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VENTILATION RATES IN OFFICE BUILDINGS

Andrew Persily
ASHRAE Member

ABSTRACT

The ventilation rate of an office building impacts the building air quality in terms of both thermal comfort and pollutant levels. Although office building ventilation systems are generally designed to provide specific amounts of ventilation under given conditions of weather and occupancy, the actual ventilation rates can be very different from the building design values. These differences between design and performance occur for a variety of reasons involving the design, installation, maintenance, and operation of the equipment, as well as interactions between the ventilation system and the building structure. Actual, measured ventilation rates in office buildings are required to compare the ventilation performance to design rates and ventilation standards, and to provide realistic inputs for models that predict pollutant levels, estimate pollutant exposures, and calculate thermal loads in buildings.

The National Institute of Standards and Technology (NIST, formerly the National Bureau of Standards) has been studying ventilation in office buildings for several years. This research has included the measurement of ventilation rates in 14 office buildings for periods on the order of one year, and has produced a data set of about 3000 ventilation measurements under a range of weather and building operation conditions. These data are a unique source of actual ventilation rate measurements in office buildings, and are the subject of this paper. Although measurements in only 14 buildings are insufficient to make generalizations regarding the impact of building age, construction, ventilation system type, and building location, these data do provide an indication of current practice. Although the ventilation rates vary considerably among the buildings and for each individual structure, many of the buildings have ventilation rates below recommended levels and/or design values during significant portions of the year.

INTRODUCTION

Air exchange is required in buildings in order to provide acceptable air quality in terms of indoor contaminant levels and thermal comfort. Although a specified level of air exchange does not guarantee acceptable air quality without the control of pollutant source strengths, ventilation standards and guidelines exist for most building types. For example, ASHRAE Standard 62, Ventilation for Acceptable Air Quality (ASHRAE 1989), specifies minimum levels of outdoor air intake for various space types. This standard is based on maintaining a comfortable interior environment, free from contaminant irritation and adverse health effects. It cannot, however, guarantee the maintenance of acceptable indoor air quality in the presence of unusually high contaminant sources. The ASHRAE standard specifies 10 L/s (20 cfm) per person in general office space with different recommendations in spaces such as conference rooms, reception areas, and bathrooms. HVAC design specifications for office buildings, in addition to specifying the airflow rates for each air-handling system, specify the minimum amount of outdoor air intake for these systems. These minimum amounts are generally based on some guideline, such as the ASHRAE standard.

In recent years, air exchange rates have been measured in several office buildings using tracer gas techniques (Persily and Grot 1985). The National Institute of Standards and Technology (NIST) has made measurements of air exchange in 14 office buildings, monitoring each building over about one year and making more than 3000 air exchange measurements. This paper summarizes the results of these measurements and compares the results to recommended levels of ventilation and to each building's minimum outdoor air intake specifications. In most of the office buildings studied, the measured air exchange rates are below recommended levels and/or design values during a significant portion of the building's occupied hours.

OFFICE BUILDING VENTILATION

All of the buildings discussed in this paper, and most modern office buildings in North America, are mechanically ventilated. The purpose of these ventilation systems is to provide conditioned air in order to maintain the interior air temperature and relative humidity at comfortable levels for the building occupants, as well as to maintain appropriate conditions for equipment and materials within the building. In addition, mechanical ventilation is intended to provide sufficient outdoor air to keep various indoor contaminants at acceptable levels. The net air exchange rate of an office building includes both the outdoor air intake associated with the mechanical ventilation system plus the rate of infiltration of outdoor air through the building envelope.

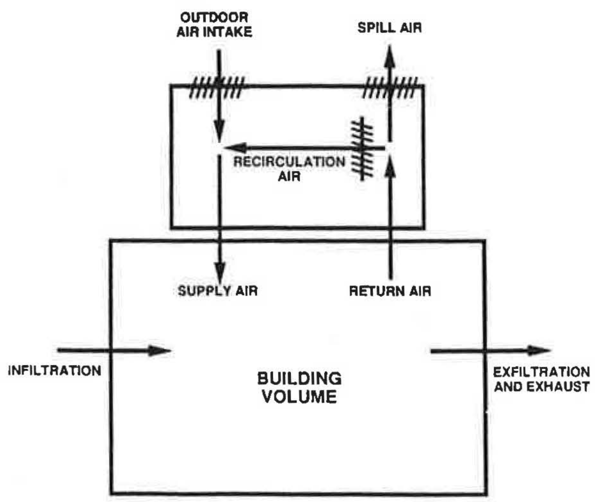

Figure 1 Schematic of a building ventilation system

National Institute of Standards and Technology, Gaithersburg, MD.

TABLE 1

Basic Building Information

Building	Year of Construction	Number of Stories	Floor Area (m^2)
A	1974	7	71,000
B	1987	7	46,000
C	1969	15	28,000
D	1984	3	12,100
E	1984	3	12,100
F	1981	7	66,400
G	1982	5	14,600
H	1977	2	1,900
I	1978	8	18,600
J	1978	4	6,900
K	1972	5	3,600
L	1977	15	20,700
M	1975	4	5,300
N	1981	6	48,500

TABLE 2

Description of the Buildings Mechanical Ventilation Systems

	Supply Fan Capacity		Minimum Outdoor Air Intake		
Building	Air changes per hour	(cfm/ft^2)	Air changes per hour	(cfm/ft^2)	Percent of Supply Air
A	*	*	*	*	*
B	3.0	(.61)	*	*	*
C	1.7	(.24)	1.70	(.24)	100%
D	4.3	(.92)	0.72	(.15)	16%
E	4.3	(.92)	0.72	(.15)	16%
F	4.1	(.82)	*	*	*
G	2.9	(.63)	*	*	*
H	3.1	(.77)	0.42	(.10)	13%
I	2.5	(.43)	*	*	*
J	3.1	(.67)	1.82	(.40)	60%
K	5.5	(1.78)	0.90	(.29)	16%
L	3.8	(1.27)	0.36	(.12)	9%
M	2.4	(.80)	0.53	(.17)	21%
N	2.8	(.55)	0.36	(.07)	13%

* Information unavailable.

The rate of air exchange associated with a mechanical ventilation system (see schematic in Figure 1) is determined by a control system that varies the position of outdoor air intake, recirculation, and exhaust dampers within the air-handling system, and may also vary the fan airflow rates. There are a wide variety of air-handling systems and associated controls, but the systems in modern North American office buildings are generally of two basic types—constant volume and variable air volume (VAV). In a constant-volume system, the supply fan always moves the same amount of ventilation air and the temperature of this supply air is varied to meet the space-conditioning load within the building. In these systems, the amount of outdoor air intake is modulated by varying the position of the intake, recirculation, and exhaust dampers. Regardless of the amount of outdoor air intake, these dampers are always supposed to be positioned such that the supply airflow rate minus the return airflow rate is maintained at a constant level. This difference is intended to provide make-up air for toilet and other exhausts, and to maintain a slight positive pressure across the building envelope to control infiltration. These damper positions may be modulated by an automatic control system that responds to changes in indoor and outdoor air temperature and humidity, or they may be controlled manually by the building operator.

In variable-air-volume systems, the supply air temperature is kept constant and the supply airflow rate into the building is varied to meet the space-conditioning load. VAV systems are more common in newer buildings for reasons of reduced energy consumption and better control of local environmental conditions. The outdoor air intake control in VAV systems is essentially the same as in constant-volume systems, in that damper positions modulate in order to vary the air intake rate. Regardless of the mode of operation, both types of systems are always supposed to supply the minimum amount of outdoor air specified in the ventilation system design.

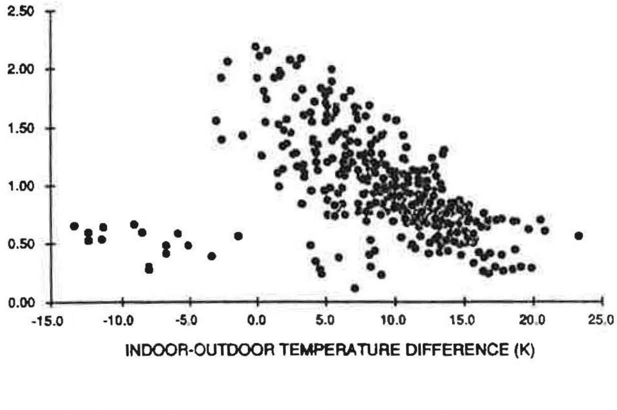

Figure 2 *Air exchange rate vs. indoor-outdoor temperature difference for Building B*

There are basically three modes of outdoor air intake control, corresponding to hot, cold, and mild outdoor air temperatures. Figure 2 is a plot of the air exchange rate data for Building B (one of the buildings discussed in this paper) vs. the indoor-outdoor air temperature difference. During hot weather, the amount of outdoor air intake is generally minimized to control the space-conditioning load within the building. During mild weather, outdoor air may be used to cool the building (a so-called economizer cycle), although some building air-handling systems are not equipped to take advantage of such "free-cooling." Most systems cut back the outdoor air intake to a minimum level during very cold weather in part to protect the heating and cooling coils in the air-handling systems from freezing.

In addition to the intentional outdoor air intake through the ventilation system, the net air exchange rate of a mechanically ventilated building also includes unintentional infiltration of air through leaks in the building envelope. The amount of envelope infiltration depends on the envelope airtightness and the strength of the infiltration driving forces, i.e., indoor-outdoor air temperature differences, wind, and mechanical equipment operation. In the design and operation of most modern, mechanically ventilated office buildings, the rate of envelope infiltration is generally assumed to be negligible. In fact, measurements and modeling of air exchange in office buildings has shown that envelope infiltration rates are often the same order of magnitude as the rates of intentional outdoor air intake (Persily 1985; Persily and Norford 1987). Although the envelope infiltration rate of an office building may be large enough to meet the outdoor air intake requirements of that building, infiltration air should not be relied upon for ventilation since its rate cannot be predicted, the incoming air is neither conditioned nor filtered, and there is no control over the distribution of this air within the building.

The air exchange characteristics of every building are unique due to differences in outdoor air intake controls, system operation schedules, envelope airtightness, and interior configuration. These factors determine the air exchange rate of a building at any given time and the distribution of air exchange rates over time. As mentioned above, the air intake rate through the mechanical ventilation system is determined by the time of day and season, as well as by the weather. The envelope infiltration rate is also determined by the weather, as well as by the operation of the mechanical ventilation system (itself a function of time and weather). Therefore, in order to characterize a building's air exchange performance, many air exchange measurements are required over a range of outdoor environmental conditions and times of day and season. The air exchange rate during minimum outdoor air intake conditions is of particular interest in characterizing air exchange in a building. The distribution of the building's air exchange rates over a year, specifically the amount of time that the building operates at this minimum level of ventilation, is also important.

DESCRIPTIONS OF THE BUILDINGS

This section provides a brief description of each of the 14 buildings studied by the NIST, including information on their air-handling systems, outdoor air intake controls, and specified design levels of minimum outdoor air intake, if available. These buildings are denoted as Buildings A through N, and Table 1 presents some basic information for each building. All but one of these buildings are less than 20 years old, and they range in floor area from about 2000 to 70,000 m^2 (about 22,000 to 750,000 ft^2). These are the total conditioned floor areas of the buildings (including corridors and lobbies), as opposed to rentable or occupiable floor areas. Buildings A and B, and G through N are federal office buildings, while Building F is a state office building. Buildings C through E are privately owned, although Building C is leased to the federal government. All of the buildings contain predominantly office space, with Building A containing some laboratories.

Basic information on the mechanical ventilation systems for each of the 14 buildings is presented in Table 2. All of the buildings have VAV systems, except for Buildings C and K, and all of the VAV systems employ economizer cycles. Most of the VAV buildings have constant-volume air handlers serving some of the smaller areas within the buildings, such as lobbies. Building C has a constant-volume system with 100% outdoor air intake, with no capability of recirculating air. Building K also has a constant-volume system. The amount of outdoor air intake in the building is modulated manually, with the building operator adjusting this proportion based on the interior and exterior environmental conditions.

Table 2 lists the supply fan capacity and the minimum outdoor air intake rate for each building, where available, in units of air changes per hour (ach) and in cfm/ft^2. The minimum outdoor air intake as a percentage of the total supply air is also given. These quantities are based on the mechanical equipment specifications for each building. The fan capacity in the VAV systems is the maximum capacity, which may not necessarily be realized in practice. The fan capacity in air changes per hour is simply the specified airflow rate divided by the building volume. The volume used is the total floor area from Table 1 multiplied by the ceiling height. In all buildings except C, this ceiling height includes the return air plenum due to the fact that return air is recirculated in all of these buildings. In Building C there is no return air plenum and the ceiling height of the occupied space is used. For all of the buildings except Building K, the fan capacity is between about 2 and 4 ach. The supply airflow rate per unit floor area is between 0.5 and 1 cfm/ft^2 in most of the buildings, with Building C below this range and Buildings K and L above it. The minimum outdoor air intake rate is generally between 1/3 and 1 ach. The specifications for Building J yield a minimum outdoor air intake rate of 1.82 ach, which is probably an error in the specifications. Building C has a minimum outdoor air intake rate of 1.7 ach, but since this building always operates at 100% outdoor air intake, this number is reasonable. Other than Building C (with 100% outdoor air intake) and Building J (with a suspected error in the ventilation specifications), the outdoor air intake for all of the buildings is between about 10% and 20% of the supply airflow rate.

AIR EXCHANGE MEASUREMENT TECHNIQUE

The air exchange rates in these buildings were measured using the tracer gas decay technique. This technique has been used for many years in both residential and commercial buildings to determine air exchange rates (ASTM 1983; Hunt 1980; Persily 1988). In this procedure, a harmless and nonreactive tracer gas is released into the building and mixed thoroughly with the interior air. Once the tracer gas concentration within the building is uniform, one monitors the decay in tracer gas concentration over time. The rate of decay of the logarithm of concentration is equal to the air exchange rate of the building during the time of the test. It is crucial that the tracer gas be uniformly mixed with the interior air such that the tracer gas concentration within the building can be characterized by a single value. If these conditions of uniform concentration are not achieved, then the measurement results are not valid.

In these measurements, sulfur hexafluoride (SF_6) was injected into the building supply fans in a manner that facilitated achieving a uniform tracer gas concentration within the building. The tracer gas was then allowed to mix for a period from 20 minutes to one hour, depending on the building. Different amounts of time were required to achieve a uniform concentration of tracer gas within each of the buildings, due to differences in air distribution systems, interior configuration, and ventilation system airflow rates among the buildings. In order to verify that a uniform tracer gas concentration had indeed been achieved, the concentration was sampled at many locations within each building. The rate of tracer gas concentration decay at each of these air sample locations was determined over a period of one to two hours, during which time the exterior and interior environmental conditions and fan operation status were monitored and recorded.

TABLE 3

Summary of Building Air Exchange Measurements

Building	Number of Measurements	Mean Air Exchange Rate	Median Air Exchange Rate
A	228	1.73	1.65
B	392	0.97	0.41
C	521	0.90	0.91
D	544	0.99	0.94
E	536	0.80	0.72
F	127	1.15	1.12
G	93	0.89	0.90
H	94	0.78	0.50
I	175	0.75	0.67
J	93	0.29	0.25
K	52	0.54	0.40
L	131	0.73	0.65
M	46	1.19	0.96
N	90	0.99	1.07
All Buildings	3122	0.94	0.89
All Buildings Except A and C	2373	0.88	0.80

These measurements employed microcomputer-based, automated tracer gas measurement systems that controlled the tracer gas injection, the air sampling, and the tracer gas concentration measurement, and recorded the tracer gas concentrations, the environmental conditions, and the fan operation status. These systems ran unattended and were capable of monitoring 10 air sampling locations, with the tracer gas concentration at each location being monitored once every 10 minutes. In buildings in which 10 air sample locations were insufficient to characterize the interior tracer gas concentration, more than one of the automated systems were employed.

RESULTS

Hundreds of tracer gas decay tests were conducted in each of these 14 buildings for a total of more than 3000 air exchange measurements. Tests were conducted in each building for at least one month during each season of the year, with some buildings tested for longer periods. No special equipment operation schedules were employed during these tests, i.e., the buildings were occupied and operated in the same manner as would have occurred had the measurement equipment not been installed. Even with the large number of measurements made in each building, the data set for each building is not necessarily representative of the building's average performance due to the dependence of air handler operation and air exchange rate on exterior weather conditions. Although the results cannot be interpreted to yield rigorous measures of the building's average or typical performance, they still may be expected to provide approximations of the building's typical air exchange rates. The more data points collected for a building, the better these data can be expected to approximate the building's average air exchange performance.

Figures 3 through 16 show air exchange rate frequency distributions for each of the buildings, and Table 3 shows each building's mean and median air exchange rate. In the figures, the vertical axis is the number of measured air exchange rates in each 0.25 ach interval of air exchange rates. The table contains the mean and median air exchange rate of each building and of all the buildings together, as well as the number of measurements made in each building.

Most of the frequency distributions can be characterized as "log normal," with a predominance of lower air exchange rates. Such a distribution is characterized by a median value that is below its mean. Those buildings with a large number of measurements clearly exhibit this trend, e.g., Figures 4 (Building B), 6 (D), and 7 (E). Buildings with a smaller number of measurements are more apt to exhibit a "scattered" distribution of air exchange rates, e.g., Figures 10 (Building H), 11 (I), and 15 (M).

The air exchange rates for some of the buildings, due to unique characteristics of their ventilation and control systems, yield distributions that are different from the log normal distribution seen in the buildings with automatically controlled VAV systems. For example, the air exchange rates measured in Building C (see Figure 5) are almost all in the range from 0.75 to 1.0 ach, with about one-third as many between 1.0 and 1.25. The data from Building C exhibit this distribution because the building has a constant-volume air-handling system with 100% outdoor air intake. The relatively small number of air exchange rates below 0.75 ach occurred during extreme weather conditions (either very hot or very cold) when the air handlers are turned off, presumably to reduce the space-conditioning load of the building. Building K, in Figure 13, is the only other building with a constant-volume

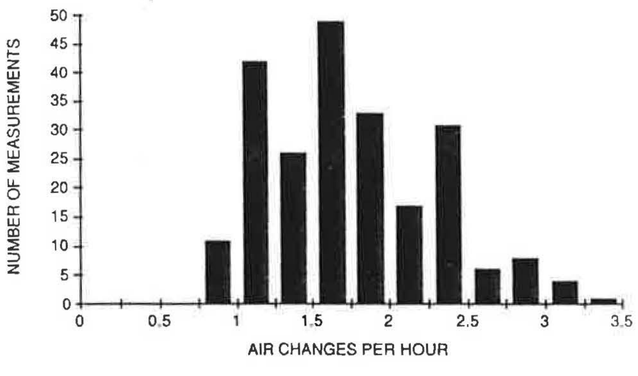

Figure 3 Frequency distribution of air exchange rates in Building A

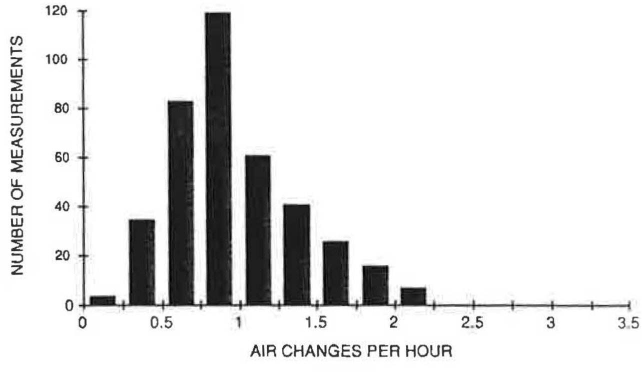

Figure 4 Frequency distribution of air exchange rates in Building B

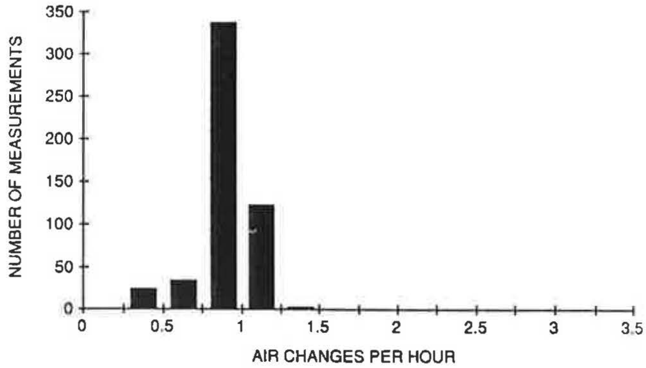

Figure 5 *Frequency distribution of air exchange rates in Building C*

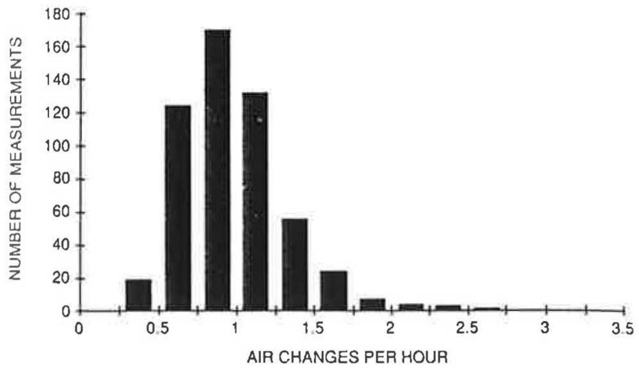

Figure 6 *Frequency distribution of air exchange rates in Building D*

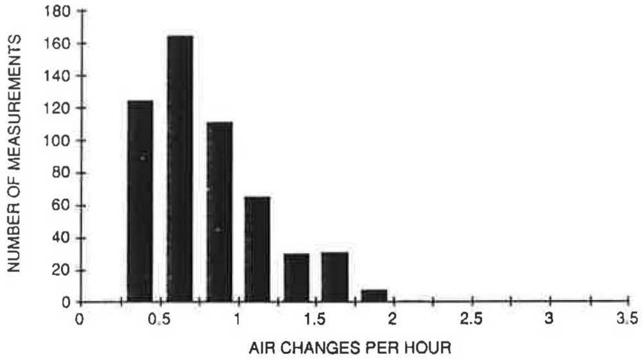

Figure 7 *Frequency distribution of air exchange rates in Building E*

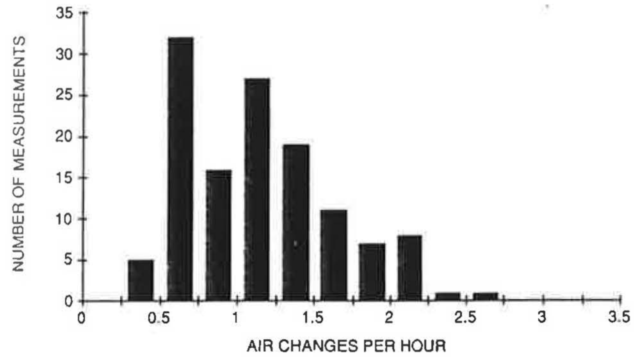

Figure 8 *Frequency distribution of air exchange rates in Building F*

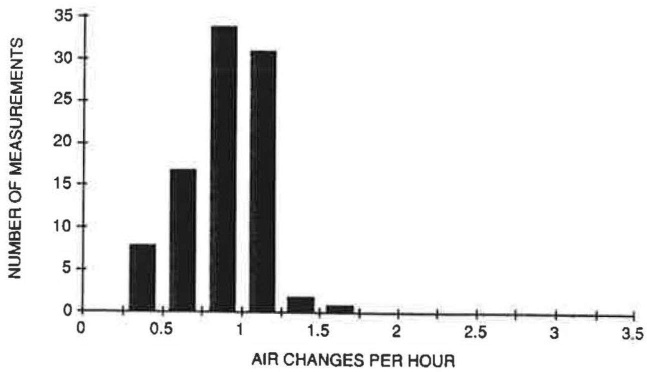

Figure 9 *Frequency distribution of air exchange rates in Building G*

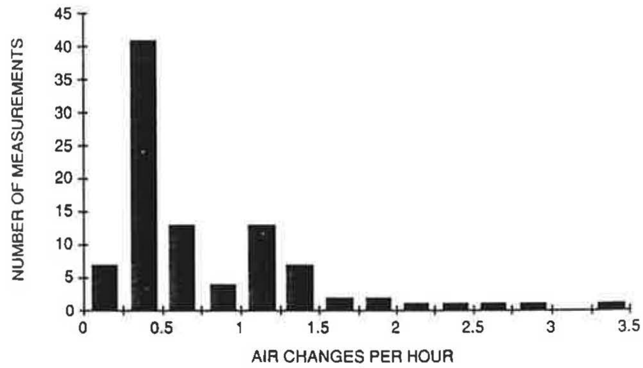

Figure 10 *Frequency distribution of air exchange rates in Building H*

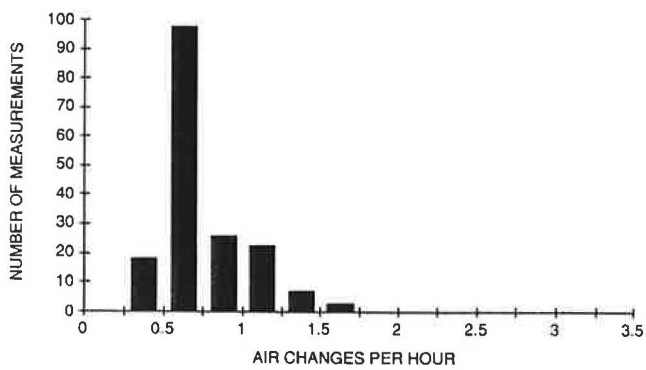

Figure 11 *Frequency distribution of air exchange rates in Building I*

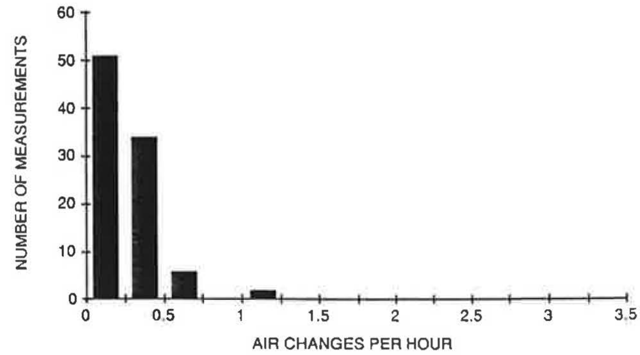

Figure 12 *Frequency distribution of air exchange rates in Building J*

air-handling system and it exhibits a predominance of air exchange rates less than 0.5 ach. The data above 1.0 ach were collected under extremely windy conditions when the envelope infiltration rate of the building was very large, making the total air exchange rate much larger than the mechanical ventilation system's contribution.

About half of the buildings have mean and median air exchange rates between about 0.9 or 1.0 ach. Buildings H, J, and K have median air exchange rates of less than 0.5. Building A has much larger air exchange rates than the other buildings—a mean of 1.73 and a median of 1.65 ach. As noted above, Building C also has an unusual distribution of air exchange rates, due to its unique air-handling system. Because Buildings A and C have very different air exchange characteristics from the other 12 buildings, the data from these two buildings are neglected in some of the analyses that follow. The ventilation characteristics of the remaining 12 buildings appear to be fairly typical of modern mechanically ventilated office buildings.

Figure 17 is a frequency distribution of the measured air exchange rates in all of the buildings, and Figure 18 is the distribution without Buildings A and C. The effect of the large number of measurements in these two buildings, and their higher values relative to the other buildings, is evident in comparing these two figures. The mean air exchange rate for all of the buildings is 0.94 ach, and the median is 0.89. Neglecting the data collected in Buildings A and C, the mean air exchange rate is 0.88 ach and the median is 0.80. Because there are a different number of measurements in each building, these "all-building" distributions are biased by the data from those buildings with larger numbers of measurements. In order to avoid this bias, each building's distribution was normalized by dividing the number of measurements in each range by the total number of measurements in the building. These values were then multiplied by 100 to yield the distribution that would have existed had there been 100 measurements in each building. These distributions were then combined to yield the "unbiased" distributions in Figures 19 and 20.

The above distributions of air exchange data provide useful statistical information on the air exchange rates that occur in these particular buildings, but the question remains of how these measured values compare to the minimum ventilation levels specified for each building and to recommended levels of ventilation. The specified level of minimum outdoor air intake for each building is given in Table 2 in units of ach. The recommended minimum level of outdoor air intake in ASHRAE Standard 62 (ASHRAE 1989) is 10 L/s (20 cfm) per person. In the previous version of the standard (ASHRAE 1981) there were two levels, depending on whether smoking was permitted in the space. When smoking was permitted, the level was 10 L/s (20 cfm) per person, and when there was no smoking the minimum level of outdoor air intake was reduced to 2.5 L/s (5 cfm) per person. Other levels of interest include 5 L/s (10 cfm) and 7.5 L/s (15 cfm) per person. The latter value is the amount of ventilation required to keep the steady-state carbon dioxide concentration below 1000 ppm given the CO_2 generation rate associated with one person. The former value is employed in other ventilation guidelines.

These ventilation recommendations can be converted to ach by making assumptions about the building volume associated with one person. The ASHRAE standard recommends that one assume an occupant density of seven people

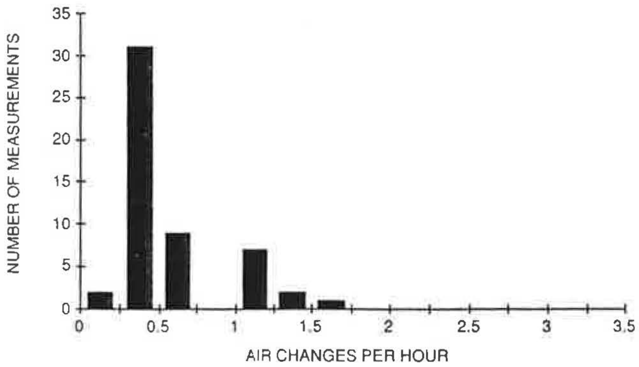

Figure 13 *Frequency distribution of air exchange rates in Building K*

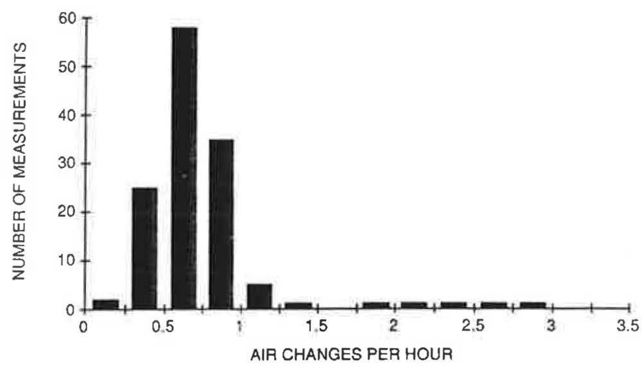

Figure 14 *Frequency distribution of air exchange rates in Building L*

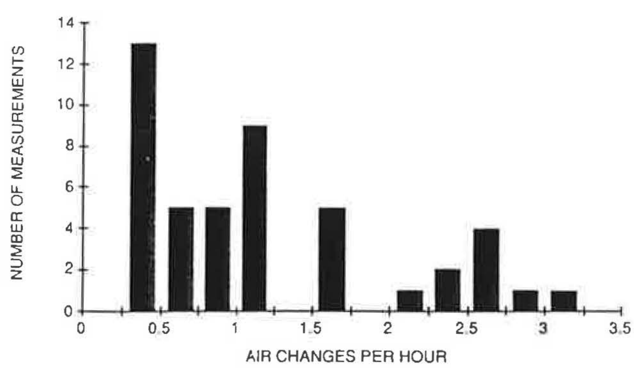

Figure 15 *Frequency distribution of air exchange rates in Building M*

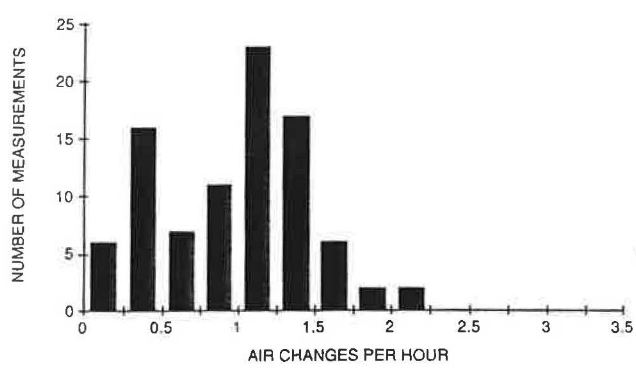

Figure 16 *Frequency distribution of air exchange rates in Building N*

TABLE 4

Ventilation Levels in Air Changes per Hour

Ventilation per Person	Ceiling Height of 3.5 m (11.5 ft)	Ceiling Height of 2.44 m (8 ft)
10 L/s (20 cfm)	0.72	1.03
7.5 L/s (15 cfm)	0.54	0.77
5 L/s (10 cfm)	0.36	0.52
2.5 L/s (5 cfm)	0.18	0.26

These calculated air exchange rates are based on an assumed occupant density of 7 people per 100 m^2 (1000 ft^2).

per 100 m^2 (1000 ft^2), unless a more accurate value is available. Therefore, the volume associated with one person is 14.3 m^2 (143 ft^2) multiplied by the ceiling height of the space. In most modern office buildings, there is a return air plenum above the suspended ceiling through which the interior air flows back to the air-handling system. Since this return air is generally recirculated into the supply airstream, the ceiling height employed in this volume calculation should include the height of this plenum. A typical ceiling height in this case is 3.5 m (11.5 ft).

Table 4 contains the four recommended levels of ventilation in units of ach for a typical ceiling height in an office building employing a return air plenum, and for the ceiling height in Building C, which does not have a return air plenum. The ASHRAE standard of 20 cfm per person converts to 0.72 ach in a typical office building, and 1.03 ach in Building C. These values are approximate due to the assumed values of occupant density and ceiling height.

Referring back to Table 2, in which the available ventilation system design specifications were given for the buildings, we can compare the specified levels of minimum outdoor air intake to the "standard" levels in Table 4. Buildings D and E have minimum outdoor air intake levels corresponding to 10 L/s (20 cfm) per person, while the levels in Buildings L and N correspond to 5 L/s (10 cfm). Building M is at 7.5 L/s (15 cfm) per person and Building H is somewhat less than this level.

The calculated air exchange rates in Table 4 were compared with the measured values in the 14 buildings and the results are shown in Table 5. This table shows the percentages of air exchange measurements in each of the buildings that are below 10, 7.5, 5, and 2.5 L/s (20, 15, 10, and 5 cfm), respectively. These percentages are also given for all of the

TABLE 5

Comparison to Minimum Levels of Ventilation

Building	Percent of Air Exchange Rate Measurements Below Given Level				
	< 10 L/s (20 cfm)	< 7.5 L/s (15 cfm)	< 5 L/s (10 cfm)	< 2.5 L/s (5 cfm)	< Design Level*
A	0%	0%	0%	0%	**
B	27%	12%	4%	0%	**
C	82%	13%	5%	0%	100%
D	23%	11%	0%	0%	23%
E	49%	26%	8%	0%	49%
F	24%	7%	0%	0%	**
G	25%	10%	1%	0%	**
H	64%	57%	24%	1%	37%
I	59%	16%	2%	0%	**
J	98%	92%	81%	18%	100%
K	81%	65%	42%	0%	81%
L	60%	27%	5%	1%	5%
M	39%	35%	0%	0%	30%
N	30%	27%	16%	0%	16%
All Buildings	45%	20%	8%	1%	52%
Normalized***	47%	28%	13%	1%	49%
All Buildings except A and C	41%	23%	10%	1%	49%****
Normalized***	49%	33%	16%	2%	43%****

* Minimum level of outdoor air intake from ventilation system design specifications.
** Design value unavailable.
*** These percentages are based on a normalized distribution for each building in which there are 100 air exchange rate measurements in each building.
**** These percentages do not include the data collected in Building J, but do include the data collected in Building C.

buildings together, both with and without Buildings A and C. Both all-building data sets, normalized to account for the different numbers of measurements in each of the buildings, are also analyzed.

From Table 5, it can be seen that only Building J has a significant number of measured air exchange rates below 2.5 L/s (5 cfm). Several of the buildings have a significant number

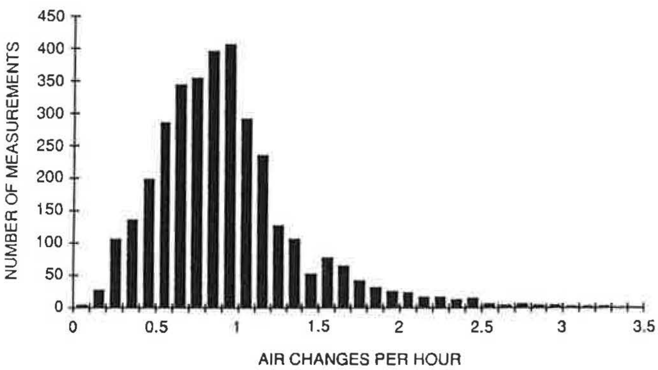

Figure 17 *Frequency distribution of air exchange rates in all buildings*

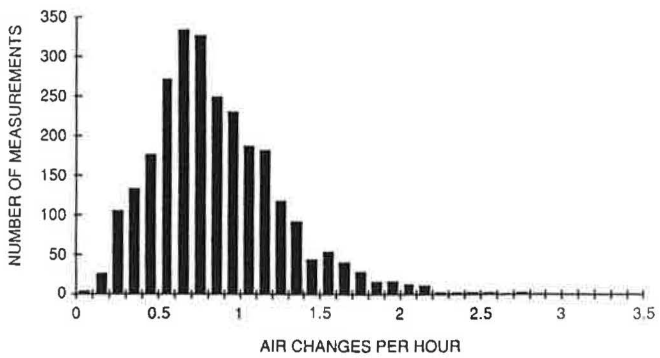

Figure 18 *Frequency distribution of air exchange rates in all buildings except A and C*

of measured air exchange rates below the three higher ventilation levels. Building A, with its unusually high air exchange rates, was always above 10 L/s (20 cfm) per person. More than 40% of the measured air exchange rates in all of the buildings are below the ASHRAE standard's recommendation of 10 L/s (20 cfm). Correcting for the different number of air exchange rate measurements in each of the buildings, and neglecting the data for the two buildings (A and C) with unusual air exchange characteristics, this percentage increases to almost 50%.

The last column of Table 5 shows the percent of measured air exchange rates in each building that are below the building's design level for minimum outdoor air intake. The data from Buildings C and J are always below the design level, with varying percentages in the other buildings for which a design value was available. Considering all of the data in all of the buildings, 52% of the measured air exchange rates were below their design values. Normalizing to account for the different numbers of measurements in the buildings reduces this percentage to 49%. The design specification for the minimum level of outdoor air intake in Building J is suspected of being an error, as mentioned earlier, and therefore these percentages are also given for all of the buildings except J. Therefore we see that these buildings, and presumably others, are ventilated at levels below their minimum outdoor air intake specifications for significant periods of time.

SUMMARY

The air exchange rates of mechanically ventilated office buildings include both uncontrolled air infiltration through the building envelope and intentional outdoor air intake through the ventilation system. The outdoor air intake rate is generally not constant, as the ventilation control system responds to weather and interior loads. However, the ventilation system is always supposed to supply a minimum amount of outdoor air. This minimum level of ventilation is part of the ventilation system design specifications and is generally based on recommendations in ventilation standards and guidelines.

The actual air exchange rate in a mechanically ventilated building is determined by the ventilation system design including the outdoor air intake controls, the system's operation schedules, the building envelope airtightness, and the interior configuration of the building. This air exchange is an inherently complex phenomenon, with proper performance requiring careful attention to the design, installation, operation, and maintenance of several systems and components. The actual air exchange rates in these buildings can be quite different from their design values, and tracer gas measurements are the only reliable way to determine the actual air exchange rates.

The NIST has studied the air exchange characteristics of 14 office buildings in the U.S. using the tracer gas decay technique, and these 3000 air exchange rate measurements constitute a unique data set. With only 14 buildings, it is impossible to make generalizations regarding the effects on air exchange of building age, construction style, and ventilation system type. Most of the buildings exhibit a log-normal distribution of air exchange rates with a median value below the mean. Some of the buildings have unique air exchange characteristics such as high or low air exchange rates compared with the other buildings, or relatively constant air exchange rates in buildings with constant-volume ventilation systems. The most significant difference in the buildings is in the air exchange rate under conditions of minimum outdoor air intake. This value is of interest in relation to both the building's design specifications and to recommended levels of ventilation.

The average air exchange rate for all of the buildings is about 0.9 ach. About one-half of the measured air exchange rates are below the buildings' minimum outdoor air intake design specifications. About 40% of the measured air exchange rates are below the 10 L/s (20 cfm) per person recommendation in the ASHRAE ventilation standard.

ACKNOWLEDGMENTS

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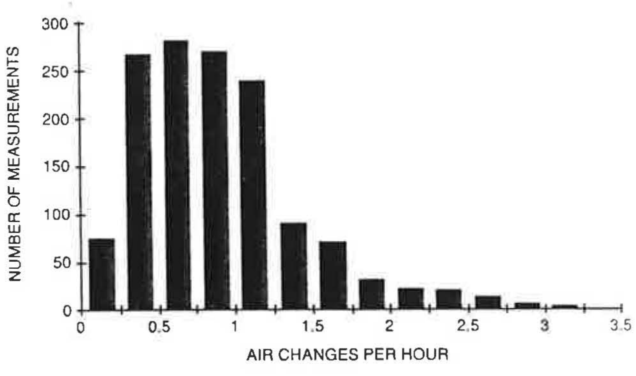

Figure 19 *Unbiased frequency distribution of air exchange rates for all buildings*

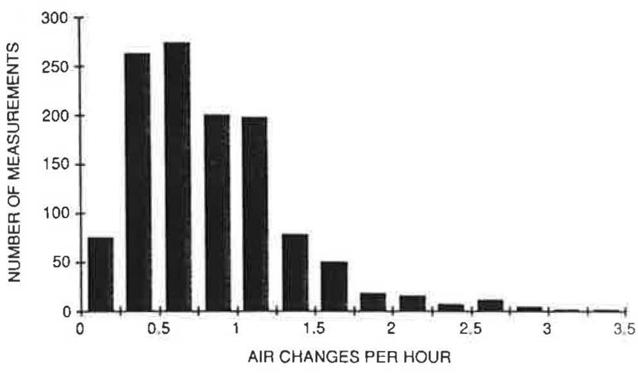

Figure 20 *Unbiased frequency distribution of air exchange rates for all buildings except A and C*

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DISCUSSION

Arthur E. Wheeler, Wheeler Engineering Co., Towson, MD: In calculating cfm per person from air changes per hour, how did you determine the effective building volume and number of occupants?

A. Persily, National Institute of Standards and Technology, Gaithersburg, MD: The relationship between cfm per person and air changes per hour depends on the volume assumed to be associated with each person. As discussed in the paper, I assumed an occupant density of 7 people per 1000 ft^2 and a ceiling height dependent on the buildings. If alternative assumptions are appropriate for a particular building, these calculations can easily be adjusted.

Stephen A. Roosa, ICI Americas Inc., Charlestown, IN: After having described the sample building as having high infiltration rates, can you determine or detail the relative components of infiltration and mechanical ventilation for the buildings tested?

Persily: The relative quantities of infiltration and intake in a building depend on many building-specific factors, including envelope airtightness, weather, and ventilation system zoning and operation. In one of the buildings, we have made simultaneous measurements of infiltration and intake (see Persily and Nostrand, *ASHRAE Transactions*, Vol. 93, Part 2).

Carl N. Lawson, LRW Engineers, Tampa, FL: In your study of these buildings, which type of system—VAV or CAV—seemed to function the best?

Persily: Due to the small number of buildings tested, it is impossible to make generalizations regarding ventilation system type. In fact, the type of system is probably less important than the quality of the system design, installation, operation, and maintenance.

William A. Turner, Harriman Associates, Auburn, ME: You stated that infiltration rates were significant in the study building. We have not found this to be the case in low-rise commercial buildings. Could you comment on this?

Persily: The amount of infiltration will vary significantly among buildings. Unfortunately, there is too little data to make generalizations about the effects of building type. Your results in low-rise commercial buildings could be due to reduced stack effects compared to tall buildings and/or more successful pressurization of the building interior in these buildings. Building-specific explanations require building-specific measurements.

Turner: We have found that outside air is most likely to be less than design in leaky buildings, I assume because of excess leakage at design conditions. Could you comment on this?

Persily: I find your observations interesting, though the correlation may be fortuitous rather than intentional. I find it hard to believe that building operators are making valid assessments of envelope leakage. I also find it difficult to give them credit for such conscientious efforts to control outdoor air intake rates.

Richard Gorman, NIOSH, Cincinnati, OH: How were the buildings selected for study?

Persily: Each of the buildings was studied for a different reason, ranging from poor thermal performance to indoor air quality complaints. Some were tested due to unique design features. Only two of the buildings were characterized by a large number of indoor air quality complaints.

James E. Woods, Honeywell Indoor Air Quality, Golden Valley, MN: Congratulations on an excellent presentation on data that are important to improving our knowledge of objective measures of ventilation. Would you please comment on the influence of multiple systems within a building and of multiple zones within a system (i.e., on ventilation efficiency)?

Persily: Although the tracer gas decay measurements are based on an assumption of the building being a single, well-mixed zone, there are certainly cases in which the supply air distribution is not uniform within a building. This non-uniform distribution is sometimes due to the existence of multiple air handlers, and can also exist when there is only a single air handler. The result is that certain areas within a building (zones, floors, sections of a floor, or rooms) receive proportionally less supply air (and outdoor air) relative to other areas of the building. These variations in supply air distribution can impact thermal comfort and air quality, and new measurement techniques are being developed and applied to quantify these variations.