CH-99-14-2

Distribution System Leakage Impacts on Apartment Building Ventilation Rates

Iain S. Walker, Ph.D.
Member ASHRAE

ABSTRACT

Forced air distribution systems in residential buildings are often located outside the conditioned space, for example, in attics, crawl spaces, garages, and basements. Leaks from the ducts to these unconditioned spaces or outside can change flows through the registers and change the ventilation rates of the conditioned spaces. In this study, duct leakage flows were measured in several low-rise apartment buildings. The leakage flow measurements and other data about the apartments were used to develop a prototype apartment building. The multizone airflow model COMIS was then used on this prototype building to determine internal flows within the building, airflows through the building envelope, and the impacts of the duct leakage on the ventilation rates. The effects of sealing the duct leaks were also examined in order to determine changes in infiltration rates resulting from duct retrofits. The simulation results showed that for the prototype tested here, the excess return leakage tended to decrease envelope infiltration flows by about 20%, but the total infiltration load, including return duct leaks, more than doubled during system operation.

INTRODUCTION

There is a growing body of knowledge illustrating the effects of duct leakage on building energy consumption (Walker et al. 1996; Jump et al. 1996; Palmiter and Francisco 1996; Cummings et al. 1994; ASHRAE 1998). Leaks to outside conditioned space from supply ducts represent a direct loss of space-conditioning energy. For return duct leaks from outside conditioned space, the effect on the duct system is more subtle. What is important is the difference in temperature (or enthalpy for cooling systems) between indoor air (that should be entering the return duct) and air surrounding the returns that enters the return system through the leaks. For example, a return leak in a cold basement cools the air in the return duct. This results in cooler air being supplied to the conditioned space and longer system on-times to meet the same building load. The last effect of duct leakage is the change of building ventilation rate due to imbalances between the supply and return register flows into and out of the conditioned space. In a system with no leaks (or equal supply and return leaks), there is the same flow out of the supplies as into the returns, and the flow through the envelope of the building will not be affected by the duct system during system operation. However, if there are more supply duct leaks than return duct leaks to unconditioned spaces, then the return register will suck more air out of the conditioned space than enters through the supply registers. This depressurizes (relative to when the system is not operating) the space and results in more air being drawn in through the envelope of the building, thus increasing the ventilation rate and the energy load of the building. Conversely, with excess return leakage, the conditioned space becomes pressurized and the inflow through the envelope is reduced, hence reducing the airflow rate through the envelope of the building. In addition, individual rooms in the conditioned space can be pressurized or depressurized more than others when systems have multiple supply registers and few return registers. For example, the flow for a room with only a supply register can be limited by the flow restriction of a closed door between the room and the space with the return register. This pressurizes the room and reduces its infiltration rate (an estimate of the magnitude of this effect will be discussed later). Note that in this paper, the pressurization and

Iain S. Walker is a staff scientist at Lawrence Berkeley National Laboratory, Berkeley, Calif.

depressurization caused by system operation are determined relative to when the system is off and not on an absolute basis.

A key point in this paper is the separation of the envelope flows from the total ventilation rate. The total ventilation includes the flow into return leaks from outside the conditioned space. The net effect of system operation then depends on the magnitudes of both the duct leakage flows and the changes in envelope flows. If the return leak flow is greater than the reduction in envelope flow, then the net effect is to increase the infiltration load. For excess supply leaks, this complication does not occur and the supply leakage flows are made up by extra inflow through the building envelope only.

To obtain an estimate for the magnitude of these duct leakage effects on the envelope flows, calculations were made using the multizone ventilation model COMIS (Feustal and Raynor-Hoosen 1990). As with all model simulations, the applicability and interpretation of the results depend on how realistic the input data is. In this study, the duct system flows, envelope leakage, and interzonal leakage (e.g., door undercuts) were all based on field measurements in several apartment buildings. This implies that the results were typical for the housing stock used for these studies: low-rise apartment buildings.

For this study, field measurements were made of duct system flows in 23 apartments in eight buildings in New York State. Some of these measurements are discussed in greater detail in Walker et al. (1996). The duct system measurements were made before and after a duct retrofit. The retrofit involved sealing duct leaks and adding insulation to the exposed ducts in the apartment building basements (these were the accessible portions of the duct systems). Additional measurements in other similar apartment buildings were used to estimate envelope leakage (NYSERDA 1994). A prototype building was created that had typical characteristics by analyzing the layout of all the apartments in the study. Example apartment characteristics included floor area, register locations, and floor plan. The prototype building was used in the multizone airflow model COMIS to calculate ventilation flows for the apartments for three cases. The first case had no forced air system running and only natural ventilation (wind and stack effects)—this is a reference case to which the other cases are compared. The second case used measured duct system flows before the ducts were retrofitted. The third case used revised system flows based on measurements after duct leaks in the basement were sealed. Simulations were performed using COMIS on an hourly basis for the winter (December through February). Comparing the results between the three cases allowed estimation of the impact of duct system leaks on the ventilation rates (and, therefore, building load) of these apartment buildings.

FIELD STUDY RESULTS

The following is a brief summary of the field measurements. More details of these measurements were presented in Walker et al. (1996).

Duct System and Apartment Characteristics

Sketches were made of apartment and building floor plans, including register and duct locations. The visible duct lengths and diameters were also recorded. All of the apartments were heated by natural gas furnaces located in the building basements. The only exposed ductwork was in the basement, with the remainder of the duct systems in the wall and joist spaces. All but one of the buildings used a single furnace feeding four apartments, and this is the configuration that was used in the COMIS simulations. The duct systems were similar in all the apartments, using uninsulated sheet metal for both supply and return. In several buildings, sections of the returns were run in joist spaces by putting sheet-metal panning along the bottom of the joists.

All of the systems had more supply ducts and registers than returns. The average per apartment was four supply registers and a single return register. The supply registers were located in the bathroom, bedrooms, and living rooms with a single return register in the living room (as shown in Figure 1). The imbalance of supply and return registers indicates that the system flows will change the pressure differences between the rooms in the apartments and between apartments within the building. The supply register flows may pressurize rooms containing supplies only relative to outside and other apartments in the building (particularly rooms containing returns).

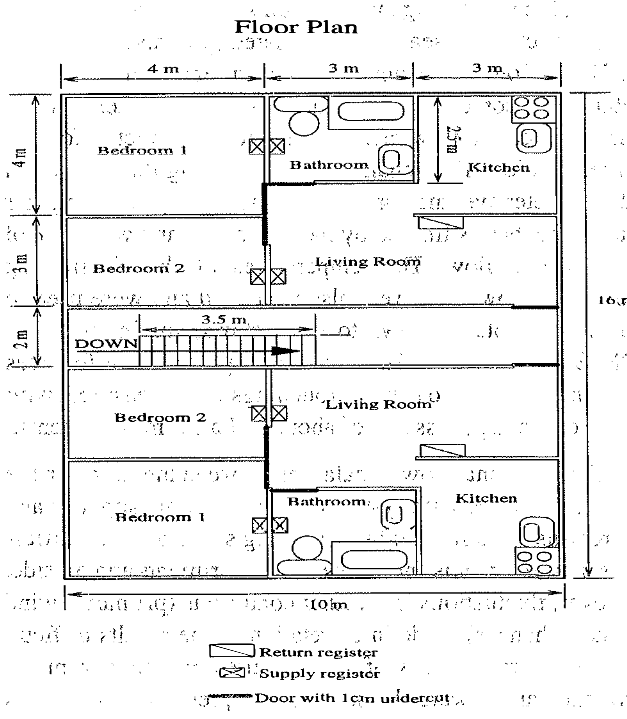

Figure 1 Prototype apartment building: two story, four apartments. The apartment building has two identical floors with a full basement below the first floor. Each floor and the basement is 2.5 m high.

These potential imbalances can be poor from an indoor air quality perspective because they may create flows between apartments carrying moisture, odors, etc.

Duct System Retrofit

The retrofit procedure consisted of sealing leaks in both supply and return ducts with mastic and tape and wrapping the ducts in foil-backed glass-fiber insulation (approximately 50 mm [2 in.] thick). Some leaks were located by simple visual inspection (e.g., large holes and joints between duct sections and ducts and plenums) and others by using smoke sticks to visualize the air leakage. The following are a couple of examples of the large holes that were found in these duct systems. In one system, two supply ducts had been cut off near the supply plenum and had been "sealed" by stuffing glass-fiber insulation into the exposed stub end of the duct. In another system, there was a disconnected supply duct and two openings in the return ducts that were 40 cm × 20 cm (approximately 17 in. × 7 in.) and 25 cm × 13 cm (approximately 10 in. × 5 in.). The large holes were sealed before any flow measurements were made because they were considered to be "repair" of duct systems, rather than leak sealing.

Duct System Measurements

All of the following measurements were made before and after the ducts were sealed and insulated (pre- and post-retrofit). The airflows were measured at each register using a flow capture hood combined with a fan-assisted flowmeter. The fan assist allowed the flow measurement to be corrected for any register and leak flow changes due to placing the flow hood and flowmeter over the register. The uncertainty in the register measurements was limited by the flowmeter and was ±3% of the measured flow. The temperatures of the air flowing through the flowmeter were also measured and were used to convert the volume flows to mass flows, for input to the COMIS simulations. The operating pressure differences between the ducts and their surroundings were measured, with typical operating pressures of about 50 Pa for most systems.

The additional flow imbalances between the rooms in the conditioned space with systems having multiple supplies and few returns were studied by measuring some pressure differences between rooms and between the apartments and outside. However, fluctuations in weather conditions (primarily wind pressure changes) made interpretation of the results difficult because the magnitudes of the pressures resulting from the flow imbalances were the same as the pressure fluctuations arising from the weather. Also, the same average weather conditions were required with the system on and off so as to separate the effects of the distribution system from the naturally occurring pressure differences due to the natural infiltration flows. Without extensive instrumentation and long-time data collection, the field measurements were not able to reliably determine these effects.

Envelope and Interior Partition Leakage

The exterior envelope leakage for apartment walls (and ceilings for the second floor) was determined from the results of field tests using blower doors to pressurize apartments (NYSERDA 1994). Expressed as a 4 Pa leakage area, a typical result from the field tests of buildings similar to the ones in this study was 6 cm^2/m^2 (0.1 in.^{2}/ft^2). It was assumed thatthis leakage was evenly distributed over the envelope. In other words, there were no specific leakage locations (e.g., around doors or windows) on the envelope. The NYSERDA (1994) report (and other similar field tests) shows that the interior partition leakage area at 4 Pa is typically 1 cm^2/m^2 (0.017 in.^{2}/ft^2). This interior partition leakage was also applied to the floors of the apartments and to the ceiling of the second floor apartments. As with the exterior leakage, this interior partition leakage was assumed to be evenly distributed over interior surfaces.

For exterior leakage of the basement, a value of 3 cm^2/m (0.142 in.^{2}/ft) of perimeter was used. Because some of the basements in the field study were extremely leaky due to poorly fitting doors and windows, the simulations were repeated to determine if having a leaky basement would affect the results significantly. The leaky basements had ten times the leakage of the regular basements (30 cm^2/m [1.42 in.^{2}/ft]).

COMIS PROTOTYPE

Figure 1 shows the floorplan for the prototype building that was based on the apartment layouts recorded in the field. The prototype had four apartments with two apartments each on two floors. The basement was all below grade but did have envelope leaks to the outside through the leaks around the top of the foundation, window wells, and doors. The single return register for each apartment was in the floor of the living room, and the four supply registers were in the living room, the two bedrooms, and the bathroom. The two floors of the apartment building had identical floor plans, and the basement has the same footprint but has no interior partitions. The conditioned floor area of the apartments was 70 m^2 (750 ft^2) per apartment for a total of 280 m^2 (3000 ft^2) for the building. Note that this did not include the stairwells or hallways because they have no registers and are not heated directly. The ceiling height for both floors and the basement was 2.5 m (8 ft). The opening in the staircase between floors was 3.5 m^2 (38 ft^2). There were door undercuts of 1 cm (0.4 in.) between rooms in the apartment and between the apartment and the hallway that were typical of the undercuts found in the field. The simulations were repeated for a single case with the interior doors for the bedrooms and bathrooms open. For all the simulations, it was assumed that the doors to the hallway remained closed. There was a single open "doorway" between the kitchen and the living room with no door in it.

To obtain appropriate flow rates for the COMIS prototype system, the flows were combined for all the tested systems. The register flows for all the apartments were summed and expressed in terms of flow per unit floor area. The floor area of the prototype building (280 m^2 [3000 ft^2]) was then used to calculate the total flow for supply and return. The flow from each register was then determined by dividing the total supply flow by the number of supply registers (four in each of four apartments, totaling 16) and the number of return registers (one in each of the apartments, totaling four). The flows are summarized in Table 1.

TABLE 1
Summary of Field Measurements and COMIS Simulation Register Flows

	Supply		Return	
	Pre-Retrofit	Post-Retrofit	Pre-Retrofit	Post-Retrofit
Total supply flow for all apartments, kg/s (cfm)	5.03 (8870)	5.45 (9610)	3.10 (5470)	4.08 (7190)
Total floor area for all apartments, m^2 (ft^2)	1800 (19380)	1800 (19380)	1800 (19380)	1800 (19380)
Flow, kg/sm^2 (cfm per ft^2)	0.0028 (0.458)	0.0030 (0.496)	0.0017 (0.282)	0.0023 (0.370)
Total prototype register flows for 280 m^2 (3000 ft^2) system, kg/s (cfm)	0.78 (1370)	0.844 (1490)	0.479 (846)	0.631 (1113)
Flow per prototype register, kg/s (cfm)	0.049 (86)	0.053 (93)	0.120 (212)	0.157 (278)
Leakage flows to and from prototype basement, kg/s (cfm)	0.064 (120)	—	0.151 (267)	—

COMIS was not used to model the duct system because the duct systems in these buildings were complex and mostly out of view and most of their characteristics were unknown. Instead, the measured register flows were included as source and sink terms for each apartment. In addition, the basement also included source and sink terms for leakage flows between the basement and the ducts.

The use of source and sink terms made the register and leakage flows constant throughout the simulations. It is possible that weather-induced pressures may change system flows; however, the system pressures were between one and two orders of magnitude greater than the weather-induced pressures. Therefore, the weather impact on the duct system flows was very small (on the order of 1% or less). Given the uncertainties in flow measurement and the parametric nature (rather than case study) of the comparisons in this paper, it was acceptable to assume the forced air system flows are constant.

The system leakage was split between leaks from the basement (that were sealed by the retrofit) and leaks from outside (not repaired). The implied assumption used here was that the duct system leaks not from the basement are from outside. Some of these leaks could have been to or from the interstitial spaces in the building (floor joist or wall stud cavities) rather than to outside. However, without any knowledge of exact leak locations, the above assumption was the simplest method of dealing with the duct leaks. In addition, many of these interstitial spaces communicated indirectly with outside (e.g., open tops of wall cavities) and so the duct leak airflow may be to or from outside via these flow paths. There were energy-use implications for this assumption, but for the subject of changing envelope flows (and bearing in mind that we are not modeling an individual building, just doing a parametric study) the assumption should be satisfactory.

Figures 2a through 2c illustrate the register and duct leakage flows used in the simulations. In these figures, the indicated register flows and envelope flows are totals for all four apartments. Assuming the same fan flow pre- and post-retrofit and that the post-retrofit supply flows are equal to the fan flow (0.84 kg/s [1490 cfm]), the difference between pre- and post-retrofit supply register flows (0.78 kg/s [1370 cfm]) was pre-retrofit supply leakage to the basement (0.06 kg/s [120 cfm]). Similarly, for returns, the difference between pre- and post-retrofit register flows was the leakage from the basement (0.15 kg/s [267 cfm]). The post-retrofit remaining difference between

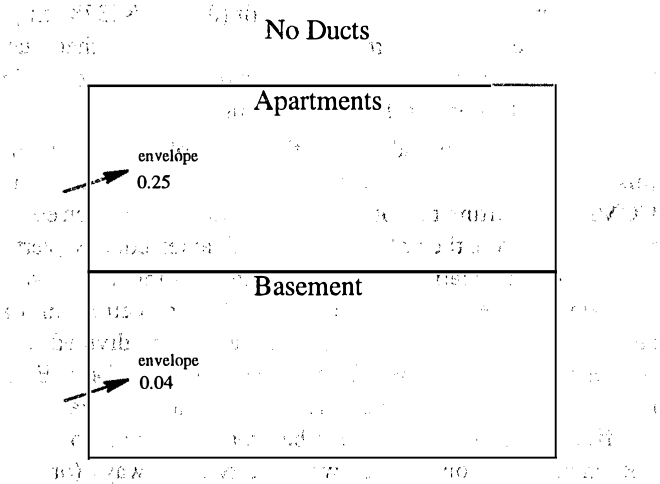

Figure 2a *Flow in through envelope with forced air system not operating. All flows in kg/s.*

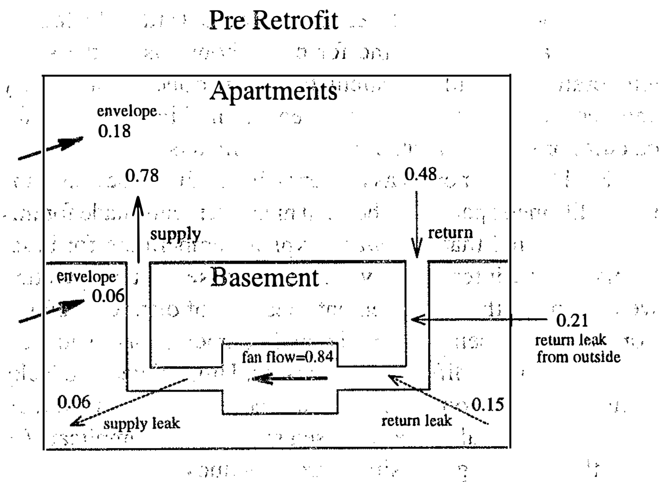

Figure 2b *Envelope, register, and duct leakage flows, pre-retrofit. All flows in kg/s.*

Post Retrofit

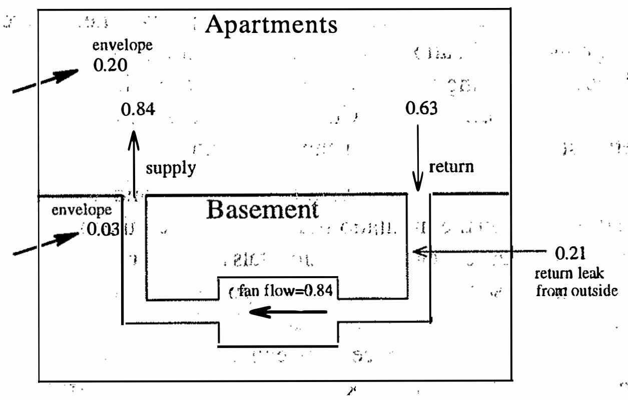

***Figure 2c** Envelope, register, and duct leakage flows, post-retrofit. All flows in kg/s.*

supply and return register flows was return leakage from outside that is unchanged by the retrofit (0.21 kg/s [378 cfm]). This return leakage flow from outside was the flow that must be added to the change in apartment envelope flows to obtain the total infiltration for the apartment building.

The distributed leakage on the walls of the apartments (discussed in the measurements section) was modeled in COMIS by splitting the total leakage for the wall into ten equal parts. These were then placed on the wall at ten equally (vertically) spaced locations. The floor and ceiling leaks were grouped together for each section of floor or ceiling into a single leak. The floor, ceiling, and walls were divided into sections bounded by the edges of the zone they form. Each room in the apartments acted as a zone, so that each apartment had five zones: two bedrooms, a bathroom, a living room, and a kitchen. Additional zones were the two hallways (one on each floor) plus the basement, for a total of 23 zones. Combining all the zones and the duct flows resulted in about 400 flow paths to be solved by COMIS.

The indoor temperatures used in the COMIS calculations are fixed and are the same for every hour. Using the same temperatures for all the calculations was done for simplicity and because we are not simultaneously making heat transfer calculations. The apartments and hallways were at 20°C (68°F). The basement was cooler at 10°C (50°F) because it is unconditioned space and the field measurements made for this study indicated that this was a typical temperature for basements in the winter. Large variations in basement temperature were found in the measurements because of different ventilation rates for basements (cold ones had open doors to outside, for example) and different duct losses. Uninsulated and leaky ducts tended to "condition" the basement and make it warmer; however, a typical value was used so as not to complicate (or bias) the modeling by using extreme values.

For simplicity, the fan was assumed to operate all of the time (i.e., no on-time weighting has been applied). It would have required a considerably more sophisticated analysis (including a thermal analysis of the building) to determine fractional on-times and weigh the results appropriately.

Wind Pressure Coefficients and Weather Data

The wind pressure coefficients were taken from the *1989 ASHRAE Handbook—Fundamentals*, chapter 14 (ASHRAE 1989), where wind pressure data are given every 45 degrees of wind direction. These data were input to COMIS for use in calculating wind pressures on the building. To account for different wind pressures on each face of the building, the exterior walls of each zone were treated separately for each face.

The weather data were taken from TMY files for Albany, N.Y., and the city of New York. These two cities both had different winter climates, with New York being 9.5°C (17°F) warmer than Albany at 99% design conditions (ASHRAE 1997) but with higher wind speeds. The COMIS simulations were performed for each hour of the winter (December through February) so that a wide range of temperature differences, wind speeds, and wind directions (and combinations of all these) were reflected in the results rather than a few special configurations.

RESULTS

In the analysis of the COMIS results, both the inflow through the building envelope and the total building inflow including return duct leaks are given. This separation was done because the impact of air infiltration changes on energy use of the building may be calculated two ways:

1. If a duct efficiency model is used, the return leaks count as a reduction in distribution system efficiency (e.g., proposed ASHRAE Standard 152P [ASHRAE 1998] and Francisco and Palmiter [1998]), and the net change in envelope flow is needed to account for changes in infiltration load. This prevents double counting of the return duct leak effect.
2. For basic infiltration load calculations, the total including return leaks is required.

The infiltration for all four apartments has been added together to obtain the total infiltration into the apartments. In the following discussion, the infiltration refers to flow into the apartments or basement only. In the following tables, the infiltration rates in kg/s are also presented in terms of air changes per hour (ACH) by dividing by the apartment or basement volume and air density and multiplying by 3600 s/h.

CASE 1—Change in Envelope Flow Only

Table 2 and Figures 2a through 2c show that the operation of the duct system reduces the infiltration rates through the building envelope. The reduction in envelope inflow was about 30% in the pre-retrofit case and 22% in the post-retrofit case. The retrofit, therefore, increased the infiltration rate by about 8% compared to the pre-retrofit case. This implies an increase in infiltration load for the apartments due to the retrofit for this case. Table 2 also shows how the excess return leakage in the

TABLE 2
Apartment and Basement Infiltration Rates for Winter Conditions

Location	Duct Configuration	Basement kg/s (cfm) [ACH]	All Apartments kg/s (cfm) [ACH]	Reduction in Apartment Infiltration Due to Duct System kg/s (cfm) [ACH]	Reduction in Apartment Infiltration Due to Duct System %
Albany	No Ducts	0.04 (70) [0.38]	0.22 (390) [0.94]	-	-
Albany	Pre-Retrofit	0.06 (105) [0.61]	0.15 (265) [0.64]	0.07 (125) [0.30]	32
Albany	Post-Retrofit	0.03 (50) [0.34]	0.17 (300) [0.72]	0.05 (90) [0.23]	23
New York	No Ducts	0.04 (70) [0.40]	0.25 (440) [1.09]	-	-
New York	Pre-Retrofit	0.06 (105) [0.60]	0.18 (315) [0.78]	0.07 (125) [0.31]	28
New York	Post-Retrofit	0.03 (50) [0.37]	0.20 (350) [0.85]	0.05 (90) [0.24]	20

basement in the pre-retrofit case increased the basement infiltration rate. The basement had a slightly lower infiltration rate in the post-retrofit case compared to no ducts because there are no duct leaks in the basement and the apartments are pressurized relative to the basement due to remaining excess return leaks from outside (resulting in greater supply than return flows). Therefore, the basement had air flowing into it from the apartments above, which acts to reduce its infiltration rate. The apartment envelope inflow was higher in New York than Albany because of the slightly more extreme climate in terms of windspeed.

CASE 2—Change in Total Inflow, Including Return Leaks

Table 3 shows that the leaky duct system's net effect was to increase total infiltration for the building. In addition, the retrofit acted to reduce this extra ventilation by about one-half. The leaks in the pre-retrofit duct system increased the total building infiltration by about 125%, more than doubling the infiltration. The additional infiltration was reduced to about 70% by the basement leak-sealing retrofit. The retrofit reduced the infiltration rate by about 0.6 ACH compared to the pre-retrofit case.

Infiltration for Separate Apartments

The COMIS results have also been analyzed on an apartment-by-apartment basis, rather than the average overall four apartments, as given in Tables 2 and 3. The standard deviation of the average infiltration from apartment to apartment was about 10%. This result showed that all the apartments have similar infiltration rates so that there are no large imbalances between apartments. A strong stack effect would have made the infiltration for the first floor apartments significantly greater than for the second floor apartments. Therefore, the natural infiltration was dominated by wind effects (with the duct system off) and by the combination of the duct system and wind effects when the system is operating. This result was also significant because it implies that on-time weighting would not have changed the result due to the weak dependence on outdoor temperature.

Effect of Open Interior Doors

Open bedroom and bathroom doors can act to reduce the pressure differences generated by rooms having supply or return registers only. To test for the magnitude of this effect, COMIS was also run with these interior doors open for January in Albany. The net effect was small, with only a 6% reduc-

TABLE 3
Apartment Infiltration Rates for Winter Conditions Including Duct System Leakage Flows

Location	Duct Configuration	All Apartments kg/s (cfm) [ACH]	All Apartments + Duct System Infiltration kg/s (cfm) [ACH]	Increase in Building Infiltration Due to Duct System kg/s (cfm) [ACH]	Increase in Building Infiltration Due to Duct System %
Albany	No Ducts	0.22 (390) [0.94]	-	-	-
Albany	Pre-Retrofit	0.15 (265) [0.64]	0.51 (900) [2.20]	0.29 (510) [1.26]	135
Albany	Post-Retrofit	0.17 (300) [0.72]	0.38 (670) [1.63]	0.16 (280) [0.70]	74
New York	No Ducts	0.25 (440) [1.09]	-	-	-
New York	Pre-Retrofit	0.18 (320) [0.78]	0.55 (970) [2.34]	0.29 (510) [1.25]	115
New York	Post-Retrofit	0.20 (350) [0.85]	0.41 (720) [1.76]	0.16 (280) [0.68]	62

tion in total envelope flows with the doors open compared to the above results with all interior doors closed.

Effect of Leaky Basement

The following results are for the simulations with the basement ten times more leaky. The major effects were increased basement ventilation and a change in the flow through the basement ceiling (the floor of the first floor apartments). The leakier basement experienced less pressure difference across its boundaries because of its increased leakage to outside. Table 4 shows how the operation of the duct system in a leaky basement increased basement leakage, by about a factor of 4, and reduced the infiltration rates into the apartments, but only by about 5%. The reduction in infiltration was about 33% in the pre-retrofit case and 22% in the post-retrofit case. The retrofit, therefore, increased the infiltration rate by about 11% compared to the pre-retrofit case, a slightly larger change than for the less leaky basements discussed above.

The total infiltration flows, including the system leakage, are shown in Table 5. Table 5 shows that the leaky basement changed the infiltration rates by only a few percent compared to the standard basement results shown in Table 3.

Estimate of Changes to Building Heating Load

A simple method was applied here that used seasonal on-time weighted outdoor temperatures for New York of 0.5°C (33°F) for outside air and a typical measured basement temperature of 10°C (40°F) to estimate the energy losses associated with the changes in envelope flow and the return duct leakage. In each case, these results were relative to the building with the system not operating.

Pre-retrofit, there was a reduction in flow through the envelope with an associated reduction in infiltration load of 1400 W (4.8 kBtu/h). The return leak from the basement more than canceled this out, with an added load of 1500 W (5.1 kBtu/h). The return leaks from outside added another 4200 W (14.3 kBtu/h) to the building load, for a net effect of an increase of 4300 W (14.7 kBtu/h). After sealing the basement duct leaks, the envelope load was decreased by 970 W (3.3 kBtu/h), with the same 4200 W (14.3 kBtu/h) additional load from outside, for a net increase in load of 3200 W (11 kBtu/h). Note that this did not account for reduced losses due to sealing the supply leaks or changes in conductive losses from the duct system.

Recalculating these losses using the 99% design temperature from ASHRAE (1997) of –9°C (16°F) resulted in an

TABLE 4
Apartment and Leaky Basement Infiltration Rates for Winter Conditions

Location	Duct Configuration	Basement kg/s (cfm) [ACH]	All Apartments kg/s (cfm) [ACH]	Reduction in Apartment Infiltration Due to Duct System kg/s (cfm) [ACH]	Reduction in Apartment Infiltration Due to Duct System %
Albany	No Ducts	0.21 (370) [1.57]	0.21 (370) [0.90]	-	-
Albany	Pre-Retrofit	0.24 (420) [1.80]	0.14 (250) [0.58]	0.07 (125) [0.32]	35
Albany	Post-Retrofit	0.20 (350) [1.53]	0.16 (280) [0.70]	0.05 (90) [0.20]	22
New York	No Ducts	0.27 (480) [2.04]	0.25 (440) [1.05]		-
New York	Pre-Retrofit	0.30 (530) [2.23]	0.17 (300) [0.72]	0.08 (140) [0.33]	32
New York	Post-Retrofit	0.27 (480) [2.00]	0.19 (335) [0.83]	0.05 (90) [0.23]	21

TABLE 5
Apartment Infiltration Rates for Winter Conditions Including Duct System Leakage Flows

Location	Duct Configuration	All Apartments kg/s (cfm) [ACH]	All Apartments + Duct System Infiltration kg/s (cfm) [ACH]	Increase in Building Infiltration Due to Duct System kg/s (cfm) [ACH]	Increase in Building Infiltration Due to Duct System %
Albany	No Ducts	0.21 (370) [0.90]	-	-	-
Albany	Pre-Retrofit	0.14 (250) [0.58]	0.50 (880) [2.15]	0.29 (510) [1.24]	138
Albany	Post-Retrofit	0.16 (280) [0.70]	0.38 (670) [1.62]	0.17 (300) [0.71]	79
New York	No Ducts	0.25 (440) [1.05]	-	-	-
New York	Pre Retrofit	0.17 (300) [0.72]	0.53 (930) [2.29]	0.29 (510) [1.23]	117
New York	Post-Retrofit	0.19 (335) [0.83]	0.41 (720) [1.75]	0.16 (280) [1.69]	66

increase in load of 6400 W (22 kBtu/h) pre-retrofit and 4800 W (16 kBtu/h) post-retrofit. Note that the basement temperature used for these design condition calculations was 5°C (41°F) so that it was halfway between indoor and outdoor conditions (just as for the seasonal temperature calculations above).

To put these losses into perspective, the capacity of the furnace (based on measured plenum temperatures and fan flow) was about 40 kW (135 kBtu/h). Assuming 60% oversizing gave an apartment building load of about 25 kW (85 kBtu/h). Therefore, the infiltration losses due to the duct system represented about 26% of the load on the building (pre-retrofit) and consumed about 16% of the system capacity at design conditions.

SUMMARY AND CONCLUSIONS

Field measurements in eight apartment buildings in New York State were used to characterize a prototype building for use in COMIS simulations. The prototype building had a floor plan and duct layout based on typical duct systems. The register and duct leakage flows were based on the average of measured flows from the field study. The prototype building was used in the COMIS multizone infiltration model to calculate hourly infiltration rates in New York City and Albany, New York. The effects of the duct system operation were determined by averaging infiltration rates for the winter months (December, January, and February). Three cases were simulated: no duct system, pre-retrofit duct flows, and post-retrofit duct flows. The difference between the pre- and post-retrofit duct flows was that the post-retrofit case had no duct leakage to or from the basement.

The simulation results show that the duct system leakage results in reductions in flow through the envelope (by up to 30%). However, if the return leaks are included to obtain the total inflow of outside air into the building, the operation of the duct system more than doubles the infiltration rate. After the basement duct leakage was sealed, the extra infiltration was approximately halved to about 70% of the infiltration with the system off. Increasing basement leakage or opening interior doors did not have a significant effect on the added infiltration, and neither did the change in climate from New York to Albany.

These large changes in infiltration rate significantly increased the winter infiltration heating load for these buildings by about 26% at design conditions (reduced to 19% by sealing basement duct leaks). Note that this load increase was for infiltration only and does not include the effects of supply duct leakage or conductive losses from the ducts.

ACKNOWLEDGMENTS

This work was supported by the Assistant Secretary for Conservation and Renewable Energy of the U.S. Department of Energy, Office of Building Technologies, Existing Buildings Research Program, under Contract No. DE-AC03-76SF00098.

The research reported here was supported by the New York State Energy Research and Development Authority.

REFERENCES

ASHRAE. 1989. *1989 ASHRAE Handbook—Fundamentals.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE. 1997. *1997 ASHRAE Handbook—Fundamentals.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE. 1998. Proposed ASHRAE Standard 152P. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Cummings, J.B., J.J. Tooley, M. Moyer, and R. Dunsmore. 1994. Impacts of duct leakage on infiltration rates, space conditioning energy use, and peak electrical demand in Florida houses. *Proc.1994 ACEEE Summer Study,* Vol. 9, pp. 65-76.

Feustal, H.E., and A. Raynor-Hoosen, eds. 1990. Fundamentals of the multizone airflow model—COMIS. *AVIC Technical Note 29.* Coventry, U.K.: Air Infiltration and Ventilation Centre (International Energy Agency, Annex 5).

Jump, D.A., I.S. Walker, and M.P. Modera. 1996. Field measurements of efficiency and duct retrofit effectiveness in residential forced air distribution systems. *Proc. 1996 ACEEE Summer Study,* vol. 1, pp. 147-155.

NYSERDA (New York State Energy Research and Development Authority). 1994. *Simplified blower door techniques for multi-family buildings.*

Palmiter, L., and P. Francisco. 1996. A practical method for estimating the thermal efficiency of residential forced air systems. *Proc.1996 ACEEE Summer Study,* vol. 1, pp. 177-185.

Walker, I.S., M.P. Modera, A. Tuluca, and I. Graham. 1996. Energy effectiveness of duct sealing and insulation in two multifamily buildings. *Proc.1996 ACEEE Summer Study,* vol. 1, pp. 247-254.