Performance of Duct Leakage Measurement Techniques in Estimating Duct Efficiency: Comparison to Measured Results

Paul W. Francisco, Ecotope, Inc., Seattle, WA
Larry Palmiter, Ecotope, Inc., Seattle, WA

ABSTRACT

Duct leakage is recognized as a major source of energy losses in residential buildings, and is one of the most important parameters for estimating duct efficiency. However, quantifying duct leakage has proven to be extremely difficult. Several methods of estimating duct leakage have been proposed. This paper focuses on the predictions of supply duct leakage from a study in which duct efficiency estimates were made using a variety of duct leakage measurement techniques, and were compared to measured efficiencies using the coheat test methodology. The leakage measurement methods tested in this study include the duct pressurization test and house pressure test that are found in the current version of ASHRAE Standard 152P, as well as three other methods: the supply-blocked house pressure test, where the supply registers are partially blocked instead of the return grilles; the "hybrid test", which combines a total duct system pressurization test with a portion of the house pressure test; and the "nulling test", which uses a calibrated fan to counteract the pressure change across the envelope due to duct leakage. The two forms of the house pressure test showed a large amount of scatter. The duct pressurization test showed significantly less scatter, but is more time-consuming. The performance of the hybrid test fell between the house pressure test and duct pressurization test. Though only tested in a few cases, the nulling test performed well, providing cause for optimism and further study. The comparisons of estimated efficiencies using these methods to measured efficiencies provide insight into the importance of accurate measurement of duct leakage, as well as the ability of each measurement method to provide good predictions of duct efficiency. The results have implications for ASHRAE Standard 152P and raise the possibility that newer techniques may be improvements over the methods in the standard.

Introduction and Background

In the past decade ducts in residential forced-air distribution systems have been recognized as significant sources of wasted energy. As a result, there is growing interest in the understanding of the efficiency of duct systems on the part of utilities, weatherization programs, building code regulators and others.

One of the major sources of losses from ducts is air leakage. Many duct systems have substantial leakage at the connections between sections of ducts and along the seams of ducts. In some cases, catastrophic failure results in a partial or complete disconnect, resulting in large leakage to (or from, in the case of returns) an unconditioned space such as a crawl space or attic. The cause of most leakage is either poor installation (e.g. forcing ducts together that are not truly the correct sizes) or the lack of sufficient mechanical fasteners, such as sheet metal screws for metal duct or cable ties for flexible duct. Many ducts are held together by nothing more than friction or cloth duct tape, both of which are known to be insufficient for the purpose.

Unfortunately, duct leakage is extremely difficult to quantify accurately. This is a problem for several reasons. One reason is that duct thermal efficiency models currently in use, such as that in proposed American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Standard 152P (ASHRAE 1999), rely heavily on the level of duct leakage to make their predictions. Another reason is that, without a simple, accurate method of estimating duct leakage, it is very difficult for retrofit contractors to identify those houses at which a large enough problem exists to warrant corrective measures. Further, some of the simplest techniques for estimating duct leakage do not separate out supply and return leakage individually, or do not distinguish between leakage to inside the house and leakage that escapes to other locations. These are important distinctions because the impact of supply leakage is very different from the impact of return leakage on efficiency and financial impact, and leakage to inside the house has little or no impact on efficiency or cost. It is important to separate out these different types of leakage when making any assessment of the situation and appropriate response at an individual house.

This paper compares the predictions of a number of different leakage estimation methods on real duct systems in houses in the field. Two of these methods, the duct pressurization test and the house pressure test, are part of ASHRAE Standard 152P and have been extensively used. Two of the other methods were developed in an attempt to address some of the problems with the house pressure test; these are the supply-blocked house pressure test and the hybrid test. The final test is a new test developed by the authors and is called the nulling test. The testing was performed as part of an ASHRAE-funded project to validate Standard 152P in the field (Francisco and Palmiter 1999; Francisco and Palmiter 2000). The comparisons in this paper are restricted to supply leakage, as this is usually the more important portion of the leakage (though not always, especially in the case of a warm, humid climate such as Florida) and the portion on which the most extensive data was taken in these homes.

Leakage Test Descriptions

Duct Pressurization Test

The duct pressurization test is a very commonly used duct leakage measurement method and is part of proposed ASHRAE Standard 152P. This method requires placing a barrier between the supply and return portions of the ductwork, frequently at the filter slot, and sealing off all of the registers. A calibrated fan is attached to the duct system, frequently at the blower cabinet, and the ducts are pressurized to a specified pressure. A blower door is also used to pressurize the house such that the pressure between the ducts and the house is zero; the leakage measured is then leakage to outside.

One major drawback of this test is that it is time-consuming, especially if there are a lot of registers to seal off. Another drawback of this test is that the measured leakage is at a pressure that may be quite different from the pressures across the leaks at operating conditions. Assumptions then need to be made as to what the actual pressures are, frequently based on pressures measured at registers and at the plenums during normal operation. In Standard 152P, the supply pressure used to estimate leakage under normal conditions is the average of the pressures measured at the registers using a pressure pan when the system is operating normally.

House Pressure Test

The house pressure test is also part of proposed ASHRAE Standard 152P. This test combines a blower door test with pressures measured across the ceiling, at the midpoint of the return duct, and at a supply register to estimate duct leakage. The pressures across the ceiling are made with the air handler off and on, and the duct pressures are measured with the air handler on. In addition, all of these pressures are also measured with and without the return grille(s) partially blocked.

The change in pressure across the ceiling due to turning on the air handler provides an estimate for the unbalanced duct leakage. By partially blocking the return grille(s) and repeating the test, estimates are made of the supply and return leakage separately. The equations for obtaining the leakage estimates can be found in ASHRAE (1999). There are also equations to correct for the change in neutral level due to duct leakage when all of the ducts are either high or low, and a correction for the portion of the envelope leakage that is due to holes in the ducts.

There are a number of problems with this test. First, the derivation of the equations was based on assuming that the walls are airtight and the ceiling and floor are equally leaky. When this assumption is not valid, the results can be very different.

Another problem relates to the location of the return duct pressure measurements. The ratio of pressure with and without the return grille(s) blocked can be very different for various locations along the length of the return ducting. It can be very difficult to properly locate the pressure measurement tap, and the results can vary by a large amount due to the placement. Further, in some cases (e.g. two return ducts that meet near the air handler) the midpoint can be very difficult to define. Since the beginning of this project the standard has been amended to prohibit use of this test in houses with multiple return branches and in houses where the filter is not at the return grille. Unfortunately, these limitations exclude a very large fraction of the overall housing stock.

In an attempt to address some of the problems with this test, a modification was proposed in which the supply registers are partially blocked instead of the return grille(s). This is referred to as the supply-blocked house pressure test.

Hybrid Test

Another test that was proposed to address problems with the methods in Standard 152P is the hybrid test. This test combines a duct pressurization test with the house pressure test. The duct pressurization test is done on the whole system rather than supply and return separately, and only the portion of the house pressure test with all registers and grilles open is performed. This saves the time of separating the supply from the return and eliminates the uncertainty due to the blocking of the return grilles. However, this test has the problem with operating pressures in that the supply and return sides can be greatly different during the duct pressurization test, as discussed previously. It is also subject to uncertainty regarding the distribution of building leakage. Further, in some cases the supply and return pressures can be very different from each other during the test, and as this difference increases the application of an average of the two to the entire duct system can become increasingly problematic.

The Nulling Test

The nulling test consists of two parts: measurement of unbalanced duct leakage and separation into supply and return components. The test is predicated on the assumption that any change in the pressures across the building envelope due to turning on the air handler is due to unbalanced duct leakage. As with the house pressure test, pressures across the building envelope are used. However, no assumptions are made as to the distribution of leakage within the envelope, and no equations are necessary.

To estimate the unbalanced duct leakage, the pressure change due to turning on the air handler is measured. Then, with the air handler operating, a calibrated fan, referred to as a nulling fan, is used to zero out the pressure change. The flow through the nulling fan is the unbalanced duct leakage.

To estimate the supply and return leakage separately, a barrier is placed between the supply and return sides as in the duct pressurization test, and another calibrated fan is attached to the air handler cabinet (this is currently necessary in Standard 152P for measuring air handler flow). The process used for unbalanced leakage is then repeated. The fan attached to the air handler is used to provide the same flow through the system as under normal conditions. If this fan draws air from the house it is effectively an airtight return, and the unbalanced leakage is the supply leakage. If this fan draws air from outside the conditioned space, the return leakage is 100% and the unbalanced leakage is the supply flow, which can be subtracted from the air handler flow to get supply leakage. Combining the supply leakage with the unbalanced leakage provides the return leakage.

Taking the air from outside of the conditioned space is less desirable for two reasons. First, subtracting two large numbers to get a small number, as would be the case unless there is catastrophic supply duct leakage, can lead to higher errors in the estimates. Second, this method uses measured flow rates from two different fans that were not calibrated to each other. Since even calibrated fans have some uncertainty associated with them, the errors will potentially be very large. For example, the uncertainty for each fan may be ±3%. If one is high and one is low, the errors due to combining results from them may be large regardless of the level of uncertainty inherent in field measurement.

As with all leakage tests, the nulling test is sensitive to noise from gusty winds. Another problem is that leaks in the ducts can have an impact on the neutral level during the times when the air handler is off. When the air handler is switched on, these leaks are shut off. The best pressure to match would be the pressure across the envelope with the holes in the ducts sealed off and the air handler off. The inability to know this pressure can create a bias.

Best Estimate

In order to ascertain the accuracy of the results of the previous test methods, an independent measure of the duct leakage is required. This was obtained by subtracting the flow through the supply registers as measured with a calibrated propeller flow hood from the air handler flow. The results of this method were considered to be the best estimate of duct leakage and were used as the basis against which other methods were compared. The result was placed into the equation for total supply duct leakage (including leakage to indoors and outdoors) based on a duct pressurization test to estimate an operating pressure. This pressure was then input into the equation for supply duct leakage to outdoors to get the supply leakage at operating conditions. This extrapolation of the operating pressure from one test to another was small because all of the houses were single-story with all of their ducts outside the conditioned space, so nearly all of the leakage was to outside.

This method can not be considered a widely applicable method for estimating duct leakage. One reason for this is that the application of the operating pressure obtained from the total supply duct leakage equation to the equation for leakage to outdoors is only valid if the leakage to indoors is minimal. This excludes houses with ducts in interior spaces. All houses in this study were single-story houses with all ducts in unconditioned spaces. Another reason is that sufficiently accurate measurement of register flows requires a flow hood that is no longer commercially available.

Site Descriptions

Ten houses were tested, providing 26 distinct cases by varying duct configuration. Measured efficiencies were obtained via the short-term coheat method, in which the house is alternately heated by the furnace and by electric space heaters. Temperature control switches every two hours. Computer-controlled dataloggers cause the electric heaters to maintain the same temperature in each room as was measured during the prior period of heating by the furnace. Only the second half of each control period is used in the analysis to minimize transient effects. The ratio of the energy consumption of the electric space heaters to that by the furnace is the duct efficiency. For gas furnaces, the furnace consumption is modified by the combustion efficiency.

Two of the houses (designated T01 and T04) are manufactured homes, and were tested as part of a retrofit program in Eugene, Oregon (Siegel et al. 1997). The leakage tests were performed both before and after retrofit (signified by "a" and "b", respectively), so these houses contributed four comparisons. Three houses (G04, G06, G08) are heated by gas furnaces and were part of a retrofit program in the Puget Sound region (Davis et al. 1998). These received the majority of the leakage tests only after duct retrofits were performed; this provided three more comparisons.

The remaining five houses (A01, A02, A03, A04, A05) were newly recruited for this project and are all heated by electric furnaces. Each was tested with the ducts in four different configurations, where each configuration changed the amount of leakage in the supply ducts, return ducts, or both. The coheat testing was done in two cases at each house; in the other two configurations temperature measurements were made throughout the house and the duct system. Results from the coheat tests were combined with these temperature measurements to infer a distribution efficiency for these two configurations. Loss of data in one configuration resulted in these five houses providing 19 efficiency comparisons.

All of the site-built houses are single-story. Seven of these eight houses have the supply ducts in a vented crawl space, while the other (A02) has ducts in the attic. Six of the eight have return ducts in the attic; the other two (G04 and A05) have the return ducts in the crawl space.

Results

Table 1 compares the "best estimate" of supply leakage with estimates from the house pressure test and duct pressurization methods as described in Standard 152P. These results are shown graphically in Fig. 1.

The house pressure test tend to be biased low relative to the best estimate, averaging about 22 cfm less leakage, although there are a few very large overestimates of the leakage. The median discrepancy is about twice as large. Comparing the absolute values of the differences, which provides a measure of how far off of agreement the methods typically are,

Table 1. Comparison of best estimate of supply leakage to predictions using methods in Standard 152P

Site ID	Supply Leakage (cfm)			Difference from Best Estimate	
	Best Estimate	House Press. Test	Duct Press.	House Press. Test	Duct Press.
T01a	94	88	115	-6	21
T01b	24	0	32	-24	8
T04a	144	100	215	-44	71
T04b	45	0	64	-45	19
G04	69	20	166	-49	97
G06	45	28	94	-17	49
G08	86	15	77	-71	-9
A01a	217	167	249	-50	32
A01b	232	137	242	-95	10
A01c	103	92	109	-11	6
A01d	130	0	103	-130	-27
A02a	281	227	278	-54	-3
A02b	426	494	357	68	-69
A02c	165	110	197	-55	32
A02d	401	456	382	55	-19
A03a	149	109	193	-40	44
A03b	112	0	140	-112	28
A03d	109	0	140	-109	31
A04a	65	24	113	-41	48
A04b	78	315	112	237	34
A04c	167	365	235	198	68
A04d	166	151	228	-15	62
A05a	197	179	182	-18	-15
A05b	261	226	240	-35	-21
A05c	252	167	253	-85	1
A05d	294	272	300	-22	6
Mean	**166**	**144**	**185**	**-22**	**19**
Median	**146**	**110**	**188**	**-40**	**20**
Mean Absolute Difference				**65**	**32**
Median Absolute Difference				**50**	**28**

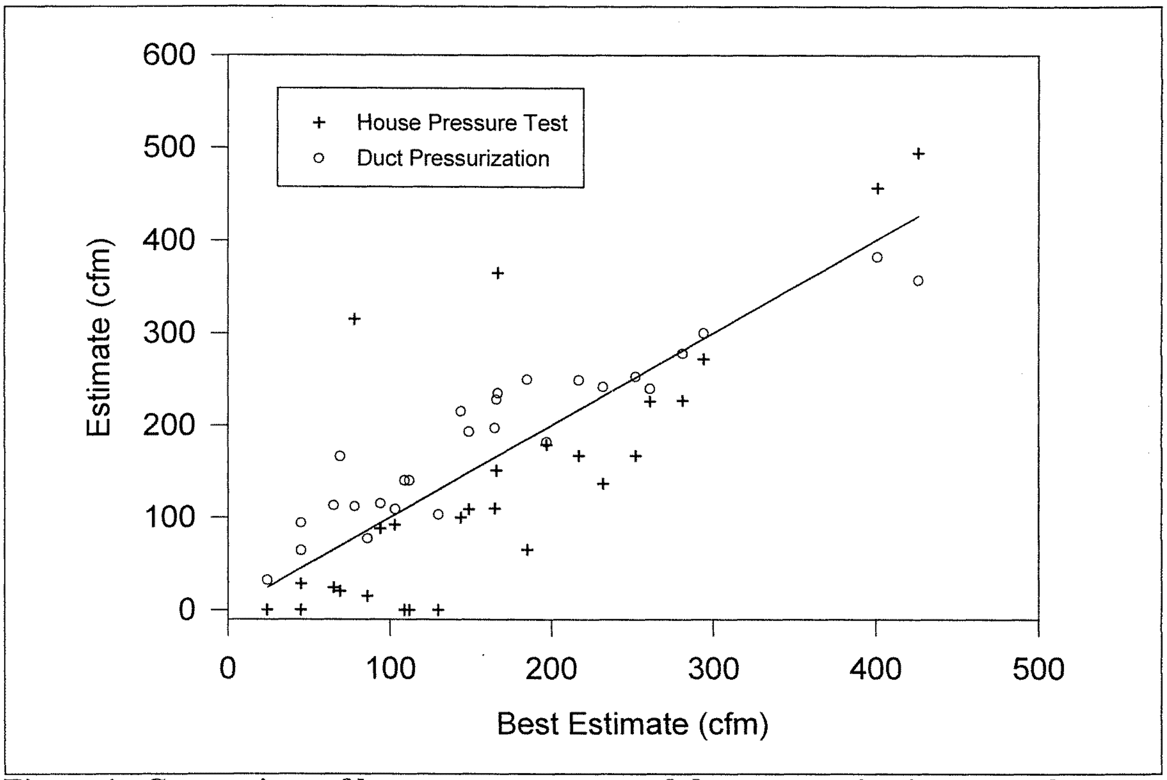

Figure 1. Comparison of house pressure test and duct pressurization test to best estimate of supply leakage. The line is a best estimate one-one line.

shows that on average the house pressure test leakage estimates of supply leakage are 65 cfm different than the best estimate. This is about 8% of the typical air handler flows measured in this study.

The house pressure test results are based on measuring the return duct pressure at the midpoint of the duct, as specified in Standard 152P. The results can change significantly if the pressure is measured elsewhere in the return duct, as shown in Fig. 2. This graph shows that the supply leakage tends to be underestimated even further if the pressure is measured at the return grille, though there are some very large overestimates using this location. If the pressure is measured at the plenum, the leakage is usually overestimated, frequently by a large amount. Since it can be extremely difficult to assure that the pressure is measured at the midpoint, it is likely that results based on this method would frequently be worse than suggested in Table 1, with the magnitude of the discrepancy unknown.

The duct pressurization method fares somewhat better, though it is biased high relative to the best estimate, predicting an average of 19 cfm more supply leakage. The median difference is similar, at 20 cfm more than the best estimate. Looking at the absolute differences shows that the duct pressurization method averages only about half of the discrepancy of the house pressure test. This is reinforced in Fig. 1, which shows that the scatter from the duct pressurization test is much smaller than that from the house pressure test. Note that, since the barrier between the supply and return sides was at the filter slot, it is possible that some leakage in the air handler cabinet that is actually return leakage would be seen as supply leakage. However, the location in the air handler cabinet that is most likely to have substantial leakage is around the door, and this was sealed by the attachment of the duct pressurization fan. Further, any other leakage sites found were taped over prior to testing.

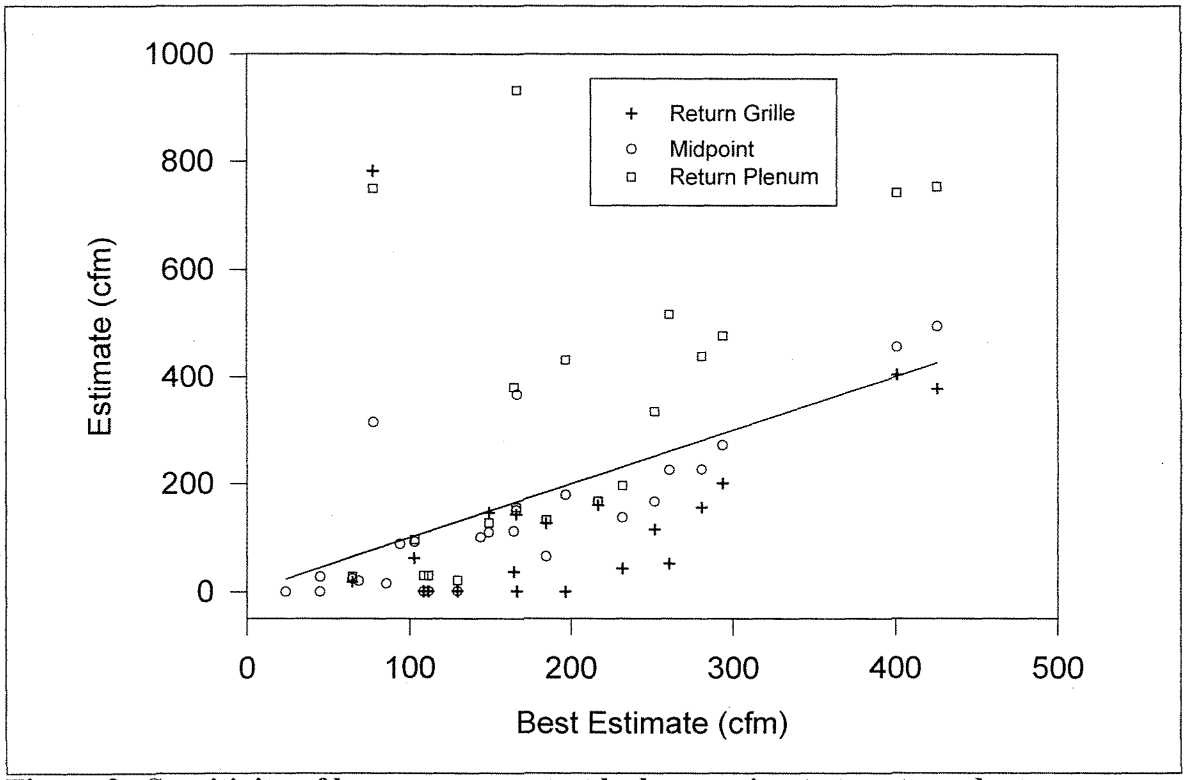

Figure 2. Sensitivity of house pressure test leakage estimate to return duct pressure measurement location (the line is a best estimate one-one line)

Table 2 compares the supply leakage estimates from the supply-blocked house pressure test (HPT-Sup. Blocked), the hybrid test, and the nulling test to the best estimate. These results are shown graphically in Fig. 3.

Despite the hope that the supply-blocked version of the house pressure test would improve on the results of the return-blocked version, this does not appear to be the case. The bias is larger and the results tend to be further from the best estimate for the supply-blocked test than for the return-blocked test. Restricted to those cases in which the supply-blocked house pressure test was done, the median discrepancy is 75 cfm high relative to the best estimate, compared to 41 cfm low for the return-blocked version. The median absolute discrepancy is 82 cfm for the supply-blocked version, compared to 71 cfm for the return-blocked version. This represents more than half of the average estimated leakage from the supply-blocked test.

The hybrid test tends to be biased low relative to the best estimate, with a median underprediction of about 20 cfm. The median absolute difference is 53 cfm, which is about one-third of the average estimated leakage from the hybrid test. The discrepancy for this sample is comparable to the discrepancy of the house pressure test, which had an absolute median difference of 54 cfm.

The nulling test shows significantly more promise as a possible improved method for measuring duct leakage. There is no noticeable bias, and the median absolute discrepancy for the twelve cases in which it was performed is only 32 cfm, which represents about 15% of the median leakage estimated by this method. The median absolute difference for the twelve cases is comparable to that from the duct pressurization test on the entire set of homes, and lower than the other methods. This method has the advantage over the duct pressurization test of more accurately predicting whether the leakage is supply or return dominated, since changes in envelope pressure are used.

Table 2. Comparison of best estimate of supply leakage to predictions using methods not in Standard 152P

	Supply Leakage (cfm)				Difference from Best Estimate		
Site ID	**Best Estimate**	**HPT-Sup. Blocked**	**Hybrid Test**	**Nulling Test**	**HPT-Sup. Blocked**	**Hybrid Test**	**Nulling Test**
G04	69		54			-15	
G06	45	120	64		75	19	
G08	86	64	46		-22	-40	
A01a	217	300	197		83	-20	
A01b	232	314	152		82	-80	
A01c	103	139			36		
A01d	130	92			-38		
A02a	281		172			-109	
A02b	426		349	403		-77	-23
A02c	165		33	159		-132	-6
A02d	401			366			-35
A03a	149	178	129	115	29	-20	-34
A03b	112	197	-2	57	85	-114	-55
A03d	109	197	-2	57	82	-111	-52
A04a	65	151			86		
A04b	78	0			-78		
A04c	167	18	7	236	-149	-160	69
A04d	166	275	182	283	109	16	17
A05a	197		234	197		37	0
A05b	261		314	269		53	8
A05c	252		294	283		42	31
A05d	294		401	376		107	82
Mean	**182**	**157**	**154**	**225**	**29**	**-36**	**0**
Median	**166**	**151**	**152**	**216**	**75**	**-20**	**-3**
Mean Absolute Difference					**73**	**68**	**34**
Median Absolute Difference					**82**	**53**	**32**

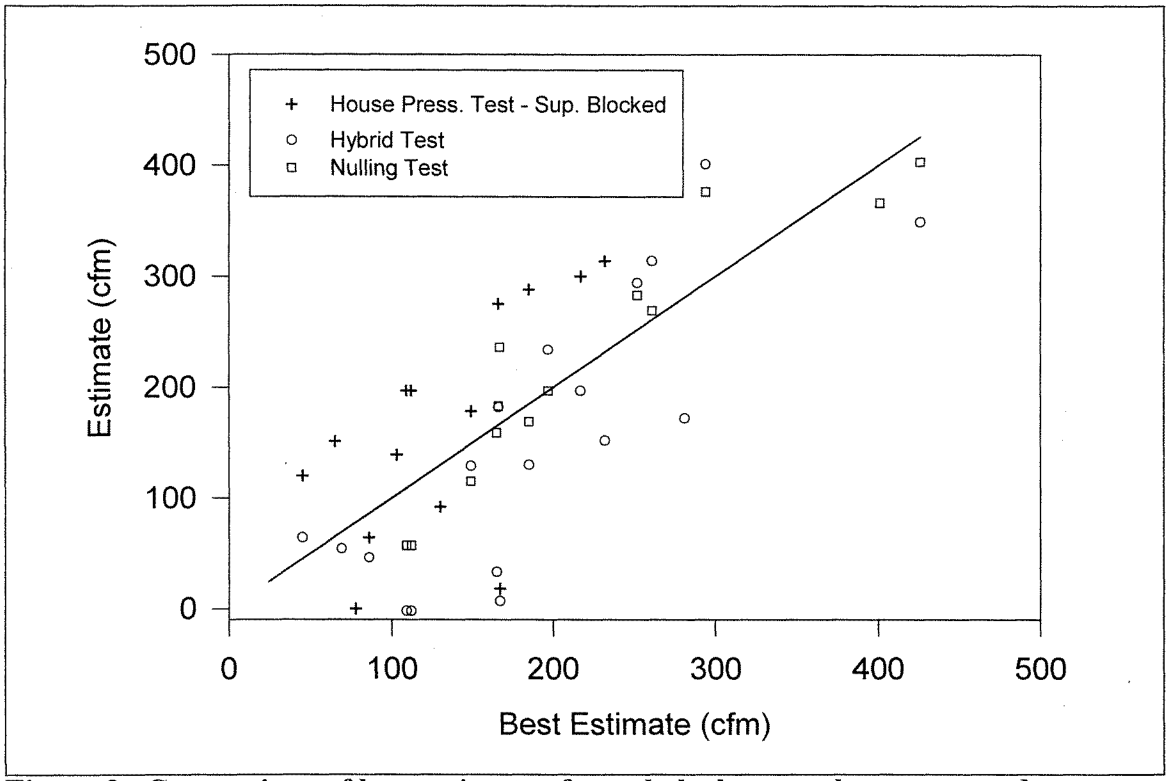

Figure 3. Comparison of best estimate of supply leakage to three proposed measurement techniques not in Standard 152P: supply blocked house pressure test, hybrid test, and nulling test (the line is a best estimate one-one line)

Implications for Duct Efficiency

Though the leakage diagnostic results show a wide variation in the abilities of the methods to reasonably predict supply duct leakage, this does not directly answer the question of how much impact this has on the prediction of duct efficiency. This question can be more directly answered by looking at the duct efficiencies predicted using each method and comparing them to the measured efficiencies obtained via the coheat method.

Table 3 provides some summary statistics to illustrate the importance of making good estimates of duct leakage when attempting to estimate duct efficiency. More detailed results for individual houses can be found in the final project report (Francisco and Palmiter 1999). The efficiency estimates used in generating Table 3 use all of the same inputs except for the supply and return duct leakage estimates (e.g. the conduction efficiency and zone temperatures are the same for all cases). For each leakage diagnostic, Table 3 shows the mean and median percentage point difference from the measured value, absolute mean and median percentage point difference, and the minimum and maximum absolute difference.

Table 3 shows that both versions of the house pressure test and the hybrid test tend to have much greater errors than the duct pressurization test or the nulling test. Even though the bias from the duct pressurization test (3.4 percentage points lower than measured efficiencies on average) is similar to the hybrid test and greater than the supply-blocked house pressure test, the median discrepancy is a lot lower and the scatter is also less. The nulling test outperforms all of the other methods (other than the best estimate) on all statistics.

Table 3. Differences from Measured Efficiencies Using Different Methods of Estimating Duct Leakage (Calculated - Measured)

	Best Estimate	Duct Pressurization	HPT-Ret. Blocked	HPT-Sup. Blocked	Hybrid	Nulling
Mean	1.0	-3.4	5.3	-1.1	3.2	-0.9
Median	0.4	-0.9	4.3	-4.6	2.5	0.2
Abs. Mean	2.1	6.7	8.9	10.0	8.1	3.3
Abs. Median	1.1	2.8	7.4	10.2	5.8	2.2
Abs. Min.	0.1	0.2	0.8	1.4	1.1	0.1
Abs. Max.	9.2	31.8	27.2	18.2	20.7	8.2

In addition to providing insight into which methods predict the efficiency best, Table 3 also shows that this level of error in estimating duct leakage can cause large errors in predicted efficiency, and that it is very important to make good, reliable estimates of duct leakage.

It must be cautioned that not all tests were performed in all cases, so these summary numbers are not entirely comparable. For example, for the cases in which the nulling test was done, the maximum difference for the return-blocked house pressure test is 17.2 percentage points and the maximum difference for the hybrid test is 18.8 points.

Findings and Conclusions

This paper compares the predictions of several methods to estimate supply duct leakage to an independent "best estimate".

It should be kept in mind that the sample size in this study is small, and that certain configurations can have a sizeable impact on the overall results. Also, these houses do not represent a random sample or a sample that is representative of the wide variety of house and duct types.

1) As shown in Table 3, obtaining a good estimate of duct leakage can be crucial in getting a reasonable estimate of duct efficiency.

2) The house pressure test does not perform well in many cases. Even taking extreme measures to place the return duct pressure tap in the proper location, this method provided several large errors in estimating the leakage, with resulting poor estimates of efficiency. Typical errors in leakage estimates were about half of the predicted leakage, and these errors were about twice those from the duct pressurization test. The leakage estimates resulted in an average discrepancy in efficiency estimate of more than five percentage points and a mean absolute discrepancy of nearly nine percentage points. When the pressure tap was placed in different locations than that specified, the results got worse.

3) The duct pressurization test does a better job of estimating the leakage than the house pressure test, with efficiency results that show less bias and somewhat less scatter. There are several cases where the results are quite bad, however. The average difference

between the efficiencies using this method and measured is about 3.4 percentage points, with the estimates being low. The mean absolute difference is nearly seven percentage points.

4) The supply-blocked house pressure test does not show improvement over the return-blocked version. The typical errors in leakage estimates are similar, and though there is less bias in resulting efficiency estimates than from the return-blocked version, the scatter is still quite large.

5) The hybrid test also performed similarly to the house pressure test regarding duct leakage estimates. The resulting efficiency estimates were somewhat better, though not as good as those from either the duct pressurization test or the nulling test.

6) The nulling test shows significant promise. Leakage estimates tend to be about as good as the duct pressurization test based on scatter, but also has lower bias. The efficiency estimates were also quite good, and there were none of the extremely poor individual estimates like those obtained with other methods. Only 12 tests using this method were done, so more testing would be desirable.

Acknowledgments

The work presented in this paper was sponsored by ASHRAE, RP-1056, and the United States Department of Energy. The project manager was John Andrews, Brookhaven National Laboratory.

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