Field Investigation of Duct System Performance in California Light Commercial Buildings (Round II)

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ABSTRACT

Light commercial buildings, one- and two-story with package roof-top HVAC units, make up approximately 50% (of the number of buildings) of the non-residential building stock in the U.S. Despite this fact little is known about the installed performance of these package roof-top units and their associated ductwork. These simple systems use similar duct materials and construction techniques as residential systems (which are known to be quite leaky). This paper discusses a study to characterize the buildings, quantify the duct leakage, and analyze the performance of the ductwork in these types of buildings.

Over the 1996 and 1997 cooling seasons, this study tested twenty-five packaged roof-top systems in sixteen different buildings located in northern California. All of these buildings had the ducts located in the cavity between the drop ceiling and the roof deck. In 30% of these buildings, this cavity was functionally outside both the building's air and thermal barriers. The effective leakage area of the ducts in this study was nearly 3 times that in California residential buildings [ELA_{25} (cm^2/m^2 floor area) 3.7 for light-commercial compared to 1.3 for residential]. For these systems, the average supply-side leakage rate was 26% of the system flow rate.

This paper looks at the thermal analysis of the ducts, from the viewpoint of supply effectiveness. Conduction effectiveness gauges the fraction of the capacity available at the supply-air plenum that is delivered to a supply-air register. Effectiveness calculations are done on a register basis and include the length of a cycle, and whether the fan is always on or if it cycles with the cooling equipment. Combining effectiveness and leakage numbers yields delivery efficiency. The ten systems tested in 1997 had an average delivery efficiency of 65%.

Introduction

Light commercial buildings, primarily one- and two-story buildings with individual HVAC package roof-top units serving floor areas less than 10,000 ft^2, make up a significant portion (50% of the number of buildings) of non-residential building stock in the U.S. and California (CBECS, 1995). Commercial retail strip-malls are among the largest percentage of light commercial buildings. This stock also consists of offices, restaurants and professional buildings.

It is common knowledge in the construction industry that first-cost dominates construction practices in these buildings. This potentially leads to short-cuts in construction practices and/or using lower grade materials (in the case of duct work this shows up as sloppy connections, and the use of low grade duct tapes). These short-cuts (along with lack of maintenance) often result in buildings that appear visually distressed five to ten years after they are built; moisture damage due to leaky roofs, and uncontrolled infiltration are the most common visual indicators of problems. The buildings use constant air-volume (CAV) package roof-top units for HVAC, and as with the buildings, if not to a

greater degree, first-cost dominates (in the buildings visited), with the same potential problems of poor construction practice and/or lower grade materials.

Slowly the industry and research community are acknowledging that duct-work in residential HVAC systems leak, often in excess of 25% of the rated flow (Jump, et al., 1996). Roof-top units in commercial buildings use the same duct-work and installation techniques as residential systems (combinations of sheet-metal, duct-board, and flex-duct). Considering construction standards and practices, it would be a surprise if ducts in small commercial systems did not leak. The industry acknowledges that the ducts "may" leak, but since, in commercial buildings, the ducts are largely inside the building, there has been little interest in their performance, and in quantifying the extent and the impact of duct leakage. While the ductwork may be physically inside the building, inside the ceiling cavity, this cavity is often outside the building's thermal and air barrier. Thus ducts in many light-commercial buildings are subject to the same loss mechanisms as residential ducts located in attics.

Other Work

Researchers have recently documented the leakage characteristics of residential ducts ([Andrews 1996], [Andrews and Modera 1992], [Jump et al 1996], [Modera 1993], [Palmiter and Francisco 1994]). This study uses California residential data obtained at Lawrence Berkeley National Laboratory (LBNL) for various studies (Jump, et al., 1996). Delp et al documented the 1996 portion of this work (Delp et al, 1998). Other than anecdotal evidence, the only other significant work in the area of small commercial systems is from the Florida Solar Energy Center (FSEC). FSEC looked at the entire building envelope in a study titled "Uncontrolled Air Flow in Non-Residential Buildings" (Cummings, et. al., 1996). Their primary concern was with uncontrolled flow across the building envelope. They did envelope leakage studies in 70 light-commercial buildings, and duct leakage measurements in 43 of these buildings.

Goals

The goals for this current study fell in three basic areas: building and HVAC system characterization, duct leakage, and duct thermal losses. Characterization involved identifying unit sizes, occupied areas, and the location of the thermal and air barriers. Duct leakage information came from direct pressurization effective leakage area measurements, yielding the effective leakage area. Information on thermal losses came from single-day temperature monitoring (6-12 hours of monitoring), yielding conduction effectiveness.

Methods

Building selection consisted of buildings with package roof-top cooling systems, whose owners/occupants were willing to cooperate with the study. All of the buildings in this study were occupied, which meant working around the schedules of the occupants. This required the tests to be as non-intrusive as possible, and consisted of three distinct parts: walk-through characterization, leakage and flow measurements, and thermal measurements.

Over the 1996 and 1997 cooling seasons there were sixteen buildings involved in the current study. Three of which were separate LBNL office spaces in buildings of differing ages and construction practices. The remainder were: three Stockton area office buildings, five office spaces located in Sacramento, a shoe repair store located in a Sacramento area strip-mall, two Sacramento area libraries,

a health food store in Marin county, and a Marin county gymnastics facility. In total, twenty-five CAV HVAC systems in these sixteen buildings were tested.

Walk-Through Information

A simple walk-through with the occupants yielded most of the characterization information. Major items of importance were the name plate information on the HVAC equipment, duct material and location, building thermal barrier, and building air barrier. Other items such as occupancy schedules, internal loads, etc. were obtained by filling out a questionnaire with the building occupants.

Leakage Measurements

Effective leakage area (ELA) is an abstraction that represents an equivalent size orifice that has the same flow as the leaks in the system for a given pressure. This study measured effective leakage areas using a modified duct pressurization method, as described by Delp et al [Delp et al 1998]. The method uses a single set-up to measure the combined leakage area of both the supply and return duct systems. The calibrated fans used in this study have an uncertainty of ±3% of the reading, and the pressure gauges ±0.1 Pa. Randomly applying these uncertainties to the measured values should yield an uncertainty in the calculated combined ELA of not greater than ±5%.

Thermal Measurements

This study used small, battery-operated self-contained thermistor/loggers for all the thermal measurements. These thermistor/loggers have a resolution and accuracy of approximately 0.2^{O}C, and store 1,800 data points. This resolution and accuracy leads to ±3% uncertainty in effectiveness calculations. The loggers have a delayed start feature, allowing them to be left in place to start simultaneously at a pre-determined date. We collected the following temperatures: outside air, ceiling cavity, room, supply plenum, and at least one supply register.

Results

Results are presented in three primary sections: building and HVAC characteristics, duct leakage area, and conduction losses.

Building and HVAC Characterization

Figure 1 shows the floor area versus the unit size, for both the LBNL and the FSEC data sets. The important point here is the floor area served by each unit. This figure shows that the California (LBNL) buildings are similar to those in Florida (FSEC). Light-commercial buildings frequently have a greater load density (ton/ft^2) than single-family residential homes, due to internal loads such as equipment, lights, and people. Unfortunately with many light-commercial buildings accurate load information is not available during design, and contractors/engineers resort to a rule-of-thumb approach to equipment selection, often resulting in oversized equipment. (Less than half of the systems tested had any plans.) It is worth noting the values in the figures are installed capacities, and do not necessarily correspond to actual space loads.

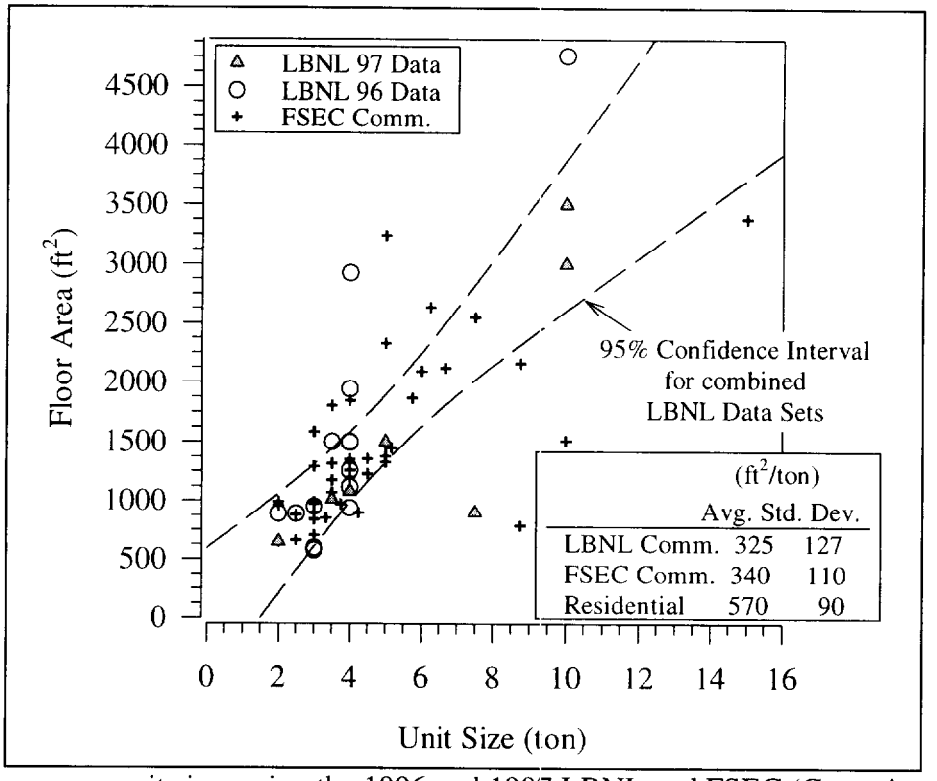

Figure 1. Floor area -vs- unit size: using the 1996 and 1997 LBNL and FSEC (Cummings, et al., 1996) commercial data along with residential (Jump, et al., 1996) summary information. The FSEC unit size is derived from the total installed capacity in the building divided by the number of units.

The twenty-five systems had an average unit size of 4.9 tons, this compares with the FSEC data of 4.5 tons, and the residential of 2.9 tons (Jump, et al., 1996).

The average floor area served by each unit was 1,575 ft^2 for the current study, 1,400 ft^2 for the FSEC buildings, and 1,800 ft^2 for the residential buildings. Since the area served by each commercial unit is smaller than residential, and the units have a greater capacity, commercial buildings have larger units on a floor area basis than residential buildings. The commercial buildings averaged between 325 and 340 ft^2/ton while the California residential buildings averaged 570 ft^2/ton. Assuming duct loss mechanisms scale with capacity, this indicates light-commercial buildings potentially have greater duct losses on a building floor area basis than residential buildings.

In order to understand the dynamics of duct losses, details of the building need to be determined. Figure 2 summarizes many of the characterization details pertaining to the buildings. All the buildings had a drop ceiling with the duct runs in the ceiling cavity. Because of this, two critical building details are the location of the thermal and the air barrier. Fifty percent of the buildings had insulation placed at the roof deck, 38% on the ceiling tiles, and the remainder had insulation at both locations. Thirty eight percent of the buildings had a directly vented ceiling cavity. In these buildings, the lay-in acoustical ceiling tiles formed the major air barrier. In 56% of the buildings the primary thermal barrier was at the ceiling tiles, which implies that the ducts are entirely outside the conditioned space. In 25% of the buildings the ceiling cavity acted like a buffer zone, with the temperature floating between the room and outside temperatures. With these buildings, the thermal barrier is in-between the roof and ceiling. In the remainder of the buildings the thermal barrier was at the roof, however even in these buildings, the ceiling cavity temperature was slightly higher than the room.

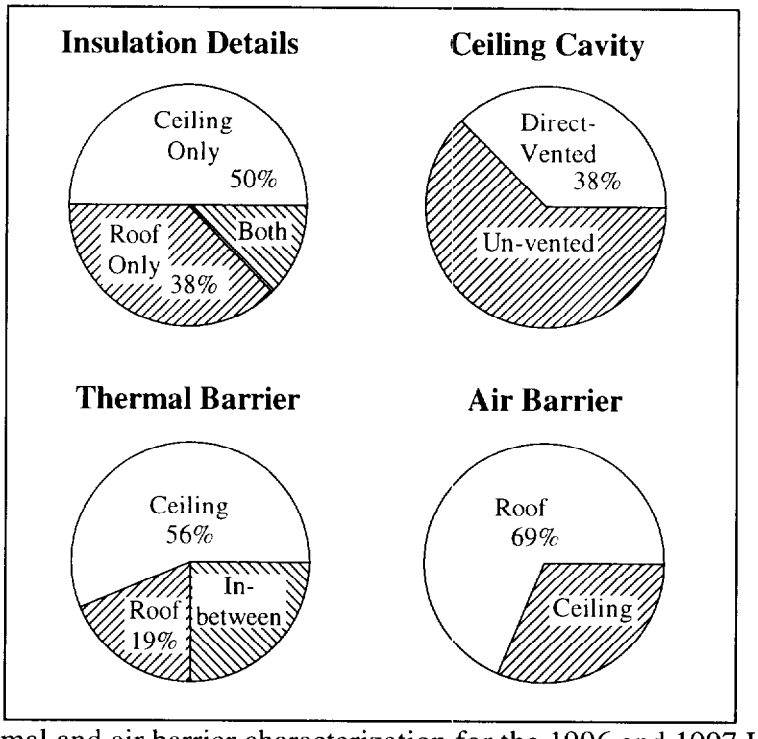

Figure 2. Building thermal and air barrier characterization for the 1996 and 1997 LBNL commercial buildings.

Figure 3 summarizes HVAC unit characterization details. Duct material fell into two basic types (both with some insulation): all metal trunk-and-branch, and flex-octopus (flexible duct with individual ducts running in as straight as line as possible to the register from the plenum). 52% of the systems had all metal ducts, while the remainder had some form of flex-octopus. There are two types of basic ductwork configurations found with the typical light-commercial package roof-top unit: bottom discharge, and side discharge. Bottom-discharge eliminates ductwork exposed outside since it penetrates the roof directly under the unit. The typical side-discharge installation includes 90^0 elbows directly off the unit, ideally cutting down on the amount of duct exposed on the roof. Economics and local practice govern which method is used. Bottom discharge units require the use of a special curb to support the unit, while side discharge units typically use a field-fabricated platform for the unit. 40% of the HVAC units had bottom-discharge ductwork, while the remainder used a side-discharge arrangement.

Air side economizers minimize cooling energy use when it is cooler outside than inside. Fifty six percent of the units had some sort of economizer; however, they were not checked for functionality. Only 16% of the units had functioning minimum outside air (either an intentional opening in the return duct directly to outside, or a minimum setting on the economizer). All of the others either had no outside air provisions, or had the dampers permanently shut.

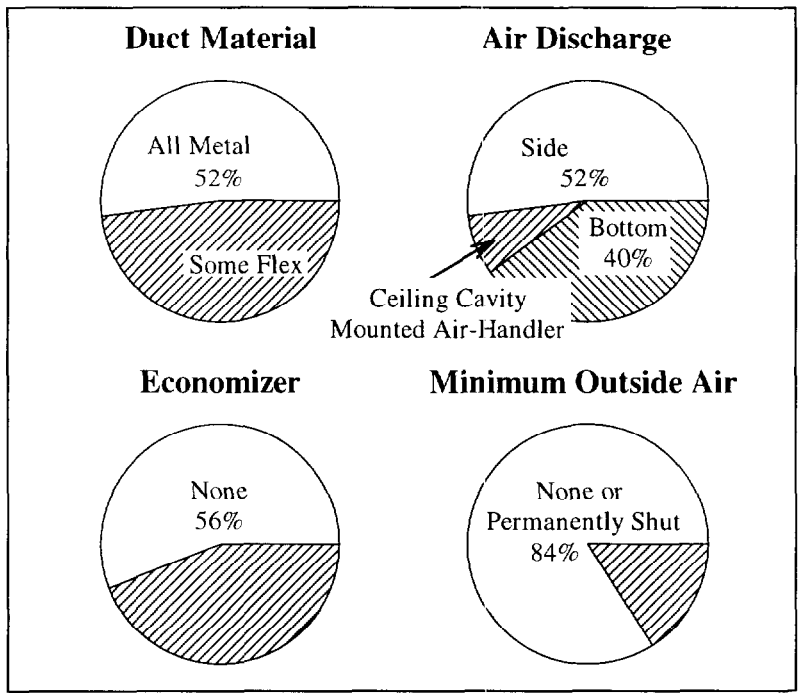

Figure 3. Characterization of HVAC unit details for the 1996 and 1997 LBNL commercial buildings.

Leakage Area of the Duct Systems

The main emphasis of the current study was to measure the leakage area of the ducts. There are several ways to compare the systems to each other, and to other data sets. The goal of comparison is to find a way to normalize the data, making direct comparison of different systems possible.

Figure 4 shows the combined leakage area (ELA_{25}) versus the unit size for both commercial data sets. The data have a large spread in values. The dashed lines in the figure represent the 95% confidence interval for a linear regression on the combined LBNL data sets. This interval is the region where there is a 95% confidence in the predicted value. By observation, the LBNL and the FSEC leakage values fall in the same broad general range for any given unit size. Normalizing leakage area with the unit size (cm^2/ton) does not yield a constant due to the large spread in values. However, the residential and FSEC commercial data sets had similar average values for leakage area per ton (cm^2/ton), while the LBNL (both 96 and 97) commercial buildings had ~30% higher average value, possibly due to a greater spread in the data.

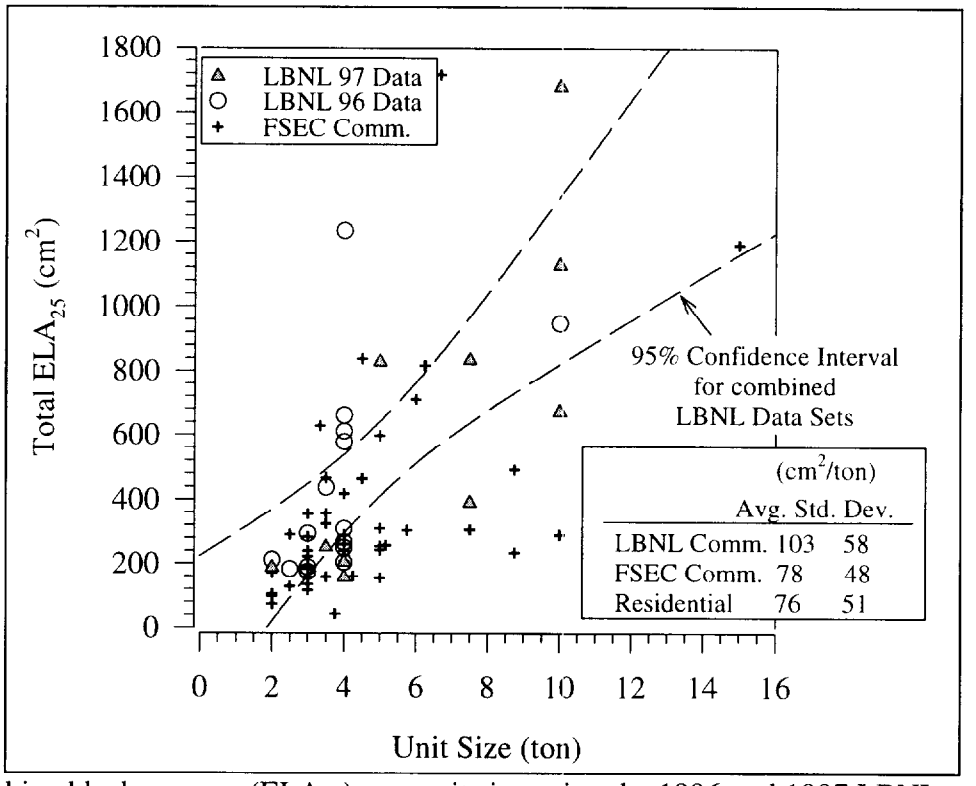

Figure 4. Combined leakage area (ELA_{25}) -vs- unit size using the 1996 and 1997 LBNL and FSEC (Cummings, et al., 1996) commercial data along with residential (Jump, et al., 1996) summary information. Combined leakage area includes both supply and return leakage. The FSEC unit size is derived from the total installed capacity in the building divided by the number of units.

Figure 5 shows the combined leakage area (ELA_{25}) versus the floor area for both commercial data sets. Again, the data show a large spread in values. The dashed lines in the figure represent the 95% confidence interval for a linear regression on the combined LBNL data sets. The LBNL data grouping is similar to, and slightly higher than, the FSEC data. As an order of magnitude estimator on a larger stock of buildings, in residential work, it is common to present building envelope leakage results by normalizing leakage area with floor area (cm^2/m^2). The average cm^2/m^2 in the LBNL data set was 2.8 times that of the residential data, while the FSEC data was just over 2 times the residential. These data suggest that light-commercial duct systems leak air at a rate much greater than residential systems, for any given floor area.

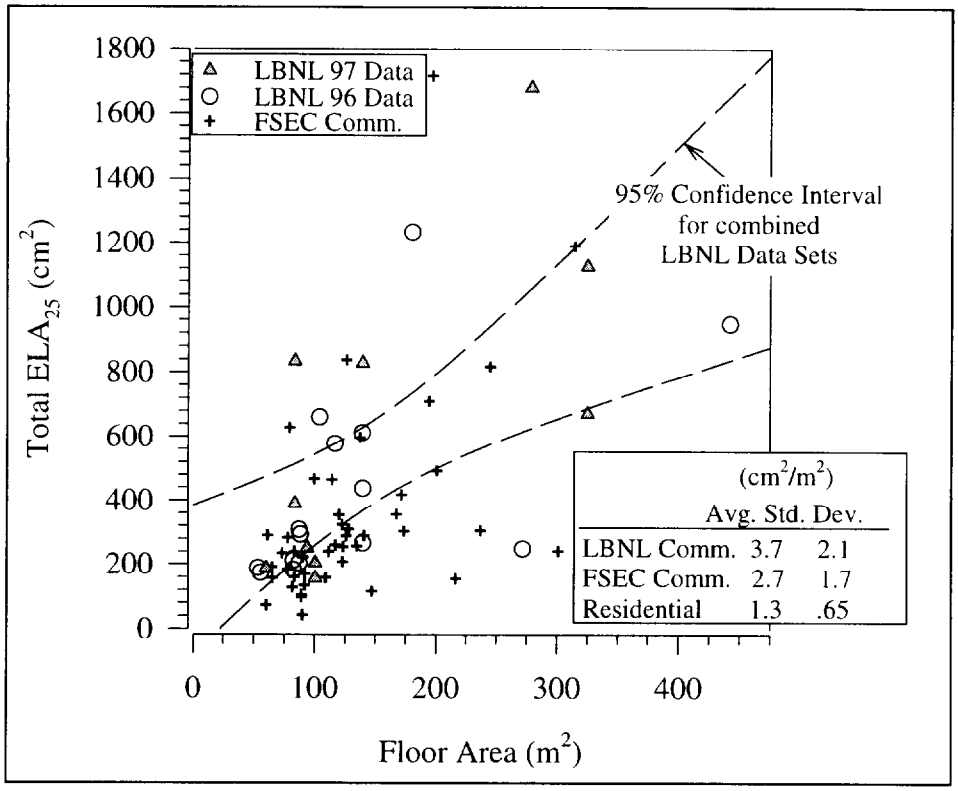

Figure 5. Combined leakage area (ELA_{25}) -vs- floor area using the 1996 and 1997 LBNL and FSEC (Cummings, et al., 1996) commercial data along with residential (Jump, et al., 1996) summary information. Combined leakage area includes both supply and return leakage.

Figure 6 has taken the normalized combined ELA_{25} effective leakage areas (normalized by equipment capacity, floor area, and the number of registers; ELA/ton, ELA/m^2, and ELA/reg) and further normalized these values by dividing by the average of the initial normalized value. A value of 1 is then the average of the sample. These twice-normalized values are plotted against a subjective opinion of the condition of the equipment/ductwork. This opinion was that of the researchers and was based on visual clues such as damaged ducts, damaged HVAC cabinets, the presence of mastic, and the general appearance above the ceiling cavity. The possible ratings were poor, fair, good, very good, and excellent. Regardless of the normalization value chosen, the figure shows that the researchers did not do a very good job of predicting which systems had a high ELA_{25}.

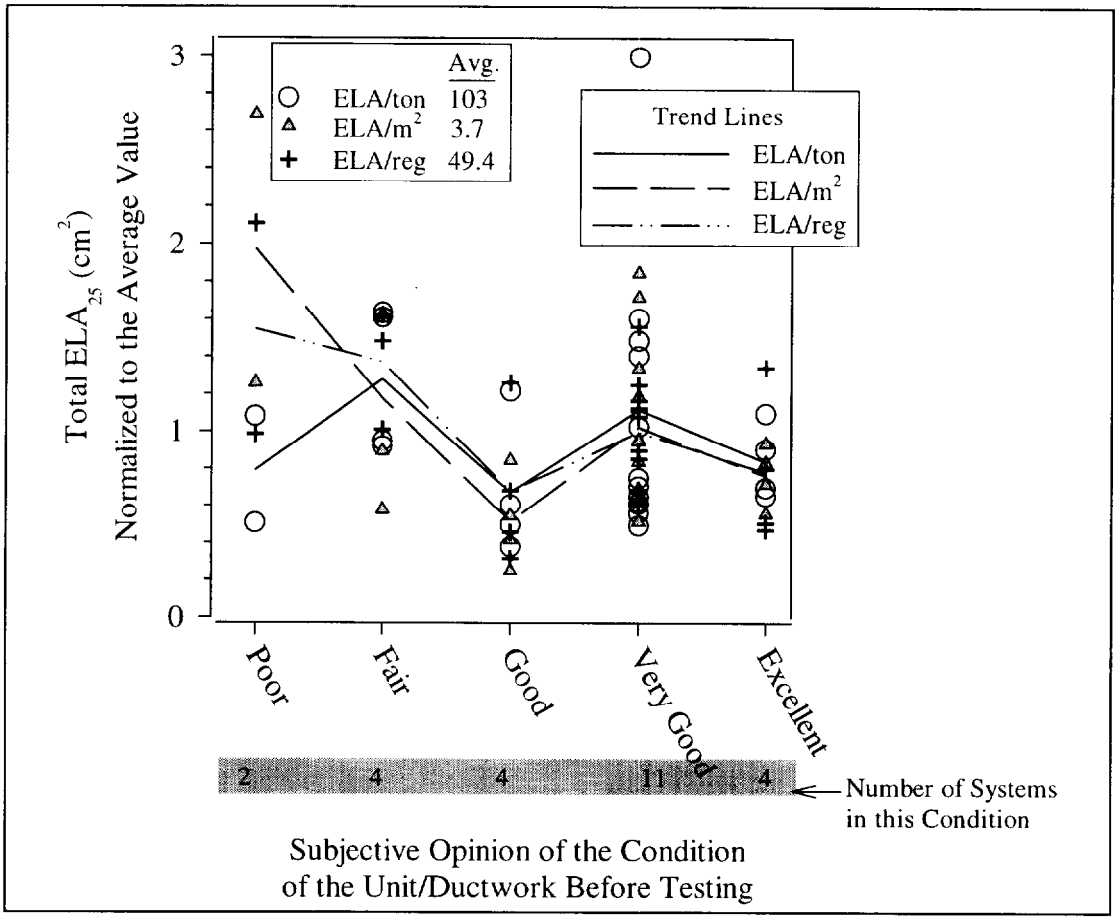

Figure 6. Normalized total effective leakage area (ELA_{25}) vs. a subjective opinion of the condition of the HVAC unit and its duct system, using the 1996 and 1997 LBNL light-commercial data. Total effective leakage area includes both supply and return leakage. The normalized values (ELA/ton, ELA/m^2, and ELA/reg) are further normalized by dividing by the appropriate average of the normalized values.

Table 1 shows the summation of all the register and fan flows. The average leakage using both 1996 and 1997 data sets was 26% on the supply side. The total return-side flow was lower than the total supply-side flow due to the introduction of outside air in many of the systems (only 61% of the fan flow was through the registers; the rest was from return leaks and outside air).

Table 1. Summation of all register and fan flows using both 1996 and 1997 LBNL light-commercial data. The total floor area was 34,885 ft^2.

	cfm	cfm/ft^2
Sum of Supplies	32,102	0.92
Sum of Returns	26,283	0.75
Sum of Fan Flows	43,386	1.24

Conduction Losses

For this work, conduction losses are defined as combined thermal duct losses. These losses include conduction, convection, radiation, and thermal-cycling. The magnitude of conduction losses was investigated in terms of "conduction effectiveness," which for this study concerns sensible losses only. Delp et al describe the analysis method and loss mechanisms in detail (Delp et al 1998). Conduction effectiveness gauges the fraction of the capacity available at the supply-air plenum that is delivered to a supply-air register. Neglecting leakage, it is the ratio of the delivered capacity at the registers to the potential capacity at the plenum (1).

$$\varepsilon_{s,i}(t) \equiv \frac{\textit{Delivered Capacity at Register } i}{\textit{Potential Capacity at the Plenum}} = \frac{T_{reg,i}(t) - T_{room}(t)}{T_{plenum}(t) - T_{room}(t)} \tag{1}$$

Where:

$\varepsilon_{s,i}(t)$: Conduction effectiveness for register i at time t

$T_{reg,i}(t)$: Register i temperature at time t

$T_{room}(t)$: Room temperature at time t

$T_{plenum}(t)$: Supply plenum temperature at time t

The total supply effectiveness ε_s is the sum of the individual effectivenesses for each register weighted by the airflow mass fraction for that register (2):

$$\varepsilon_s = \sum_i \left(\frac{\dot{m}_i}{\dot{m}_{fan}} \right) \varepsilon_{s,i} \tag{2}$$

Where:

$\dot{m}_i$: Flow rate at register i

$\dot{m}_{fan}$: Flow rate through the system fan

A similar conduction effectiveness approach works for the return duct system. Return duct losses in a cooling system tend to raise the temperature of the air; therefore, the return effectiveness is the ratio of the minimum energy required to condition the space to the actual energy required to condition the space (3).

$$\varepsilon_r \equiv \frac{\textit{Minimum Energy}}{\textit{Actual Energy}} = \frac{T_{supply\ plenum} - T_{room}}{T_{supply\ plenum} - T_{return\ plenum}} \tag{3}$$

Delivery efficiency, the ratio of the delivered capacity at the registers to the energy put into the duct system, is the number in which we are ultimately interested. Due to return-side losses (heat gains in cooling mode), the energy put into the system will not always correspond to the potential capacity at the plenum. Delivery efficiency is the product of the supply and return effectivenesses (4):

$$\eta_{del} \equiv \frac{Delivered\ Capacity\ at\ the\ Registers}{Actual\ Energy\ put\ into\ the\ Ducts} = \varepsilon_s \cdot \varepsilon_r \quad (4)$$

Table 2 summarizes the thermal measurements in the 1997 buildings. Average on-times ranged from 20-100%. The total supply effectiveness is based on a flow weighted average of the registers measured, multiplied by the assumed fraction of air reaching the registers (one minus the assumed leakage). The return effectiveness is calculated assuming (a) that there is no leakage in the return air ductwork and (b) that the conduction loss in the return ductwork is half that of the supply ductwork. Rounded up to the nearest 5%, the average of these calculated delivery efficiencies was 65%. Average temperature rises at the end of an on-cycle (from the plenum to a register) ranged from 0.2 to 3^{0}C.

Table 2. Summary of 1997 LBNL Light-Commercial Building Thermal Measurements

	Office1	Office2	Office3	Office4	Office5 a	Office5 b	Library 1	Library 2	Club1a	Club1b
Unit Size (ton)	4	4	10	5	3.5	2	10	10	7.5	7.5
On-Time	56%	63%	98%	64%	100%	20%	66%	30%	61%	78%
Assumed Leakage	10%	10%	35%	20%	5%	0%	5%	18%	15%	18%
Average ε_s	75%	80%	59%	68%	86%	38%	83%	65%	78%	72%
Assumed ε_r	92%	94%	96%	91%	96%	72%	94%	90%	95%	93%
η_{del}	69%	75%	57%	62%	82%	27%	78%	58%	74%	67%
Register Number	Average ΔT (from the plenum to a register) at the end of each on-cycle (°C)									
1	1.5	1.2	1.3	0.4	0.7	0.9	0.9	3.4	0.9	0.9
2	2.2	0.8	0.3	0.6	0.6	1.1	0.9	0.4	0.9	0.4
3	n/a	n/a	n/a	0.4	0.2	3.0	n/a	0.3	0.4	0.2
4	n/a	n/a	n/a	0.3	1.8	2.5	n/a	4.5	n/a	1.0

Summary and Conclusions

Each of the twenty-five systems in the sixteen buildings in the current study had at least one of the following problems: torn and missing external duct wrap, poor workmanship around duct take-offs and fittings, disconnected ducts, and improperly installed duct mastic. Where there was ceiling tile insulation, installation was, at best, very uneven. Visual indicators alone are not good at identifying poor systems. While systems that appeared poor usually had high ELA_{25}'s, the systems with the highest ELA_{25}'s looked, upon initial inspection, like good systems. On a floor area basis, the light-commercial buildings (both in Florida and California) have duct ELA_{25}'s nearly three times as high as California residential buildings. Furthermore, these ducts are located outside the conditioned space, and often outside the building's air barrier.

Effectiveness calculations allow investigation of duct system thermal losses. Combined with leakage information these calculations provide the duct system delivery efficiency. The delivery

efficiency in these buildings averages approximately 65%. These low efficiencies are due to the multiplicative effects of leakage and conduction losses.

This study did not attempt to quantify the amount of outside air entering each building. However, observations made during the characterization phase of this project suggests the buildings visited in this study will have very low quantities of outside air.

A relatively small data set (in California and Florida) forms the basis for these conclusions; additional data are needed to better characterize this large national stock of buildings. Understanding duct-system performance requires both leakage and thermal loss information. Thermal measurements require sufficient time resolution to capture transient information. We have plans to continue with this characterization and leakage measurement work by testing additional systems, along with gathering more complete (multiple registers, and sufficient time resolution) thermal data.

Acknowledgments

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