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Residential Duct System Leakage: Magnitude, Impacts and Potential for Reduction

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ABSTRACT

This paper discusses the issues associated with leakage in residential air distribution systems, touching on the prevalence of duct leakage, the impacts of duct leakage, and on the techniques available for sealing duct systems. The issues examined in detail are: present techniques for measuring the leakage area of ducts, existing data bases of duct leakage area measurements, the impacts of duct leakage on space-conditioning energy consumption and peak demand, and the ventilation impacts of duct leakage. The paper also includes a brief discussion of techniques for sealing duct systems in the field. The results derived from duct leakage area and driving pressure measurements indicate that in regions in which distribution systems pass through unconditioned spaces, air infiltration rates will typically double when the distribution fan is turned on, and that the average annual air infiltration rate is increased by 30 to 70% due to the existence of the distribution system. Estimates based upon a simplified analysis of leakage-induced energy losses also indicate that peak electricity demands due to duct leakage can be as high as 4 kW in Sacramento, California and West Palm Beach, Florida, and that peak loads on the order of 1 to 2 kW are highly likely in these locations. Both peak loads and annual energy impacts are found to be strongly dependent on the location of the return duct, an attic return costing approximately 1500 kWh more energy than a crawlspace return in the two climates examined.

INTRODUCTION

Approximately 50% of the households in the U.S. have central warm air furnaces and air distribution ducts (DOE 1984), which translates into approximately 1 million miles of residential ducts. Given their widespread use, and the fact that they represent the vital link between houses and their space-conditioning plants, the energy and comfort effectiveness of residential duct systems are regularly revisited as a topic of study. Interested parties have included the Gas Research Institute (Orlando 1980), researchers at the National Bureau of Standards and Princeton University (Grot 1981), and Brookhaven National Laboratory (BNL 1984), as well as a special project committee of the American Society of Heating Refrigerating and Air-Conditioning Engineers (SP43 1986), all of whom have reached the same conclusion, that air distribution systems can have a significant impact on residential heating and cooling. In addition, a number of recent studies have measured large changes in building ventilation due to air distribution system operation. Researchers at Oak Ridge National Laboratory, using tracer gas decays, measured an average increase of 80% in the infiltration rate of 31 Tennessee houses due to air distribution system operation (Gammage 1986). Similarly, researchers at the Florida Solar Energy Center (FSEC) measured a tripling of infiltration rates with distribution system operation in nine Florida houses. In a more detailed test in a single house, FSEC measured an infiltration-rate doubling due to distribution-system operation with internal doors open, and a further doubling of that rate obtained by closing the doors between rooms during system operation (Cummings 1986). Both the infiltration rate increases in the Tennessee houses and the initial doubling of the air change rate of the Florida house were attributed to duct system leakage, whereas the second infiltration doubling in the Florida house was attributed to system imbalances due to inadequate return-air pathways, stemming from improper undercutting of internal doors.

Three potential inadequacies are usually identified with residential air distribution systems: heat conduction through the duct surfaces, leakage between the ducts and their surroundings, and improper balancing of supply and return flows. Without minimizing the importance of conduction or imbalances not due to leakage, it will be shown that air leakage alone has enormous impacts on residential energy use and ventilation. This paper attempts to summarize the present state of knowledge concerning air leakage in duct systems. The paper includes detailed examinations of present techniques for measuring duct leakage area, existing data bases of duct leakage area measurements, the impacts of duct leakage on space-conditioning energy consumption and peak demand, and the ventilation impacts of duct leakage. The paper also includes a brief discussion of techniques for sealing duct systems in the field.

DUCT LEAKAGE

For ducts in heated spaces, leaks can cause pressure and temperature imbalances between zones, whereas leaky ducts that pass through unconditioned zones cause increased infiltration heat losses by pressurizing or depressurizing the entire building. Furthermore, leaks from supply ducts to unconditioned zones waste conditioned air during system operation, air which is at temperatures significantly higher than room air in the winter, and enthalpies significantly lower than room air in the summer.

To estimate the magnitude of duct system leakage, several studies that have measured the leakage area from duct systems to unconditioned spaces can be examined. These studies have measured leakage area to unconditioned spaces (as opposed to conditioned spaces) for several reasons, including: 1) leakage to unconditioned spaces has more important implications, 2) techniques for sealing ducts in inaccessible places had not been well developed, and 3) unconditioned-space leakage could be measured simply using the standard blower door used for whole-house leakage measurements. The measured duct leakage results from these studies are presented in terms of Effective Leakage Area (ELA) in Table 1. As will be discussed below, ELA is probably not the most appropriate yardstick for characterizing duct leakage area, however it is presently the standard yardstick for building leakage area characterization (ASHRAE 1985, 1989).

Table 1: Measured Leakage of Residential Duct Systems to Unconditioned Spaces

Sample Houses	Sample Size (-)	Effective Leakage Area Mean (cm^2)	Effective Leakage Area Standard Deviation (cm^2)	Mean Leakage Fraction (%)	Data Source
California Post-1980	26	186	155	21	(Modera 1986)
California Garden Apts.	55	191	77	34	(Modera 1986) (Diamond 1987)
Oregon	12	136	80	11	(Robison 1988)*
Miscellaneous	30	144	N/A	14	(Reinhold 1983)
Texas	40	N/A	N/A	14**	(Caffey 1978)

* Subset of raw data from this study.
** Based upon leakage at 62 Pa.

The results in Table 1 indicate that duct system leakage area represents a significant fraction of whole-house leakage area. As will be shown below, this fraction is made even more significant by the large fan-induced pressures driving air flow through the duct-system leaks. Table 1 also indicates that absolute duct

leakage area is relatively uniform between samples, but that both the absolute and fractional duct leakage are seemingly higher for the California houses.

As the results in Table 1 come from different studies using different measurement techniques, it is worth describing the techniques used in each study, including the merits of each technique and the compatibility of the results from the different techniques. In general, all of the techniques used to obtain the data in Table 1 are based upon measurements very similar to those traditionally used to measure the leakage of a building envelope, namely creating a steady pressure differential across the building envelope and measuring the flow required to maintain that differential. All of the techniques treat the duct system as part of the envelope, thereby measuring only the flow through duct leaks to or from the outside. As the duct system is meant to be at the same pressure as the interior of the house, there shouldn't be any measured flow through leaks between the ducts and the house. This is the fundamental difference between these techniques and the industry-standard leakage measurement procedures for high pressure duct systems (SMACNA 1985). The standard procedure uses a separate fan to pressurize the ducts but not the house, thereby measuring the total leakage of the duct system, both to the house and to the outside. Although it would be ideal to obtain data using both techniques, as this would provide a measure of the internal/external leakage split, the author is not aware of any such studies.

The technique that applies to most of the data in Table 1 determines the leakage of a duct system by subtracting the leakage determined with a standard blower door test with the registers and returns sealed from that measured with all returns and registers open. This technique, which was used in all the reported studies except the Texas study, has flow uncertainty as its largest defect, as the duct leakage flow rate is determined by subtraction of two relatively large flow rates. The major advantages of this technique are the minimal additional equipment requirements (relative to standard envelope leakage measurements), and the relatively high accuracy with which the pressure difference across the ducts is measured.

Two variations of a similar principle were used in the Texas study and in an additional set of measurements made in the Oregon study, namely to reduce flow measurement uncertainty by separately measuring the flow through the duct leaks with a flow hood. In the Oregon study all registers and returns except one were sealed, and the flow hood (a portable rectangular duct fitted with a calibrated bi-directional rotating-vane anemometer) was fitted to the unsealed register. The blower door was then used to create pressure differentials across the envelope of the building, and therefore across the duct leaks to the outside*. The Oregon study used a separate measurement of the pressure differential across the ductwork at a single location deemed to be representative of the average pressure drop across the duct leaks. This separate pressure measurement is needed because of pressure drops across the flow hood and friction in the ductwork.

* It is assumed that a similar technique was used in the Texas study, however the details are not presented in the paper. Also, the Texas study used a device called a "Super-Sucker" rather than a standard blower door, and only included measurements at one pressure differential (62 Pa).

However, due to the likely non-uniformity of the leaks, the flows and the friction in the ducts, the pressure distribution in the duct system is neither uniform nor linearly variable. This non-uniformity of pressure differentials (which can be interpreted as a pressure uncertainty), combined with the non-linearity of duct leaks, is the major shortcoming of this measurement technique. This uncertainty is likely to be highest with very leaky ducts (higher flow rates), implying that the blower-door technique is probably better for leakier ducts, whereas the Oregon technique is likely to be better for tighter duct systems.

As a point of comparison, the results obtained using both the blower-door and flow-hood techniques in 11 houses from the Oregon study were compared. In these 11 houses the blower door gave 136 ± 88 cm^2, whereas the flow hood gave 131 ± 88 cm^2, indicating no apparent bias between the two techniques. On the other hand, an examination of the ratio of flow-hood to blower-door results for these houses, assuming a log-normal distribution, yields an average ratio of 1.11, and a geometric spread factor of 2.0. This geometric spread factor, which can be interpreted as the factor by which 1.11 must be multiplied and divided by to include 68% of all points, indicates that there is a very large scatter between the results obtained with the two techniques.

The alternate Oregon technique has an important advantage over the other techniques, in that it includes separate measurements of supply-side and return-side leakage. By separating the return from the supply side with a plastic sheet at the fan, the flow hood can be used to separately measure the supply and and return flows. As will be shown below, the location of duct leaks has a significant impact on their implications for ventilation and energy use. The measured split between supply and return leakage is presented in Table 2.

Table 2: Measured Split Between Return and Supply Leakage Area in Residential Duct Systems (to Unconditioned Spaces)*

	Pressurization	Depressurization
Sample Size	11	11
Average Supply Leakage Area, ELA (cm^2)	43±24	49±11
Average Return Leakage Area, ELA (cm^2)	75±65	93±91
Average Supply Flow Exponent** (-)	0.80±.16	0.68±.08
Average Return Flow Exponent** (-)	0.74±.15	0.64±.08
Average Return/Supply Ratio (%/%)	57/43	59/41
Average Return/Supply Ratio [%/%] (Assuming Press on Supply, Depress on Return)	64/36	

* Based upon a subset of raw flow-hood data from the Oregon study (Robison 1988).

** The exponent obtained in a power-law fit of the data. The flow behavior of the leaks in the pressure range of interest is completely described by the ELA and flow exponent.

Several observations can be made based upon the results presented in Table 2. First, it is clear that the returns contain a large fraction of the duct leakage. Based upon the fact that returns usually have considerably less surface area (joints, etc.) than the supply ducts, this result is unexpected. However, two possible explanations are: 1) that return ducts typically receive less attention during construction due to the perception that they do not contain conditioned air, and 2) that return ducts normally contain the filter, which is typically not installed in a very airtight manner. The second observation is that depressurization tests seem to give consistently higher leakage values and consistently lower flow exponents. Two possible explanations for the leakage difference between pressurization and depressurization are: 1) that a number of the leaks close on pressurization or open on depressurization (e.g., joints between rectangular ducts which

can flex open under depressurization), and 2) that there is some bias in the measurement procedure, stemming, for example, from the fact that the flow direction through a duct is likely to affect the appropriateness of the point chosen to measure the pressure differential. Either of these two effects could also explain the observed bias between the exponents determined for pressurization and depressurization.

As can be seen in the last two rows of Table 2, the use of pressurization data to characterize supply-side leakage and depressurization data to characterize the return-side leakage has a significant effect on the leakage split determined (Lambert 1988). The choice of this methodology assumes that the first explanation for the pressurization/depressurization bias is the accurate one. As will be seen below, this split is an important parameter in determining the impacts of duct leakage, and therefore resolution of this issue is needed to provide accurate impact estimates.

VENTILATION IMPACTS OF DUCT LEAKAGE

The infiltration and ventilation impacts of duct system leakage are significantly larger than those for building envelope leaks. This is due to the larger pressure differentials driving the flow through duct leaks. These pressure differentials, caused by the normal operation of the distribution-system fan, have been characterized by pressure differential measurements in about a dozen houses. These pressure differentials have been measured either with the static pressure taps of pitot tubes inserted through holes drilled in the ducts (Oregon measurements), or with a static pressure probe designed to be dragged through a duct (California house). The results of pressure measurements made under normal operation of the distribution fans in 11 Oregon houses are presented in Table 3.

Table 3: Measured Pressure Differentials Across Return and Supply Duct Walls During Normal Fan Operation*

Location	Mean Pressure Differential (Pa)	Standard Deviation (Pa)
Supply (Near Fan)	50	22
Supply (Mid-Duct)	25	17
Return (Mid-Duct)	47	22

* Based upon a subset of 11 houses from the Oregon study (Robison 1988).

The results in Table 3 indicate that the pressures across duct leaks are typically on the order of 40 Pa, approximately 10 times larger than the reference pressure of 4 Pa for effective leakage area, which was chosen to be representative of the wind-induced and stack-induced pressures driving infiltration through building envelopes.

Based upon the magnitudes of supply and return duct leakage area in Tables 1 and 2, and on the pressures driving flow through these leaks (see Table 3), the magnitude of duct leakage flows can be determined. By combining these flows with a simplified model of natural infiltration, unbalanced mechanical ventilation, and balanced mechanical ventilation, the ventilation impacts of duct leakage can then be estimated. Finally, using a reasonable estimate for the fractional on-time of the distribution fan, estimates of the average annual ventilation impacts of duct leakage can be made.

Building envelope infiltration, or duct system air flows while the system is not operating, can be determined using the effective leakage area in an equation such as (ASHRAE 1985):

$$Q = L\sqrt{\frac{2\Delta P}{\rho}} \tag{1}$$

where

Q = flow rate (m^3/s),

L = effective leakage area (m^2),

ΔP = pressure difference across the leak (Pa), and

ρ = density of air (kg/m^3).

To make an accurate determination of the flow through duct-system leaks during system operation, because the pressure differential is significantly larger than 4 Pa, the assumption of square-root flow in equation 1 is no longer applicable. Thus, not only the leakage area, but also the the flow exponent is needed to determine the flow at operating pressures. Equation 2 presents the standard power-law description of the flow through building leaks, substituting ELA for the flow coefficient (Modera 1983):

$$Q = L\sqrt{\frac{2\Delta P_{ref}}{\rho}}\left(\frac{\Delta P}{\Delta P_{ref}}\right)^n \tag{2}$$

ΔP_{ref} = reference pressure differential for defining ELA (4 Pa).

To illustrate the importance of using a power-law flow model (Equation 2) rather than an orifice flow model (Equation 1), the flow through 100 cm^2 of duct leakage at 40 Pa is 294 m^3/h with the orifice model, versus 488 m^3/h with the power-law model (using average n = 0.72). Thus, in this typical situation, the orifice model underpredicts the flow by 40%.

To determine the impact of duct leakage on infiltration and ventilation, the effect will be divided into two parts: 1) the contribution of duct leakage to the total leakage of the building envelope (applicable when the system is not in operation), and 2) the interaction between natural infiltration and flows through duct leaks under fan-induced pressure differentials. The first of these terms is relatively straightforward to compute, as to first order the natural infiltration rate scales directly with the leakage area. The second term requires an additional piece of information, the return/supply leakage split, due to the fact that leakage flows on the supply side tend to depressurize the house, whereas leakage flows on the return side tend to pressurize the house. Equation 3, which is normally used to analyze the interaction between natural infiltration and mechanical ventilation systems, can be used to analyze the impacts of duct leakage air flows (Feustel 1986). To do so, the leakage flows must be divided into balanced and unbalanced components, whereby:

$$Q_{vent} = \sqrt{Q_{wind}^2 + Q_{stack}^2 + Q_{unbalanced}^2} + Q_{balanced} \tag{3}$$

where

Q_{vent} = total ventilation rate (m^3/s),

Q_{wind} = wind-induced ventilation rate (m^3/s),

Q_{stack} = stack-induced ventilation rate (m^3/s),

$Q_{balanced}$ = ventilation rate due to balanced leakage in the supply and return (m^3/s), and

$Q_{balanced}$ = ventilation rate due to unbalanced leakage in the supply and return (m^3/s).

To get a more accurate estimate of the ventilation impacts of duct leakage, Equation 3 should be modified to account for the fact that if the return leakage flow is comparable to the distribution fan flow, the supply leakage flow should be corrected to account for the loss of fresh ventilation air before it gets into the house. Equation 4 incorporates this correction by adding one additional parameter:

$$Q_{effvent} = \sqrt{Q_{wind}^2 + Q_{stack}^2 + Q_{unbalanced}^2} + Q_{balanced}\left(1 - \frac{Q_{balanced} + Q_{unbalanced}}{Q_{fan}}\right) \tag{4}$$

where

$Q_{effvent}$ = effective ventilation rate (m^3/s), and

Q_{fan} = air flow rate through the distribution fan (m^3/s).

Table 4 contains estimates of the ventilation impacts of leakage in supply and return ducts, using various assumptions for the split between supply and return leakage. The choice of 0.5 air changes per hour (ach) as the natural infiltration rate is based upon a national average specific infiltration rate of 0.27 $m^3/h\ cm^2$. This climate statistic, which represents the average annual infiltration rate per unit of envelope leakage area, was derived to characterize the driving forces for natural infiltration in U.S. cities (Sherman 1986). Under these assumptions the results in Table 4 correspond to assuming that 15% of the building leakage area is located in the duct system, which is consistent with the measured fractions in Table 1.

Table 4: Estimated Impacts of Duct Leakage on Ventilation Rates during Fan Operation*

Leakage Configuration	Q_{return} (m^3/h)	Q_{supply} (m^3/h)	Q_{vent} Equation 3 (ach)	$Q_{effvent}$ Equation 4↓ (ach)	$\frac{Q_{effvent}}{Q_{natural}}$ Equation 4↓ (-)
100% of leaks in return	800	0	1.9	1.9	3.8
100% of leaks in supply	0	550	1.4	1.4	2.7
50% of nominal leakage in supply (airtight return)	0	275	0.81	0.81	1.6
50%/50% leakage split	400	275	1.2	1.1	2.1
64%/36% leakage split	510	200	1.3	1.2	2.4

* Based upon 180 m^2 floor area houses, with 0.5 ach naturally induced infiltration (i.e., $\sqrt{Q_{wind}^2 + Q_{stack}^2}$=216$m^3/h$) and 140 cm^2 of duct leakage, and using 30 Pa for the driving pressure in the supply ducts, and 50 Pa in the return ducts.

↓ Based upon 1800 m^3/h flow through distribution system fan.

The results in Table 4 indicate significant impacts of duct leakage on ventilation rates during system operation, and also demonstrate the importance of knowing the location of the leaks. The first three configurations are mainly for illustrative purposes, the final two configurations being more likely. The second and third configurations are meant to describe houses with zero-length sealed-cabinet

returns, a system likely to be found in some houses. The second configuration effectively assumes that the mean duct-system leakage values are applicable to all duct systems independent of whether there is a return duct, whereas the third configuration assumes that the measurements in Table 2 are only applicable to houses with leaky returns, and that houses without return ducts have half the total leakage of houses with returns. The actual situation is likely to be somewhere in between these two scenarios. The reader should note that although the third configuration has half the leakage of the others, it still results in a 60% ventilation rate increase. Finally, although the likely doubling of ventilation presented in configurations 4 and 5 seems unbelievably high, it is consistent with the increases observed in Tennessee and Florida (Gammage 1986; Cummings 1986).

To obtain estimates of the overall impacts of duct leakage on annual average ventilation, the last three leakage configurations in Table 4 were applied to two cities, Sacramento CA, and West Palm Beach FL, and the results are presented in Table 5.

Table 5: Estimated Impacts of Duct Leakage on Average Annual Ventilation Rates*

Leakage Configuration	$\overline{Q_{no-duct}}$ (ach)	$\overline{Q_{natural}}$ (ach)	$\overline{Q_{effvent}}$** Equation 4↓ (ach)	$\frac{\overline{Q_{effvent}}}{\overline{Q_{no-duct}}}$ Equation 4↓ (-)
Sacramento 50%/50% leakage Split	0.39	0.46	0.62	1.6
W Palm Beach 50%/50% Leakage Split	0.44	0.52	0.68	1.5
Sacramento 64%/36% Leakage Split	0.39	0.46	0.67	1.7
W Palm Beach 64%/36% Leakage Split	0.44	0.52	0.72	1.6
Sacramento 50% Supply-Only Leakage	0.39	0.42	0.52	1.3
W Palm Beach 50% Supply-Only Leakage	0.44	0.48	0.57	1.3

* Based upon 180 m^2 floor area houses as in Table 4, using the same envelope leakage values (i.e., 800 cm^2 or 4.4 cm^2/m^2), 140 cm^2 of duct leakage, 30 Pa for the driving pressure in the supply ducts, and 50 Pa in the return ducts.

** Assuming 30% average on-time of the distribution system, and no correlation between system operation and natural infiltration.

↓ Based upon 1800 m^3/h flow through distribution system fan.

The results in Table 5 indicate that the existence of normally leaky ducts in a house typically increases the annual average ventilation rate by more than 50%, and that even in the most conservative scenario the existence of the duct system increases ventilation between 30% and 40%.

ENERGY AND PEAK LOAD IMPACTS OF DUCT LEAKAGE

Having determined the supply and return leakage flows, estimating the energy and peak load impacts of duct systems requires additional knowledge about the temperatures of the air being lost from the supply ducts and the air being drawn into the return duct. At the level of detail presented in this report, the peak (rather than the annual average) heating and cooling loads are easier to estimate directly. Namely, picking an outdoor air temperature (and dewpoint for cooling), as well as an attic air temperature for the peak hour, the additional load due to duct system leakage can be estimated directly assuming that the system is operating at capacity during that hour. For the heating season, the peak load can be computed by using:

$$E = (Q_{vent} - Q_{no-duct})(T_{in} - T_{out})\rho c_p + Q_{supply}(T_{supply} - T_{in})\rho c_p - Q_{return}(T_{return-space} - T_{out})\rho c_p \quad (5)$$

For the cooling season, the peak load can be computed by using:

$$E = (Q_{vent} - Q_{no-duct})(h_{out} - h_{in}) + Q_{supply}(h_{in} - h_{supply}) + Q_{return}(h_{return-space} - h_{out}) \quad (6)$$

Table 6 contains estimates of peak heating and cooling loads and demands due to duct systems in Sacramento CA and West Palm Beach FL, based upon Equations 5 and 6, and assuming various duct leakage distributions and return locations.

Table 6: Estimated Increases in Peak Cooling and Heating Loads and Demands due to Duct Leakage*

Leakage Configuration	Cooling		Heating		
	Load (kW)	Demand (kW)	Load (kW)	Resist. Demand (kW)	Heat-Pump Demand (kW)
Sacramento 50%/50% crawl. return	1.6	0.66	4.0	4.0	1.3
W Palm Beach 50%/50% crawl. return	3.7	1.5	3.3	3.3	1.1
Sacramento 50%/50% attic return	5.8	2.3	4.0	4.0	1.3
W Palm Beach 50%/50% attic return	8.4	3.4	3.3	3.3	1.1
W Palm Beach 64%/36% attic return	9.8	3.9	2.8	2.8	0.94
W Palm Beach 50% supply-only leakage	2.6	1.0	2.9	2.9	0.96

* Based upon the houses and flows in Table 5 (ignoring density variations in flows), using summer design dry-bulb and mean coincident wet-bulb, and winter dry-bulb at 2.5% level from ASHRAE Handbook Chapter 24, assuming 65 °C peak summer attic temperature, 15 °C 90% RH cooling supply air, summer indoor condition of 25/18.5 °C DB/WB, summer crawlspace temperature 3 °C cooler than ambient, 45 °C heating supply air, winter indoor temperature of 21 °C, winter attic and crawlspace temperatures 3 °C warmer than ambient, COP of 2.5 for cooling, COP of 3 for heat-pump heating, and 100% efficiency for resistance heating. It should be noted that under peak heating conditions the COP will probably be lower than 3, particularly if the capacity of the system is exceeded, causing electric resistance back-up to come on.

The results in Table 6 indicate that the peak cooling demand and peak heating demand impacts of duct leakage are enormous. For the worst-case leakage configuration in West Palm Beach the summer peak due to duct leakage is almost 4 kW, which, when multiplied by 500,000 residences, would be equivalent to 2 GW of peak generating capacity simply to meet the load due to duct leakage. It should be noted however that most air-conditioners will not be sized to meet this load, implying that the utility will not see all of this peak demand, but rather the air conditioners will not be able to maintain comfort conditions. Similarly, for these same 500,000 houses, the winter peak in Sacramento and West Palm Beach would be between 1.5 and 2 GW for resistance heating, and around 0.5 GW for heat-pump heating. Table 6 also shows a wide variability of duct leakage impacts, indicating the importance of climate and return duct location. Looking at climate first, it is clear that in the hot humid Florida climate the cooling peak impacts are two to three times as large as those in the dry hot Sacramento climate. The effect of return duct location is equally severe, showing an approximate tripling of the summer peak demand when the return is located in the attic compared to when it is located in the crawlspace.

Although an hourly simulation is an appropriate tool for determining the annual energy impacts of duct system leakage, a rough estimate can be obtained by making some broad simplifying assumptions about the operation of the distribution system. Namely, knowing that the fractional on-time of the distribution system is proportional to the load, if it is assumed that the losses from the distribution system are also proportional to the load, then the total energy impact can be estimated by:

$$E = \int (\mathit{fractional\ on-time})^2 E_{\max} dt \tag{7}$$

where

$E_{\max}$ = is the peak energy demand, as quoted in Table 6 (kW).

Splitting the year into heating, cooling and shoulder seasons, the number of heating and cooling hours can be determined from the peak cooling and heating loads, the annual heating and cooling degree days, and an assumed seasonal load shape. Table 7 contains estimates of the total annual energy impacts of duct leakage made by with Equation 7 for the same scenarios as in Table 6, and assuming that load shape is a half sinusoid for both seasons.

Table 7: Estimated Increase in Annual Energy Consumption due to Duct Leakage*

Configuration	Sacramento Consumption		W Palm Beach Consumption	
	Heat Pump (kWh)	Resistance (kWh)	Heat Pump (kWh)	Resistance (kWh)
50%/50% crawl. return	2300	6000	4000	4500
50%/50% attic return	3400	7000	8900	9400
64%/36% attic return	3500	7000	10100	10500
50% supply-only leakage	2000	5000	2700	3200

* Based upon the peak demands in Table 6, assuming sinusoidal variations of the load over heating and cooling seasons in Equation 7, using 1300 cooling hours and 2800 heating hours in Sacramento, and 4900 cooling hours and 500 heating hours in West Palm Beach.

Not surprisingly, the results in Table 7 indicate significant energy impacts of duct leakage, as well as a large range of impacts depending upon the assumed leakage distribution. However, although the trends and the orders of magnitude in Table 7 are probably correct, the numbers are based upon a rather simplified model, and that hourly simulations which take into account building dynamics, occupant behavior, and the operational characteristics of HVAC equipment, should be performed.

DISCUSSION

Given the apparently large impacts of duct system leakage, two questions arise: 1) Why has duct leakage received so little attention in the past? and 2) What can be done to reduce duct leakage? As for the first of these questions, there are a number of reasons, the principal reason being that the magnitude of the problem had not been fully realized in the past. Also, the issue of distribution systems in single-family residences is one that tends to fall between the cracks in most building energy research programs; they are not usually considered as equipment, nor are they really part of the building envelope. Thus, there has been little directed responsibility in the building energy research community for understanding, measuring, and improving the airtightness of residential duct systems. The duct manufacturing industry develops standards for designing airtight duct

systems, however, manufacturers are not normally responsible for the quality of installation, which most likely accounts for a large fraction of duct leakage. In many respects the present situation is similar to that of building-envelope air-tightness a decade ago.

As for the possibilities for reducing duct leakage, there are several, some of which have received at least preliminary examination. Starting with taping, the traditional procedure for sealing duct systems, there are several issues. The biggest advantage of this technique is that it uses off-the-shelf hardware (i.e., duct tape), however there are two drawbacks to using such a technique. The first drawback is the uncertainty about the longevity of the tape seals. The second issue is that of the accessibility of ducts for taping, which, although less of an issue in new construction, is an important issue in retrofit projects. This latter issue was examined to a certain extent in the Oregon study, in which it was found that only about 40% of the leaks could be sealed by taping (Lambert 1988).

One obvious alternative to taping which can provide access to the entire duct system is an internal-access sealing technique. However, the technical alternatives for internal sealing of duct systems generally involve more sophisticated technology. To date the author has briefly examined one technology presently used to immobilize dust inside duct systems. This technique involves fogging the duct system with an air-suspended sealant which should deposit in the duct holes upon exiting, similar in principle to pour-in sealant for automotive radiators. This technology, although it has shown some promise in a preliminary laboratory examination, is in need of further development and testing.

Another potential technique would be to modify existing technologies for performing in-situ internal sealing of pipes. These technologies range from mechanical carts that tape as they roll through gas pipelines (Smith 1983) to flexible plastic liners that expand until they stick to pipe walls. However, both of these technologies would require significant modification to make them applicable to non-circular ducts, elbows, tees, and "Y's".

One additional set of alternatives involves robots that can somehow "see" holes in ducts and seal them, or that seal an entire duct section on command. Such techniques could utilize existing video technology; however, the associated sealing components would require considerable development, and cost reductions for the video components are probably necessary.

On the policy side, there are several issues: prescriptive standards, performance standards, and test standards. In commercial building high-pressure duct systems, various standards already exist, however, analogous standards are virtually nonexistent for residential low-pressure systems. In general, as many of the problems in residences are likely due to poor construction quality, prescriptive standards may not be very effective. On the other hand, although performance standards would be more effective, they could not be promulgated without generally accepted test standards, which do not exist at the present time. Also, performance standards are generally not looked upon favorably by most builders, which will create some resistance to their adoption. There is one data set in this area worth noting (Lambert 1988), which shows a statistically significant difference in duct leakage between houses built to meet the Model Conservation

Standards (MCS) and a group of control houses in the Pacific Northwest. Correcting for differences in floor area, the MCS houses seem to have approximately 50% of the duct leakage of the control houses.

CONCLUSIONS AND RECOMMENDATIONS

The primary conclusion to be drawn from this paper is that leakage in residential air distribution systems is likely to have a large impact on energy consumption, peak utility demands, and ventilation in a significant fraction of the U.S. housing stock. The results obtained from duct leakage area and driving pressure measurements indicate that in regions in which distribution systems pass through unconditioned spaces, air infiltration rates will typically double when the distribution fan is turned on, and that the average annual air infiltration rate is increased by 30 to 70% due to the existence of the distribution system. Analyses also indicate that peak electricity demands due to duct leakage can be as high as 4 kW in hot, humid climates (with return ducts containing 64% of the duct leakage area, and passing through the attic), and that peak loads on the order of 1 to 2 kW are likely in less extreme climates, or with less extreme return duct conditions. Based upon a simplified analysis procedure, duct leakage in Sacramento CA and West Palm Beach FL is calculated to cause 2000 to 10000 kWh/year increases in annual energy consumption, results which should be applicable to most of the sun belt states. Associated with these results are recommendations for a more robust research effort in this area, the development of measurement standards, and the subsequent development of prescriptive and/or performance standards.

The second major conclusion to be drawn from this paper is that the distribution of duct leakage between the supply and return sides can have significant impacts on the implications of duct leakage. This result is highlighted by the observation that return-side leakage represents a surprisingly large fraction of total duct leakage. Both peak loads and annual energy impacts are found to be strongly dependent on the location of the return duct, with an attic return costing from 1000 to 5000 kWh more end-use energy than a crawlspace return. Based upon these observations, research and measurement technique standardization in this area should include (if not focus on) separating supply and return leakage.

Finally, there appear to be a number of duct sealing options worth examining at the present time, in particular the internal-access sealing technologies. Efforts in this area are likely to produce commercially cost-effective techniques which would be usable in retrofit as well as new construction. One note of caution relative to such technologies is that if they are as effective as expected, the results presented in this paper suggest that the ventilation implications of tight duct systems be carefully evaluated before implementing a wide-scale duct sealing policy.

REFERENCES

ASHRAE 1985. *ASHRAE Handbook 1985 Fundamentals*, chapter 22, Atlanta, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc.

ASHRAE 1989. ASHRAE Standard 119, "Air leakage performance for detached single-family residential buildings" Atlanta, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc.

BNL 1984. "Plan for the conduct of research on residential thermal distribution and utilization" Architectural and Building Systems Division, Brookhaven National Laboratory, Upton NY.

Caffey, G. 1978. "Residential air infiltration" *ASHRAE Trans.* Vol. 85, Part 1.

Diamond, R.C. 1987. "Energy use in housing for the elderly: the effects of design, construction, and occupancy" Phd Dissertation, Berkeley, CA, Center for Environmental Design Research, University of California.

Cummings, J.B. 1986. "Central air conditioner impact upon infiltration rates in Florida homes" Cape Canaveral, FL, Florida Solar Energy Center.

DOE/EIA 1984. "Housing characteristics 1982" Washington D.C., Energy Information Administration, DOE/EIA-0314(82), pp. 57.

Feustel, H.E.; Modera, M.P.; and Rosenfeld, A.H. 1986. "Ventilation strategies for different climates," Lawrence Berkeley Laboratory, LBL-20364, *Proceedings of ASHRAE IAQ 86 Conference, Managing Indoor Air for Health and Energy Conservation*, April 20-23, Atlanta.

Gammage, R.B.; Hawthorne, A.R.; and White, D.A. 1986. "Parameters affecting air infiltration and air tightness in thirty-one east Tennessee homes" *Measured Air Leakage of Buildings, ASTM STP 904, H.R. Trechsel and P.L. Lagus, Eds.*, pp. 61-69, Philadelphia, American Society for Testing and Materials.

Grot, R.A.; and Harrje, D.T. 1981. "The transient performance of a forced warm air duct system" *ASHRAE Trans.* Vol. 88, Part 1.

Lambert Engineering 1988. "Field investigation of residential duct leakage", Oregon Department of Energy Contract No. 90023, Bend, OR Lambert Engineering.

Modera M.P.; Sherman M.H.; and Levin P.A. 1983. "A detailed examination of the LBL infiltration model with the mobile infiltration test unit" *ASHRAE Trans.* Vol. 89, Part 2.

Modera, M.P. 1986. "Final report: residential air leakage database compilation", Lawrence Berkeley Laboratory Report LBL-23740.

Orlando, J.A.; and Gamze, M.G. 1980. "Analysis of residential duct losses", Final Report, GRI-79/0037,Gamze-Korobkin-Caloger, Inc., Contract No. 5011-341-0156, Chicago.

Reinhold, C.; and Sonderegger, R.C. 1983. "Component leakage areas in residential buildings", *Proceedings of the Fourth Air Infiltration Centre Conference*, Elm, Switzerland, Sept 26-28, Lawrence Berkeley Laboratory Report LBL-16221.

Robison, D.; and Lambert, L. 1988. "Field investigation of residential heating duct leakage" *Proceedings of 1988 ACEEE Summer Study on Energy Efficiency in Buildings*, Washington D.C., American Council for an Energy Efficient Economy.

SMACNA 1985. "HVAC air duct leakage test manual" Vienna, VA, Sheet Metal and Air Conditioning Contractors National Association, Inc.

Smith, R.B. 1983. "Internal wrapping method and apparatus", U.S. Patent No. 4,415,390, November 15.

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