Field Comparison of Design and Diagnostic Pathways for Duct Efficiency Evaluation

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A new method of test for residential thermal distribution efficiency is currently being developed under the auspices of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). This test method will have three main approaches, or ''pathways,'' designated Design, Diagnostic, and Research. The Design Pathway uses builder's information to predict thermal distribution efficiency in new construction. The Diagnostic Pathway uses air-flow, temperature, and pressure-difference tests—intended to take one to four hours—to evaluate thermal distribution efficiency in a completed house. For forced-air systems, three distinct techniques are being considered, one based on thermal inputs and outputs in the duct system, the second based on pressure and leakage-area measurements, and the third based on pressure differentials induced in the house by partial blockage of the return duct. This paper presents and discusses the results of Design Pathway calculations based on measured duct-system and floor-plan layouts and surface areas (in lieu of building plans) for fifteen residential duct systems in Long Island, New York. These are compared with measured Diagnostic Pathway efficiencies in eight of these homes.

INTRODUCTION

A new method of test for residential thermal distribution efficiency is being developed under the auspices of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). Titled ''Method of Test for Steady-State and Seasonal Efficiency of Residential Thermal Distribution Systems,'' its ASHRAE numerical designation will be Standard 152. A draft version of the standard has been prepared by the ASHRAE committee responsible for its development. This paper reports some results of field measurements on forced-air heating systems carried out in accordance with this draft; because of this focus, the standard will be treated here as referring to ''ducts'' and ''heat'' even though it includes hydronic systems and air conditioning.

Background

An extensive literature on energy losses in residential duct systems has grown over the past decade. It indicates that these systems typically lose 25% to 40% of the thermal energy delivered to them by the space conditioning equipment. Much of this literature is discussed and analyzed in Andrews and Modera 1992, and will not be further reviewed here. More recent studies (Andrews, Krajewski, and Strasser 1996; Palmiter and Francisco 1994; Proctor and Pernick 1992) have been consistent with older data. It is important to note that ASHRAE's decision to develop Standard 152 was based on solid evidence that duct energy losses are a national problem.

The draft standard currently being used by the ASHRAE committee is divided into three main approaches, or ''pathways,'' designated Design, Diagnostic, and Research. The Design Pathway uses builder's information to predict the efficiency of a duct system that has yet to be built. The Diagnostic Pathway uses calibrated fans (blower door and duct blower), temperature measurements, and pressure-difference tests to evaluate duct efficiency in a completed house. The Research Pathway uses electric coheating to evaluate generic types of distribution systems and to validate the other two pathways. Because of certain issues associated with the coheating technique, its inclusion in the standard will probably be delayed. It is also possible that the ''pathway'' nomenclature may be changed in the version of the standard that goes out for public review.

The main outputs from Standard 152 will be two figures of merit called delivery efficiency and distribution efficiency (Modera, Andrews, and Kweller 1992; Andrews 1994) *Delivery efficiency* is the ratio of heat delivered through the registers to heat sent into the ducts by the furnace or heat pump. *Distribution efficiency* is a somewhat more complicated ratio, of which the numerator is the purchased energy (fuel + electric) that would be needed to heat the house if its distribution system had no energy losses and no effects on the equipment or building shell, and the denominator is the purchased energy needed with the actual distribution system. Distribution efficiency accounts not only for direct energy losses but also for system interactions between the duct system and the rest of the building, including the heating equipment.

Because duct efficiencies are affected by the outdoor temperature, the draft standard specifies that they are to be determined for two outdoor-temperature conditions, the ASHRAE 99% design temperature and a seasonal-average temperature. The standard thus will report design and seasonal delivery and distribution efficiencies (four quantities). Note that the use of ‘‘design’’ in design efficiency refers to severity of outdoor temperature, while in Design Pathway it refers to the fact that the building has not yet been built. The rest of this section briefly describes the Design and Diagnostic Pathways. Complete prescriptions may be found in the draft standard (ASHRAE 1995, 1996).

Design Pathway. The Design Pathway is intended to provide a way to predict thermal distribution efficiency as a function of design choices and environmental conditions that can be summarized in a small number of parameters. It will give builders a tool that will help them choose efficient duct systems. It calculates delivery efficiency by means of a formula embodying derived quantities that account for conductive heat loss from the return and supply ducts and duct leakage as a fraction of total air flow. The delivery efficiency is then converted to distribution efficiency by using two sets of factors. One set represents interactions between the ducts and the conditioned space, including the impact of duct leakage on air infiltration, thermosyphon effects, losses due to thermal storage under cycling conditions, and regain of heat lost to the space surrounding the ducts. The last of these may be included in the delivery efficiency in the final version of the standard. The other set of factors represents interactions between the ducts and the equipment, including duct resistance to air flow and the impact of duct losses on the efficiency of variable-capacity equipment.

Diagnostic Pathway. In contrast to the Design Pathway, which is for homes that have yet to be built, the Diagnostic Pathway is intended to determine whether an existing duct system should be repaired. The Diagnostic Pathway relies on measurements to evaluate the duct system’s efficiency, but it is understood that the time and labor requirements for these tests must be kept low. For the Diagnostic Pathway, three different ways to measure delivery efficiency are being considered. Two of these, designated Level 1 tests (Method A and Method B) were expected to require about four hours for a two-person team to complete, while the third test, designated Level 2, was expected to require only about 45 minutes.

Method A evaluates delivery efficiency by directly measuring heat input and output. The heat input to the duct system is equated to the output of the heating equipment. This can be measured in one of two ways. First, the air flow through the equipment and the temperature difference between the return and supply plenums are measured under conditions as near as possible to steady state; the duct heat input is then the product of air flow rate, temperature difference, air density and specific heat. For furnaces, a second measure of heat into the ducts is the product of fuel input and steady-state efficiency. Method A evaluates the heat output from the ducts by measuring the flow rates and temperatures of air passing through all return and supply registers. The net heat flow through any register is the product of the air flow rate, density, specific heat, and temperature difference between the register air and the conditioned space. Net heat flow from the ducts is then set equal to the sum of heat flows from the supply registers minus the sum of heat flows into the return registers.

Method B measures duct leakage using a small calibrated fan (duct blower) to pressurize the ducts to 25 pascals. At the same time, a full-size blower door pressurizes the conditioned space to the same value. This ensures that duct leaks within the conditioned space (which do not detract from efficiency) are not included in the measurement. The duct leakage rate at 25 pascals is used to estimate the leakage under normal operating pressures by assuming the usual proportionality between leakage flow rate and pressure difference to the 0.6 power. These leakage flows, together with the directly measured system fan flow, are then substituted into the formulas of the Design Pathway to obtain the design and seasonal delivery efficiencies.

The Level 2 method replaces the duct-pressurization test of Method B by a faster technique that measures the pressure difference between the conditioned space and the attic under a variety of controlled conditions. The envelope flow coefficient, measured with a blower door, is also needed. Direct measurement of system fan flow is replaced by inference from manufacturer’s data on the fan coupled with a measured pressure difference across the fan. The remainder of the Level 2 procedure uses the Design Pathway methodology in the same way as Method B.

All three Diagnostic Pathway methods convert delivery efficiency to distribution efficiency in the same way as is done in the Design Pathway, but using observed rather than specified values for the relevant parameters.

Scope

Although the scope of Standard 152 will include both air conditioning and hydronic systems, this paper concentrates on the portion of the standard dealing with forced-air heating. Further restricting the scope, it addresses only the Design and Diagnostic Pathways. Dimensional measurements were taken on 14 homes in Long Island, New York during the late summer and the fall of 1995. One of the homes had separate duct systems upstairs and downstairs and is treated as two separate entities. The final sample therefore has 15 entries.

Of these 15 systems, 7 used gas as the heating fuel, 6 used oil, and 2 used electric heat pumps. This breakdown is statistically consistent with an unpublished study of warm-air heating systems in the local utility's service area, which would have predicted 9 gas, 5 oil, and 1 heat pump. Nine of the homes had ducts primarily in the basement, three in the attic, two in the conditioned space, and one between floors in a condominium apartment complex. Eleven of the duct systems served heated floor areas between 100 and 200 m^2, while 3 had less floor area and one had more. The average floor area was 136 m^2. All but three of the homes were single-family detached.

The primary intent of this study was to exercise the draft standard for consistency between approaches, sensitivity to variations of input parameters, and ease of use. Design Pathway results are presented for the 15 systems, with Diagnostic Pathway data currently available on 8 of these.

METHODOLOGY

The sample of homes was obtained through reader responses to an article about earlier work on duct efficiency. An initial visit to each home was made to discuss the purposes of the project, answer homeowners' questions about duct efficiency, measure the duct system, and sketch the layout of rooms and registers. Relevant information about the heating plant was also collected from the nameplate. These data were intended to serve as a proxy for the information available from a complete set of building plans. The time for this visit by one person averaged 2 hours.

The second stage of the project was to perform Diagnostic Pathway measurements on these homes. A third stage of the project will perform Research Pathway tests on some of these same houses. The discussion below details the methodology used to implement the Design and Diagnostic Pathways.

Design Pathway

The following information was gathered or calculated from the living-space and duct layouts measured and sketched during the initial two-hour visit:

- Heated floor area.
- Return and supply duct surface area: both total area and also broken down by duct environment (e.g. conditioned space, attic, basement, exterior wall, etc.).
- Return and supply duct insulation levels, determined by observation (generally uninsulated or standard duct wrap).
- Nameplate thermal output of the heating equipment.
- In homes with ducts in a basement, insulation condition of the basement ceiling (and exterior walls, if known).

The one area where some deviation from the draft standard was required was with respect to system air-flow rate and temperature rise across the equipment. The draft standard specifies that the flow rate shall be either 100% or 90% of the value specified by the equipment manufacturer, the percentage depending on whether or not the duct system was designed according to Manual D of the Air Conditioning Contractors of America (ACCA).. In most cases, this information was not available. The following convention was used instead. The temperature rise across the equipment was assumed to equal 40 K for furnaces and 17 K for heat pumps. The fan flow rate was then determined from the equipment's thermal output rate, obtained either from the nameplate or by locating the model number in an industry directory.

For duct leakage, the draft standard provides a choice between specifying an acceptable level of leakage and requiring a post-construction test or, alternatively, of using a default value (as percent of total flow) that currently is set at 20% of total flow in the supply and 20% of total flow in the return. The author chose to use the default values because using actual measured leakage flows did not seem to represent a fair test of a design pathway (whose user would not have access to such data). Also, it was important to find out how duct efficiencies using these defaults would compare with the results of Diagnostic Pathway tests.

For supply- and return-duct surface areas, the draft standard gives a choice between using actual values if available from the building plans or, alternatively, of using an algorithm to predict them from heated floor area and the number of registers. Although the measured duct areas (simulating complete plans) were used in the Design Pathway efficiency calculations, a separate comparison of measured and calculated duct areas and resulting efficiencies was carried out. These comparisons are discussed in the Results section.

The design and seasonal values of temperatures surrounding the ducts were calculated as prescribed in the draft standard, using an ASHRAE 99% design temperature of −14°C for a nearby Long Island location. For ducts in an uninsulated basement, the design and seasonal ''duct-ambient'' temperatures specified by the draft standard were 10°C and 11°C, respectively. If the basement ceiling is insulated, these values dropped to 5°C and 6°C. For attic ducts, the prescribed design and seasonal values for Long Island were −14°C and 3°C, respectively.

To obtain distribution efficiency, it is necessary to account for system interactions. For the systems studied here, the most important interactions were changes in the air infiltration rate caused by duct leakage and the effective regain of 25% to 50% of the heat lost from ducts in a basement.

Diagnostic Pathway, Method A. The primary in-the-field effort required for this method was to measure the temperature and flow rate of air passing through the registers. Air-flow rates were measured (with the fan on but the burner or compressor off) by means of a duct blower attached to an open-ended box, with the open end held against the register opening. By adjusting the speed of the duct blower, the pressure difference between the room and the space in the box enclosing the register could be brought to zero, at which point the flow through the duct blower (read from its calibration chart) was judged to equal the flow through the register under normal operation. The alternative is to use a calibrated flow hood. The argument against the flow hood is that its accuracy is questionable at the low flow rates (usually less than 0.1 m^3/s) typically found in supply registers. The duct blower was used primarily, supplemented in some cases with the flow hood.

The energy input to the ducts was measured using the two different methods mentioned in the Introduction. The first method requires measurement of the air flow rate through the system fan and also the temperature rise through the equipment under steady-state conditions. The fan-flow rate was measured by blocking off the return plenum and then, with the system fan on but not the burner or compressor, using a duct blower to replicate in the supply ducts the pressure regime (relative to the conditioned space) that existed under normal operation. The air flow through the duct blower should then be equal to the system air flow under normal operation. For the second method, with a gas furnace, the fuel input rate was measured using a stopwatch to time the fastest-moving dial on the gas meter. Gas volume is converted to energy units using energy density data from a recent utility bill. For oil-heat systems, a small meter was temporarily installed in the burner fuel line between the pump and the nozzle.

Finally, Method A requires an algorithm to convert duct efficiencies obtained under environmental temperature conditions at the time of the test to those expected for the design and seasonal-average temperatures. At the time of writing, the draft standard still lacked this algorithm, so a provisional correction procedure was used, which resulted in seasonal distribution efficiencies 4% to 8% lower than the raw values obtained from Method A in the draft standard.

The Method A tests were sufficiently time-consuming that we were unable to complete our entire protocol in a single working day. For various reasons, the developers of the Diagnostic Pathway elected, during the winter of 1996, to delete Method A pending further refinement. Both of these factors led us to discontinue the Method A tests after the first three homes.

Diagnostic Pathway, Method B. The main on-site effort here involved measuring the air leakage from the supply and return duct systems with all registers sealed. Using a blower door to pressurize the house while a duct blower pressurized the ducts, the pressure in the living space was made equal to that in the ducts. Thus, the duct leakage rate measured with the duct blower was that to the outside (including the basement). Leakage rates in the return and supply ducts were measured separately. These leakage rates, combined with values for the average pressure within the duct system under normal operation, enable the duct leakage under actual operating conditions to be estimated. System fan flow rate is measured in the same way as in Method A.

The draft standard specified that operating pressures in the return and supply ducts are to be obtained by averaging the pressure differences across a temporary barrier (pressure pan) placed over each register in turn. This appeared to work well on the supply side, where there are usually enough registers that covering one should not perturb the system so much as to invalidate the method. In one house that had only 6 supply registers, the average pressure-pan reading was significantly higher than the pressure in the supply plenum under normal operation (41 vs. 28 Pa). This was attributed to the hypothesis that with so few registers, covering one could increase the operating pressure significantly. In this case, therefore, the operating pressure was taken as 28 rather than 41 pascals. Finally, in Houses 2 and 9, the pressure-pan readings were inadvertently omitted, and in these cases it was necessary to fall back on a relationship that appears in the Design Pathway for calculating operating pressure, i.e. $P = (P_{sp} + 12)/2$, where P is the desired operating pressure and P_{sp} is the pressure in the supply plenum.

On the return side, where the number of registers is usually much smaller (one or two for all the houses tested to date), placing a barrier over a register clearly will change the pressure distribution significantly. A later revision of the test method specified that when there is only one return register, the return-duct pressure is to be taken as one-half the pressure in the return plenum. The author followed this procedure in all cases, even when there were two return registers, except for House 4, which had a platform return. In that case it seemed more appropriate to use the pressure measured within the platform and not divide it by two.

As discussed in the Introduction, the remaining factors influencing duct efficiency were calculated the same way they are in the Design Pathway. Use of the Design Pathway methodology for the remaining calculations eliminated the need, encountered in Method A, for an algorithm to convert duct efficiencies from their as-measured values to values under design and seasonal conditions.

Diagnostic Pathway, Level 2. The Level 2 tests were carried out as specified in the draft standard, with the exception that the measured fan-flow rate was used in lieu of a nameplate value. Measurements of the pressure difference between the attic and the conditioned space, under as-found conditions with the system fan off and then with it on, determine the imbalance between supply and return leakage. Following this, the attic-house pressure difference is again measured with the system fan on and the return registers partially blocked. This provides the second equation needed to evaluate the supply and return leakage separately. Operating pressures in the return and supply ducts are also needed in the equations. A pressure pan on one of the supply registers is used to estimate a typical operating pressure in the supply duct. A plastic tube inserted into the return duct ''approximately mid-way between the grille and the plenum'' (ASHRAE 1996, Section 8.4.2) is used to estimate the operating pressure in the return duct. The Level 2 test method relies on multiple measurements of the attic-house pressure difference to improve accuracy. This pressure difference is measured 30 times with the fan off, 20 times with the fan on, and 10 times with the fan on and the return register partially blocked.

RESULTS

Results for the Design Pathway (15 systems) are discussed first. Then Diagnostic Pathway measurements are discussed for the eight houses at which testing has been done.

Design Pathway

The main objectives of the Design Pathway studies were, first, to see whether reasonable duct efficiencies would be obtained; second, to compare the measured duct surface areas with the default values given by the draft standard; and third, to provide a baseline with which the Diagnostic Pathway results could be compared.

Duct Efficiencies. The characteristics of these homes and the resulting values of distribution efficiency, calculated using the Design Pathway, are shown in Table 1. The seasonal distribution efficiencies shown were calculated using the seasonal values for the temperature of the space surrounding the ducts, as discussed above. Figure 1 summarizes these seasonal distribution efficiencies obtained using the Design Pathway.

The mean distribution efficiency was 63.5%. This is within the expected range of 60% to 75% reported in earlier literature (reviewed in Andrews and Modera 1992), although it is somewhat on the low side, especially considering that most of the houses in the sample have their ducts in a basement, for which there is some regain of lost heat. This is, however, in line with the intent of the developers of the Design Pathway, who wanted the results to be somewhat low when default options are used.

Duct Surface Areas. Duct surface area is important because, together with insulation level and temperature difference across the duct walls, it governs the amount of conductive heat loss. Measured surface areas of return and supply ductwork in these houses were compared with the values obtained from the algorithm in the draft standard that computes return- and supply-duct surface areas as fractions of the heated floor area, using as inputs the number of stories of the house, the type of duct material, and the number of registers. Figures 2 and 3 show scatterplot comparisons of the calculated and measured surface areas of the return and supply ducts, respectively. Ideally, the calculated values should represent duct surface areas outside the conditioned space (and not total duct areas) because these are what the Design Pathway needs as inputs. For the measured values, both the total duct surface area and the surface area outside the conditioned space are shown.

The average calculated return duct area was 15.1 m^2, while the average measured value was 15.6 m^2, of which 11.4 m^2 was outside the conditioned space. The average calculated supply duct area was 49.4 m^2, while the average measured value was 41.5 m^2, of which 36.3 m^2 was outside the conditioned space. Although the calculated duct surface areas agreed fairly well with the measured total surface areas, the surface areas outside the conditioned space, which are germane to heat-loss calculations, were on average significantly less. At the time of writing, there was no provision in the algorithm for giving credit in cases where a significant portion of the ductwork is within the conditioned space.

Perhaps the most important question here is what effect the differences between the measured and calculated duct surface areas had on the calculated duct efficiencies. Figure 4 shows a scatterplot comparison of the seasonal distribution efficiency determined using the calculated duct area vs. the same efficiency using the measured duct area outside the conditioned space. The dashed line shows where the two values are equal.

Eleven of the pairs of values lie within 3 percentage points of the line of equal values, and all but one lie within 5 percentage points of this line. In all but three cases, the difference was in the direction of the algorithm producing a lower efficiency than the measured duct surface areas, again in accord with the desire to encourage as much use of real (as opposed to default) values as possible.

The single outlier was House 13. For this house, the algorithm predicted a much larger supply duct surface area than

Table 1. *House Data and Design-Pathway Seasonal Distribution Efficiencies*

House Number, Type, and Number of Stories	Heated Area (m2)	Heating Fuel	Duct Location	Duct Material (Bold if Supply Ducts Insulated)	Distribution Efficiency
1. SFD (2)	104	Gas	Bsmt.	Sheet Metal	0.66
2. SFD (1)	167	HP	Bsmt.	**Sheet Metal + Flex**	0.54
3. SFA (1)	149	Gas	Attic	**Sheet Metal + Flex**	0.57
4. SFA (2)	101	HP	Note 3	Unknown	0.68
5. Apt. (1)	67	Gas	Note 3	Sheet Metal	0.63
6d. SFD (2)	119	Oil	Bsmt.	**Sheet Metal + Flex**	0.63
6u. SFD (2)	92	Oil	Attic	**Flex**	0.60
7. SFD (2)	121	Gas	Attic	**Sheet Metal + Flex**	0.52
9. SFD (1)	140	Oil	Bsmt.	**Sheet Metal + Flex**	0.66
10. SFD (2)	242	Oil	Bsmt.	Sheet Metal	0.57
11. SFD (2)	139	Gas	Bsmt.	Sheet Metal	0.71
12. SFD (2)	197	Oil	Bsmt/ Attic	Sheet Metal (Partly Insulated)	0.64
13. SFD (2)	191	Oil	Note 3	Sheet Metal	0.69
14. SFD (1)	68	Gas	Bsmt.	**Sheet Metal**	0.74
15. SFD (1)	137	Gas	Note 3	**Sheet Metal**	0.68

Note 1: SFD and SFA = Single family detached and attached, respectively. House 5 is a garden-apartment condo unit. House 6u and 6d are upstairs and downstairs duct systems.
Note 2: Under Heating Fuels, HP = Electric heat pump.
Note 3: Bsmt. = Basement; house 5 had its ducts in the ceiling space between it and the unit directly above it in the condominium complex; houses 4 and 13 had >50% of ducts in the conditioned space; house 15 ducts are in a partial basement and in a slab.

actually is in the house. In addition, much of the duct area that does exist is within the conditioned space. The distribution efficiencies obtained from the diagnostic pathway for this house were greater even than the design-pathway efficiency using measured duct areas, and much greater than that obtained using the calculated duct areas. As mentioned above, at present there is no credit in the duct-area algorithm for ducts being in the conditioned space. Even using the measured duct area, there is no credit for the reduced leakage to the outside that ducts in the conditioned space should bring with them, unless a duct test is specified.

Diagnostic Pathway

The discussion of results begins with general cross-comparisons between the different techniques. It then proceeds to a brief consideration of uncertainties in measurement.

Energy Input to Ducts. For three houses, values could be compared for the energy delivered to the ducts as obtained from (1) fan flow and temperature difference across the equipment, and (2) fuel input rate and flue-gas efficiency measurements. For House 1 these were 20.6 kW and 22.4

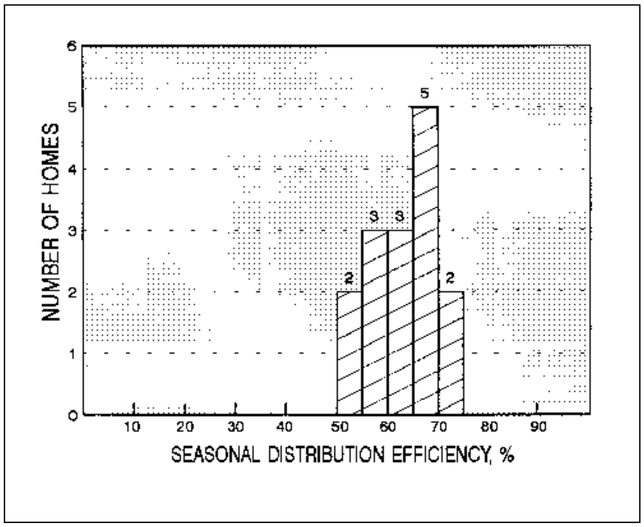

Figure 1. *Seasonal Distribution Efficiencies Predicted by the Design Pathway*

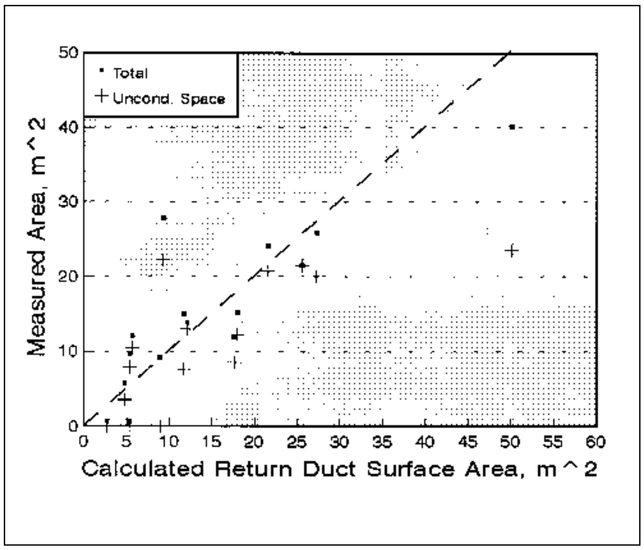

Figure 2. *Return-Duct Surface Areas*

kW, respectively. For House 9 they were 27.0 kW and 28.9 kW. For House 13 they were 17.3 kW and 16.7 kW. These values differ on average by 6%.

Duct Leakage. Values for duct leakage obtained using various methods are shown in Tables 2 and 3 for return and supply ducts, respectively. Examining these tables, one first notices the negative values for the Method A (input-output) results for Houses 1 and 14. In these houses, the sum of the measured air flows through all the supply registers exceeded the measured air flow at the system fan. The same was true for the total return-register flows. Setting Method A aside for the moment, agreement between the other two test methods can be summarized as follows. For the sixteen measure-

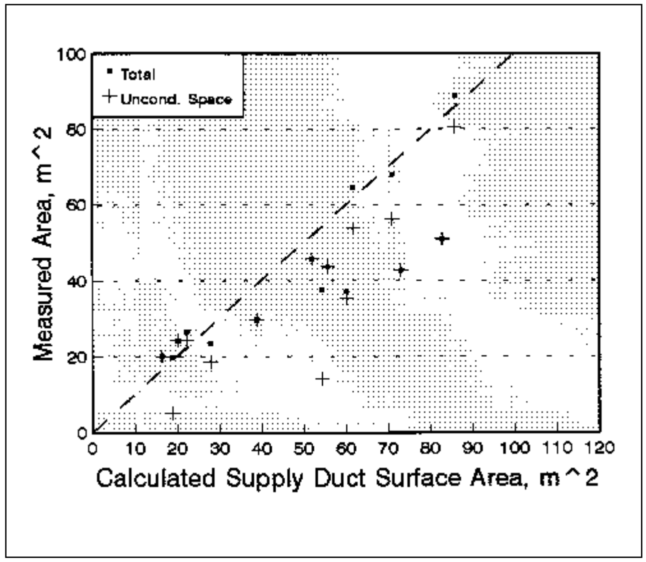

Figure 3. *Supply-Duct Surface Areas*

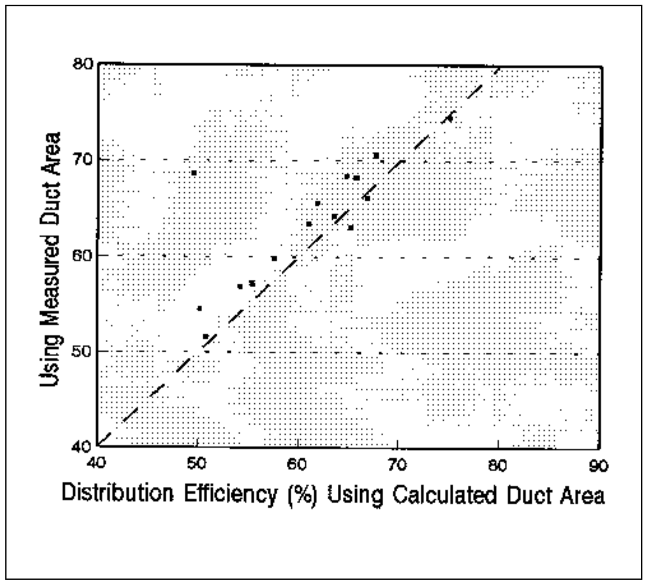

Figure 4. *Efficiencies Using Calculated and Measured Duct Areas*

ments (supply and return leakage in 8 houses), the average discrepancy between Method B and the Level 2 test method was 7% of system fan flow.

Duct Efficiencies. The final comparison was between the bottom-line figure of merit as determined by each of the methods, namely the seasonal distribution efficiency. Table 4 gives the values obtained for this quantity by each of the four procedures. Of all the numbers calculated under the test method, this is the one that should correlate most closely with annual energy use. Ideally, the three diagnostic values should be nearly the same for all the houses, with the design

Table 2. Comparison of Return Duct Leakage Rates (m3/s and % of System Fan Flow)

House / Method	1	2***	3	4	9***	13	14***	15
Input-Output (Method A)	<0	Not Avail.	Not Avail.	Not Avail.	0.162 (30%)	Not Avail.	<0	Not Avail.
Pressurization Tests (Method B)	0.046 (11%)	0.085 (13%)	0.012 (2%)	0.022 (7%)	0.155 (29%)	0.000 (0%)	0.114 (27%)	0.071 (16%)
Level 2 Tests on House-Attic P's	0.114 (26%)	0.109 (17%)	0.002 (0%)	0.059 (20%)	0.260 (48%)	0.000 (0%)	0.101 (24%)	0.101 (23%)

Note: Each entry gives leakage from outside to return duct for a given house and measurement technique. Compare with Design Pathway default value at 20% of system fan flow. In houses marked *** a modified return-pressure measurement was needed in the Level 2 tests (see text).

Table 3. Comparison of Supply Duct Leakage Rates (m3/s and % of System Fan Flow)

House / Method	1	2***	3	4	9***	13	14***	15
Input-Output (Method A)	<0	Not Avail.	Not Avail.	Not Avail.	0.112 (21%)	Not Avail.	<0	Not Avail.
Pressurization Tests (Method B)	0.083 (19%)	0.134 (21%)	0.109 (16%)	0.048 (16%)	0.146 (27%)	0.038 (7%)	0.061 (14%)	0.052 (12%)
Level 2 Tests on House-Attic ΔP's	0.086 (20%)	0.033 (5%)	0.131 (19%)	0.022 (7%)	0.131 (24%)	0.020 (4%)	0.043 (10%)	0.097 (22%)

Note: Each entry gives leakage from supply duct to outside for a given house and measurement technique. Compare with Design Pathway default value at 20% of system fan flow. In houses marked *** a modified return-pressure measurement was needed in the Level 2 tests (see text).

value perhaps somewhat lower. For this sample of houses, the average discrepancy between the seasonal distribution efficiency measured using Method B and that obtained from the Level 2 test method was 5 percentage points, with Level 2 averaging 2.5 percentage points higher than Method B. The Design Pathway efficiency averaged 3 percentage points lower than the mean of Method B and Level 2.

Measurement Uncertainties. Method A depends on a subtraction of two energy rates, each of which depends on an air-flow measurement. Moreover, the two air flows (registers and system fan) are measured using different techniques. This may give rise to large percentage uncertainties. In two out of three houses, we obtained unphysical results, namely that the total air flow through the supply registers, as measured using the duct-blower technique, exceeded the measured flow at the system fan.

The second difficult thing to measure in Method A has been steady-state temperatures at the supply plenum. The temperature difference between the return plenum and the supply plenum may still be climbing slowly after 15 minutes of continuous burner ontime, even when a thermocouple has been in the supply plenum continuously the whole time.

Table 4. *Comparison of Seasonal Distribution Efficiencies (%)*

Method / House	1	2	3	4	9	13	14	15
Input-Output (Method A)	69	Not Avail.	Not Avail.	Not Avail.	59	Not Avail.	80	Not Avail.
Pressurization Tests (Method B)	66	53	62	73	60	76	78	70
Level 2 Tests on House-Attic ΔP's	68	66	58	82	59	78	81	67
Design Pathway	66	54	57	68	66	69	74	68

This again can have a significant effect on the accuracy of Method A.

In favor of Method A is the fact that it includes in a measurement what Method B and Level 2 calculate in part from theory, namely the portion of the duct heat losses caused by conduction through the duct walls.

The Method B tests were straightforward, although taping over the registers (required in this method) is time-consuming. Method B has the merit that errors in measured duct leakage should not have as much effect on duct efficiency as similar percentage errors in flow rate in Method A.

The Level 2 test was quick and easy to do. The results presented here cannot determine whether it is sufficiently accurate to use in Standard 152. Early sensitivity studies have identified the pressure in the return duct as a variable whose correct measurement is of particular importance.
In fact, for three of the houses in this sample, use of the raw return-duct pressures produced unphysical results, namely air leakage *into* the supply ducts. We diagnosed the problem as resulting from the measurement point not being sufficiently close to the midpoint of the return duct. It can be very difficult to ascertain, when pushing a pressure-measurement hose into a duct, just how far its open end has actually gone. Where the return duct follows a circuitous path, it can be virtually impossible to position it accurately. To deal with these cases, we established a proviso that the return duct pressure used in the calculation could not be less than half the pressure difference between the return plenum and the conditioned space. For the three houses that had this problem, this procedure produced duct leakages with the correct sign and average differences between Level 2 and Method B that were comparable to those for the other five houses. The author concluded from the sensitivity studies and from the experience in these houses that appropriate specification of the return-pressure measurement is critical to the success of the Level 2 procedure.

CONCLUSIONS

Although the data so far do not warrant many firm conclusions, the following can be said:

- The Design Pathway gave seasonal distribution efficiency values that fell in the expected range and peaked in the middle.
- Duct surface areas calculated using the Design Pathway default algorithm were consistent with the total duct surface areas measured in this sample of homes. Consideration in the standard should be given to reducing the rated surface areas when efforts are made to place ducts within the conditioned space.
- In the Level 2 test, the method of measuring the pressure in the return duct may need more precise specification.

ACKNOWLEDGMENTS

This research was supported by the Building Equipment Division, Office of Building Technologies, U.S. Department of Energy, for which I am grateful. I thank Yusuf Celebi, Barbara Pierce, and John Strasser for their assistance with the Diagnostic Pathway field tests. I am especially grateful to the owners of the fifteen homes included in the study. Finally, I thank Esher Kweller of the U.S. Department of Energy for encouragement and support that has gone far beyond the usual functions of program management.

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