Airtightness of Commercial and Institutional Buildings: Blowing Holes in the Myth of Tight Buildings

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ABSTRACT

It is often assumed that commercial and institutional buildings are fairly airtight and that envelope air leakage does not have a significant impact on energy consumption and indoor air quality in these buildings. Furthermore, it is also assumed that more recently constructed buildings are tighter than older buildings. The fact of the matter is that very few data are available on the airtightness of building envelopes in commercial and institutional buildings. The data that do exist show significant levels of air leakage in these buildings and do not support correlations of airtightness with building age, size, or construction. This paper presents the airtightness data that are available and the limited conclusions that can be drawn from these data.

INTRODUCTION

Many discussions in the popular press and the technical literature refer to commercial and institutional buildings, and newer buildings in particular, as being airtight. These "tight buildings" are often blamed for a host of indoor air quality problems, including high rates of health complaints among building occupants and more serious illnesses. Furthermore, discussions and analyses of energy consumption in commercial and institutional buildings are generally based on the assumption that envelope air leakage is not a significant portion of the energy used for space conditioning. These statements regarding the impacts of building airtightness are almost never supported by any test data for the buildings in question. They are also often based on confusion between building envelope tightness and low ventilation rates.

Building envelope airtightness is important based on its relevance to the estimation of building ventilation rates as they impact energy consumption and indoor air quality. Envelope airtightness is one critical input to building airflow models (Feustel and Dieris 1991; Walton 1997), which predict air leakage rates through the building envelope induced by outdoor weather and ventilation system operation. These predicted airflow rates can then be used to estimate the energy consumption associated with air leakage and to investigate the potential for energy savings through improvements in envelope airtightness and in ventilation system control (Emmerich and Persily 1998). In addition, these airflow rates can be used to predict indoor contaminant levels and occupant exposure to indoor pollutants and then to evaluate the impacts of various indoor air quality control strategies. Therefore, it is important to have reliable values of envelope airtightness for commercial and institutional buildings.

In discussions of envelope airtightness and ventilation, it is important to distinguish between envelope leakage or infiltration and outdoor air intake or ventilation. *Leakage* and *infiltration* refer to the unintentional and uncontrolled flow of outdoor air into a building through leaks in the building envelope caused by pressures induced by weather and ventilation equipment operation. *Outdoor air intake* and *ventilation* are the intentional and, ideally, controlled flow of outdoor air into a building via either a mechanical or natural ventilation system. A building can be very tight in terms of leakage and have sufficient, or even too much, outdoor air ventilation. Similarly, a building can have a very leaky envelope but have insufficient outdoor air ventilation under some circumstances, particularly during mild weather conditions. In mechanically ventilated buildings, it is desirable to have a tight envelope, as envelope leakage has several potentially negative consequences. These include uncontrolled and unconditioned outdoor air intake, thermal comfort problems, material degradation and moisture problems that can lead to microbial growth and serious indoor air quality problems.

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Building envelope airtightness can be measured with fan pressurization testing, which provides a numerical value that quantifies the physical airtightness of a building. This paper reports on the analysis of envelope airtightness data on 139 commercial and institutional buildings assembled from the published literature. It is the only such collection and analysis that have been presented to date and is, therefore, the only known basis for making statements regarding the airtightness of this group of buildings. Nonetheless, the number of buildings is small and they are not a random sample of the building stock at large. Therefore, any conclusions from this analysis have limited generalizability.

MEASURING ENVELOPE AIRTIGHTNESS

The airtightness of building envelopes is measured using a fan pressurization test in which a fan is used to increase (or decrease) the pressure within a building above (or below) the outdoor pressure. The airflow rate through the fan required to maintain this induced pressure difference is then measured. Generally, a series of pressure differences is induced during a pressurization test, ranging from about 10 Pa (0.04 in. of water) to as high as 75 Pa (0.3 in. of water). These elevated pressures are used in order to override the pressure differences induced by weather effects, that is, indoor-outdoor air temperature difference and wind speed. Therefore, the test results are independent of weather conditions and provide a measure of the physical airtightness of the exterior envelope of the building. As mentioned earlier, envelope airtightness values can be used in airflow models to predict building infiltration rates induced by weather and ventilation system operation. There is no simple calculation method or rule of thumb to relate envelope airtightness to infiltration in commercial buildings due to the complexity of these buildings and the effects of ventilation system operation. Generally, multizone airflow models must be used to relate airtightness to infiltration (Feustel and Raynor-Hoosen 1990; Feustel and Dieris 1991; Walton 1997).

ASTM Standard E779 (ASTM 1987) is a test method that describes the fan pressurization test procedure in detail, including the specifications of the test equipment and the analysis of the test data. In conducting a fan pressurization test in a commercial building, the building's own air-handling equipment can sometimes be employed to induce the test pressures. A CGSB standard exists that describes the use of the air-handling equipment in a building to conduct such a test (CGSB 1996). In other cases, a large fan is brought to the building to perform the test. The same procedure is often used to measure the airtightness of single-family residential buildings, where the test equipment is generally referred to as a blower door (Sherman 1995). Chapter 25, "Ventilation and Infiltration," of *ASHRAE Fundamentals* (ASHRAE 1997) contains a short description of fan pressurization testing.

The results of a fan pressurization test are in the form of a series of indoor-outdoor pressure differences and the airflow rates required to induce them. The results of such a test, based on these data, are reported using a variety of parameters. Often, the test results are reported in terms of the airflow rate at some reference pressure divided by the building volume, floor area, or surface area. Such normalization accounts for building size in interpreting the test results. In other cases, the pressure differences and airflow rates are fitted to a curve of the form

$$Q = C\Delta p^n,$$

where Q is the airflow rate induced to maintain the indoor-outdoor pressure difference Δp, C is referred to as the flow coefficient, and n is the flow exponent. Once the values of C and n have been determined from the test data, the equation can be used to predict the airflow rate through the building envelope at any given pressure difference. Often, especially in houses, this equation is used to calculate the airflow rate at an indoor-outdoor pressure difference of 4 Pa (0.016 in. of water). This airflow rate is then used to estimate the so-called effective leakage area (ELA) of the building, which is the area of an orifice with a discharge coefficient of 1 that would result in the same airflow rate at the reference pressure difference. Effective leakage area is sometimes calculated at pressure differences other than 4 Pa (0.016 in. of water) and for other values of the discharge coefficient.

The airtightness data presented in this paper are collected from a number of different studies that use different units to report envelope airtightness. The results in this paper are presented as airflow rates at an indoor-outdoor pressure difference of 75 Pa (0.3 in. of water) normalized by the surface area of the building envelope. (When necessary, this conversion was based on an assumed value of the flow exponent of 0.65.) The values of envelope airtightness are given in units of $m^3/h \cdot m^2$, which can be converted to cfm/ft^2 by multiplying by 0.055. Another common airtightness unit used in houses is the effective leakage area at 4 Pa (0.016 in. of water), which can also be normalized by the surface area of the building. To convert the 75 Pa airflow rate to the 4 Pa ELA normalized by the surface area, in units of cm^2 of leakage area per m^2 of wall area, one multiplies by 0.16.

Another common measure of airtightness that is often used in single-family residential buildings is the air change rate at 50 Pa (0.2 in. of water). This air change rate is the airflow rate required to achieve a 50 Pa (0.2 in. of water) pressure difference divided by the building volume. There have been a much larger number of pressurization tests conducted in single-family residential buildings than in the commercial buildings that are the subject of this paper (Sherman and Dickerhoff 1998). Based on the residential building data obtained in the U.S. (ASHRAE 1997), a value of 2 air changes per hour, or 2 h^{-1}, at 50 Pa could be considered a very tight house, while a value of 5 h^{-1} could be considered moderately tight. A value of 10 h^{-1} could be considered as typical, while 20 h^{-1} or higher would be considered leaky. While the data on residential buildings are not sufficient to support these designations based on a sound statistical analysis, these values are useful reference points.

TABLE 1
Summary of Commercial Buildings Analyzed

Dataset	Country/State	Number of Buildings	Mean Number of Stories	Mean Age (Years)	Range of Ages (Years)
NIST Offices	USA	8	6.1	18.3	8 - 23
NRC Offices	Canada	8	18.5	27.5	24 - 34
BRE Offices	UK	10	NA[1]	17.2	7 - 35
FL Offices	USA/FL	22	1.0	25.8	4 - 67
NY Schools	USA/NY	13	NA	NA	NA
NRC Schools	Canada	11	1.0	31.7	25 - 46
FL Schools	USA/FL	7	1.0	27.4	8 - 33
NRC Retail	Canada	10	NA	31.4	18 - 44
FL Retail	USA/FL	6	1.0	21.8	4 - 32
Industrial	Sweden	9	NA	NA	NA
FL Industrial	USA/FL	9	1.1	24.9	4 - 57
FL Other	USA/FL	25	NA	NA	NA
Other	Canada	1	5	10	10

[1] NA means that this information is not available for that group of buildings.

SOURCES AND SUMMARY OF DATA

This paper is based on the evaluation of measured envelope airtightness data from commercial and institutional buildings around the world. Based on a review of the published literature, airtightness data were assembled for 139 buildings. The buildings include office buildings, schools, retail buildings, industrial buildings, and a number of other building types. Table 1 contains a summary of the buildings that are considered in this paper, including information on building type, location, number of stories, and age. The largest number of buildings tested, 69 of the 139 buildings, were part of a study conducted by the Florida Solar Energy Center (FSEC) (Cummings et al. 1996). These 69 buildings fall into the categories of office buildings, schools, retail buildings, industrial buildings, and other. The 70 other buildings considered include office buildings from the U.S. (Persily and Grot 1986; Persily et al. 1991), Canada (Tamura and Shaw 1976), and the U.K. (Perera et al. 1997), school buildings from New York (Brennan et al. 1992) and Canada (Shaw and Jones 1979), retail buildings from Canada (Shaw 1981), and industrial buildings from Sweden (Lundin 1986).

It should be apparent from Table 1, and from closer examination of the data on which this table is based, that the 139 buildings are not a representative collection of commercial buildings around the world or within any given country. Rather, each dataset was obtained in an individual study conducted to demonstrate the applicability of a measurement technique and to obtain some limited airtightness data for a building type in a given area. This small number of buildings, relative to the number of commercial buildings that exist, and their lack of representativeness limit the generalizability of any conclusions drawn from studying the data.

Note that there is a predominance of one-story buildings for all but the office buildings and that almost all of the buildings from the Florida study have only one story. The mean ages of the buildings in the data sets all range from about 20 to 30 years and the ranges of ages in each dataset are similar, with the exception of the NRC buildings, which tend to be somewhat older than the rest of the buildings.

Table 2 summarizes the airtightness data, again grouped by building data set as in Table 1. For each of the data sets, except the "other" category in Table 1, Table 2 presents the mean air leakage rate at 75 Pa in units of $m^3/h{\cdot}m^2$, as well as the standard deviation and the minimum and maximum values. These values are also presented for all 139 buildings, the buildings in the Florida study alone, and the 70 buildings not from the Florida study. The mean airtightness value for all the buildings is 27.1 $m^3/h{\cdot}m^2$, but the range and standard deviation are large. The buildings from the Florida study tend to be leakier than the rest, with a mean airtightness value of 34.0 $m^3/h{\cdot}m^2$ compared to 20.3 $m^3/h{\cdot}m^2$ for the rest of the buildings. The two tightest groups of buildings are the schools in New York and the industrial buildings in Sweden. There is no particular reason to expect these buildings to be tighter than the rest, other than the tendency of buildings in Nordic countries to be tighter than those in North America and the rest of Europe. Among the four data sets of office buildings, the mean airtightness values are lowest in the Canadian buildings, followed by the U.S. (National Institute of Standards and Technology [NIST]), UK (Building Research Establishment [BRE]), and Florida buildings.

TABLE 2
Summary of Airtightness Data

Air Leakage at 75 Pa, m³/h·m²				
Dataset	**Mean**	**Standard Deviation**	**Minimum**	**Maximum**
NIST Offices	15.3	12.3	3.9	43.3
NRCC Offices	10.6	5.4	4.9	22.5
BRE Offices	23.3	11.9	10.8	41.7
FL Offices	36.0	28.6	5.8	124.5
NY Schools	8.5	4.3	2.7	14.7
NRCC Schools	28.3	8.4	17.6	44.1
FL Schools	24.5	15.4	10.9	53.9
NRCC Retail	49.3	19.6	20.6	71.3
FL Retail	33.0	24.9	4.0	75.1
Industrial	5.7	2.4	2.7	10.2
FL Industrial	41.4	26.6	12.6	97.1
All 139 Buildings	27.1	21.5	2.7	124.5
Florida Study	34.0	23.1	4.0	124.5
Non-Florida Buildings	20.3	17.4	2.7	71.3

Table 3 presents airtightness values for single-family residential buildings in units of the airflow rate at 75 Pa normalized by surface area. As mentioned earlier, these residential building tightness values are presented as reference points for comparison and are not based on any particular buildings.

TABLE 3
Air Leakage Value for U.S. Houses[1]

Air Leakage at 75 Pa, m³/h·m²	
Tight, 2 h⁻¹ at 50 Pa	
One-Story House	3.5
Two-Story House	4.3
Moderately Tight, 5 h⁻¹ at 50 Pa	
One-Story House	8.8
Two-Story House	10.7
Typical, 10 h⁻¹ at 50 Pa	
One-Story House	17.5
Two-Story House	21.4
Leaky, 20 h⁻¹ at 50 Pa	
One-Story House	35.0
Two-Story House	42.8

[1] The one-story house is assumed to have a floor area of 150 m^2 (1610 ft^2) and a ceiling height of 2.4 m (8 ft.). The two-story house is assumed to have a floor area of 100 m^2 (1080 ft^2) on each floor. Both houses are assumed to have a square floor plan.

Comparing these residential leakage values to those for the commercial buildings in Table 2, it is seen that the mean airtightness values for the commercial buildings fall in the range of typical to leaky houses. Therefore, in terms of airtightness per unit envelope area, a measure of airtightness of the envelope construction itself, it is seen that the commercial buildings that have been evaluated are not particularly airtight relative to U.S. houses and some are quite leaky. Note that the airtightness values of typical U.S. houses are not exceptional when compared with houses constructed with the goal of achieving high levels of airtightness, particularly those in the Nordic countries and Canada (ASHRAE 1997; Proskiw 1995), where values less than 2 h^{-1} at 50 Pa are not uncommon.

ANALYSIS

The airtightness data for commercial and institutional buildings were analyzed to assess the impact of a number of factors on envelope airtightness including building age, wall construction, building type, and number of stories. It is important to note that the small number of buildings tested limits the strength of any conclusions concerning the impacts of these factors on envelope airtightness.

Building Age

The first parameter, building age, has been cited in conventional wisdom as a prime determinant of airtightness, with references to "hermetically sealed modern office buildings" and the "fact" that new buildings are tighter than older buildings. Figure 1 is a plot of the airtightness at 75 Pa vs. year of construction for the 117 buildings for which the year of construction is reported. The 69 buildings in the Florida study

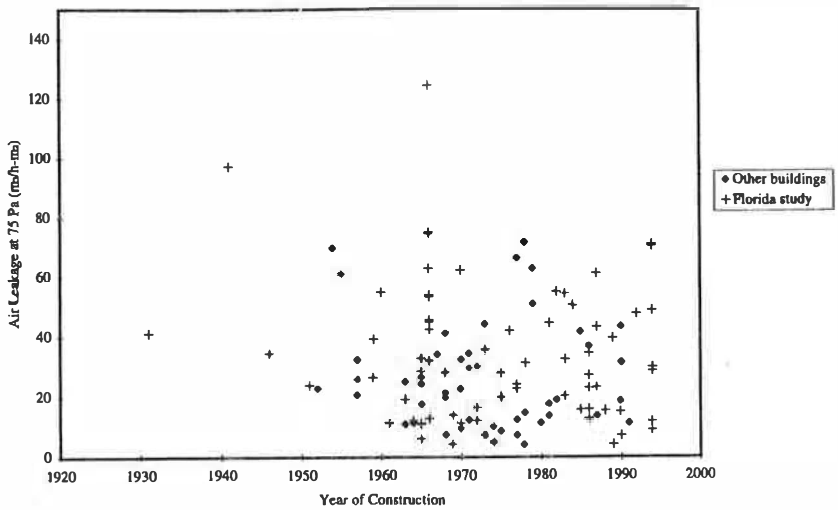

Figure 1 Airtightness vs. year of construction.

are distinguished from the rest of the buildings in the plot. No correlation between airtightness and year of construction is evident for the buildings as a group or for the two subsets of buildings. The buildings constructed before 1960 appear to be leakier than the rest, but the number of such buildings is too small to draw any firm conclusions. Regardless of the situation with the older buildings, there is no suggestion that newer buildings are tighter.

One might speculate that buildings get leakier as they get older, as seals deteriorate and buildings settle. This suggestion was investigated by plotting airtightness against the age of the building when tested. Since the date of the pressurization tests was not given in the references, the difference between the year of publication and year of construction of the building is used as a surrogate for the building age. Figure 2 is a plot of the airtightness vs. this measure of building age when tested. Again, no correlation between airtightness and age is evident, with the exception of a relatively small number of older buildings.

Wall Construction

In many of the buildings tested, information was available on wall construction, and the airtightness data were examined relative to this factor. Figure 3 presents the air leakage at 75 Pa for each type of wall construction considered. For each wall type, the plot shows the mean value of envelope air leakage value, plus and minus one standard deviation, and the minimum and maximum values. The number of buildings of each wall type is shown on the horizontal axis. The wall types of the buildings in the references were not generally described in any detail; therefore, the

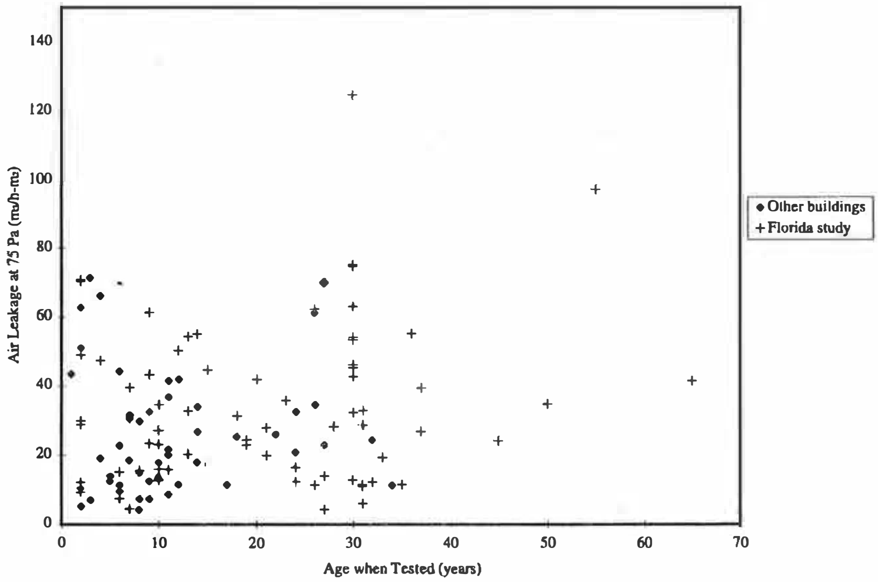

Figure 2 Airtightness vs. age when tested.

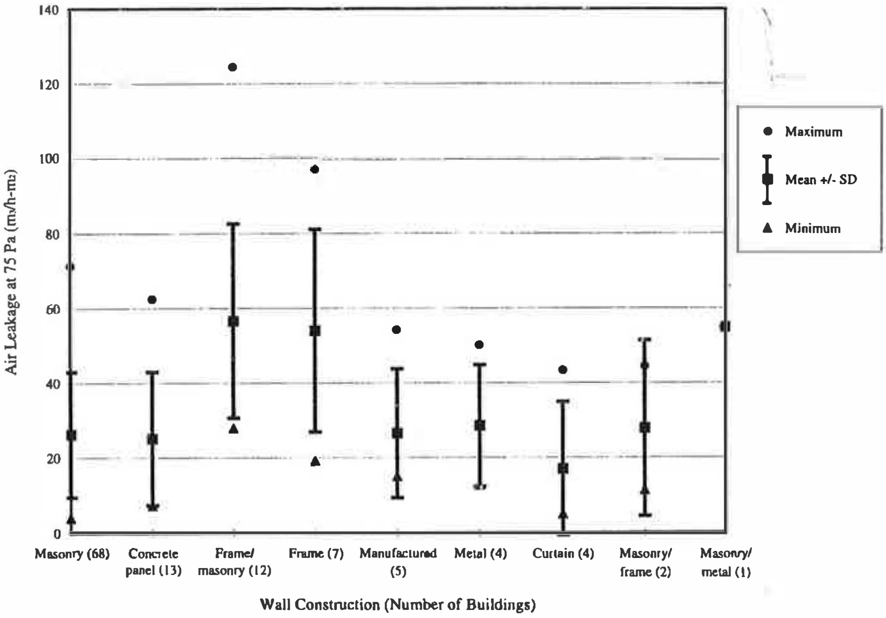

Figure 3 *Airtightness values grouped by wall construction.*

classifications may not be the same for each group of buildings. In addition, the Florida study included some wall types not included in the other studies, including frame/masonry, frame, masonry/frame, and masonry/metal. Examining the mean air leakage values, it is seen that the masonry, concrete panel, manufactured, metal, curtain, and masonry/frame buildings were similar in airtightness, with insignificant differences in the mean values relative to the values of the standard deviations. These mean air leakage values are all around 25 $m^3/h{\cdot}m^2$. The frame/masonry and frame buildings appear to be somewhat leakier, about 55 $m^3/h{\cdot}m^2$, but their mean values appear to be dominated by some particularly leaky buildings. Also, the masonry/metal building is in the 55 $m^3/h{\cdot}m^2$ range, but there is only one building with that wall type. Therefore, for the buildings studied, wall construction does not appear to have a significant impact on envelope airtightness. However, there is a suggestion that frame walls may be somewhat leakier.

Building Type

The airtightness values were also examined with respect to the type of building. Figure 4 presents the air leakage at 75 Pa by building type. As in Figure 3, the mean, plus and minus one standard deviation, and the minimum and maximum air leakage values are presented for each building type, along

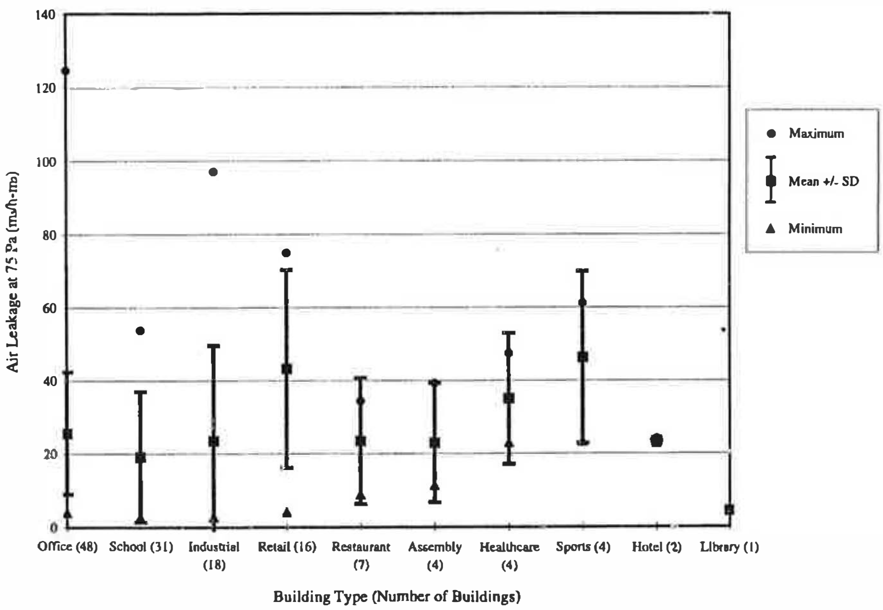

Figure 4 *Airtightness values grouped by building type.*

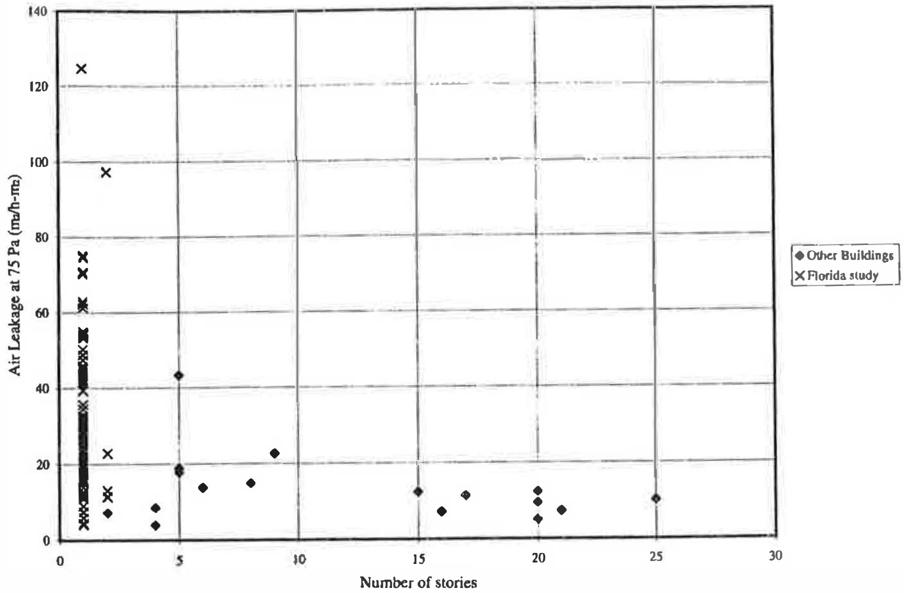

***Figure 5** Airtightness vs. number of stories.*

with the number of buildings of that type. The three most common building types, office, school and industrial, all have a mean value of about 25 m^3/h·m^2. In addition, the mean air leakage values for the restaurants, assembly buildings, and hotels are also in that same range. The mean for the retail buildings is somewhat higher, over 40 m^3/h·m^2. The health care and sports buildings are also leakier, but there are very few of these buildings. It is interesting to note that the minimum air leakage for the four most common building types, including retail, are all very similar. This similarity could indicate that there is nothing inherent in this building type that would preclude the existence of a tight envelope. As in the case of wall construction, building type does not appear to have a significant impact on envelope airtightness for the buildings studied, with the exception that the retail buildings in this group are somewhat leakier.

Number of Stories

The air leakage values were also examined relative to the number of stories of the buildings tested. Figure 5 is a plot of the air leakage at 75 Pa vs. number of stories, based on those buildings for which the number of stories was reported. This plot reveals an impact of building height on airtightness, with the taller buildings appearing to be tighter and the shorter buildings covering the full spectrum of airtightness values. All of the buildings with 15 stories or more have air leakage values less than 12 m$_3$/h·m^2. The buildings with five to ten stories are around 20 m^3/h·m^2, with one exception, and the one- and two-story buildings range from as low as about 3 m^3/h·m^2 to as high as 124 m^3/h·m^2. All of the taller buildings (15 stories or more) are office buildings, with one from the NIST study of U.S. office buildings and the rest from the National Research Council (NRC) study in Canada. They also all have concrete panel or curtain wall construction. The mid-height buildings (five to ten stories) are also office buildings, plus one five-story apartment building. Three of the buildings with air leakage values of about 20 m^3/h·m^2 or less have concrete panel walls and one has masonry walls; the leakiest of the group (about 43 m^3/h·m^2) has a curtain wall. Without additional study of the construction, it is difficult to explain the trends seen in Figure 5, but it appears that the type of construction seen in the taller buildings lends itself to more airtight envelopes. Taller buildings might require more careful design and construction to deal with the more demanding structural requirements, such as increased wind loads, and with the control of rain penetration. The one- and two-story buildings do not necessarily have the same level of performance requirements, and they include more types of wall constructions than the taller office buildings. These factors may result in buildings that are much leakier. However, some of the shorter buildings achieve the same levels of airtightness as the taller buildings. Finally, even the tighter buildings have airtightness values that correspond to only moderately tight single-family residential buildings, according to the classifications in Table 3.

SUMMARY

A data set of 139 commercial buildings was assembled from the published literature, and their air leakage values, as determined by fan pressurization testing, were examined. The buildings examined, including 90 in the U.S., are clearly a tiny fraction of the total number of commercial and institutional buildings that exist. The 1995 Commercial Building Energy Survey (CBECS) database includes 4.6 million commercial buildings in the U.S. alone (DOE 1997). In addition, the buildings discussed in this paper are not a random sample in terms of size, age, construction, or any other factor. Therefore, no statistically based generalizations can be made regarding the influence of these factors on envelope airtightness. Nonetheless, conventional wisdom implies that newer buildings are tighter than older buildings. This hypothesis was examined with these data and no correlation was seen. Nor was any correlation seen between air leakage and the age of the buildings when tested. Furthermore, the air leakage of these buildings was compared with that of single-family residential buildings, for which a great deal more air leakage data exist. Based on this comparison, the commercial buildings were not seen to be significantly tighter than U.S. houses, which are fairly leaky compared with residential buildings in other countries.

Other factors besides age were examined with respect to their impact on airtightness. For the buildings studied, wall construction does not appear to have a significant impact on envelope airtightness, but there is a suggestion that frame walls may be somewhat leakier. Also, building type does not have a significant impact on envelope airtightness for the buildings studied, with the exception that the retail buildings in this group appear to be slightly leakier. The air leakage data from these buildings do reveal an impact of building height on airtightness, with the taller buildings being tighter on average and the shorter buildings covering a wide range of airtightness from low to high. Without additional study of the construction, it is difficult to explain this trend, but the taller buildings may be tighter because the type of construction seen in these buildings leads to more airtight envelopes.

This database of envelope airtightness of commercial and institutional buildings is limited in number and randomness, making generalizations regarding correlations of airtightness with age or any other particular building feature difficult. In order to make such generalizations and to perform more reliable estimates of energy efficiency opportunities through air leakage control, more airtightness data need to be collected in commercial and institutional buildings. A research effort involving the testing of randomly selected buildings would produce a dataset from which statistically valid generalizations could be drawn regarding the airtightness of the building stock and the impact of building age, construction type, and other features.

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