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Ventilation Design And Performance In U.S. Office Buildings

By Andrew Persily, Ph.D., Fellow ASHRAE, **Josh Gorfain** and **Gregory Brunner**

Building ventilation is a primary determinant of indoor air quality (IAQ) as it impacts contaminant concentrations and occupant comfort in terms of the odor perception and irritation. However, relatively few measurements of office building ventilation performance have been conducted, and those data that exist generally have not used consistent measurement methods and have not involved representative collections of buildings.

The U.S. Environmental Protection Agency (EPA) Building Assessment Survey and Evaluation (BASE) study was conducted to assess IAQ, including ventilation, in a large number of randomly selected office buildings throughout the U.S.[1] Ventilation performance assessment was a key part of the survey, and this article presents a summary of the analysis of the ventilation information collected as part of the study. The full report[2] contains a more complete description of the analysis and a more detailed presentation of the results.

The EPA BASE study was originally conceived to address the data gap that exists regarding IAQ in public and commercial office buildings. As described in the study protocol,[3] the primary goal was to define the status of the existing building stock with respect to determinants of IAQ and occupant perceptions.

The BASE protocol addresses three major areas: thermal comfort and environmental measurements; building and HVAC characterization; and an occupant questionnaire.

It is expected that the BASE data will be used to develop distributions of IAQ, building and HVAC characteristics, generate new hypotheses regarding, for ex-

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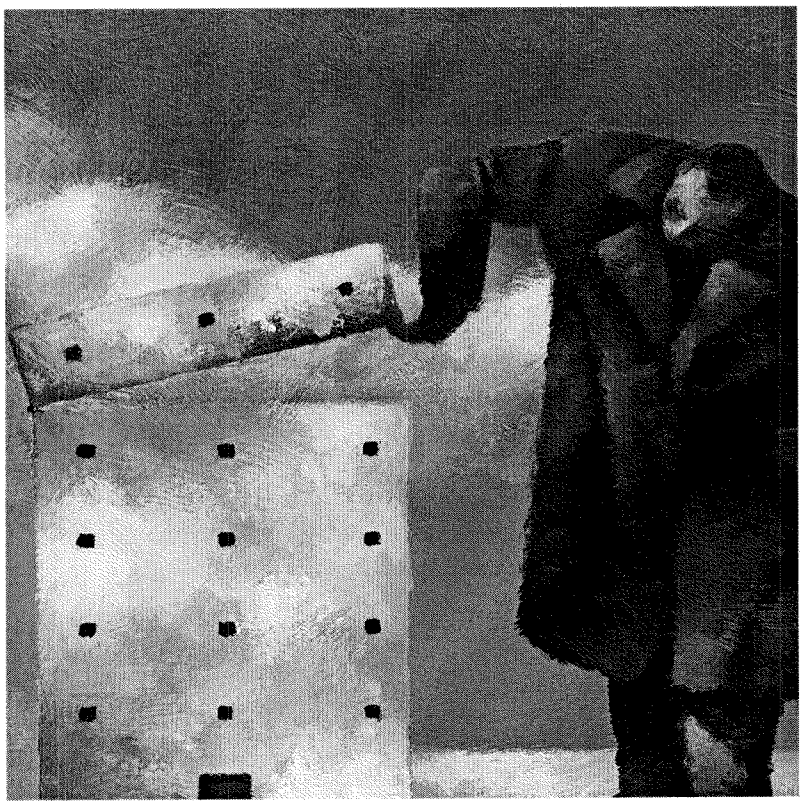

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ample, the causes of occupant symptoms, establish standardized protocols for IAQ studies, and develop guidance on building design, construction, operation, and maintenance.

The purpose of the ventilation analysis was to obtain information on ventilation system design and performance for the BASE office buildings. These data provide a unique opportunity to obtain new information for U.S. office buildings including ventilation system design values, measured ventilation performance, and the relationship of these measurements to design values and to requirements in standards.

The results also will be used to investigate relationships of ventilation to the contaminant concentrations and occupant symptoms determined in the BASE study. In addition, this study was performed to evaluate the BASE protocol with respect to its ability to obtain reliable ventilation performance data.

Description of Analysis

The BASE study focused on specific study spaces within the BASE buildings, with the spaces selected based on criteria described in the protocol.[3] One important criterion is that the space have at least 25 occupants, but preferably 50 to 60. The ventilation analysis focuses on the study spaces and the ventilation systems serving these spaces in terms of both design and measured performance, primarily supply airflow and outdoor air intake rates. In addition, occupancy levels are examined.

Another key ventilation performance parameter assessed in the study is the outdoor air fraction, i.e., the ratio of the outdoor air intake to the supply airflow. It is of interest as a performance parameter itself and as a means of determining the outdoor air intake when multiplied by the supply airflow. The outdoor air fraction was determined in two ways: dividing the measured outdoor airflow by the measured supply airflow and through the measurement of carbon dioxide (CO_2) concentrations in the outdoor, supply and recirculation airstreams. Outdoor air intake rates were determined using three approaches:

- Direct measurements of the volumetric airflow in the outdoor air intake duct using standard air speed traverse approaches;
- Difference between direct measurements of the supply and recirculation volumetric airflows; and
- Outdoor air fraction based on CO_2 multiplied by the supply airflow.

While three methods were used in the study, this article only presents the results of the first two based on direct volumetric airflow measurement. Outdoor air ventilation rates were also estimated from peak CO_2 concentrations in the space, but these results are not discussed in this paper. All the results are discussed and compared in the full report.[2]

Results

Building and Study Space Characteristics

Table 1 summarizes the characteristics of the 100 buildings in the BASE study. The year of construction ranges from 1850 to 1996, though most had been renovated at some point. The total number of stories, below and above grade, ranges from 1

	Year of Construction	Number of Stories	Gross Floor Area m² (ft²)	Occupied Floor Area m² (ft²)
Mean	1961	10	24 800 (266,000)	16 400 (177,000)
Standard Deviation	31	11	27 900 (300,000)	18 500 (199,000)
Median	1972	6	14 000 (151,000)	8500 (91,000)

Table 1: Characteristics of the 100 buildings in the BASE study.

	Occupied Floor Area, m² (ft²)	Number of Workstations	Workstations Per 100 m² (1,000 ft²)
Mean	1540 (16,600)	72	5.3 (4.9)
Standard Deviation	740 (8,000)	19	2.0 (1.9)
Median	1430 (15,400)	68	4.8 (4.5)

Table 2: Study space characteristics.

to 61. The gross floor area of the buildings ranges from 1700 m² (18,000 ft²) to 134 200 m² (1,445,000 ft²).

The occupied floor areas, which exclude atria, vacant office space, hallways, stair and elevator shafts, mechanical rooms and core areas, range from 600 m² (6,000 ft²) to 98 500 m² (1,060,000 ft²).

Of the 100 buildings, all but three are mechanically ventilated; ninety-nine of the buildings are air-conditioned, and all are heated. While the BASE buildings are larger on average than U.S. office buildings, with only 11% of U.S. office buildings having 50 or more occupants, it is worth noting that office buildings with more than 50 occupants account for about 73% of U.S. office workers.[2]

Some of the study space characteristics are summarized in *Table 2*. The occupied floor area of the 100 spaces ranges from 430 m² (4,600 ft²) to 6440 m² (69,300 ft²). The mean number of workstations is 72, which corresponds to 5.3 workstations per 100 m² of floor area (4.9 per 1,000 ft²). The mean occupant density is below the default value of 7 per 100 m² (1,000 ft²) for office space in ANSI/ASHRAE Standard 62-2001,[4] but close to the default value of 5 per 100 m² (1,000 ft²) in Addendum *n* to the standard.[4]

Ventilation System Design Parameters

The study spaces in the 97 mechanically ventilated buildings are served by a total of 141 air-handling systems. Of these systems, 50 are constant air volume (CV) and 91 are variable air volume (VAV).

Table 3 presents information on outdoor air intake control, including the number of buildings that use temperature or enthalpy economizer cycles.

Twenty-one buildings have dedicated outdoor air fans, with 11 of those also conditioning the air. There are five 100% outdoor air systems, and 88 with fixed minimum outdoor air intake dampers. A small number control outdoor air intake using airflow monitoring, supply/return fan tracking or building pressure.

The availability of design information varied among the systems. However, the information that did exist was analyzed and the results are summarized in *Table 4*. This table includes the design supply airflow capacity normalized by floor area, the ratio of design supply and return airflows, the design minimum outdoor air intake per person and per unit floor area, the ratio of the design minimum outdoor air intake and the design supply air capacity, and the occupant density.

Outdoor Air Intake Control	Number of Buildings
Economizer Cycle (Temperature Control)	50
Economizer Cycle (Enthalpy Control)	21
Dedicated Outdoor Air Fan, Conditioned *	11
Dedicated Outdoor Air Fan, Unconditioned *	10
100% Outdoor Air	5
Fixed Minimum Outdoor Air Damper	88
Outdoor Air Intake Controlled Via Monitoring	2
Outdoor Air Intake Controlled Via Supply/Return Fan Tracking	5
Outdoor Air Intake Controlled By Building Pressure	4

* Conditioned refers to filtration, and heating or cooling, prior to delivery to the air handler.

Table 3: Outdoor air intake control.

	Design Supply Airflow Capacity L/s·m² (cfm/ft²)			Supply/Return
	All Systems	CV	VAV	
No. of Values	134	47	87	41
Mean	6.04 (1.19)	7.01 (1.38)	5.52 (1.09)	1.14
Standard Deviation	3.99 (0.79)	5.33 (1.05)	2.94 (0.58)	0.22
Median	5.23 (1.03)	5.63 (1.11)	5.06 (1.00)	1.11

	Design Min. Outdoor Air Intake		Min. OA/ Supply	Occupant Density No./100 m² (1,000 ft²)
	L/s (cfm) per person	L/s·m² (cfm/ft²)		
No. of Values	74	76	76	137
Mean	18.4 (39.0)	0.90 (0.18)	0.19	5.5 (5.1)
Standard Deviation	13.7 (29.0)	1.04 (0.20)	0.22	6.7 (6.3)
Median	15.2 (32.1)	0.58 (0.11)	0.12	3.9 (3.7)

Table 4: System design values for buildings in the BASE study.

For the 134 air-handling systems for which design data could be located, the mean of the design supply airflow is close to 5 L/s·m² (1 cfm/ft²), as expected based on cooling loads and supply air temperatures in office buildings. The median is even closer to the expected supply capacities, and the mean is slightly higher for CV systems than for VAV systems. The ratio of the design supply to return airflow could be determined for 41 of the systems, and the mean value is 1.14. This value is consistent with the common design intent to provide more supply than return air to a space to achieve positive pressurization and to ensure that toilet and other exhaust systems are able to function.

The mean and median values of the design minimum outdoor air intake per person are above the minimum outdoor air requirement for office space in ANSI/ASHRAE Standard 62-2001[4] of 10 L/s (20 cfm) per person, as well as in Addendum *n* to the standard.[5]

The per person design values in *Table 4* are based on the number of workstations in the study space, since the number of occupants on which the design was based is not available. Alternatively, using the default occupant density in Standard 62-2001 of seven people per 100 m² (1,000 ft²) yields a mean per person outdoor air intake of 13.1 L/s (25.8 cfm) and a median of 8.5 L/s (16.7 cfm). Note that the design minimum outdoor air intake is available for only 76 of the 141 systems.

The mean ratio of the minimum outdoor air intake to supply airflow capacity is 0.18 and the median is 0.12, consistent with expected values of 10% to 20%. The mean value of the design occupant density is 5.5 people per 100 m² (5.1 per 1,000 ft²). As noted when discussing the study spaces, these values are below the default value in Standard 62-2001, but close to the value in Addendum *n*.

The BASE study also obtained information on the frequency of a number of system maintenance activities. *Table 5* summarizes the frequency of some inspection and maintenance activities that might be expected to impact ventilation airflows. The values in the table are the number of BASE buildings with reported frequency, not the number of air handlers. The air handler inspections appear to occur fairly often, but there is no information on the extent of these inspections. The other four activities are reported to occur much less often, particularly ductwork inspections and system testing, adjusting and balancing.

Frequency	Air Handler Inspection	Ductwork Inspection	Controls Inspection	Controls Recalibration	Testing, Adjusting, Balancing
	Number of Buildings				
Daily	14	0	14	0	0
Weekly	5	0	2	0	0
Monthly	23	1	4	4	0
Quarterly	29	2	12	3	0
Semiannually	6	1	11	7	0
Annually	3	4	14	10	3
As Needed	4	32	28	58	52
None	0	59	12	15	43

Table 5: Reported frequencies of system maintenance activities.

	Measured Occupant Density, No./100 m² (No./1,000 ft²)	Measured Density/ Number of Workstations
No. of Values	824	824
Mean	4.0 (3.7)	0.78
Standard Deviation	1.7 (1.6)	0.24
Median	3.6 (3.3)	0.76

Table 6: Summary of measured occupant density.

Measured Occupant Density

The number of occupants was determined at least four times in each study space. *Table 6* summarizes these observations and shows that on average the actual occupancy is about 80% of the design occupancy as defined by the number of workstations.

Ventilation Performance Measurements

This section presents the ventilation system performance measurements for the air handlers serving the study spaces and for the study spaces themselves. There are 562 ventilation measurement events, that is, the total number of times that the ventilation measurements were made on the study space air handlers.

Supply Airflow

Of the 562 measurement events, 495 include measurements of the system supply airflow. In some cases, the supply airflow is estimated by adding the outdoor air intake and the recirculation airflow, resulting in a total of 536 measured supply airflow values. The measured supply airflows are compared with the design supply capacities in the 512 cases where a design value exists.

Figure 1 is a plot of the ratio of the measured supply airflow to the design value against outdoor temperature. The mean value of the measured to design ratio is 0.83. The mean is 0.72 for the VAV systems and 1.07 for the CV systems. The VAV systems are expected to have a lower ratio of measured to design, since these systems modulate the supply airflow in response to internal loads.

Note that for the VAV systems, the ratio decreases for outdoor temperatures below about 15°C (59°F), presumably due to the lower cooling loads at these temperatures. The CV data exhibit little dependence on temperature. Four CV points have a ratio of about 4.5, all of which correspond to a single air handler for which the design value may be in error or out of date.

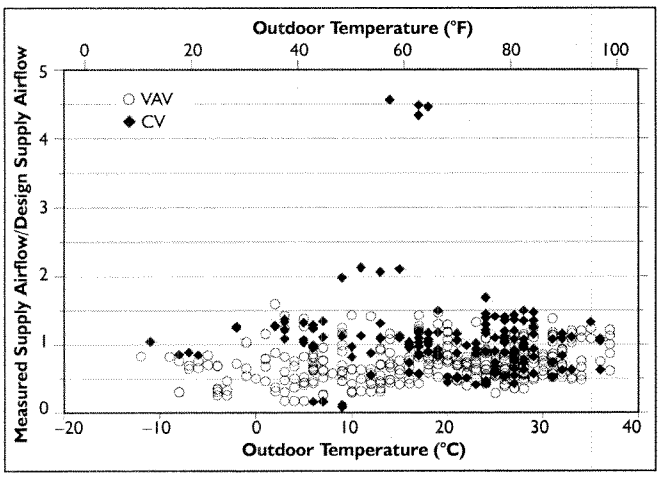
The supply airflows for the individual air handlers were combined to determine the total supply airflow to each study space, yielding 384 values. The results are summarized in *Table 7*. Again the rates in the VAV systems are lower than the CV systems, and the averages are close to the expected value of 5 L/s·m² (1 cfm/ft²).

Outdoor Air Fraction

The outdoor air fraction was determined by dividing the measured outdoor airflow by the measured supply airflow. The mean of the measured outdoor air fractions is 0.37, i.e., 37% outdoor air intake.

Figure 2 is a plot of the outdoor air fraction against outdoor air temperature, with systems having economizer cycles distinguished from those that do not. (While some of the values are greater than one, consideration of the measurement uncertainty reveals that none of them are significantly different from 100% outdoor air intake.) Note that most of the low outdoor air intake values, i.e., outdoor air fractions below about 0.25, correspond to temperatures greater than 20°C (68°F).

As expected, the systems with economizer cycles tend to have higher outdoor air fractions at milder temperatures than systems without economizers, while the non-economizer data exhibit less variation. However, some exceptions exist to this general dependence, which could be due to a variety of causes such as temperature and humidity sensors being out of calibration.



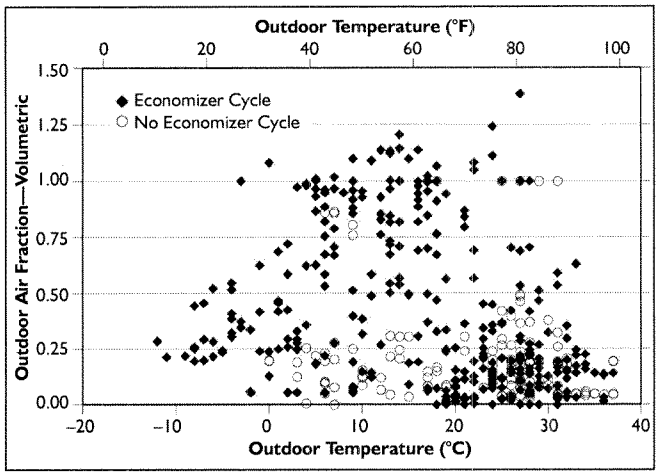


Figure 1 (left): Ratio of measured to design supply airflow vs. outdoor temperature. Figure 2 (right): OA fraction vs. outdoor temperature.

	Supply Airflow/Floor Area L/s·m² (cfm/ft²)		
	All Systems	VAV	CV
Mean	5.27 (1.04)	4.75 (0.94)	6.86 (1.35)
Standard Deviation	3.11 (0.61)	2.81 (0.55)	3.46 (0.68)
Median	4.80 (0.94)	4.39 (0.86)	5.72 (1.13)

Table 7: Summary of measured supply airflows to study spaces.

Figure 3 is a plot of whole building air change rates measured with the tracer gas decay method plotted against outdoor air temperature from a previous study of a building with an economizer.[6] While the data in *Figure 2* suggest the same pattern, the BASE data typically include only four points for each building over a narrow temperature range, and not all the BASE buildings have economizer cycles.

Outdoor Air Ventilation

Of the 562 measurement events, 510 include measurements of the system outdoor air intake. *Figure 4* is a plot of the ratio of the measured outdoor air intake to the design intake vs. outdoor air temperature for the 267 cases where such a design value exists. Again, systems with economizer cycles are distinguished from those without. The mean ratio of the measured to design outdoor airflow is 1.93, including one case (not shown) where the measured value is about 30 times larger than the design minimum. The mean is 2.28 for the economizer systems and 1.37 for non-economizer systems. Economizer systems are expected to have a higher ratio of measured to design, since they increase the outdoor air intake during free cooling and the design value is a minimum.

Outdoor air ventilation rates in the study spaces were calculated from the values for the individual air handlers and are summarized in *Table 8*. The mean value is high relative to the 10 L/s (20 cfm) per person value specified in many current building codes (based on Standard 62). However, 17% are still below 10 L/s (20 cfm) per person and 9% are below 5 L/s (10 cfm). The table also presents the outdoor air rates in L/s·m² (cfm/ft²) of floor area and air changes per hour.

The per person outdoor air rates in *Table 8* were analyzed to identify those for which the outdoor air fraction was below 20%, presuming that those values correspond to conditions of minimum outdoor air intake. The mean of these values is 13.7 L/s (28.9 cfm) per person based on the measured number of occupants, which is much closer to the requirement in Standard 62-2001. Normalizing by the number of workstations rather than the measured number of occupants results in a mean of 10.5 L/s (22.2 cfm) per person and a median of 9.4 L/s (20.0 cfm) per person.

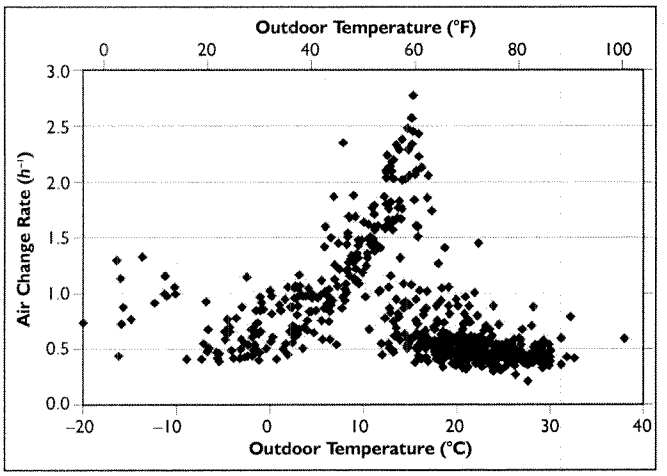
Among these values corresponding to minimum outdoor air intake, 41% are below the per person requirement in Standard 62-2001 based on the measured number of occupants and 50% are below that requirement based on the actual number of workstations. In other words, under minimum outdoor air intake, about one-half of the measured outdoor air intake rates are below the requirements in Standard 62-2001 based on the "design" occupant density in the space (i.e., the number of workstations).

Note that the per person outdoor air requirements for an office building in Addendum *n* to the standard are not much different from those in the 2001 version of the standard, and, therefore, these same percentages are likely to apply to the addendum as well.

As noted, the measured per person outdoor air ventilation values are high relative to the outdoor air requirement in Standard 62-2001. These values are higher than might be expected for two primary reasons: the occupant density is below design and the outdoor air fraction is frequently not at minimum. If each outdoor air measurement is adjusted to the design occupant density and to a minimum outdoor air fraction, then the per person ventilation values are more reasonable.

Discussion

The analysis of the ventilation-related information from the BASE study provides a unique characterization of ventilation system design and performance in U.S. office buildings. As expected based on thermal load considerations, but never previously verified, the average value of the design supply air



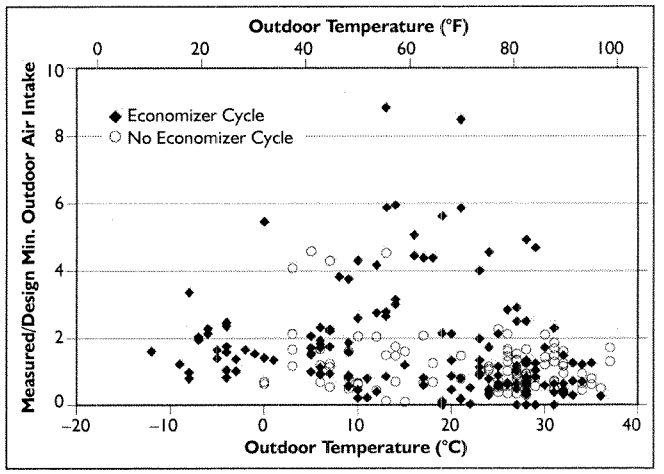


Figure 3 (left): Measured air change rates vs. outdoor air temperature.[6] Figure 4 (right): Ratio of measured to design outdoor airflow vs. outdoor temperature.

capacity is about 5 L/s·m² (1 cfm/ft²). The design minimum outdoor air intake on a per person basis is higher than expected based on the requirement in Standard 62-2001 of 10 L/s (20 cfm) per person. However, the higher value noted is based on the actual number of workstations served by each system. If the per person design value is based on the default occupant density in the standard, the mean value of the minimum outdoor air intake per person is much closer to the requirement in Standard 62.

The BASE study also provides valuable information on occupant density in office spaces. The mean number of workstations per 100 m² (1,000 ft²) is about five, as compared with the default value in Standard 62-2001 of seven. However, the recent revision of that standard via Addendum *n* reduces the default value to five, which is supported by these data. The measured occupant density in the spaces is lower still, with a mean of 4.0 people/100 m² (3.7 people/1,000 ft²), which corresponds to about 80% of the workstations being occupied.

	Per Person L/s (cfm) per person	Per Unit Floor Area L/s·m² (cfm/ft²)	Air Changes Per Hour, h^{-1}
Mean	55 (117)	2.04 (0.40)	2.00
Standard Deviation	74 (158)	2.54 (0.50)	2.45
Median	30 (63)	1.03 (0.20)	0.98

Table 8: Summary of measured outdoor air ventilation.

The mean measured supply airflow is close to the mean design value, i.e., 5 L/s·m² (1 cfm/ft²). As might be expected, these supply values are relatively independent of outdoor air temperature for the constant volume systems but tend to increase for warmer temperatures in the VAV systems. The measured outdoor air fraction, i.e., the ratio of the outdoor air intake to the supply airflow, has a mean value of about 40%. Measured outdoor air ventilation rates per person tend to be higher than some might expect, with a mean of 55 L/s (117 cfm) per person. Yet 17% of these measured values are still below the 10 L/s (20 cfm) per person requirement in Standard 62-2001.

While these values are high on average relative to the standard's requirements, the high outdoor air fractions and the low occupancy relative to the default occupancy value in the standard can explain most of the high values. Considering only those values that correspond to minimum outdoor air intake, the mean ventilation rate is 11 L/s (23 cfm) per workstation. About one-half the ventilation rates under minimum outdoor air intake are below 10 L/s (20 cfm) per person. Given the representativeness of the BASE buildings, this prevalence of "low" rates may very well exist in U.S. office buildings in general.

Another key outcome of this study is the documentation of measured airflow rates that are quite different from their design values. While not necessarily unexpected, this finding highlights the need for good system commissioning and maintenance if design intent is going to be realized in practice. Related to the need for regular system maintenance is the importance of designing and configuring systems to facilitate these maintenance activities by providing access to key system components.

Acknowledgments

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References

1. Womble, S.E., et al. 1996. "Developing baseline information on buildings and indoor air quality (BASE '95)." *Proceedings of ASHRAE IAQ '96. Paths to Better Building Environments* 109–117.
2. Persily, A.K., and J. Gorfain. 2004. *Analysis of Ventilation Data from the U.S. Environmental Protection Agency Building Assessment Survey and Evaluation (BASE) Study*. National Institute of Standards and Technology, NISTIR 7145.
3. EPA. 2003. *A Standardized EPA Protocol for Characterizing Indoor Air Quality in Large Office Buildings*. U.S. Environmental Protection Agency.
4. ASHRAE. 2001. ANSI/ASHRAE Standard 62-2001, *Ventilation for Acceptable Indoor Air Quality.*
5. ASHRAE. 2003. Addendum *n* to ASHRAE Standard 62-2001, *Ventilation for Acceptable Indoor Air Quality.* www.ashrae.org.
6. Persily, A.K., W.S. Dols and S.J. Nabinger. 1992. *Environmental Evaluation of the Federal Records Center in Overland Missouri.* National Institute of Standards and Technology, NISTIR 4883.