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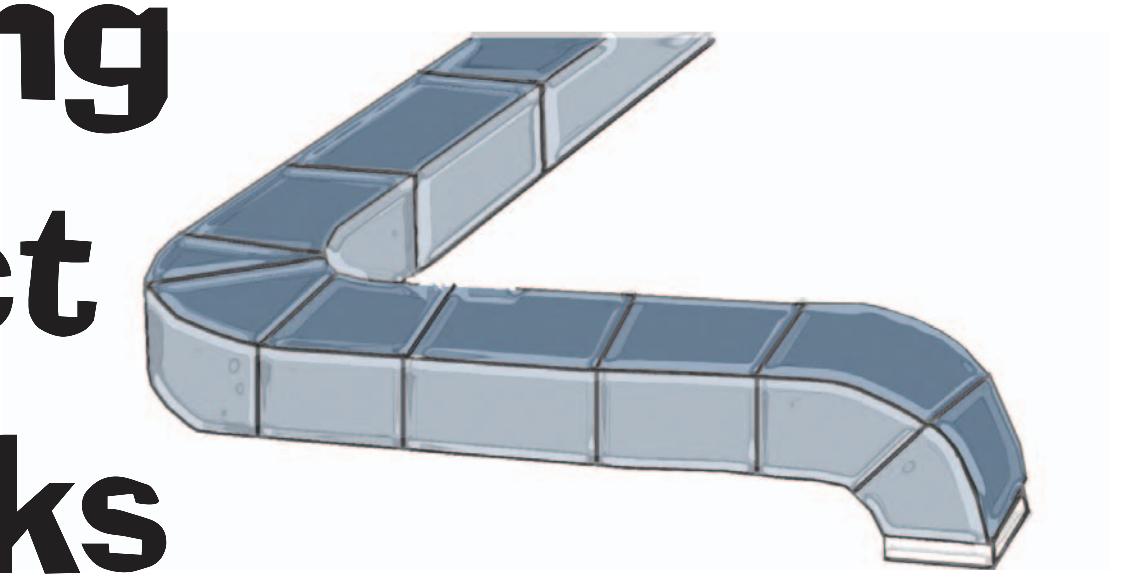
Fixing Duct Leaks



In Commercial Buildings

By Mark Modera, Ph.D., P.E., Member ASHRAE

In contrast to residences, standards dealing with duct leakage in commercial buildings have existed for many years (e.g., SMACNA's *HVAC Air Duct Leakage Test Manual* [1985]). However, duct leakage is common in certain types of commercial buildings, and in certain system components. Unfortunately, these problems have had little attention.

Examples of this inattention to duct leakage include typical light commercial strip malls. They also include large existing commercial buildings that did not receive adequate duct tightness testing either during construction or when construction, performance, or operation changed significantly. Another issue is inattentiveness to commercial building duct system components downstream of VAV boxes.

This article discusses issues associated with duct leakage in these types of buildings and components, and presents case studies of leakage measurements and repair in these applications.

Building Classification

The question of when duct leakage is significant in a commercial building depends heavily upon the building type and duct system, the location of leakage, and the amount of leakage. Key distinguishing factors between commercial buildings are whether they are similar in size and equipment type to residences, or whether they contain larger, more complex HVAC systems. The first group of buildings is referred to in this article as thermally dominated commercial buildings. The second group is large commercial

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buildings whose HVAC energy use is more heavily impacted by fans.

Thermally Dominated Commercial Buildings

A thermally dominated commercial building works much like a single-family sunbelt residence, typically conditioned by ductwork located above the ceiling, and connected to small rooftop packaged equipment with fans that often cycle with the call for heating or cooling. In these buildings, the majority of the HVAC energy consumption is for heating and/or cooling the air, rather than the fan.

Large Commercial Buildings

In large commercial buildings, the operation of the fan(s) usually is not in direct synchronization with heating and cooling delivery. The fans typically run constantly, although often not at a constant flow rate, during building operation. In addition, the longer transport distances and control requirements in large buildings also translate into higher pressure differentials experienced by the central fan(s). The combination of these factors translates into a higher fraction of HVAC energy consumed by the fan, even though many of the fans have higher efficiencies than those found in standard packaged HVAC equipment.

Impacts of Duct Leakage

Ducts in the ceiling plenum space may appear to be in the conditioned space but are not. Fan power can be impacted by duct losses even if all the thermal energy returns to the conditioned spaces. As is discussed later, a ceiling plenum space has different energy implications depending on where the insulation is located, and whether the ceiling plenum is used as a return or exhaust duct.

In a light commercial strip mall (thermally dominated commercial building), the key determinants of duct leakage energy implications are the degree of leakage, and the location of the ductwork relative to the thermal and air boundaries of the conditioned space. At one end of the spectrum is ductwork that can be seen from within the occupied space, for which there is little energy to be saved by sealing or insulating that ductwork.

On the other hand, when ductwork is located above a “T-bar” or plaster ceiling, the thermal resistance of the ceiling relative to the roof is a key determinant of how much energy savings can be realized. The relative tightness of the ceiling with respect to the roof deck also is significant.

Field studies in California have shown that the insulation in light commercial buildings can be found on the ceiling, on the roof, or in both places (*Figure 1*), and that a non-trivial fraction of the buildings tested (38%) had ceiling tiles acting as the air barrier of the building due to the installation of turbine vents on the roof that make the roof less airtight than the ceiling.

Figure 1 shows that in older light commercial buildings in California, insulation was located only on the ceiling about 50% of the time, only on the roof deck 38% of the time, and both places 12% of the time.[1] According to that report, “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.”

Another study indicated that California buildings that received building permits during a time that required roof insulation showed a much smaller fraction of ceiling insulation.[2] Interestingly, a limited study in Wisconsin did not have any trouble finding buildings with ceiling insulation.[3]

To quantify the significance of the location of building insulation and air barriers, ANSI/ASHRAE Standard 152-2004, *Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems*, was applied to the three types of ceiling plenum configurations for Bakersfield, Calif., Milwaukee and Atlanta.* The input parameters to the standard are summarized in *Table 1*, and the results of those analyses are presented in *Figures 2* and *3*.

Figure 2 demonstrates that the location of insulation has a greater effect on energy efficiency than climate has over the heating season. This result was even more pronounced in cooling. *Figure 3* shows the large impact of insulation location upon the energy savings associated with moving from 35% duct leakage split evenly between supply and return, to 6% evenly split leakage (chosen leakage levels based upon field studies described later).

Figure 3 also indicates that the largest percentage savings occur under cooling design conditions, which can be explained

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*Although Standard 152-2004 was designed for residential systems, the results it provides for light commercial retail or office buildings are not exact, but are workable. Factors that reduce the appropriateness of these results include large exhaust fans for cooking, or operating conditions that vary dramatically from those for residences.

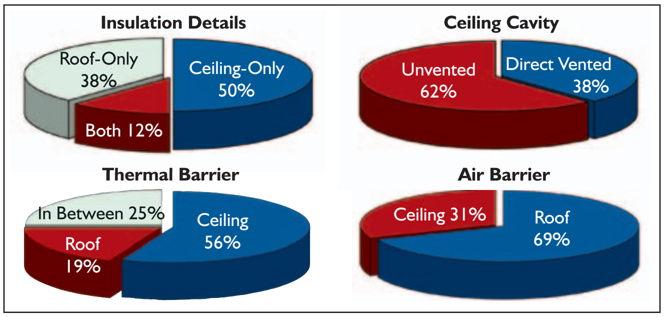

Figure 1: Characterization of the ceiling plenums with ductwork in light commercial buildings.[1] *The thermal barrier locations were determined by temperature measurements, where "in between" means that the plenum temperature floated in between the indoor and outdoor temperature.*

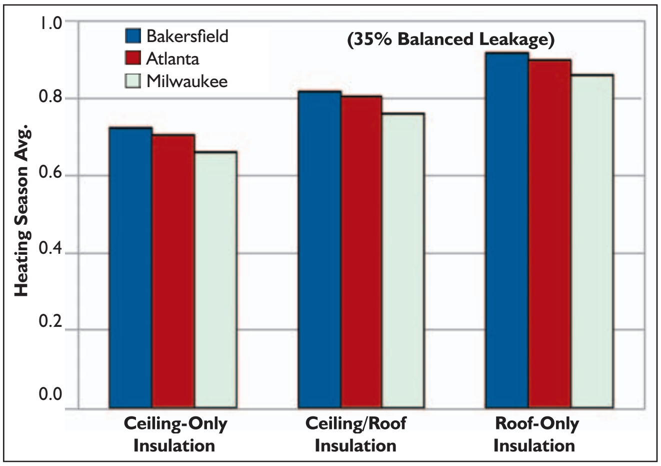

Figure 2: Heating season duct efficiencies calculated using Standard 152-2004 for light commercial ducts located above an unvented drop ceiling.

by the fact that the ceiling plenum temperature is most extreme relative to the duct system under cooling design conditions.

All of the Standard 152-2004 analyses are based upon the assumption that the fan is cycling with the equipment. The additional energy implications of continuous fan operation, although not incorporated into Standard 152-2004, have been shown to depend upon the duty cycle of the heating/cooling equipment.[4] Continuous fan operation has the largest negative impacts at low part load ratios.

Standard 152-2004 underestimates the influence of insulation location for a light commercial ceiling plenum, as the temperatures in the plenum are not calculated, and the impact of the insulation only is captured via the fraction of duct losses recovered. Efficiencies should be higher, and percentage savings should be somewhat lower for roof-only configurations. However, as most losses are regained (90% regain) in roof-only insulation configurations, these effects should be relatively modest.

Duct Leakage in a Large Commercial Building

In large commercial buildings, several mechanisms exist by which energy use is impacted by duct leakage and conduction losses. One mechanism is the effective short circuiting of heating and cooling energy back to the return prior to reaching the desired zone. This short circuiting means that the fan has to move more air to meet a given load, thereby increasing the fan energy non-linearly.[5]

Building Floor Area-Cycle	2,000 ft^2 (186 m^2)
Duct Location	Supply and Return Ducts In Unvented Ceiling Plenum
Duct System R-Value	4°F ft^2/Btu/h (0.7°C m^2/W)
Duct System Surface Area	640 ft^2 (59 m^2)
Heating System Capacity	60,000 Btu/h (17 600 W)
Cooling System Capacity	46,000 Btu/h (13 500 W)
Heating System Flow	1,400 cfm (660 L/s)
Cooling System Flow	1,400 cfm (660 L/s)
Duct Material	Plastic Flexduct
Thermal Regains	
Ceiling-Only Insulation	10%
Ceiling/Roof Insulation	50%
Roof-Only Insulation	90%

Table 1: Inputs used for Standard 152-2004 analysis of light commercial duct leakage.

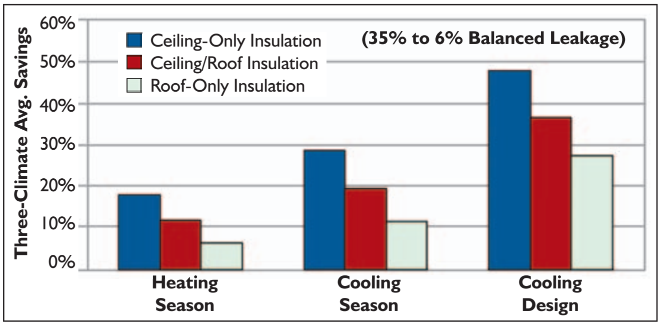

Figure 3: Heating and cooling duct efficiencies calculated using Standard 152-2004 for light commercial ducts located above an unvented drop ceiling (average savings for Atlanta; Bakersfield, Calif.; and Milwaukee).

At the most basic level, fan power increases with fan flow raised a power between 2 and 3, stemming from the fact that fan power scales with the product of fan pressure differential and flow, and that the pressure differential increases with the flow raised to a power between 1 and 2. Using the power 2.4 from Franconi et al.,[5] a 15% leak translates to a 40% increase in fan power.

A secondary impact of the increased fan power is an increase in cooling load associated with the heat generated by the increased fan power, resulting in higher cooling energy use.

Another mechanism by which duct losses in large commercial buildings increase energy use stems from the fact that thermal losses to the return air are not all recaptured by the building or the HVAC system. Some fraction of return air typically is exhausted from the building, thereby throwing away that fraction of the supply air thermal energy lost to the return airstream. This fraction of air exhausted can be as high as 100% in buildings such as laboratories, hospitals or casinos.

Other factors that determine the energy impacts of duct leakage or conduction losses include the use of ceiling plenum returns and the use of induction VAV boxes. The use of ceiling plenum returns vs. ducted returns tends to increase the energy impacts of supply duct leakage, as all of the losses to a ceiling plenum return go directly to the return/exhaust, whereas a larger fraction of the supply losses are likely to be drawn into the conditioned spaces before being pulled into ducted returns.

The degree to which supply losses make it to the conditioned space in ducted return systems depends upon the pressure in the ceiling plenum relative to the conditioned space, which in turn depends somewhat upon the ratio of supply to return duct leakage.

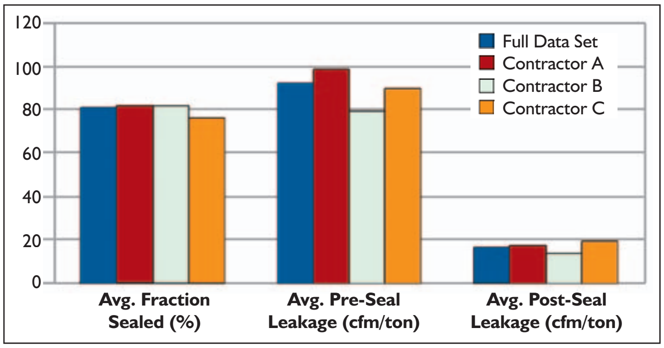

Figure 4: Results of Southern California pilot test of aerosol-based duct sealing in light commercial buildings, where cfm refers to measured leakage cfm at 0.1 in. w.g. (25 Pa) duct pressure.

In the case of ceiling plenum returns, most of the energy lost to the ceiling plenum tends to be returned or exhausted due to the larger effective UA value (thermal conductance) of the return/exhaust airstream as compared to the UA value of the ceiling. In this type of construction, fan powered or system powered induction boxes tend to reduce the energy impacts of supply duct leakage, as the airflows drawn from the ceiling plenum reduce the fraction of the supply losses that are returned to the system fan. The induction flows can be thought of as a form of recovery of supply duct losses.

To place these energy flows in perspective, consider that a return airflow of 0.85 cfm/ft^2 (4.3 L/s/m^2) has an effective thermal conductance of 0.92 Btu/h/°F per ft^2 of floor area (5.2 W/°C/m^2). Assuming that the ceiling area is equal to the floor area, this conductance should be compared to a ceiling thermal conductance of 0.32 Btu/h/°F (1.8 W/°C), corresponding to a 0.75 in. (1.8 cm) thick acoustical ceiling tile. On the other hand, induction box flows can be less than, equal to, or greater than system fan flows, depending on the load of the space.

Supply losses to ceiling plenums also affect economizer and terminal reheat coil operation. For economizers, the colder return air temperature associated with supply air cooling losses to the return air decrease the use of economizers controlled by return air temperature, decreasing the temperature at which outside air is introduced. For terminal reheat coils, assuming that the minimum settings at the VAV boxes are not adjusted, supply duct leakage reduces minimum airflows at the coils, thereby reducing reheat coil energy use during minimum air operation.

One final consideration with respect to ceiling plenums is that thermal recovery of supply losses by conditioned spaces does not necessarily improve matters during simultaneous heating and cooling, where cooling losses can be recovered by zones that require heating, and vice versa.

Although all of these effects have not been quantified on a systematic basis, Franconi et al.,[5] uses detailed building and system simulation to provide a reasonable quantification of the impacts of duct leakage in a large commercial building, calculating a 60% increase in fan power due to 20% duct leakage split on average equally between upstream and downstream of the VAV boxes. Those simulation results also show little impact of part load ratio on the percentage savings. Diamond et al.,[6] measured an increase in system fan power of 25% to 35% due to increasing duct leakage from 5% to 20%.

Uncontrolled Airflows

Another impact of duct leakage in commercial buildings that is not discussed in this article is that of leakage on uncontrolled airflows and pressures.[7] The impacts of these uncontrolled airflows often are much larger than the energy implications of that leakage, ranging from depressurization causing moisture damage in walls and backdrafting of combustion equipment, to transport and disperse of chemical or biological pollutants.

Field Measurements of Duct Leakage

Published measurements of duct leakage in light commercial buildings have generally been limited to Florida and California. Delp et al., summarizes duct leakage results from Florida and California, expressing the leakage in terms of effective leakage area (effective hole size) per unit floor area. The reported values were 0.053 in.^{2}/ft^2 floor area (3.7 cm^2/m^2 floor area) for 25 California light commercial systems, 0.039 in.^{2}/ft^2 floor area (2.7 cm^2/m^2 floor area) for 39 Florida light commercial systems, and 0.019 in.^{2}/ft^2 floor area (1.3 cm^2/m^2 floor area) for California residential systems. Although the size of the holes in the ducts is a convenient tool for comparing construction quality, it has to be combined with the pressures across the leaks to determine their impact on energy performance. Delp et al., also presents a comparison of measured fan flows and supply grille flows for 35,000 ft^2 (3250 m^2) of light commercial floor space in California, which indicated 1.24 cfm/ft^2 (6.3 L/s/m^2) at the fan, and 0.92 cfm/ft^2 (4.7 L/s/m^2) at the grilles, or supply duct leakage of 26% of fan flow.

A much larger data set of light commercial duct leakage areas was acquired in a pilot test of duct sealing for electric demand reduction in Southern California. The average measured pre-sealing leakage for 364 light commercial duct systems tested in this study was 0.03 in.^{2}/ft^2 floor area (2 cm^2/m^2 floor area), calculated based upon assuming 340 ft^2 of floor area per ton of air-conditioning capacity (9 m^2 per kW cooling capacity).

Existing Large Commercial

Considerably less published scientific data exists on duct leakage in large commercial buildings as compared to light commercial buildings, mostly due to the extra difficulties associated with making leakage measurements in these buildings. One difficulty in large buildings is their size and accessibility, leading to much higher measurement costs. Another difficulty with duct leakage measurements in large commercial buildings is the temporal variability of fan, branch and leakage flow rates.

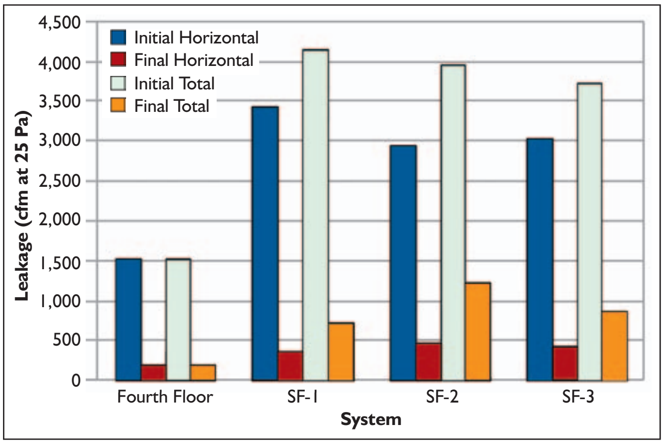

Figure 5: Summary of initial and final leakage measured by fan pressurization of each duct system in a 78,000 ft^2 (7200 m^2) commercial office building. Totals include leakage in vertical shafts and unsealed horizontal runs in the penthouse mechanical rooms for SF-1, 2, 3.

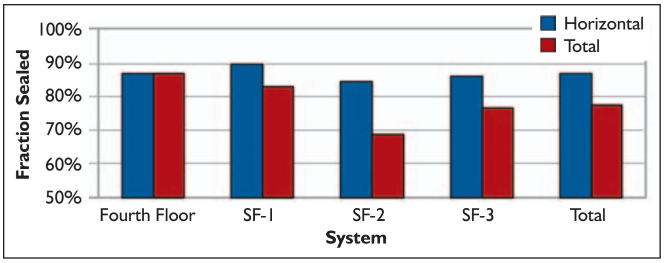

Figure 6: Summary of leakage sealed by HVAC system in a 78,000 ft^2 (7200 m^2) commercial office building. Totals include leakage in vertical shafts and unsealed horizontal runs in the penthouse mechanical rooms for SF-1, 2, 3.

As it is generally impractical to seal all the diffusers simultaneously and measure leakage flow under a presumably uniform duct pressure in a large commercial building, one way of avoiding the size issue is to measure the leakage of a sample duct system branch. This technique involves isolating the branch at the VAV box, and thus does not provide a measurement of leakage upstream of the VAV boxes. Several techniques for measuring duct leakage upstream of the VAV boxes based upon closing those dampers are the subject of current research, as is a technique that determines branch leakage flow by subtracting the sum of diffuser flows from a branch flow measurement under a representative flow condition.

The duct leakage value needed to evaluate the appropriateness of sealing is the percentage of fan flow being leaked. As noted earlier, this can sometimes be measured directly, but often is based upon separate measurements of duct leakage area and operating pressures. In large buildings, this process is complicated by the variable operating conditions of different parts of the system. Specifically, leaks upstream of the VAV dampers generally see a relatively constant pressure determined by the pressure setpoint of the system fan. Therefore, the flow through these leaks is relatively constant in absolute terms, but variable as a percentage of fan flow.

On the other hand, the flows through leaks downstream of the VAV dampers vary almost proportionally to the branch flow rate (leaks vary with duct pressure to the power 0.6, whereas branch flow varies with VAV box pressure to the power 0.5). Thus, downstream leaks represent a relatively constant percentage leakage. The variations in pressures seen by leaks that influence the leakage flows are further compounded by spatial variations in leakage levels (e.g., leaks at diffusers vs. at VAV boxes) that make the variations in pressure more important.

Another key issue in large commercial duct leakage is the large variability of the results to date. Researchers at Lawrence Berkeley Laboratory measured duct leakage in six large commercial buildings, three of which showed 5% leakage, while the other three showed 15%, 17% and 25% supply duct leakage.

While duct leakage measurements are limited, test and balance reports that include fan flow as well as diffuser flow measurements could be used under certain circumstances. One limitation of these measurements is that some test and balance protocols are single pass, whereby each diffuser damper is adjusted on the spot to produce the desired flow. A similar problem occurs when VAV boxes are not all opened simultaneously during testing, which is a fairly common protocol. In both cases, the difference between the fan flow and the sum of diffuser flows is no longer a good estimate of duct leakage (generally underestimating leakage).

Duct Sealing in Commercial Buildings

A recent development in sealing duct leakage in commercial buildings involves a technology that seals leaks from the inside out. This technology, known as aerosol-based sealing, works by pressurizing a duct system with a fog of sealant particles. By temporarily blocking the diffusers, the sealant laden air is forced to the leaks. Maintaining mild turbulence keeps the sealant particles suspended until they reach the leaks. The pressure maintained within the duct system causes the air to accelerate as it exits through the leaks, causing the particles to be flung against the walls of the leaks when they cannot turn as sharply as the accelerating air.[8,9,10]

Due to its ability to access leaks without accessing the exterior of ductwork located above a ceiling, the aerosol-based sealing technology has been used during the last few years to seal duct leaks in light and large existing commercial buildings.

Light Commercial Sealing Results

Figure 4 summarizes the results of a field study in southern California of aerosol-based duct sealing in light commercial buildings. The systems sealed are located in San Bernadino, Riverside, and Orange counties, and were screened by the HVAC contractors to have ceiling insulation below the ductwork. Of the 360 systems sealed, 300 had complete data acquired, including data on the size of the equipment.

The average equipment size was 3.9 tons (14 kW) and the median size was 3.5 tons (12 kW), with the smallest unit having 2 tons (7 kW) of capacity, and the largest 12.5 tons (44 kW). As indicated in *Figure 4,* all of the HVAC contractors had approximately the same level of performance, sealing approximately 80% of the leakage encountered, which resulted in duct systems with leakage of approximately 16 cfm/ton of cooling (3.4 cm^2 per kW of cooling) after the process.

In addition to showing that the technology could seal a significant majority of duct leakage encountered in these types of existing buildings, this field study also demonstrated that the sealing process could be performed on a production basis, with one contractor regularly sealing 10 to 15 tons (35 to 53 kW) of cooling equipment per day at a single site with one crew.

Large Commercial Sealing

The aerosol-based sealing technology also has been used on a production basis in a large commercial building. The technology was used to seal all of the ductwork in a (~40-year-old) 78,000 ft^2 (7200 m^2) four-story commercial office building in which duct leakage for the constant volume systems had been identified by test and balance reports. *Figure 5* summarizes the initial and final leakage measured by fan pressurization during the sealing process for the ducts connected to the three penthouse supply fans that serve the east, west and central sections of the building, as well as for the ducts from two rooftop packaged units serving the fourth floor.

Figure 6 summarizes the percentage of leakage encountered that was sealed for those same duct systems. The distinction between horizontal and total leakage was made because the total leakage measurement included measurements of leakage in sections with various controls and dampers that were scheduled for replacement and, therefore, not sealed. The horizontal duct sections were all externally insulated sheet metal, and the vertical shafts were all internally lined sheet metal ducts with cross-sectional dimensions of approximately 3 by 4 ft (0.9 by 1.2 m).

The sealing for each section in this building, as for all other aerosol sealing applications, is displayed during the sealing process and recorded for future reference by the computer control systems used for all applications. *Figure 7* shows a typical sealing plot for a ductwork section being sealed. All of the duct sealing added up to 25 separate injections and sealing plots (similar to *Figure 7*) for this building.

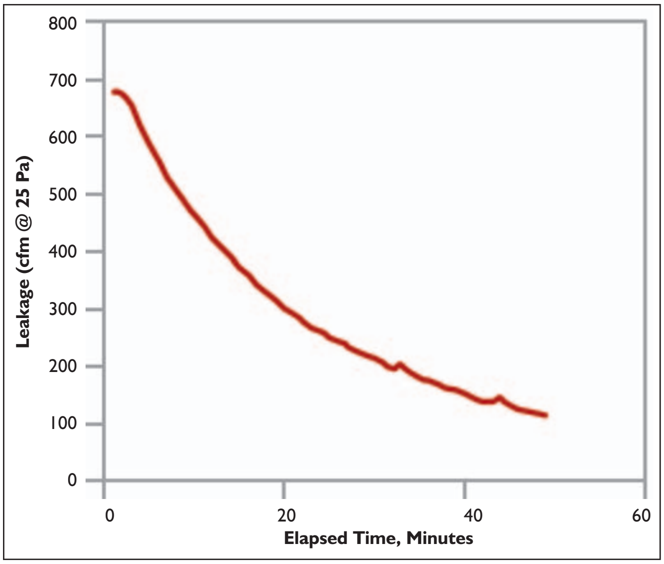

Figure 7: Example sealing profile (third floor northwest in a 78,000 ft^2 [7200 m^2] commercial office building).

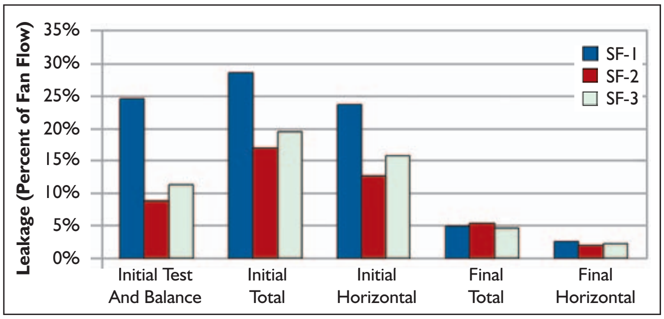

Figure 8: Summary leakage before and after sealing in a 78,000 ft^2 (7200 m^2)commercial office building, computed based upon fan flows from a test and balance report, using measured diffuser flows for initial test and balance results, and measured leakage cfm at 0.1 in. w.g. (25 Pa) duct pressure for all other results.

The leakage of the penthouse systems in this building, expressed as a fraction of fan flows from the test and balance report, are presented in *Figure 8*. These results suggest that the 0.1 in. w.g. (25 Pa) reference pressure for fan pressurization is on the high side for this building, as the leakages based upon measurements at this pressure are all higher than the leakages calculated from diffuser measurements in the test and balance reports.

On the other hand, the author was unable to determine why the 0.1 in. w.g. (25 Pa) reference pressure seems more appropriate for SF-1 as compared to SF-2 and SF-3, and does not have detailed information on the accuracy of the test and balance reports.

Overall, the leakage of the horizontal duct sections was reduced to 2% to 3% of fan flow, and the overall leakage was reduced to less than 5% of fan flow, even including the unsealed duct sections.

Summary and Conclusions

Ducts in commercial buildings leak, particularly in light commercial buildings, which appear to leak more than residential ducts, at least in California. In large commercial buildings some duct systems leak, while others do not, making detection of duct leakage a key activity.

Duct leaks are worth sealing in light commercial buildings whenever the ducts are located above an insulated ceiling. The situation is more complicated in large commercial buildings. Examining large commercial duct leakage from an energy perspective leads to the following considerations: higher leakage, higher exhaust air fractions and ceiling plenum returns make sealing more attractive, whereas induction terminal boxes and ducted returns make sealing less attractive.

This article demonstrates that aerosol sealant injection can seal ductwork leaks successfully in light commercial and large commercial existing building applications.

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