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ABSTRACT

Research was performed at two houses to evaluate the duct system airtightness test (DSAT) and the house pressure test (HPT) duct leak estimation procedures of the proposed ASHRAE Standard 152P, Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems. *Two hybrid estimation methodologies were also examined. Duct leaks were created so that direct measurement of duct leakage could be performed as a basis for comparison.*

In general the various test methods do not predict duct leakage accurately, with deviation of 25% or more (from measured leakage) for most test methods. Some deviation results from inaccurate characterization of duct operating pressure. The standard DSAT appears to predict duct leakage accurately when duct operating pressures are well known. However, accurately characterizing duct operating pressure is no trivial task; therefore, the prospect of accurately characterizing duct leakage using currently available methods appears to be uncertain.

INTRODUCTION

ASHRAE Standard 152P, *Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems*, has been developed as a tool to predict (by both testing and calculating) the efficiency of residential thermal distribution systems. The standard defines "distribution system efficiency" (DSE) as the ratio between the energy consumed by the cooling or heating appliance if the distribution system has no losses (or gains) or impact on the equipment or building loads and the energy consumed by the same appliance connected to the distribution system under test. DSE is a value that falls between 0 and 1, where 1 represents 100% efficiency (no losses). DSE can be determined for both seasonal and design conditions. The portion of the standard that assesses air distribution system efficiency has received the most attention and is the focus of this paper.

Standard 152P predicts air distribution system efficiency by means of two steps. First, test methods are employed to determine the amount (air flow rate) of duct leakage. Second, these duct leakage air flow rates (both supply and return) are input to a series of algorithms that calculate the seasonal and design distribution system efficiency based on a number of variables. These variables include the size of the house, the surface area and insulation level of the ducts, the type and location of the ducts, and the temperature and humidity levels of indoors, outdoors, and various buffer zones. These algorithms then calculate the efficiency of the air distribution system.

It is the purpose of this paper to present research results that evaluate the accuracy of the Standard 152P duct leakage prediction methodologies, as well as two other hybrid methodologies, compared to direct measurement of duct leakage.

Research Houses

Two houses were selected to perform this research. They are both located in east central Florida about 5 to 10 miles (8 to 16 km) from the Atlantic Ocean. More extensive presentation of the Standard 152P duct leakage prediction testing at these two houses, plus energy savings monitoring and analysis, can be found in Cummings et al. (1999).

House 1 is a split-level, 33-year-old house, with four bedrooms and about 1800 ft^2 (167 m^2) of floor area. The lower floor and middle floor are concrete block on a concrete slab

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construction. The upper floor is located above the garage and family room. The air handler for the 2.5 ton air conditioner is located in a hallway closet. The return is an enclosed air-handler support platform with a grille opening into the hallway; there is no return ductwork. The supply ductwork (89% round metal and 11% flex duct by surface area) is 92% in the attic and 8% in the garage. Total duct surface area is 384 ft^2 (35.7 m^2) or 22% of the house floor area. The insulation of the metal duct is 0.5 in. (1.3 cm) craft-back fiberglass insulation. A blower door test was performed; it found house airtightness to be 9.1 air changes per hour at 0.2 in. w.c. (50 Pa) ($Q_{env,50}$), which indicates that this is a moderately leaky house but somewhat typical for a Florida house built in 1965.

House 2 is a single-story four-year-old house, with four bedrooms and 2350 ft^2 (218 m^2) of floor area. Construction is concrete block slab-on-grade. The air handler for the 5-ton air conditioner is located in the attached garage. It sits on a return plenum formed by the air-handler support platform, and a return duct runs from the single ceiling return near the center of the house to the return plenum. Thirty-seven percent of the return is in the attic and 95% of the supply is in the attic, with the balance of each in the garage. Total duct surface area is 758 ft^2 (70.5 m^2) or 32% of the house floor area. The ductwork is a mix of ductboard and flex duct, all with R6 insulation. Ductboard composes 73% of the return system and 23% of the supply ductwork. A blower door test was performed, which found house airtightness to be 4.3 $Q_{env,50}$, indicating that this is a tight house.

DUCT LEAKAGE TEST METHODS

Two duct leakage test methods are contained in the proposed ASHRAE Standard 152P: the duct system airtightness test (DSAT) and the house pressure test (HPT).

In the DSAT, the duct system is either depressurized or pressurized by means of a calibrated blower to "measure" the cumulative hole size of the leaks in the duct system. This test is done with the air handler off, registers masked off, and the duct system divided (masked) at the air handler. The operating pressure of the duct system is also obtained (air handler operating and registers unmasked). Given the duct hole size and the duct pressure, air leakage into return leaks and out of supply leaks is calculated.

In the HPT, changes in house pressure are carefully monitored when the air handler is turned on and turned off. Dominant supply leaks will depressurize the house. Dominant return leaks will pressurize the house. The degree of change in house pressure is a function of the net duct leakage (supply leak to outside minus return leak from outside) and the airtightness of the house. Large net duct leakage and a tight house will produce large changes in house pressure when the air handler is turned on. To further enhance the house pressure signal, the test is repeated with return grilles partially blocked to produce approximately –0.4 in. w.c. (–100 Pa) in the return. This increase in pressure increases return leakage air flow and decreases supply leakage air flow; therefore, the house pressure is significantly changed.

Based on these measured house pressures and return and supply ductwork pressures, supply leakage air flow and return leakage air flow are calculated. Because the accuracy of the HPT is dependent upon the size of the duct leakage, the airtightness of the house, and the level of pressure fluctuation induced by wind, ASHRAE Standard 152P places limitations on the conditions under which this test can be applied. These conditions include limitations on the size of the measured pressure change and the size of the pressure fluctuations.

Two additional test methods, developed by John Andrews (1998), were also evaluated: hybrid DSAT and hybrid HPT (blocked supply). In the hybrid DSAT, the duct system is not divided. The calibrated blower is typically mounted to the air handler, and the entire duct system is taken to 0.1 in. w.c. (25 Pa). Given this test result and the operating pressure of the air distribution system, a total duct leakage air flow rate can be calculated.

In order to split the leakage into return and supply leakage, a simplified HPT is performed. Based on the results of the HPT, the total duct leakage is subdivided into return and supply leakage. In the hybrid HPT, the supply registers are blocked instead of the return and a variety of calculations are used to estimate return and supply duct leakage. The accuracy of the hybrid HPT is also strongly influenced by house airtightness and wind-induced pressure.

Field Testing of Duct Leakage Test Methodologies

In order to evaluate the above described duct leakage test methodologies, various duct leaks were created in the two test houses. In house 1, five different "created" duct leak configurations were produced. In house 2, three different "created" duct leak configurations were produced. In all cases, the duct leak configurations were produced by round or rectangular holes at only one, two, or at most three duct locations so that direct measurement of the leakage air flow rates (by means of hot wire, flow hood, flow grid, etc.) was readily possible. Table 1 summarizes the eight created duct leak configurations.

While duct leakage from the created leaks was measured directly with reasonable accuracy, the remaining leakage that is diffused throughout the system cannot be measured directly under normal operating conditions. This diffused leakage can, however, be reasonably estimated using the DSAT and the actual duct system pressures. (Note that use of DSAT-predicted diffuse leakage as part of the "best estimate" creates a problem because the DSAT is one of the methods being evaluated. However, because the diffuse leakage is much smaller than the created leakage and because the DSAT—when combined with actual duct operating pressure—has been shown in this study to predict quite accurately, the authors feel that this is an acceptable means of obtaining the best estimate.)

TABLE 1

"Best estimate" duct leakage air flows cfm (L/s) based on measurements (measured by hot wire, flow hood, etc.) at known (created) leak sites plus the calculated duct leakage from the diffuse (small distributed) duct leaks based on the DSAT test and actual system-wide pressure.

Config.	Best Estimate of Duct Leaks	
	Supply Leaks	Return Leaks
1-1		178 (84.0)
1-2	119 (56.2)	
1-3	173 (81.7)	
1-4	221 (104.3)	
1-5	221 (104.3)	178 (84.0)
2-1		302 (142.5)
2-2	260 (122.7)	
2-3	287 (135.5)	350 (165.2)

TABLE 2

Duct system airtightness test data (leakage to outdoors) based on the standard DSAT for each of the eight duct system configurations. These are the air flow rates through the duct leak openings (to outdoors) when the ductwork is at –0.100 in. WC (–25 Pa) with respect to the zone where the ducts are located.

Config.	Supply Duct Airtightness $Q_{25,s}$ cfm (L/s)	Return Duct Airtightness $Q_{25,r}$ cfm (L/s)	Combined Q_{25} cfm (L/s)
1-1	105 (49.6)	168 (79.3)	273 (128.9)
1-2	320 (151.0)	21 (9.9)	341 (161.0)
1-3	442 (208.6)	21 (9.9)	463 (218.5)
1-4	500 (236.0)	21 (9.9)	521 (245.9)
1-5	500 (236.0)	168 (79.3)	668 (315.3)
2-1	45 (21.2)	391 (184.6)	435 (205.3)
2-2	310 (146.3)	30 (14.2)	340 (160.5
2-3	310 (146.3)	391 (184.6)	700 (330.4)

TABLE 3

Duct system airtightness data (leakage to outdoors) based on the hybrid DSAT for each of the eight duct system configurations.

Config.	Supply Duct Airtightness $Q_{25,s}$ cfm (L/s)	Return Duct Airtightness $Q_{25,r}$ cfm (L/s)	Combined Q_{25} cfm (L/s)
1-1	76 (35.9)	187 (88.3)	263 (124.1)
1-2	188 (88.7)	94 (44.4)	282 (133.1)
1-3	242 (114.2)	114 (53.8)	356 (168.0)
1-4	276 (130.3)	110 (51.9)	386 (182.2)
1-5	342 (161.4)	278 (131.2)	620 (292.6)
2-1	67 (31.6)	350 (165.2)	417 (196.8)
2-2	210 (99.1)	17 (8.0)	227 (107.1)
2-3	245 (115.6)	385 (181.7)	630 (297.4)

DSAT Duct Leakage Method

The DSAT method was performed for each of the eight duct leak configurations. The intermediate outputs of the DSAT, Q_{25s} and Q_{25r} (the air flow rate through the supply leaks and return leaks at 0.1 in. w.c. [25 Pa] pressure), are used in the duct leakage calculation methodology and are presented in Table 2. Once these values are obtained, Q_s and Q_r (supply and return leakage rates) are calculated (see section on "Calculating Duct Leakage with 152P DSAT Algorithms").

Table 3 presents data for the hybrid DSAT. Note that $Q_{25,s}$, $Q_{25,r}$, and Q_{25}, in Table 3 are not direct test data nor are they an intermediate step in the calculation procedure.They are shown for comparison to the standard DSAT. The reader can find the procedures for calculating Q_s and Q_r in Andrews (1998). For both the standard DSAT and the hybrid DSAT, the final estimated duct leakage air flow requires an accurate representation of duct operating pressures, which is discussed in the section "Calculating Duct Leakage with 152P HPT Algorithms."

HPT Duct Leakage Method

The HPT method was performed for each of the eight duct leak configurations. An example of the HPT field test data is presented in Table 4. Also included in Table 4 is the blocked supply test procedure (see the "on SB" in the table). Pressures are expressed with respect to (wrt) the attic, except return and supply pressures, which are "wrt indoors."

The data of Table 4 are for a dominant return leak in house 2 (configuration 2-1). Note that when the air handler is turned on, house pressure increases from about 0.0012 in. w.c. (+0.3 Pa) to 0.0164 in. w.c. (+4.1 Pa) and that when the return register is partially blocked to produce 0.340 in. w.c. (–84.7 Pa) in the return, house pressure goes to 0.0586 in. w.c. (+14.6 Pa). This illustrates the responsiveness of a tight house to large duct leaks.

Duct System Operating Pressure

Both the standard 152P DSAT and HPT methodologies require measurement of duct system operating pressure. For DSAT, the accuracy of the absolute pressure is critical to calculate estimated duct leakage. For HPT, it is the relative pressure (ratio of pressure readings before and after blocking the return or supply) that is important. According to 152P, supply pressure is obtained by means of a pressure pan. With the air handler operating, a pressure pan is placed over each supply register, one register at a time. For the DSAT, the supply duct operating pressure is taken to be the average of the pressure pan readings. For the HPT, only one supply register need be tested.

On the return side, there are also differences between

TABLE 4a

Standard (return blocked) house pressure test and hybrid (supply blocked) house pressure test data (in. WC) for configuration 2-1 (large return leak). House pressure (ten 5-sec averages) wrt the attic with the air handler on and off, and with the return blocked (RB) and the supply blocked (SB), and average return and supply duct operating pressure.

AH status	1	2	3	4	5	6	7	8	9	10	avg.
on	0.0164	0.0164	0.0164	0.0168	0.0164	0.0164	0.0160	0.0168	0.0168	0.0176	0.0166
off	0.0020	0.0016	0.0016	0.0012	0.0012	0.0016	0.0012	0.0008	0.0008	0.0008	0.0013
on	0.0164	0.0160	0.0160	0.0160	0.0160	0.0160	0.0160	0.0160	0.0156	0.0152	0.0160
on, dP in duct				return –0.084			supply 0.060*				
off	0.0024	0.0024	0.0020	0.0016	0.0012	0.0012	0.0012	0.0012	0.0008	0.0008	0.0015
on RB	0.0582	0.0578	0.0582	0.0582	0.0590	0.0586	0.0586	0.0582	0.0598	0.0606	0.0587
on RB, dP in duct				return –0.340			supply 0.0337*				
on SB	0.0120	0.0100	0.0096	0.0104	0.120	0.0108	0.0116	0.0104	0.0096	0.0088	0.0105
on SB, dP in duct				return –0.0626			supply 0.211*				
off	0.0020	0.0028	0.0016	0.0020	0.0032	0.0040	0.0020	0.0024	0.0024	0.0024	0.0025

* supply operating pressure by means of pressure pan

TABLE 4b

Standard (return blocked) house pressure test and hybrid (supply blocked) house pressure test data (Pa) for configuration 2-1 (large return leak). House pressure (ten 5-sec averages) wrt the attic with the air handler on and off, and with the return blocked (RB) and the supply blocked (SB), and average return and supply duct operating pressure.

AH status	1	2	3	4	5	6	7	8	9	10	avg.
on	4.1	4.1	4.1	4.2	4.1	4.1	4.0	4.2	4.2	4.4	4.15
off	0.5	0.4	0.4	0.3	0.3	0.4	0.3	0.2	0.2	0.2	0.32
on	4.1	4.0	4.0	4.0	4.0	4.0	4.0	4.0	3.9	3.8	3.98
on, dP in duct	return –20.9		supply 14.9*								
off	0.6	0.6	0.5	0.4	0.3	0.3	0.3	0.3	0.2	0.2	0.37
on RB	14.5	14.4	14.5	14.5	14.7	14.6	14.6	14.5	14.9	15.1	14.63
on RB, dP in duct	return –84.7		supply 8.4*								
on SB	3.0	2.5	2.4	2.6	3.0	2.7	2.9	2.6	2.4	2.2	2.63
on SB, dP in duct	return –15.6		supply 52.5*								
off	0.5	0.7	0.4	0.5	0.8	1.0	0.5	0.6	0.6	0.6	0.62

* supply operating pressure by means of pressure pan

DSAT and HPT. For DSAT, if there are less than five return registers (both of these houses have only one return), then return pressure is set to be plenum/2 (return plenum divided by 2). In house 1, there is only a return plenum and no return ductwork. In house 2, there is both return ductwork and a return plenum. For HPT, return pressure is measured on the air-handler side of the filter when the filter is at the grille or midway between the return grille and plenum when the filter is located at the plenum. In both houses, the filters were located at the grille.

How well do the 152P methods perform in predicting duct operating pressure? The answer is they generally predict poorly. Table 5 presents duct operating pressure based on three approaches: (1) the 152P test methods, (2) our best estimate of actual systemwide pressure based on pressure tap measurements, and (3) our best estimate of duct operating pressure weighted by where the leaks are located. The pressure pan and plenum/2 predict pressures that are quite different from our best estimate of systemwide pressure, which is based on pressure tap measurements. Note that our best estimate of systemwide pressure is based on measurements from 14 pressure taps at house 1 and 8 pressure taps at house 2, and the pressure measurements are weighted according to the surface area of each section of the duct system.

For house 1, the pressure pan predicts supply pressure

TABLE 5a

Duct system pressures (in. WC) for the duct system configurations based on different duct pressure measurements methods. On supply side: (1) pressure pan duct operating pressure, (2) actual systemwide duct operating pressure (derived by correcting the pressure pan readings based on pressure tap readings), and (3) actual weighted duct operating pressure (weighting to where the leakage actually is occurring). On the return side: (1) plenum divided by 2 (DSAT), (2) actual system-wide, (3) actual weighted duct operating pressure (weighting to where the leakage is actually occurring).

	Supply Duct Pressures			Return Duct Pressures		
Config.	Pressure Pan	Actual Systemwide	Actual Weighted	Plenum/2	Actual Systemwide	Actual Weighted
1-1	0.0919	0.0474	0.0474	–0.0470	–0.1253	–0.0980
1-2	0.0842	0.0434	0.0253	–0.0647	–0.1683	–0.1683
1-3	0.0818	0.0422	0.0205	–0.0643	–0.1671	–0.1671
1-4	0.0703	0.0398	0.0221	–0.0253	–0.1711	–0.1711
1-5	0.0723	0.0418	0.0241	–0.0478	–0.1277	–0.0996
2-1	0.0691	0.0800	0.0800	–0.0422	–0.1225	–0.0695
2-2	0.0446	0.0478	0.0815	–0.0771	–0.1707	–0.1707
2-3	0.0490	0.0534	0.0920	–0.0474	–0.1345	–0.0779

TABLE 5b

Duct system pressures (Pa) for the duct system configurations based on different duct pressure measurements methods. On supply side: (1) pressure pan duct operating pressure, (2) actual systemwide duct operating pressure (derived by correcting the pressure pan readings based on pressure tap readings), and (3) actual weighted duct operating pressure (weighting to where the leakage actually is occurring). On the return side: (1) plenum divided by 2 (DSAT), (2) actual system-wide, (3) actual weighted duct operating pressure (weighting to where the leakage is actually occurring).

	Supply Duct Pressures			Return Duct Pressures		
Config.	Pressure Pan	Actual Systemwide	Actual Weighted	Plenum/2	Actual Systemwide	Actual Weighted
1-1	22.9	11.8	11.8	–11.7	–31.2	–24.4
1-2	21.0	10.8	6.3	–16.1	–41.9	–41.9
1-3	20.4	10.5	5.1	–16.0	–41.6	–41.6
1-4	17.5	9.9	5.5	–16.3	–42.6	–42.6
1-5	18.0	10.4	6.0	–11.9	–31.8	–24.8
2-1	17.2	19.9	19.9	–10.5	–30.5	–17.3
2-2	11.1	11.9	20.3	–19.2	–42.5	–42.5
2-3	12.2	13.3	22.9	–11.8	–33.5	–19.4

87% high compared to the best estimate and plenum/2 predicts return pressure 62% low compared to best estimate. For house 2, the pressure pan predicts systemwide supply pressure quite well, predicting 10.2% low compared to the best estimate, while plenum/2 predicts return pressure poorly, predicting 61% low compared to the best estimate.

Other research has recorded problems with the pressure measurement methods of 152P. In two other Florida houses, pressure pan readings were 66% higher (house 1) and 15% higher (house 2) than best estimate systemwide pressure, while plenum/2 was 66% and 60% lower than best estimate, respectively (Cummings and Withers 1999). Francisco and Palmiter (1999) also report that "the method of estimating the operating static pressure for the duct pressurization test tends to overestimate the actual operating static pressure at the leakage sites."

A further problem in correctly characterizing duct operating pressure is that duct leakage may be concentrated in one part of the duct system, and the operating pressures in that part of the duct system may be substantially different from the systemwide average. In cases where duct leakage is concentrated at one or more specific locations, accurate prediction of duct leakage requires weighting the pressures to reflect where the holes are located. Therefore, Table 5 also presents "actual weighted" duct system pressure. This pressure is determined by weighting pressure according to where the leaks are located based on hole size, not leakage air flow. For example, if 90% of the supply leakage equivalent hole area (Q_{25}) is located at one opening, the pressure at that location receives a 90% weighting and the remainder of the system receives a 10% weighting. In general, this approach would not be considered a practical approach to carrying out a duct system airtightness test because of the difficulties associated with knowing where the leaks are located, how much leakage is located in each section, and what the pressure is right at the leak site. The purpose of our developing actual weighted pressure is to identify whether the various test methods can work well if duct operating pressure can be accurately characterized.

As can be seen in Table 5, actual weighted pressure can vary substantially from systemwide pressure. In house 1, supply weighted pressure is, on average, 35% lower than systemwide pressure because the large created leaks were located in a low-pressure section of the system. In house 2, supply weighted pressure is, on average, 40% higher than systemwide pressure because the large created leaks were located in a high-pressure section of the system. Significant differences also exist between actual weighted and systemwide pressure on the return side of the system.

In summary, there are significant problems with the way Standard 152P measures duct system pressure. These discrepancies can produce substantial errors in prediction of duct leakage flow, as will be seen in the next section. Improved measurement techniques are required to yield better prediction of systemwide pressure. Furthermore, even if a means for measuring actual systemwide pressure is developed, there will still remain the problem of characterizing the operational pressure that exists where the major duct leaks are located.

How much error in predicting duct leakage air flow results from these errors in pressure measurement? For the DSAT, the errors can be large. For house 1, pressure pan overprediction by 87% will lead to overprediction of leakage by about 46%, and plenum/2 underprediction by 62% will lead to underprediction of leakage by about 44%. For house 2, pressure pan underprediction by 10% will lead to underprediction of leakage by about 6%, and plenum/2 underprediction by 61% will lead to underprediction of leakage by about 43%. For the HPT, the midpoint pressure measurement also misses the mark, but this creates less error because in the HPT it is the ratio of the pressures, with the return blocked and unblocked, that is used.

Calculating Duct Leakage with 152P DSAT Algorithms

Once the DSAT has been completed and the duct system operating pressures have been obtained, estimated duct leakage is calculated. For the DSAT, the calculation is rather simple.

$$Q_s = Q_{25,s}\,(dP_s/25)^{0.6}$$

$$Q_r = Q_{25,r}\,(dP_r/25)^{0.6}$$

where Q_s and Q_r are supply and return duct leakage flow rates, $Q_{25,s}$ and $Q_{25,r}$ are the duct leak air flow rates (cfm) at the 25 Pa test pressure, and dP (Pa) is the operating pressure in the ductwork. Calculated duct leakage based on the various approaches to duct pressure measurement are presented in Table 6.

Consider an example for supply leaks for configuration 2-2 using pressure pan, actual systemwide pressure, and actual weighted pressure.

TABLE 6a

Predicted duct leakage air flows (cfm; to and from outdoors) based on the standard DSAT for each of the eight duct system configurations and measured duct leakage. Predicted leakage is shown based on three different duct pressure measurements: (1) pressure pan or plenum/2, (2) "actual" systemwide duct operating pressure, and (3) actual weighted duct operating pressure (weighting to where the leakage actually is occurring). Measured leakage is based on measurements (measured by hot wire, flow hood, etc.) at known leak sites plus predicted leakage from DSAT for distributed leaks (using actual systemwide pressure).

Config.	Predicted Supply Leak			Measured Supply Leaks	Predicted Return Leak			Measured Return Leaks
	Pressure Pan *dP*	Actual *dP* Systemwide	Actual *dP* Weighted		Plenum/2	Actual *dP* Systemwide	Actual *dP* Weighted	
1-1	99.9	67.1	65.1		106.5	191.9	166.0	178
1-2	292.5	196.4	154.2	119	16.2	28.8	29.6	
1-3	392.2	263.4	196.5	173	16.1	28.7	29.4	
1-4	403.6	286.8	228.9	221	16.4	29.1	29.9	
1-5	411.1	295.4	237.9	221	107.6	194.1	167.5	178

TABLE 6a

Predicted duct leakage air flows (cfm; to and from outdoors) based on the standard DSAT for each of the eight duct system configurations and measured duct leakage. Predicted leakage is shown based on three different duct pressure measurements: (1) pressure pan or plenum/2, (2) "actual" systemwide duct operating pressure, and (3) actual weighted duct operating pressure (weighting to where the leakage actually is occurring). Measured leakage is based on measurements (measured by hot wire, flow hood, etc.) at known leak sites plus predicted leakage from DSAT for distributed leaks (using actual systemwide pressure).

2-1	35.6	38.8	38.8		239.9	440.0	313.1	302
2-2	190.6	198.4	273.4	260	26.2	40.9	40.9	
2-3	201.3	212.1	293.9	287	261.3	465.4	335.4	350

TABLE 6b

Predicted duct leakage air flows (L/s; to and from outdoors) based on the standard DSAT for each of the eight duct system configurations and measured duct leakage. Predicted leakage is shown based on three different duct pressure measurements: (1) pressure pan or plenum/2, (2) "actual" systemwide duct operating pressure, and (3) actual weighted duct operating pressure (weighting to where the leakage actually is occurring). Measured leakage is based on measurements (measured by hot wire, flow hood, etc.) at known leak sites plus predicted leakage from DSAT for distributed leaks (using actual systemwide pressure).

Config.	Predicted Supply Leak			Measured Supply Leaks	Predicted Return Leak			Measured Return Leaks
	Pressure Pan *dP*	Actual *dP* Systemwide	Actual *dP* Weighted		Plenum/2	Actual *dP* Systemwide	Actual *dP* Weighted	
1-1	47.2	31.7	30.7		50.3	90.6	78.4	84.0
1-2	138.1	92.7	72.8	56.2	7.7	13.6	14.0	
1-3	185.1	124.3	92.7	81.7	7.6	13.6	13.9	
1-4	190.5	135.4	108	104.3	7.7	13.7	14.1	
1-5	194.0	139.4	112.3	104.3	50.8	91.6	79.1	84.0
2-1	16.8	18.3	18.3		113.2	207.7	147.8	142.5
2-2	90.0	93.6	129.0	122.7	12.4	19.3	19.3	
2-3	95.0	100.1	138.7	135.5	123.3	219.7	158.3	165.2

$Q_s = 309.8 \text{ cfm } (11.1/25)^{0.6} = 190 \text{ cfm}$
(11.1 Pa from pressure pan)

$Q_s = 309.8 \text{ cfm } (11.9/25)^{0.6} = 198 \text{ cfm}$
(11.9 Pa is actual systemwide *dP*)

$Q_s = 309.8 \text{ cfm } (20.3/25)^{0.6} = 273 \text{ cfm}$
(20.3 Pa is actual weighted *dP*)

$Q_s = 146.2 \text{ L/s } (11.1/25)^{0.6} = 89.7 \text{ L/s}$
(11.1 Pa from pressure pan)

$Q_s = 146.2 \text{ L/s } (11.9/25)^{0.6} = 93.5 \text{ L/s}$
(11.9 Pa is actual systemwide *dP*)

$Q_s = 146.2 \text{ L/s } (20.3/25)^{0.6} = 128.9 \text{ L/s}$
(20.3 Pa is actual weighted *dP*)

In this example, our measured best estimate duct leakage air flow for configuration 2-2 is 260 cfm (122.7 L/s), so "actual weighted" is by far the closest, clearly indicating the importance of weighting the pressure to where the duct leakage occurs. Note that the pressure pan overestimates duct operating pressure when looking at the systemwide but underestimates "actual weighted" in this case because it turns out that the large created supply leak was located in a portion of the supply ductwork that had much higher pressure.

Looking at all eight configurations, the reader will note that there are actually ten different "created" duct leaks when considering the supply leaks and the return leaks separately (configurations 1-5 and 2-3 have both a supply leak and a return leak). For the ten duct leaks, average absolute difference of predicted versus measured is 8.2% when using actual weighted pressure. When actual systemwide pressure is used, average absolute deviation is 25.5%. If the 152P methods of measuring operating pressure (pressure pan and plenum/2) are used, then the average absolute deviation is 61.4%.

CALCULATING DUCT LEAKAGE WITH 152P HPT ALGORITHMS

Once the HPT has been completed and the duct system operating pressures have been obtained, estimated duct leak-

TABLE 7a

Predicted duct leakage air flows (cfm; to and from outdoors) based on the standard HPT for each of eight duct system configurations and compared to measured duct leakage. Predicted leakage is shown based on three different duct pressure measurements: (1) pressure pan (supply) or mid-point pressure (return), (2) "actual" systemwide duct operating pressure, and (3) actual weighted duct operating pressure (weighting to where the leakage actually is occurring). Measured leakage is based on site measurements at known leak sites plus predicted leakage from DSAT for distributed leaks (using actual systemwide pressure).

	Predicted Supply Leak				Predicted Return Leak			
Config.	Pressure Pan *dP*	Actual *dP* Systemwide	Actual *dP* Weighted	Measured Supply Leaks	Mid-Point Return *dP*	Actual *dP* Systemwide	Actual *dP* Weighted	Measured Return Leaks
1-1	1.9	120.0	30.8		112.9	231.0	141.9	178
1-2	93.1	99.6	96.6	119	0.0	5.5	2.5	
1-3	128.0	145.5	143.3	173	0.0	17.6	15.4	
1-4	184.9	269.3	319.5	221	19.6	104.0	154.2	
1-5	171.9	269.2	193.3	221	107.9	205.2	129.3	178
2-1	0	0	0		283.3	283.3	283.3	302
2-2	199.8	193.1	194.5	260	6.6	0	1.3	
2-3	45.7	119.9	52.7	287	185.9	260.1	192.9	350

TABLE 7b

Predicted duct leakage air flows (L/s; to and from outdoors) based on the standard HPT for each of eight duct system configurations and compared to measured duct leakage. Predicted leakage is shown based on three different duct pressure measurements: (1) pressure pan (supply) or mid-point pressure (return), (2) "actual" systemwide duct operating pressure, and (3) actual weighted duct operating pressure (weighting to where the leakage actually is occurring). Measured leakage is based on site measurements at known leak sites plus predicted leakage from DSAT for distributed leaks (using actual systemwide pressure).

	Predicted Supply Leak				Predicted Return Leak			
Config.	Pressure Pan *dP*	Actual *dP* Systemwide	Actual *dP* Weighted	Measured Supply Leaks	Mid-Point Return *dP*	Actual *dP* Systemwide	Actual *dP* Weighted	Measured Return Leaks
1-1	0.90	56.6	14.5		53.3	109.0	67.0	84.0
1-2	43.9	47.0	45.6	56.2	0	2.6	1.2	
1-3	60.4	68.7	67.6	81.7	0	8.3	7.3	
1-4	87.3	127.1	150.8	104.3	9.3	49.1	72.8	
1-5	81.1	127.1	91.2	104.3	50.9	96.9	61.0	84.0
2-1	0	0	0		133.7	133.7	133.7	142.5
2-2	94.3	91.1	91.8	122.7	3.1	0	0.61	
2-3	21.6	56.6	24.9	135.5	87.7	122.8	91.0	165.2

TABLE 8a

Predicted duct leakage air flows (cfm; to and from outdoors) based on the hybrid DSAT for each of eight duct system configurations and compared to measured duct leakage. Predicted leakage is shown based on three different duct pressure measurements: (1) pressure pan (supply) or return plenum (return), (2) "actual" systemwide duct operating pressure, and (3) actual weighted duct operating pressure (weighting to where the leakage actually is occurring). Measured duct leaks is based on site measurements at known leak sites plus predicted leakage from standard DSAT for distributed leaks (using actual systemwide pressure).

Config.	Predicted Supply Leak			Measured Supply Leaks	Predicted Return Leak			Measured Return Leaks
	Pressure Pan *dP*	Actual *dP* Systemwide	Actual *dP* Weighted		Plenum/2	Actual *dP* Systemwide	Actual *dP* Weighted	
1-1	70.6	68.2	58.7		181.6	179.2	169.8	178
1-2	185.2	155.5	129.9	119	91.1	61.4	35.8	
1-3	234.9	193.5	147.3	173	106.9	65.5	19.4	
1-4	253.9	210.7	166.8	221	88.6	45.4	1.5	
1-5	313.4	282.6	232.3	221	249.3	218.6	168.3	178
2-1	0	81.0	28.6		283.3	364.3	311.9	302
2-2	193.2	193.2	199.3	260	0	0	6.1	
2-3	116.3	224.5	212.2	287	256.4	364.6	352.4	350

TABLE 8b

Predicted duct leakage air flows (L/s; to and from outdoors) based on the hybrid DSAT for each of eight duct system configurations and compared to measured duct leakage. Predicted leakage is shown based on three different duct pressure measurements: (1) pressure pan (supply) or return plenum (return), (2) "actual" systemwide duct operating pressure, and (3) actual weighted duct operating pressure (weighting to where the leakage actually is occurring). Measured duct leaks is based on site measurements at known leak sites plus predicted leakage from standard DSAT for distributed leaks (using actual systemwide pressure).

Config.	Predicted Supply Leak			Measured Supply Leaks	Predicted Return Leak			Measured Return Leaks
	Pressure Pan *dP*	Actual *dP* Systemwide	Actual *dP* Weighted		Plenum/2	Actual *dP* Systemwide	Actual *dP* Weighted	
1-1	33.3	32.2	27.7		85.7	84.6	80.1	84.0
1-2	87.4	73.4	61.3	56.2	43.0	29.0	16.9	
1-3	110.9	91.3	69.5	81.7	50.5	30.9	9.2	
1-4	119.8	99.5	78.7	104.3	41.8	21.4	0.71	
1-5	147.9	133.4	109.6	104.3	117.7	103.2	79.4	84.0
2-1	0	38.2	13.5		133.7	171.9	147.2	142.5
2-2	91.2	91.2	94.1	122.7	0	0	2.9	
2-3	54.9	106.0	100.2	135.5	121.0	172.1	166.3	165.2

age is calculated (Table 7). For the HPT, the calculation procedures may be found in Standard 152P (working draft January 1999).

The HPT predicts duct leakage cfm well in a few cases but poorly in the majority of cases. For the ten duct leaks, the average absolute deviation is 33.3% for actual weighted and 26.6% for actual systemwide pressure. When the 152P methods of measuring operating pressure are used (pressure pan and midpoint), then the average absolute deviation is 32.3%.

Calculating Duct Leakage with the Hybrid DSAT Method

The hybrid DSAT was done and duct leakage calculations were performed. Table 8 presents the results of the hybrid DSAT for the various duct pressure measurement approaches.

The hybrid DSAT predicts return leak flow rates rather well but generally underestimates supply duct leakage flow rates. For the ten duct leaks, the average absolute deviation is 11.7% for actual weighted duct pressure and 17.1% for actual systemwide pressure duct pressure. For the four return leaks, the average absolute deviation was only 3.5% for actual weighted duct pressure and 12.1% for actual systemwide duct pressure. For the six supply leaks, the average absolute devi-

TABLE 9a

Predicted duct leakage air flows (cfm; to and from outdoors) based on the hybrid HPT for each of the eight duct system configurations and compared to measured duct leakage. Predicted leakage is shown based on three different duct pressure measurements: (1) pressure pan duct operating pressure, (2) "actual" systemwide duct operating pressure, and (3) actual weighted duct operating pressure (weighting to where the leakage actually is occurring). Measured leakage is based on site measurements at known leak sites plus predicted leakage from DSAT for distributed leaks (using actual systemwide pressure).

Config.	Predicted Supply Leak			Measured Supply Leaks	Predicted Return Leak			Measured Return Leaks
	Pressure Pan *dP*	Actual *dP* Systemwide	Actual *dP* Weighted		Mid-Point Return *dP*	Actual *dP* Systemwide	Actual *dP* Weighted	
1-1	255.0	93.0	84.7		366.0	204.1	195.7	178
1-2	238.9	94.1	94.1	119	144.8	0.0	0.0	
1-3	360.9	129.0	146.1	173	233.0	1.1	18.2	
1-4	387.8	165.4	165.3	221	222.5	0.0	0.0	
1-5	392.0	139.9	156.1	221	328.0	75.9	92.1	178
2-1	16.9	20.6	31.7		300.1	303.8	315.0	302
2-2	193.2	193.2	193.1	260	0.0	0.0	0.0	
2-3	163.1	121.6	143.1	287	303.3	261.7	283.2	350

TABLE 9b

Predicted duct leakage air flows (L/s; to and from outdoors) based on the hybrid HPT for each of the eight duct system configurations and compared to measured duct leakage. Predicted leakage is shown based on three different duct pressure measurements: (1) pressure pan duct operating pressure, (2) "actual" systemwide duct operating pressure, and (3) actual weighted duct operating pressure (weighting to where the leakage actually is occurring). Measured leakage is based on site measurements at known leak sites plus predicted leakage from DSAT for distributed leaks (using actual systemwide pressure).

Config.	Predicted Supply Leak			Measured Supply Leaks	Predicted Return Leak			Measured Return Leaks
	Pressure Pan *dP*	Actual *dP* Systemwide	Actual *dP* Weighted		Mid-Point Return *dP*	Actual *dP* Systemwide	Actual *dP* Weighted	
1-1	120.4	43.9	40.0		172.8	96.3	92.4	84.0
1-2	112.8	44.4	44.4	56.2	68.3	0	0	
1-3	170.3	60.9	69.0	81.7	110.0	0.52	8.6	
1-4	183.0	78.1	78.0	104.3	105.0	0	0	
1-5	185.0	66.0	73.7	104.3	154.8	35.8	43.5	84.0
2-1	8.0	9.7	15.0		141.6	143.4	148.7	142.5

TABLE 9b

Predicted duct leakage air flows (L/s; to and from outdoors) based on the hybrid HPT for each of the eight duct system configurations and compared to measured duct leakage. Predicted leakage is shown based on three different duct pressure measurements: (1) pressure pan duct operating pressure, (2) "actual" systemwide duct operating pressure, and (3) actual weighted duct operating pressure (weighting to where the leakage actually is occurring). Measured leakage is based on site measurements at known leak sites plus predicted leakage from DSAT for distributed leaks (using actual systemwide pressure).

2-2	91.2	91.2	91.1	122.7	0	0	0	
2-3	77.0	57.4	67.5	135.5	143.2	123.5	133.7	165.2

ation was 17.2% for actual weighted duct pressure and 20.4% for actual systemwide duct pressure. When the 152P methods of measuring operating pressure are used (pressure pan and plenum/2), then the average absolute deviation is 30.8%.

Calculating Duct Leakage with the Hybrid HPT Method

The hybrid HPT was performed and duct leakage calculations were carried out. Table 9 presents the results of the hybrid HPT for the various duct pressure measurement approaches.

The hybrid HPT tends to underpredict supply duct leakage rather consistently by about 25% to 30% and predicts return leakage poorly as well. For the ten duct leaks, the average absolute deviation was 24.8% for actual weighted and 28.9% for actual systemwide pressure. When the 152P methods of measuring operating pressure were used, the average absolute deviation was 63.5%.

TABLE 10

Average absolute deviation of predicted duct leakage from measured data for the ten largest created duct leaks (expressed as percent of measured duct leakage). In the first column, supply leaks are predicted based on pressure pan method (average of all registers) and return leaks are predicted based on the ret_plen/2, plenum pressure, or midpoint pressure depending upon the test method.

	Standard *dP* Method	Actual *dP* Systemwide	Actual *dP* Weighted
DSAT	61.4%	32.6%	8.2%
HPT	32.3%	26.6%	33.3%
hybrid DSAT	30.8%	17.1%	11.7%
hybrid HPT	63.5%	28.9%	24.8%

SUMMARY AND CONCLUSIONS

Two methods of duct air leakage estimation are contained in proposed ASHRAE standard 152P, the DSAT and the HPT. Andrews (1998) has also proposed two hybrid test methods, hybrid DSAT and hybrid HPT.

Based on data from two houses, the DSAT method works well if the duct operating pressures are accurately characterized (Table 10). Note that in Table 10, the numbers are percent deviation from best estimate "measured data," that is, the difference of predicted from measured divided by the measured, averaged for all ten created leaks.

- The standard DSAT, when using the pressure pan pressure measurement, yields an average 61.4% deviation from measured. This very poor result seems to be related to two factors: (1) the pressure pan does not accurately characterize duct system operating pressure, and (2) because of concentrated leaks, the pressures at the leak sites deviate from systemwide pressures.
- The standard DSAT when combined with best-estimate systemwide pressure also predicts poorly, on average, with an average deviation of 32.6%. This large deviation occurs, the authors believe, because the created duct leaks are concentrated so that in many cases 80% to 90% of the total Q_{25} is concentrated in one location and the duct operating pressure at the concentrated leak location is different from the systemwide pressure.
- If the duct operating pressure is weighted to account for the concentration of the leakage, prediction improves substantially. The standard DSAT, when using the actual weighted pressure, predicts the duct air leakage to within 8.2% average deviation from measured. This is a reasonably good result. One of the ten leaks (configuration 1-2 supply leak) accounts for a large portion of the deviation. The prediction at this leak site has a deviation of 29.6% from measured. This configuration has the smallest created duct leak and, therefore, the greatest potential for prediction error. Excluding this leak, the average deviation from measured using actual weighted pressure is 5.8%. In another study of two houses, the standard DSAT with actual weighted pressure predicted with average deviation of 6.0% (Cummings and Withers 1999).
- The HPT method does not work reliably, regardless of which duct operating pressure is used. The HPT predicts no better than 27% average deviation from measured.
- The hybrid DSAT, which is simpler and quicker compared to the standard DSAT, predicts less accurately than the standard DSAT but more accurately than the HPT. It has an average deviation from measured of 11.7% when using actual weighted pressure and 17.1% when using actual systemwide pressure. Use of Stan-

dard 152P pressure measurement methods causes a 30.8% deviation from measured. In another study of two houses, the standard DSAT with actual weighted pressure predicted with an average deviation of 28.3% (Cummings and Withers 1999), suggesting that the hybrid DSAT may not consistently perform as well as the 11.7% deviation found in this study.

- The hybrid HPT can be considered unreliable. Using actual weighted pressure, it is predicts more accurately than the standard HPT, 24.8% versus 33.3%, but with the other pressure measurement methods its prediction is worse than the standard HPT.

In general, the various test methods do not predict duct leakage accurately. Predicted duct leakage deviates by 25% or more for most test methods. Some of the deviation is the result of inaccurate characterization of duct operating pressure. With the standard DSAT, the prediction becomes more accurate the closer the pressure measurement comes to reality (actual weighted pressure). With the hybrid DSAT, actual weighted pressure appears to improve prediction accuracy. With the standard and hybrid HPT, the relationship to pressure is not clear. For the standard HPT, the greatest deviation from measured leakage occurs with actual weighted pressure. For the hybrid HPT, actual weighted pressure yields the best accuracy, but even this has an average deviation of 25%.

Two major conclusions come from this study:

1. The standard and hybrid duct leakage test methods do not provide reliable results. The standard DSAT shows significant promise, however, when duct operating pressure is accurately characterized. Accurate duct operating pressure, however, is not easily obtained, especially when leakage is concentrated.

2. The measurement of normal air distribution system operating pressure is crucial—and is no trivial task. The method for measuring supply pressures in the proposed standard is placement of a pressure pan over registers with the air handler operating. This method is fast, but it does not reliably characterize duct operating pressure. In house 1, it overestimates by 87% and in house 2 it underestimates by 10%. In other research, it has been found to overestimate duct operating pressure (see Francisco and Palmiter 1999 and Cummings and Withers 1999). The 152P method for determining return pressures seriously underestimates duct operating pressure for the two houses in this study, which have central return grille configurations. Because duct operating pressure is critical to accurate estimation of duct leakage air flow rates, it is imperative that improved methods be developed to accurately characterize duct pressure.

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REFERENCES

Andrews, J. 1998. *Two new duct leakage tests.* Brookhaven National Laboratory, March 26.

ASHRAE. 1999. *ASHRAE Standard 152P, Method of test for determinating the design and seasonal efficiencies of residential thermal distribution systems.* Advanced Working Draft, 99/1. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Cummings, J.B., C.R. Withers, and N. Moyer. 1999. *Field research to verify duct air leakage measurements and distribution efficiency computations of ASHRAE Standard 152P.* Florida Solar Energy Center, July.

Cummings, J.B., and C.R. Withers. 1999. *Assessment of the duct leakage estimation procedures of the standard and alternative test methodologies of ASHRAE 152P.* Florida Solar Energy Center, December.

Francisco, P.W., and L. Palmiter. 1999. *Field validation of ASHRAE Standard 152,* Final report. Ecotope, October 5.