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A Field Study of Exterior Duct Leakage in New Wisconsin Homes

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by

Scott Pigg, Energy Center of Wisconsin
Paul Francisco, University of Illinois

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(800.762.7077, focusonenergy.com)

Project Manager

Scott Pigg

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SUMMARY

This report summarizes a field study of exterior duct leakage in 19 new Wisconsin homes. The goals of the study were to quantify duct leakage in homes with exterior duct runs and to compare several methods for assessing duct leakage. Of particular interest for the study was how actual duct leakage compares to current national default values (as defined by RESNET), and whether Wisconsin homes can be reliably screened for duct leakage using less expensive methods than duct pressurization.

The 19 homes (all unoccupied at the time of testing) were assessed between February 2007 and February 2008 using a day-long protocol involving the following four methods of duct leakage assessment:

1. duct pressurization testing (Duct Blaster™);
2. pressure-pan testing;
3. blower-door based duct leakage assessment using the Delta-Q method; and,
4. nulling testing.

All of the homes in the study had at least some duct runs outside the conditioned envelope of the building. However, the homes varied in the extent to which the ductwork was exposed to conditions outside the thermal envelope of the home:

- **Low-exposure homes**: eight homes had the majority of ductwork inside the conditioned envelope; these were typically homes with only the supply runs for a bonus room over a garage outside the conditioned envelope.
- **Moderate-exposure homes**: seven homes had a mix of inside and outside ductwork; these were typically two-story homes with second-floor supplies through the attic.
- **High-exposure homes**: four homes had the majority of ductwork outside the conditioned envelope; these were typically slab-on-grade homes with duct runs through the attic and the heating system located in a mechanical closet in the garage.

The homes for the study were identified through Focus on Energy staff and the network of Wisconsin energy consultants associated with the Wisconsin Energy Star Homes Program. This meant that the majority of the homes tested were of relatively energy efficient construction, and therefore not necessarily representative of all Wisconsin new homes.

All of the homes in the study were heated with gas forced-air furnaces and cooled with conventional split-system air conditioning. Except for the four high-exposure homes (and one moderate-exposure home), the furnaces were located in conditioned full basements.

FINDINGS

Following are the key findings from the study:

- None of the low- or moderate-exposure homes showed significant duct leakage to the outside under actual operating conditions. Measured supply leakage was less than two percent of total air handler flow in all cases (though in two cases, measurement uncertainty allowed for actual supply leakage of up to five percent). Return leakage—which is less costly from an energy standpoint—was similarly low for these homes.

- All of the high-exposure homes showed signs of significant duct leakage. Nulling tests of leakage—which was the most accurate method used in the study—could not be completed at two of the four homes, but in general, the test data for these homes pointed to significantly higher leakage rates on both the supply and return sides.

- Duct leakage under actual operating conditions was generally less than that measured by standard duct pressurization tests. These results indicate that actual leak pressures are typically less than those induced under pressurization testing, which involves pressurizing the duct system to 25 Pascals. Thus, duct leakage estimates that directly use duct pressurization results will overestimate actual duct leakage.

- Seasonal duct distribution system losses for the low- and moderate-exposure homes in the study appear to be significantly lower than current RESNET default assumptions. In the absence of testing, current RESNET standards require an assumed distribution system efficiency loss of 12 percent for ducts located in conditioned space and 20 percent for ducts located outside conditioned space. We estimate actual losses in the study homes to be generally less than five percent for homes with low duct exposure and less than ten percent for homes with moderate exterior exposure—and most of the losses in these homes are attributable to conductive losses rather than air leakage. (A ten percent distribution system loss translates into about $100 of annual heating and cooling costs for the typical new Wisconsin home at current fuel rates.) Only the four homes with high exterior exposure had estimated seasonal distribution system losses that were comparable to the current RESNET default values.

- The Delta-Q method of assessing duct leakage has promise, but the data indicate that the results are sensitive to wind. We developed an approximate method to assess the reliability of Delta-Q estimates of duct leakage, however additional methodological work is needed in this area.

- Pressure pan measurements can likely be used to screen for significant duct leakage for homes that have low or moderate exterior duct exposure and have the air handler in a conditioned basement. If the high-pressure portions of the duct system are inside the conditioned space, then pressure pan measurements are likely to detect non-trivial leakage. For all types of homes, high pressure pan readings indicate sizable holes somewhere in the duct system.

- The reliability of measured leakage to the outside from duct pressurization tests depends on the level of leakage to the *interior*: High interior leakage makes for less precise measurements of exterior leakage. This reinforces the need to properly seal registers before conducting leakage-to-outside tests using duct pressurization. It also indicates that exterior leakage measurements in homes that use building cavities or panned joists as duct runs are subject to substantial error.

INTRODUCTION

Because ducts are pressurized and carry conditioned air meant to heat or cool living spaces, duct leakage can impose a significant energy penalty on residential heating and cooling systems. Leaks to the outside on the supply side of the system directly reduce system efficiency by diverting to the outside heated or cooled air meant for conditioned spaces. Leaks to the exterior on the return side of the system tend to suck unconditioned air requiring heating, cooling or dehumidification into living spaces, and thus also impose an additional burden on the heating and cooling systems. In recognition of these phenomena, ratings standards for residential buildings, such as those developed by the Residential Energy Services Network (RESNET), include duct leakage as an important assessment parameter.

However, many homes in Wisconsin and throughout the Midwest have little or no ductwork that runs through unconditioned spaces. Some feel that national standards for testing and required default assumptions for duct leakage impose an unnecessary burden on Midwestern housing stock. The standards are primarily intended for housing stock in other parts of the country where basements are less common and many homes have substantial amounts of ductwork in attic or crawl spaces.

The purpose of this research effort was to examine levels of exterior duct leakage in new Wisconsin homes, as well as to assess various methods for measuring (or diagnosing) duct leakage.

STUDY SAMPLE

For the study, we sought to obtain detailed duct leakage measurements for 20 new Wisconsin homes with at least some duct work outside the thermal envelope of the building. Candidate homes for the study came from the network of Wisconsin energy efficiency consultants who work with a variety of builders of custom and production homes. These consultants suggested homes with at least some ductwork outside the thermal envelope. Note that this requirement alone placed the study homes well outside the mainstream for Wisconsin homes, where most homes have all ductwork inside conditioned space. Data from a 2000 Energy Center characterization study of Wisconsin homes indicate that nearly 90 percent of new homes in the state have all ductwork either in conditioned or basement spaces within the pressure envelope of the building (Pigg and Nevius, 2000).

Nineteen homes were recruited for the study between February 2007 and February 2008. All of the homes were heated with gas forced-air furnaces and cooled with conventional split-system central air conditioners. Twelve of the nineteen homes in the study were built to qualify for either Energy Star certification or EPACT tax credits. To be in the study, the homes needed to be substantially completed but unoccupied. The homes generally had not had special attention paid to the ductwork prior to involvement in the study (one home had undergone a fogging test for gross leakage, however).

The homes were intentionally selected to represent a range of duct exposures, and can be placed into three categories, based on the approximate fraction of the ductwork that was outside the thermal envelope:

- <u>Low exterior duct exposure</u> (eight homes) — the typical home in this group had a bonus room over a garage with supply runs to this room in the garage ceiling, and all other ductwork inside the conditioned envelope. The furnaces for these homes—and much of the ductwork—were located in full basements.

- Moderate exterior duct exposure (seven homes) — exterior ductwork for the typical home in this group consisted of attic supply runs to second-floor ceiling supply registers. As with the first group, furnaces for these homes (with one exception) were located in full basements.

- High exterior duct exposure (four homes) — none of these homes had basements, and consequently much of the duct system was located in the attic. Three of the homes were of slab-on-grade construction and the fourth had a crawlspace. Two of the four homes had all (or most) supplies through attic spaces; of the other two, one had supplies through a crawlspace, and the other had supplies through the foundation slab. All of the homes had returns through the attic. Three of the four homes had the furnace located in a mechanical closet in the garage; the fourth was located in a first-floor mechanical closet.

Though hard data are difficult to come by, based on the recruitment process for this study, it appears likely that most Wisconsin homes with ductwork outside conditioned space would fall into the low or moderate exposure category.

More detailed descriptions for each site can be found in Appendix A.

TEST METHODS

Four methods were employed to assess duct leakage in each home:

- Duct pressurization
- Delta-Q
- Nulling
- Pressure pan testing

DUCT PRESSURIZATION

Duct pressurization is used to measure total duct system leakage (i.e. leakage both inside and outside the thermal envelope) and leakage to the outside at artificially-induced duct pressures. Measuring total duct system leakage involves masking all registers, pressurizing the duct system with a calibrated fan (typically to 25 Pascals), and then recording airflow flow through the fan at the known level of pressurization—much like a standard blower-door test measures house leakage at a known pressure.

To measure leakage to the outside, a blower door is used to pressurize the house to a given level. The duct pressurization fan is then used to zero out any pressure differences between the ducts and the house; the flow through the duct pressurization fan with the duct pressure zeroed with respect to the (pressurized) house represents the level of duct leakage to the outside.

Because this testing is conducted at artificially-induced pressures, the results are not necessarily indicative of the amount of leakage that occurs under actual operating conditions. However—like a blower door test—it provides a quantified and repeatable measure of duct leakage.

Duct pressurization testing was conducted for this study using Energy Conservatory Duct Blaster™ equipment and DG-700 digital pressure gauges. The protocol involved measuring total duct system leakage at 25 Pascals, and leakage to the outside at 25, 50 and 100 Pascals. In addition, to gauge the sensitivity of the leakage-to-outside results to measurement of the pressure difference between the ducts and the house, flow readings were taken at zero, 0.2, 0.5 and 1.0 Pascals of pressure difference between the ducts and the house.

All of the above was repeated twice: once for the entire duct system (supply and return), and once for the supply side of the duct system only. The latter was achieved by installing an airtight block in the filter slot to isolate the supply ductwork from the return ductwork. Return leakage was then estimated by subtracting supply leakage from the supply-and-return measurements.

DELTA-Q

"Q" is a common symbol for flow in engineering contexts, and Delta-Q is premised on the idea that duct leakage can be estimated by looking at the difference in blower door airflow with and without the air handler operating. A Delta-Q test thus involves measuring blower door flow across a wide range of house-to-outside pressures both with the air handler operating and without it operating, and then statistically extracting the estimated leakage from the resulting data. The process has been greatly facilitated with software developed by the Energy Conservatory that largely automates the process. See Walker et al. (2001) for more details of the basic concept of the Delta-Q test.

Unlike duct pressurization, Delta-Q measurements of duct leakage to the outside are meant to reflect leakage under actual operating conditions. Also Delta-Q testing does not require equipment beyond a blower door that is capable of being controlled by a laptop computer. However, because the underlying duct leakage signal is typically small, the results can be affected by wind gusts at inopportune moments, leading to questions about the reliability of a given test.

Moreover, there is not a general consensus regarding the details of how to conduct and analyze Delta-Q tests. At present there are two test methods: *ramping*, in which the blower door is quickly operated through a range of house pressures while recording data on airflow and house pressure; and *stations*, which involves collecting data at each of a number of discrete pressure levels. See Francisco (2006) for a description of and initial results for the "ramping" technique of Delta-Q test data collection. The "stations" technique is the method described in Walker et al. (2001).

There are also multiple approaches to analyzing the data collected under a Delta-Q test to estimate duct leakage. Unless noted otherwise, the results reported in this study use the *scanning* technique. This approach assumes that the leakage can be characterized by a single pressure on each of the supply and return sides. The method is implemented by scanning through a range of user-selected possible supply and return leak pressures to identify the pair that provides the best least-squares fit to the observed data, which are then considered to be the characteristic leak pressures for the system.

For this study, a protocol of multiple Delta-Q tests was implemented at each site. These tests involved both ramping and stations tests, as well as repeat tests and control tests to help assess the reliability of the Delta-Q method (a control test is a Delta-Q test in which the air handler is never turned on, and for which the actual leakage is therefore known to be zero).

NULLING

The idea behind the nulling approach is that duct leakage to the outside induces a pressure difference across the building shell. An equal airflow in the opposite direction will nullify that pressure difference: if the opposing airflow is created with a calibrated fan, then the airflow through the fan can be measured and the amount of duct leakage thus quantified. See Francisco and Palmiter (2001) for a detailed description of the nulling test.

Though simple in theory, in practice nulling is difficult to implement. This is because the house-to-outside pressure differences induced by duct leakage are generally very small (often less than one Pascal), making the duct leakage signal difficult to distinguish among pressure readings that vary from moment to moment due to wind. This makes it necessary to average readings over time to reliably average out wind effects.

With the assistance of Collin Olson of the Energy Conservatory, we developed a semi-automated, computer-driven nulling procedure that cycled the air handler on and off (at 15- to 20-second intervals) over 20 to 30 cycles, while recording house-to-outside pressure. This process was repeated for several nulling fan flow levels that were chosen to attempt to bracket the flow needed to nullify the duct leakage. A linear regression of house pressure against nulling fan flow was then used to derive the final estimate of the nulling flow (and a statistical confidence interval) required to exactly offset the duct-leakage induced house pressure. As with duct pressurization, the entire process was repeated twice: once for the entire duct system (which estimates the amount of unbalanced duct leakage, i.e. which of the supply or return leakage is greater and by how much), and once with the supply side of the duct system isolated. (In the latter case, a second duct blaster was needed to provide airflow to the air handler at a pressure mimicking the return side of the duct system.) The estimated return leakage was the difference between the entire duct system nulling test (i.e. the unbalanced nulling test) and the supply-only nulling test.

PRESSURE PAN TESTING

Pressure pan testing is not a duct leakage quantification approach, but rather a leakage diagnostic tool. It involves depressurizing the house with a blower door (typically to -50 Pascals) with the air handler off, and then sequentially placing a gasketed pan (or other occlusion device, such as tape or pillow) over each supply or return register and measuring the pressure difference across the pan. The magnitude of the pressure reading is an indication of the degree to which the duct in question is connected to the outdoors: large readings indicate significant leaks. This is similar to zone pressure testing of unconditioned zones in a house, but specially crafted for ducts.

Interpreting pressure pan readings can be tricky. The closer a given hole in the ducts is to the register being measured, the larger the pressure pan reading for that register. Therefore, small readings at a number of registers may be indicative of a large leak that is far away from the reading locations or small leaks at the boots; the energy implications for these two types of leaks are very different. Also, registers that are close together (e.g. back-to-back through an interior wall) can lead to false low readings.

For this study, pressure pan readings were taken for all supply and return registers while the house was depressurized to 50 Pascals.

RESULTS

OVERVIEW OF MEASURED DUCT LEAKAGE

FIGURE 1, MEASURED SUPPLY AND RETURN DUCT LEAKAGE TO OUTSIDE.

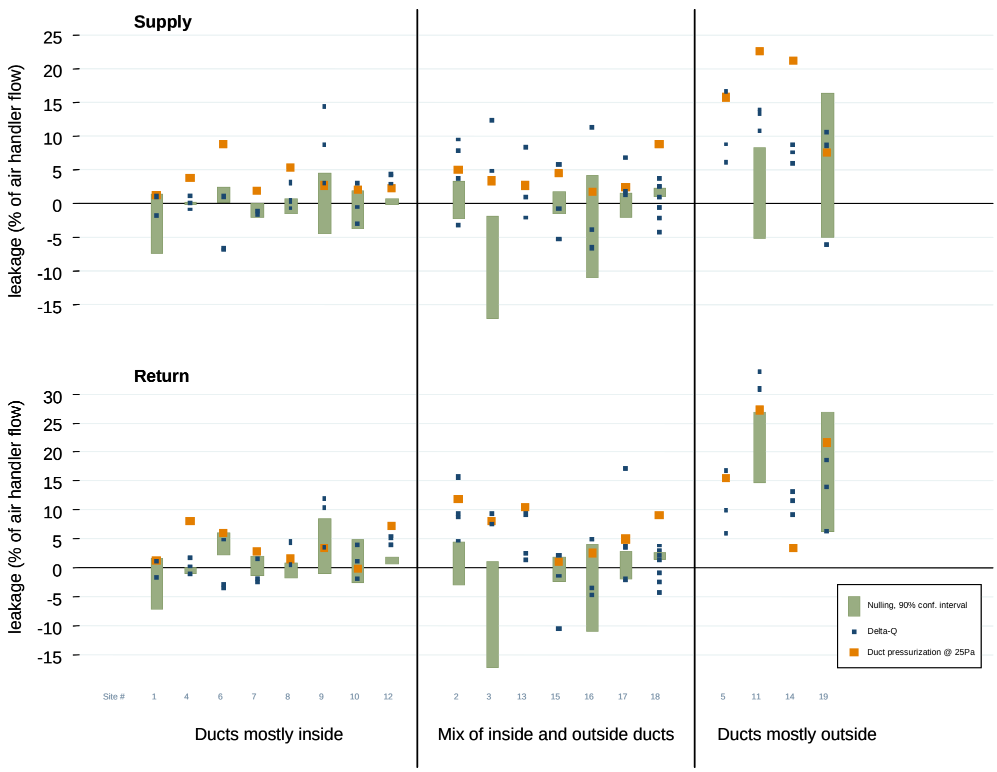


Figure 1 summarizes the results from the three methods that quantify duct leakage: the figure shows the 90% confidence interval for the nulling results, as well as point estimates for all (non-control) Delta-Q tests, and the measured duct leakage from pressurization testing at 25 Pascals.

In general, the results indicate low levels of leakage under actual operating conditions—except for the four sites with most or all ductwork outside the conditioned envelope, which show considerably higher leakage rates. Aside from these four homes, none of the confidence intervals for supply leakage estimated from the nulling method exceed five percent, and only two of the sites have return leakage confidence intervals that exceed five percent.[1]

Some of the Delta-Q test results (which include both the “ramping” and “stations” test methods) indicate higher rates of leakage, but the preponderance of data suggests low leakage rates for all but the four sites with most ductwork outside conditioned space.

In addition, the nulling and Delta-Q estimates of duct leakage under actual operating conditions are generally lower than the measured leakage to outside using the duct pressurization method. This suggests that duct leakage under actual operating conditions tends to occur at lower driving pressures in these homes than the 25 Pascals used for pressurization testing.

[1] The analysis methods used for nulling and Delta-Q tests allow for negative estimates of duct leakage, even though this is physically nonsensical. This is done to avoid a positive bias in estimate leakage when measured leakage is close to zero.

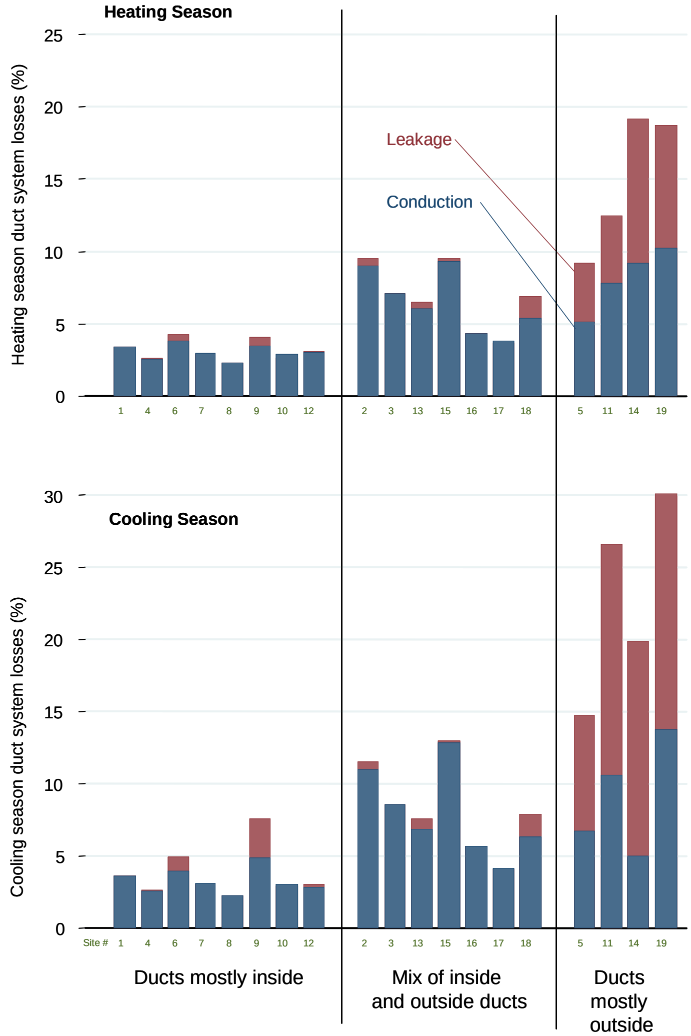
ESTIMATED DUCT SYSTEM LOSSES

We used methods put forth in ASHRAE Standard152 (ASHRAE, 2004) to estimate overall duct system losses based on the duct system characteristics and measured leakage for each site. This method takes into account duct location and insulation level as well as measured leakage to the outside to estimate seasonal losses due to conduction and leakage.[2]

The results (Figure 2) suggest seasonal duct losses of less than 5 percent in general for the sites with minimal exterior duct exposure, between 5 and 15 percent losses for sites with a mix of interior and exterior ductwork, and up to 30 percent losses among the four sites with mostly exterior ductwork. Note that for all but the four high-exposure sites, duct *leakage* plays very little role in overall duct system losses; rather the estimates were dominated by conduction losses.

As a point of reference, for a typical new Wisconsin home with about 1,000 annual hours of heating system operation (and a 75-kBtuh furnace) and 300 annual hours of cooling (2.5 ton, SEER-13 central AC system), 10 percent distribution system losses would add about $95 per year to heating costs (at $1.25 per therm) and about $7 worth of cooling (at 10 cents per kWh)—assuming the system air handler is not operated continuously.

FIGURE 2, ESTIMATED DUCT SYSTEM LOSSES (BASED ON ASHRAE 152).



Current RESNET standards require a default assumption of 12 percent duct system distribution efficiency losses where ducts are located in conditioned space, and 20 percent losses for ducts located outside of conditioned spaces (RESNET, 2006). Based on this standard, the low-exposure homes would have default estimated duct losses close to 12 percent, the moderate-exposure homes would be somewhere between 12 and 20 percent, and the high-exposure homes would have default distribution losses of about 20 percent. While actual distribution losses appear to be comparable for the last category of homes, applying the default values to the other homes would over-state the actual losses—in some cases significantly.

[2] We use the following heuristic to choose among the various duct leakage estimates for each site: (1) use the nulling test point estimate of leakage if it is greater than zero; (2) otherwise use the upper boundary of the 90% confidence interval if it is greater than zero; (3) otherwise use the median of the (non-control) Delta-Q test results.

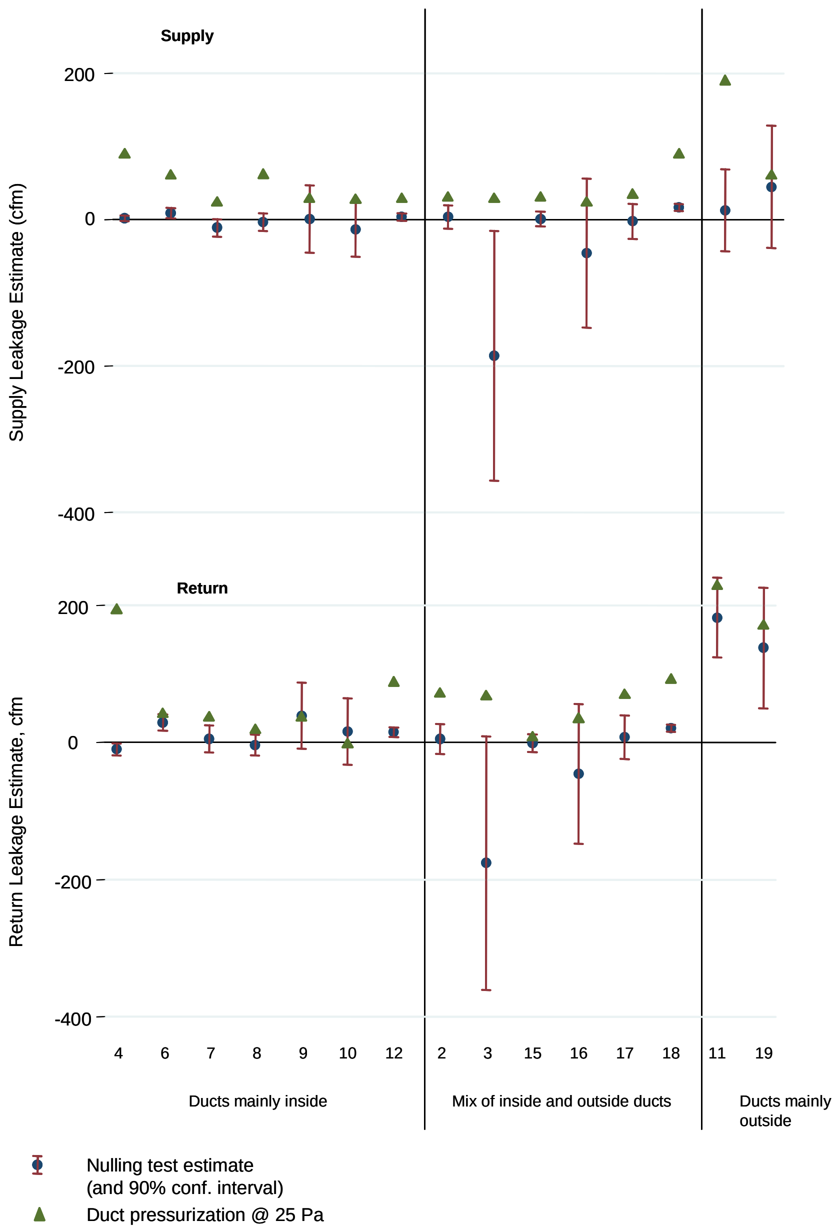
FINDINGS RELATED TO DUCT-TESTING METHODS

This section discusses the findings of the various test methods from the study with regard to their accuracy, the extent to which they provide appropriate feedback, and problems with each test. “Actual” leakage here is based on the nulling test results, with consideration of the uncertainty estimates from this test.

Duct Pressurization

Figure 3 compares the results of the nulling test to duct pressurization results at 25 Pascals for supply and return ducts, restricted to only cases where both tests were successfully completed. The graph shows that the leakage at 25 Pascals is always higher than the central estimate of the nulling test with the exception of return leakage at Sites 9 and 10. In fact, of 15 cases there are only 4 supply cases and 7 return cases where the duct pressurization result falls within the 90% confidence interval of the nulling test.

FIGURE 3, NULLING AND DUCT PRESSURIZATION ESTIMATES OF SUPPLY LEAKAGE.

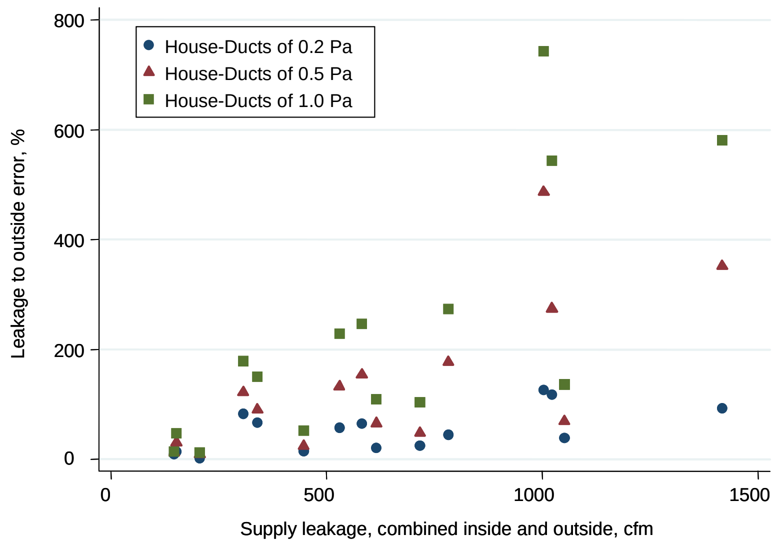


These results indicate that, in these homes, the actual pressures acting on the duct leaks are usually far less than 25 Pascals, and that using the leakage at 25 Pascals as a proxy for the operating leakage will significantly overestimate the energy losses due to leakage. Even for the two cases where the duct pressurization result is lower than the central nulling estimate the leakage is quite low (less than 50 cfm).

Another aspect of duct pressurization tests that was investigated was the impact of leakage to inside on the resolution of the estimates of leakage to outside. Since leakage to outside estimates require that the pressure difference between the house and the ducts be zero, a small error in adjusting this pressure difference could result in a large error in the leakage estimate if the leakage to inside is large. For example, if the pressure between the house and the ducts was actually 0.2 Pascals instead of 0 Pascals, and the leakage to inside was large, the flow to inside at 0.2 Pascals could be large, and would be read as additional leakage to outside.

Figure 4 shows the results of this investigation for supply leakage only. In addition to the leakage estimate at zero Pascals between the house and the ducts, additional estimates were made with the pressure between the house and ducts at 0.2, 0.5, and 1.0 Pascals.

FIGURE 4, DUCT PRESSURIZATION LEAKAGE ERROR VS. TOTAL LEAKAGE RATE, FOR THREE HOUSE-DUCT PRESSURES.



As the figure shows, there is a general increasing trend of percentage error as the combined leakage total (inside plus outside) gets larger, with duct-house pressure errors of as small as a Pascal causing errors of several hundred percent in the leakage to outside estimate. There are several implications of this finding. First, it shows how important it is to zero out the pressure difference between the house and the ducts as precisely as possible when there is substantial leakage to inside. Second, it calls into question the results of duct pressurization tests whenever there is substantial leakage to inside and the ducts may not all be truly at the same pressure (i.e. if the pressure in the ducts differs along the duct length then there will be some areas with non-zero pressure which may in turn provide a significant errant flow in the leakage to outside measurement). Third, since unsealed registers act as leaks to inside, these results emphasize the need to seal all registers as completely as possible.

Delta-Q

While the Delta-Q test has shown considerable promise in giving results that are believable and easy to obtain, there remain questions about both the accuracy and repeatability of the results. At the time that this study was undertaken there were no uncertainty estimate methods available. (A new trial uncertainty estimate method is currently being evaluated; see Appendix C for details.) However, several additional Delta-Q tests were performed to investigate the accuracy and repeatability of the results as well as the relative merits of different sampling protocols and analysis techniques. The two sampling protocols evaluated were the “ramping” and “stations” protocols, and the two analysis techniques evaluated were “non-negative least squares (NNLS)” and “scanning.”

CONTROL TESTS

So-called “control” tests were done by not turning on the air handler fan throughout the testing. Since there was no possibility of a duct leakage signal the true value of the leakage should have been zero for both supply and return leakage for these tests. Any deviation from zero is an indication of the level of accuracy of the Delta-Q test for these special cases, which could also be viewed as analogous to cases where there was no leakage (such as in homes with all ducts inside the conditioned space).

Due to time constraints, only one control test was done at most houses, with the sampling protocol alternating between ramping and stations for each house. Figure 5 shows the supply and return control test results for both the ramping and stations protocols. Both NNLS and scanning analysis techniques are shown in these graphs.

For the ramping protocol, most of the scanning results are negative whereas all of the NNLS results are zero or positive. The NNLS method requires that the results be non-negative, but the tendency for the scanning results to be negative was not expected. However, with a small sample size it is quite possible that this tendency is circumstantial. Most of the cases of scanning are still within 50 cfm of zero (10 of 12 supply cases and 8 of 12 return cases).

For the stations protocol there are more cases of leakage estimates that are more than 50 cfm from zero. In addition, the scanning results are more frequently positive, and often provide similar results as the NNLS analysis technique. It should be kept in mind that this does not imply that scanning with stations provides positive leakage estimates for control tests in general. There was very little overlap in the homes at which both stations and ramping control tests were done so the difference in apparent pattern is again possibly just circumstantial.

Figure 6 recasts the data as box plots, to show the distribution of different combinations of test methods and analysis

FIGURE 5, DELTA-Q CONTROL TESTS.

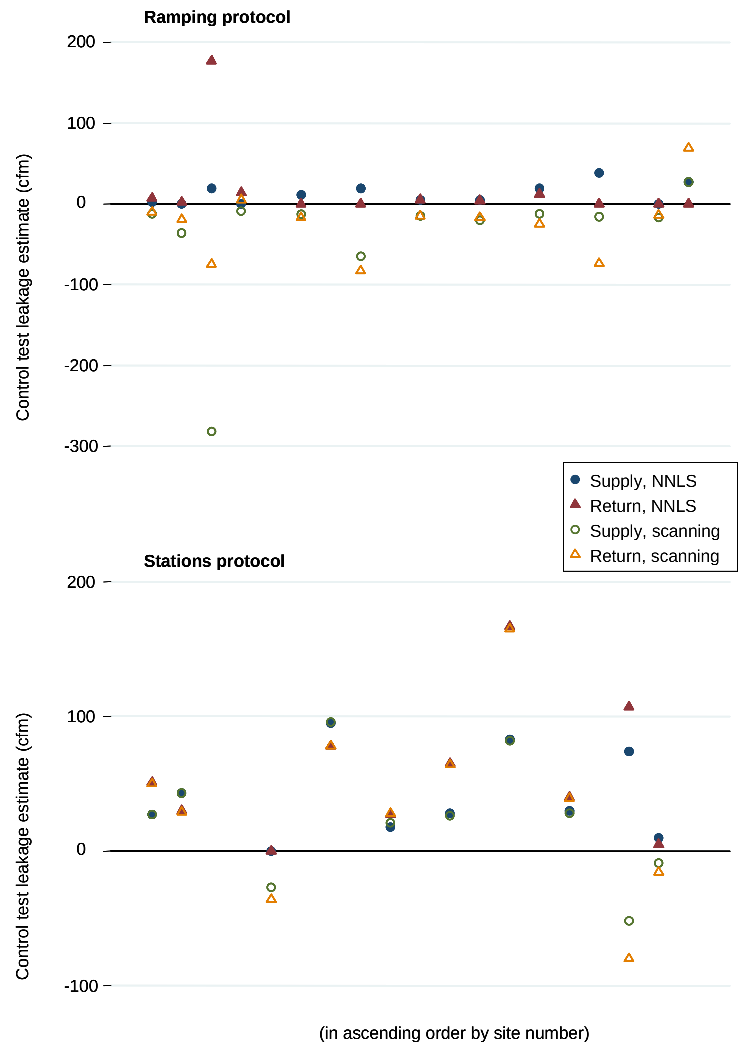
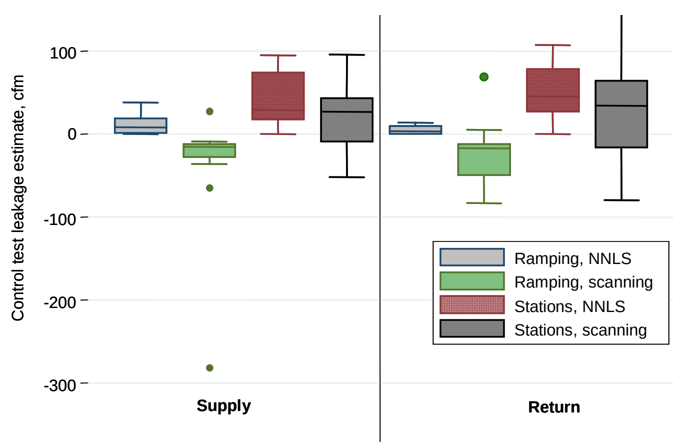


FIGURE 6, CONTROL TEST BOX PLOTS.



technique, separately for supply and return. As before, the NNLS results are pinned at a minimum of zero. This graph shows that the ramping method tends to have a tighter distribution and less of a bias away from zero. Because the NNLS technique prevents negative values it is expected that the distribution using NNLS will be tighter, but the results also do not indicate the real variation in results just from the data. For example, if the average leakage had been 100 cfm rather than zero, the chances of the NNLS changing the result from a negative value to zero is much smaller, and the range in leakage estimates would be more likely to be similar to the scanning analysis results.

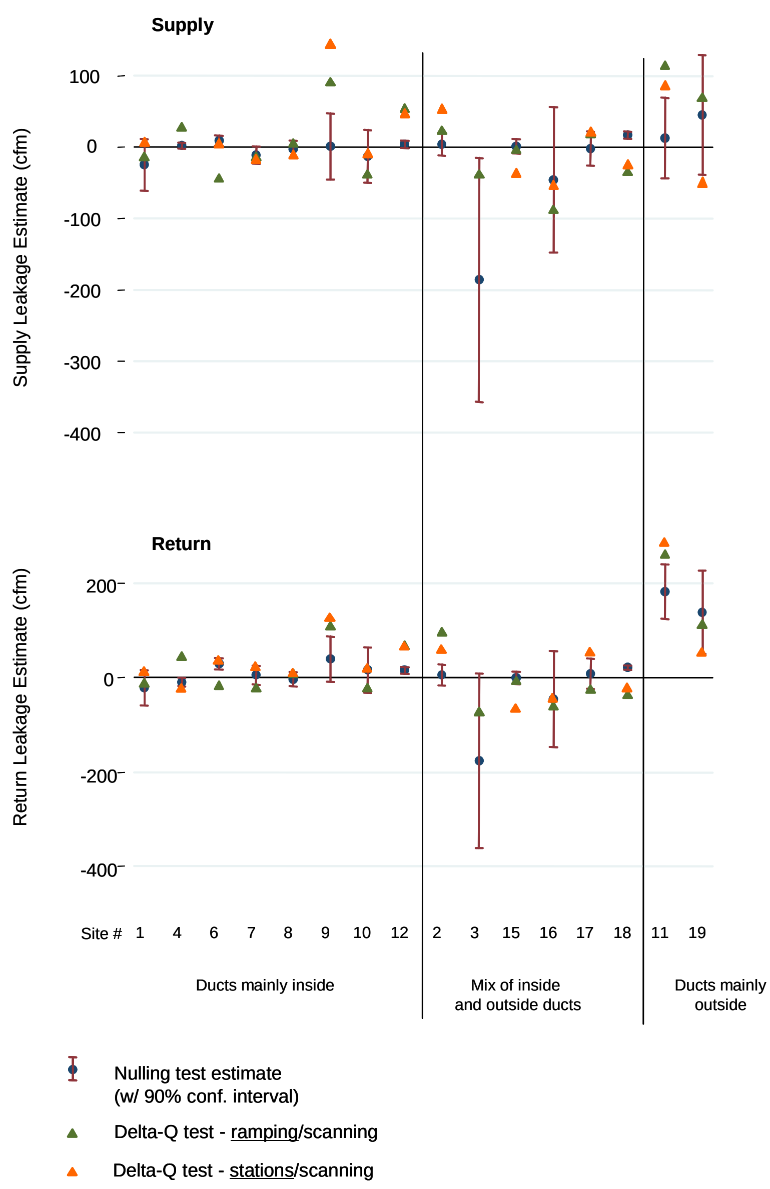
COMPARISON TO NULLING TESTS

For normal tests (i.e. those where the air handler was turned on in an effort to quantify actual leakage) the nulling tests were used for the accuracy assessment of the Delta-Q tests.

Figure 7 compares Delta-Q results using both the ramping and stations protocols to the nulling results. About half of the time the Delta-Q estimate falls outside the 90% confidence interval of the nulling test. This does not mean, however, that the Delta-Q result is statistically significantly different from the nulling test. Although there is no generally accepted method for assessing the uncertainty in Delta-Q tests, a preliminary method we developed using control-test data (See Appendix C) suggests that most of the differences between Delta-Q and nulling estimates shown here are not statistically distinguishable.

These results reinforce three points: the sensitivity of the testing methods to noise due to wind; the need for development of uncertainty estimates for the Delta-Q test; and the importance of users of the test paying attention to any uncertainty estimates when making decisions based on the test results.

FIGURE 7, DELTA-Q TESTS COMPARED TO NULLING RESULTS.



REPEATABILITY

Besides accuracy, repeatability of the Delta-Q test is also of interest. This would be especially true if the test was to be used to evaluate the success of air sealing. If the test is not sufficiently repeatable then its ability to identify reductions on the order of typical leakage reductions is compromised.

To begin to look at the repeatability of the Delta-Q test repeated tests were done at each house. Due to time constraints only one of the sampling protocols (ramping or stations) was repeated at each house, typically switching from house to house and using the protocol that was not used for the control test.

FIGURE 8, REPEAT VS. INITIAL DELTA-Q TEST.

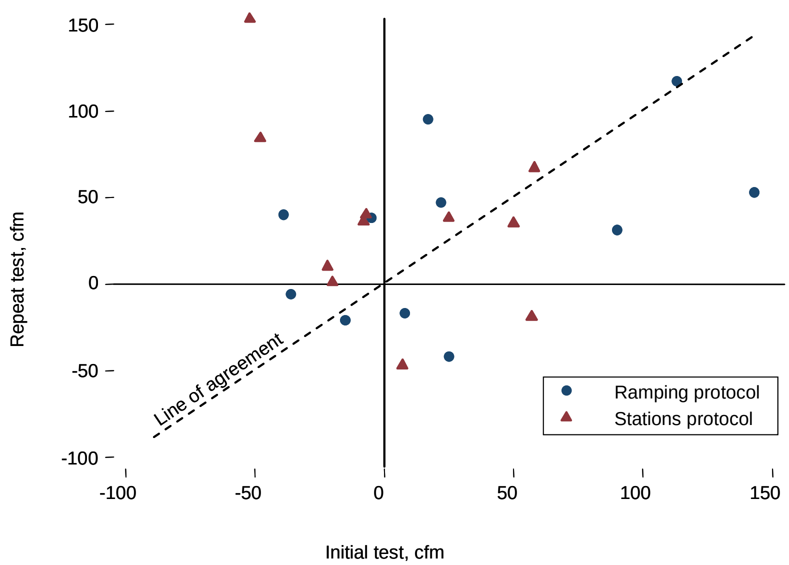


Figure 8 shows the results of repeated tests, separately for ramping and stations protocols, for supply leakage only. This graph shows that there are several large discrepancies between the initial test and the repeat test for both protocols. For the supply side, the ramping protocol is somewhat better than the stations protocol, with an average different between the two tests of 46 cfm compared to about 59 cfm for the stations tests. However, the trend is reversed for the return side, with the ramping tests averaging about 69 cfm difference between the two repeats compared to about 44 cfm for the stations tests. The ability to identify the unbalanced leakage between repeats is similar for the two protocols, with the ramping protocol averaging a difference between repeats of 26 cfm for unbalanced leakage compared to about 30 cfm for stations. It is notable that there is not as much of a discrepancy between repeats for unbalanced leakage as for the individual components, indicating that the supply and return leakage estimates move somewhat together.

These results do not give a clear indication whether ramping or stations show superior performance.

RAMPING VS. STATIONS

The results from these tests are not conclusive regarding which protocol, ramping or stations, is preferable. Ramping appeared to do better on the control tests. For normal operation tests the two protocols performed comparably to each other.

The ramping protocol generally takes less time, and can provide clearer feedback regarding the change in the wind throughout the test. The stations protocol allows for a standard error to be set that the data at a single station need to meet before moving on; however, on a moderately windy day, it can take an inordinate amount of time to achieve this standard error level, and it was determined in the course of this project that a maximum amount of time had to be set for data collection at a station before moving on.

In the event that a step needs to be repeated due to some problem such as a hose being stepped on, the time required to repeat the step is generally shorter for stations since an individual station requires less sampling time than a ramp.

Overall, the project team developed a preference for the ramping protocol. While this is somewhat subjective, and while there are advantages to the stations protocol, this does provide an indication of what the team found most useful and informative. In the absence of data showing superior performance by the stations protocol on either accuracy or repeatability it is left to subjective positions such as these to determine what method to use going forward.

NNLS VS. SCANNING

As with the two protocol methods, there was not a clearly superior analysis technique between NNLS and scanning. When both methods gave a positive leakage estimate they were typically very similar to each other. NNLS gives the appearance of providing better results on homes with low leakage or on control tests because of not allowing negative results. However, this does not allow for a statistical analysis regarding the uncertainty of the results, whereas the scanning technique does allow for a means of estimating uncertainty in a systematic manner.

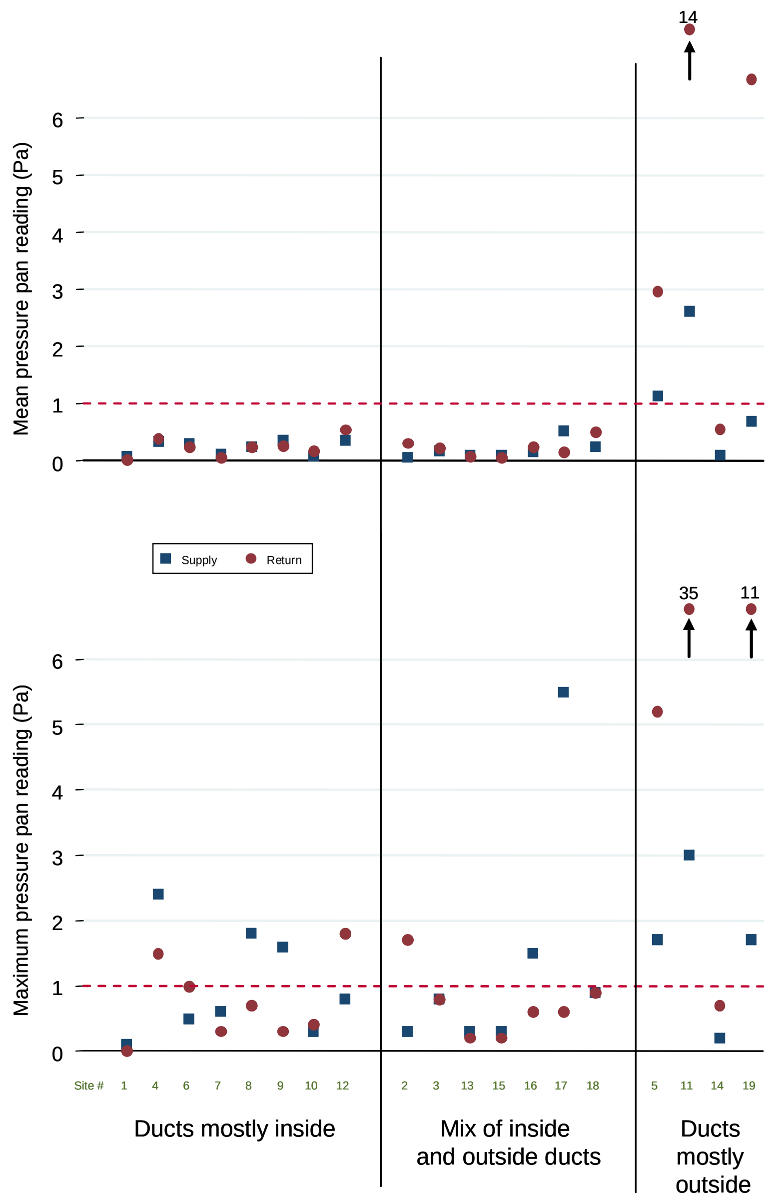
Since it is not physically possible to have negative leakage, it is expected that in general use negative results would be interpreted to mean low leakage, unless the uncertainty was very large due to effects such as wind. As a result, the scanning technique is preferable because of the additional statistical analysis opportunities available.

Pressure Pan

Figure 9 shows the mean and maximum pressure pan readings recorded at each site. None of the low- or moderate-exposure homes had average pressure readings that exceeded 1 Pascal, and about half had no individual readings that exceeded this level. We also note here that separate testing in two low-exposure homes where known leaks were introduced (see Appendix B) suggests that between 4 and 9 square inches of leakage area is sufficient to produce a 1 Pascal pressure pan reading.

In contrast, three of the four high-exposure sites had significantly higher pressure pan readings. The remaining site (Site 14) stands in contrast: no pressure pan readings exceeding 1 Pascal were recorded at this site, despite measured duct leakage to the outside that was 20 to 25 percent of air handler flow (160 to 190 cfm) under 25 Pascals of duct pressurization.

FIGURE 9, MEAN AND MAXIMUM PRESSURE PAN READINGS.



These results suggest strongly that the pressure pan can at least be used as a good screening tool. If the average pressure pan reading in a home is less than 1 Pascal then it is highly likely that leakage to outside is low and that no further duct leakage evaluation is warranted. If pressure pan readings are high (say, greater than 5 Pascals) that clearly indicates large leakage that needs to be addressed. Intermediate values for pressure pan readings may well be more uncertain, since pressure pan readings do not provide actual leakage estimates. However, other more complex techniques could be used for homes that fall into this intermediate level to more clearly assess whether leakage is excessive, without requiring such complex testing on homes for which the simpler techniques are clear in their qualitative assessment of duct leakage.

CONCLUSIONS

Overall, the testing data from the 19 homes in this study indicate low duct leakage rates and low overall duct system losses for homes with low or moderate exterior duct exposure. The four homes with most or all ductwork outside the conditioned envelope, however, showed higher leakage rates and much higher overall duct system losses.

Default values for duct system losses under current RESNET standards (12% in conditioned spaces and 20% in unconditioned spaces) likely significantly overstate the losses for Wisconsin homes that have low or moderate exterior exposure.

The Delta-Q test continues to show promise, but more development is needed before it is truly ready for general use. Specifically, a validated method to estimate uncertainty on an individual house is critical for assessing the results. Additionally, methods for reducing the uncertainty, especially due to wind noise, need to be evaluated so as to minimize the number of cases in which the results do not provide a clear qualitative assessment of whether or not the leakage level is of concern.

While this development continues, the Delta-Q test could certainly be used as a screening tool. Leakage estimates that are clearly low could obviate the need for performing additional, more time-consuming tests such as the Duct Blaster test. Moderate leakage levels (within the level of uncertainty) may require a Duct Blaster test to determine whether the leakage really is excessive. Depending on the program, high leakage levels could also obviate the need for more cumbersome testing. If a pre-post comparison was required then other, more repeatable testing such as the Duct Blaster test is likely necessary.

Similarly, under the right circumstances, pressure pan testing is likely to reveal non-trivial duct leakage to the outside in homes where the air handler is located in the basement. Pressure pan testing is most likely to miss leaks (i.e. false negatives) that are far away from the registers where pressure pan measurements are made. Requiring that the air handler (and by default, the trunk lines) be in a conditioned basement means that it is unlikely that there will be leakage paths in the high-pressure portion of the duct system that is distant from the pressure-pan testing locations. Any remaining leakage paths are much more likely to be located relatively close to a register, and will be readily manifested in one or more elevated pressure pan readings. In all homes, elevated pressure pan readings reflect sizable holes somewhere in the duct system, and thus pressure pans are unlikely to provide false positives (though the actual leakage through holes near the register may be small).

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APPENDIX A — SITE DETAILS

TABLE 1, SITE DESCRIPTIONS.

Site	Location (and test date)	Description of exterior ducting	Testing and Site Notes
1	Barneveld (02/21/07)	Supply duct runs to bonus room over garage. (Category 1)	Construction was not quite finished and included a section of open floor-joist pan return in the lower level. This was sealed with cardboard prior to testing. HRV present at this site (sealed for testing).
2	Mukwonago (02/23/07)	Central supply trunk to attic with flex-duct supply runs to ceiling registers for the 2nd floor. (Category 2)	
3	West Bend (03/02/07)	Central supply trunk to attic with flex-duct supply runs to ceiling registers for the 2nd floor. (Catelgory 2)	Tested under very windy conditions.
4	Suamico (03/06/07)	Supply duct runs to bonus room over garage. (Category 1)	Double return connection to furnace
5	Appleton (03/07/07)	Furnace in mechanical closet off garage. Supplies through unvented poured concrete crawlspace. Returns through attic. (Category 3)	Exterior-grade, weatherstripped door for mechanical closet in garage, but closet is also isolated from interior of house.
6	Green Bay (03/12/07)	Supply duct runs to bonus room over garage. (Category 1)	Two HVAC systems for this house. Tested only the system with exterior duct runs serving 2nd floor.
7	Green Bay (03/13/07)	Supply duct runs to bonus room over garage. (Category 1)	
8	Greenville (03/14/07)	Supply runs through exterior wall to cantilevered section of 2nd floor. (Category 1)	HRV present at this site (sealed for testing).
9	Oconomowoc (03/29/07)	High 2nd floor returns through attic via flex-duct. (Category 1)	
10	Waukesha (04/03/07)	Supply duct runs to bonus room over garage. (Category 1)	Zoned system; dampers were opened for testing.
11	Whitewater (04/18/07)	Slab-on-grade construction with furnace in mechanical closet off garage. Supplies and returns through attic. (Category 3)	
12	Madison (04/19/07 and 04/24/07)	Supply duct runs to bonus room over garage via garage ceiling. (Category 1)	Nulling tests were conducted five days after the other testing at this site.
13	Stevens Point (05/24/07)	Vertical building chase in garage carries supply ducts to kneewall attic. (Category 2)	
14	Hayward (05/30/07)	Slab-on-grade construction with supplies in slab. Returns in attic. Furnace in mechanical closet off garage. (Category 3)	
15	Plover (06/07/07)	Air handler in conditioned loft in second floor. 2nd floor supplies and returns through attic. (Category 2)	
16	Stevens Point (06/08/07)	2nd floor returns through attic. Supply duct runs to bonus room over garage. (Category 2)	
17	Fitchburg (07/09/07)	Supply duct runs to bonus room over garage via garage ceiling. Supply runs behind kneewall. (Category 2)	
18	Lake Mills (09/20/07 and 09/21/07)	2nd floor supplies through attic (Category 2)	Two days of testing at this site, including overnight nulling.
19	Whitewater (12/18/07)	Slab-on-grade construction with furnace in 1st floor mechanical closet. Supplies and returns through attic areas behind kneewalls. (Category 3)	

TABLE 2, FLOOR AREA, VOLUME AND NUMBER OF BEDROOMS.

Site	**Floor area** (ft^2)				**Volume** (ft^3)				**Bedrooms**
	Basement	1st floor	2nd floor	Total	Basement	1st floor	2nd floor	Total	
1	1,632	2,208	0	3,840	13,056	16,332	0	29,388	3
2	1,369	1,369	1,257	3,995	10,952	12,321	11,313	34,586	4
3	1,294	1,294	1,182	3,770	10,352	12,654	9,456	32,462	3
4	1,920	1,920	870	4,710	15,360	19,470	7,275	42,105	4
5	2,034	2,034	0	4,068	8,136	18,306	0	26,442	3
6	2,368	2,376	1,562	6,306	21,312	25,408	12,109	58,829	4
7	1,598	1,598	705	3,901	5,640	14,382	6,345	26,367	3
8	1,024	1,024	963	3,011	8,192	8,903	7,704	24,799	3
9	1,220	1,220	1,144	3,584	10,614	10,980	9,332	30,926	4
10	2,691	2,691	296	5,678	24,219	27,178	2,247	53,644	4
11	0	1,372	0	1,372	0	13,328	0	13,328	{}
12	908	908	1,248	3,064	7,264	7,264	9,984	24,512	4
13	2,227	2,240	905	5,372	19,486	32,037	6,813	58,336	4
14	0	1,248	0	1,248	0	9,984	0	9,984	3
15	NA	NA	3,780	NA	NA	NA	NA	36,822	NA
16	1,978	1,978	750	4,706	15,824	15,824	6,000	37,648	3
17	1,312	1,312	1,793	4,417	11,414	13,061	14,930	39,405	4
18	944	944	966	2,854	7,552	7,552	7,728	22,832	3
19	NA	NA	NA	NA	NA	NA	NA	13,832	

FIGURE 10, EXTERIOR PHOTOS OF STUDY SITES.

APPENDIX B — PRESSURE PAN MEASUREMENTS IN TWO HOMES WITH INTRODUCED DUCT LEAKS

This appendix summarizes pressure pan tests made at two Wisconsin homes in 2006, where leaks of known sizes were introduced to exterior duct runs. The exterior ductwork for both homes consisted of ductwork through the garage ceiling for bonus rooms: in this respect, the homes are thus most comparable to the low-exposure homes discussed in the main body of this report.

Testing involved taking pressure pan readings at all supply and return registers in the bonus rooms. In addition, to assess the impact of boot leakage—which occurs at the boundary between the duct system and the house envelope—measurements were taken before and after efforts were made to seal the boots.

Both homes were tested by Collin Olson of the Energy Conservator and Joe Nagan, Home Building Technology Services. The descriptions and data presented below are distilled from more detailed site notes prepared by Collin Olson.

SITE "A" (TESTED ON APRIL 20, 2006)

This home was of fairly tight construction (983 cfm @ 50 Pa), and some effort had been made by the builder to air seal the ductwork in unconditioned space.

For the testing, leaks were added to two different locations in a supply trunk as well as one location in a return duct. All three leak sites were located in the garage attic above the north edge of the garage and immediately to the north of the bonus room. The supply leaks are identified as "Near" (closest to the main body of the house, or to the west) and "Far" (furthest from the main body of the house, or to the east). In addition, measurements were made before and after sealing the register boots

Pressure pan measurements were made at five registers: the four floor registers in the bonus room, the return grille in the bonus room and the floor supply register in the nearby SW bedroom. Three readings were recorded at each location under each leakage condition.

Table 3 shows the resulting data before the boots were sealed, and

Table 4 shows the comparable data after boot sealing. Sealing the boots reduced the pressure pan readings by about 0.5 Pascals on average. Supply pressure pan readings in the bonus room generally exceeded 1.0 Pascals at about 4 square inches of added leakage prior to the boot sealing and at about 9 square inches after boot sealing. Rough calculations suggest that these leakage areas would be equivalent to about 1 to 2 percent of system flow, based on a measured duct static pressure of 5 Pascals (at cooling speed) and a typical cooling-mode airflow of 1,000 cfm.

TABLE 3, SITE "A" PRESSURE PAN READINGS BEFORE BOOT SEALING.

Added leakage (in.²)		Pressure pan reading (Pa)																	
		Supply register in NW corner of bonus room			Supply register in SW corner of bonus room			Supply register in NE corner of bonus room			Supply register in SE corner of bonus room			Return register in bonus room			Supply register in SW bedroom		
Near	Far																		
0	0	0.5	0.5	0.4	0.4	0.4	0.4	0.7	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.1	0.0
25	0	2.3	2.7	2.7	2.6	2.4	2.3	3.3	3.3	3.4	3.1	3.0	3.1	0.6	0.6	0.6	0.1	0.2	0.2
25	25	8.7	8.5	8.5	6.6	6.6	6.6	7.6	7.8	7.8	8.1	7.6	7.7	0.5	0.5	0.5	0.3	0.3	0.3
0	25	3.1	3.2	3.1	2.9	2.9	2.8	3.5	3.6	3.6	4.2	4.2	4.2	0.5	0.5	0.5	0.1	0.1	0.1
0	9	1.6	1.6	1.6	1.4	1.5	1.4	1.3	1.2	1.2	1.5	1.5	1.5	0.4	0.5	0.5	0.1	0.0	0.0
0	4	1.1	1.1	1.1	1.0	1.0	1.0	0.9	0.9	0.9	1.2	1.1	1.1	0.4	0.5	0.5	0.1	0.0	0.0
0	2	1.0	1.0	1.0	1.0	0.9	0.9	0.9	0.9	0.9	0.9	0.8	0.8	0.5	0.5	0.5	0.0	0.0	0.0
0	0	0.7	0.6	0.6	0.6	0.5	0.6	0.7	0.7	0.7	0.6	0.6	0.6	0.5	0.5	0.5	0.0	0.0	0.0

TABLE 4, SITE "A" PRESSURE PAN READINGS AFTER BOOT SEALING.

Added leakage (in.²)		Pressure pan reading (Pa)																	
		Supply register in NW corner of bonus room			Supply register in SW corner of bonus room			Supply register in NE corner of bonus room			Supply register in SE corner of bonus room			Return register in bonus room			Supply register in SW bedroom		
Near	Far																		
0	0	0.2	0.2	0.2	0.2	0.2	0.2	0.4	0.4	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.1	0.0	0.0
25	0	1.9	1.7	1.7	1.7	1.6	1.8	2.5	2.4	2.5	2.6	2.6	2.6	0.1	0.1	0.2	0.0	0.1	0.1
25	25	7.7	7.6	7.7	6.0	6.3	6.3	6.6	6.9	6.8	6.9	6.8	6.2	0.2	0.2	0.2	0.2	0.2	0.1
0	25	2.6	2.3	2.4	2.4	2.5	2.4	3.1	3.0	3.0	3.6	3.6	3.9	0.1	0.1	0.2	0.1	0.0	0.1
0	9	1.1	1.9	1.1	0.9	0.9	1.0	0.9	1.1	1.0	1.1	1.2	1.2	0.1	0.1	0.1	0.0	0.0	-.1
0	4	0.7	0.6	0.6	0.6	0.7	0.6	0.5	0.6	0.5	0.7	0.6	0.7	0.1	0.2	0.1	0.0	0.0	0.0
0	2	0.5	0.5	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.2	0.2	0.2	0.0	0.0	0.0
0	0	0.3	0.4	0.3	0.3	0.3	0.2	0.4	0.4	0.4	0.3	0.3	0.3	0.2	0.2	0.2	0.0	0.0	0.0

SITE "B" (TESTED ON MAY 4, 2006)

Site "B" was a considerably tighter house (697 cfm @ 50 Pa) with a similar bonus room arrangement. Testing at this home was similar to that at Site "A," except that leaks were added only at a single location, and the testing also included pressure pan tests with the house depressurized to 100 Pascals in addition to the more standard 50 Pascals of depressurization.

The 8x14" supply trunk for the bonus room was located on the north side of the room (the right side viewed from the front of the house, which faces east). The supply trunk was about 9 feet in length and had four takeoffs for the four registers in the bonus room (Figure 11), labeled here as Supply 1 through Supply 4 from furthest to nearest. The single return register for the room ran through an interior wall. At the time of testing, it appeared that no significant effort was made by the builder or HVAC contractor to air seal the attic supply ducts, aside from the application of duct wrap on the attic supply trunk.

FIGURE 11 , SITE "B" BONUS ROOM SUPPLY TRUNK AND TAKE-OFFS.

Table 5 and Table 6 show the pressure pan data before and after boot sealing. Pressure pan readings in the supply registers (post boot sealing) exceeded 1 Pascal at between 4 and 9 square inches of added leakage when the house was depressurized to 50 Pascals.

TABLE 5, SITE "B" PRESSURE PAN READINGS BEFORE BOOT SEALING.

Added Leakage (In.^{2})	House Press. (Pa)	Pressure pan reading (Pa)														
		Supply 1			Supply 2			Supply 3			Supply 4			Return		
0	50	0.7	0.7	0.7	0.7	0.8	0.8	0.9	0.8	1.0	1.1	1.1	1.0	0.1	0.1	0.1
0	100	1.3	1.4	1.4	1.2	1.2	1.1	1.7	1.8	1.8	2.2	2.2	2.2	0.1	0.1	0.1

TABLE 6, SITE "B" PRESSURE PAN READINGS AFTER BOOT SEALING.

Added leakage (In.^{2})	House press. (Pa)	Pressure pan reading (Pa)														
		Supply 1			Supply 2			Supply 3			Supply 4			Return		
0	50	0.4	0.4	0.3	0.4	0.4	0.4	0.3	0.3	0.4	0.6	0.3	0.3	0.1	0.1	0.1
25	50	3.7	4.1	4.4	4.3	4.2	4.1	4.5	4.5	4.4	4.5	4.3	4.3	0.3	0.2	0.2
25	100	6.9	6.5	6.7	7.7	7.8	7.8	7.6	7.4	7.4	8.1	8.1	8.1	0.3	0.4	0.4
9	50	1.4	1.4	1.4	1.4	1.5	1.4	1.4	1.4	1.4	1.5	1.5	1.5	0.1	0.1	0.1
4	50	0.9	0.8	0.8	0.9	1.0	1.0	0.8	0.8	0.8	0.8	0.8	0.8	0.2	0.1	0.1
2	50	0.6	0.6	0.7	0.5	0.6	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.0	0.1	0.1
0	50	0.6	0.6	0.6	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.1	0.1	0.1

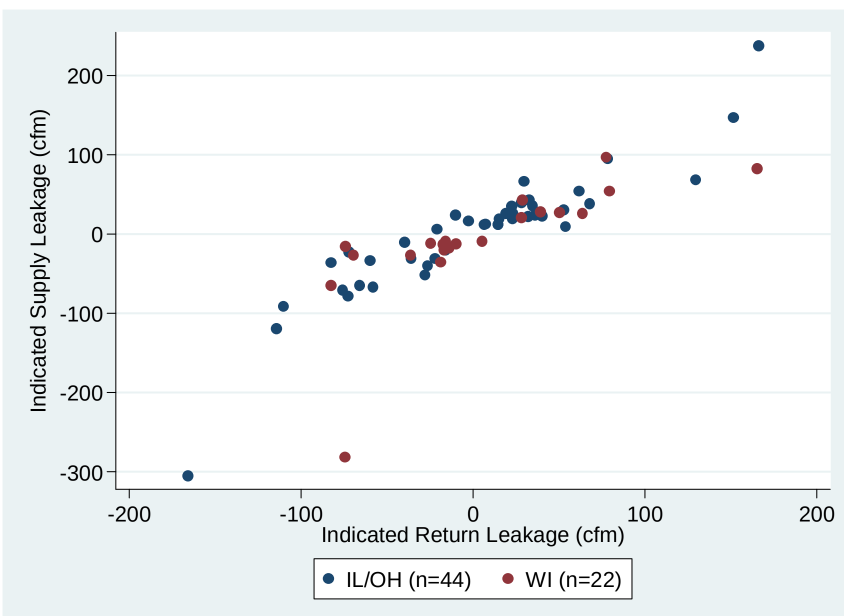
APPENDIX C — A PRELIMINARY METHOD FOR ASSESSING UNCERTAINTY IN DELTA-Q ESTIMATES OF DUCT LEAKAGE

The utility of the Delta-Q approach to measuring duct leakage is hampered by the absence of a method to readily quantify the reliability of the results from a particular Delta-Q test. Because the Delta-Q method is generally looking for small differences in house pressure due to duct leakage, the results can be thrown off by wind gusts that occur at inopportune moments during the testing.

This appendix addresses this issue by examining data from control tests where the air handler is never operated during the test. If the air handler is not operated during a Delta-Q test, there can be no duct leakage, and the correct value of leakage is known to be zero. The degree to which a Delta-Q control test departs from this known (zero) leakage provides insight into the test uncertainty from the method.

Here, we examine results from 66 Delta-Q control tests: 22 conducted as part of this study, and 44 tests completed under a prior research project in Illinois and Ohio under the direction of Paul Francisco (Francisco, 2006). As Figure 12 shows, the control tests showed a wide range of both positive and negative leakage estimates, though the test results average to within a cfm or two of the correct value of zero.[3] Twenty one percent of the control tests yielded a supply or return leakage estimate greater than +50 cfm, which might be considered an approximate threshold for remediation or further investigation (50 cfm would represent about 6% leakage for a typical Wisconsin system tested at 800 cfm of airflow).

FIGURE 12, DELTA-Q CONTROL TEST RESULTS.



[3] The results here were analyzed using the "scanning" technique which allows for negative estimates of duct leakage even those these are nonsensical from a physical standpoint.

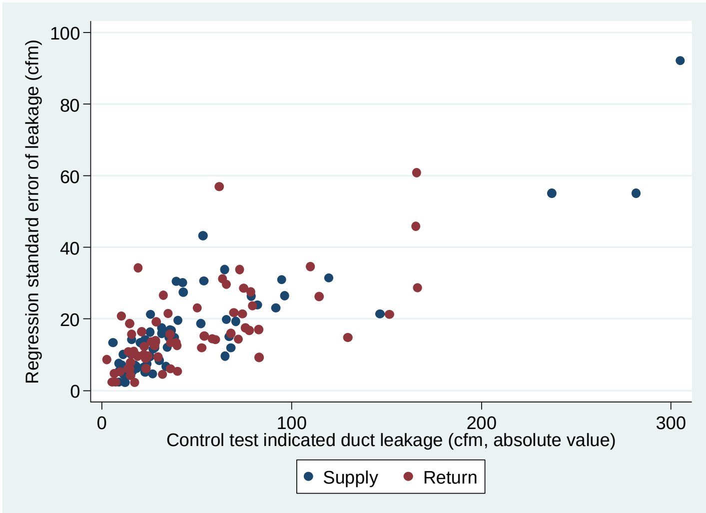
To avoid mistakenly taking action based on the one-in-five "false positive" rate observed here, a method of quantifying the test uncertainty from the test data is needed. Such a method would produce wide estimates of uncertainty when conditions are similar to those that produced large non-zero control test values in the data above, and would provide narrow confidence intervals under calm conditions that produce more accurate Delta-Q estimates.

One reliability criterion that has been proposed is to take Delta-Q estimates as accurate to within one percent of the measured house leakage at 50 Pascals: in other words, if house leakage @50Pa is measured as 2,000 cfm, then the Delta-Q estimates of duct leakage are accurate to within ± 20 cfm.

Unfortunately, the control-test data do not bear the reliability out this method: 67 percent of the supply leakage confidence intervals produced by this method did not include the known leakage (zero), as did 82 percent of the return leakage confidence intervals. Even after adding an artificial known leakage to the control test data (more on this later), the confidence intervals around the estimates missed the true value in 30 to 70 percent of cases. Our conclusion is that this approach over-estimates the reliability of Delta-Q's indicated duct leakage values.

Collin Olson of the Energy Conservatory suggested an alternative approach involving an empirical multiplier applied to the regression statistics from the Delta-Q computations. The duct leakage estimates from Delta-Q derive directly from linear regression coefficients, for which estimates of uncertainty (i.e., standard errors) are easily obtainable. However, the standard regression estimates of uncertainty almost certainly underestimate the true uncertainty in the Delta-Q leakage estimates, because they do not incorporate the fact that data points that go into the algorithm are not independent of one another (they are correlated in time) and that the algorithm must first hunt through a range of possible leak pressures to find the best-fit pressures for the data.

FIGURE 13, STANDARD ERROR OF INDICATED LEAKAGE VERSUS INDICATED LEAKAGE (ABSOLUTE VALUE), CONTROL TESTS (N=66).



Nonetheless, if the actual uncertainty in the estimates is well-correlated with the regression estimates of standard error, then a simple multiplier can be applied to correct for the bias in the regression estimates of uncertainty. As Figure 13 shows, there does appear to be a reasonable correlation between the two: control tests with large indicated leakage values (i.e., large errors given the true leakage of zero) tend to have large regression standard errors.

Based on this finding, we analyzed the control-test data for a multiplier that would come the closest to providing correct confidence intervals—that is, confidence intervals that will include the correct value at the desired confidence level.[4] Based on the control-test data, it appears that a multiplier of 3 reasonably accounts for the bias in the standard regression estimates of uncertainty. To construct an approximate 95% confidence-level uncertainty band around a Delta-Q estimate of duct leakage, we take 3 times the regression standard error and multiply this by 1.96 (the last being the standard *z* multiplier to turn a standard error—which represents about a 68% confidence level—into a 95% confidence level estimate).

If this procedure were to work perfectly, then 95 percent of the confidence intervals so constructed would include the correct value and 5 percent of confidence intervals would not include the correct value. As Table 7 shows, a multiplier of 3 does provide an approximation of 95% confidence level uncertainty bands: the constructed confidence intervals for supply leakage overestimate the uncertainty somewhat and the procedure somewhat underestimates the uncertainty for return leakage.

TABLE 7, CONFIDENCE INTERVAL NON-COVERAGE RATES FOR CONTROL TESTS WITH AND WITHOUT ADDED ARTIFICIAL SIGNAL.

Non-coverage rate for control-test constructed 95% confidence intervals, based on regression standard errors * 3.0.				Data set		
				WI n=22	IL/OH n=44	Combined n=66
Supply						
Control test, as-is				4.5%	2.3%	3.0%
		Supply	Return			
w/ added artificial signal	50 Pa leak(s)	100 cfm	100 cfm	0.0%	2.3%	1.5%
		100 cfm	0 cfm	9.1%	2.3%	4.5%
	10 Pa leak(s)	100 cfm	100 cfm	4.5%	6.8%	6.1%
		100 cfm	0 cfm	0.0%	2.3%	1.5%
Combined average				3.6%	3.2%	3.3%
Return						
Control test, as-is				13.6%	9.1%	10.6%
		Supply	Return			
w/ added artificial signal	50 Pa leak(s)	100 cfm	100 cfm	9.1%	9.1%	9.1%
		100 cfm	0 cfm	13.6%	9.1%	10.6%
	10 Pa leak(s)	100 cfm	100 cfm	13.6%	11.4%	12.1%
		100 cfm	0 cfm	4.5%	9.1%	7.6%
Combined average				10.9%	9.5%	10.0%

[4] Confidence intervals are always expressed in terms of a confidence level, the latter reflecting the risk one is willing to take that the correct value is not within the stated confidence interval. For example if we report confidence intervals at a "95 percent confidence level" it means that we expect that among 100 such reported confidence intervals, 95 will include the true value and 5 will not. Higher confidence levels imply wider confidence intervals: at the extreme we can be 100 percent confident only that a true value lies within the range of ± infinity

Table 7 also shows the confidence interval coverage rates when various known artificial leakage signals are added to the pure noise control test data. This assessment helps verify that the method works in the face of actual duct leakage in addition to reasonably representing the uncertainty in test results when little or no leakage is present.

Finally, we applied the method to an LBL data set of seven homes with repeated Delta-Q test results. Although the true duct leakage is not known for these homes, if one can assume that the average of the multiple tests per home (which ranged from 6 to 19 tests) is close to the true value, then the method can be used to assess the percentage of cases where the constructed confidence interval includes or excludes the multi-test average. The results show that 7 percent of the 68 constructed supply leakage confidence intervals included the overall site average, as did 4 percent of the return leakage confidence intervals. This further suggests that the method provides a reasonable approach to obtaining Delta-Q uncertainty bands at a 90 to 95 percent confidence level.

When this method is applied to the 45 non-control ramping Delta-Q tests conducted for this study, the median 90% confidence interval is ± 60 cfm, with nine of ten calculated confidence intervals falling between about ±20 cfm and ±175 cfm.