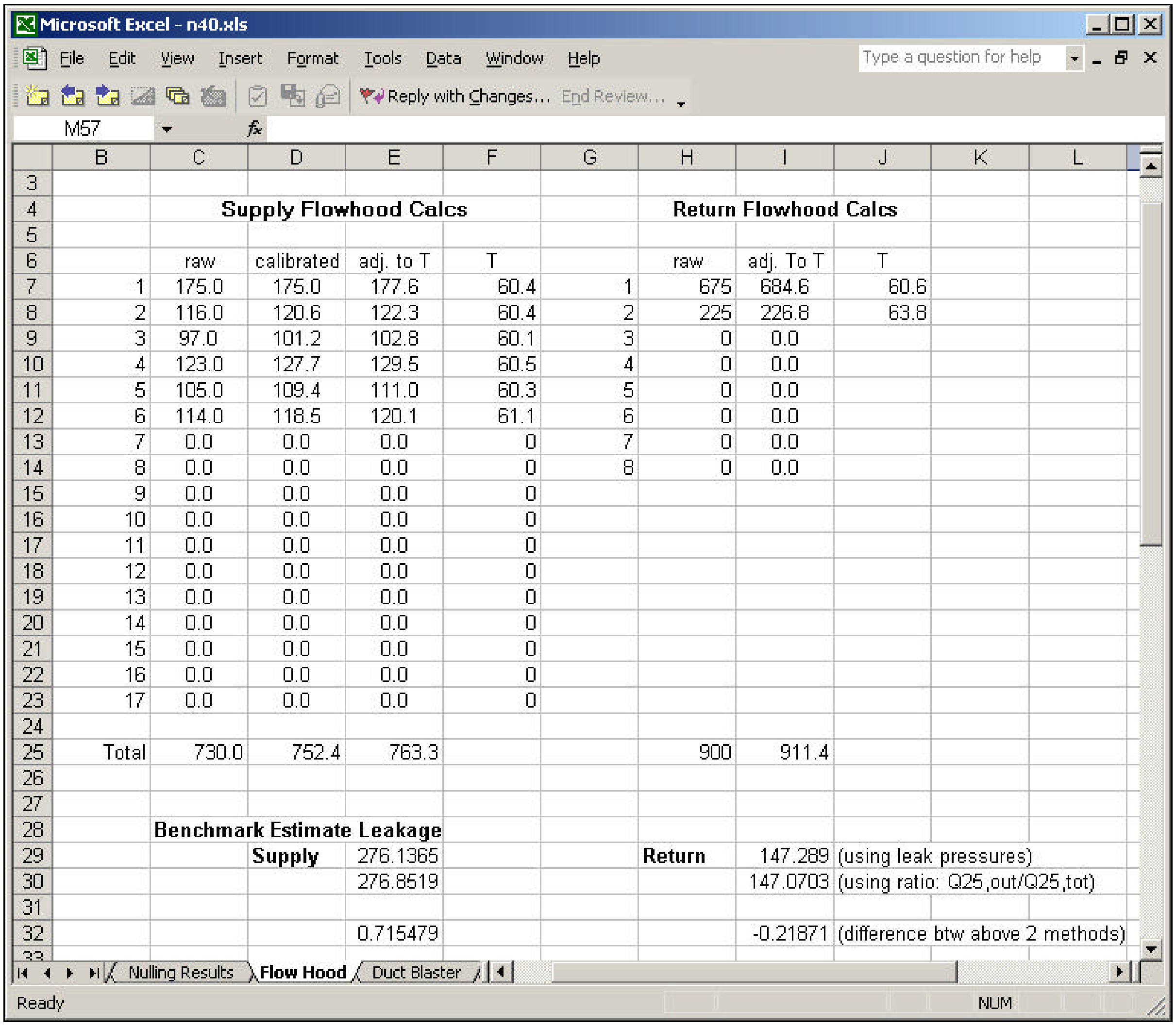
The manual measurements of the register flows, and the temperature of the air flowing through the registers, are recorded on the “Flow Hoods” page seen in Fig. 4-6. On the supply side, the individual raw register flows are automatically run through the calibration equation required by the Fast-1 flow hood (see appendix D) and adjusted to a temperature of 68°F. The return flow hood, having been factory calibrated at the start of the study, is just adjusted here for temperature.

As described in Chapter 2, when performing the benchmark estimate test, subtracting the sum of the register flows from the air handler flow provides an estimate of total leakage to both inside and outside. There are two ways of adjusting the estimate to reflect only leakage to outside, thus giving the result which is most relevant to energy use issues, and making it comparable to the other methods. The first result under the “Benchmark Estimate Leakage” heading in Fig. 4-6 uses the estimated leak pressure (discussed in Chapter 2), and the coefficients and exponents estimated by the fan pressurization test for leakage to outside to adjust the raw leakage flow estimated in this test.

This method of adjustment can lead to errors because the estimate of leak pressure relies on good results from both parts of the fan pressurization test. It is possible for the raw benchmark estimate flow to be well outside the measurement range of the fan pressurization test and thus require a large extrapolation. Combining this with even slightly erroneous estimates of the coefficients and exponents can lead to poor estimates of the leak pressure in some houses. This method was not used in this study due to these issues, but was included for comparison.

The second way of adjusting the raw benchmark estimate is also described in Chapter 2 and was the method used in this study. In this method, the benchmark estimate of total leakage is multiplied by the ratio of leakage to outside to total leakage at 25 Pa as determined by fan pressurization tests.

The difference between these methods was calculated in the software and is shown in the last line of Fig. 4-6. The difference was typically small, but did at times show adverse effects from large extrapolations in the first method.



| | B | C | D | E | F | G | H | I | J | K | L |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3 | | | | | | | | | | | |
| 4 | | Supply Flowhood Calcs | | | | | Return Flowhood Calcs | | | | |
| 5 | | | | | | | | | | | |
| 6 | | raw | calibrated | adj. to T | T | | raw | adj. To T | T | | |
| 7 | 1 | 175.0 | 175.0 | 177.6 | 60.4 | 1 | 675 | 684.6 | 60.6 | | |
| 8 | 2 | 116.0 | 120.6 | 122.3 | 60.4 | 2 | 225 | 226.8 | 63.8 | | |
| 9 | 3 | 97.0 | 101.2 | 102.8 | 60.1 | 3 | 0 | 0.0 | | | |
| 10 | 4 | 123.0 | 127.7 | 129.5 | 60.5 | 4 | 0 | 0.0 | | | |
| 11 | 5 | 105.0 | 109.4 | 111.0 | 60.3 | 5 | 0 | 0.0 | | | |
| 12 | 6 | 114.0 | 118.5 | 120.1 | 61.1 | 6 | 0 | 0.0 | | | |
| 13 | 7 | 0.0 | 0.0 | 0.0 | 0 | 7 | 0 | 0.0 | | | |
| 14 | 8 | 0.0 | 0.0 | 0.0 | 0 | 8 | 0 | 0.0 | | | |
| 15 | 9 | 0.0 | 0.0 | 0.0 | 0 | | | | | | |
| 16 | 10 | 0.0 | 0.0 | 0.0 | 0 | | | | | | |
| 17 | 11 | 0.0 | 0.0 | 0.0 | 0 | | | | | | |
| 18 | 12 | 0.0 | 0.0 | 0.0 | 0 | | | | | | |
| 19 | 13 | 0.0 | 0.0 | 0.0 | 0 | | | | | | |
| 20 | 14 | 0.0 | 0.0 | 0.0 | 0 | | | | | | |
| 21 | 15 | 0.0 | 0.0 | 0.0 | 0 | | | | | | |
| 22 | 16 | 0.0 | 0.0 | 0.0 | 0 | | | | | | |
| 23 | 17 | 0.0 | 0.0 | 0.0 | 0 | | | | | | |
| 24 | | | | | | | | | | | |
| 25 | Total | 730.0 | 752.4 | 763.3 | | | 900 | 911.4 | | | |
| 26 | | | | | | | | | | | |
| 27 | | | | | | | | | | | |
| 28 | | Benchmark Estimate Leakage | | | | | | | | | |
| 29 | | | Supply | 276.1365 | | | Return | 147.289 | (using leak pressures) | | |
| 30 | | | | 276.8519 | | | | 147.0703 | (using ratio: Q25,out/Q25,tot) | | |
| 31 | | | | | | | | | | | |
| 32 | | | | 0.715479 | | | | -0.21871 | (difference btw above 2 methods) | | |

Figure 4-6. "Flow Hood" page in test software, showing results of the benchmark estimate.

# 5
# BENCHMARK ESTIMATE VALIDATION

In order to assess the accuracy of any of the leakage test methods, it is necessary to have an independent benchmark leakage estimate to which the results can be compared. For this study, the benchmark estimate is based on the difference between air handler flow and the sum of register flows as measured by a flow capture hood, with adjustments to the result made to account for leakage to inside based on static fan pressurization tests. This test is described in detail in the "Leakage Test Descriptions" section.

This benchmark estimate procedure has been used previously with apparent success. In a study validating the performance of ASHRAE Standard 152P (Francisco and Palmiter 1999; 2000), using the leakage results of this method in the Standard 152P model gave extremely good agreement with measured duct distribution efficiencies. In an earlier study to examine the accuracy of the nulling and Delta-Q tests in nine homes (Francisco et al. 2002a; 2002b; 2003) the method provided results that were, on average, in good agreement with the nulling test, despite the fact that the two tests share nothing in their methodologies. Comparisons to the Delta-Q and fan pressurization tests showed biases consistent with what was expected. Modeling efforts have shown that the Delta-Q test tends to be biased high, and the fan pressurization test has long been considered to be biased high.

## RATIONALE FOR BENCHMARK ESTIMATE VALIDATION

The benchmark estimate method has raised concern, however, for two reasons. One is the problem of subtracting two large numbers (air handler flow and sum of register flows) to get a smaller number (duct leakage). A small percentage discrepancy in one of the larger numbers can manifest itself as a large error in the smaller number. However, as long as the measurement devices have been calibrated and the errors are scatter rather than bias, over a large enough sample there should be little bias of the average results.

The other primary concern with this method is the reliance on flow capture hoods, especially on the supply side. Flow capture hoods were initially designed for commercial systems, with larger airflows than typical for residential supply registers. The most common measurement technology in these hoods is a pressure drop technology, usually with at least four pressure drop stations within the hood. The accuracy of the flow measurements depends greatly on the degree to which the pressure locations are representative of the entire flow. Residential supply registers tend to be much smaller than the hoods, raising concern that the flow may not expand sufficiently by the time the air passes by the sensing elements, especially if the register creates a jet of air. Attempts to resize pressure drop flow hoods for residential-scale applications have resulted in a number of hoods with very narrow throats, raising concern that the hoods themselves would be restrictive enough to change the airflow of the registers they are measuring, especially at higher flows. Registers that cause swirl also can lead to large errors in all flow hoods.

It has been long perceived by researchers in the residential sector that pressure drop flow hoods are highly unreliable for accurately measuring flow. This has been verified in a recent laboratory study (Walker et al. 2001b; Wray et al. 2002). That study focused on registers that generated outlet conditions that were essentially “worst-case” flow patterns (swirls and jets), and included considerations of poor placement of the flow hood over the register.

The flow hood used in this study to measure supply register flows does not use a pressure drop to calculate the flow. Instead, it uses a propeller that spans nearly the entire exit area of the hood, which is sufficiently large that it rarely adds enough resistance to cause a major change of the flow through the register. This type of flow hood was also evaluated in the study by Walker et al., and performed reasonably well even without having been calibrated by the investigating team. It was sensitive to swirl to a lesser degree than many of the pressure drop hoods. However, in those cases most representative of field conditions, and with care taken to place the hood as centered over the register as possible, the results were quite good. Much of the errors for these cases could be corrected by calibrating the flow hood. It is notable that, when taken by Walker et al. into the field in one home with standard register types, this type of flow hood was within 1% of the overall flow. Discrepancies were sometimes larger on individual registers, but the results suggest that the errors are more scatter than bias, and with enough registers the error in the overall flow will often be small.

In the current study, the flow hood used for measuring supply flows was calibrated both before and after the study on a register similar to the ones most often found in these homes, which should improve the results. In addition, the type of supply register most often found in these homes is a typical floor register, which provides a more favorable flow pattern for the flow hood. When performing the tests, care was taken to center the flow hood over the register as well as possible. Inaccessible registers were sealed off at the beginning of all testing and were left sealed throughout all tests.

Concern about the benchmark estimate was significantly less on the return side because return flows tend to be more uniform, less turbulent, and easier to measure by conventional hoods. In addition, residential return flows are often of the same magnitude as the commercial flows for which flow hoods were originally designed. However, validation was done for the return side as well to confirm the accuracy of these assumptions. Both because of the magnitude of the return flows and the general assumption that there would not be much problem measuring flows on the return side with conventional hoods, a standard pressure drop hood was used to measure the return grille flows. This hood was acquired at the beginning of the project and was calibrated by the manufacturer prior to shipping and following field testing. It was also calibrated in-house following the fieldwork.

## BENCHMARK ESTIMATE VALIDATION METHODOLOGY

The extent of the concern about the benchmark estimate resulted in a modification to the original scope of the project, to include a subset of homes on which additional tests were performed to validate the benchmark estimate technique. The approach was to locate homes with very low leakage, and then to introduce a known leak that could be directly measured. The flow through the added leak could then be compared to the change in leakage estimated by the benchmark estimate, as well as by the other measurement methods.

Low initial leakage was desired, because introducing a large leak has the potential to change the pressure distribution throughout the duct system, potentially changing the leakage at other leakage sites. Therefore, minimizing the initial leakage reduces the chances for a significant bias in the comparisons due to changing pressures within the ducts.

Added leaks were usually created by disconnecting a duct. On the return side, the leaks were sometimes added by cutting a large hole in a duct or junction box. Measurement of the flow through the added leak was done using a calibrated flow station at the end of the disconnected duct; examples are shown in Figure 5-1. Supply disconnects were done at the end of branch runs and before the elbows, such that the flow station would be placed after many diameters of upstream duct, often 20 or more. The flow station was calibrated in this configuration prior to use in the field. On the return side, the flow station was placed at the end of a long straight section of duct prior to the added leak, again providing many upstream diameters of duct.

Benchmark estimate validation testing was done on five homes. Due to the desire to compare all methods to the known leak, a full day of testing was required for each leakage configuration. At the first house at which the additional testing was done, advance screening showed it to have tight ducts; as a result, testing took two days, one with an added supply leak and the other with an added return leak. The other four homes that received additional testing were all located by the initial, as-found testing showing that the duct leakage was low. These homes were all retested as soon as possible after the initial visit, with an additional day for each of the two added leaks. For the home with no initial, as-found visit, the baseline leakage for each of the supply and return sides was taken from the day when no leak was added on that side, e.g. the baseline supply leakage was measured on the day with the added return leak.

Figure 5-1. Examples of an added supply leak (left) and added return leak (right), measured with a calibrated flow station.

## BENCHMARK ESTIMATE VALIDATION RESULTS

The discussion that follows refers to house identification numbers, which are the identification numbers from the full project. The identification numbers are followed by an “A”, “S”, or “R”, corresponding to as-found duct leakage, added supply leak, and added return leak, respectively. Site N04 did not have a separate as-found test, so there is no N04A.

It should also be noted that there were cases where the air handler flow changed when a leak was added. This is especially the case if a hole was added to the return side, since this makes it much easier for the air handler fan to draw air. In order to simplify the analysis, all of the air handler flow and leakage estimates were adjusted to the air handler flow measured in the as-found case, except for site N04, which was adjusted to the added supply leak case. Leakage estimates were adjusted by maintaining the same percentage leakage.

### Supply Leakage

Table 5-1 compares the flow station measurement of the added supply leak to the measurements from the benchmark estimate, the nulling test, and the Delta-Q test for the supply side. The measurements from all of the methods are the estimated amount of leakage above the as-found leakage, so they are directly comparable to the flow station leakage.

This table shows that the benchmark estimate worked extremely well, indeed better than expected. The maximum difference in terms of actual flow was less than 7 cfm, at N04S, and the average difference was about 3 cfm. Taking the mean of the absolute values of the differences gives an average discrepancy of about 4 cfm. When expressed as a percentage of the flow station leakage, the maximum discrepancy was less than 6%, at N12S, with an average difference of about 2% of flow station leakage. All cases were within 1% of the air handler flow, with a mean absolute difference of about 0.5% of air handler flow.

The nulling test performed well on the supply side except for at Site N04S. The reason for this large discrepancy is unclear, although there was a significant amount of wind on the day during which the as-found supply leakage was measured. Including Site N04S, the nulling test has about four times the error of the benchmark estimate, although the mean absolute discrepancy is still only about 18 cfm and about 2% of the air handler flow. With N04S removed, the nulling test has a bias similar to that of the benchmark estimate (means are about the same), with scatter about twice as big (absolute means about double).

The Delta-Q test errors were usually larger, except for at Site N04S. Unlike the nulling test, the errors are also broadly distributed, i.e. there is no grouping of discrepancies with one outlier. The average discrepancy based on the Delta-Q test is about 32 cfm, about 30% higher than the flow station estimate. The mean and mean absolute differences are identical because the Delta-Q test results are always higher in these houses than the flow station result. The average errors represent about 4% of the air handler flow.

These results suggest very strongly that the basic procedure of the benchmark estimate of taking the difference between the air handler flow and the sum of the supply register flows can work extremely well, when carefully using this type of flow hood on the types of registers commonly seen in the houses in the Puget Sound region. They also suggest that the nulling test is usually another good method, though subject to occasional large errors. The errors in the Delta-Q test are smaller than the average error of 55% of leakage reported in a previous study (Francisco et al. 2002a; 2002b; 2003), but still show a notable bias.

Table 5-1. Supply-Side Benchmark Estimate Validation Results.

| | **N04S** | **N12S** | **N17S** | **N33S** | **N36S** | **Mean** | **Mean Abs.** |
|---|---|---|---|---|---|---|---|
| | | | | | | | |
| Air Handler Flow (cfm) | 949 | 697 | 1114 | 733 | 1122 | 923 | 923 |
| | | | | | | | |
| Leakage (cfm) | | | | | | | |
| Flow Station | 151.3 | 110.5 | 108.4 | 101.4 | 127.4 | 119.8 | 119.8 |
| Benchmark Estimate | 158.1 | 116.8 | 112.3 | 97.9 | 127.6 | 122.6 | 122.6 |
| Nulling Test | 206.5 | 119.1 | 112.1 | 90.4 | 136.8 | 133.0 | 133.0 |
| Delta-Q Test | 152.0 | 130.8 | 160.4 | 173.4 | 141.5 | 151.6 | 151.6 |
| | | | | | | | |
| Difference (cfm) | | | | | | | |
| Benchmark Estimate | 6.8 | 6.3 | 3.9 | -3.4 | 0.2 | 2.7 | 4.1 |
| Nulling Test | 55.2 | 8.6 | 3.6 | -11.0 | 9.4 | 13.2 | 17.6 |
| Delta-Q Test | 0.7 | 20.3 | 52.0 | 72.0 | 14.1 | 31.8 | 31.8 |
| | | | | | | | |
| Difference (% Flow Station Leakage) | | | | | | | |
| Benchmark Estimate | 4.5 | 5.7 | 3.6 | -3.4 | 0.2 | 2.1 | 3.5 |
| Nulling Test | 36.5 | 7.8 | 3.4 | -10.8 | 7.4 | 8.8 | 13.2 |
| Delta-Q Test | 0.4 | 18.4 | 48.0 | 71.0 | 11.0 | 29.8 | 29.8 |
| | | | | | | | |
| Difference (% Air Handler Flow) | | | | | | | |
| Benchmark Estimate | 0.7 | 0.9 | 0.3 | -0.5 | 0.0 | 0.3 | 0.5 |
| Nulling Test | 5.8 | 1.2 | 0.3 | -1.5 | 0.8 | 1.3 | 1.9 |
| Delta-Q Test | 0.1 | 2.9 | 4.7 | 9.8 | 1.3 | 3.8 | 3.8 |

**Return Leakage**

Table 5-2 compares the flow station measurement of the added return leak to the measurements from the benchmark estimate, the nulling test, and the Delta-Q test for the return side. As for Table 5-1 detailing the supply side, the measurements from all of the methods are the estimated amount of leakage above the as-found leakage, so they are directly comparable to the flow station leakage.

These results paint a very different picture for the benchmark estimate. All of the estimates are differ from the flow station measurement by more than twice the largest error on the supply side. Overall the errors are about seven times greater on the return side than were seen on the supply side. This result goes against the conventional perception that the flow hoods will work better on the return side.  One likely explanation is that, since there is often only one return grille (three of the houses), and never more than three in this group of homes, there is little opportunity for cancellation of errors.  Once there is an error in the grille flow measurement, this error will appear in the benchmark leakage estimate.

For the nulling test, it has been speculated that the return results will be worse than the supply results (Andrews 2001).  This is because the return leakage estimates are based on both the unbalanced and the supply-only portions of the test, and an error in either can cause an error in the return estimate.

These cases do not support this expectation.  The probable reason for this is that there are features about the house and ducts that can cause errors in the nulling test, and if these are present in both portions of the test then they will cancel each other out when making the return leakage estimate.  An example of a feature that can have this type of effect is the duct leaks themselves, which can shift the baseline neutral level with the air handler off relative to what it should have been had there been no ducts.  Ideally, the shift in neutral level due to the duct leaks when the air handler is on, which is to be nulled out in this test, should be relative to the neutral level with no ducts.

Table 5-2.  Return-Side Benchmark Estimate Validation Results.

| | **N04R** | **N12R** | **N17R** | **N33R** | **N36R** | **Mean** | **Mean Abs.** |
|---|---|---|---|---|---|---|---|
| | | | | | | | |
| Air Handler Flow (cfm) | 949 | 697 | 1114 | 733 | 1122 | 923 | 923 |
| | | | | | | | |
| Leakage (cfm) | | | | | | | |
| Flow Station | 139.0 | 91.1 | 156.1 | 99.6 | 158.6 | 128.3 | 128.3 |
| Benchmark Estimate | 155.3 | 59.5 | 127.7 | 50.5 | 176.0 | 113.8 | 113.8 |
| Nulling Test | 154.4 | 98.4 | 129.8 | 109.1 | 178.3 | 134.0 | 134.0 |
| Delta-Q Test | 158.1 | 114.2 | 208.8 | 115.6 | 215.3 | 162.4 | 162.4 |
| | | | | | | | |
| Difference (cfm) | | | | | | | |
| Benchmark Estimate | 16.3 | -31.7 | -28.4 | -46.2 | 17.4 | -14.5 | 28.0 |
| Nulling Test | 15.4 | 7.2 | -26.3 | 12.5 | 19.7 | 5.7 | 16.2 |
| Delta-Q Test | 19.0 | 23.1 | 52.8 | 18.9 | 56.7 | 34.1 | 34.1 |
| | | | | | | | |
| Difference (% Flow Station Leakage) | | | | | | | |
| Benchmark Estimate | 11.7 | -34.8 | -18.2 | -47.8 | 11.0 | -15.6 | 24.7 |
| Nulling Test | 11.0 | 8.0 | -16.8 | 12.9 | 12.4 | 5.5 | 12.2 |
| Delta-Q Test | 13.7 | 25.3 | 33.8 | 19.6 | 35.8 | 25.6 | 25.6 |
| | | | | | | | |
| Difference (% Air Handler Flow) | | | | | | | |
| Benchmark Estimate | 1.7 | -4.5 | -2.5 | -6.3 | 1.6 | -2.0 | 3.3 |
| Nulling Test | 1.6 | 1.0 | -2.4 | 1.7 | 1.8 | 0.7 | 1.7 |
| Delta-Q Test | 2.0 | 3.3 | 4.7 | 2.6 | 5.0 | 3.5 | 3.5 |

The expectation for the Delta-Q test is that the performance would be similar on the return side as it was on the supply side. This is because there is nothing different about the procedure for estimating return leakage using the Delta-Q test. The test uses, effectively, a symmetric protocol and symmetric equations for the supply and return leaks.

These results support that assumption. The return results show an average overestimation of the leakage at just over 25% compared to nearly 30% for the supply side. Expressed as a percentage of air handler flow, the return estimates are biased high by 3.5% of air handler flow compared to the 3.8% on the supply side. Given the number of houses in this group, and the sensitivity of the Delta-Q test to assumptions of, for example, leakage pressures and exponents, these results can be considered effectively the same magnitude of bias for the supply and return leakage estimates.

The primary conclusion of the results on the return side is that the benchmark estimate is probably not as reliable as would have been desired, especially considering that the primary concern of this method had been on the supply side. These results also illustrate the importance of cancellation of scatter-type errors when measuring register and grille flows. It is probably the case that, on the return side, the nulling test is in fact the best estimate of leakage of the methods applied to each house in the study.

# 6
# AIR HANDLER FLOW RESULTS AND IMPORTANCE TO DUCT EFFICIENCY

Measurement of air handler flow is not explicitly required for any of the methods. It is simple to obtain as part of the nulling test, since the setup for the supply-only portion of the nulling test is the same as the setup for measuring the air handler flow using a calibrated fan. For the Delta-Q and fan pressurization tests, additional measurements are required to quantify air handler flow.

However, air handler flow is extremely important for evaluating the impact of duct losses, including leakage, on the overall performance of the conditioning distribution system. It also has major implications for the performance of the equipment itself. Furnaces are designed to operate with a certain temperature rise, which depends on the air handler flow. Heat pumps and air conditioners rely greatly on the air handler flow to provide sufficient rates of heating and cooling (see Rodriguez et al. 1995 and Parker et al. 1997 for a discussion of this issue).

The impact of air handler flow on the efficiency of duct systems can be seen by inspecting the equation for the duct delivery efficiency. This efficiency, which is called the delivery effectiveness in ASHRAE Standard 152P (ASHRAE 2003), is the fraction of the potential conditioning energy generated by the conditioning equipment that actually enters the home via the supply registers. It does not include the effects of thermal regain, any interaction between the duct leakage and natural infiltration, or other side effects. The equation can be written as:

$$\eta_0 = \alpha_s\beta_s - \alpha_s\beta_s\left(1-\alpha_r\beta_r\right)\frac{\Delta T_r}{\Delta T_e} - \alpha_s\left(1-\beta_s\right)\frac{\Delta T_s}{\Delta T_e} \qquad \textbf{(6-1)}$$

where $\eta_0$ = the duct delivery efficiency

$\alpha_s$ = supply leakage efficiency (fraction of air handler flow <u>not</u> lost to supply leakage)

$\alpha_r$ = return leakage efficiency (fraction of air handler flow <u>not</u> lost to return leakage)

$\beta_s$ = supply conduction efficiency

$\beta_r$ = return conduction efficiency

$\Delta T_r$ = temperature difference between inside and the return duct zone

$\Delta T_s$ = temperature difference between inside and the supply duct zone

$\Delta T_e$ = temperature change (rise or drop) across the conditioning equipment

Of the seven terms that go into the calculation of the delivery efficiency, five of them depend heavily on the air handler flow. The only two that do not are the temperature differences between inside and the duct zones.

Both of the leakage efficiencies are fractions of air handler flow. The equation shows that, if two houses have the same supply leakage but one house has a larger air handler flow, the efficiency penalty for that house will be less than that for the house with the lower flow.

The conduction efficiencies are also functions of air handler flow, and can be expressed as

$$\beta = \exp\left( -\frac{UA}{m_e c_p} \right) \qquad \textbf{(6-2)}$$

where $U$ = heat loss rate of the ducts (reciprocal of the duct insulation R-value)
$A$ = surface area of the ducts
$m_e$ = mass flow rate of air through the ducts (air handler mass flow rate)
$c_p$ = specific heat of air

As the air handler flow rate increases, the conduction efficiency increases, resulting in improved delivery efficiency assuming everything else is held fixed.

The temperature rise (or drop) across the equipment can be expressed as

$$\Delta T_e = \frac{q_{cap}}{m_e c_p} \qquad \textbf{(6-3)}$$

where $q_{cap}$ = conditioning equipment output capacity

For a fixed equipment capacity, an increase in flow rate decreases the temperature change, resulting in a reduction in delivery efficiency assuming everything else is held fixed.

The overall effect that the air handler flow rate has on the efficiency varies from case to case, since the impact on the temperature rise (or drop) at least partially compensates for the impacts on the leakage and conduction efficiencies. However, it is clear that it is not possible to evaluate duct efficiency or potential savings from duct improvements without also having the air handler flow rate.

In this study the air handler flow was always measured using a calibrated fan called a Duct Blaster® while the supply-leakage-only portion of the nulling test was performed. Every effort was made to ensure that there was as little bypass as possible, meaning that paths for air to enter the air handler without being metered by the Duct Blaster® were sealed off. Seams around the air handler were taped, and pressures in the return duct were checked to verify that the barrier between the return ducts and the air handler was airtight.

The air handler flow was also measured in some houses using a calibrated plate called a TrueFlow™ Air Handler Flow Meter. Measurement with this device was frequently not possible for downflow gas furnaces unless the furnace had an electronic air cleaner, because the “V”-shaped filter rack common in these systems blocks off sensing holes of the device, which would provide errant results. Consequently, many of the latter half of the homes did not receive this measurement, since it became necessary to drop the restriction against this type of filter arrangement in order to satisfactorily recruit homes into the study. Of the 51 homes tested, 32 were tested using the TrueFlow™ Air Handler Flow Meter.

Table 6-1 shows a summary of the air handler flow rates that were measured during the course of this study. The results are also shown in Fig. 6-1. Note that in Table 1 the entries for the ratio of the two methods are not based on the other cells in the same column.

The general tendency of the TrueFlow™ to underestimate the air handler flow was surprising, since in an earlier field study the agreement between the two methods was extremely close (Palmiter and Francisco 2000a, 2000b; Francisco and Palmiter 2003). The discrepancy was tracked down to the calibration coefficients supplied by the manufacturer.

Table 6-1. Summary of Results of Duct Blaster® and TrueFlow™ Methods of Estimating Air Handler Flow.

| | n | Mean | Median | Minimum | Maximum |
|---|---|---|---|---|---|
| Duct Blaster® | 48 | 929 | 930 | 425 | 1423 |
| Duct Blaster® (only TrueFlow™ cases) | 32 | 899 | 910 | 425 | 1318 |
| TrueFlow™ | 32 | 833 | 847 | 387 | 1134 |
| Ratio, TrueFlow™ to Duct Blaster® | 32 | 0.936 | 0.913 | 0.812 | 1.101 |

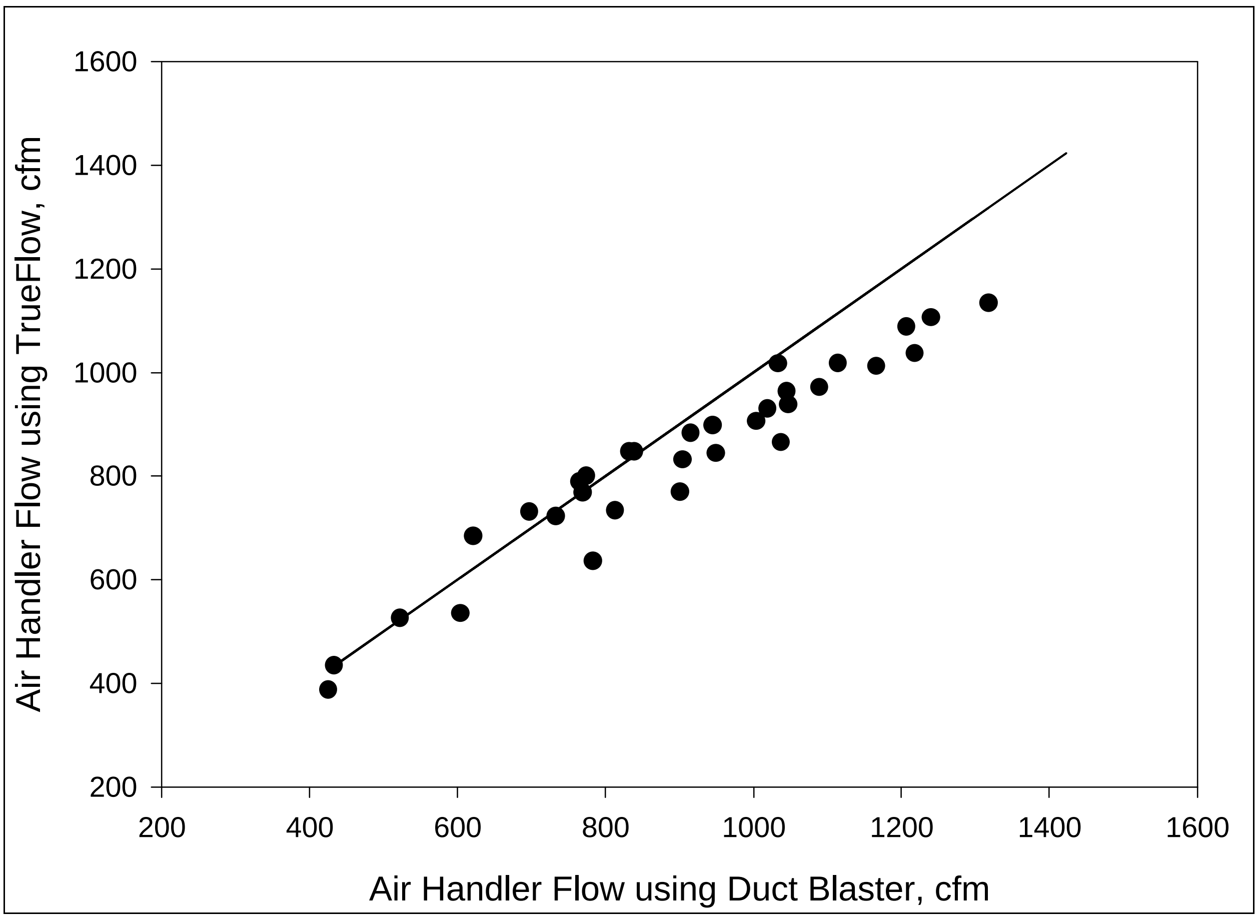



Figure 6-1. Comparison of TrueFlow™ and Duct Blaster® air handler flow estimates. The line is a one-one line representing perfect agreement.

The manufacturer had found that the coefficients were dependent on whether or not there was a sharp turn shortly before the filter slot, and the coefficients were chosen to minimize the maximum error. The coefficients for ducts with a distance of straight duct prior to the filter slot, as is common in the homes in this study, are higher, and would lead to improved agreement with the Duct Blaster®. Discussions with the manufacturer have led to a reopening of this decision, with the result that they will begin providing two coefficients for each size plate, one for situations with the sharp turn and one for cases with a distance of straight duct prior to the filter slot. These changes will rectify approximately two-thirds to three-quarters of the discrepancy found in this study, which would bring the air handler flow estimates well within the accuracy of the device.

For the purposes of this study, the air handler flow measurements using the Duct Blaster® were used for all further analysis.

# 7
# LEAKAGE TEST RESULTS

This section is split into several portions. The first portion discusses the results of the leakage tests as described by their developers at the time that the project started. The second portion discusses potential modifications to the Delta-Q test. The third portion investigates the pressures at the leaks, and the final portion discusses the impacts of leakage estimate on the overall thermal distribution efficiency of ducts.

## UNMODIFIED TESTS

This section details the results of the leakage testing for the tests as described by the developers at the time of that this project was started. The Delta-Q test has undergone a number of minor changes with regard to both the protocol and the analysis technique throughout this time period, with changes made to the recommended house pressure stations and to the method of selecting duct pressures as inputs to the Delta-Q equations. Several of these suggested modifications will be examined in a later section.

This section also evaluates the fan pressurization test using two different assumptions for leak pressures. The first is a uniform pressure of 25 Pa for all houses, which is often used by field technicians evaluating the leakage of ducts. This is also a means of estimating the airtightness of the ducts, which can be viewed as the overall area of the holes in the ducts without regard to the pressures at these leaks. The other pressure assumption is half of the plenum pressure, which is the assumption specified in ASHRAE Standard 152 (ASHRAE 2003). This assumption attempts to apply a pressure that is pertinent to the duct system under consideration, in an effort to more accurately estimate the leakage under normal operating conditions. Previous work has shown that, if the pressures at the leaks are known, the fan pressurization method can estimate the leakage very accurately (Cummings et al. 1999; 2000), but that when these pressures are unknown the method often gives spurious answers (e.g. Francisco and Palmiter 1999; 2000; Francisco et al. 2002a; 2002b; 2003; Walker and Modera 1998; Walker et al. 1998b; Andrews 2000b; 2002).

Due to the quantity of data and the complexity of the issues involved, each of the unmodified tests will be examined separately prior to a comparative summary of the tests. In addition, since the benchmark estimate has been shown to be much more reliable on the supply side than on the return side, the discussion will focus on the supply leakage results. As described previously, it is unclear whether the nulling test will have greater or lesser errors on the return side. For the Delta-Q test, there is no reason to expect that the performance will be fundamentally different on the return side compared to the supply side due to the symmetric nature of the test.

In order to give homes equal weight, only as-found conditions will be considered in this section. In addition, the three manufactured homes tested are excluded from the main group of houses. These will be discussed separately due to the differences in building construction and duct configuration between manufactured and site-built homes.

**Nulling Test Results**

*Supply Leakage*

Figure 7-1 compares the nulling test results to the benchmark estimate. Results are expressed as a fraction of air handler flow in order to normalize across houses for a more robust comparison. The line is a one-one line, indicating perfect agreement between the two methods.

This figure shows a general tendency to follow the line, but with a fair amount of scatter. The mean absolute difference compared to the benchmark estimate is about 25 cfm, or about 3% of air handler flow. The root-mean-squared (RMS) error is about 3.5% of air handler flow.

One house, site 21, showed exceptionally large disagreement. This site is called out in Fig. 7-1. This site had a highly unfortunate combination of characteristics for the nulling test. It was the leakiest house in the study, with an air change rate at 50 Pa of 29 ACH50. High leakage houses present a problem for two reasons. One is that the resolution of the measurements is not as good, since a fan flow of a certain amount has less of an effect in a leaky house than in a tight house. Also, if there is wind, a leaky house will allow more wind-induced flow through the envelope, increasing the chances of the nulling test reading wrong by a large amount. There was, in fact, a lot of wind at this house on the day of testing. There also was neither a useful attic nor crawl space for use as the reference to dampen the wind. As a result, the envelope pressure was

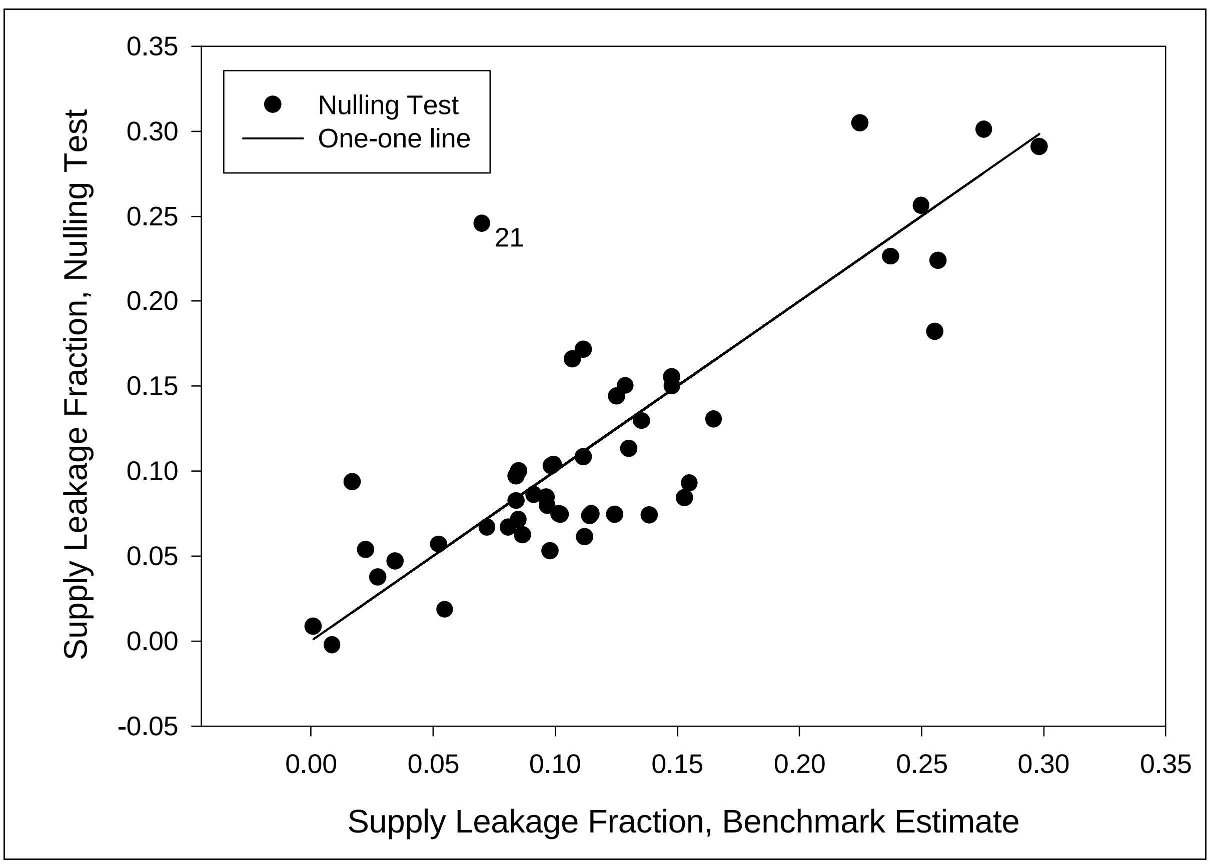



Figure 7-1. Comparison of nulling test and benchmark estimate supply leakage fractions.

measured across a door to a mother-in-law apartment that was not served by the duct system. Though this room was able to dampen the effect of the wind somewhat, the leakiness of the room was such that the dampening was not as much as would have been desirable.

In this case, the discrepancy between the nulling test and the benchmark estimate was about 76 cfm, which is the second largest in the study. This might not have been a huge problem in many houses, but the furnace in this home was small, and only measured 433 cfm. As a result the error caused by the wind was a very large fraction of the air handler flow.

Analysis of the data on the remainder of the homes showed two factors to be largely responsible for the larger discrepancies. One of these two was measurement noise due to wind, and the other was the number of stories served by the duct system. Other factors, such as the magnitude of the leakage, the estimated leak pressure, and the degree of pressure change across the envelope due to turning on the air handler were not explanatory factors.

Figure 7-2 illustrates the effect that these two characteristics have on the agreement between the nulling test and the benchmark estimate. Site 21 has been excluded from this graph. The y-axis represents the absolute value of the difference between the nulling test result and the benchmark estimate result as fraction of the air handler flow. The x-axis is the sum of the standard deviations of the readings of the reference envelope pressure for the five samples taken during the supply-only portion of the nulling test. This is used as a surrogate for the wind, because in some cases it was not possible to locate the anemometer such that the wind would always be recorded. Higher wind speeds tend to result in larger standard deviations of the reference envelope pressure.

The horizontal line at 0.04 (a difference of 4% of air handler flow) corresponds to about half of the maximum discrepancy with Site 21 removed. The vertical line at 1.5 corresponds to an average standard deviation of 0.3 for the five stations; this magnitude of standard deviation was typically only seen on windy days. The symbols correspond to whether the ducts served a single story (“S”) or multiple stories (“M”).

This graph shows that, of the 13 cases with differences greater than 4% of air handler flow, 11 of them were multi-story houses. Of the other 34 homes, only 12 were multi-story. This shows that, while multi-story homes do not always have larger errors, they are much more prone to have significant discrepancies.

The most likely cause of this lies in the estimation of the benchmark estimate rather than the nulling test. The benchmark estimate is essentially a two-stage process. The first stage is subtracting the sum of the register flows from the air handler flow. The second is the correction for leakage to inside. This correction uses the ratio of the results of two fan pressurization tests, one that measures only the duct leakage to outside at a specified pressure and the other that measures the combination of duct leakage to outside and to inside at a specified pressure. In the benchmark estimate procedure, the ratio used is the leakage to outside at 25 Pa divided by the combined leakage at 25 Pa. This ratio is multiplied by the difference between the air handler flow and the sum of the register flows to obtain the benchmark estimate of duct leakage to outside.

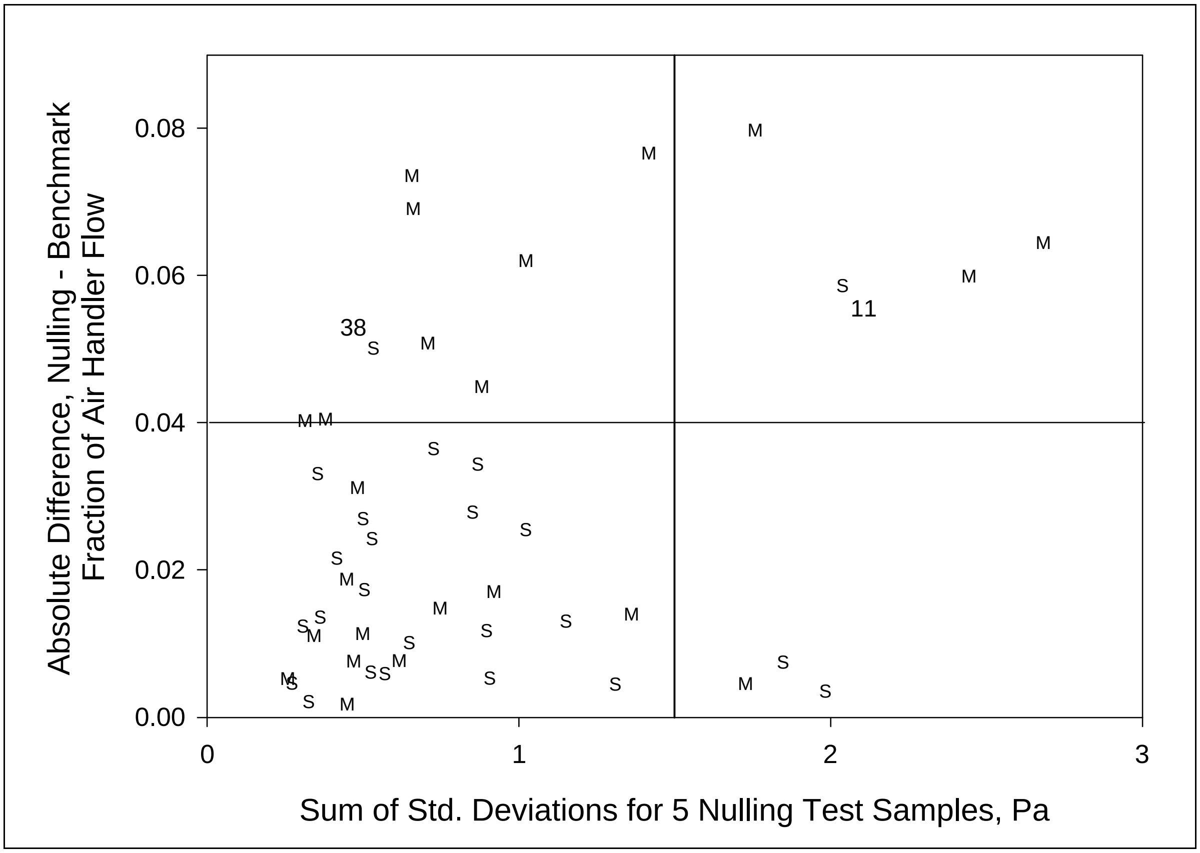



Figure 7-2. Error sources for the nulling test vs. benchmark estimate comparison – number of stories and wind noise.

This process implicitly assumes that the leakage to inside is at the same pressure as the leakage to outside. If this is not the case, then there will be an error in the benchmark estimate. This problem does not often manifest itself in single-story homes because all of the ducts are outside the conditioned space, leading to very low (or nonexistent) leakage to inside. This problem also did not manifest itself in the benchmark validation tests because there was little as-found leakage to either inside or outside, and the only leaks that were added were to outside.

On average, single-story and multi-story homes had a similar amount of supply leakage to inside (about 45 cfm, with medians about 28 cfm). This indicates that most multi-story homes had fully ducted supplies with low leakage. However, the cases that show the largest errors in the upper left quadrant of Fig. 7-4 tend to be multi-story houses that did have large leakage to inside. The overall evidence suggests that this may be a primary source of the problem, but that in many multi-story homes the process will work fine. The issue is not a generally larger error, but rather a greater uncertainty with individual cases that have large errors in the benchmark estimate.

On the return side, however, there tended to be much larger leakage to inside in multi-story homes. On average, multi-story homes had about 106 cfm of leakage to inside, compared to only 37 cfm for single-story homes. The median for multi-story homes was about 85 cfm, whereas the median for single-story homes was about 19 cfm. The reason that the multi-story homes have so much more leakage to inside on the return side is that many homes use building cavities as return ducts, which tend to be leaky.

In a previous study of nine homes, (Francisco et al. 2002a; 2002b; 2003) test homes were restricted to those having a single story to avoid this problem. One of the secondary goals of the current project was to determine how well the benchmark estimate would work in multi-story homes. The conclusion based on this sample of homes is that it can perform well, but there will be a higher fraction of homes with large errors. It could be argued that, for multi-story homes with little wind, the nulling test may be the best "benchmark" of the tests performed.

There are two single-story houses with errors greater than 4% of air handler flow. One of these, site 11, had high winds. The other, site 38, actually behaved like a multi-story home with regard to duct leakage. This was an older home, with the water heater located behind the furnace in an interior closet. The water heater had recently been replaced, and the contractor had to remove the furnace from the closet to replace the water heater. There was evidence that, in the attempt to put the furnace back in the closet, it was not placed on the ducts leading through the floor and into the crawl space well, resulting in a sizeable leak at the back of the plenum to the inside of the closet. Access was extremely limited, so attempts to seal this leak prior to testing were largely unsuccessful.

It is also of interest that there were some houses at which there were significant winds that still produced good comparison between the nulling test and the benchmark estimate. This shows that, while wind does increase the uncertainty of the nulling test, it does not guarantee a poor result. However, these results combined with the results of site 21 suggest that performing the nulling test under high-wind conditions is likely to produce questionable results.

*Return Leakage*

As stated in the "Benchmark Estimate Validation" section, the quality of the benchmark estimate on the return side is questionable. It is therefore difficult to state with certainty how accurate any of the methods are, beyond what can be stated based on knowledge of how the tests work. On the return side, the nulling test averaged about 3% of air handler flow lower than the benchmark estimate, with an average leakage fraction of 10% compared to 13%.

It is not clear at this point whether the nulling test should be more or less accurate than on the supply side. For the five benchmark estimate validation homes, the results were slightly better on the return side, but with a sample size that small it is not possible to generalize. It is likely, however, that over a large sample the errors in the nulling test would not be wholly different on the return side.

It is worth noting that the average agreement between the nulling test and the benchmark estimate would have been much closer if the return-side flow hood readings had not been adjusted for the calibration. However, given that the calibrations were done and that the manufacturer's post-study calibration tended to agree with that done by Ecotope, the results presented include the effects of the calibration. At this time it is not understood why applying the calibration would worsen the results.

*Manufactured Home Results*

Manufactured homes present an interesting opportunity for the nulling test. Unlike site-built homes, where the need to do the supply-only portion of the test makes the time and setup requirements daunting, the lack of a return duct system in manufactured homes means that only the simple, unbalanced leakage portion of the test is required. This also means that the nulling test estimate of return leakage is zero by definition, which is correct for these systems.

These homes also present the multi-story house problem for the benchmark estimate, despite the fact that they are single-story houses. This is because the ducts, other than the crossover duct for multi-section houses (e.g. double wide homes), are located in a belly space. This space is located under the floor in the crawl, and is characterized by an insulated blanket beneath the ducts. With regard to airflow, this space is often similar to an exterior wall, in that it has some communication with both the indoors and outdoors. As a result, some duct leakage in these homes is expected to make it back into the home, behaving like duct leakage to inside.

Table 7-1 compares the nulling test leakage with the benchmark estimate leakage in the three manufactured homes tested in this study. Results are presented both in terms of cfm and as a percentage of air handler flow.

This table shows that the nulling test always provides a leakage estimate greater than the benchmark estimate. Two of the cases are fairly close, within 2% of air handler flow. The third has a discrepancy of about 33 cfm, or about 4.5% of the air handler flow. The average discrepancy is about 20 cfm, or 2.3% of air handler flow. This is larger than for the site built homes, though it must be cautioned that the sample size of three is not large enough to make any general assertions as to whether this is a problem with the nulling test or whether leaks to inside are causing errors in the benchmark estimate.

It is worth noting here that the Delta-Q test, modified to eliminate the return from the evaluation technique, provides results very similar to the nulling test. This may indicate that the benchmark estimate results are questionable in these homes, likely due to duct leakage to inside.

Table 7-1. Nulling Test Results for Three Manufactured Homes.

| | Nulling Test | | Benchmark Estimate | | Difference | |
|---|---|---|---|---|---|---|
| Site | cfm | % air handler flow | cfm | % air handler flow | cfm | % air handler flow |
| 41 | 54.7 | 4.6 | 35.4 | 3.0 | 19.3 | 1.6 |
| 45 | 63.5 | 7.5 | 56.4 | 6.6 | 7.1 | 0.9 |
| 49 | 41.7 | 5.7 | 9.1 | 1.3 | 32.6 | 4.5 |
| Avg. | 53.3 | 6.0 | 33.6 | 3.6 | 19.7 | 2.3 |

**Delta-Q Test**

*Supply Leakage*

Figure 7-3 compares the Delta-Q test results to the benchmark estimate on the supply side. As for the nulling test, results are expressed as a fraction of air handler flow. The line is a one-one line, indicating perfect agreement between the two methods. These results assume that the duct leakage pressure to be entered into the Delta-Q equations is half of the plenum pressure and that the duct leakage exponent is 0.6. These results also use the data for house pressures ranging from 25 Pa to –25 Pa in increments of 5 Pa, excluding 0 Pa. Later sections will describe the effects of changing these assumptions.

This figure shows that the Delta-Q test does track the benchmark estimate, though there is significant scatter and a tendency to overestimate. The mean absolute difference with respect to the best estimate is about 32 cfm and the RMS error is about 4.5% of air handler flow. This is about 28% greater scatter than for the nulling test.

There is some indication of a correlation of error with the number of stories for the Delta-Q test, as well, though the contrast between single- and multi-story homes is not as sharp. In this case, however, it is the single-story homes that dominate the group with the largest errors, as seen in Fig. 7-4. For single-story homes, the Delta-Q averages 2.0% of air handler flow greater leakage than the benchmark estimate, and 2.5% of air handler flow greater than the nulling test. For multi-story homes, the agreement with the benchmark estimate is very close, on average, and the

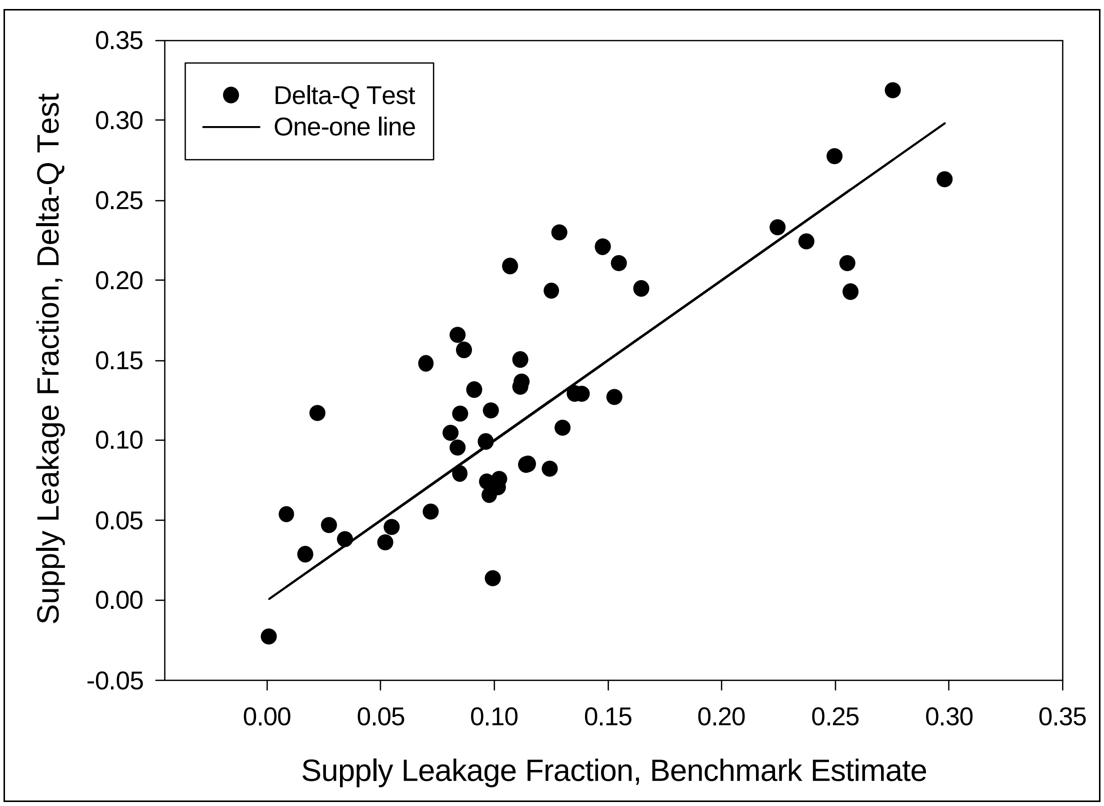



Figure 7-3. Comparison of Delta-Q test and benchmark estimate supply leakage fractions.

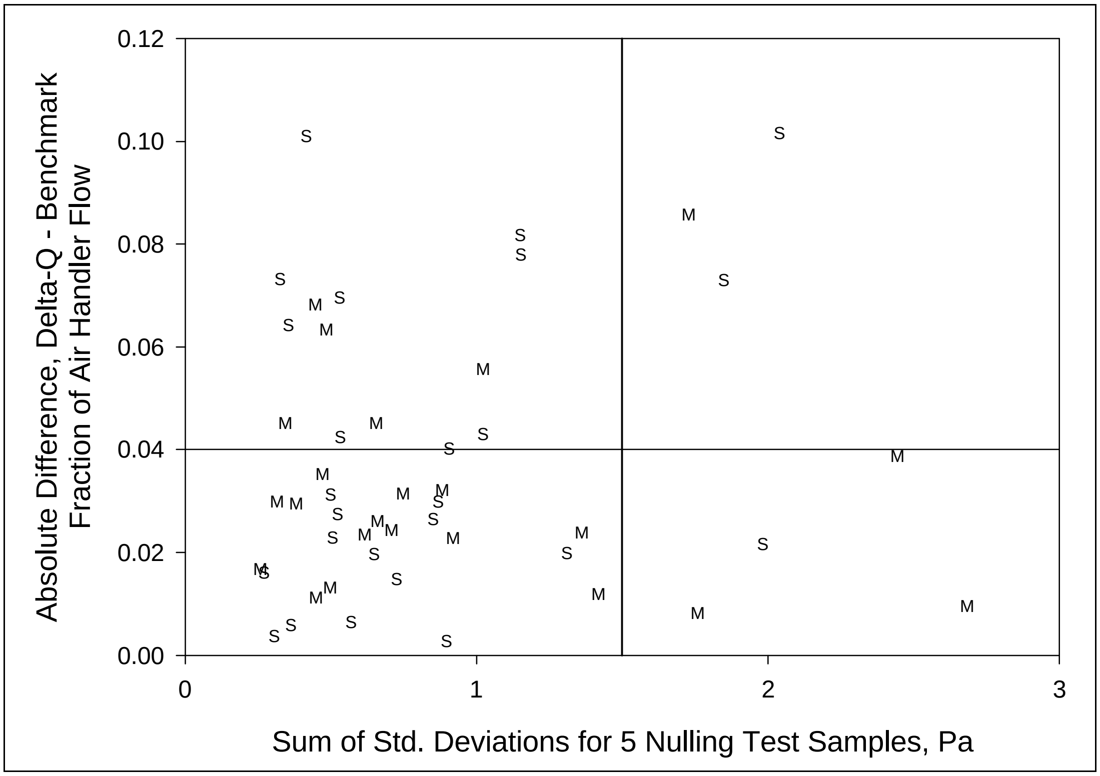



Figure 7-4. Error sources for the Delta-Q test vs. benchmark estimate comparison – number of stories and wind noise.

difference compared to the nulling test is only about 1% of air handler flow. Therefore, even if the nulling test is the actual better measurement for multi-story homes, the Delta-Q test performs significantly better in these homes than in single-story homes.

The primary reason that the Delta-Q test would perform better in multi-story homes is the greater connection between the ducts and inside. This greater connection can come in the form of leaks to inside, as well as the number of registers. Multi-story houses had a median number of registers of 11, compared to 9 for single-story homes, meaning that there were more intentional holes to the ducts from the house in the multi-story cases. As discussed regarding the benchmark estimate, the multi-story homes did not have greater average leakage to inside on the supply side than did single-story homes, though there were individual cases that had large leaks to inside. On the return side, however, the use of building cavities as ducts does greatly increase the connection between the house and the ducts for multi-story homes through leakage.

One of the primary flaws in the Delta-Q test has been shown to be the failure of the assumption that the pressure between the ducts and the house remains constant throughout the test (Francisco et al. 2002a; 2002b; Palmiter et al. 2003). This assumption is true when there are no duct leaks, but when there are leaks to the outside then the pressures within the ducts change relative to the house. When there are leaks to inside, however, the greater communication between the ducts and the house results in the assumption being more nearly true. In the limit, with ducts all inside the conditioned space, the pressure between the ducts and the house will remain constant regardless of the duct leakage.

Figures 7-5a and 7-5b show examples of how the duct pressure changes relative to the house throughout the Delta-Q test. There are four cases shown in each figure. In each panel of Figure 7-5b, the absolute value of pressure between the return plenum and the house is shown to maximize the ability to see the changes in pressure. The top line in each panel of Figure 7-5b is the external static, which is the difference between the supply and return plenum pressures. (When the return plenum pressure is expressed as a positive number, the external static pressure becomes the sum of the two plenum pressures.)

The top left panel in each figure is from one of the homes on which benchmark validation testing was performed. No leaks were added in the case shown in this panel, so there is little leakage. The result is that the duct pressures do not change significantly throughout the Delta-Q testing. With the air handler off, the changes are about 1 Pa across the entire range of the test.

The top right panel in each figure is from a case with significant leakage on each side (about 12%), but still fairly well balanced leakage. These graphs show that, despite the balanced leakage, the level of leakage is sufficient to cause noticeable changes in the plenum pressures

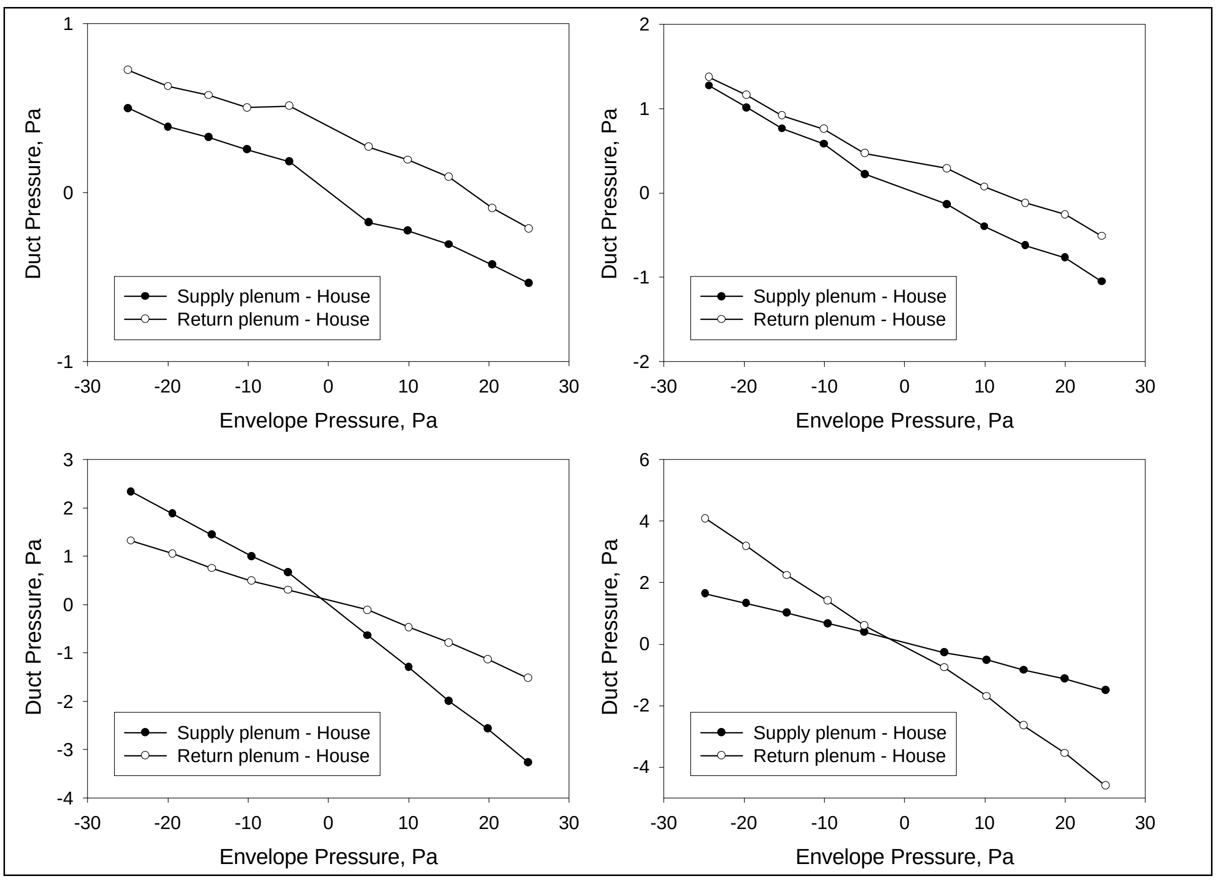



Figure 7-5a. Change in duct pressure relative to house during Delta-Q test with air handler off for four cases: minimal balanced leakage (top left), significant balanced leakage (top right), large supply-dominated leakage (lower left), and large return-dominated leakage (lower right).

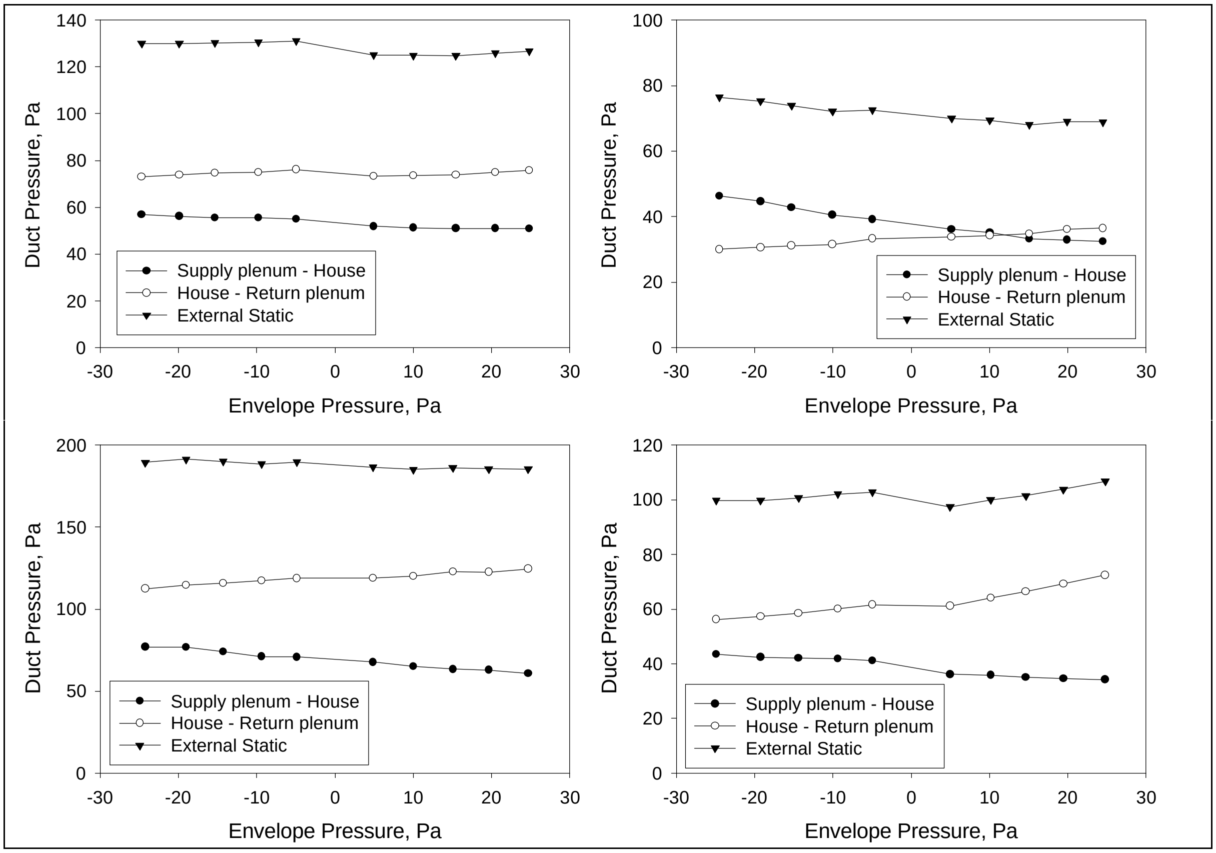



Figure 7-5b. Change in duct pressure relative to house during Delta-Q test with air handler on for four cases: minimal balanced leakage (top left), significant balanced leakage (top right), large supply-dominated leakage (lower left), and large return-dominated leakage (lower right).

relative to the house. With the air handler off, the changes are about 1.5-2 Pa for the range of the Delta-Q test, with the supply and return changes quite similar to each other. With the air handler on, the changes are about 14 Pa for the supply side and about 6 Pa for the return side across the full range of house pressures. This is compared to pressures of about 35-40 Pa under normal operation.

The fact that the supply changes more than return both with the air handler off and with the air handler on suggests that the supply may have slightly more leakage, which is in agreement with the benchmark estimate (12.9% of air handler flow compared to 10.3% on the return side). Both the nulling test (15.0% supply, 15.5% return) and Delta-Q (23.0% supply and 25.4% return) show more leakage on the return side, though for the nulling test the return leakage is only about 3 cfm greater than the supply leakage.

The lower left panel in each figure shows a case with a large leak on the supply side and a moderate leak on the return side. With the air handler off, the return changes by about 2 Pa, which is only slightly more than for the case in the upper right panel. However, the supply duct pressure changes by about 6 Pa relative to the house over the course of the Delta-Q test. With the air handler on, both supply and return plenum pressures change by about 13-17 Pa throughout the test. This is a smaller fraction of the normal operating pressures than for the upper right panel, in large part because this home was a two-story building, and there were leaks to inside.

The final panel in each figure shows a case with very large return leakage from outside due to a panned-joist return that went the length of the house and spanned two joist bays.  This graph shows large changes in duct pressure on both the supply and return sides, both with the air handler off and on.  With the air handler off, the supply pressure changes by about 3 Pa relative to the house across the range of the test.  The return, however, changes by almost 9 Pa, which is nearly 20% of the total range of house pressures considered.  In addition, it shows a greater change in the return plenum pressure during the pressurization portion of the Delta-Q test when the air handler is on.  This is due to the magnitude of the return-dominated, unbalanced leakage, and the fact that the pressurization portion of the test impacts the return side more than the supply side.

There also appears to be a correlation between the bias and the estimated leak pressure as determined by combining the benchmark estimate of leakage with the fan pressurization test to outside, as described in Chapter 2.  This is shown in Figure 7-6.  This graph shows that there is a general downward trend with increasing leak pressure.  This was also found in a theoretical modeling evaluation of the Delta-Q test (Palmiter et al. 2003).  At lower pressures, the Delta-Q test tends to be biased high, while at higher pressures the test actually begins to underestimate.  The general tendency for the Delta-Q test to overestimate the leakage indicates that leaks tend to be at lower pressures.  This will likely be the case in the majority of homes since there are often elbows shortly after the plenum, each of which causes a significant pressure drop.

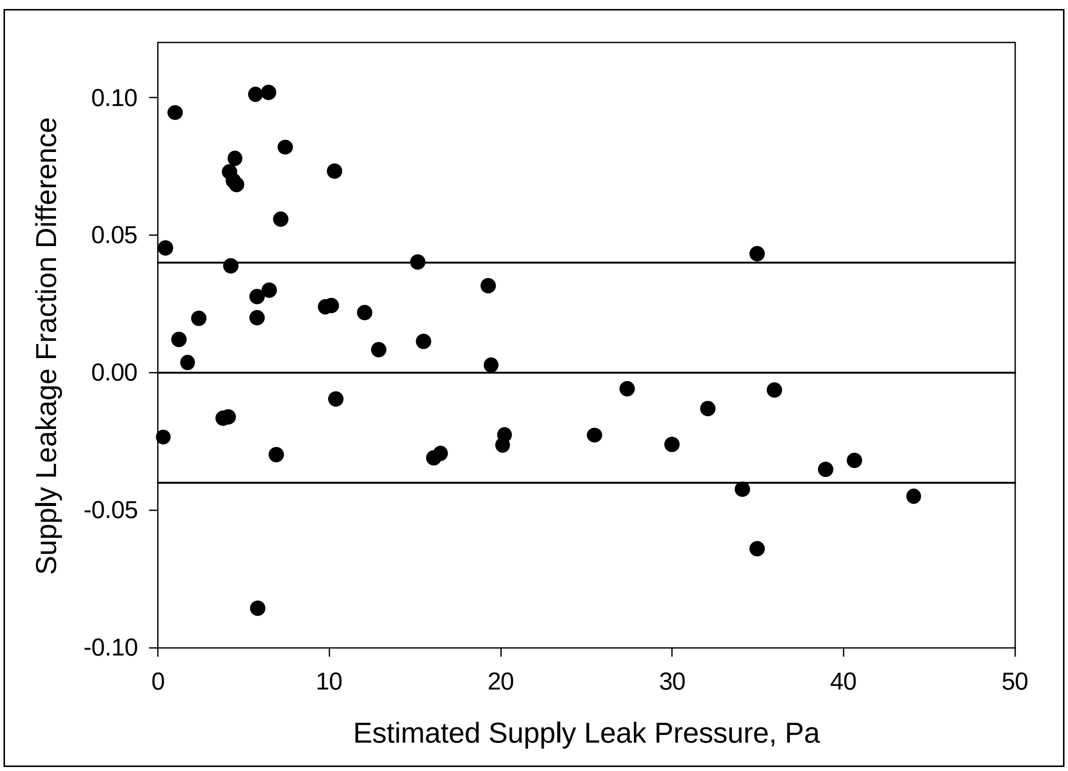



Figure 7-6.  Difference between Delta-Q test and benchmark estimate vs. supply leakage pressure.

For comparison, a similar graph is shown for the supply nulling test results in Fig. 7-7. The points above a difference of 0.04 are all cases with significant wind. Removing these points, there is little correlation between bias and leak pressure in this graph, indicating that the appearance of the trend in Fig. 7-6 is primarily due to the Delta-Q test and not the benchmark estimate.

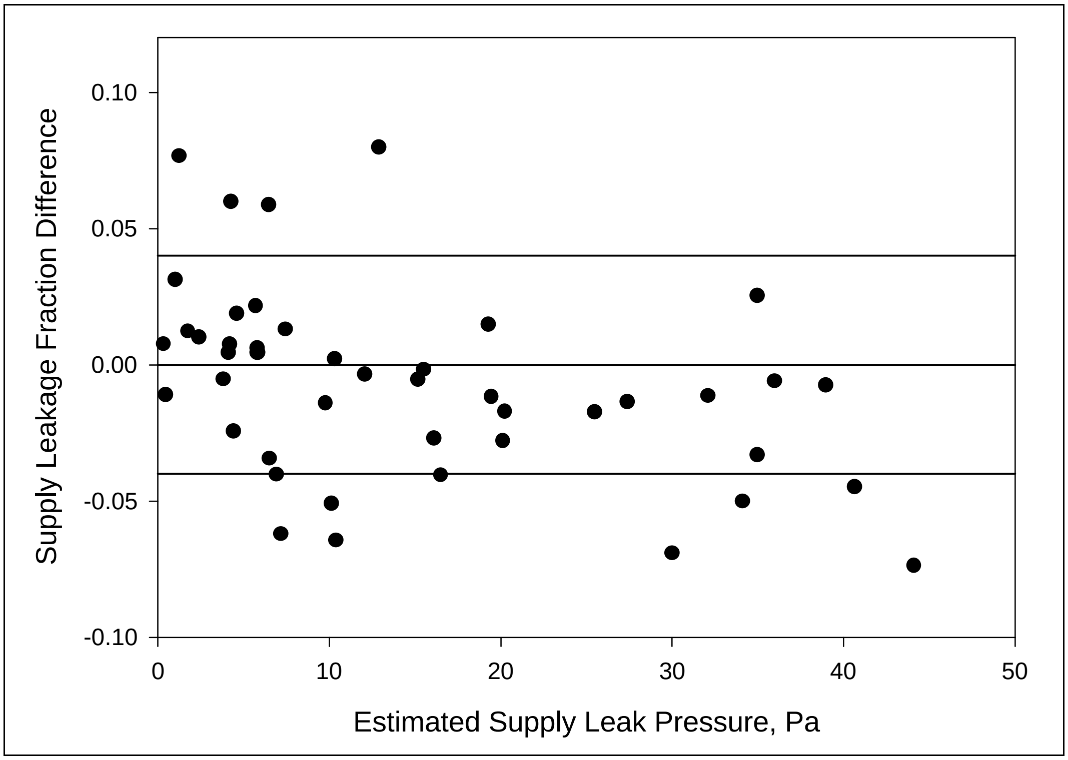



Figure 7-7. Difference between nulling test and benchmark estimate vs. supply leakage pressure.

*Return Leakage*

On the return side, the Delta-Q test compared very well with the benchmark estimate, on average. However, since the benchmark estimate did not perform well on the return side in the benchmark estimate validation, this may not be a positive result. Because the Delta-Q test is symmetric in both the test protocol and the analysis equations, there is no reason to believe that the performance would be better on the return side than on the supply side. This assertion is supported by the benchmark estimate validation results comparing the Delta-Q test with the flow station measurement of the added leakage.

*Manufactured Home Results*

One of the major drawbacks to the Delta-Q test formulation is that it requires that a return pressure be input, and it will provide an estimate of return leakage. This is true even for homes with no return system. This was shown to be a problem in previous work (Francisco et al. 2002a; 2003) which recommended that a modified form of the equations be used for these houses that eliminates the return portion.

If the current equations are used, it is unclear what "duct" pressure to ascribe to a system that has no return duct. Three options were considered here. The first is 1 Pa, corresponding to the small pressures often measured in the furnace closet. The second is 15 Pa, which is about the pressure drop across a typical filter. The last is 10000 Pa, which is nothing more than an attempt to make the denominator of the return term of the equation large enough to hopefully have the term drop out.

Table 7-2 shows the results of these three pressure assumptions. Both the 1 Pa and 10000 Pa results are poor, with large non-zero results for the return leakage and values for the supply side that disagree with both the nulling test and the benchmark estimate. The 15 Pa results are better, with return leakages that are smaller and supply leakage estimates that are nearer to the nulling test. Given that the known return leakage is 0 for these cases, however, the results are still less than satisfying.

Table 7-3 shows the results with the return excluded from the analysis. These results are nearly identical to the results from the nulling test, indicating that the Delta-Q test worked well for these cases as long as the change to the equations was made. Since it is straightforward to remove the return from the equation, it is again recommended that this change be made for homes without return ducts.

Table 7-2. Delta-Q Results for Manufactured Homes with Different Return Pressure Assumptions.

| | Pressure = 1 Pa | | Pressure = 15 Pa | | Pressure = 10000 Pa | |
|---|---|---|---|---|---|---|
| Site | Supply | Return | Supply | Return | Supply | Return |
| 41 | 56 | 30 | 54 | 7 | 66 | 18 |
| 45 | 79 | 75 | 73 | 15 | 84 | 22 |
| 49 | 43 | -7 | 45 | -1 | 42 | -3 |

Table 7-3. Delta-Q Results for Manufactured Homes with Return Removed from Analysis.

| | Delta-Q Test | | Benchmark Estimate | | Difference | |
|---|---|---|---|---|---|---|
| Site | cfm | % air handler flow | cfm | % air handler flow | cfm | % air handler flow |
| 41 | 49.5 | 4.2 | 35.4 | 3.0 | 14.1 | 1.2 |
| 45 | 62.5 | 7.3 | 56.4 | 6.6 | 6.1 | 0.7 |
| 49 | 45.3 | 6.2 | 9.1 | 1.3 | 36.2 | 5.0 |
| Avg. | 52.4 | 5.9 | 33.6 | 3.6 | 18.8 | 2.3 |

**Fan Pressurization Test**

Figure 7-8 shows two versions of the fan pressurization test compared to the benchmark estimate, represented as a fraction of air handler flow. The circles are the estimates using half of the plenum pressure, as described in ASHRAE Standard 152 (ASHRAE 2003). The triangles are the estimates using a fixed pressure of 25 Pa for all cases.

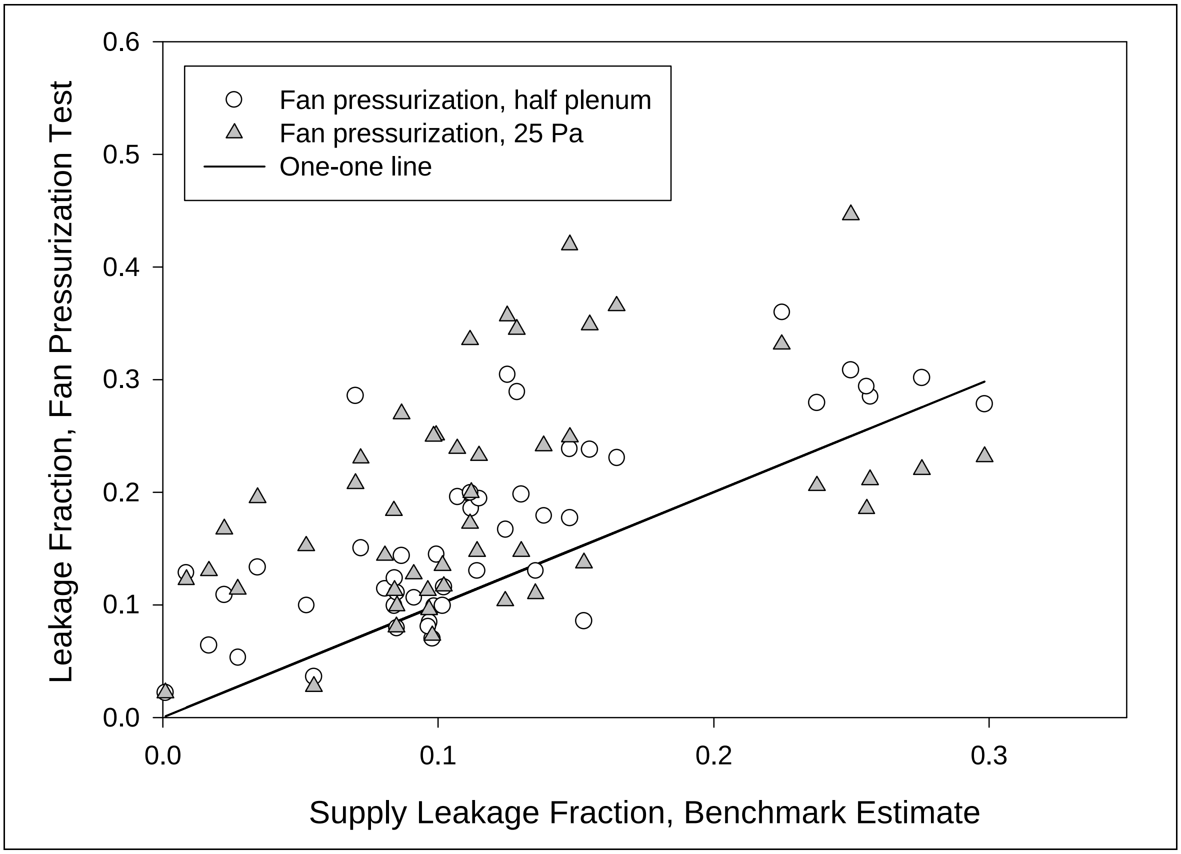



Figure 7-8. Comparison of supply leakage estimates from fan pressurization with benchmark estimate.

This figure illustrates that both versions tend to grossly overestimate the leakage, with the estimates using 25 Pa as the pressure having very large scatter and bias. On average, the estimates are 16.6% leakage and 19.6% leakage for the half plenum and 25 Pa assumptions, respectively. These are both much higher than the 11.8% average leakage for the benchmark estimate. Of the two, using half of the plenum pressure is clearly better, but neither are as good as the nulling test or Delta-Q test.

The fan pressurization test using half the plenum pressure is likely to perform better on the return side than on the supply side. This was one of the conclusions from previous work (Francisco and Palmiter 1999; 2000). This is because returns tend to be single ducts, and distributed leakage is more likely to be represented accurately by half of the plenum pressure.

**Unmodified Leakage Test Comparison**

Table 7-4 shows a statistical summary of the unmodified leakage test methods for the supply side with site 21 excluded. Because of the apparent greater uncertainty in the benchmark estimate when there are multiple stories in the home, the table is split up to allow for comparisons with single-story only, multiple story only, and the overall results.

This table shows that the nulling test agrees very well on average with the benchmark estimate for the single-story homes, where the benchmark estimate shows a high degree of accuracy on the supply side. This is true regardless of whether the results are expressed as a mean or a median. The mean absolute difference is less than 2% for these homes, and the RMS error is also low, at 2.4%.

The Delta-Q test shows an apparent overestimation bias, which is consistent with previous field, laboratory, and simulation studies. Expressed as a mean, this bias is about 14% of the leakage or 2% of the air handler flow. This agrees well with the results of a recent simulation study evaluating the bias of the Delta-Q test (Palmiter et al. 2003). Expressed as a median, the bias is about 30% of the leakage or nearly 3% of the air handler flow. The mean absolute difference and RMS error of the Delta-Q test compared to the benchmark estimate, as a percentage of air handler flow, are both about twice those for the nulling test. This bias is noticeably smaller than the bias found in the previous field study, but is still significant.

Table 7-4. Supply Leakage Comparison Across Test Methods.

| Test Method | cfm | | % air handler flow | | Difference from Benchmark Estimate, % of air handler flow | | |
|---|---|---|---|---|---|---|---|
| | Mean | Median | Mean | Median | Mean | Mean Absolute | RMS |
| | | | | | | | |
| **Single-story (n=24)** | | | | | | | |
| Benchmark Estimate | 104.6 | 100.4 | 11.9 | 10.2 | -- | -- | -- |
| Nulling Test | 98.7 | 98.0 | 11.4 | 9.2 | -0.5 | 1.9 | 2.4 |
| Delta-Q Test | 119.3 | 130.1 | 13.9 | 13.0 | 2.0 | 3.9 | 4.9 |
| Fan Pressurization, half plenum | 133.5 | 127.7 | 15.6 | 13.2 | 3.7 | 4.2 | 5.7 |
| Fan Pressurization, 25 Pa | 163.4 | 180.1 | 19.7 | 17.8 | 7.8 | 9.3 | 12.1 |
| | | | | | | | |
| **Multi-story (n=23)** | | | | | | | |
| Benchmark Estimate | 121.5 | 102.4 | 11.9 | 11.2 | -- | -- | -- |
| Nulling Test | 110.3 | 80.5 | 10.9 | 8.4 | -1.0 | 3.5 | 4.3 |
| Delta-Q Test | 121.4 | 123.3 | 12.1 | 11.7 | 0.2 | 3.4 | 3.8 |
| Fan Pressurization, half plenum | 169.0 | 137.9 | 17.2 | 15.0 | 5.3 | 6.3 | 7.5 |
| Fan Pressurization, 25 Pa | 184.1 | 179.9 | 19.3 | 18.5 | 7.4 | 9.3 | 11.4 |
| | | | | | | | |
| **Overall (n=47)** | | | | | | | |
| Benchmark Estimate | 112.9 | 102.4 | 11.9 | 10.7 | -- | -- | -- |
| Nulling Test | 104.4 | 90.7 | 11.2 | 8.6 | -0.7 | 2.7 | 3.5 |
| Delta-Q Test | 120.3 | 124.7 | 13.0 | 11.8 | 1.1 | 3.7 | 4.4 |
| Fan Pressurization, half plenum | 150.9 | 131.0 | 16.4 | 14.3 | 4.5 | 5.2 | 6.6 |
| Fan Pressurization, 25 Pa | 173.5 | 180.1 | 19.5 | 18.4 | 7.6 | 9.3 | 11.7 |

Both fan pressurization test results show greater discrepancy than either the nulling test or the Delta-Q test on this subset of homes, with the use of a pressure of 25 Pa being about twice as bad as the use of half of the plenum pressure.  In both cases, the fan pressurization test tends to overestimate the leakage.

For multi-story homes, the nulling test is significantly lower than the benchmark test, by about 10% of the leakage (1% of air handler flow) when expressed as a mean and 20% when expressed as a median.  The mean absolute and RMS errors, as a percentage of air handler flow, are both about 75% greater than for the single-story homes.  This is likely a greater problem with the benchmark estimate than with the nulling test.

The Delta-Q test shows good agreement with the benchmark estimate, on average, for the multi-story homes.  Expressed as a median, however, it is 20% higher than the best estimate as a percentage of leakage.  The mean absolute difference and RMS error are slightly better than those from the nulling test.  As discussed earlier, however, it is likely that, of the tests performed, the nulling test is the best indicator of the leakage in these homes.  Compared to the nulling test, the Delta-Q test averages about 10% of the leakage (1.2% of air handler flow) higher, with a median about 50% higher as a percentage of leakage.

Table 7-5 shows the results on the return side.  Due to the questionable accuracy of the benchmark estimate, errors with respect to the benchmark estimate are not shown.  It is, however, of interest to see how the average leakage compares with the supply leakage.

This table shows that, on average, the leakage is about balanced.  It also shows that, on average, the fan pressurization estimates are better than they are on the supply side.  This is consistent with the previous field study.

Table 7-5.  Return Leakage Comparison Across Test Methods.

| **Test Method** | **Mean, cfm** | **Mean, % air handler flow** |
|---|---|---|
| Benchmark Estimate | 127.7 | 13.1 |
| Nulling Test | 96.7 | 10.0 |
| Delta-Q Test | 123.7 | 12.9 |
| Fan Pressurization, half plenum | 130.3 | 13.6 |
| Fan Pressurization, 25 Pa | 138.8 | 14.9 |

One of the primary concerns regarding the Delta-Q test is the tendency to overpredict (i.e. false positives of large leakage).  During the course of this project, Ecotope has been contacted by a number of program managers interested in the Delta-Q test.  In one of these cases, leakage tests were to be used to rate installers of equipment, and there was little tolerance for failing installations that should have passed.  Systematically overestimating the leakage is also a concern when financial decisions are being made based on the potential savings associated with sealing the ducts.  If a homeowner is trying to decide whether to pay $500 for duct sealing work, the measurement needs to be good.  On the other hand, if the program is paid for by the agency such as the utility, then it is probably more permissible to have some fraction of homes sealed that did not really need it.

While it is true that the Delta-Q results suggest that, on average, the Delta-Q test worked fairly well, when the test does not perform well the result is usually to overestimate the leakage, often by a large amount. It certainly cannot be expected that any method will ever be exact, but it would be desirable to have errors small enough that reasonable judgments can be made. For example, it may be that the threshold is 10% leakage as percentage of air handler flow, and any result within 2% of air handler flow of the threshold is also considered to meet the standard.

Table 7-6 shows how the nulling test and Delta-Q test perform in the context of false positives on the supply side. The leakage level in the first column is the "threshold". For each of the nulling and Delta-Q tests, the number of cases above that threshold is shown, followed by the number of false positives, where a false positive is defined as a case where the test estimated a leakage greater than the threshold but the benchmark estimate did not. In addition, the average, minimum, and maximum leakage levels of the false positives are shown.

For the nulling test, site 21 is excluded because it distorts the results. At this site, the nulling test estimated about 25% leakage, while the benchmark estimate measured less than 10% leakage, so it would be an additional false positive in each row.

These results show that the nulling test has few false positives, and those that occur have small errors. For the Delta-Q test, however, the false positive rate is high, nearly 50% of cases in the 15% and 20% leakage groups. For the 10% and 15% levels, the average errors are large. This shows that, despite the reasonable performance of the Delta-Q test on average, there are cases that predict large leakage that does not exist, and one cannot be certain that these predictions constitute a large leak.

Table 7-6. Comparison of False Positive Rates and Magnitudes for Nulling and Delta-Q Tests.

| | Nulling Test | | | | | Delta-Q Test | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | # of cases | | Estimated leakage, % | | | # of cases | | Estimated leakage, % | | |
| Leak | > leak | false + | Mean | Min | Max | > leak | false + | Mean | Min | Max |
| 10% | 19 | 2 | 10.3 | 10.3 | 10.4 | 29 | 8 | 13.2 | 10.5 | 16.6 |
| 15% | 11 | 4 | 16.1 | 15.0 | 17.1 | 17 | 8 | 19.3 | 15.0 | 23.0 |
| 20% | 6 | 0 | -- | -- | -- | 11 | 5 | 21.8 | 20.9 | 23.0 |

## DELTA-Q TEST MODIFICATIONS

Due to the simplicity of performing the Delta-Q test, it has been the source of significant interest. Further, the results of this testing and previous work have given cause for optimism that, with some sort of minor modification, the results can be made better for those cases where the test has problems. With this in mind, several modifications to the test were examined for these homes.

There are three primary areas to consider when making changes to the Delta-Q test. The first of these is changes to the underlying theory. This was beyond the scope of this project; however, there is currently work being conducted that is looking at the theoretical behavior of the Delta-Q test. Previous work has identified theoretical problems, and there is hope that this further work will provide additional insights that will lead to an improvement. Examples of identified theoretical problems are the assumption that the pressure between the ducts remains constant throughout the Delta-Q test, and the assumption that leaks reverse when the house pressure is equal and opposite the leakage pressure under normal operation.

The second type of potential modification is to the testing procedure. The primary possibility here is to change the range and spacing of the envelope pressures caused by the blower door. At various times, the protocol for the Delta-Q test has suggested performing the test over a range of ±50 Pa between the house and outside, in 10 Pa increments, with samples also taken at ±5 Pa but not at 0 Pa. This differs from the protocol that was in place at the start of this project, which included measurements from ±25 Pa in 5 Pa increments, excluding 0 Pa. In order to look at these two methods in this project, data was collected from ±25 Pa in 5 Pa increments, as well as at ±30, ±40, and ±50 Pa. These stations provide a full set for evaluating both of the recommendations.

Another possibility for modifying the testing procedure that was considered but not tested was to space the stations exponentially, e.g. at ±1, 2, 4, 8, 16, and 32 Pa. This was not done in this project due to the additional amount of time that would have been required to collect these additional points, but there is some thought that collecting more data at lower envelope pressures (i.e. closer to normal operating conditions) would improve the results.

The third and final type of potential modification is to the input assumptions for characteristic duct leakage pressure and leakage exponent. There are few realistic options regarding the exponent, since measuring the exponent would require doing additional tests with extensive setup and time requirements. However, the results of using the measured exponents were evaluated in these houses to determine whether using these exponents would result in a marked improvement.

With regard to the pressure assumptions, however, there are a number of possible choices. At the time that this project was initiated, the recommendation was to use half of the plenum pressure as measured under normal operating conditions. There has been some amount of switching back and forth by the test developers between this recommendation and the recommendation of using the full plenum pressure. Andrews (2000a) showed that, for a theoretical set of cases, the full plenum worked slightly better. Francisco et al. (2002a; 2002b; 2003) found that half of the plenum pressure was better, on average, in nine homes tested under a variety of conditions.

Another suggestion that has been made is to perform a non-linear least-squares regression to estimate the pressures, rather than assume them (Walker et al. 2002). In order to avoid diverging results, constraints on the minimum and maximum pressure are required. The technique used by the test developers, and hence in this project, is to use an arctangent curve between the minimum house pressure station + 1 Pa and the maximum pressure station + 5 Pa. For example, envelope pressures ranged from ±25 Pa, the duct pressures for the Delta-Q calculation would be constrained to be between 6 and 30 Pa.

A third suggestion for a different pressure assumption, which actually falls into both the second and third categories of potential modifications, is to measure the plenum pressure at each envelope pressure station and use some fraction of that (e.g. half or full plenum). This requires a change to the testing protocol, because the supply and return plenum pressures would have to be measured concurrently with the house and fan pressures.

In addition to these possible pressure assumptions, use of the estimated actual leakage pressures was considered. As with the exponents, it is not practical to use these in general. However, it was of interest in this study to see whether using these pressures would improve the results. These estimated leak pressures were obtained using a combination of the benchmark estimate of leakage and the fan pressurization test for leakage to outside, as described in Chapter 2.

Any of the pressure assumptions could be combined with any exponent assumption and with any range and incrementing of house pressures. It is not practical to evaluate all possible combinations of these potential modifications. As a result, modifications were made one at a time. The cases discussed here are as follows, with a name assigned to each in order to make it easier for the reader to follow the discussion:

1) Duct pressures = half normal operating plenum pressures, testing range ±25 Pa (unmodified test); name “Delta-Q”.
2) Duct pressures = half normal operating plenum pressures, testing range ±50 Pa; name “dq50”.
3) Duct pressures = full normal operating plenum pressures, testing range ±25 Pa; name “dqfull”.
4) Duct pressures = pressures determined from constrained non-linear fit, testing range ±25 Pa; name “dqfit”.
5) Duct pressures = half plenum pressures measured at each station, testing range ±25 Pa; name “dqeach”.
6) Duct pressures = estimated leakage pressures, testing range ±25 Pa; name “dqpsest”.
7) Duct pressures = half normal operating plenum pressures, testing range ±25 Pa, exponents as measured from fan pressurization tests; name “dqnfp”.

All cases other than case 7 (dqnfp) used assumed duct leakage exponents of 0.6 for both the supply and return sides. Some estimates were also done using unconstrained fitting for pressures and for some of the cases listed above but with the testing range of ±50 Pa, with results showing greater errors relative to the benchmark estimate than the unmodified test.

The results are presented in Table 7-7 and Figs. 7-9 through 7-11. These results are restricted to supply leakage due to the questions about the benchmark estimate on the return side. The figures are broken up into three for readability. Delta-Q results are referred to by the case number described previously.

The boxes are described as follows: the horizontal line indicates the median; the box indicates the inter-quartile range (IQR), where the bottom of the box indicates the 25$^{th}$ percentile and the top of the box indicates the 75$^{th}$ percentile; the “whiskers” at the ends of the lines correspond to roughly three standard deviations long or to the extreme value (when there are no outliers); and all other points are outliers. Thus the boxes include half of the data. Table 7-7 includes the inter-quartile distance (IQD) which is the difference between the 25$^{th}$ and 75$^{th}$ percentiles. The boxes appear in the order in which they are listed in the legend.

Each figure contains the benchmark estimate and the unmodified Delta-Q test results (case 1). Figure 7-9 also includes the two most common simple modifications (case 2 – dq50, changing the testing range; and case 3 - dqfull, using the full plenum pressure). Figure 7-10 also includes the more complex but practical modifications (case 4 - dqfit, constrained fit; and case 5 - dqeach, half plenum from each test station). Figure 7-11 also includes the two modifications that are not practical for general-use, but use more accurate leakage characteristics for these homes (case 6 - dqpsest, estimated leakage pressures; and case 7 - dqnfp, measured leakage exponents).

In each of the three figures, only as-found cases are included, and manufactured homes are excluded. In Fig. 7-9, one additional home is excluded because of a measurement problem for the higher envelope pressure stations that resulted in a nonsensical leakage estimate. In Fig. 7-11, the home with a conditioned basement is excluded because the estimated leakage pressure is near zero, resulting in a nonsensical leakage estimate. In Table 7-7, both of the additional houses that are excluded in the figures are excluded for comparability.

These results are somewhat surprising, in that nearly every modification makes the agreement with the benchmark estimate worse. The only exception is case 5 - dqeach, which uses plenum pressures measured at each envelope pressure station. This was expected to improve the results, since it at least partially addresses the problem of the duct pressure not being constant relative to the house throughout the Delta-Q test.

The worse agreement for case 2 – dq50, where the range is expanded to ±50 Pa, indicates that the problems with the Delta-Q test are rarely a lack of high-pressure measurements. Rather, the larger spacing between stations appears to be worsening the agreement, and it is likely that there is more of a problem of insufficient data at low pressures than at high pressures. Figure 7-9 shows that using the larger range of pressures not only increases the bias, but the IQR gets larger as well, indicating increased scatter.

Table 7-7. Statistical Comparison of Benchmark Estimate to Unmodified and Modified Delta-Q Test Predictions.

| Test | Mean | | Median | IQD | Mean Absolute Difference from Benchmark |
|---|---|---|---|---|---|
| | cfm | Percentage of air handler flow | | | |
| | | | | | |
| Benchmark | 115.4 | 12.2 | 11.2 | 6.3 | -- |
| | | | | | |
| Case 1 – Delta-Q | 122.5 | 13.4 | 12.7 | 11.4 | 3.7 |
| Case 2 – dq50 | 130.8 | 14.3 | 12.3 | 11.5 | 4.2 |
| Case 3 – dqfull | 130.8 | 14.0 | 13.0 | 10.8 | 3.7 |
| Case 4 – dqfit | 156.6 | 17.3 | 15.3 | 11.3 | 6.7 |
| Case 5 – dqeach | 119.5 | 13.1 | 11.9 | 11.0 | 3.5 |
| Case 6 – dqpsest | 155.1 | 17.5 | 14.0 | 13.8 | 7.8 |
| Case 7 - dqnfp | 127.5 | 14.0 | 12.5 | 11.8 | 4.1 |

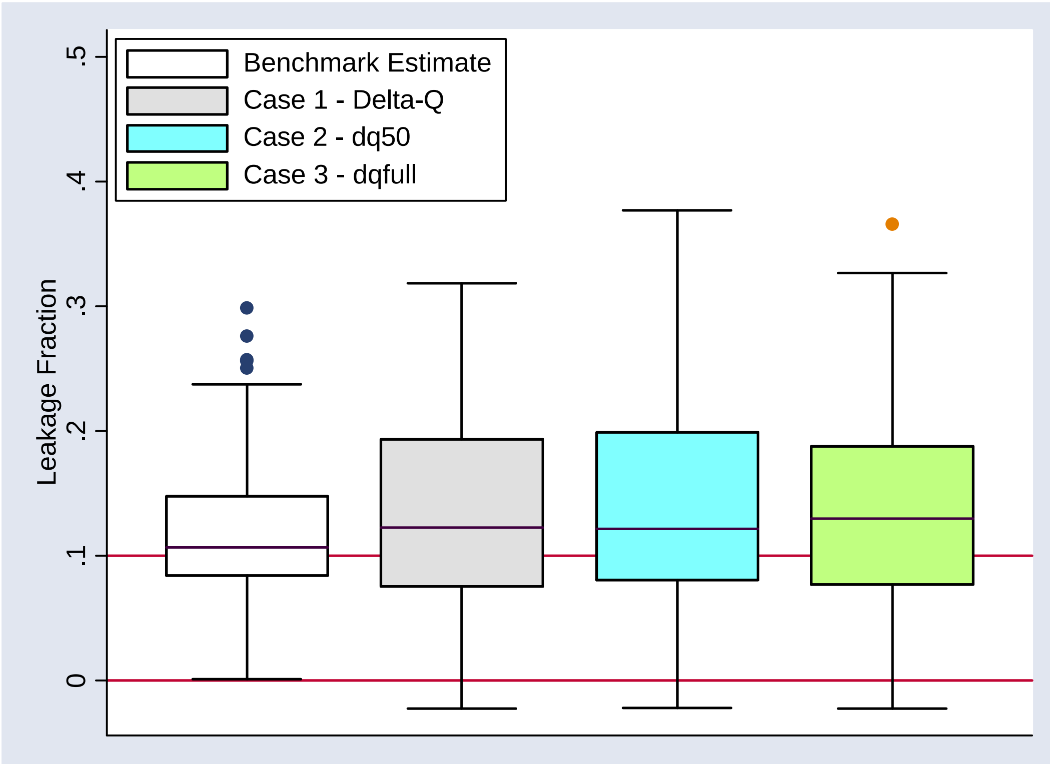



Figure 7-9. Comparison of benchmark estimate and unmodified Delta-Q test (case 1) to case 2 (dq50 - range increased to ±50 Pa) and case 3 (dqfull - use full plenum pressures).

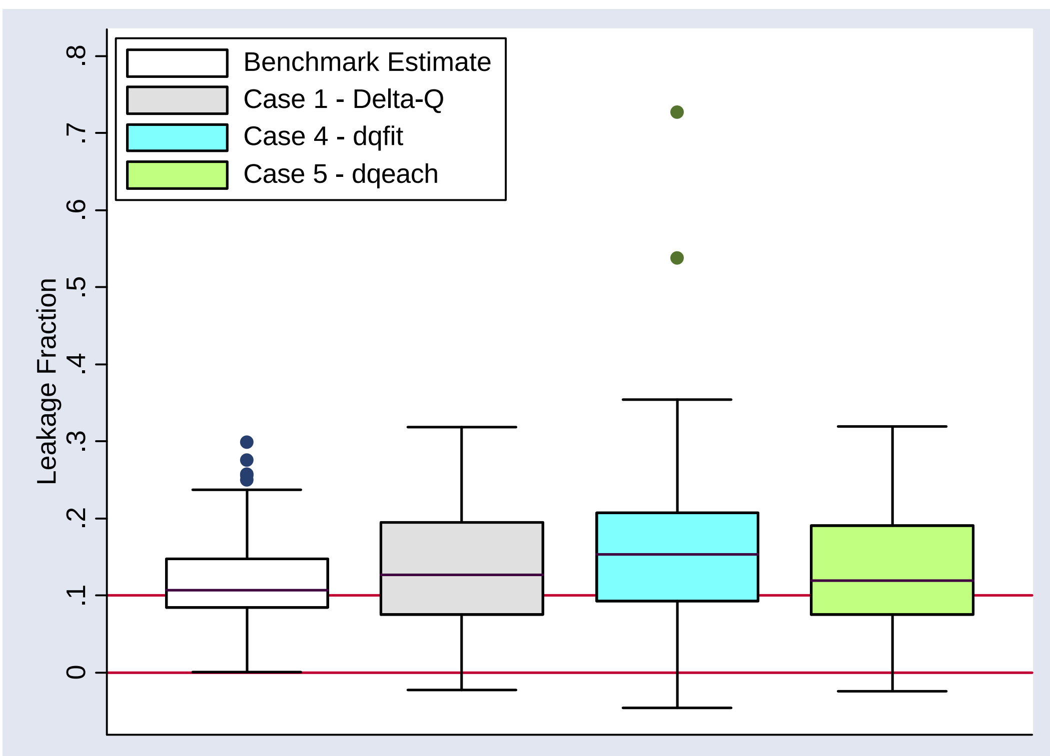



Figure 7-10. Comparison of benchmark estimate and unmodified Delta-Q test (case 1) to case 4 (dqfit - pressure fitting) and case 5 (dqeach - use half plenum pressures as measured at each envelope pressure).

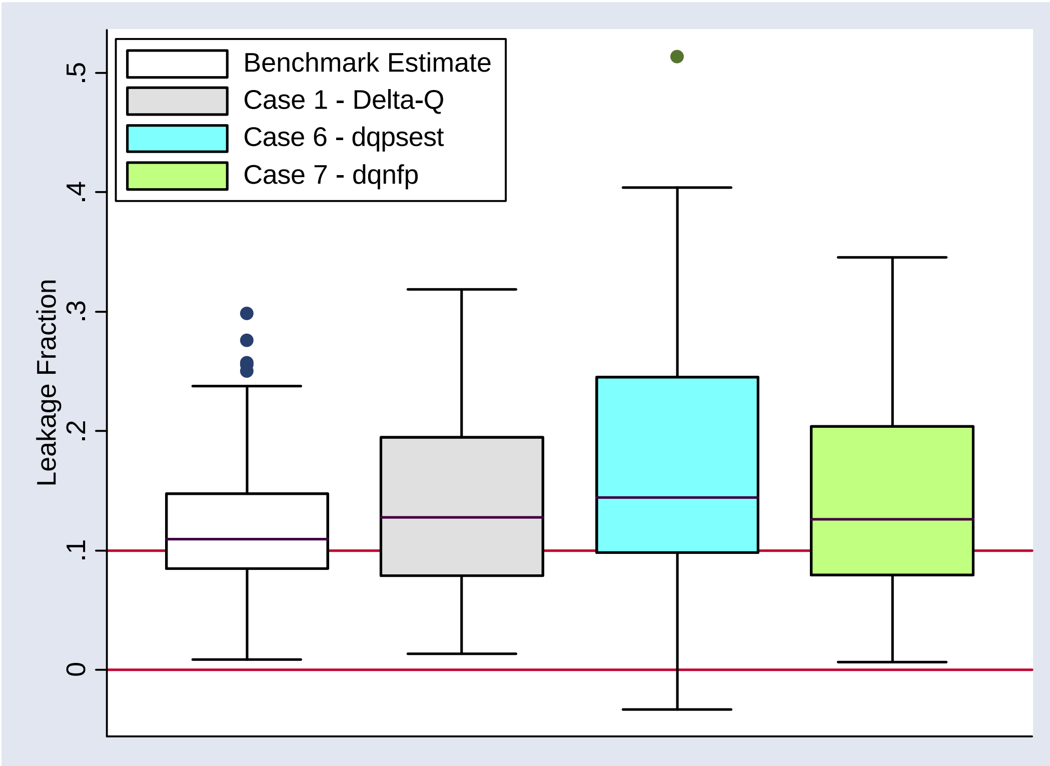



Figure 7-11. Comparison of benchmark estimate and unmodified Delta-Q test (case 1) to case 6 (dqpsest - use estimated leak pressure) and case 7 (dqnfp - use measured leakage exponent).

The worse agreement for case 3 - dqfull, using the full plenum pressure, reinforces the result of the previous study (Francisco et al. 2002a; 2002b; 2003). There are cases where using the full plenum pressure is an improvement, but overall the performance is worse. The IQR is smaller, suggesting that this technique may be more robust, but that is insufficient to overcome the greater bias.

Case 4 - dqfit, with constrained pressure fitting, shows extremely poor agreement. The lower quartile, in fact, is nearly as large as the median for the benchmark estimate. This was not expected in advance. Further investigation of this problem showed that part of the problem is that, due to the overall shifting of pressures within the duct relative to the house as the envelope pressure was changed, flow through the leaks did not reverse at the envelope pressure equal-but-opposite to the leak pressure under normal operating conditions. Another possible explanation is that the Delta-Q curve is not always smooth, especially at the pressures at which leaks reverse, and attempting to apply a non-linear regression to this sort of curve to minimize the least squares of the differences is the wrong sort of optimization. In short, finding a pressure that causes the shape of the Delta-Q curve to most closely match the measured data results in a pressure that does not actually represent the leaks, and minimizing the least squares does not minimize the error in the leakage estimates. Significant effort has gone into developing this fitting technique, but these results suggest that the technique should be dropped.

Case 5 - dqeach, where plenum pressures are measured at each house pressure station, does show improved results. The IQR is similar to that from the unmodified Delta-Q test, and the bias relative to the benchmark estimate is reduced. The primary problem with this technique is that it requires additional pressure measurement channels when doing the test, which then requires additional equipment.

Case 6 - dqpsest, with the leak pressures estimated using other tests performed at each house, shows very poor agreement. This may be due, in large part, to the problem described in the discussion of case 4 - dqfit, where the leaks do not actually reverse at the envelope pressure that is equal-but-opposite to the pressure at the leak under normal operation. It may also be that pressures at the leaks are often at low pressures, and there is insufficient data at the low pressures to be able to get a good estimate using lower pressures. Leaks are often at low pressures because of the pressure losses associated with the bends immediately after the air handler. For the cases in Fig. 7-11, the average estimated leak pressure was about 16 Pa, with a median at about 10 Pa.

Case 7 - dqnfp, with the measured exponents from the fan pressurization tests, also performs surprisingly poorly. The results are not very different from the unmodified test, and actually look more like case 2. This indicates that the assumed leakage exponents of 0.6 are, on average, reasonable choices.

The results from cases 4-6 highlight a very important fact about the Delta-Q test, which is that the change in duct pressure relative to the house as the test is performed is a major problem for the test. In cases 4 - dqfit and 6 - dqpsest, the primary goal is to attempt to use a pressure that is more representative of the pressure at the leaks. However, these two cases provide results that are much worse than any other attempted modification, in part because the pressures at which the leaks reverse during the Delta-Q test are not the same as the leak pressures.

On the contrary, case 5 - dqeach is the only modification that showed improvement. This is also the only modification that attempted to account, in some way, for the changing duct pressures relative to the house during the Delta-Q test. This suggests strongly that dealing with this problem more directly is likely the most important step in improving the Delta-Q test.

As stated previously, the primary drawback to case 5 is the need to measure the duct pressures concurrently with the other measurements of the Delta-Q test, thus requiring additional equipment. One possibility to overcome this would be to additionally measure the supply and return plenum pressures only at the maximum pressurization and depressurization of the house, e.g. ±25 Pa, and interpolate at each station using these results and the plenum pressure measurements with the blower door off.

While this does require additional pressure measurements, these extra pressures can be measured at the conclusion of the Delta-Q sample without requiring additional equipment. The hassle of removing the pressure hoses from the measurement instrument is small because it is only done twice during the course of the test.

Table 7-8 and Figure 7-12 show the results of applying this interpolation technique to these homes. This table includes the same screening as Table 7-7.

Table 7-8. Investigation of Plenum Pressure Interpolation Scheme for Improving Delta-Q Test.

| Test | Mean | | Median | IQR | Mean Absolute Difference from Benchmark |
|---|---|---|---|---|---|
| | cfm | Percentage of air handler flow | | | |
| | | | | | |
| Benchmark | 115.4 | 12.2 | 11.2 | 6.3 | -- |
| | | | | | |
| Unmodified | 122.5 | 13.4 | 12.7 | 11.4 | 3.7 |
| Case 5 - dqeach | 119.5 | 13.1 | 11.9 | 11.0 | 3.5 |
| Interpolation | 118.9 | 13.0 | 12.0 | 11.1 | 3.4 |

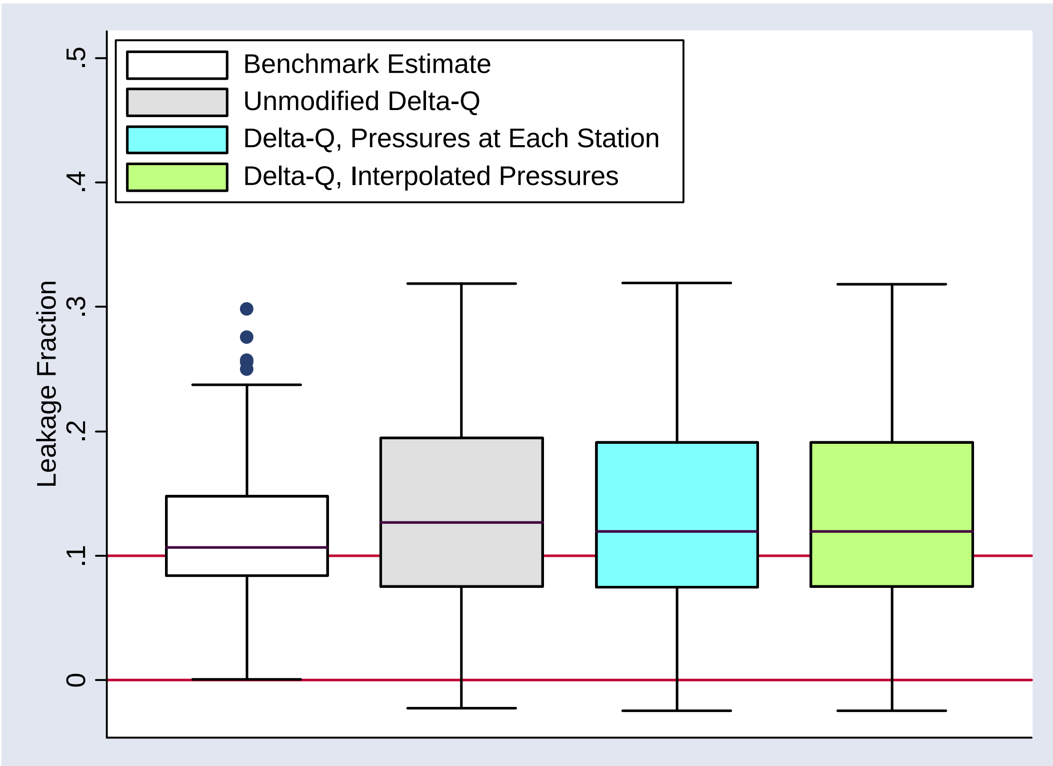



Figure 7-12. Investigation of interpolation strategy for duct pressures in Delta-Q test.

These results show that there is virtually no difference between using the actual measured pressures at each station compared to using the interpolated values. While the results are still less satisfactory than would be desirable, this suggests that, if nothing further is done to modify the Delta-Q test, at a minimum the interpolation strategy should be employed. This result notwithstanding, further evaluation of the Delta-Q test should be done with an eye towards improving the performance further.

## PRESSURES AT THE LEAKS

Much has been made of the problem of estimating the pressures at the leaks. It is this lack of knowledge that causes the fan pressurization test to be unsuitable for measuring actual leakage under normal operating conditions. It is also this lack of knowledge that has led to the method of performing a non-linear least-squares fit to the Delta-Q data, with the hope that this would improve the results. It is, therefore, of interest to analyze these pressures themselves, independent of the leakage results.

There is typically not a single pressure at the leaks. If the leakage is distributed, there will be many different pressures at the various leaks. However, it is convenient to effectively collect these pressures into a single effective pressure. This single pressure is what has been sought after for both the fan pressurization test and the Delta-Q test.

In order to obtain a benchmark estimate of the effective pressure, the power law leakage curve from the fan pressurization test was solved for the pressure that would provide the benchmark estimate of leakage to outside, as described in Chapter 2. The results are shown in Figs. 7-13 and 7-14.

Figure 7-13 compares the leakage pressure to the plenum pressure on the supply side. Plenum pressures ranged from under 12 Pa to over 113 Pa, with an average of about 45 Pa. Estimated leakage pressures ranged from under 0.5 Pa to over 67 Pa, with an average of about 16 Pa. Only one home had an estimated leak pressure over 45 Pa.

One case has an effective pressure greater than the plenum pressure. This could result for a variety of reasons, including measurement error and poor location of the pressure tap in the supply plenum. Other than this one point, all of the leakage pressures are less than the plenum pressure, with a wide range.

Figure 7-14 shows the leakage pressure as a fraction of plenum pressure. Excluding the point that has a greater leakage pressure than plenum pressure, the leakage pressure ranges from less than 1% of the plenum pressure to greater than 86% of the plenum pressure. Unfortunately, there is no clear cluster around one value, illustrating the difficulty of using any rule-of-thumb to estimate leakage pressure. On average, the leakage pressure is about 32% of the plenum pressure.

Figure 7-15 shows the comparison of the estimated pressures using the pressure fitting technique for the Delta-Q test to the estimated actual leak pressures. This pressure fitting technique, as described by the developers, is constrained to prevent diverging results. The lower horizontal line is at 6 Pa, which is the minimum resulting pressure allowed. The upper horizontal lines are at 25 Pa and 30 Pa, which are the upper limit of the test pressures and the maximum allowable pressure from the fitting procedure, respectively.

The most apparent feature of this graph is that nearly all of the pressures resulting from the pressure fitting technique are at or near the maximum allowable. There are only five cases where the constrained pressure fitting results in a pressure lower than 20 Pa. In addition, there

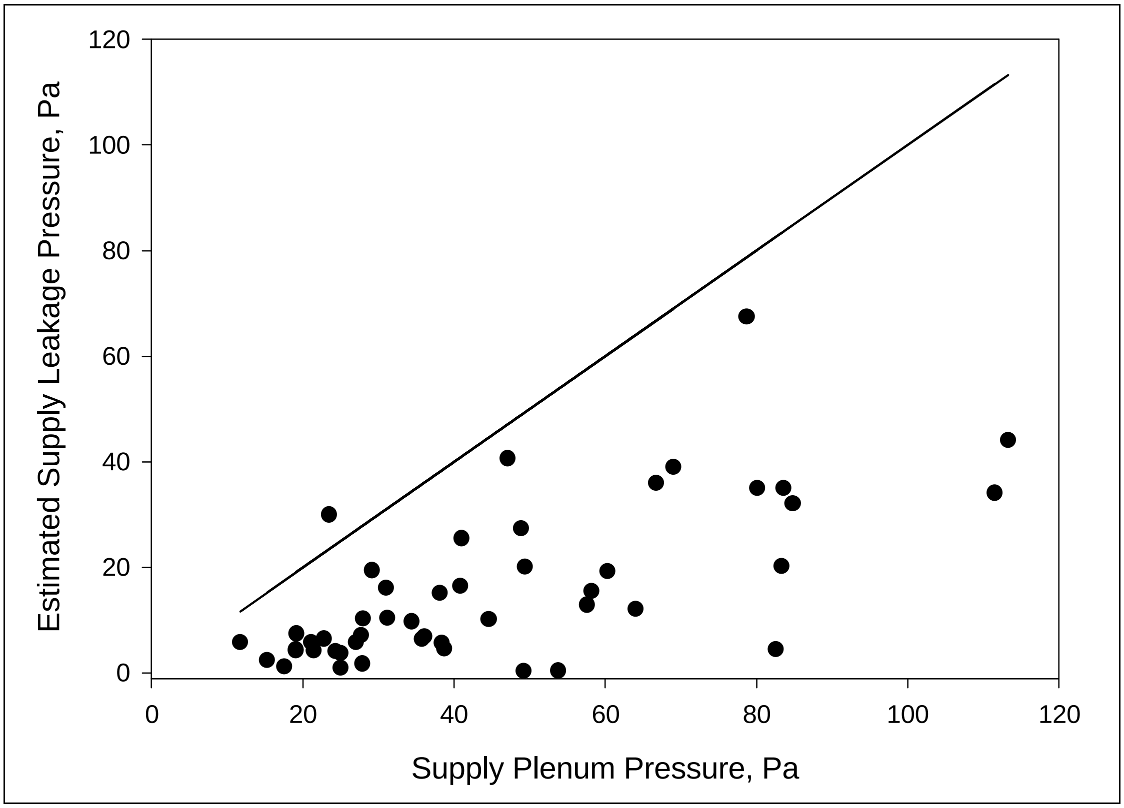



Figure 7-13. Comparison of estimated supply leakage pressure to supply plenum pressure.

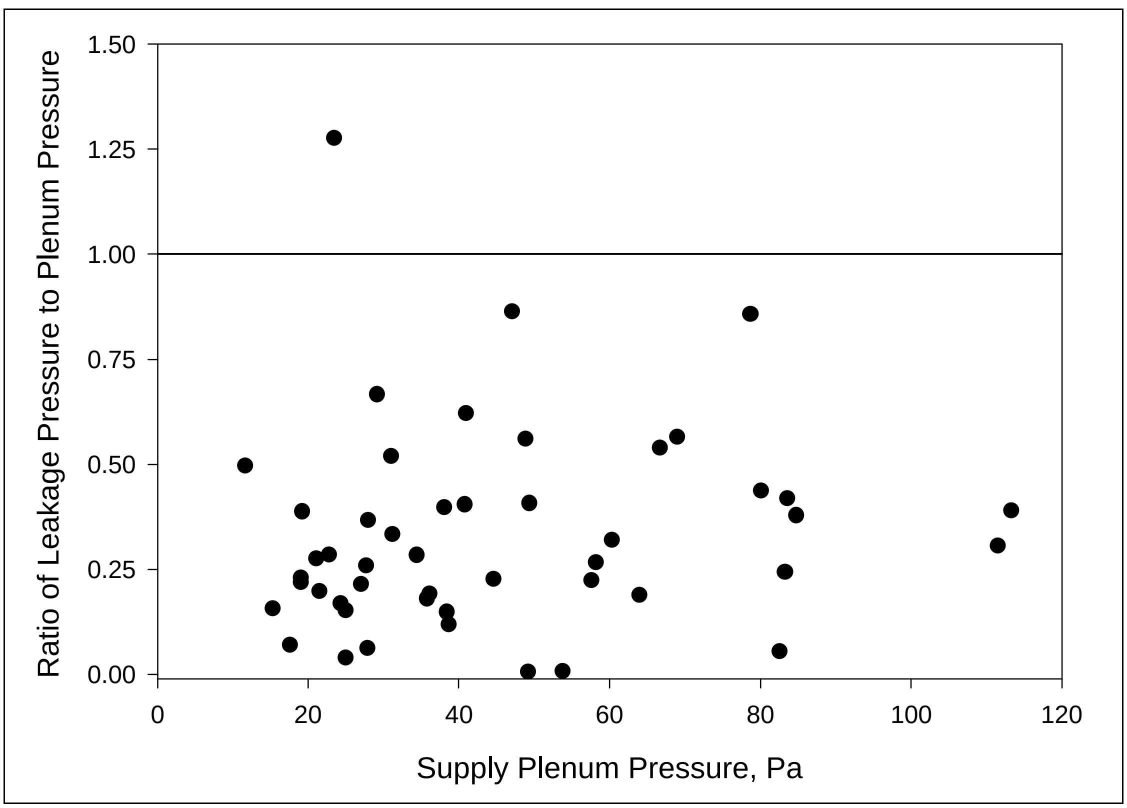



Figure 7-14. Ratio of estimated supply leakage pressure to supply plenum pressure.

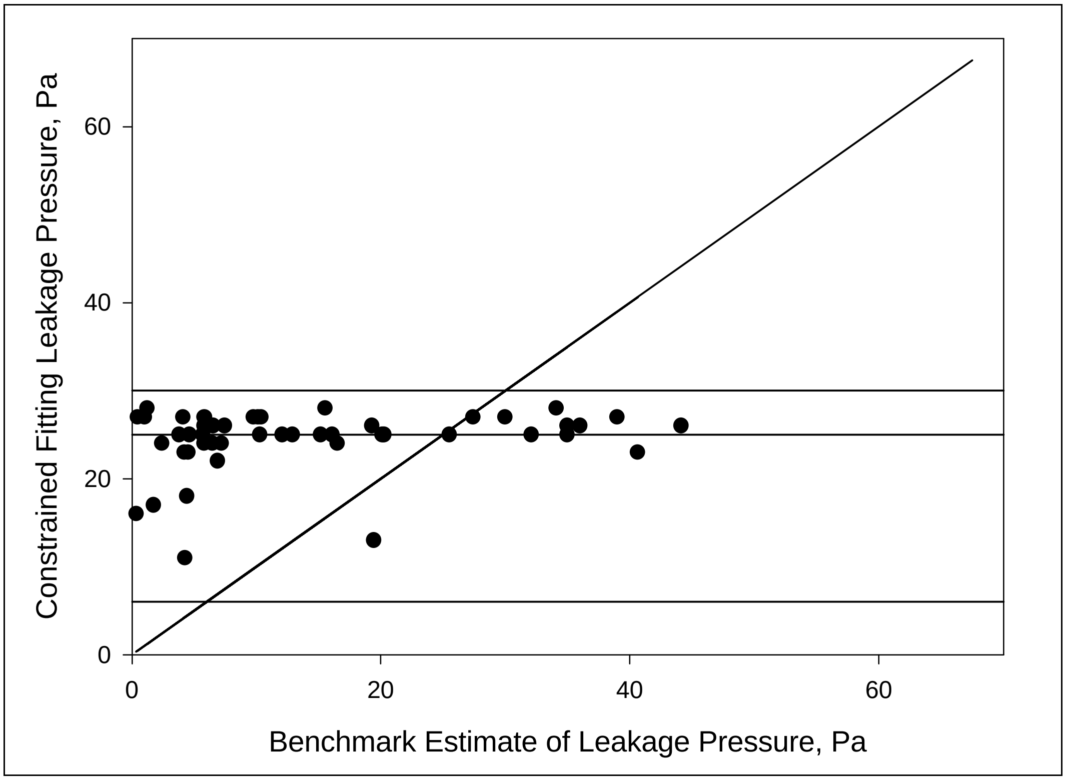



Figure 7-15. Estimated leak pressures from Delta-Q constrained pressure fitting compared to estimated actual leak pressures.

are only three cases where the benchmark estimate of the leakage pressure is below the maximum allowable fit pressure and the resulting fit pressure is below the benchmark estimate. This indicates a general tendency to overestimate the leakage pressure, with the constraint being the primary factor that prevents the overestimation.

Figure 7-16 shows the results of an unconstrained fitting, with two divergent points removed. This shows a much wider spread, as expected, but it still shows a general tendency to overestimate the leakage pressure. The primary cases where this is not true are those with high benchmark estimates of the leakage pressure. Most of these cases have large leaks at or near the plenum, as well as other leaks distributed throughout the system as is common in duct systems.

These trends were compared to the results of simulations done to evaluate the Delta-Q test, including the pressure fitting routine without constraints (Palmiter et al. 2003). That study showed that, when there was a single leak, the pressure fitting technique overestimated the leakage pressure in every case, regardless of where the leak was. The only situation studied where the pressure fitting did not overestimate the leakage pressure were those cases with two leaks, one at the plenum pressure and one at a lower pressure. This is similar to the cases shown in Fig. 7-16 with the fit pressures lower than the benchmark estimate of the leakage pressure. This agreement would appear to qualitatively support the conclusions of the theoretical work. There are differences in the magnitude of the discrepancies between the theoretical work and the field study, with the pressure fitting technique working less well in the field study. This is likely

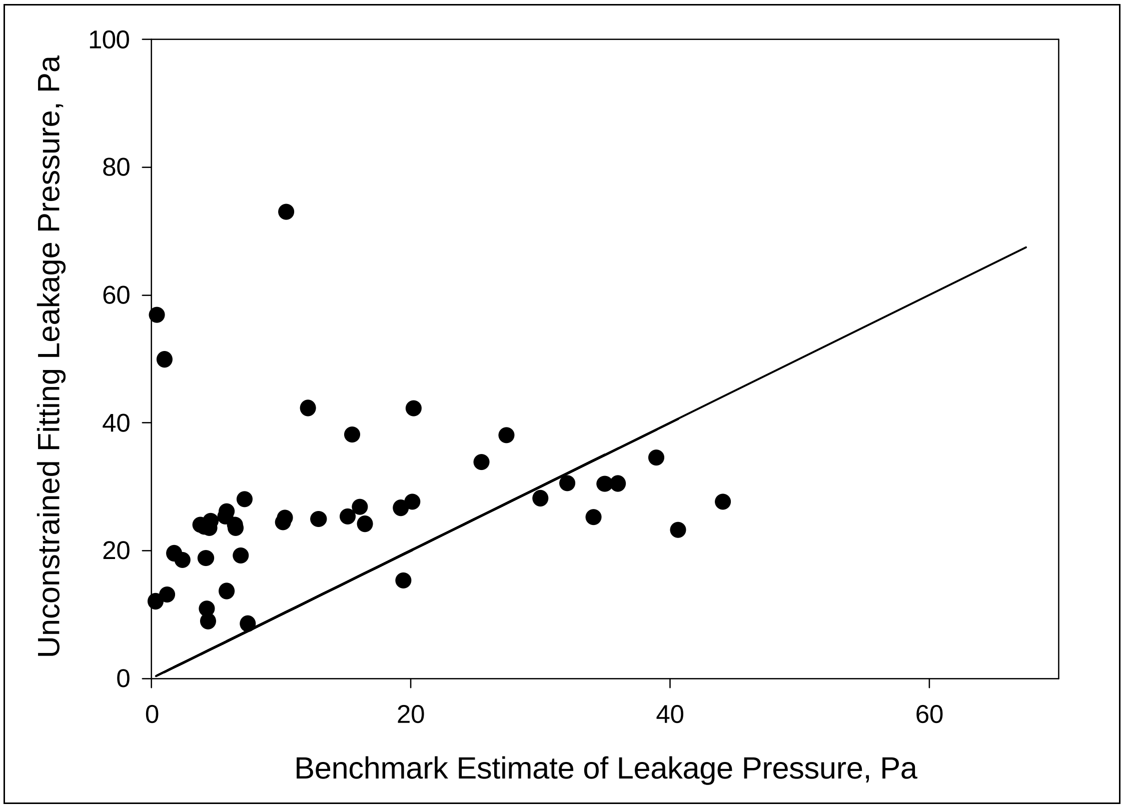



Figure 7-16. Estimated leak pressures from Delta-Q unconstrained pressure fitting compared to estimated actual leak pressures.

due to the more complex nature of the leaks in the field than in the idealized cases analyzed in the simulations.

Another feature that was noticed in the simulation study was that the leakage pressure that was estimated by the pressure fitting technique often was “pinned” at or near one of the sampling pressures due to local minima at these stations. Analysis of the field data shows a similar phenomenon, as shown in Fig. 7-17. This graph is restricted to cases with leakage pressures below 45 Pa. The horizontal lines are at 20 and 25 Pa, which are the largest two of the nominal targets for the Delta-Q test. This graph shows that there are many cases with leakage pressures from the pressure fitting technique at or near 25 Pa, with several also in the vicinity of 20 Pa. This “pinning” behavior suggests that the “leakage” pressure is often determined more by the choice of sampling stations than by the leakage of the ducts.

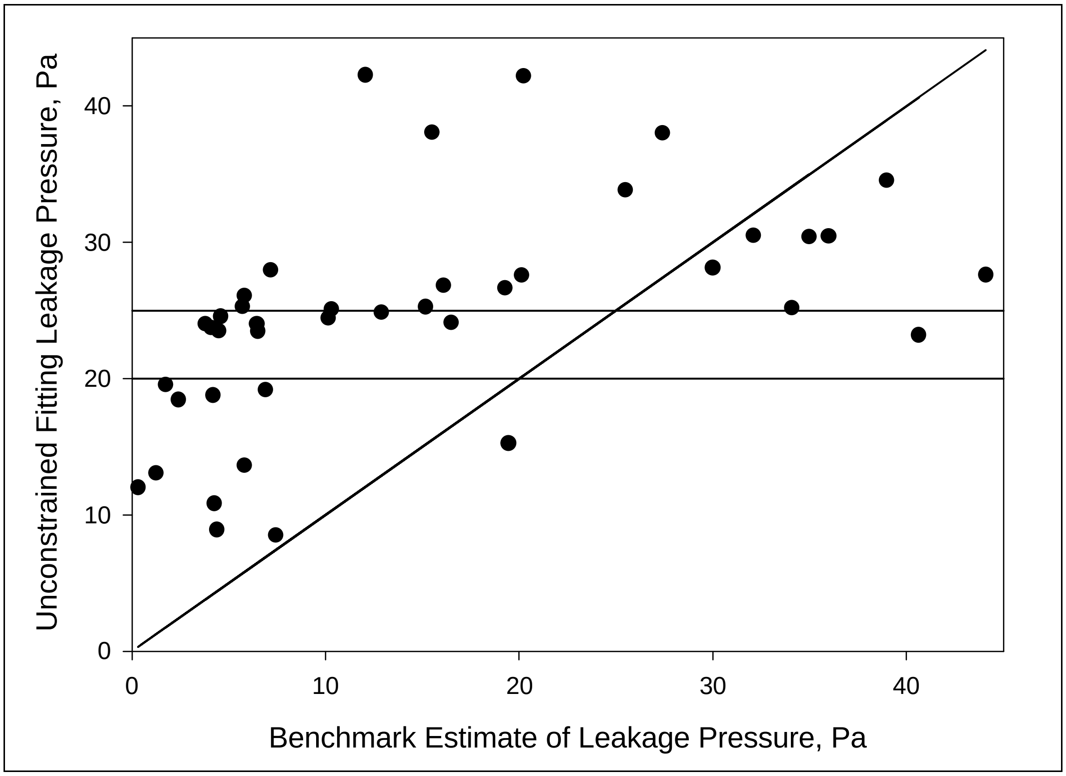



Figure 7-17. Tendency of estimated leak pressures from Delta-Q pressure fitting to be pinned at sampling points.

## IMPACT OF LEAKAGE ON DUCT EFFICIENCY

Duct leakage is just one component influencing the thermal distribution system efficiency of forced-air systems. It is, therefore, of interest to examine how much of an impact the duct leakage has on the efficiency. In order to look at this question in a larger sample of homes, Brookhaven National Laboratory provided a small amount of additional funding for the purpose of collecting additional information that is required for estimating duct efficiency, and to use the model in ASHRAE Standard 152P (ASHRAE 2003) for making efficiency estimates. The primary additional measurements were the duct surface area and estimated insulation level, as well as the insulation level of the buffer space in which ducts were located.

All of the results presented here are using the model in ASHRAE Standard 152, under seasonal conditions for Seattle. The cycling loss factor from Standard 152P is included. These houses are a subset of the homes for which the data is available; future work may include applying the model to more cases.

Modeling was done using a the benchmark estimate, the nulling test, and five permutations of the Delta-Q test. These five are, in order:

1) Using half plenum pressure, data taken from +/- 25 Pa in 5 Pa increments (Case 1).
2) Using half plenum pressure, data taken at +/-5 Pa and from +/-10 Pa to +/- 50 Pa in 10 Pa increments (Case 2).
3) Using full plenum pressure, data taken from +/- 25 Pa in 5 Pa increments (Case 3).

4) Fitting for the leak pressures using the algorithm provided by LBNL, data taken from +/- 25 Pa in 5 Pa increments (Case 4).
5) Using half of the pressure measured at the plenum at each pressure station, data taken from +/- 25 Pa in 5 Pa increments (Case 5).

Efficiency estimates were generated for eight houses. Two of the houses, sites 17 and 36, were part of the benchmark estimate validation testing, and so each have three sets of results. These are designated with an "a" for as-found duct leakage, "s" for the case with the supply leak added, and "r" for the case with the return leak added. This provides a total of 12 sets of results.

Table 7-9 shows the supply leakage results for these 12 cases, expressed as leakage efficiency (the fraction of air that makes it into the conditioned space, i.e. 1 – [leak fraction]). This is done because the leakage efficiency is the parameter that is used in the thermal efficiency model.

This table shows that, on average, about 10% of the system airflow is lost through supply leakage for these 12 cases. This is less than the average leakage for the entire sample of homes in this project, despite having the cases with added leakage, so it is expected that the efficiency results will also be higher than would be the average for all homes in the study. The lack of larger leaks also means that conditions should be favorable for the Delta-Q test, which allows for highlighting any problems with specific variants.

Table 7-10 shows the resulting duct efficiencies. These results are also shown in Figs. 7-18 and 7-19. Though the return leakage efficiencies are not presented, the appropriate return leakage was used for each set of duct efficiency estimates.

Figure 7-18 shows compares the efficiency estimates from the nulling test and the unmodified Delta-Q test (case 1) to the efficiencies using benchmark estimate of leakage. Figure 7-19 drops the nulling test, and compares the five versions of Delta-Q to the benchmark estimate. In both graphs, the line represents perfect agreement with the results using the benchmark estimate.

As expected due to the lack of cases with large leaks, neither the nulling test nor the unmodified Delta-Q test show many large discrepancies, though there are some exceptions, most notably site 7 for the nulling test and site 18 for the Delta-Q test. Both of these sites experienced significant wind during testing. The Delta-Q test also noticeably underestimates the efficiency at site 17s, by about 4.5 percentage points. This is one of the two cases in this set with an added supply leak. It is expected that the Delta-Q test will underestimate the efficiency in those cases where it has problems due to the tendency to overestimate the leakage.

Comparing the Delta-Q tests variants shows that the only one that improves the results is case 5, where the plenum pressure is measured at each station and used in the analysis, rather than just a single measurement of plenum pressure with the blower door off. This is consistent with the overall leakage results for the study. The Delta-Q test modified to collect data at house pressures of +/- 50 Pa made the results noticeably worse, and the worst set was using the pressure fitting technique.

Table 7-9. Supply Leakage Efficiency Estimates from Different Methods.

| Site | Benchmark | Nulling | Delta-Q, ½ plenum, +/- 25 Pa | Delta-Q, ½ plenum, +/- 50 Pa | Delta-Q, plenum, +/- 25 Pa | Delta-Q, fit, +/- 25 Pa | Delta-Q, ½ each, +/- 25 Pa |
|---|---|---|---|---|---|---|---|
| 1 | 0.865 | 0.871 | 0.871 | 0.867 | 0.871 | 0.871 | 0.871 |
| 7 | 0.983 | 0.907 | 0.971 | 0.967 | 0.976 | 0.977 | 0.973 |
| 8 | 0.903 | 0.920 | 0.926 | 0.941 | 0.920 | 0.906 | 0.927 |
| 10 | 0.898 | 0.926 | 0.924 | 0.916 | 0.916 | 0.887 | 0.925 |
| 17a | 0.965 | 0.952 | 0.961 | 0.960 | 0.964 | 0.949 | 0.963 |
| 17s | 0.865 | 0.853 | 0.819 | 0.811 | 0.833 | 0.789 | 0.830 |
| 17r | 0.941 | 0.950 | 0.916 | 0.914 | 0.920 | 0.926 | 0.927 |
| 18 | 0.916 | 0.903 | 0.834 | 0.840 | 0.870 | 0.800 | 0.846 |
| 23 | 0.888 | 0.892 | 0.867 | 0.835 | 0.823 | 0.848 | 0.868 |
| 36a | 0.915 | 0.929 | 0.921 | 0.907 | 0.913 | 0.881 | 0.922 |
| 36r | 0.894 | 0.909 | 0.908 | 0.893 | 0.890 | 0.891 | 0.910 |
| 36s | 0.801 | 0.807 | 0.794 | 0.769 | 0.787 | 0.726 | 0.802 |
| Avg. | 0.903 | 0.902 | 0.893 | 0.885 | 0.890 | 0.871 | 0.897 |

Table 7-10. Distribution Efficiency Estimates Using Different Leakage Estimates, %.

| Site | Benchmark | Nulling | Delta-Q, ½ plenum, +/- 25 Pa | Delta-Q, ½ plenum, +/- 50 Pa | Delta-Q, plenum, +/- 25 Pa | Delta-Q, fit, +/- 25 Pa | Delta-Q, ½ each, +/- 25 Pa |
|---|---|---|---|---|---|---|---|
| 1 | 78.0 | 77.0 | 77.4 | 77.0 | 77.4 | 77.7 | 77.5 |
| 7 | 93.1 | 85.2 | 91.9 | 91.5 | 92.4 | 92.5 | 92.1 |
| 8 | 84.2 | 85.7 | 86.2 | 87.4 | 85.7 | 84.4 | 86.3 |
| 10 | 78.3 | 81.5 | 81.3 | 80.4 | 80.4 | 77.2 | 81.4 |
| 17a | 75.3 | 73.6 | 74.3 | 74.2 | 74.6 | 73.1 | 74.5 |
| 17s | 65.4 | 64.3 | 60.9 | 60.1 | 62.5 | 58.5 | 62.0 |
| 17r | 72.2 | 73.5 | 70.2 | 69.5 | 71.0 | 71.3 | 71.3 |
| 18 | 82.3 | 80.4 | 74.6 | 76.0 | 77.9 | 71.9 | 75.7 |
| 23 | 81.8 | 81.0 | 80.0 | 77.5 | 76.9 | 78.7 | 80.1 |
| 36a | 81.1 | 83.0 | 82.1 | 80.6 | 81.2 | 77.7 | 82.3 |
| 36r | 78.4 | 80.5 | 79.1 | 77.1 | 78.1 | 78.3 | 79.4 |
| 36s | 66.8 | 66.9 | 64.3 | 60.7 | 63.9 | 56.9 | 65.2 |
| Avg. | 78.1 | 77.7 | 76.9 | 76.0 | 76.8 | 74.9 | 77.3 |

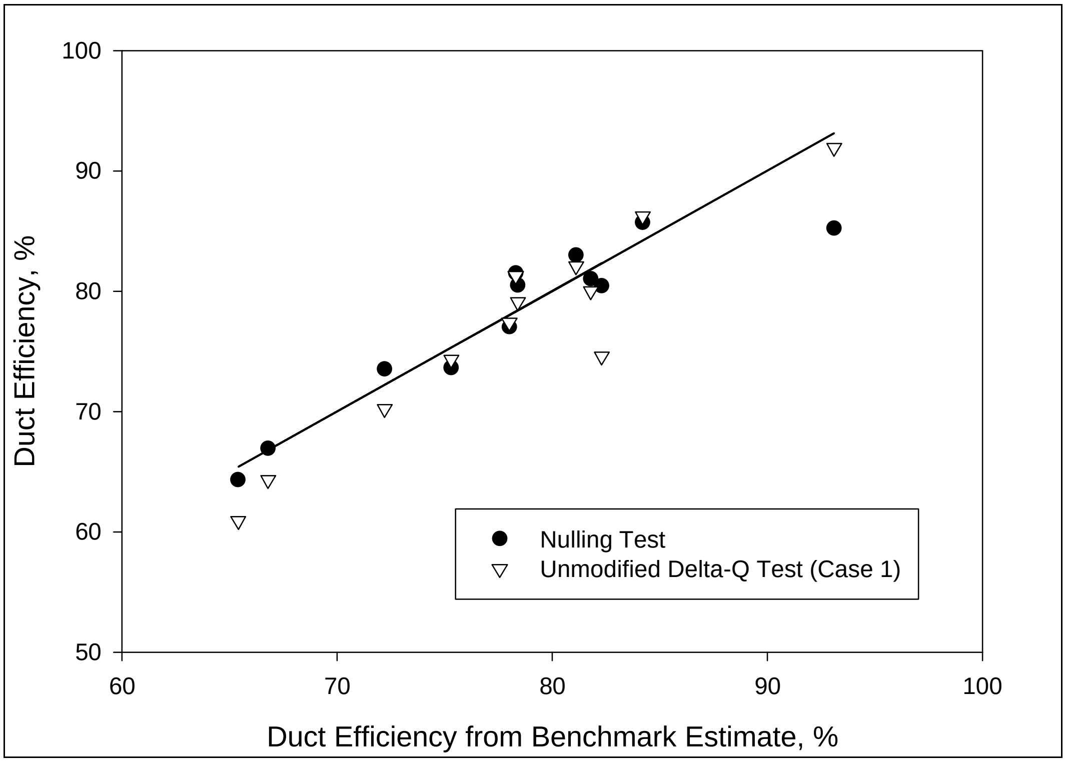



Figure 7-18. Efficiency estimates for the nulling test and unmodified Delta-Q test (case 1) compared to the benchmark estimate.

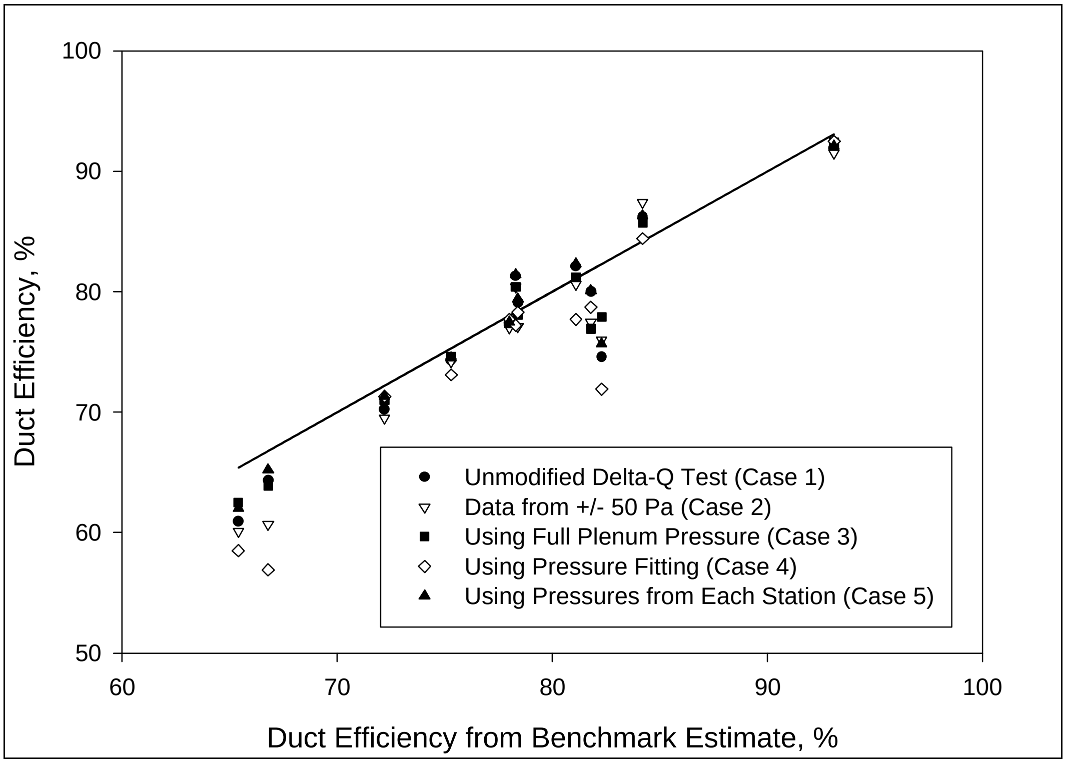



Figure 7-19. Efficiency estimates for five variations of the Delta-Q test compared to the benchmark estimate.

On average, all of the methods performed reasonably well for this subset of homes, with the notable exception of the pressure fitting technique.  This technique averaged more than three percentage points lower than the benchmark estimate, with three of twelve cases off by about 7-10 percentage points.  It is worth noting, however, that the pertinent figure of merit in terms of retrofit potential is the duct efficiency loss.  Since the duct efficiency loss is usually less than 50%, an error in efficiency estimate will be a larger fraction of the efficiency loss.  Thus, a small error in duct efficiency has the potential to be a significant fraction of the savings potential.

Figure 7-20 compares the leakage efficiency to the overall duct efficiency using the benchmark estimate.  This graph shows that the duct efficiency generally follows the supply leakage efficiency.  The three cases with much lower duct efficiency for the level of leakage are all from site 17.  At this site, the majority of the ducts were uninsulated sheet metal, resulting in large conduction loss and hence a much lower overall efficiency.  The other deviations from a straight line are primarily due to varying conduction losses, return-side losses, and buffer space insulation levels.

These results cannot be said to be conclusive on the adequacy of any one method due to the general absence of homes with large leakage.  They do show, however, that both the nulling and Delta-Q test can often provide inputs that give reasonable efficiency numbers.  They also show that both methods are prone to occasional failure.  The Delta-Q test, as expected based on the leakage results, does not perform quite as well as the nulling test.

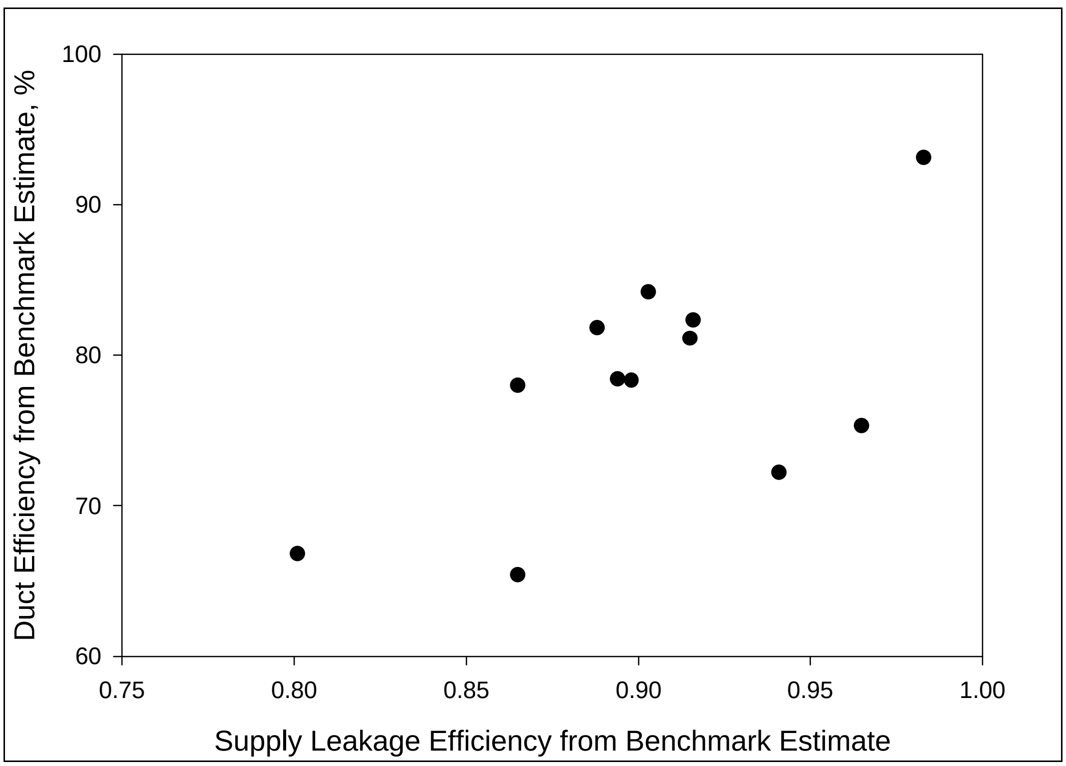



Figure 7-20.  Comparison of duct efficiency to leakage efficiency, based on benchmark estimate.

Perhaps the most important finding here with regard to the Delta-Q test is that many of the attempts to improve the results have not panned out in these houses, especially the pressure fitting technique. This is consistent with the leakage estimation performance in the full study. There is no evidence in either this subset of efficiencies or in the leakage results as a whole to suggest that, in the field scenario, using full plenum, using +/- 50 Pa data, or pressure fitting provides a benefit, and often can make the results worse.

The other important result of the duct efficiency investigation is that the average efficiency of the as-found cases is about 82%. This is likely higher than would be found in the full sample from this project, because many of the larger leaks were not included in this subset. However, even with the lower leakage levels in this subset, nearly 20% of the conditioning energy is lost, on average, indicating that there remains significant potential for energy savings via a variety of mechanisms. The best solution would be to move the ducts within the conditioned space, such that all of the losses directly through the ducts would be recovered to the house.

## OTHER EFFECTS

It was hoped at the outset of the project that it would be possible to investigate correlations between duct leakage and heating system, and also evaluate any seasonal effects on duct leakage. Because the recruitment process resulted in the vast majority of homes having gas furnaces, the bulk of which were downflow, it was not possible to perform a valid statistical analysis of the impacts of heating system on duct leakage. There also were no seasonal effects that could be attributed specifically to time of year; the recruitment process resulted in different styles of homes being predominantly tested during different times of year, so any apparent correlations could be due to differences in house type. Other than wind speeds tending to be higher at some times of the year than others, it is not clear that there should be any seasonal effects on duct leakage.

## TIME AND COSTS OF THE TEST METHODS

Table 7-11 provides estimates of the amount of time required for the nulling, Delta-Q, and fan pressurization tests, as well as the equipment required. Exact times and costs may vary depending on the type of house, any problems that arise, and the skill of the technicians.

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. This installation of the second fan is especially time-consuming if the air handler is outside of the conditioned space, because a second frame (such as for a blower door) is needed and a long flexible duct must be stretched between the fan and the air handler. 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 one more calibrated fan than the Delta-Q test.

The setup for the nulling test is essentially identical to that for the Delta-Q test if there is no ducted return system, in which case the time-consuming aspect of setting up the second fan is not required.  In addition, in this special case, the material requirements are the same as for the Delta-Q test.

Except for the special case of no ducted return system, the Delta-Q test is the fastest test from start to finish as a stand-alone diagnostic.  The actual testing time is the longest of the tests, but the setup is significantly faster than any of the other methods.  It also requires the least amount of equipment, so it has the lowest initial investment.

The fan pressurization test requires a similar amount of equipment as the nulling test, although a laptop is less important.  The setup time is significantly greater due to the need to seal off all of the registers and grilles.  Once the setup is complete, the test can be done in a short amount of time.

Table 7-11.  Time and Materials Required for the Nulling, Delta-Q, and Fan Pressurization Tests

| Test | Setup Time | Test Time | Equipment |
|---|---|---|---|
| Nulling | 45-75 minutes, depending on the ease of placing the barrier between supply and return.  *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).* | 15 minutes (longer in windy conditions) | • 2 calibrated fans that can run at low pressures and flows<br>• Pressure gauge, preferably one that can connect to a computer<br>• Laptop preferable<br>• Total cost, without laptop, approximately $4000 |
| Delta-Q | 15-30 minutes (installation of pressure hoses and a calibrated fan in the envelope) | 30 minutes | • 1 calibrated fan<br>• Pressure gauge, preferably one that can connect to a computer<br>• Laptop preferable<br>• Total cost, without laptop, approximately $2500 |
| Fan Press. | 60-90 minutes, depending on number of registers, including placing barrier between supply and return and tests on both sides of the system | 20 minutes | • 2 calibrated fans<br>• Pressure gauge<br>• Total cost approximately $4000 |

# 8
# SUMMARY OF SAMPLE CHARACTERISTICS

Although the primary goal of this study was to compare the duct leakage test methods, it was hoped the sample would be large enough to be roughly representative of the single-family housing stock in the Puget Sound region. At the present time very little is known about the distribution of duct leakage and related variables in the housing stock. For example, one question that may be of interest is the fraction of the existing housing stock that has duct leakage greater than 20 percent.

The purpose of this section is to provide a statistical summary of selected home characteristics and test results in a format that allows one to assess the statistical distribution of the characteristics across the sample of homes. There were 48 single-family stick-built homes and 3 manufactured homes. This summary is restricted to the single-family homes only. Unless otherwise noted all of the data presented below is based on a sample size of n=48.

The data is presented in tables that all have an identical format. The first entry in each data row is the variable label. This is followed by the sample mean. The seven remaining columns present selected quantiles of the data: the sample minimum, followed by the 10$^{th}$ percentile, the 25$^{th}$ percentile, the 50$^{th}$ percentile (the median), the 75$^{th}$ percentile, the 90$^{th}$ percentile, and the sample maximum. This allows easy assessment of some of the distributional properties. For instance, the central half of the sample lies between the 25$^{th}$ and 75$^{th}$ percentiles. The difference of the 75$^{th}$ and 25$^{th}$ percentiles is the interquartile difference, a robust measure of spread.

All of the tables are placed at the end of the discussion. The discussion of the tables is limited to the summary of median results and cross comparison of single-story and multi-story homes. However, the curious reader will find many interesting observations to be made with respect to the range of values and comparisons of other quantiles.

Examination of the data as well as our observations when conducting the field tests at the homes suggested the multi-story homes had different characteristics than the single-story homes. Therefore, each tabulated topic, except for combustion analysis results, is actually shown in three separate summary tables; one for all homes combined; one for single-story homes; and one for multi-story homes. There were 25 single story homes and 23 multi-story homes in the sample.

Tables 8-1a through 8-1c present basic size information on the homes: floor area, volume, and average ceiling height. Table 8-1a is for all 48 homes, Table 8-1b is for single-story homes, and Table 8-1c is for multifamily homes. The median floor area was 1668 square feet for the sample as a whole. The median area for single-story homes was 1541 square feet versus 1812 square feet for the multi-story homes. The median volume was 13592 cubic feet for the sample as a whole. The median volume for single-story homes was 11845 cubic feet versus 14788 cubic feet for the multi-story homes. The ceiling height was calculated as the ratio of volume to floor area. It increases from 7.83 feet in the one story case to 8.22 feet for the multi-story case. Thus the volume increases more than the floor area when comparing multi-story to single-story homes, likely due to the prevalence of high cathedral-ceiling living/dining areas in the multi-story homes.

Tables 8-2a through 8-2c present physical information about that portion of the supply ductwork that was located in unconditioned zones. Due to time constraints and lack of suitable access, it was not always possible to gather this information, so the sample size is only 39 instead of 48. The surface area of the supply ductwork is one of the physical characteristics that determine the conductive heat loss from the ducts; the other is the R-value of the duct walls. The unit of duct area in the tables is square feet while the unit of R-values is ($ft^2$*hr*F / Btu).

The median supply-duct surface area for the sample as a whole is 296 square feet or about 17.5 percent of the floor area. It is interesting to note that the multi-story homes actually had a somewhat smaller supply duct surface area in unconditioned spaces than the single-story homes: 257 versus 248 square feet. Correspondingly, the duct area as a percentage of floor area drops from 20.6% for single-story homes to 15.0% for multi-story homes.

One possible explanatory factor for this is the fact that multi-story homes tend to have smaller footprints than single-story homes. For example, a 2200 square foot multi-story home may have a footprint of only 1100 square feet, compared to the single-story median of over 1500 square feet. Much of the ductwork serving second stories and the two-story portions of split level homes are located within interior walls, so they are not counted in these surface areas.

The level of supply duct insulation in these homes was fairly low, with medians of R-3.1 for the single-story and R-4 for the multi-story homes. It should be noted that all uninsulated ductwork was assigned an R-vale of 1.5, which is the effective R-value for uninsulated, shiny ductwork..

The pressures in the duct system play a very important role with respect to air leakage into or out of the duct system. Tables 8-3a through 8-3c display pressures in the duct system, all given in Pa. Plenum pressures were measured throughout the duration of the various duct leakage tests. The values in the table are those pertaining to normal operation of the system. The median plenum pressures were 38.2 Pa on the supply side and 53.2 Pa on the return side. The sum of these two pressures provides a rough estimate of the external static pressure. This estimate is actually somewhat low because the pressures were measured in the plenums, and not external to the air-handling unit. The median external static was 101.4 Pa for the sample as a whole. It is of interest to compare this with 0.2 inches of water or about 50 Pa, which is the standard rating external static pressure used by residential equipment manufacturers.

Comparing the single-story and multi-story cases, we see that the median supply plenum pressure was somewhat larger for the multi-story homes: 40.8 versus 35.8 Pa. This reflects the presence of longer duct runs (much of which is internal to the home) in the multi-story case. In contrast, the median return plenum pressures for multi-story homes were significantly lower, 48.9 versus 60.1 Pa. This is due to the use of leaky internal building cavities for parts of the return system. Because they are leaky, the air handler does not have to pull as hard to get air, reducing the pressures in the return plenum. Other tables discussed later also reflect the large influence of non-ducted return runs.

The fan pressurization test data was used to estimate an apparent leak pressure separately for the supply and return systems. These leak pressures are for leaks to or from outside only. This procedure is discussed in more detail in Chapter 2. The apparent leak pressures are summarized in Tables 8-3a through 8-3c. The median leak pressure on the supply side was only 10.2 Pa or about 27% of the plenum pressure, versus 20 Pa or about 38% of the plenum pressure on the return side. Median supply-side leak pressures were about the same for multi-story as for single-story homes: 10.1 versus 10.3 Pa. Median return-side leak pressures were much lower for multi-story homes: 14.3 versus 27.4 Pa, a ratio of almost 2-to-1.

The low return leak pressures for multi-story homes are due to the use of building cavities for return runs. It is common to assume that, because the building cavities are inside the conditioned space, all of the leakage is from inside. However, it is often the case that the building cavities communicate to outside, so these returns can have a large impact on the apparent leakage pressure for more reasons than the simple lowering of the plenum pressure.

In addition to the fan pressurization tests, the leakage of the home envelope was also measured using a blower door with all supply and return registers sealed in order to exclude the duct leakage. Tables 8-4a through 8-4c present the house leakage test results. It is customary to state the house leakage as CFM50 (flow in cfm at 50 Pa pressure difference) and ACH50 (air changes per hour at a pressure difference of 50 Pa). The last row of the tables labeled ACHnatural is a rough estimate of the heating season natural infiltration rate. It is calculated as ACH50 divided by 20.

The median CFM50 for the sample as a whole is 2162 cfm corresponding to an ACH50 of 9.43 ACH and a natural infiltration rate of 0.47 ACH. The median CFM50 for multi-story homes is actually less than that for single-story homes: 2149 cfm versus 2206 cfm. Since the multi-story homes have greater floor areas and volumes, this indicates that they are of tighter construction than the single-story homes. Indeed, many of the multi-story homes were of more recent vintage. Because the air change rates are calculated as the leakage normalized for house volume, the median ACH50 and ACHnatural values for multi-story homes are considerably less than those for single-story homes: 7.62 versus 10.19 ACH50 and 0.38 versus 0.51 ACHnatural, respectively.

Fan pressurization tests were done separately for the supply and return sides of the duct system resulting in power-law leakage curve fits. These fits were used to predict the total duct leakage (includes both leakage to outside and leakage to inside) and the leakage to outside at a pressure of 25 Pa. The leakage to inside was then obtained by subtraction of outside from total leakage. See Chapter 2 for more details on the fan pressurization tests. The results are presented in Tables 8-5a through 8-5c. It should be noted that the mean leakage to outside plus mean leakage to inside equals the mean total leakage but that does not hold true for the medians and other quantiles. Also notice that the means for return leakage are skewed in Table 8-5a and Table 8-5c by the presence of one home with huge leakage due to a very large panned joist return run. The last two rows of the tables give the leakage to inside as a fraction of the total leakage.

The median supply leakage to outside at 25 Pa for the sample as a whole was much greater than the return leakage to outside: 113.6 cfm versus 40.8 cfm. This reflects the fact that for many of these homes the return runs were rather short and had few connections, as is common for homes with central returns. The median supply leakage to inside for the entire sample was larger than that for the return side: 53.9 versus 31.3 cfm. However, when expressed as a fraction of the total duct leakage the medians for the two sides are more similar: 25.9% leakage to inside for the supply side versus 28.5% for the return side. For both sides the leakage to inside was much smaller than the leakage to outside. The median total leakage at 25 Pa on the supply side was also much greater than that on the return side: 228.2 versus 130.7 cfm.

The median supply leakage to outside at 25 Pa for the multi-story homes was almost exactly the same as that for the single-story homes: 179.9 versus 180.1 cfm. However, the median return leakage to outside was much larger for the multi-story homes: 154.1 versus 52.9 cfm. This is again due to the prevalence of panned joist and building cavity return runs in the multi-story homes. The median supply leakage to inside for the multi-story homes was slightly smaller than that for the single-story homes: 26.2 versus 29.7 cfm. The median return leakage to inside for multi-story homes was much larger: 84.8 versus 19.3 cfm. This again reflects the greater use of building cavities for return runs in multi-story homes.

The median total duct leakage at 25 Pa on the supply side was larger for the multi-story homes: 265.6 versus 220.8 cfm. The median total duct leakage on the return side for multi-story homes was more than three times larger than that for single-story homes: 317.6 versus 86.8 cfm.

The fraction of leakage to inside at 25 Pa on the supply side for multi-story homes was smaller than that for the single-story homes: 22.1% versus 27.6%. This indicates that the supply ducts running within the walls to the second story are quite tight. Most of the leakage to inside for single-story homes is likely located around the registers.

However, on the return side, the multi-story homes show a considerably larger fraction of leakage to inside: 36.2% versus 25.5% for the single-story homes. The fraction of leakage to inside for the single-story homes is about the same on the return and supply sides, while in the multi-story homes the fraction of leakage to the inside is much greater on the return side.

The air handler flow and total flows through the supply and return registers were measured under normal operating conditions. The unbalanced register flow (total supply register flow minus total return register flow) is also of interest. Tables 8-6a through 8-6c summarize these measurements and also summarize the number of supply and return registers and the average flow per register.

Table 8-6a shows the data for the sample as a whole. The median air handler was 930 cfm. The median supply flow was slightly larger than the median return flow: 754 versus 729 cfm. Although on average the return and supply flows are about the same, this does not imply that the supply and return flows were nearly balanced on each individual home. The row labeled Unbalanced Flow shows the degree of discrepancy. The median unbalanced flow was supply dominated at 28.7 cfm, but the unbalanced flow ranges from about -123 to +215 cfm at the $10^{th}$ and $90^{th}$ percentiles respectively.

For the sample as a whole, the median number of supply registers was 10 and the median number of return registers was 2. For each individual home the flow per register was calculated on both the supply and return sides. The median supply flow per register was 79.4 cfm while on the return side the median flow per register was 445.2 cfm.

Tables 8-6b and 8-6c show the air handler and register flow results for single-story and multi-story homes respectively. As one might expect, the median air handler flow for the multi-story homes is greater than that for the single-story homes: 927 versus 839 cfm. The median supply register flows is also greater for the multi-story homes: 763 versus 723 cfm. However, the median return register flows are about the same: 729 versus 728. This reflects the greater return leakage for the multi-story homes. The median unbalanced register flow shows a large difference: 54.2 cfm (supply dominated) for the multi-story homes versus -20.6 cfm (return dominated) for the single-story homes, again reflecting the greater leakage on the return side for multi-story homes.

The median number of supply registers was greater for multi-story homes: 11 versus 9. The median supply flow per register was smaller for the multi-story homes: 68.8 versus 85.5 cfm. The increase in number registers therefore outweighs the increase in flow for the multi-story homes. The median return flow per register was smaller for the multi-story homes because much of the flow was coming from other locations within the home and outside due to the use of building cavities: 426 versus 474.3 cfm.

The primary goal of this study was to compare three different methods for measuring duct leakage under normal operating pressures. These results are summarized in Tables 8-7a through 8-7c in terms of leakage in cfm and in Tables 8-8a through 8-8c in terms of leakage as a fraction of the air handler flow. The present discussion will be brief because these data have already been extensively discussed in Chapter 7.

Table 8-7a gives the results for the sample as a whole. Comparing the median supply leakage for the three methods gives: 94 cfm for the nulling test, 102.1 cfm for the benchmark estimate method, and 124 cfm for the Delta-Q method. The spread for the results at the 75$^{th}$ percentile is similar, however the quantiles below the median show little difference among methods, while the highest quantiles show a reversal of ranks with Delta-Q being the lowest of the methods and the nulling test the greatest.

Comparing the median return leakage for the three estimates gives 69 cfm for the nulling test, 99 cfm for the benchmark estimate method, and 98.4 cfm for the Delta-Q test. This pattern persists across quantiles with the Delta-Q and benchmark estimate methods being close while the nulling method is lower.

The last three rows of the table show the unbalanced leakage (calculated as supply leakage minus return leakage) for each of the three methods. The nulling method and the Delta-Q method have similar median unbalanced leakage: 17.4 and 15.5 cfm respectively. The benchmark estimate method has a median unbalance very close to zero. This general pattern persists across quantiles with the Delta-Q and nulling methods being somewhat more positive than the reference method.

Tables 8-7b gives the results for single-story homes. Comparing the median supply leakage for single-story homes gives 98.6 cfm for the nulling test, 97.4 cfm for the benchmark estimate method, and 125.5 cfm for the Delta-Q test. These results compare closely with those for the whole sample. However, in this case the reversal at higher quantiles is not present although the pattern for the lower quantiles is similar to those for the whole sample. Comparing the median return leakage for single-story homes gives 58.8 cfm for the nulling test, 79.7 cfm for the benchmark estimate method, and 62 cfm for the Delta-Q test. So for these homes the median return leakage is similar for the nulling and DeltaQ tests while the benchmark estimate method gives a result somewhat higher. This pattern occurs for most of the quantiles. The unbalanced flows for the single-story homes show dominant supply leakage for all three methods.

Table 8-7c gives the results for multi-story homes. Comparing the median supply leakage for multi-story homes gives: 80.5 cfm for the nulling test, 102.4 cfm for the benchmark estimate method, and 123.3 cfm for the Delta-Q test. The median for the nulling test is not as close to the benchmark estimate method as it was for the single-story homes. At the 75$^{th}$ percentile there is agreement between the Delta-Q and benchmark estimate methods, both being considerably larger than the nulling method. However at the 25$^{th}$ percentile there is close agreement between the nulling method and the benchmark estimate method with the Delta-Q method being larger. No clear picture emerges from the data.

Comparing the median leakage on the return side for multi-story homes gives: 103.9 cfm for the nulling method, 128.1 cfm for the benchmark estimate method, and 122.7 cfm for the Delta-Q test. The nulling method is about 20% less than the Delta-Q method for most of the quantiles while the Delta-Q method is closer to the benchmark estimate method.

The qualitative conclusions from Tables 8-8a through 8-8c are essentially the same as the discussion for Tables 8-7a through 8-7c and will not be repeated here.

A commercial combustion analyzer was used in conjunction with clocking the gas meter to measure the performance of the gas furnaces. Unfortunately there were a number of cases where this was not possible for a variety of reasons. We did not make combustion efficiency measurements for any of the condensing furnaces, so there are no high efficiencies reported. Some homes had propane furnaces, which precluded measuring the gas flow. In addition, some of the measurements are missing for some homes. The results are given in Table 8-9. The resulting sample size for the various items presented in the table ranges from 28 to 38 homes.

The first and second rows of Table 8-9 give the nominal capacity from the nameplate and the measured capacity from clocking the meter in kBtu/hr. The median nominal rating was 75 kBtu/hr while the median measured capacity was almost identical 76.4 kBtu/hr. The third line gives the percentage overfire/underfire (i.e. the ratio of measured capacity to nominal capacity). The median is 1.1% overfired. Based on the quartiles, about 50% of the furnaces were overfired or underfired by more than 5%.

The 4$^{th}$ row of Table 8-9 gives the maximum carbon monoxide measurement (max CO in ppm). The measurements are made in each of typically 3 or 4 ports for an atmospheric burner or in the flue for induced draft furnaces. The measurements are made before dilution with air from the draft hood. In the case of atmospheric draft furnaces, the maximum CO is from the port with the highest reading. The median value is 25 ppm, which is fairly good; however 25% of the homes had readings greater than 48 ppm and 10% of the homes had readings of 120 ppm and above. The local gas company has a safety threshold of 100 ppm. Of particular concern is the fact that, of 38 homes tested, 2 had CO readings that went off-scale on the meter (i.e., greater than 2000 ppm). In all cases elevated readings were reported immediately to the homeowners.

The last row of Table 8-9 gives the measured efficiency of the furnace. The median value is 80% and the quartiles are at 78.5% and 81.1%. In general, the measurements agreed fairly well with catalog efficiency data when that was available for comparison.

Table 8-1a. House Area, Volume, and Average Ceiling Height (n=48)

| **Variable** | **Mean** | **Min** | **10%** | **25%** | **50%** | **75%** | **90%** | **Max** |
|---|---|---|---|---|---|---|---|---|
| Area ($ft^2$) | 1647 | 707 | 1071 | 1268 | 1668 | 1914 | 2400 | 2683 |
| Volume ($ft^3$) | 13753 | 5036 | 8583 | 10632 | 13592 | 15819 | 19200 | 27549 |
| Ceiling Ht (ft) | 8.29 | 7.12 | 7.58 | 7.67 | 8.00 | 8.48 | 9.42 | 11.32 |

Table 8-1b. House Area, Volume, and Average Ceiling Height for Single-Story Homes (n=25)

| **Variable** | **Mean** | **Min** | **10%** | **25%** | **50%** | **75%** | **90%** | **Max** |
|---|---|---|---|---|---|---|---|---|
| Area ($ft^2$) | 1492 | 849 | 856 | 1211 | 1541 | 1757 | 2130 | 2501 |
| Volume ($ft^3$) | 11757 | 6510 | 7087 | 9730 | 11845 | 13564 | 16330 | 19620 |
| Ceiling Ht (ft) | 7.93 | 7.17 | 7.58 | 7.67 | 7.83 | 8.01 | 8.66 | 9.00 |

Table 8-1c. House Area, Volume, and Average Ceiling Height for Multi-story Homes (n=23)

| **Variable** | **Mean** | **Min** | **10%** | **25%** | **50%** | **75%** | **90%** | **Max** |
|---|---|---|---|---|---|---|---|---|
| Area ($ft^2$) | 1814 | 707 | 1488 | 1588 | 1812 | 1994 | 2436 | 2683 |
| Volume ($ft^3$) | 15924 | 5036 | 11532 | 13638 | 14788 | 18263 | 21110 | 27549 |
| Ceiling Ht (ft) | 8.67 | 7.12 | 7.67 | 7.95 | 8.22 | 8.98 | 11.31 | 11.32 |

Table 8-2a. Supply Duct Surface Area in Unconditioned Space and R-value (n=39)

| **Variable** | **Mean** | **Min** | **10%** | **25%** | **50%** | **75%** | **90%** | **Max** |
|---|---|---|---|---|---|---|---|---|
| Supply Duct Area ($ft^2$) | 285 | 81 | 207 | 222 | 296 | 342 | 409 | 451 |
| Pct. of Floor Area | 17.8 | 7.2 | 10.0 | 13.7 | 17.5 | 20.9 | 25.5 | 29.8 |
| Supply R-value | 4.0 | 1.5 | 1.7 | 2.0 | 4.0 | 5.1 | 7.4 | 8.1 |

Table 8-2b. Supply Duct Surface Area in Unconditioned Space and R-value for Single-Story Homes (n=20)

| **Variable** | **Mean** | **Min** | **10%** | **25%** | **50%** | **75%** | **90%** | **Max** |
|---|---|---|---|---|---|---|---|---|
| Supply Duct Area ($ft^2$) | 301 | 81 | 210 | 248 | 312 | 346 | 406 | 451 |
| Pct. of Floor Area | 21.2 | 9.5 | 16.2 | 18.7 | 20.6 | 23.8 | 29.0 | 29.8 |
| Supply R-value | 3.7 | 1.5 | 1.5 | 2.0 | 3.1 | 5.0 | 7.4 | 7.4 |

Table 8-2c. Supply Duct Surface Area in Unconditioned Space and R-value for Multi-Story Homes (n=19)

| **Variable** | **Mean** | **Min** | **10%** | **25%** | **50%** | **75%** | **90%** | **Max** |
|---|---|---|---|---|---|---|---|---|
| Supply Duct Area ($ft^2$) | 267 | 107 | 116 | 216 | 257 | 336 | 409 | 409 |
| Pct. of Floor Area | 14.2 | 7.2 | 7.5 | 11.8 | 15.0 | 16.8 | 20.1 | 20.1 |
| Supply R-value | 4.3 | 1.5 | 1.9 | 2.4 | 4.0 | 5.9 | 7.4 | 8.1 |

Table 8-3a. Duct Pressures in Pa (n=48)

| **Variable** | **Mean** | **Min** | **10%** | **25%** | **50%** | **75%** | **90%** | **Max** |
|---|---|---|---|---|---|---|---|---|
| Supply Plenum | 44.9 | 11.7 | 19.1 | 25.0 | 38.2 | 59.2 | 83.3 | 113.3 |
| Return Plenum | 58.8 | 8.1 | 20.2 | 37.2 | 53.2 | 74.4 | 115.9 | 143.8 |
| External Static | 103.8 | 31.0 | 52.5 | 68.2 | 101.4 | 139.8 | 165.9 | 186.3 |
| Supply Leak | 15.6 | 0.3 | 1.7 | 4.6 | 10.2 | 22.9 | 36.0 | 67.5 |
| Return Leak | 32.8 | 0.0 | 5.6 | 10.9 | 20.0 | 33.8 | 119.0 | 147.1 |

Table 8-3b. Duct Pressures in Pa (one story n=25)

| **Variable** | **Mean** | **Min** | **10%** | **25%** | **50%** | **75%** | **90%** | **Max** |
|---|---|---|---|---|---|---|---|---|
| Supply Plenum | 43.7 | 11.7 | 19.1 | 24.3 | 35.8 | 64.0 | 82.6 | 11.5 |
| Return Plenum | 62.1 | 8.1 | 28.6 | 41.4 | 60.1 | 76.3 | 115.9 | 143.8 |
| External Static | 105.9 | 38.9 | 54.5 | 70.4 | 101.6 | 140.9 | 171.2 | 181.2 |
| Supply Leak | 16.5 | 1.7 | 4.1 | 5.7 | 10.3 | 25.5 | 35.0 | 67.5 |
| Return Leak | 44.2 | 4.5 | 7.4 | 13.7 | 27.4 | 48.2 | 134.1 | 147.1 |

Table 8-3c. Duct Pressures in Pa (multi-story n=23)

| **Variable** | **Mean** | **Min** | **10%** | **25%** | **50%** | **75%** | **90%** | **Max** |
|---|---|---|---|---|---|---|---|---|
| Supply Plenum | 46.3 | 17.6 | 21.5 | 25.0 | 40.8 | 58.2 | 83.3 | 113.3 |
| Return Plenum | 55.3 | 9.9 | 20.2 | 29.7 | 48.9 | 74.4 | 106.7 | 125.1 |
| External Static | 101.5 | 31.0 | 52.5 | 58.8 | 101.4 | 137.9 | 159.2 | 186.3 |
| Supply Leak | 14.6 | 0.3 | 1.0 | 4.3 | 10.1 | 20.2 | 39.0 | 44.1 |
| Return Leak | 20.9 | 0.0 | 3.1 | 9.1 | 14.3 | 23.0 | 32.0 | 119.0 |

Table 8-4a. House Leakage from Pressure Test at 50 Pa with Registers Sealed

| **Variable** | **Mean** | **Min** | **10%** | **25%** | **50%** | **75%** | **90%** | **Max** |
|---|---|---|---|---|---|---|---|---|
| CFM50 | 2376 | 969 | 1191 | 1631 | 2162 | 2952 | 3829 | 4921 |
| ACH50 | 11.40 | 4.17 | 5.88 | 7.18 | 9.43 | 13.71 | 21.88 | 29.03 |
| ACHnatural | .57 | .21 | .29 | .36 | .47 | .69 | 1.09 | 1.45 |

Table 8-4b. House Leakage from Pressure Test at 50 Pa with Registers Sealed for Single-Story Homes (n=25)

| **Variable** | **Mean** | **Min** | **10%** | **25%** | **50%** | **75%** | **90%** | **Max** |
|---|---|---|---|---|---|---|---|---|
| CFM50 | 2253 | 969 | 1190 | 1406 | 2206 | 2872 | 3700 | 3829 |
| ACH50 | 12.17 | 5.88 | 7.11 | 8.14 | 10.19 | 13.45 | 21.88 | 29.03 |
| ACHnatural | .61 | .29 | .36 | .41 | .51 | .67 | 1.09 | 1.45 |

Table 8-4c. House Leakage from Pressure Test at 50 Pa with Registers Sealed for Multi-story Homes (n=23)

| **Variable** | **Mean** | **Min** | **10%** | **25%** | **50%** | **75%** | **90%** | **Max** |
|---|---|---|---|---|---|---|---|---|
| CFM50 | 2509 | 1062 | 1502 | 1785 | 2149 | 3037 | 4335 | 4921 |
| ACH50 | 10.56 | 4.17 | 4.88 | 6.18 | 7.62 | 14.14 | 21.65 | 24.13 |
| ACHnatural | .53 | .21 | .24 | .31 | .38 | .71 | 1.08 | 1.21 |

Table 8-5a.  Duct Pressure Test Results at 25 Pa in cfm (all homes n=48)

| **Variable** | **Mean** | **Min** | **10%** | **25%** | **50%** | **75%** | **90%** | **Max** |
|---|---|---|---|---|---|---|---|---|
| Supply Out | 171.8 | 11.4 | 87.1 | 113.6 | 180.0 | 214.4 | 281.0 | 332.4 |
| Return Out | 136.4 | 16.5 | 23.1 | 40.8 | 83.6 | 197.5 | 270.5 | 1014.0 |
| Supply In | 70.3 | 4.2 | 20.2 | 30.2 | 53.9 | 88.4 | 143.4 | 312.5 |
| Return In | 115.2 | 0.4 | 5.5 | 10.5 | 31.3 | 98.4 | 271.1 | 1533.3 |
| Supply Tot | 242.1 | 111.7 | 124.9 | 185.2 | 228.2 | 285.6 | 369.7 | 467.7 |
| Return Tot | 251.6 | 23.2 | 36.9 | 74.4 | 130.7 | 301.7 | 491.8 | 2547.3 |
| Supply %In | 28.1 | 3.0 | 8.8 | 15.3 | 25.9 | 34.2 | 50.7 | 95.9 |
| Return %In | 32.4 | 1.2 | 4.7 | 11.8 | 28.5 | 45.6 | 73.8 | 96.0 |

Table 8-5b.  Duct Pressure Test Results at 25 Pa in cfm (one story n=25)

| **Variable** | **Mean** | **Min** | **10%** | **25%** | **50%** | **75%** | **90%** | **Max** |
|---|---|---|---|---|---|---|---|---|
| Supply Out | 160.5 | 26.0 | 87.1 | 112.3 | 180.1 | 200.2 | 218.7 | 298.8 |
| Return Out | 73.9 | 16.5 | 19.7 | 34.3 | 52.9 | 88.1 | 193.9 | 201.5 |
| Supply In | 57.9 | 12.0 | 20.2 | 23.0 | 61.2 | 85.7 | 101.6 | 143.4 |
| Return In | 25.7 | 0.4 | 1.6 | 6.7 | 19.3 | 32.8 | 59.9 | 122.9 |
| Supply Tot | 218.4 | 111.7 | 117.6 | 181.0 | 220.8 | 247.6 | 321.7 | 388.1 |
| Return Tot | 99.6 | 23.2 | 34.5 | 46.2 | 86.8 | 136.9 | 203.5 | 261.4 |
| Supply %In | 27.7 | 5.2 | 8.8 | 12.3 | 27.6 | 34.7 | 46.9 | 76.7 |
| Return %In | 25.8 | 1.2 | 3.7 | 10.1 | 25.5 | 31.7 | 52.4 | 84.2 |

Table 8-5c.  Duct Pressure Test Results at 25 Pa in cfm (multi-story n=23)

| **Variable** | **Mean** | **Min** | **10%** | **25%** | **50%** | **75%** | **90%** | **Max** |
|---|---|---|---|---|---|---|---|---|
| Supply Out | 184.1 | 11.4 | 94.1 | 133.2 | 179.9 | 239.7 | 283.4 | 332.4 |
| Return Out | 204.3 | 23.0 | 46.8 | 69.9 | 154.1 | 243.6 | 384.8 | 1014.0 |
| Supply In | 83.8 | 4.2 | 28.1 | 37.3 | 52.6 | 90.4 | 230.9 | 312.5 |
| Return In | 212.6 | 8.0 | 11.3 | 27.3 | 89.9 | 181.6 | 630.1 | 1533.3 |
| Supply Tot | 267.9 | 124.9 | 138.1 | 209.9 | 265.6 | 348.3 | 370.9 | 467.7 |
| Return Tot | 416.9 | 58.1 | 79.1 | 127.7 | 317.6 | 441.4 | 800.1 | 2547.3 |
| Supply %In | 28.6 | 3.0 | 10.4 | 15.4 | 22.1 | 31.3 | 53.0 | 95.9 |
| Return %In | 39.5 | 5.3 | 11.5 | 21.8 | 36.2 | 47.0 | 78.9 | 96.0 |

Table 8-6a. Air Handler and Register Flows in cfm (n=48)

| Variable | Mean | Min | 10% | 25% | 50% | 75% | 90% | Max |
|---|---|---|---|---|---|---|---|---|
| Air Handler Flow | 929 | 425 | 621 | 767 | 930 | 1099 | 1224 | 1423 |
| Total Supply Flow | 774 | 307 | 518 | 622 | 754 | 922 | 1088 | 1234 |
| Total Return Flow | 733 | 261 | 421 | 588 | 729 | 883 | 1005 | 1157 |
| Unbalanced Flow[1] | 40.3 | -199.2 | -122.9 | -46.6 | 28.7 | 83.2 | 214.8 | 498.8 |
| Supply per Reg. | 81.0 | 37.0 | 51.4 | 63.0 | 79.4 | 94.3 | 117.5 | 159.0 |
| Return per Reg. | 485.9 | 74.3 | 140.2 | 323.0 | 445.2 | 703.7 | 863.6 | 1085.7 |
| No. Supply Reg. | 10.1 | 3 | 7 | 8 | 10 | 12 | 15 | 16 |
| No. Return Reg. | 1.98 | 1 | 1 | 1 | 2 | 2 | 3 | 7 |

1. Supply Flow minus Return Flow through registers only. Negative numbers mean that more air is going through return registers than through supply registers.

Table 8-6b. Air Handler and Register Flows in cfm (single story n=25)

| Variable | Mean | Min | 10% | 25% | 50% | 75% | 90% | Max |
|---|---|---|---|---|---|---|---|---|
| Air Handler Flow | 889 | 425 | 604 | 733 | 839 | 1047 | 1132 | 1423 |
| Total Supply Flow | 745 | 307 | 518 | 612 | 723 | 890 | 1057 | 1234 |
| Total Return Flow | 748 | 315 | 520 | 646 | 728 | 887 | 1018 | 1157 |
| Unbalanced Flow[1] | -3.6 | -199.2 | -122.9 | -71.1 | -20.6 | 45.3 | 76.8 | 454.2 |
| Supply per Reg. | 87.2 | 55.0 | 61.8 | 74.0 | 85.5 | 98.9 | 117.5 | 131.2 |
| Return per Reg. | 529.7 | 74.3 | 157.4 | 323.1 | 474.3 | 728.0 | 887.0 | 1025.9 |
| No. Supply Reg. | 8.76 | 3 | 6 | 8 | 9 | 10 | 13 | 14 |
| No. Return Reg. | 1.92 | 1 | 1 | 1 | 2 | 2 | 3 | 7 |

1. Supply Flow minus Return Flow through registers only. Negative numbers mean that more air is going through return registers than through supply registers.

Table 8-6c. Air Handler and Register Flows in cfm (multi-story n=23)

| Variable | Mean | Min | 10% | 25% | 50% | 75% | 90% | Max |
|---|---|---|---|---|---|---|---|---|
| Air Handler Flow | 973 | 522 | 697 | 813 | 972 | 1166 | 1224 | 1318 |
| Total Supply Flow | 805 | 407 | 540 | 692 | 763 | 991 | 1110 | 1122 |
| Total Return Flow | 717 | 261 | 421 | 556 | 729 | 880 | 979 | 1086 |
| Unbalanced Flow[1] | 88.0 | -188.2 | -47.6 | 16.7 | 54.2 | 199.9 | 236.7 | 498.8 |
| Supply Flow per Reg. | 74.2 | 37.0 | 41.9 | 54.3 | 68.8 | 90.1 | 100.9 | 159.0 |
| Return Flow per Reg. | 438.2 | 81.7 | 140.2 | 297.4 | 426.0 | 518.1 | 737.9 | 1085.7 |
| No. Supply Reg. | 11.57 | 6 | 7 | 10 | 11 | 14 | 15 | 16 |
| No. Return Reg. | 2.04 | 1 | 1 | 1 | 2 | 2 | 3 | 5 |

1. Supply Flow minus Return Flow through registers only. Negative numbers mean that more air is going through return registers than through supply registers.

Table 8-7a. Duct Leakage under Normal Operating Pressures in cfm (n=48)

| Variable | Mean | Min | 10% | 25% | 50% | 75% | 90% | Max |
|---|---|---|---|---|---|---|---|---|
| Supply Nulling | 104.4 | -1.7 | 38.4 | 65.1 | 94.0 | 112.0 | 232.1 | 355.8 |
| Supply Benchmark | 111.1 | 0.5 | 23.9 | 70.3 | 102.1 | 126.8 | 227.4 | 365.1 |
| Supply Delta-Q | 119.2 | -11.8 | 35.9 | 71.0 | 124.0 | 152.0 | 199.8 | 321.9 |
| Return Nulling | 97.2 | -39.9 | 8.0 | 44.5 | 69.0 | 140.8 | 233.8 | 416.8 |
| Return Benchmark | 125.4 | 4.1 | 40.6 | 61.2 | 99.0 | 172.1 | 259.5 | 473.5 |
| Return Delta-Q | 120.6 | -22.6 | 18.1 | 52.4 | 98.4 | 157.6 | 269.9 | 458.1 |
| Unbalanced[1] Nulling | 7.3 | -319.5 | -128.3 | -39.9 | 17.4 | 54.0 | 138.8 | 296.1 |
| Unbalanced[1] Benchmark | -14.3 | -370.2 | -156.5 | -53.6 | 1.1 | 34.6 | 100.4 | 180.5 |
| Unbalanced[1] Delta-Q | -1.4 | -309.3 | -141.8 | -36.7 | 15.5 | 63.3 | 117.7 | 226.0 |

1. Supply Leakage minus Return Leakage to outside. Negative numbers mean that there is greater return leakage than supply leakage.

Table 8-7b. Duct Leakage under Normal Operating Pressures in CFM (one story n=25)

| **Variable** | **Mean** | **Min** | **10%** | **25%** | **50%** | **75%** | **90%** | **Max** |
|---|---|---|---|---|---|---|---|---|
| Supply Nulling | 99.0 | 17.5 | 38.4 | 62.1 | 98.6 | 110.5 | 139.0 | 272.1 |
| Supply Benchmark | 101.6 | 20.9 | 35.3 | 71.0 | 97.4 | 116.9 | 141.5 | 266.4 |
| Supply Delta-Q | 117.1 | 24.4 | 42.4 | 64.1 | 125.5 | 149.7 | 175.1 | 288.0 |
| Return Nulling | 75.2 | -39.9 | 8.0 | 38.6 | 58.8 | 93.6 | 148.5 | 416.8 |
| Return Benchmark | 103.0 | 18.6 | 40.6 | 51.0 | 79.7 | 111.6 | 189.5 | 473.5 |
| Return Delta-Q | 86.9 | -22.6 | 18.1 | 25.6 | 62.0 | 116.6 | 161.5 | 458.1 |
| Unbalanced[1] Nulling | 23.9 | -319.5 | -51.7 | -20.8 | 21.3 | 76.0 | 138.5 | 296.1 |
| Unbalanced[1] Benchmark | -1.4 | -370.2 | -76.8 | -34.3 | 11.7 | 34.8 | 65.6 | 146.2 |
| Unbalanced[1] Delta-Q | 30.2 | -309.3 | -36.0 | -1.9 | 28.6 | 80.2 | 111.4 | 226.0 |

1. Supply Leakage minus Return Leakage to outside. Negative numbers mean that there is greater return leakage than supply leakage.

Table 8-7c. Duct Leakage under Normal Operating Pressures in CFM (multi-story n=23)

| **Variable** | **Mean** | **Min** | **10%** | **25%** | **50%** | **75%** | **90%** | **Max** |
|---|---|---|---|---|---|---|---|---|
| Supply Nulling | 110.3 | -1.7 | 55.1 | 68.1 | 80.5 | 117.0 | 263.7 | 355.8 |
| Supply Benchmark | 121.5 | 0.5 | 13.0 | 69.3 | 102.4 | 150.5 | 227.4 | 365.1 |
| Supply Delta-Q | 121.4 | -11.8 | 22.2 | 77.8 | 123.3 | 154.3 | 233.9 | 321.9 |
| Return Nulling | 121.0 | -12.8 | 23.1 | 52.0 | 103.9 | 206.6 | 252.5 | 267.9 |
| Return Benchmark | 149.7 | 4.1 | 46.9 | 71.2 | 128.1 | 253.8 | 264.7 | 340.7 |
| Return Delta-Q | 157.2 | -16.4 | 42.4 | 91.1 | 122.7 | 268.0 | 270.9 | 359.7 |
| Unbalanced[1] Nulling | -10.7 | -184.4 | -176.7 | -122.1 | 12.6 | 45.2 | 152.9 | 189.4 |
| Unbalanced[1] Benchmark | -28.2 | -201.1 | -178.4 | -132.8 | -9.1 | 33.9 | 100.4 | 180.5 |
| Unbalanced[1] Delta-Q | -35.8 | -233.1 | -146.2 | -131.9 | -19.7 | 38.2 | 117.7 | 144.8 |

1. Supply Leakage minus Return Leakage to outside. Negative numbers mean that there is greater return leakage than supply leakage.

Table 8-8a. Duct Leakage Under Normal Operating Pressures as Percent of Air Handler Flow (n=48)

| Variable | Mean | Min | 10% | 25% | 50% | 75% | 90% | Max |
|---|---|---|---|---|---|---|---|---|
| Supply Nulling | 11.5 | -0.2 | 4.7 | 6.9 | 8.9 | 15.0 | 24.6 | 30.5 |
| Supply Benchmark | 11.8 | 0.1 | 2.7 | 8.4 | 10.5 | 14.3 | 25.0 | 29.8 |
| Supply Delta-Q | 13.1 | -2.3 | 3.8 | 7.5 | 12.3 | 19.4 | 23.0 | 31.9 |
| Return Nulling | 10.4 | -3.9 | 1.0 | 4.6 | 8.3 | 15.4 | 23.7 | 36.8 |
| Return Benchmark | 12.9 | 0.8 | 4.3 | 7.7 | 10.3 | 15.3 | 22.6 | 41.8 |
| Return Delta-Q | 12.5 | -5.2 | 1.9 | 5.4 | 10.2 | 20.3 | 26.0 | 40.5 |
| Unbalanced[1] Nulling | 1.1 | -28.2 | -14.2 | -4.0 | 1.7 | 5.8 | 15.2 | 32.8 |
| Unbalanced[1] Benchmark | -1.1 | -32.7 | -17.5 | -6.5 | 0.1 | 4.0 | 10.8 | 20.3 |
| Unbalanced[1] Delta-Q | 0.6 | -27.3 | -16.0 | -3.7 | 1.3 | 8.2 | 14.1 | 25.0 |

1. Supply Leakage minus Return Leakage to outside. Negative numbers mean that there is greater return leakage than supply leakage.

Table 8-8b. Duct Leakage Under Normal Operating Pressures as Percent of Air Handler Flow (single-story n=25)

| Variable | Mean | Min | 10% | 25% | 50% | 75% | 90% | Max |
|---|---|---|---|---|---|---|---|---|
| Supply Nulling | 11.9 | 1.8 | 4.7 | 7.4 | 9.7 | 15.0 | 24.6 | 30.1 |
| Supply Benchmark | 11.7 | 2.7 | 5.2 | 8.5 | 10.2 | 13.5 | 25.0 | 27.6 |
| Supply Delta-Q | 14.0 | 3.6 | 4.6 | 7.6 | 13.1 | 19.5 | 23.0 | 31.9 |
| Return Nulling | 8.7 | -3.9 | 1.0 | 4.4 | 7.2 | 9.6 | 15.9 | 36.8 |
| Return Benchmark | 11.1 | 4.1 | 4.3 | 7.1 | 9.9 | 11.7 | 18.5 | 41.8 |
| Return Delta-Q | 9.5 | -5.2 | 1.9 | 3.1 | 6.3 | 12.8 | 22.0 | 40.5 |
| Unbalanced[1] Nulling | 3.2 | -28.2 | -4.6 | -2.5 | 2.4 | 9.8 | 13.6 | 32.8 |
| Unbalanced[1] Benchmark | 0.7 | -32.7 | -7.3 | -3.7 | 2.5 | 4.2 | 10.8 | 16.2 |
| Unbalanced[1] Delta-Q | 4.5 | -27.3 | -4.5 | -0.1 | 2.6 | 10.7 | 14.9 | 25.0 |

1. Supply Leakage minus Return Leakage to outside. Negative numbers mean that there is greater return leakage than supply leakage.

Table 8-8c. Duct Leakage Under Normal Operating Pressures as Percent of Air Handler Flow (multi-story n=23)

| Variable | Mean | Min | 10% | 25% | 50% | 75% | 90% | Max |
|---|---|---|---|---|---|---|---|---|
| Supply Nulling | 10.9 | -0.2 | 5.3 | 6.7 | 8.4 | 14.4 | 22.6 | 30.5 |
| Supply Benchmark | 11.9 | 0.1 | 1.7 | 8.1 | 11.2 | 15.3 | 23.7 | 29.8 |
| Supply Delta-Q | 12.1 | -2.3 | 2.9 | 6.6 | 11.7 | 19.3 | 22.4 | 26.3 |
| Return Nulling | 12.3 | -2.5 | 2.5 | 4.8 | 11.4 | 20.3 | 23.7 | 34.4 |
| Return Benchmark | 14.8 | 0.8 | 5.3 | 8.2 | 12.9 | 21.1 | 28.8 | 34.6 |
| Return Delta-Q | 15.8 | -3.1 | 4.8 | 8.5 | 14.0 | 22.2 | 28.3 | 38.9 |
| Unbalanced[1] Nulling | -1.3 | -25.2 | -16.3 | -10.4 | 1.2 | 5.2 | 15.2 | 18.8 |
| Unbalanced[1] Benchmark | -2.9 | -19.1 | -18.8 | -13.0 | -1.0 | 3.7 | 9.7 | 20.3 |
| Unbalanced[1] Delta-Q | -3.7 | -24.7 | -17.8 | -13.7 | -1.9 | 4.0 | 10.1 | 16.3 |

1. Supply Leakage minus Return Leakage to outside. Negative numbers mean that there is greater return leakage than supply leakage.

Table 8-9 Combustion Test Results (n=28 to 38)

| Variable | Mean | Min | 10% | 25% | 50% | 75% | 90% | Max |
|---|---|---|---|---|---|---|---|---|
| Nominal Capacity (kBtu/h) | 74.4 | 39.0 | 46.0 | 66.0 | 75.0 | 80.0 | 100.0 | 125.0 |
| Measured Capacity (kBtu/h) | 75.8 | 37.1 | 46.2 | 57.3 | 76.4 | 92.2 | 99.8 | 137.6 |
| Overfire Percentage | -0.5 | -19.6 | -12.1 | -5.9 | 1.1 | 5.5 | 9.6 | 10.9 |
| Maximum CO (ppm) | 143 | 11 | 16 | 20 | 25 | 48 | 120 | 2100 |
| Efficiency (%) | 79.8 | 74.6 | 77.2 | 78.5 | 80.0 | 81.1 | 82.3 | 82.8 |

# 9
# CONCLUSIONS

This project has provided a lot of insight into the performance of various leakage tests. Some results simply confirmed prior impressions, while other results were surprising. In those cases where prior impressions were confirmed, the confidence in the results is greatly enhanced due to the sample size. Previous field studies of the nulling test and Delta-Q test have either been much more limited in sample size or lacked an independent leakage estimate to which these methods could be compared.

**Benchmark Estimate**

One of the most surprising results of the study relates to the benchmark estimate, which combines air handler flow with register and grille flows, with an adjustment made to account for leakage to inside. Many researchers have considered this method to be reasonable on the return side, but several of these same researchers believed the results on the supply side would be highly questionable due to the perceived lack of accuracy of flow hood measurements on residential supply systems. This may be true in many cases, such as where the flow hood has not been calibrated, where the registers provide adverse flow conditions such as swirl, the flow hood is not used carefully, or the flow hood was not really designed for supply-side use.

However, the benchmark estimate validation tests found that it was on the return side that this method of estimating leakage fell short. Much of the reason for this may be the lack of cancellation of errors across return grilles in a single home, since many homes have only one return grille, and rarely more than three. There is also evidence that the flow hood used for return grille flows, though calibrated, did not perform well in the field.

On the supply side, however, the benchmark estimate was shown to be more accurate than expected in those houses in which validation testing was performed. When comparing the benchmark estimate results on the supply side to the added known leak, the maximum error was less than 7 cfm, and no error in these houses was greater than 1% of the air handler flow.

Indeed, when the Delta-Q test is compared to the nulling test on the return side, the results are much more consistent with the supply-side results than if either are compared to the benchmark estimate for return leakage.

There is evidence in the supply-side benchmark estimate results that the correction for leakage to inside was not as good as was desired for homes with a significant amount of ducts in the conditioned space, primarily multi-story homes. The correction procedure contains an implicit assumption that leaks to inside are at the same effective pressure as the leaks to outside. This may be a reasonable assumption in some cases, but it does not always hold true. As a result, for these types of homes, the nulling test may actually be the best estimate of the methods tested.

**Nulling Test**

The nulling test was found to work very well in most houses. For single-story homes, where the benchmark estimate is the most accurate on the supply side, the nulling test showed very little bias relative to the benchmark estimate. The mean absolute error was less than 2% of air handler flow, and the RMS error was 2.4% of air handler flow. There was also little tendency for the nulling test to overestimate the flow by a large amount. This was a concern because many applications for duct leakage testing have a low tolerance for false positives, i.e. estimating excessive leakage when the leakage is actually within allowable limits.

Because the nulling test does not perceive leakage to inside as different from airflow through registers, there is no conceptual reason to believe that the performance should be worse for multi-story homes. Therefore, though there is larger disagreement between the nulling test and the benchmark estimate for multi-story homes, it is likely the benchmark estimate that is causing the problem more than the nulling test.

The benchmark estimate validation tests showed little difference in the accuracy of the nulling test estimates on the return side compared to those on the supply side. This is counter to the expectation that the return results would be worse because the return estimates are based on combining two tests, the unbalanced leakage test and the supply-only test. The small sample size of these validation homes prevents a firm conclusion from being drawn, but these results are encouraging.

As determined in previous studies, the primary source of error for the nulling test appears to be noise due to wind. The test is done at a few small pressures, so significant wind can make accurate pressure measurements nearly impossible. One method for dealing with the wind noise is to do the nulling test at three distinct flows rather than pressures, and sample for an extended period of time. While this does often allow for obtaining reasonable looking data, there is still much greater uncertainty as to the accuracy of the results.

Other than wind noise, the primary drawback to the nulling test is the time-consuming nature of the setup for the supply-only measurement. The difficult and time-consuming part of the setup is the same as is done for measuring air handler flow using a calibrated fan, so if this test of air handler flow is also being done then the nulling test requires little additional setup and time. Other than homes where this testing is being done, however, the nulling test is probably only practical for use by contractors in homes without ducted return systems since at these homes only the unbalanced leakage portion of the test is required. This portion of the nulling test is fast and requires little setup. Examples of houses for which this would be appropriate are many manufactured homes and homes with platform returns.

**Delta-Q Test**

Qualitatively, the results confirmed previous findings on the performance of the unmodified Delta-Q test. This test, which uses envelope pressures to ±25 Pa, and assumes a leak pressure of half the plenum pressure, showed the same tendency to overestimate the leakage as in other studies, both by the authors and by other researchers. The magnitude of the overestimation was not as great in this study as it was in the previous study by the authors. The larger bias in the previous study can at least partially be explained by the results of two houses in a sample size of only nine homes.

In this study, the unmodified Delta-Q test had a bias of about 2% of air handler flow relative to the benchmark estimate of supply leakage in the single-story homes, with an RMS error of nearly 5% of air handler flow. The bias was smaller for multi-story homes, even when compared to the nulling test, which is probably the best estimate available for that set of homes.

As seen in previous studies and in theoretical modeling of the Delta-Q test, one of the most major problems is the failure of the assumption that the pressure difference between the ducts and the house remains constant throughout the test. The Delta-Q equations implicitly require this to be true, but these pressures can actually change by 20% or more in practice. The result tends to be an overprediction of the flow, which is in agreement with both lab and field studies.

It is this assumption that is a likely cause of the improved agreement with the nulling test in multi-story homes. There tend to be more registers as well as increased leaks to inside in multi-story homes. Since the ducts are then better connected to the house, they can be more easily pressurized or depressurized along with the house, and the assumption will often be closer to true. This agrees with simulation results, which have found that the Delta-Q test works better when the ducts become more connected to the house.

Due to the symmetry of the Delta-Q test, there is no reason to believe that the results would be substantially different on the return side compared to the supply side. When compared to the nulling test, which is likely the best estimate available on the return side, this holds true. On average, the Delta-Q test is 2.5% of air handler flow higher than the nulling test on the supply side and 2.9% higher than the nulling test on the return side.

Because of the tendency of the Delta-Q test to overpredict the leakage, sometimes by large amounts, caution needs to be taken when deciding whether to use the test for a specific application. If there is low tolerance for false positives, the Delta-Q test may not be an acceptable alternative.

The modifications to Delta-Q contained a mix of surprising results and confirmations of previous findings.

The use of envelope pressures to ±50 Pa was first considered because it would cover a broader range of leakage pressures. This was considered to be likely to reduce the errors of Delta-Q when leaks were at these larger pressures. However, the results show that the overall performance of the Delta-Q test is worse when this change is made. Part of the reason for this is that, in order to avoid increasing the time required to perform the test substantially, some of the lower envelope pressures are dropped.

It appears that the coarser spacing between pressures at the lower end of the range causes the results to become worse more than the increased range might improve the results. Further evaluation shows that the Delta-Q test has its largest errors at lower pressures, and that the majority of the leaks are at lower pressures. This suggests that focusing efforts at the lower end of the pressure range is more important than expanding the range.

The use of the full plenum pressure instead of half the plenum pressure as the assumed leak pressure was first proposed because theoretical work suggested that this choice would have a smaller bias and uncertainty. However, as was found in previous work, the use of the full plenum pressure also reduces the accuracy of the test, on average. The disagreement with the theoretical work suggests that the nature of leakage in real duct systems is sufficiently different from theoretical and lab conditions in a way that causes the half plenum pressure to be a better choice for the leak pressure surrogate.

Perhaps the most surprising result regarding Delta-Q test modifications is the finding that the two worst options of the modifications evaluated are those that attempt to apply a more accurate estimate of the leakage pressure. These modifications are the pressure fitting technique and the use of the estimated actual leakage pressures as based on other tests.

It has been assumed that, if the true leakage pressure is used, the results will be improved. Not only was this not the case in these homes, but on average the results from these modifications were more than twice as far away from the unmodified Delta-Q result as any other modification investigated. These results show that attempts to improve the estimation of the leakage pressure are not the appropriate means to improve the Delta-Q test.

A primary reason for this is that the pressures across the leaks change as the test is being done. One of the physical effects that the Delta-Q test is looking for is a reversal of flow across a leak, which would manifest itself as an inflection point in the data. However, this reversal will occur at a different pressure than occurs across the leak under normal operation, and fitting the Delta-Q curve to determine a leak pressure is finding the wrong pressure. This problem is similar to the problem of the assumption that the pressure between the ducts and the house remains constant throughout the Delta-Q test.

A related finding to the failure of the use of “improved” leak pressures to increase the accuracy of the result is that the pressures obtained from the pressure fitting tend to be significantly higher than the estimated leak pressures using other tests. This was also found in theoretical work on the Delta-Q test. Another finding in the theoretical work that was also seen in the data was the tendency for the pressures resulting from the fitting technique to fall on pressures used as envelope pressure stations. This finding suggests that the choice of pressure stations has as much or more to do with the “leak” pressure obtained from fitting than the actual pressures at the leaks. The theoretical work found that the cause of this phenomenon is that the envelope pressure stations cause local minima in the fitting curve, such that the fitting process can get “stuck” at these pressures.

The modification that used leakage exponents as estimated from fan pressurization tests instead of the assumed exponents of 0.6 also did not improve the results. This result was surprising, but it suggests that assuming an exponent of 0.6 is not a bad assumption. It may be that the failure of actual exponents to improve results is for reasons similar to the failure of leakage pressures to improve the results, in that the process of the Delta-Q test may actually change the apparent exponents at the leaks. It is not possible to determine this from the data collected in this study, however. This method is also not practical from a general use standpoint, because the additional time required to estimate the exponents is significant.

The only modifications that were evaluated that showed any improvement to the results of the Delta-Q test were those that attempted to address the fundamental flaw in the assumption of the constant duct-to-house pressure. The primary modification that was made to address this was to measure the plenum pressure at each envelope pressure station, and use these pressures in the Delta-Q analysis. In this study we performed the Delta-Q analysis using half of these pressures, consistent with the unmodified test. The result of using these pressures was to reduce the average bias by about a third, and based on medians reduce the bias by about half. This improvement is significant, although there are still homes with large overestimates of leakage.

The primary drawback with measuring the plenum pressure at each envelope pressure station is that additional pressure measurement equipment is required. The most common pressure measurement meters for this type of work have two channels, which are required for the blower door fan flow and for the envelope pressure. Measuring the plenum pressures at each station would require a second meter.

As a result, a variant to this modification was analyzed, whereby the plenum pressures were only measured additionally at the maximum envelope pressure stations (25 Pa and –25 Pa). Pressures for each station were then estimated by interpolating between these pressures and the plenum pressures measured with the blower door off. Pressures were interpolated separately for the pressurization and depressurization portions of the test, because the slopes can be very different between these two sides.

The result of this simplification was that the estimates were virtually unchanged, on average, compared to using the measured pressures at each station.

The failure to find a modification to Delta-Q that more completely corrected the errors was disappointing. This suggests that the only way to make the Delta-Q test as accurate as desired over a broad range of leakage conditions is to reformulate the basic underlying model. In the absence of that, the interpolation of duct pressures from pressures measured at the maximum envelope pressures and the duct pressures measured with the blower door off is a simple method of improving the results. This change should be incorporated in further use of the Delta-Q as based on the current derivation.

Another conclusion about the Delta-Q test that has also been stated in previous studies is that there needs to be a separate equation for homes without a return duct system. The equations as they are currently written require a return duct pressure to be entered, and when there is no return duct it is not clear what one should do.

**Fan Pressurization Test**

As has been noted in many projects, the fan pressurization test can often provide leakage estimates that are greatly different than the actual leakage. This is because this test is not designed to measure leakage at operating conditions. This test is accurate when estimating the effective leakage area of the holes in the ducts, but it does not address the pressures across the leaks. As has been seen in previous work, the estimates from the return side are much better than the estimates on the supply side, primarily because the return side is often a single, long duct instead of a complex system of many ducts.

**Overall Duct Leakage**

One of the primary findings of interest when looking at the sample as a whole is that the average leakage in these homes tends to be about 12% of air handler flow on each the supply and return sides. For each side of the duct system approximately 15% of the total sample has leakage greater than 20% of air handler flow and an additional 10% has leakage greater than 15% of the air handler flow. In many cases, the homes with large leakage on one side do not have large leakage on the other side. Approximately a quarter of the sample has leakage on either the return or supply side greater than 25%, with an additional 15% with leakage greater than 15% of air handler flow on either the supply or return side.

**Final Summary**

One of the primary recommendations from this work is to make the modification to the Delta-Q test that interpolates duct pressures between those measured at maximum envelope pressures and those measured with the blower door off, with the results used at each envelope pressure station for the Delta-Q analysis. This improves the results over any other Delta-Q variant evaluated.

Possible reformulation of the Delta-Q test model should be considered, with a focus being to account for the changes in the pressure between the ducts and the house as the test is performed.

The nulling test is most appropriate when there is no return duct system, but care must be taken to minimize the effects of wind.

The benchmark estimate method did not meet expectations on the return side, and also was subject to greater errors on the supply side in houses with multiple stories. This can be a useful technique in careful research, but is not a candidate for general use.

Despite the size of the sample tested, there were not enough homes with large leakage to allow a thorough investigation of the causes of errors in the Delta-Q test when large leakage is present. These homes often cause the Delta-Q test to perform poorly, and it is these same cases that are of most interest to individuals and organizations attempting to target duct leakage sealing efforts. As a result, it is desirable to test an additional sample of homes to more fully understand the failure modes of the leakage tests.

# 10
# ACKNOWLEDGMENTS

A large, intensive field study such as this requires the assistance of many people. The authors express their gratitude to the following people and organizations for their contributions, helping make the project a success.

First and foremost, we thank the National Energy Technology Laboratory (NETL) for funding the project. There have been two NETL project managers during the course of the project, both of whom supported our decisions regarding the design and implementation of the study. The current project manager is Parrish Galusky. The former project manager was William Haslebacher.

We also thank Esher Kweller of the U.S. Department of Energy, who was the original program manager, for his enthusiastic support and guidance in getting the project off the ground, and for helping set the primary goals. The current program manager is Arun Vohra.

Dr. John Andrews of Brookhaven National Laboratory was also instrumental in setting the goals, and assisted in the design of the benchmark estimate validation procedure. Dr. Andrews also provided guidance on what some of the modifications of Delta-Q to be analyzed would be, and participated in discussions regarding the strengths and weaknesses of all of the tests. Dr. Andrews also spent several days with us in the field participating in the testing of a home, both for quality assurance and for general observance of the work.

Collin Olson of The Energy Conservatory spent many hours developing the software used for the data collection. Collin was very timely and responsive to numerous requests to enhance the software. Collin also participated in one field test.

Gary Nelson of The Energy Conservatory provided valuable input on performing the test methods. He also provided staff time at no cost, and participated in one field test.

Ron Rothman of The Energy Conservatory provided both material and advisory support regarding equipment calibrations.

Two organizations provided major assistance in recruiting. Shannon McCormick of Puget Sound Energy, a local utility, sent a solicitation to the company web site for participation in the project, and also directed customers with concerns about their ducts to us. Karen Price at the Seattle Chapter of the Northwest EcoBuilding Guild also supported out effort by supplying information to members of the guild.

Darryl Dickerhoff of Lawrence Berkeley National Laboratory provided us with the equations and computer code for the pressure fitting technique for the Delta-Q test.

Last but certainly not least, we thank the 51 homeowners for allowing us into their homes for what was typically more than 8 hours of intensive field testing, and for working with us on

everything from scheduling to making sure the house could be tested efficiently. Our thanks go out especially to those homeowners who allowed repeat visits for the benchmark estimate validation testing, and yet more thanks to the one who allowed us yet another 2-day visit when Dr. Andrews visited.

# *11* REFERENCES


American Society of Heating, Refrigerating, and Air-Conditioning Engineers. 2003. *ASHRAE Standard 152P: Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems*. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, GA.

Andrews, J.W., and M.P. Modera. 1991. *Energy Savings Potential for Advanced Thermal Distribution Technology in Residential and Small Commercial Buildings.* Brookhaven National Laboratory informal report.

Andrews, J.W. 2000a. *Measurement Uncertainties in the Delta Q Test for Duct Leakage.* Brookhaven National Laboratory report BNL-67894, Upton, NY.

Andrews, J.W. 2000b. "Reducing Measurement Uncertainties in Duct Leakage Testing". Proceedings of the 2000 ACEEE Summer Study on Energy Efficiency in Buildings, Monterey, CA.

Andrews, J.W. 2001. *Analysis of Measurement Uncertainties in the Nulling Test for Air Leakage from Residential Ducts.* Brookhaven National Laboratory report BNL-68430.

Andrews, J.W. 2002. "Laboratory Evaluation of the Delta Q Test for Duct Leakage". Proceedings of the 2002 ACEEE Summer Study on Energy Efficiency in Buildings, Monterey, CA.

Cummings, J. B., J. J. Tooley, N. Moyer, and R. Dunsmore. 1990. "Impacts of Duct Leakage on Infiltration Rates, Space Conditioning Energy Use, and Peak Electrical Demand in Florida Homes." Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings, Monterey, CA.

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

Cummings, J., C.R. Withers, and N. Moyer. 2000. "Evaluation of the Duct Leakage Estimation Procedures of ASHRAE Standard 152P". ASHRAE Transactions 2000. American Society for Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, GA.

Davis, B., J. Siegel, P. Francisco, and L. Palmiter. 1997. *Measured and Modeled Heating Efficiency of Eight Natural Gas-Heated Homes*. Ecotope, Inc., Seattle, WA.

Francisco, P.W., and L. Palmiter. 1999. *Field Validation of ASHRAE Standard 152.* Final report for the American Society for Heating, Refrigerating, and Air-Conditioning Engineers. Report 1056-RP. Ecotope, Inc., Seattle, WA.

Francisco, P.W., and L. Palmiter. 2000. "Field Validation of Standard 152P (1056-RP)". ASHRAE Transactions 2000. American Society for Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, GA.

Francisco, P.W. and L. Palmiter. 2001. "The Nulling Test: A New Measurement Technique for Estimating Duct Leakage in Residential Homes". ASHRAE Transactions 2001. American Society for Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, GA.

Francisco, P.W., L. Palmiter, and B. Davis. 2002a. *Improved Ways to Measure Residential Duct Leakage.* Final report for the American Society for Heating, Refrigerating, and Air-Conditioning Engineers. Report 1164-RP. Ecotope, Inc., Seattle, WA.

Francisco, P.W., L. Palmiter, and B. Davis. 2002b. "Field Performance of Two New Residential Duct Leakage Measurement Techniques". Proceedings of the 2002 ACEEE Summer Study on Energy Efficiency in Buildings, Monterey, CA.

Francisco, P.W., L. Palmiter, and B. Davis. 2003. "Insights into Improved Ways to Measure Residential Duct Leakage". ASHRAE Transactions 2003. American Society for Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, GA.

Francisco, P.W. and L. Palmiter. 2003. "Field Evaluation of a New Device to Measure Air Handler Flow." ASHRAE Transactions 2003. American Society for Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, GA.

Gaston, C. 1999. Pennsylvania State University – York, York, PA. Personal Communication to author. February 4.

Jump, D., I. S. Walker, and M. P. Modera. 1996. "Field Measurements of Efficiency and Duct Retrofit Effectiveness in Residential Forced Air Distribution Systems." Proceedings of the 1996 ACEEE Summer Study on Energy Efficiency in Buildings, Monterey, CA.

Modera, M. P. 1989. "Residential Duct System Leakage: Magnitude, Impacts and Potential for Reduction." ASHRAE Transactions 1989. American Society for Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, GA.

Olson, J. R., L. Palmiter, B. Davis, M. Geffon, and T. Bond. 1993. *Field Measurements of the Heating Efficiency of Electric Forced-Air Systems in 24 Homes*. Bonneville Power Administration, Portland, OR.

Palmiter, L., J. R. Olson, and P. W. Francisco. 1995. *Measured Efficiency Improvements from Duct Retrofits on Six Electrically Heated Homes*. Electric Power Research Institute report TR-104426, Palo Alto, CA.

Palmiter, L. and P.W. Francisco. 2000a. *Development of a Simple Device for Field Air Flow Measurement of Residential Air Handling Equipment: Phase II*. Final report, Ecotope, Seattle, Washington.

Palmiter, L. and P.W. Francisco. 2000b. “A New Device for Field Measurement of Air Handler Flows.” Proceedings of the 2000 ACEEE Summer Study on Energy Efficiency in Buildings, Monterey, CA.

Palmiter, L., E. Kruse, and P. Francisco. 2003. *Simulation Analysis of Bias in the Delta-Q Duct Leakage Test.* Ecotope, Inc., Seattle, WA.

Parker, D. S. 1989. “Evidence of Increased Levels of Space Heat Consumption and Air Leakage Associated with Forced Air Heating Systems in Houses in the Pacific Northwest.” ASHRAE Transactions 1989. American Society for Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, GA.

Parker, D., J. Sherwin, R. Raustad, and D. Shirey III. 1997. “Impact of evaporator coil airflow in residential air-conditioning systems.” ASHRAE Transactions 1997. American Society for Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, GA.

Robison, D. H., and L. A. Lambert. 1988. *Field Investigation of Residential Duct Leakage*. Prepared for the Oregon Department of Energy under Contract No. 90023.

Rodriguez, A.G., D. O'Neal, J. Bain, and M. Davis. 1995. *The Effect of Refrigerant Charge, Duct Leakage, and Evaporator Air Flow on the High Temperature Performance of Air Conditioners and Heat Pumps*. Texas A&M Energy Systems Laboratory report ESL-TH-95/08-01, College Station, TX.

Siegel, J., B. Davis, P. Francisco, and L. Palmiter. 1996. *Measured Heating System Efficiency Retrofits in Eight Manufactured (HUD-Code) Homes*. Ecotope, Inc., Seattle, WA. For the Electric Power Research Institute, Palo Alto, CA and the Eugene Water and Electric Board, Eugene, OR.

Siegel, J., J. McWilliams, and I.S. Walker. 2003. “Comparison Between Predicted Duct Effectiveness from Proposed ASHRAE Standard 152P and Measured Field Data for Residential Forced Air Cooling Systems.” ASHRAE Transactions 2003. American Society for Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, GA.

Walker, I.S., and M.P. Modera. 1998. “Field Measurements of Interactions Between Furnaces and Forced-Air Distribution Systems”. ASHRAE Transactions 1998. American Society for Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, GA.

Walker, I.S., K. Brown, J. Siegel, and M.H. Sherman. 1998a. “Saving Tons at the Register.” Proceedings of the 1998 ACEEE Summer Study on Energy Efficiency in Buildings, Monterey, CA.

Walker, I.S., M.H. Sherman, J.A. Siegel, D. Wang, C. Buchanan, and M.P. Modera. 1998b. *Leakage Diagnostics, Sealant Longevity, Sizing and Technology Transfer in Residential Thermal Distribution Systems: Part II.* Lawrence Berkeley National Laboratory report LBNL-42691, Berkeley, CA.

Walker, I.S., M.H. Sherman, and J. Siegel. 1999. *Distribution Effectiveness and Impacts on Equipment Sizing for Residential Thermal Distribution Systems*. Lawrence Berkeley National Laboratory report LBNL-43724.

Walker, I.S., M.H. Sherman, J. Wempen, D. Wang, J.A. McWilliams, and D.J. Dickerhoff. 2001a. *Development of a New Duct Leakage Test: Delta Q.* Lawrence Berkeley National Laboratory report LBNL-47308, Berkeley, CA.

Walker, I.S., C.P. Wray, D.J. Dickerhoff, and M.H. Sherman. 2001b. *Evaluation of Flow Hood Measurements for Residential Register Flows.* Lawrence Berkeley National Laboratory report LBNL-47382, Berkeley, CA.

Walker, I.S., D.J. Dickerhoff, and M.H. Sherman. 2002. "The Delta Q Method of Testing the Air Leakage of Ducts." Proceedings of the 2002 ACEEE Summer Study on Energy Efficiency in Buildings, Monterey, CA.

Wray, C.P., I.S. Walker, and M.H. Sherman. 2002. "Accuracy of Flow Hoods in Residential Applications". Proceedings of the 2002 ACEEE Summer Study on Energy Efficiency in Buildings, Monterey, CA.

# *Appendix A*
# TESTING PROTOCOL FORM

This appendix includes the protocol forms for the field testing as well as the test guide that was used as a step-by-step protocol by the field technicians. Because the software was designed to automatically record the data and provide leakage estimates from the various tests, these leakage results were not recorded on the fourth through seventh pages of the paper forms in the test protocol when out in the field. However, these pages (A-6 through A-9) are useful to show the overall scope of data and results generated, and could potentially be beneficial to others who may desire to do one or more of these tests.

The test guide that follows the protocol is included as a further aid to anyone wishing to perform one of these tests, as well as to show the extent and complexity of the full test day. The test guide begins on page A-11.

Site ID____________________

# NETL Leakage Test Protocol

## Section I: General information

*Date*______________________________________________

Field technicians___________________________________

**Occupant Information**

Name ____________________________________________________________________

Address ___________________________________________________________________

*City* _________________*State* ______________

Phone # Home ___________________________________________________________
Work ___________________________________________________________

**Home Description - Interior**

Floor Area __________________ Number of bedrooms ___________________
Volume __________________ Number of bathrooms ___________________
Number of other rooms _________________

Other notes

**Sketches**

________________ Draw a floor plan of each level of the home, noting locations of supplies, returns, and air handler.

________________ Number each supply and return register with a different number.

________________ Take pictures at the four main directions of the house. There should be shots looking toward and away from the home.

________________ Take pictures of air handler and any noteworthy interior or exterior details.

Site ID____________________

**Heating System**

Equipment type: ______ Gas furnace ______ Heat Pump ______ Electric Furnace

Flow type: ______ Upflow ______ Downflow ______ Horizontal

Nameplate Information
Make and model ________________________________________________________
Maximum outlet temperature ______________________________________________
Nominal size ________________________________________________

Filter size ________________ Filter type ____________________________

*Air Handler Location:____ Indoors _____ Garage _____ Crawl Space _____ Attic*

Supply duct locations (include approximate percentage in each):

Return duct locations (include approximate percentage in each):

Other duct notes

Site ID____________________

**Section II: Diagnostic Testing**

## Gas Furnace Combustion Diagnostics

**Clock the meter** by timing several revolutions of the ½ CCF dial (assume 1040 BTU/CCF if not otherwise known):

CCFs:__________ BTU/CCF:_________ Time:__________ seconds

Total input consumption = CCF * BTU/CCF / sec * 3600 sec/h
=_____________BTUh

**Measure combustion efficiency and CO**:

Combustion efficiency:______________________________%

$CO_2$:____________________________%

Excess air:_________________________________%

Stack temperature:__________________________________F

CO:_____________________________ppm Where measured:_______________

$O_2$:______________________________%

**Heat Pump COP**

Air Handler Flow _________ cfm Temp. split _________ F

Amp draw _________ A Voltage _________ V

COP = (Air Handler Flow * Temp. Split) / (3413 * Amp draw * Voltage) = __________

Site ID____________________

## Datalogger Setup - Pressures

Set up pressure hoses across the envelope to the attic, garage, and crawl, two to outdoors on the same wall, one to outdoors across a different wall, one to the fan that will go in the house door, one to the fan that will be mounted to the air handler, and one to each the supply and return plenums. Record in the following table.

**8-channel Pressure Datalogger**

| Channel # | Input – Ref | Description |
|---|---|---|
| 1 | | |
| 2 | | |
| 3 | | |
| 4 | | |
| 5 | | |
| 6 | | |
| 7 | | |
| 8 | | |

**2-channel Pressure Datalogger**

| Channel # | Input – Ref | Description |
|---|---|---|
| 1 | | |
| 2 | | |

List heights above floor of any pressures between house and outside:

## Delta-Q Test

For this test, the air handler will be turned on and off only after a complete pass of positive or negative Delta-Q pressure stations. This will be done in conjunction with the unbalanced portion of the nulling test, following the baseline pressure measurement stage. If air handler is in garage, open garage to outside.

Results from computer (add comments about what assumptions were made)

Supply__________ cfm Return__________ cfm Assumptions_________________

Supply__________ cfm Return__________ cfm Assumptions_________________

Supply__________ cfm Return__________ cfm Assumptions_________________

Supply__________ cfm Return__________ cfm Assumptions_________________

Site ID____________________

## Nulling Test – Unbalanced Leakage

Set-up: Close all windows and doors to the outside. If air handler is in garage, open garage to outside. Open all interior doors and close all dampers and doors on wood stoves and fireplaces. Make sure that furnace and water heater can not come on unbidden during test. Make sure all fans are off and nulling fan is capped.

1) Record pressure across building envelope with air handler off and nulling fan capped, **reference outside**. This pressure will be used as the nulling pressure in the software. A "bracket" pressure offset will be required by the software as well.
2) Uncap nulling fan, turn on air handler, and then turn on nulling fan until pressure across envelope is same as with air handler off, modified by the bracket pressure offset. Record fan pressure and flow through nulling fan.
3) Repeat for unmodified nulling pressure and for nulling pressure modified by the bracket pressure offset with the opposite sign.
4) Interpolate linearly between modified nulling pressures to estimate unbalanced leakage at exact nulling pressure.

Interpolated unbalanced leakage __________ cfm supply / return dominated (circle one)

## Nulling Test – Supply Leakage

1) Attach Duct Blaster to furnace with the return blocked off, preferably such that the air is drawn from the conditioned space
2) If air handler is in garage, open garage to outside.
3) Install Duct Blaster in doorway set to pressurize house (ring on outside) if air is drawn from conditioned space, set to depressurize house (ring on inside) if air is drawn from unconditioned space.
4) Record pressure across envelope with air handler off (all fans covered).
5) Open fans, turn on air handler, and turn on matching Duct Blaster which is attached to air handler until pressure in supply plenum is matched (same as for air handler flow test).
6) Turn on nulling Duct Blaster in doorway until pressure across envelope is same as with air handler off modified by bracket pressure offset. Record fan pressure and flow through Duct Blaster.
7) Repeat for unmodified nulling pressure and for nulling pressure modified by the bracket pressure offset with the opposite sign.
8) Interpolate linearly between modified nulling pressures to estimate supply leakage at exact nulling pressure.
9) Correct supply leakage result for any deviation of air handler flow from as-found (i.e. same correction as is used for air handler flow measurement).
10) Combine result with unbalanced leakage to estimate return leakage.

Raw interpolated supply leakage __________ cfm

Corrected interpolated supply leakage __________ cfm

Estimated return leakage __________ cfm

Site ID____________________

## Sealed Blower Door Test

Set-up: Seal all registers and grilles. Close all windows and doors to the outside. If air handler is in garage, open garage to outside. Open all interior doors and close all dampers and doors on wood stoves and fireplaces. Make sure that furnace and water heater cannot come on during test. Make sure all fans are off.

**CFM50**________________________

**ACH50:**________________________

**n:**______________________________

**C:**______________________________

## Duct Blaster Tests

Set-up:
Return opening sealed in blower compartment
Duct Blaster attached to blower access opening for supply and at return grille for return
All registers sealed with tape and paper
Attach Duct Blaster to front of air handler cabinet
Blower door set up to pressurize for leakage to outside test

| | **Total Duct Leakage** | | **Duct Leakage to Outside** | |
|---|---|---|---|---|
| | Supply | Return | Supply | Return |
| Coefficient (C) | ____ | ____ | ____ | ____ |
| Exponent (n) | ____ | ____ | ____ | ____ |
| Leakage at Half Plenum Pressure | ____ | ____ | ____ | ____ |
| Leakage at 25 Pa | ____ | ____ | ____ | ____ |

Site ID____________________

**Air Handler Flow Measurement using Duct Blaster**

Set-up: All zones with duct work opened to outdoors and to each other, where possible.

Split system by placing a barrier in the filter slot.

Install Duct Blaster in such a way that it mimics return flow into cabinet as best as possible.

Use magnetic static pressure probe in supply plenum.

Turn on air handler. Turn Duct Blaster on (no rings) and slowly increase flow until the supply plenum pressure is the same as original value. Record pressure in plenum, Duct Blaster flow pressure and CFM. (This test can be considered part of the nulling test – supply leakage portion measurement.)

| | |
|---|---|
| *Original Supply Pressure:* | ______*Pa* |
| Test Supply Pressure: | ______Pa |
| Ring # | ______ |
| Flow pressure: | ______Pa |
| Raw Air Handler CFM: | ______cfm |
| Corrected Air Handler CFM | ______cfm |

**Air Handler Flow Measurement using Flow Plate**

Place appropriate plates and spacers into filter slot. Replace furnace covers. Turn on air handler, and record pressure drop across plate.

Plate used _____________________ Spacers used _____________________

Original Supply Plenum Pressure____________Pa Supply Plenum Pressure with Plate__________Pa

Raw Air Handler Flow____________________cfm Corrected Air Handler Flow_______________cfm

Site ID____________________

**Supply Register and Return Grille Flows**

Measure supply flows and temperatures with the air handler running.  The flow hood should be centered on the register wherever possible and it should be noted where centering is not possible.  Use plastic bags or cardboard boxes if necessary to measure flow.

| Reg. # | Temp (°F) | Uncorrected Flow (cfm) | Corrected Flow (cfm) |
|---|---|---|---|
| S1 | | | |
| S2 | | | |
| S3 | | | |
| S4 | | | |
| S5 | | | |
| S6 | | | |
| S7 | | | |
| S8 | | | |
| S9 | | | |
| S10 | | | |
| S11 | | | |
| S12 | | | |
| S13 | | | |
| S14 | | | |
| S15 | | | |
| S16 | | | |
| S17 | | | |
| S18 | | | |
| S19 | | | |
| S20 | | | |
| | | | |
| R1 | | | |
| R2 | | | |
| R3 | | | |
| R4 | | | |
| R5 | | | |
| R6 | | | |
| R7 | | | |
| | | **Total**<br><br>Sup.<br><br>Ret. | **Total**<br><br>Sup.<br><br>Ret. |

# <u>NETL Testing Guide</u>

## <u>Order of Tests</u>

1. Unbalanced Nulling (Duct Blaster installed)
2. Supply-only Nulling / Air Handler Flow (add split)
3. Duct Blaster Tests (swap Duct Blaster for blower door, seal registers)
4. Sealed blower door Test
5. Delta-Q Test
6. Flow Plate
7. Register Flows
8. Duct Map

## 1. Initial Datalogger Setup

There are several channels on the datalogger that are fixed. These are:

### 1.1 Eight-channel Datalogger

**P1** is the pressure that will be used as the **main envelope pressure**. This will be the attic if the attic is found to not be affected by duct leaks and if it will not be affected by (de)pressurizing the house. The hose that comes from outside the house goes into the **reference tap**.

**P2** is the **envelope fan pressure**. The hose that comes from the fan goes into the **reference tap**.

**P3** is the **supply plenum pressure**. The hose that comes from the supply plenum goes into the **input tap**.

**P4** is the **return plenum pressure**. The hose that comes from the return plenum goes into the **input tap**.

**A1** is the **wind speed**.

**A2** is the **permanent inside temperature**

**A3** is the **permanent outside temperature**

**A4** is the **temperature** that goes onto the **envelope fan inlet**.

**A5** is the **temperature** that goes onto the **air handler assist fan inlet**, and will also be used for the **flow plate** test.

### 1.2 Two-channel datalogger

P2 is the **air handler assist fan pressure**. The hose that comes from the fan goes into the **reference tap**.

### 1.3 Other notes

P1 on the 2-channel datalogger is always turned on. It is intended to be a pressure to outside. Since it is always on, it is advisable to use it for a pressure to outside even if there are channels available on the 8-channel datalogger. This hose should go into the reference tap.

We typically measure pressure to outside on two sides of the house. One of these hoses typically goes out the door in which the blower door will be installed. A second pressure hose to outside should be run along with that one. This extra one will be used in various tests as either a) the input on the envelope fan channel when the envelope fan is pressurizing, or b) the reference for the duct pressure in the total leakage duct blaster tests. The one that is NOT the extra hose for various tests should go into the reference tap in one of the channels on the datalogger.

We also want to measure pressures to the crawl space and garage, if applicable. These all get placed into reference taps. The default taps for these are P5 and P6 on the 8-channel, respectively. P7 is used as the permanent outside tap.

Note: Of permanent pressures, only the plenum pressures get placed into the input taps. All others get placed into reference taps.

It is imperative that the attic pressure not change due to duct leaks or due to changes in the house. If this is not the case, a different pressure that meets these criteria must be placed into P1 of the 8-channel datalogger.

## 2. Laptop setup

The 8-channel datalogger gets plugged into the serial port on the back of the laptop. The 2-channel datalogger gets plugged into the PC card serial port. The serial cables themselves are interchangeable.

Create a new folder under the “netl” directory with the form n##-lastname. Make a copy of the latest software found under the “netl” directory and place it in the new folder. Rename it n##.xls.

On the setup screen of the software, make sure that the channels all have the right labels and are turned on or off as appropriate. Open the two dataloggers (if they don’t open they are probably turned off).

On the test control page, select the number of samples desired for nulling tests based on wind level (use 40 as a default – i.e. no or little wind).

# 3. Unbalanced Nulling Test

## 3.1 Setup

- Install black duct blaster in the door. If likely direction of flow is known, install that way, but it easy to change. If direction is unknown, set to depressurize (assuming extra outdoor reference was not plugged into the input of P2 on the 8-channel. Cap fan.
- Plug fan control telephone cable from 8-channel datalogger to speed controller, which should be clicked just on.

## 3.2 Testing

- On test control page, click START.
- Adjust number of samples as desired.
- Check appropriate fan direction radio button.
- Select Black Duct Blaster and appropriate ring.
- Check air handler off radio button.
- Select station 11 in the software (purple).
- SAMPLE.
- At completion, turn on air handler. Click yes for automatic brackets. Software will prompt for this and will move to station 27 (air handler on baseline).
- After air handler has ramped up, SAMPLE.
- At completion, software will go back to station 11.
- Uncap Duct Blaster.
- Adjust Duct Blaster until target pressure from station 11 is matched, SAMPLE.
- Select station 12 or 13, as desired (low bracket or high bracket). Adjust Duct Blaster until pressure from selected station is matched, SAMPLE.
- Select remaining station. Adjust Duct Blaster until pressure from selected station is matched, SAMPLE.
- At completion, check line on “nulling results” page. If straight, you will move to station 14 (post-baseline). If there is a problem, redo points as needed.
- Turn off Duct Blaster and air handler, select station 14. Cap Duct Blaster.
- Check air handler off radio button.
- When air handler has ramped down, SAMPLE.
- STOP, and save.

## 3.3 Notes

If Duct Blaster is turned around, the extra outside hose must be installed on the input of **P2** or removed as appropriate. It should be installed whenever the Duct Blaster is pressurizing, removed whenever Duct Blaster is depressurizing. The radio button for fan direction must also be manually switched.

If ring is changed, the choice in the ring select drop-down box must be changed also.

# 4. Supply-only Nulling Test

## 4.1 Setup

- Set black Buct Blaster in the door to pressurize. Cap fan.
- Install extra outside reference tap onto input of **P2** on **8-channel** datalogger.
- Place split into filter slot between supply and return.
- Attach white duct blaster to air handler via 14” gray snorkel. One end of the snorkel has a 14” collar on it and the other has the clip attachment to the duct blaster. Cap fan.
- Install **pressure hose** from **white duct blaster fan** to the **reference** of **P2** on the **2-channel** datalogger.
- Plug fan control telephone cable from 2-channel datalogger to speed controller, which should be clicked just on.

## 4.2 Testing

- On test control page, click START.
- Check pressurize radio button for both envelope fan and air handler assist fan.
- Select Black Duct Blaster and appropriate ring for envelope fan
- Select White Duct Blaster and appropriate ring (usually 0 (open fan)).
- Make sure that the supply plenum pressure (left-hand blue box at bottom of air handler Assist Fan section) is entered in the cruise pressure box at the top of this section.
- Check “Cruise P3” radio button in air handler Assist Fan section.
- Check air handler off radio button.
- Select station 15 in the software (orange).
- SAMPLE.
- At completion, uncap white duct blaster and turn on air handler. Click yes for automatic brackets.
- Make sure that the cruise checkbox for the air handler Assist Fan is checked on.
- Uncap black Duct Blaster.
- Adjust Duct Blaster until target pressure from station 15 is matched, SAMPLE.
- Select station 16 or 17, as desired (low bracket or high bracket). Adjust Duct Blaster until pressure from selected station is matched, SAMPLE.
- Select remaining station. Adjust Duct Blaster until pressure from selected station is matched, SAMPLE.
- At completion, check line on “nulling results” page. If straight, you will move to station 18 (post-baseline). If there is a problem, redo points as needed.
- Turn off both duct blasters and air handler, select station 18. Cap both Duct Blasters.
- When air handler has ramped down, SAMPLE.
- STOP, and save.

### 4.3 Notes

If Duct Blaster is turned around, the extra outside hose must be installed on the input of **P2** or removed as appropriate. It should be installed whenever the Duct Blaster is pressurizing, removed whenever Duct Blaster is depressurizing. The radio button for fan direction must also be manually switched.

If ring is changed, the choice in the ring select drop-down box must be changed also.

## 5. Duct Blaster Tests

### 5.1 Setup

- Remove black Duct Blaster from door and install blower door with rings inside the house.
- Remove pressure hose from black duct blaster and place on blower door
- Remove fan control phone cord from black duct blaster speed controller and put onto blower door speed controller, which should be clicked just on.
- Move red flow direction switch on blower door toward the house to pressurize (we don't care what the blower door flow is for these tests).
- Tape off all registers and grilles except for one return grille.
- Attach black duct blaster to return grille.
- Cap off all fans.

### 5.2 Supply Leakage to Outside Testing

- On test control page, click START.
- Select station 19 in software (turquoise, Supply duct blaster to outside).
- Select pressurize radio button for both fans.
- Select air handler off radio button.
- SAMPLE.
- When complete, select air handler on radio button.
- Make sure that 25 is entered in the envelope fan cruise pressure box, and 0 is entered in the AH assist fan cruise pressure box.
- Make sure that air handler Assist Fan box has "Cruise P3" selected.
- Make sure that air handler Assist Fan box has **white** duct blaster selected with appropriate ring.
- Uncap blower door and white duct blaster.
- Check cruise checkboxes for both fans.
- When house pressure is stable at about 25 Pa and the duct pressure is stable at about 0, SAMPLE.
- When complete, go to 50 Pa point (station 20). When house pressure is stable at about 50 Pa and duct pressure is stable at about 0 Pa, SAMPLE.
- Check results on Duct Blaster page, make sure exponent is reasonable.
- Turn both fans off.

### 5.3 Total Supply Leakage Testing

- Cap white duct blaster, leave blower door uncapped.
- Attach extra outdoor hose to reference port on **P3**.
- Select station 21 (total supply duct blaster).
- Select AH off radio button.
- SAMPLE.
- When complete, select air handler on radio button.
- Make sure that 25 is entered in the air handler assist fan cruise pressure box.
- Make sure that air handler Assist Fan box has “Cruise P3” selected.
- Make sure that air handler Assist Fan box has white duct blaster selected with appropriate ring.
- Uncap white duct blaster.
- Check cruise checkbox for air handler Assist fan.
- When duct pressure is stable at about 25, SAMPLE.
- When complete, go to 50 Pa point (station 22). When duct pressure is stable at about 50 Pa, SAMPLE.
- Check results on Duct Blaster page, make sure exponent is reasonable.
- Turn fan off.
- STOP, and save.

### 5.4 Additional setup for return duct blaster testing

- Remove fan pressure hose from white duct blaster and attach it to black Duct Blaster.
- Remove phone cord from white duct blaster speed controller and attach it to the black duct blaster speed controller.
- Move temperature probe from A5 (air handler assist fan temperature) to the black duct blaster.
- Cap off all fans, including blower door.

### 5.5 Return Leakage to Outside Testing

- On test control page, click START.
- Select station 23 in software (Return duct blaster to outside).
- Select pressurize radio button for both fans.
- Select AH off radio button.
- SAMPLE.
- When complete, select air handler on radio button.
- Uncap blower door and black duct blaster.
- Make sure that 25 is entered in the envelope fan cruise pressure box, and 0 is entered in the air handler assist fan cruise pressure box.
- Make sure that air handler Assist Fan box has “Cruise P4” selected.
- Make sure that air handler Assist Fan box has **black** Duct Blaster selected with appropriate ring.

- Check cruise checkboxes for both fans.
- When house pressure is stable at about 25 Pa and the duct pressure is stable at about 0, SAMPLE.
- When complete, go to 50 Pa point (station 24). When house pressure is stable at about 50 Pa and duct pressure is stable at about 0 Pa, SAMPLE.
- Check results on Duct Blaster page, make sure exponent is reasonable.
- Turn both fans off.

### 5.6 Total Return Leakage Testing

- Cap black Duct Blaster, leave blower door uncapped.
- Attach extra outdoor hose to reference port on **P4**.
- Select station 25 (total supply Duct Blaster).
- Select air handler off radio button.
- SAMPLE.
- When complete, select air handler on radio button.
- Make sure that 25 is entered in the air handler assist fan cruise pressure box.
- Make sure that air handler Assist Fan box has "Cruise P4" selected.
- Make sure that air handler Assist Fan box has black Duct Blaster selected with appropriate ring.
- Uncap black Duct Blaster.
- Check cruise checkbox for air handler Assist fan.
- When duct pressure is stable at about 25, SAMPLE.
- When complete, go to 50 Pa point (station 26). When duct pressure is stable at about 50 Pa, SAMPLE.
- Check results on Duct Blaster page, make sure exponent is reasonable.
- Turn fan off.
- STOP, and save.

## 6. Sealed Blower Door Test

### 6.1 Setup

- Cap off all fans.
- Switch blower door red switch to depressurize.
- Make sure that the extra outdoor hose is not attached to any datalogger.

### 6.2 Testing

- On Test Control page, click START.
- Select Blower door and appropriate ring in envelope fan section.
- Select depressurization radio button in envelope fan section.
- Select air handler off radio button.
- Select station 36 in software (yellow).

- SAMPLE.
- When complete, make sure that air handler on radio button is selected.
- Make sure that cruise pressure box in envelope fan section is set to –50 Pa.
- Check cruise checkbox.
- When house pressure is stable at about –50, SAMPLE.
- When complete, make sure that station 37 is selected, air handler still on.
- Cruise at –25 Pa, when stable SAMPLE.
- When complete, turn off fan and cap off.
- Make sure that air handler is set to off, station is still 37.
- SAMPLE.
- When complete, STOP and save.

# 7. Delta-Q Test

## 7.1 Setup

- Untape all registers and grilles. At this point, there is no more need for the Duct Blasters.
- Set blower door to depressurize. The first pressure will be –50 Pa.
- Cap off BD.
- Return air handler to normal mode – remove white duct blaster, split, and replace filter.

## 7.2 Testing - Depressurization

- Adjust number of samples as desired.
- On test control page, START.
- Make sure that air handler off radio button is selected.
- Make sure that envelope fan depressurize radio button is selected.
- Make sure that blower door and appropriate ring are selected.
- Select station 0 (lt. blue, Delta-Q baseline).
- SAMPLE.
- When complete, go to station 30 (down below nulling, DB, and flow plate tests).
- Uncap fan.
- Check Cruise checkbox for envelope fan.
- When stable, SAMPLE.
- When complete, software will move automatically to –40 Pa station. SAMPLE when stable.
- Continue through air handler off, depressurization points. When fan pressure gets low, add ring, making change in software.
- After –5 Pa point, software will move to AH on side, including changing radio button, for –5 Pa. Turn on air handler.
- Continue process through –50 Pa point. Change rings as needed, making sure that the same ring is used for both air handler off and air handler on points at each station.
- When –50 Pa point is complete, turn off blower door and air handler.

### 7.3 Testing - Pressurization

- Turn blower door around.
- Attach extra outdoor hose to input of **P2** on 8-channel datalogger.
- Start cruising at 5 Pa by checking cruise checkbox. Air handler off radio button and envelope fan pressurize radio button should be selected automatically, verify.
- When stable, SAMPLE.
- Continue as with depressurization side, changing rings as necessary.
- When all stations completed, including air handler on stations up through 50 Pa, turn off air handler and blower door.
- STOP, and save.

## 8. Flow Plate Test

### 8.1 Setup

- Remove filter and install flow plate such that pressure sampling ports in open area are facing upstream.
- Attach hoses from flow plate to input and reference of **P2** on 2-channel datalogger.
- Insert temperature probe from A5 (air handler assist fan temperature) into return plenum.

### 8.2 Testing

- On test control page, START.
- Select Flow Plates on air handler Assist Fan side.
- Select 14 inch or 20 inch in ring select dropdown box.
- Select station 29 (green).
- Select air handler on radio button.
- Turn on air handler.
- When stable, SAMPLE.
- When complete, turn off air handler.
- STOP, and save.
- Return air handler to normal operation (flow plate out, filter in).

## 9. Register Flows

These can be entered in the Register Flows tab of the software as well as in the protocol sheet. Recommendation is to record them in the protocol and then type them into the software. The software will then provide best estimate of leakage.

# *Appendix B*
# SCREENING FORM

This appendix includes the screening forms used in the phone interview.  This phone interview was used as a first attempt to screen out homes that did not meet the criteria for inclusion in the study.  Homes were only excluded if there was an obvious physical characteristic that would make it difficult to complete one or more of the leakage tests in a timely fashion.

**NETL Duct Leakage Testing Project**
**Questionnaire**

Name:_______________________________________
Address:_________________________________ City/State/Zip:_______________________
Phone (home):______________________ (work)_______________________

**About Your House**:
Number of stories:_______ Approximate floor area ______________ square feet
Single-family home? Yes / No
Manufactured home? Yes / No

**Your Heating System**:
Type (check one): ____Heat Pump ____Electric Furnace ____Gas Furnace

Furnace Orientation (check one): ____Upflow (heated air goes out top)
____Downflow (heated air goes out bottom)
____Horizontal

Location (check one): __Inside __Garage __Attic ___Crawlspace ___Basement

Can the blower cabinet (the fan which circulates air through the furnace) be easily accessed?
Yes / No

Is there a fan-only switch available (either a switch that goes from “auto” to “On” on thermostat or a switch on the side of the furnace that turns the fan on)? Yes / No

Is there at least 2 feet of clearance in front of the furnace? Yes / No

**The Furnace Filter**
Filter type (check one): ___Electronic Air Cleaner ___Fiberglass Filter ___Other (specify)

If equipment is a downflow gas furnace without an Electronic Air Cleaner, is the filter a single piece that slides in and out? Yes / No

If no above, are there two filters behind the flue and above the blower? They may be tilted and touch at the bottom such that they make a “V” at a vertical. Yes / No

**Registers/Grilles**
Total number of supply (warm air) registers:_________
Number that are toe kicks (small registers typically beneath cabinets in bath or kitchen)_______
Number that are wall registers (located vertically on a wall)?______________
Number of registers that are located under or behind very heavy pieces of furniture or cabinets where they are not accessible?____________

Total number of return (cold air) grilles:____________
Can all of them be easily accessed? Yes / No

**NETL Duct Leakage Testing Project**
**Questionnaire**

**Supply ducts**
The majority of the warm-air ducts are located in the:
____Crawlspace ____Attic ____Other (specify)

If two-story, are there ducts between floors? Yes / No

**Return ducts**:
The majority of the cold-air return ducts are located in the:
____Crawlspace ____Attic ____Other (specify)

If two-story, are there ducts between floors? Yes / No

**Access Points**
Please describe the location of your attic's access hatch or door:___________________________
Is it in a closet? Yes / No
Does it offer accessibility to the attic space? Yes / No

Please describe the location of your home's crawl space access:___________________________
Is it in a closet? Yes / No
Does it offer accessibility to the attic space? Yes / No

**Scheduling/Notes**
The testing of houses will take place over the next few months. Each house will take about 10 hours on a single day/ Please indicate any preferences for days of the week, specific dates, times of day, etc. This includes specific periods that are not acceptable, such as vacations. Also, please indicate if you desire to participate but would prefer to delay until a later time.

Please provide any additional comments, questions, or concerns you may have.

# *Appendix C*
# CALIBRATION

Laboratory calibrations were made for most of the equipment used in the NETL study both before and after the field test portion of the project. Both pre- and post-fieldwork calibrations were performed at Ecotope for the "Fast-1" propeller based flow hood and the two flow stations for 4" and 6" round metal duct used in the benchmark estimate validation tests. Both of the Duct Blasters®, and the blower door used in the study were sent to The Energy Conservatory for a custom calibration immediately prior to the start of the fieldwork. Upon completion of the study, the Duct Blasters® were returned to the Energy Conservatory for recalibration. The Alnor Balometer arrived new for this study with a calibration certificate and was both recalibrated at Ecotope and returned to Alnor for recalibration after the fieldwork was completed.

Included below is a brief description of the equipment which was calibrated at Ecotope, as well as the calibration procedure and results. These calibrations include the effects of air density on the results. A discussion of the results of the post-fieldwork calibration follows. Finally, there is a summary of the results of the pre- and post-fieldwork calibrations of the Alnor Balometer.

## CALIBRATION OF FAST-1 FLOW HOOD AND FLOW STATIONS

### Equipment Description

The Fast-1 flow hood measures the rotation speed of an aerodynamic propeller mounted in the neck of the capture hood. According to standard fluid mechanics theory, the propeller rotation speed is directly proportional to the bulk air velocity in the neck which, in turn, is directly proportional to the actual volumetric flow through the hood. Density corrections for this device use the density ratio.

The flow stations, originally manufactured by the VanEe company, measure the difference between upstream total pressure (the sum of velocity pressure and static pressure) and the downstream static pressure with paired tubing manifolds. The manifolds cross at right angles at the center of sections of 4" and 6" diameter duct. Density corrections for these devices use the square root of the density ratio.

For the "true" flow used in the Ecotope calibrations, two custom calibrated Energy Conservatory Duct Blasters® were used. The calibrations for these devices have a power law form with an exponent very close to 0.5. Density corrections use the square root of the density ratio.

An Alnor Balometer with analog display, model #6461CFM, was used to measure the return grille flows in the field. This flow hood has a double grid of plastic tubing with holes on one grid facing upstream into the flow and downstream on the other grid. The pressure difference between the upstream and downstream holes generates a flow of air through the meter, which contains a swinging vane anemometer. The deflection of the vane results in a deflection of the readout needle. The output of the swinging vane is directly proportional to the air velocity in the internal tubing. There is a knob on the body of the flow hood which has three settings for return flow. Each setting selects a different orifice to control the flow through the vane anemometer thus providing three different measurement ranges. A fourth range (low flow) can be obtained by selecting the lowest range and inserting a perforated plate on the upstream side of the grid. The values for all four flow ranges are then read on separate scales.

## Experimental Setups

### *Fast-1 Flow Hood Setup 1*

In this setup a single Duct Blaster® was used to power the flow and also to measure the true flow. The Duct Blaster® had a Mitsubishi type flow straightener and fitting immediately down stream, followed by a 10” to 6” reducer, followed by two 30” lengths of 6” galvanized sheet metal duct, followed by a 6” flow station, followed by another 30” length of 6” duct, followed by a standard right angle 4” by 10” floor register boot. A standard floor register was mounted in the boot. The flow hood was centered on the register. All connections were sealed airtight so the airflow through the flow hood was the same as that through the Duct Blaster®.

### *Fast-1 Flow Hood Setup 2*

This setup is identical to Flow hood setup 1, with the exception that the measurement of airflow was by a non-powered Duct Blaster® located upstream from the powered Duct Blaster®. This was accomplished with a 12-foot length of 10” flexible duct between the two Duct Blasters®.

### *Flow Station Setup 1*

The intended application of the flow stations in this project is for direct measurement of the air leakage from a disconnected supply duct. For this purpose the flow stations were calibrated in the same configuration. For the 6” station the setup was the same as Flow hood setup 1, except the pipe downstream of the flow station was removed. For the 4” flow station we attached a 6” to 4” reducer to the 6” flow station, followed by 30 inches of 4” duct with the 4” station attached to the end. The same reducer and 4” duct should be used in the field.

### *Flow Station Setup 2*

This configuration is the same as Flow station setup 1, except the measurements are made with the non-powered Duct Blaster® as described in Flow hood setup 2.

## Measurements and Adjustment Equations

For all data points the output of the device to be calibrated was recorded, as were the temperature of the air entering that device and the temperature and flow rate of the air entering the measurement Duct Blaster®. For the flow hood calibrations nominal flows were from about 20 cfm to about 250 cfm in roughly 20 cfm increments.

*Fast-1 Flow Hood Equations*

The Duct Blaster® flow pressures were converted to flows using the custom calibration equations. Assuming a simple square-root law, the density adjustment equations for the Duct Blaster® can be derived as follows:

The nominal flow, $Q_{nom}$, can be expressed in consistent units as

$$Q_{nom} = C\sqrt{\Delta P} \qquad \textbf{(C-1)}$$

where $Q_{nom}$ is the fan flow
$C$ is the flow coefficient
$\Delta P$ is the pressure difference across the fan

Expanding the flow coefficient as

$$C = C_d A\sqrt{\frac{2}{\rho_{cal}}} \qquad \textbf{(C-2)}$$

where $C_d$ is the discharge coefficient
$A$ is the cross sectional area perpendicular to the direction of flow
$\rho_{cal}$ is the density of the air at the time of calibration

gives

$$Q_{nom} = C_d A\sqrt{\frac{2\Delta P}{\rho_{cal}}} \qquad \textbf{(C-3)}$$

This equation gives the correct volumetric flow only when the actual density is the same as the calibration density.

The actual volumetric flow, $Q_{db}$, can be expressed as

$$Q_{db} = C_d A\sqrt{\frac{2\Delta P}{\rho_{db}}} \qquad \textbf{(C-4)}$$

where $\rho_{db}$ is the density of the air at the time of measurement.

Combining eqs. **(C-3)** and **(C-4)** gives an equation to determine the actual volumetric flow,

$$Q_{db} = Q_{nom}\sqrt{\frac{\rho_{cal}}{\rho_{db}}} \qquad \textbf{(C-5)}$$

If both densities are at the same atmospheric pressure, the correction involves only the absolute temperatures at the time of measurement, $T_{db}$, and at the time of calibration, $T_{cal}$:

$$Q_{db} = Q_{nom}\sqrt{\frac{T_{db}}{T_{cal}}} \qquad \textbf{(C-6)}$$

where each $T$ is an absolute temperature in consistent units (in this case $T_{cal}$=293.15 K = 527.67 R).

Due to the heat generated by the Duct Blaster®, the temperature of the airflow through the flow hood is somewhat higher than that at the inlet to the Duct Blaster®. Therefore a further correction was made to get the actual volumetric flow at the hood, $Q_{hood}$, at one standard atmosphere,

$$Q_{hood} = Q_{db}\frac{\rho_{db}}{\rho_{hood}} = Q_{db}\frac{T_{hood}}{T_{db}} \qquad \textbf{(C-7)}$$

The calibration of the flow hood then compares the values of $Q_{hood}$ to the raw cfm readings of the flow hood.

*Flow Station Equations*

For the flow stations, no correction for density was required due to cancellation. The calibration compared the values of the raw Duct Blaster® flows with the square root of the flow station pressure difference.

**Summary of Pre-Fieldwork Results**

*Fast-1 Flow Hood*

In comparing the $Q_{hood}$ with the raw flow hood readings, it was found that the data could be well fit by either a linear relationship or a power law relationship. Investigation of the residuals from the linear fit showed the standard deviation of the error also increased linearly with the flow, indicating that the error is a percentage error. Under these circumstances one would expect the errors from the power-law fit to be constant and the residuals showed that to be the case. Another advantage of using a log-log regression (power-law fit) is that the regression minimizes the percentage error for each observation, thus reducing the impact of the high flow points.

The values of $Q_{hood}$ and the raw flow hood readings are shown with an equality line in Fig. C-1. Notice that at flows below about 70 cfm, the points show an increasing departure from the one-one line. The same effect was seen when comparing the raw flow hood readings with the flow measured by the inline flow station. This suggests the departure is due to the flow hood. At low flows, the raw readings are lower than they should be (the propeller rotation rate is too low). This departure from the expected behavior is corrected by using a power-law fit. The data and the regression line for the power-law fit are shown in Fig. C-2.

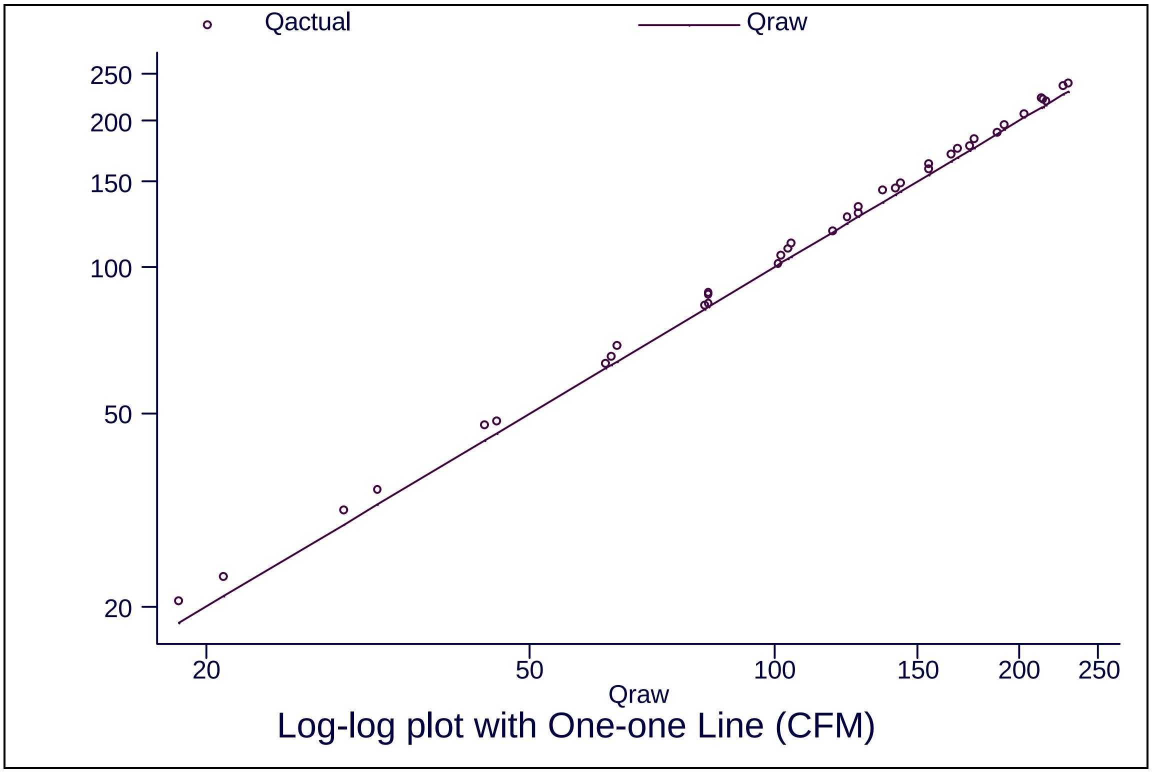



Figure C-1. True flow versus Fast-1 flow hood measurements with one-one line.

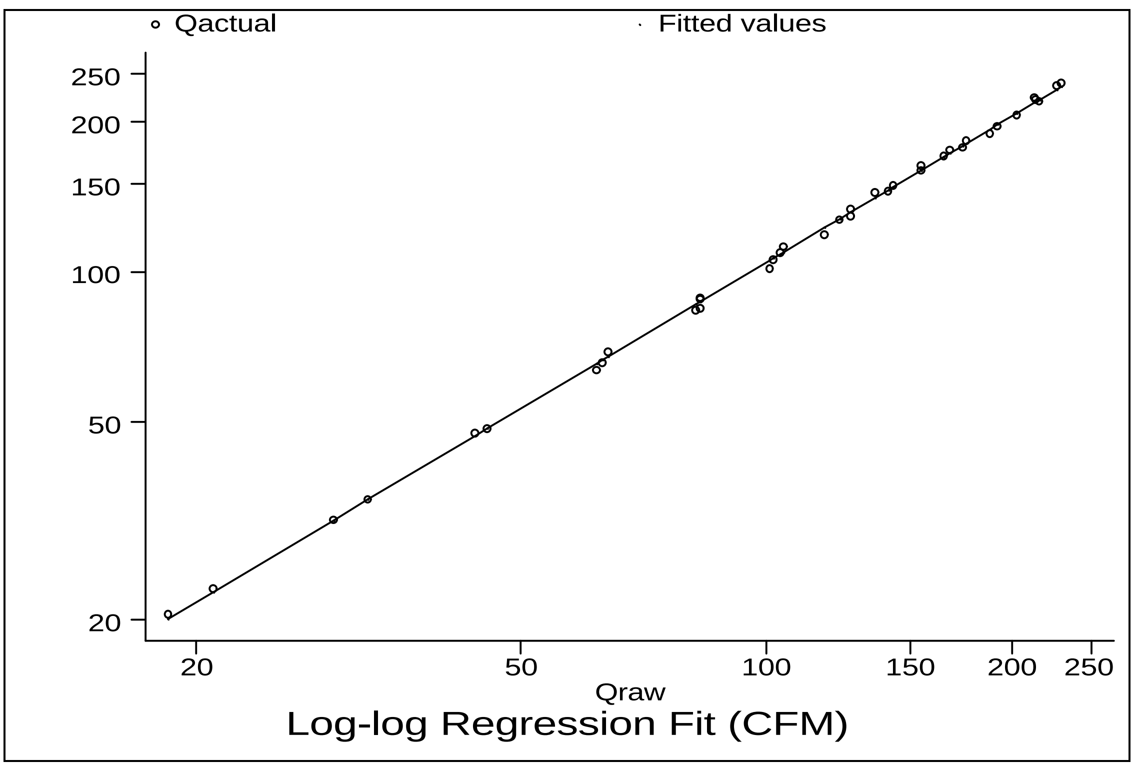



Figure C-2. True flow versus Fast-1 flow hood measurements with regression line.

The power-law fit resulted in the following calibration for the flow hood:

$$Q_{actual} = 1.166 Q_{raw}^{0.9758} \qquad \textbf{(C-8)}$$

with an RMS error of 1.8% (N = 38).

As noted above, the flow hood measures the actual volumetric flow. To convert the flow to standard cfm (scfm) the ratio of the pressures, or absolute temperatures can be used:

$$Q_{std} = Q_{actual} \frac{\rho_{actual}}{\rho_{std}} = Q_{actual} \frac{T_{std}}{T_{actual}} \qquad \textbf{(C-9)}$$

at one atmosphere.

*Flow Stations*

For the flow stations the calibrations at one atmosphere and 68 F are:

$$Q = C\sqrt{\Delta P} \qquad \textbf{(C-10)}$$

For 6" station: $C = 32.1 \pm 0.25$ or 0.8% (N = 5)
For 4" station: $C = 13.5 \pm 0.081$ or 0.6% (N = 6)

where $Q$ is the flow in cfm and the pressure is in Pascals.

To convert the station (or Duct Blaster®) flows to standard cfm (scfm):

$$Q_{std} = Q_{nom}\sqrt{\frac{\rho_{actual}}{\rho_{cal}}} = Q_{nom}\sqrt{\frac{T_{cal}}{T_{actual}}} \qquad \textbf{(C-11)}$$

This assumes the standard density is equal to the calibration density of 1.204 $kg/m^3$. The calibration temperature is 20 C = 68 F = 293.15 K = 527.67 R. One atmosphere is equal to 101,325 Pa.

**Summary of Post-Fieldwork Results**

The same calibration procedures were used for the post-fieldwork calibrations of the Fast-1 flow hood and the flow stations. The results from these tests showed very little deviation from the initial calibration. The Duct Blasters® also returned from The Energy Conservatory with calibrations virtually identical to those used throughout the fieldwork.

## ALNOR FLOW HOOD CALIBRATIONS

The Alnor Balometer, which was new for this study, was calibrated by the manufacturer upon purchase. The calibration certificate claims a tolerance of ±3% of full scale for this instrument and states that the calibration process uses “standards whose accuracies are traceable to the National Institute of Standards and Technology”. There are no calibration equations which come with the balometer; the calibration process is simply an adjustment made internally to the instrument at the calibration facility.

Calibrations performed by Ecotope at the completion of the fieldwork showed that the balometer was out of tolerance. Even more alarming was the discovery of strong orientation dependencies. Calibration equations were developed to be applied to the data for each orientation used in the field and the instrument was returned to the manufacturer for their standard calibration procedure and inspection for damage.

Alnor subsequently reported to Ecotope that the instrument was not found to be damaged, and that most of the flow hoods that were manufactured at their old facility and returned for recalibration to their new facility are roughly 10% out of specifications. This indicates that the flow hood was functioning consistently throughout the study, and agrees with an investigation of the data, in which no distinct and sudden change in agreement between the benchmark estimate (return side) and other methods could be found.

Alnor has not yet found an explanation for this discrepancy in their calibration facilities. The manufacturer did concede that the instrument is in fact subject to an orientation dependence. They also stated that their flow hoods are calibrated in only one position (that which would be used to measure a ceiling register). At the time of purchase, neither the orientation dependence nor the calibration procedure were known to the researchers at Ecotope.

Table C-1 is taken from the calibration certificates received from Alnor with the new instrument, and when it was returned for recalibration. The first column shows the four flow measurement ranges. The second column is the true (reference) flow as set by the calibration technician, and the third is the readout from the Alnor Balometer as a fraction of the true flow. Note that the

Table C-1. Alnor Flow Hood Calibration Data (cfm)

| Range | True Flow | Instrument Reading | Allowable Range |
|---|---|---|---|
| **New Calibration** | | | |
| **800-2000** | 1900 | 1900 | 1840-1960 |
| **400-1000** | 900 | 900 | 870-930 |
| **100-500** | 450 | 450 | 435-465 |
| **0-250** | 200 | 190 | 185-215 |
| **Post-fieldwork Calibration** | | | |
| **800-2000** | 1900 | 2000† | 1840-1960 |
| **400-1000** | 900 | 980† | 870-930 |
| **100-500** | 450 | 465 | 435-465 |
| **0-250** | 180 | 180 | 160-200 |

† Indicates out of tolerance.

post-fieldwork calibration data shows that the Alnor flow hood at the time of recalibration is consistently showing a bias, as opposed to simply large uncertainties.

Figures C-3 and C-4 show examples of the Ecotope post-fieldwork calibration results. Figure C-3 shows the difference between the reading on the Alnor flow hood and the true flow versus the flow hood reading for the configuration required to measure a ceiling register. This is the same orientation in which the flow hood is calibrated. The results are qualitatively in agreement with Ecotope's calibration results, but often suggested even larger corrections were necessary. Although the calibrations performed at both locations are similar to each other, they do not tend to agree with the field results.

Figure C-4 has the same axes and is for the same measurement range, but shows the corrections necessary for a wall register. In this orientation, the hood can be positioned with the meter facing the ceiling, the floor, to the right or to the left. Each of these result in a different calibration, with up and down being very similar and right and left differing greatly. Figure C-4 is for the configuration used to measure a wall register with the meter facing up.

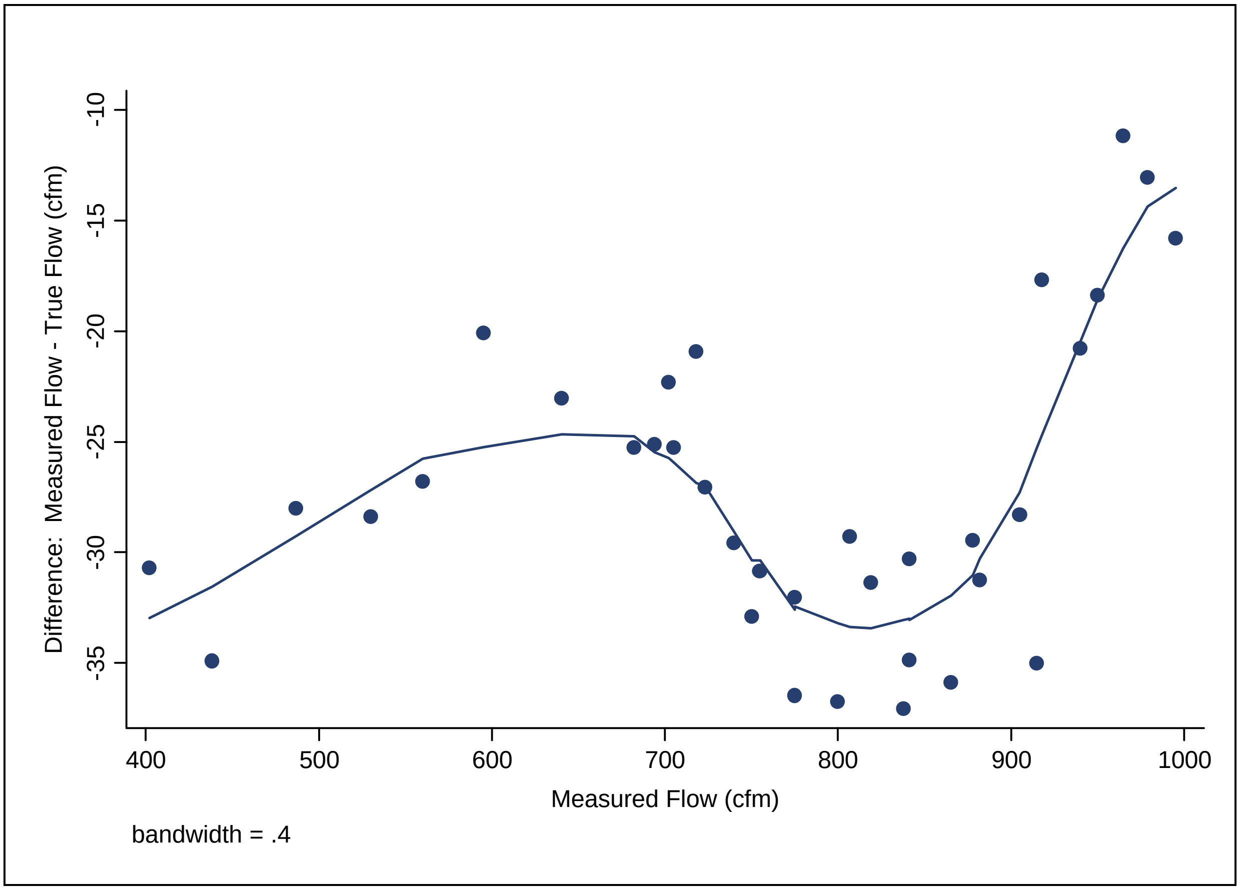



Figure C-3. Alnor flow hood corrections: Ceiling register, 400-1000 cfm range.

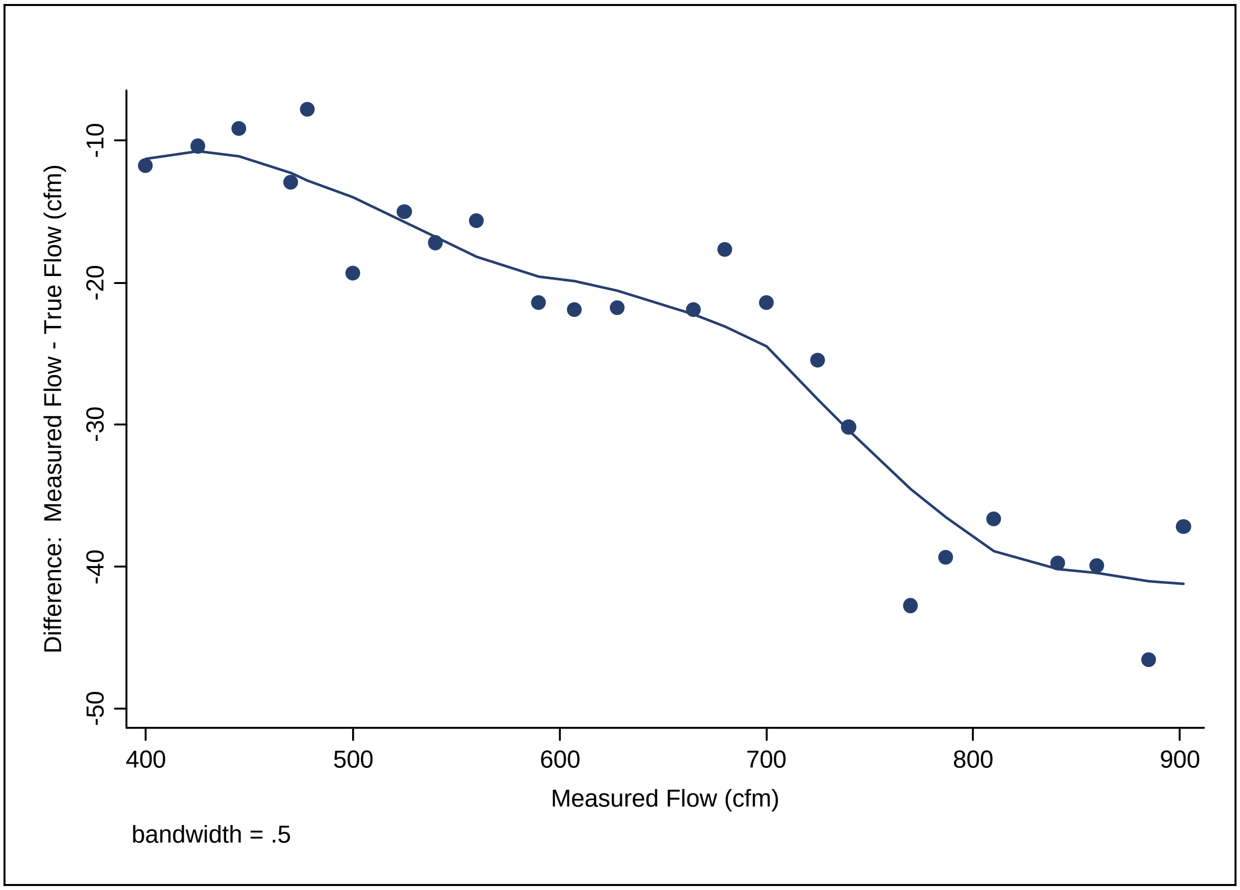



Figure C-4. Alnor flow hood corrections: Wall register, meter-up, 400-1000 cfm range.

Graphs similar to these were used to adjust the field data for each flow measurement range and hood orientation. An Alnor flow hood field measurement is located on the x-axis and the y-value of the curve at that point is the correction required. After applying these calibrations to the field data, the test methods investigated in this study are in further disagreement with one another. This has lead to the conclusion that there are either compensating errors which can lessen or even remove the bias in the field, or there is some phenomenon which causes the flow hood to perform differently in laboratory and field settings.

# *Appendix D*
# PHOTOGRAPHIC SAMPLES OF TESTED HOMES

This appendix shows examples of test cases. These are broken into three sets, one set per page, six pictures per set. The sets are test houses (page D-3), furnaces (page D-4), and duct leaks found as a result of testing (page D-5).

## SAMPLE OF HOUSES TESTED

Figure D-1. Old, small single-story home.

Figure D-2. Larger single-story home.

Figure D-3. Older two-story home.

Figure D-4. Newer two-story home.

Figure D-5. Home with a partial second story.

Figure D-6. Manufactured home.

## SAMPLE OF FURNACES TESTED


Figure D-7. Older gas furnace.

Figure D-8. Old converted furnace, belt-driven.

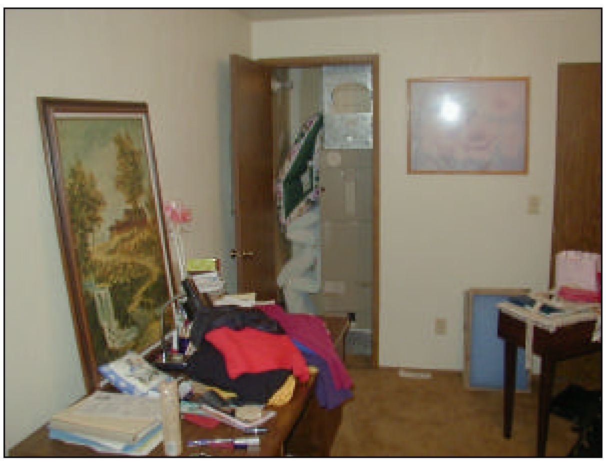


Figure D-9. Electric furnace in interior closet.

Figure D-10. Gas furnace in garage.

Figure D-11. New condensing gas furnace.

Figure D-12. Furnace in high crawl space.

## SAMPLE OF LEAKS FOUND

Figure D-13.  Double disconnected supply.

Figure D-14.  Leak at supply plenum.

Figure D-15.  Separated supply duct.

Figure D-16.  Separated elbow at supply boot.

Figure D-17.  Leaky finger joints.

Figure D-18.  Supply duct coming out of trunk.