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Building Cavities Used as Ducts: Air Leakage Characteristics and Impacts in Light Commercial Buildings

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ABSTRACT

Field testing in 70 small commercial buildings in central Florida identified that building cavities were used as part of the air distribution system in 33 buildings. The various building cavity types (number of buildings in parentheses) are: enclosed air-handler support platforms (10), mechanical closets (8), mechanical rooms (6), ceiling spaces (7), wall cavities (6), chases (1), and "other" building cavities (2). Testing found that these building cavities are considerably more leaky than standard ducts and plenums because they are generally not built to the same airtightness standard as ducts. Actual air leakage is a function not only of duct hole size but also pressure differential across the leak sites. Pressure differentials generally range from −0.080 in.WC (−20 Pa) to −0.401 in.WC (−100 Pa) in support platforms, mechanical closets and rooms, wall cavities, and chases. By contrast, ceiling plenums often operate at less than 0.004 in.WC (1 Pa) difference from the occupied space and sometimes at positive pressure with respect to outdoors.

The energy, infiltration, and relative humidity impacts of building cavity duct leakage depend upon the leak airflow rate and the temperature and humidity conditions of the air entering the leaks. Therefore, the location of the building cavity ducts is very important. If the return leak air is drawn from the occupied space, that leakage will have little or no impact on energy, infiltration, or relative humidity. At the other extreme, if the leaking air comes from a hot and humid attic space, the impacts will be large. The interaction of various building cavity duct leaks with eight different building configurations—based on the location of the primary air and thermal boundaries in the ceiling space—is discussed here. The paper concludes that building cavities should not, as a general rule, be used as a part of the air-distribution system. The exception is use of ceiling space return plenums. Ceiling plenums can be designed to operate at near neutral pressure with respect to outdoors and, therefore, can experience little or no duct leakage.

INTRODUCTION

Air-distribution systems of heating and cooling systems consist of ducts, plenums, and air handlers. When thinking of ducts or plenums, most persons generally think of round or rectangular conduits made of sheet metal, ductboard, or flexible duct that move air from one location to another. However, what is often not recognized is how often portions of the air-distribution system (ADS) are constructed using building cavities. The problem is that these building cavities that are used as ducts are generally very leaky. As a consequence, much of the ADS leakage occurs in building cavities that are used as ducts.

In residences, a variety of building cavities have been found to compose portions of the ADS, including wall cavities, floor cavities (especially "panned floor joists"), spaces formed by dropped ceilings, enclosed cavities below stairways, mechanical closets, and enclosed support platforms. In Florida, more than 50% of all air leakage from duct systems occurs in building cavities that are used as ducts, with enclosed support platforms accounting for more than 75% of this leakage (Cummings et al. 1991). Note that changes to the Florida Energy Code have greatly curtailed the use of building cavities as ducts in new Florida residential construction.

Recently completed research in 70 small commercial buildings in central Florida has found that building cavities are widely used as ducts in commercial buildings as well. In 33 of 70 small commercial buildings in central Florida, enclosed support platforms, wall cavities, ceiling spaces, mechanical closets, mechanical rooms, chases, and other building cavities were found to compose portions of the ADS. The seven types of building cavities used as ducts are

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TABLE 1
Building Cavities Used as Ducts or Plenums in 33 Small Commercial Buildings (number of occurrences in parentheses)

Building Description	Wall Cavity	Ceiling Space	Chases	AH Platform	Mechan. Room	Mechan. Closet	Other
Research office		x			x		
Auditorium	x(2)						
Church sanctuary	x						
Video productions		x		x(6)	x		
Business training office					x		
HVAC supply house						x	
Sports center		x			x		
Manufactured classroom	x(2)						
Manufactured office	x(7)						
School		x					
Pizza restaurant						x	
Health clinic						x(3)	
Sports complex				x(2)			
Sail manufacturer				x			
HVAC contractor				x			
Realty office				x			
Interior decorator						x	
Realty office				x		x	
Safety classroom							x
Government office							x
Gas company office				x			
Tax service						x	
Metal building contractor						x	
Realty office						x(2)	
Plastic fabrication				x			
Amusement park				x(2)			
Hardware store				x(2)			
Manufactured office	x						
Chinese restaurant		x					
Police station		x			x		
High school			x(4)		x(2)		
Hotel		x					
Hotel	x						

shown in Table 1. (Note that in all 33 buildings, duct leakage associated with building cavities was entirely on the return side of the system.) The following incidence of building cavities as ducts (b_ducts) was observed:

- Enclosed air-handler support platforms were used as ducts in ten buildings.
- Mechanical closets were used as ducts in eight buildings.
- Mechanical rooms were used as ducts in six buildings.
- Ceiling spaces were used as ducts in seven buildings.
- Wall cavities were used as ducts in six buildings.
- Chases were used as ducts in one building.
- "Other" building cavities were used as ducts in two buildings.

The amount of air leakage in the various b_ducts is a function of two variables: the size of the holes and the pressure differential across those holes. Normally, building cavities are quite leaky because they are not constructed to the same airtightness standards as the ducts themselves. Data on overall duct system airtightness is available from 46 of the 70 small commercial buildings in this study. How leaky are the air-distribution systems in these 46 buildings? The results are disappointing. When depressurized to 0.100 in.WC (25 Pa) by a calibrated fan (duct tester), average ADS airtightness was 341 $CFM25_{tot}/1000\ ft^2$ (173.3 L/s @ $25_{tot}/100\ m^2$) of floor area (Cummings et al. 1996). This is considerably more leaky than the SMACNA duct leakage standard, which calls for about 12 $CFM25_{tot}/1000\ ft^2$ (6.15 L/s @ $25_{tot}/100\ m^2$) for Class 6 ducts (SMACNA 1985).

AIR LEAKAGE CHARACTERISTICS OF BUILDING CAVITIES USED AS DUCTS

In most cases, leakage in the b_duct portions of the air-distribution system was not measured separately from the balance of the system. Nevertheless, there is considerable evidence of the leakiness of these building cavities. This evidence is presented in the following sections.

Air-Handler Support Platforms

Air-handler support platforms used as return plenums are relatively common in small commercial buildings in central Florida and were found in 10 of the 70 buildings. In these 10 buildings, a total of 18 support platform return plenums were found. In general, these enclosed boxes are quite leaky because of cracks and penetrations in the enclosure or because the interior portion of the plenum is connected to interior cavities of adjacent walls. Negative pressure in the plenum—often in the range of −0.080 in.WC (−20 Pa) to −0.401 in.WC (−100 Pa)—may draw air in from the surrounding zone or down walls from spaces above the ceiling (which may or may not be conditioned space). The source location for the leaking air is important. In five of the ten buildings, the plenums were completely within the conditioned space and all leaks were conditioned air. In three other cases, the plenums were located in the conditioned space, but the return leaks

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largely originated outside the conditioned space. In the other two buildings, the support platforms were in an exterior closet or an unconditioned warehouse. Consider several examples of support platform return plenums.

1. In a two-story 12,716 ft^2 (1181.3 m^2) building, seven support platform plenums were located in a first floor mechanical room and had substantial duct leakage. However, because the mechanical room was located on the first floor and was completely within and open to the conditioned space, there were no impacts on energy, air-conditioner (AC) performance, infiltration, or humidity as a result of these leaks because all the return leak air came from the conditioned space.

2. In a 2708 ft^2 (251.6 m^2) recreation building, two support platform plenums were located in closets within the conditioned space. Return leaks originated from the hot attic by two pathways. First, both plenum interiors were connected to adjacent walls so that air was drawn down the walls from the attic space above. Second, return leaks drew air from the closets themselves, depressurizing the closets to 0.012 in.WC (3.0 Pa) and 0.0012 in.WC (0.3 Pa) for AC units #1 and #2, respectively. Since the closet ceiling was suspended t-bar construction and, therefore, much leakier than floor or walls, most air drawn into the closet originated from the attic as well. For AC unit #1, return leak fraction (RLF) was 19% of total flow. For AC unit #2, RLF was 12% of total flow. Return leaks originated from the attic space above the ceiling. Return plenum repair reduced return leaks to 3.7% and 1.0%, respectively, decreased $CFM25_{tot}$ (L/s @ 25_{tot}) for the two systems combined by 81%, from 788 (371.9) to 154 (72.7), and lowered combined cooling energy use by 17.4%.

3. In a small office space of a plastics fabrication business, the air handler and support platform plenum were located in an unconditioned warehouse. Tracer gas testing revealed that 26% of the return air was leaking into the plenum and air handler combined. Repair of these leaks reduced the RLF to 2% and decreased $CFM25_{tot}$ (L/s @ 25_{tot}) from 186 (87.8) to 55 (26.0). Surprisingly, cooling energy use was reduced by only 4%. The small savings can be traced to the fact that the office space was located in the unconditioned warehouse, was very leaky (ACH50 = 50.1), and, therefore, considerable air exchange with the warehouse occurred with or without the duct leaks.

4. In a real estate office, which was housed in a converted 2142 ft^2 (199.0 m^2) single-family residence (the only converted residence in the study and only nonmanufactured building on a crawl space), two support platform return plenums were located in a mechanical closet and served two AC systems. System #1 had return leaks of 10.5%, with most return leak air originating from the crawl space. System #2, with 21.6% return leaks, was more complex. The plenum had three return grilles and two through walls to the occupied space and one into the closet. This latter grille was pulling about 300 cfm (141.6 L/s) from the closet, causing the closet to act as a return plenum and operate at −0.032 in. WC (−8 Pa). A transfer grille was located in the door to allow room air to enter the closet from the occupied space, but only 95 cfm (44.8 L/s) was entering through that grille. Consequently, approximately 200 cfm (95 L/s) of air was being drawn into the mechanical closet through leaks from the conditioned space and attic. Tracer gas tests revealed that 4.3% of system #2 return airflow (approximately 70 cfm [33.0 L/s]) was leakage into the plenum closet from outdoors (primarily the attic) because of closet depressurization and 17.3% was leakage down the walls from the attic into the enclosed support platform plenum.

Mechanical Closets

Mechanical closets used as return plenums were found in eight buildings. In this setup, air handlers draw return air from the plenum closet and, therefore, depressurize the closet. The plenum closet, in turn, draws air from the conditioned space by means of transfer grilles or ducts. Since plenum closets are much larger than enclosed support platforms, they normally have more leak area than the support platforms. However, since they operate at less negative pressure, typically in the range of −0.040 in. WC (−10 Pa) to −0.120 in. WC (−30 Pa), actual return air leakage in plenum closets is often comparable to that in enclosed support platform returns.

In one of the most extreme examples, three mechanical closets were used as plenums in a walk-in health clinic where three AC units serve a space of 2560 ft^2 (237.8 m^2). The principal problem was that the ceilings of these closets were suspended t-bar construction and that these leaky ceilings were the only barrier separating the closet plenum from the hot attic. In two of the three closets, the intent was for the air handlers (sitting on non-enclosed support platforms) to draw air from the closets and then for the closets to draw air from return ducts that entered the closet through the ceiling from the attic. In the third closet, the air handler sat on an enclosed support platform and a considerably undersized 0.5 ft × 1.2 ft (0.046 m × 0.111 m) ductboard return duct ran to the plenum. However, one end of the return plenum was not enclosed, leaving an opening of approximately 1 ft^2 (0.093 m^2). Consequently, the closet was, in actual practice, a return plenum.

Closet operating pressures were −0.049 in.WC (−12.3 Pa), −0.130 in. WC (−32.5 Pa), and −0.067 in. WC (−16.6 Pa) for systems 1, 2, and 3, respectively, and tracer gas testing found respective RLFs of 48%, 13%, and 48% (Table 2). In total, over 35% of the return air for the three AC systems was coming from the residential style attic. Monitoring found that return leak air averaged 115°F (46.1° C) during the afternoon peak periods on hot sunny days. Note that suspended t-bar type ceilings are very leaky, at best. In this application, the ceilings were even more leaky than normal because there were significant gaps in the ceiling around where the ducts passed through the ceiling or where small tile pieces had fallen.

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TABLE 2
Measured Depressurization, Return Leak Fraction, and Duct Airtightness Associated with Three Mechanical Closets Used as Return Plenums at a Walk-in Health Clinic

(I-P Units)					
Air Handler	Closet Plenum Pressure (in.WC)	Return Leak Fraction (%)	Duct Leak Total ($CFM25_{tot}$)	Duct Leak Closet Only ($CFM25_{tot}$)	Duct Leak To Out ($CFM25_{out}$)
1	−0.049	48	847	673	451
2	−0.130	13	687	NA	315
3	−0.067	48	1042	NA	514
(SI Units)					
Air Handler	Closet Plenum Pressure (Pa)	Return Leak Fraction (%)	Duct Leak Total ($L/s@25_{tot}$)	Duct Leak Closet Only ($L/s@25_{tot}$)	Duct Leak To Out ($L/s@25_{out}$)
1	−12.3	48	400.0	317.7	212.9
2	−32.5	13	324.3	NA	148.7
3	−16.6	48	491.8	NA	242.6

Airtightness tests were performed on the three duct systems. $CFM25_{tot}$ ($L/s@25_{tot}$) was 847 (400.0), 687 (324.3), and 1042 (491.8) for the three systems, respectively. $CFM25_{out}$ ($L/s@25_{out}$) was 451 (212.9), 315 (148.7), and 514 (242.6), respectively (Table 2). Thus, about half of the measured leak area for each system was to outdoors (primarily attic). On the first of the three systems, the airtightness of the closet alone was measured and $CFM25_{tot}$ ($L/s@25_{tot}$) = 673 (317.7). This indicates that 79% of the leak area of that system was plenum closet and 21% was in the balance of the air-distribution system.

Duct repairs were done. In each mechanical closet, return air was "hard-ducted" to the air handler so the closet was no longer a return plenum. Additional return ducts were also added to provide adequate return airflow. RLF declined to 0.5%, 0.0%, and 1.7%, respectively, and combined $CFM25_{tot}$ ($L/s@25_{tot}$) for the three systems declined 91% from 2576 (1215.9) to 227 (107.1). Cooling energy consumption for the clinic decreased by 25.6% from 96.7 kWh/day to 72.0 kWh/day, and cooling energy savings pay for the estimated $1300 repair cost in 3.9 years.

In another case, a mechanical closet was used as a return plenum in a metal building with a 3/12 sloped metal roof. This case is similar to the walk-in clinic because it had a mechanical closet that was substantially depressurized (−0.076 in. WC [−19 Pa]); the closet had a suspended t-bar ceiling and a large RLF (28% of air-handler airflow) drawing from the space above the ceiling.

It was different from the walk-in clinic because of the thermal and humidity conditions above the ceiling. Instead of being hot and humid, this ceiling space was warm and dry because it was not vented to outdoors, insulation batts were located on the ceiling tiles, and additional insulation batts were located at the bottom of the metal roof. If insulation had not been located at the roof, the ceiling space would have been hot and dry. If the ceiling space had also been ventilated, it would have been hot and humid. As it was, ceiling space temperatures were about 95°F (35.0° C) from 1 p.m. to 5 p.m. on hot sunny days with dew-point temperature in the range of 50°F (10.0°C) to 55°F (12.8°C), similar to that in the occupied space. By comparison, the attic conditions in the walk-in clinic were about 115°F (46.1°C) during comparable weather while dew-point temperatures were often above 75°F (23.9°C).

Repairs were done to reduce air leakage into the closet return plenum through the ceiling. This was done by reducing closet operating pressure from −0.076 in. WC (−19 Pa) to −0.016 in. WC (−4 Pa) and airtightening the ceiling. Closet depressurization was decreased by greatly increasing the size of the return air transfers into the closet (adding a louvered door), and the ceiling was tightened by caulking seams (clear silicon) between the ceiling tiles and the t-bar support members. RLF decreased from 28% to 4%, resulting in a 10.8% reduction in cooling energy use.

Mechanical Rooms

Mechanical rooms used as return plenums were found in six buildings. Like plenum closets, they are much larger than enclosed support platforms, so they normally have more leak area than the support platforms. Therefore, the potential for substantial leakage into the mechanical room plenum is large. However, based on the limited sample size of eight mechanical closets and six mechanical rooms, it appears that mechanical room plenums have fewer duct leakage problems than plenum closets. This is not because they are necessarily more airtight but because they are more commonly (at least in this sample) surrounded by plenums and other spaces containing less hostile thermal environments. In four of the six buildings that have mechanical room plenums, the plenums are located inside ceiling space return plenums (plenum in a plenum) or have ceiling space plenums located above them. In the two other cases, the thermal conditions in the spaces above the

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mechanical rooms are moderated by the fact that these spaces are inside the building air boundary and partially buffered by the thermal resistance of a concrete roof system.

Ceiling Spaces

Ceiling spaces used as return plenums were fairly common, being found in seven buildings. The air handlers draw air from the space between the ceiling and the roof deck (or in multi-story buildings, from the space between the ceiling and the floor above). The ceiling space plenum, in turn, draws air from the conditioned space by means of transfer grilles. In general, compared to all other b_ducts, the ceiling space has much greater surface area and, therefore, much greater potential leak area. On the other hand, the level of depressurization in the ceiling space (with respect to outdoors) is generally much less than in all other b_ducts. Typical ceiling plenum depressurization is about 0.004 in. WC (1 Pa) with respect to (wrt) the occupied space. As a consequence, it is possible for ceiling plenums to operate with essentially no return leakage at all. In fact, the ceiling space as a return plenum can actually cause negative duct leakage. This assertion will be explained more completely later in this section.

In two of the seven buildings that have ceiling return plenums, the return plenum operates at positive pressure wrt outdoors. In a video production building, the occupied space (below the ceiling) operated at +0.017 in. WC (+4.2 Pa) wrt outdoors, the ceiling space plenum operated at –0.0036 in. WC (–0.9 Pa) wrt the occupied space, and, therefore, the ceiling space was at +0.013 in.WC (+3.3 Pa) wrt outdoors. As a consequence, leaks in the ceiling return plenum were actually leaking outward to outdoors! In a school, the building was operating at +0.0088 in.WC (+2.2 Pa) wrt outdoors and the ceiling return plenum was operating at +0.0064 in. WC (+1.6 Pa) wrt outdoors. $CFM25_{out}$ (L/s@25) was measured for the ceiling plenum space of this one-story 16,700 ft^2 (1551.5 m^2) school. Two blower doors were installed in an exterior door of the occupied space, and two blower doors were located in the mechanical room exterior doorway. With ceiling tiles removed from the ceiling of the mechanical room (so the mechanical room and the ceiling plenum were well connected), both the occupied space and the ceiling plenum were depressurized to 0.201 in. WC (50 Pa) simultaneously. Since there was no pressure differential between the occupied space and the ceiling plenum, each test measured only leakage that occurred to outdoors. $CFM25_{out}$ (L/s@25_{out}) for the ceiling space was found to be 8234 (3886), while $CFM25_{out}$ (L/s@25_{out}) for the occupied space was 9688 (4573). Therefore, 46% of the total building leak area was ceiling space leaks to outdoors. The remainder of the building leak area was from the occupied space to outdoors.

In both of these buildings, air leakage from the ceiling space to outdoors was reduced because the ceiling space was at less pressure differential wrt outdoors because it was operating as a return plenum. This reduction in duct leakage that occurs because a ceiling space is used as a return plenum can be termed "negative duct leakage." It is negative because the amount of air leakage out of the building is actually reduced because the ceiling space is used as a plenum.

Consider what might be called an ideal design. The occupied zones of the building are designed to operate at +0.008 in. WC (+2 Pa) wrt outdoors, and the ceiling space is designed to operate at –0.008 in. WC (–2 Pa) wrt the occupied zones. Therefore, the ceiling plenum is at neutral pressure wrt outdoors; this results in essentially zero leakage between the plenum and outdoors. If, on the other hand, the ceiling space were not a plenum (i.e., return air is ducted), then the building pressure (in both occupied space and ceiling space) would be at, say, +0.0048 in. WC (+1.2 Pa) in both the occupied space and in the ceiling space (this pressure picked for purposes of discussion). As a result, it could be argued, the same amount of air would leak from the building through more leak sites (combined leak sites of the occupied space and the ceiling space) but with less pressure differential across those sites. In response to this, it could be argued that a greater portion of air leakage sites in central Florida buildings are located in the ceiling space, especially at the top-of-the-wall to roof intersection, so reduced pressure differentials in the ceiling space will tend to reduce infiltration more than at other locations in the building.

Consider another of the 33 buildings, this one with a ceiling return plenum. It is a one-story building that houses a police department. Moisture problems had been observed, especially in specific wall sections located behind furniture, where substantial mold and mildew growth had occurred. Testing found that exhaust air was greater than outdoor air, causing the occupied space to be at –0.018 in. WC (–4.6 Pa) wrt outdoors, and the ceiling return plenum was at –0.040 in. WC (–10 Pa) wrt outdoors. Three recommendations were made and followed: (1) decrease total exhaust fan flow, (2) repair leaks in the outdoor air duckworks (some "outdoor air" was actually coming from the ceiling space plenum), and (3) reduce ceiling space plenum depressurization wrt the occupied space by increasing the number of return transfer grilles. When these tasks were complete, pressures (wrt outdoors) went to –0.0004 in. WC (–0.1 Pa) in the occupied space and –0.0016 in. WC (–0.4 Pa) in the ceiling space plenum. With a small increase in outdoor air or decrease in exhaust air, the building could operate at positive pressure and the plenum at neutral pressure.

Wall Cavities

Wall cavities used as return plenums were found in six buildings. The most common application in our sample was in manufactured office buildings. In this situation, a package ("leech" type) AC unit is attached to an exterior wall. The exterior wall is widened to perhaps 0.5 ft (0.15 m) to 0.67 ft (0.20 m) to form a return plenum. The air handler draws air from the plenum, depressurizing the plenum, which, in turn,

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pulls air from the room through a grille located in the interior side of wall. These wall plenums were found to typically operate at pressures in the range of –0.040 in. WC (–10 Pa) to –0.080 in.WC (–20 Pa). Tracer gas testing found that, in general, these wall cavities were fairly airtight; the average return leak fraction was 5.4%, including leaks in the air-handler cabinet (but with outdoor air intake masked off). A total of ten such wall-cavity plenums were found in three manufactured office spaces.

Three other types of wall-cavity ducts were found. In a 5000 ft^2 (464.5 m^2) auditorium, two vertical concrete block wall enclosures acted as return ducts. These wall-cavity ducts were 6 ft (1.83 m) wide and 2.25 ft (0.69 m) deep and extended 18 ft (5.49 m) from floor to ceiling. Return grilles with dimensions of 4.5 ft (1.37 m) by 3.5 ft (1.06 m) were located at the bottom of the wall ducts. Metal ducts coming from the single 10,000 cfm (4720 L/s) air handler in the adjacent mechanical room connected to the top of these wall ducts. Return leaks occurred primarily at the top of the wall ducts where approximately 0.5 ft^2 (0.046 m^2) leak openings existed connecting each wall duct to the mechanical room, which is well ventilated to outdoors. Tracer gas tests revealed total RLF of 28%, including substantial leaks in the metal ducts and air handler in the mechanical room.

In a church building, a wall cavity served as a return duct. This duct was formed by construction of a partition wall 2.5 ft (0.76 m) from the poured concrete foundation wall on the ground level of the building. The duct was 2.5 ft (0.76 m) wide, 11 ft (3.35 m) tall, and 85 ft (26 m) long. Because this duct was located entirely inside the primary air and thermal boundaries of the building, there were no infiltration or energy consequences from the considerable leakage that existed in this duct. A duct airtightness test was performed showing that only 6.5% of the ADS leak area was to outdoors. While $CFM25_{tot}$ (L/s @ 25_{tot}) was 4471 (2110) for the entire ADS, $CFM25_{out}$ (L/s @ 25_{out}) was 292 (138). (Note that the majority of the $CFM25_{tot}$ (L/s @ 25_{tot}) was leakage in the wall plenum and in the return ducts and air handlers located in the mechanical room.) Two other tests confirmed that the vast majority of the duct leakage occurs to and from the conditioned space. Tracer gas tests found an RLF of only 2.3%, indicating that only 2.3% of the return air was originating from outdoors. A tracer gas decay test found that the total building ventilation rate only increased from 0.16 ACH to 0.23 ACH when the air handler was turned on (there was no outdoor air). It is noteworthy that indoor carbon dioxide levels increased from 600 ppm to more than 1800 ppm during a 70-minute worship service with about 240 persons in this 217,000 ft^3 (6140 m^3) building.

The final wall cavity plenum was part of a hotel's central exhaust system. In this case, a two-story building containing 40 guest rooms had an exhaust plenum formed by a 3-foot-wide (0.91 m) enclosed space between the two halves of the building. Four exhaust fans were located on the roof, drawing a total of 2799 cfm (1321 L/s) of air from the plenum and depressurizing it to 0.027 in. WC (6.8 Pa). This depressurization acted to draw air from the bathrooms of each guest room through grilles in the bathroom walls. However, when the airflow rates at the exhaust grilles were measured and summed, their total was 1324 cfm (625 L/s), or only 47% of the flow rate of the four fans on the roof, indicating substantial leakage in the exhaust plenum. Some of the remaining 53% was being drawn from outdoors, and the remainder was coming from the guest rooms through penetrations in the wall backing up to the exhaust plenum. However, no tests were performed to disaggregate the leakage sources.

Some test and balance (TAB) issues are raised by this hotel example. Consider the air balance implications of the leaks that occur in this hotel exhaust plenum and how the TAB test methodology deals with these leaks. TAB personnel measure exhaust flow through the bathroom grilles and compare these flows to the construction document specifications. Let's say the specifications call for 50 cfm (23.6 L/s) per room and that measured flow was 33 cfm (15.6 L/s) per room. In order to match specification, TAB personnel will increase the airflow rate of the exhaust fans. There are several problems with this. First, the pre-adjusted flow rate of air from the guest rooms may be 50 cfm (23.6 L/s) or greater, including airflow through wall penetrations. Therefore, if the exhaust flows are increased, the total amount of guest room exhaust air may exceed that specified, and this may lead to depressurization of the guest rooms wrt outdoors. In hot and humid climates, space depressurization often leads to moisture accumulation problems in wall assemblies. Since it is difficult to measure all building airflows and it is even more difficult to account for all duct leakage, good TAB practice should include testing building pressures to ensure that the various zones of the building operate at positive pressure wrt outdoors, especially in cooling climates. Second, increasing exhaust fan flow also results in increased exhaust fan energy use. Third, increasing fan flow does not solve the underlying problem of duct or plenum leakage. Instead of increasing exhaust fan flow, emphasis should be placed upon sealing plenum leaks to outdoors.

Improved TAB practice would look at the exhaust airflow rate both at the building primary air boundary (usually the roof deck where the exhaust fans are mounted) and at the exhaust grilles. Discrepancies between the exhaust flows at the two locations should be accounted for. If the exhaust flow rate is 2800 cfm (1322 L/s) at the roof but only 1400 cfm (661 L/s) at the bathroom exhaust grilles, then the tester knows that there are large duct leaks that should be sealed.

Chases

Chases were used as return plenums in 1 of 70 buildings, in this case a high school. Air handlers were located in mechanical rooms that served as return plenums. Horizontal chases of approximately 3 ft (0.91 m) × 3 ft (0.91 m) dimensions ran from the mechanical rooms. In addition to being return plenums, these chases also housed supply ducts serving

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the classrooms. Transfer grilles opened from the chases into the classrooms to allow room air to return to the air handlers. No tests were done to characterize ADS airtightness. However, the chases were located within the building air and thermal boundaries, so it is likely that the leaks that did exist would have little impact on infiltration rates or cooling energy consumption.

Other Building Cavities

Other building cavities were used as ducts in two buildings. The first, located in a safety training school, was a storage room that was used as a return plenum. A return duct ran from a packaged rooftop AC unit to a grille in the ceiling of the room, depressurizing the room to 0.032 in. WC (8 Pa). Transfer grilles in the walls and doors of the storage room allowed return air to enter from adjacent classrooms. Several problems existed that caused significant energy penalties. (1) The return transfer grilles were undersized. (2) The suspended t-bar ceiling was leaky; as a consequence, 45% of the return air was being drawn from the ceiling space. (3) The primary air boundary of the building was at the roof deck, but the thermal barrier (insulation) was located on top of the ceiling tiles. Therefore, the air drawn from the ceiling space was hot and dry and, thus, produced substantial cooling energy penalties.

Testing was done to characterize the airtightness of the storage room. $CFM25_{tot}$ (L/s @ 25_{tot}) was found to be 523 (247) (with return grille, transfer grilles, and door undercuts masked). Retrofits were done to reduce duct leakage into the storage room plenum, including reducing the amount of air being drawn from the storage room (a separate return duct was added to an adjacent classroom), adding return transfer grilles, and caulking the ceiling joints. As a result of tightening the ceiling, $CFM25_{tot}$ (L/s @ 25_{tot}) was reduced to 285 (134.5), which indicates that leaks in the 8 ft × 10 ft (2.44 m × 3.05 m) suspended ceiling were equal to 238 CFM25 (112 L/s @ 25). If we make the assumption that this caulking sealed 80% of the ceiling leakage, then this t-bar ceiling has leakiness of 3.7 CFM25/ft^2 (0.162 L/s @ 25/m^2). (Note that this 3.7 CFM25/ft^2 (0.162 L/s @ 25/m^2) is also equivalent to about 6.0 CFM50/ft^2 (0.263 Ls @ 50/m^2)). Measurements done in one other building found t-bar ceiling leakage of 5.5 CFM50/ft^2 (0.241 L/s @ 50/m^2). This excessive leakiness of suspended ceilings has important implications for b_ducts that use t-bar ceilings as part of their air containment. It also has important implications for overall building airtightness. The conclusion is this: If the t-bar ceiling is the primary air barrier and the ceiling space is well ventilated to outdoors, then the building will be quite leaky.

The second building cavity was of very unusual construction. This plenum was located in a government office in a 30-year-old strip mall. It was formed by using two different suspended ceilings as the top and bottom of the plenum. (The original ceiling was located about 1.5 ft (0.46 m) above the existing ceiling.) Foil-backed fiberglass ductboard was used to form the vertical walls of the plenum. Return grilles were located in the bottom of the plenum, allowing it to draw air from the conditioned space. Its approximate dimensions were 4 ft × 2 ft × 1.5 ft (1.22 m × 0.61 m × 0.46 m). Two return ducts ran from a packaged rooftop AC unit to each end of the plenum. The problem was that two ceiling tiles that constituted a portion of the top of the plenum box had been removed so that an opening of approximately 0.5 ft × 4 ft (0.15 m × 1.22 m) existed. Testing found the airtightness of this plenum to be 4595 $CFM25_{tot}$ (2169 L/s @ 25_{tot}), making it one of the leakiest b_ducts in this study. Under actual AC operation, this large opening was allowing 1572 cfm (742 L/s) of ceiling space air to enter the return, or 48% of total air-handler flow. Since the primary air boundary of the building was at the roof deck and the thermal barrier (insulation) was located on top of the ceiling tiles, the air drawn from the ceiling space was hot and dry and, thus, produced substantial cooling energy penalties.

DISCUSSION: DUCT LEAK INTERACTIONS WITH CEILING SPACE CONFIGURATION

Air leakage into the air-distribution system can have important impacts upon the building infiltration rate, indoor relative humidity, building pressure (with respect to outdoors), heating and cooling system performance, occupant comfort, building energy use, and indoor air quality. The magnitude of the impacts is a function of the amount of air leakage but also a function of the location of those leaks—in other words, from where is the air leaking? Since this paper is focusing on building cavity duct leaks, and these are almost always return leaks, the following discussion of duct leak interactions with the building configuration refers only to return leakage. The following discussion also assumes (1) that the duct leaks draw air primarily from the ceiling space or attic space, (2) that the buildings are located in hot and humid climates, and (3) that the thermal and humidity conditions described for the various ceiling space types refer to summer conditions.

The amount of air leakage is a function of two variables: the size of the holes in the ADS and the pressure differentials that exist across those holes. B_ducts are almost always very leaky; this means the cumulative hole size is large. Therefore, if large pressure differentials exist across those holes, there will be large air leaks. The energy, infiltration, and humidity impacts of return leaks in b-ducts (or any other return ductwork) are a function of two variables: the amount of air leakage entering the return leaks and the thermal conditions (both sensible and latent) of the air entering the return leaks. The thermal conditions of the return leak, in turn, are a function of the location of the primary air and thermal boundaries of the building. If the return leaks come from the conditioned space (inside the air and thermal boundaries), the impacts will be negligible. By contrast, if the return leaks come from a vented attic space (outside both the air and thermal boundaries), the impacts can be very large.

From an energy point of view, the temperature and humidity of the source air are critical. For example, air drawn

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from a hot and humid attic space will produce greater energy penalties than air drawn from a ceiling space that is inside both the primary building air and thermal (insulation) boundaries. From an infiltration (ventilation) point of view, the temperature and humidity are not relevant; rather, it is whether the air comes from outside the building envelope (primary air boundary) that is important. From an indoor relative humidity point of view, the absolute humidity of the return leak air is most important. The temperature of the return leak air is also relevant because higher temperatures will cause the AC to operate longer and dehumidify more effectively.

Sources of return leak air—in descending order of frequency of occurrence in central Florida commercial buildings— are ceiling/attic spaces, attached unconditioned spaces (warehouses, parking garages, etc.), outdoors, and crawl spaces. It is the first source, ceiling spaces and attics, that are most often the origin of b_duct return leaks and have the greatest range of environmental conditions. The space above the ceiling can have conditions (during the summer) that vary from cool and dry (like the conditioned space) to extremely hot and humid (like an attic space).

Thermal Environments of Various Ceiling Space Configurations

In commercial buildings, there is considerable variety in ceiling spaces and attic spaces in terms of where the primary air boundaries are located and where the thermal boundaries (the insulation) are located. Figure 1 illustrates eight building types (ceiling space types) as a function of the air and thermal boundaries. Note that in building types 2 through 7, the ceiling is suspended t-bar construction; therefore, it is quite leaky. In type 8, the ceiling is gypsum board or other tight construction.

It is important to understand that in types 4, 5, and 7, while the ceiling is the primary air barrier, this means only that it is more airtight than the vented ceiling space/attic space. Consider this: blower door testing in these 70 commercial buildings found that in some cases the roof decks of vented attics were the primary air barriers, which means that the leaks in the suspended ceiling are larger than the intentional vent openings of the attic space to outdoors! Following is a discussion of the eight ceiling space types and the thermal/humidity conditions that exist in each.

- In types 1 and 2, both the air and thermal boundaries are located at the roof deck. Therefore, the space below the roof deck is cool and dry, and ductwork located in this space can be considered to be inside the "conditioned space."
- In type 3, the ceiling space is hot and dry. It is hot because it is above the thermal barrier and dry because it is not ventilated.
- In type 4, the ceiling space (or attic space) is hot and humid. It is hot because it is above the thermal barrier and humid because it is ventilated.

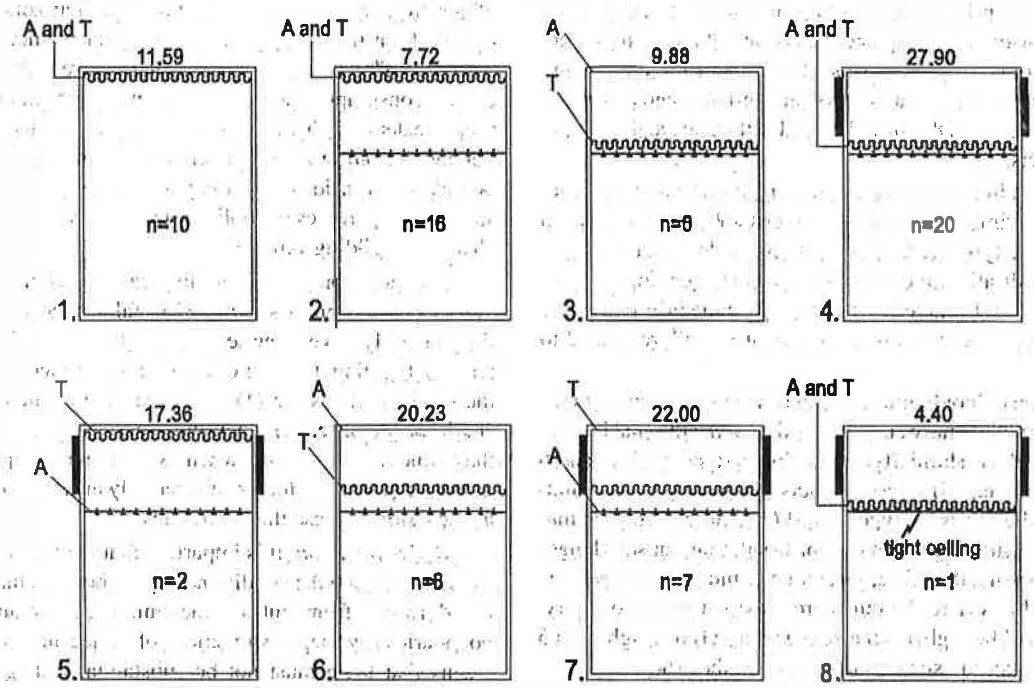

Figure 1 Ceiling space configurations in small commercial buildings. A and T stand for primary air and thermal (insulation) boundaries. N = xx is the sample size. The number above each building is average ACH50 for those buildings.

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- In type 5, the ceiling space is warm and humid. It is not hot because it is below the insulation, but it is warm and humid because it is ventilated.
- In types 6 and 7, the insulation (thermal boundary) is attached to the bottom of the truss system and so is "floating" (air above and below, not in contact with an airtight plain). The space above the thermal boundary is hot. The space below the thermal boundary may be cool or hot depending upon the direction of airflow. If the occupied space is under positive pressure, then air will flow from the occupied space into the space between the ceiling and the thermal boundary, thus keeping that space cool. If the occupied space is depressurized, then air will flow from the hot space above the insulation downward into the ceiling space below the insulation and then into the occupied space.
- In type 8, the ceiling is gypsum board (or other tight construction); by contrast, the ceilings of types 2 through 7 are suspended t-bar ceilings, which are quite leaky. (Preliminary field measurements indicate that suspended ceilings are about ten times more leaky than typical gypsum board ceilings.) This configuration is similar to type 4, except that its ceiling is much tighter, and, therefore, the overall building is much tighter. Note that ACH50 = 4.4 for the one building of type 8 compared to ACH50 = 27.9 for 20 buildings of type 4.

From an energy point of view, the location of the ADS in relation to the primary air and thermal boundaries is critical. Duct leaks from ceiling space types 1 and 2 have little effect on heating or cooling energy use; duct leaks from types 3 and 6 (hot and dry ceiling space) have large effects, and duct leaks from types 4, 7, and 8 (hot and humid ceiling space) have even larger effects.

From an infiltration (ventilation) point of view, the location of the primary air boundary is critical. Duct leaks from ceiling space types 1, 2, 3, and 6 have little effect upon the building infiltration rate. Duct leaks from the ceiling space of types 4, 5, 7, and 8 have large effects upon the infiltration rate because they draw air from a zone that is well ventilated to outdoors.

From an indoor humidity point of view, the location of the air boundary is primary and the location of the thermal boundary is secondary. Humidity will be low in types 1, 2, 3, and 6 (all else being equal) since the ducts are inside the air boundary. It will be lowest in types 3 and 6 because air drawn into duct leaks contains greater sensible load, thus causing longer AC run time and, therefore, greater dehumidification. In types 4, 5, 7, and 8, where the ducts are outside the air boundary, humidity will be higher (all else being equal) but highest in 5 because the ceiling space is not as hot as the others.

CONCLUSIONS

Building cavities used as return ducts (b_ducts) are common in small commercial buildings, being found in 33 of 70 tested buildings. These cavities are quite leaky in terms of the total leak area. The amount of air leakage is a function not only of leak area but also the pressure differentials across that leak area. Pressure differentials in b_ducts vary widely. Support platforms, mechanical closets, mechanical rooms, walls cavities, and chases experience significant negative pressures, often in the range of −0.080 in. WC (−20 Pa) to −0.401 in. WC (−100 Pa). Examples have been presented in this paper showing that b_ducts often cause substantial air leakage into the air-distribution system. Ceiling space return plenums, by contrast, are often depressurized by 0.004 in. WC (1 Pa) or less wrt the occupied zone. If the building operates at positive pressure wrt outdoors, the ceiling plenum may operate at neutral or even positive pressure wrt outdoors. Consequently, return air leakage associated with ceiling space plenums may be small or negligible.

The energy impacts of leaks in b_ducts depend upon the amount of air leakage and the conditions of the entering air. Leaks that originate from the occupied space have small or negligible impacts on cooling energy consumption. By contrast, leaks that originate from a vented attic space can cause large energy penalties. The building ventilation rate is impacted by return leaks in b-ducts if the leaks originate from spaces that are outside the primary air boundary of the building. Indoor relative humidity may increase substantially as a result of return leaks that originate from outside the primary air boundary of the building during hot and humid weather. In many cases, return leaks in b_ducts draw substantial amounts of air from hot and humid building buffer zones that are outside both the primary air and thermal boundaries of the building. This results in substantial increases in cooling energy consumption and building ventilation. In other cases, return leaks in b_ducts draw substantial amounts of air from hot and dry buffer zones that are outside the primary thermal boundary but inside the primary air boundary. This results in substantial increases in cooling energy consumption but little change in building ventilation.

In conclusion, use of building cavities as part of the air-distribution system has potential pitfalls because these cavities generally have large leak areas. Three conditions under which a building designer or contractor may wish to consider the use of b_ducts are (1) when they are located inside the conditioned space, (2) when the pressure differential across the b_duct is small, or (3) when extraordinary steps are taken to ensure that the b_duct is substantially airtight. Following is a discussion of these three variables.

B_duct location. It is important that b_ducts are not only physically inside the conditioned space but also that they will not draw air from outside the building's air and thermal boundaries by depressurization of adjacent spaces. This means that there must not be substantial leakage from the b_ducts to rooms or building cavities that may in turn draw air from outside the building air and thermal boundaries.

B_duct pressure differential. If plenum depressurization wrt unconditioned adjacent spaces can be maintained at 1 Pa

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or less, then few negative consequences are likely. Ceiling spaces used as return plenums can easily meet this criteria. Other building cavities, such as mechanical closets, mechanical rooms, or wall cavities, also can be designed to operate with minimal depressurization simply by providing sufficient return grille openings. With pressure differentials of 1 Pa or less, the energy, infiltration, and humidity impacts of b_ducts will be small or negligible.

B_duct tightening. Ensuring that b_ducts are constructed and maintained to be airtight may be a more difficult route. Since standard construction practice for building cavities is not comparable to duct airtightness construction standards, measures must be taken to set standards and establish verification protocols. Otherwise, b_ducts will not be sufficiently airtight when newly constructed. There is also the problem of ensuring that b_ducts remain airtight. It is not uncommon for various trades to cut openings in b_ducts to provide access for plumbing, electrical, etc., and not seal these openings because they may not realize these building cavities are part of the air-distribution system or realize the importance of maintaining airtightness. For these reasons, this third approach to using building cavities as ducts should be taken only with great caution.

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NOMENCLATURE

ACH50 a measure of building airtightness, is the airflow rate (expressed in building air volume exchange) through building envelope leaks when the building is depressurized to 0.201 in. WC (50 Pa).

ADS (air distribution system) is the assembly of ducts, plenums, and air handlers that conduct air from the conditioned space to the heating/cooling appliance and back to the conditioned space.

b_duct is an acronym for building cavities that are used as ducts or plenums.

CFM25 a measure of ADS airtightness, is the airflow rate through leak sites in the ADS when the ADS is depressurized to 0.100 in. WC (25 Pa), Ls@25 in SI units.

CFM25$_{out}$ is a measure of ADS leakage, where the leaks are only to outdoors. To obtain this test result, the building and ADS are depressurized simultaneously to 0.100 in. WC (25 Pa).

CFM25$_{tot}$ is a measure of ADS leakage, where the leaks are both to outdoors and to indoors.

CFM50 a measure of building airtightness, is the airflow rate through leak sites in the building envelope when the building is depressurized to 0.201 in. WC (50 Pa).

Conditioned space is considered to be all portions of the building that are located inside the primary air and thermal boundaries of the building.

Duct is a passageway—a pipe, tube, or channel— through which air moves. Airflow in a duct goes in one direction, from high pressure to low pressure.

Mechanical closet is a closet containing HVAC equipment that is smaller than a mechanical room, allowing limited or no access to persons.

Mechanical room is a room containing HVAC equipment that is large enough to allow several persons to walk around freely.

Plenum is an enclosed space that constitutes a portion of the ADS. A plenum differs from a duct in that air in a plenum is at a more or less uniform pressure and airflow is not in one direction.

Return leak fraction (RLF) is the fraction of air returning to the air handler that originates from outside the conditioned space (excluding outdoor air), typically measured by means of tracer gas, often expressed as a percent of air-handler airflow.

SMACNA is the Sheet Metal and Air-Conditioning Contractors National Association.

"wrt" is short for "with respect to" and is used to express pressure at one location compared to another location. For example, "the ceiling space plenum was at –0.010 in. WC (–2.5 Pa) wrt the occupied space but was at +0.006 in. WC (+1.5 Pa) wrt outdoors."

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