W. Stuart Dols[1] *and Andrew K. Persily*[1]

A Study of Ventilation Measurement in an Office Building

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ABSTRACT: The National Institute of Standards and Technology has conducted a study of ventilation and ventilation measurement techniques in the Bonneville Power Administration (BPA) Building in Portland, Oregon. The project involved the use of the following outdoor air ventilation measurement techniques: tracer gas decay measurements of whole-building air change rates, the determination of air change rates based on peak carbon dioxide (CO_2) concentrations, the determination of percent outdoor air intake using tracer gas (sulfur hexafluoride and occupant-generated CO_2), and direct airflow rate measurements within the air handling system. In addition, air change rate measurements made approximately three years apart with an automated tracer gas decay system were compared. Airflow rates were measured in the air handling system ductwork using pitot tube, hot-wire anemometer, and vane anemometer traverses, and good agreement was obtained between the different techniques. While accurate determinations of percent outdoor air intake were achieved using tracer gas techniques, the use of CO_2 detector tubes yielded unreliable results. Reliable determinations of ventilation rates per person were made based on SF_6 decay and direct airflow rate measurements, but the use of peak CO_2 concentrations led to overestimations of building air change rates. The measured values of the whole-building air change rates, and their dependence on outdoor air temperature, did not change significantly over a three-year period. The whole-building air change rate under minimum outdoor air intake conditions was determined to be twice the outdoor air intake rate provided by the minimum outdoor air intake fans due to leakage through the main outdoor air intake dampers.

KEYWORDS: airflow, building performance, carbon dioxide, commercial building, indoor air quality, measurements, office building, tracer gas, ventilation

Building ventilation systems are designed to provide sufficient levels of outdoor air to the building, to remove contaminants generated within the space, and to provide an environment that is thermally acceptable to the building occupants. The design of these systems is based on ventilation standards that specify minimum levels of ventilation for occupant health and comfort. It has become increasingly apparent that design values for ventilation rates are not always realized in practice both when the building is constructed and after the building has been in operation for some time [*1*]. This realization, along with increased concerns about indoor air quality, has led to the need for on-site assessment of building ventilation rates. The requirement for on-site assessment includes the need for practical and reliable procedures for making field measurements of building ventilation rates that are accessible to a range of engineering practitioners.

[1] Mechanical engineer and group leader, respectively, Building and Fire Research Laboratory, National Institute of Standards and Technology, Building 226, Room A313, Gaithersburg, MD 20899.

In order to assess different approaches for evaluating ventilation system performance, the National Institute of Standards and Technology (NIST) has conducted a study of ventilation and ventilation measurement techniques in the Bonneville Power Administration (BPA) Building in Portland, Oregon. The project involved two ventilation measurement issues: comparison of ventilation measurement techniques and changes in building ventilation rates over time. Six ventilation measurement methods were studied in the comparison: (1) whole-building ventilation rates determined by automated tracer gas (sulfur hexafluoride, SF_6) decay, (2) whole building ventilation rates based on peak carbon dioxide (CO_2) concentration, (3) percent outdoor air using SF_6 as a tracer gas, (4) percent outdoor air using an automated infrared CO_2 monitoring system, (5) percent outdoor air using CO_2 detector tubes, and (6) direct airflow rate measurements in heating, ventilating and air-conditioning (HVAC) ducts. Also, two sets of building ventilation rate measurements obtained with the automated tracer gas system were compared. One set of measurements was made between September 1987 and July 1989 [2] and the other was collected as part of the present study from July 1991 to February 1992.

During this project whole-building air change rates were monitored continuously with an automated tracer gas decay system. Percent outdoor air intake rates were also monitored continuously with an automated CO_2 monitoring system and the SF_6 system. During this period, daily peak values of CO_2 were used to calculate ventilation rates per person. Two weeks of intensive measurements of direct airflow rates and CO_2 concentrations were performed simultaneously with the automated monitoring in order to compare various methods of assessing whole-building ventilation rates. These methods were compared in terms of accuracy, ease of use, and the level of effort required to implement them.

Background

Building Description

The BPA building is a seven-story office structure with a one-story basement and a two-story underground parking garage. The conditioned office space within the building has a floor area of approximately 34 600 m^2 (372 000 ft^2) and a volume of 134 000 m^3 (4.73×10^6 ft^3), assuming an average ceiling height of 3.8 m (12.5 ft), including the return air plenum. A breezeway connects this building to another office building on the first-floor level, and a kitchen and dining room are attached at this level also (floor plans are contained in Ref *2*). A penthouse mechanical room houses the main HVAC systems, consisting of three large variable air volume (VAV) systems, one serving the center of the building and the others serving the east and west sides. These three systems serve approximately equal volumes of the building. There are also several smaller air handling systems located on and serving the B1 level.

Sketches of the three main air handling systems are shown in Ref *3*. Each system consists of two "cold" supply fans that work in parallel, one "hot" supply fan, a return fan and a minimum outdoor air handling unit. The design supply air capacity of each system is approximately 47 200 L/s (100 000 cfm) and the minimum outdoor air intake fan capacity is 2000 L/s (4200 cfm) per system, which is about 4% of the supply air capacity. Based on the building volume, the minimum design outdoor air intake rate is 0.16 air changes per hour (ACH) or 0.17 L/s · m^2 (0.034 cfm/ft^2), and the maximum supply airflow capacity is 3.8 ACH or 4.1 L/s · m^2 (0.81 cfm/ft^2). An estimate of 2000 building occupants yields minimum and maximum per-person ventilation rates, based on design airflow rates, of 3 L/s (6.3 cfm) per person and 70 L/s (150 cfm) per person. This building was designed to comply with the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Standard 62-1981, which contained a minimum outdoor air intake requirement of 2.5 L/s (5 cfm) per person in office space with no smoking present [4] and a default occupancy density of 7 people/100 m^2. These values correspond to an air change rate of approximately 0.18 ACH for an office building. ASHRAE Standard 62-1989 contains a minimum outdoor air requirement for office space of 10 L/s (20 cfm) per person [5], which corresponds to an air change rate of about 0.72 ACH.

During building occupancy, the minimum outdoor air fans run continuously to provide the design minimum of outdoor air, and the supply fans use variable-pitch fan blades to modulate airflow rate based on supply air demand in the occupied space. Supply air demand is controlled by terminal units located above the ceilings of the occupied space, which modulate supply airflow rates depending on the temperature in the zone being served by the terminal unit. As more units open, requiring additional supply airflow, the associated supply fan blades adjust to increase the airflow and maintain a supply static pressure set point in the main supply ducts. An economizer system modulates the outdoor air intake rate through the "cold" supply fan system during mild weather by modulating the main outdoor air intake (mixed-air) damper position.

Measurement Methods

Whole-Building Air Change Rates

Whole-building air change rates were determined using the tracer gas decay method [ASTM Standard Practice for Measuring Air Leakage Rates by the Tracer Dilution Method (E741-83)]. The automated tracer gas decay system injected SF_6 into the supply airstreams of the building's air handlers every three hours. Tracer gas concentrations were then sampled in ten locations every ten minutes. Tracer gas was injected into the Center, East, and West "cold" supply fans, and four air handlers serving the B1 level. An injection tube carried a metered amount of tracer gas to the supply airstream of the individual air handlers. Tracer gas injection flow rates were based on the volume served by each individual air handler. The locations being sampled were the "cold" supplies and returns of the Center, East, and West systems, the returns of the four air handlers serving the B1 level, the outdoor air, and the diagnostic center which contained the test equipment.

Whole-building air change rates were determined by a volume-weighted averaging of the decay rates of the three main return ducts. An automated tracer gas decay system consisting of a gas chromatograph coupled with an electron capture detector (GC-ECD) was used to determine SF_6 tracer gas concentrations with an uncertainty of about 10%. The accuracy of air change rates measured with this tracer gas system is a function of the uniformity of tracer gas concentration within the building and the calibration of the SF_6 analyzer. Based on the assumption of perfect mixing and the calibration of the SF_6 analyzer, the uncertainty of the air change rates is estimated to be about 10% of the measured value. The tracer gas decay technique determines the total air change rate of the building, including both intentional intake through the ventilation system and unintentional air leakage through the envelope. Previous studies have shown that air change rates due to infiltration can be of the same magnitude as the mechanical ventilation rates [6].

Direct Measurement of Ventilation System Airflows

Direct measurements of system supply and outdoor airflow rates were made during the weeks of August 6, 1991 and January 13, 1992. A hot-wire anemometer, a vane anemometer and a pitot tube with a digital manometer were used during the first week in various locations of the three main systems in order to assess the speed and reliability of these methods for measuring airflow rates in this HVAC system. Both the hot-wire and vane anemometers gave direct readings of velocity in metres per second (feet per minute) [m/s (ft/min)], and the digital manometer used with the pitot tube gave velocity pressure readings in Pascals (inches of water) which were converted to m/s (ft/min). Duct traverses were performed using the hot-wire anemometer and pitot tube in the main supply air ducts, the minimum outdoor air ducts, and the economizer outdoor air intake ducts. Traverses were also performed inside the cold supply fan housings (fan boxes) using the hot-wire anemometer and the vane anemometer. Measurement uncertainties for these airflow rates, based on the uncertainty of the measurement devices alone, were less than 3%. This uncertainty does not include measurement errors due to the use of traverse locations which do not conform with recommended guidelines [7].

The first week of measurements was performed in order to compare velocity measurements with different devices at the same location, to compare measurements of the same airflow rate at different locations, to compare measured airflow rates with design airflow rates, and to use direct airflow rate measurements to determine percent outdoor air intake. The second week of testing focused on the determination of mechanical ventilation rates under minimum outdoor air intake conditions. The results of the first week of measurements revealed that direct traverses of the fan boxes and the minimum outdoor air intake ducts with hot-wire anemometers provided a reasonable means to obtain the desired airflow rates to determine whole building ventilation rates. Therefore, during the second week, supply airflow rates were measured in the cold fan housings immediately downstream of the cooling coils, and duct traverses were performed downstream of the minimum outdoor air intake fans. During two days of the second week, the three main ventilation systems were operated at minimum outdoor air intake.

Percent Outdoor Air Intake Rate

Percent outdoor air intake rates were determined using tracer gas and direct flow measurement techniques. Tracer gas techniques involved a tracer gas balance (SF_6 or CO_2) at the air handler. Based on the measured values of the supply, return, and outdoor air tracer gas concentrations (C_S, C_R, and C_O, respectively), percent outdoor air intake was determined by

$$\%OA = (C_R - C_S)/(C_R - C_O) \tag{1}$$

Percent outdoor air intake rates were determined using four different methods: tracer gas balances employing the automated SF_6 and automated CO_2 systems, tracer gas balances based on CO_2 detector tube measurements, and direct airflow measurements. SF_6 was measured using the GC-ECD described previously, and CO_2 was measured using an infrared absorption analyzer with an uncertainty of 12.5 part per million (ppm). The CO_2 detector tubes contain a substance which changes color when exposed to CO_2 and have graduated markings on the side that indicate the concentration based on the length of substance that changes color. A handheld volumetric piston pump is used to draw the air sample into the tube. Two sampling strategies were employed using the detector tubes [8]. One sampling strategy was to measure the supply, return, and outdoor air concentrations successively, and then have three people read each tube. The other strategy was to have only one person read the tubes. Uncertainty in the measured CO_2 concentration is assumed to equal 33 ppm for the individual concentration readings using three pump strokes to perform a single measurement. The value of 33 ppm is based only on the resolution of the graduated markings on the detector tube, assuming the user can resolve the tube readings within 100 ppm. Erroneous graduated markings on the detector tubes caused by calibration errors could lead to larger uncertainties. Uncertainty in percent outdoor air intake measurements, $\Delta\%OA$, is based on the propagation of uncertainty in using Eq 1. Each tracer gas concentration measurement has an associated uncertainty due to the measurement uncertainty of the sampling equipment. The uncertainty in percent outdoor air measurements is given by

$$\Delta\%OA = 100 \times \left[\frac{\Delta C_R^2 + \Delta C_S^2}{(C_R - C_O)^2} + \frac{(C_R - C_S)^2(\Delta C_R^2 + \Delta C_O^2)}{(C_R - C_O)^4}\right]^{1/2} \quad (2)$$

where

ΔC_R = uncertainty in return air concentration measurement,
ΔC_S = uncertainty in supply air concentration measurement, and
ΔC_O = uncertainty in outdoor air concentration measurement.

Larger uncertainties will occur when differences between the return and outdoor concentrations are relatively small. Also, the more uncertain the tracer gas concentration measurements the greater the uncertainty in percent outdoor air intake measurements.

Direct airflow measurements to determine percent outdoor air intake were mostly performed under minimum outdoor air intake conditions. The percent outdoor air intake is the ratio of the measured outdoor air intake rate and the measured supply airflow rate. The supply airflow rates were measured upstream of the supply fans inside the fan housings. Under minimum outdoor air intake, the outdoor air intake rates were measured downstream of the minimum outdoor air intake fans. The percent outdoor air intake under economizer operation was determined by the direct airflow method on only one occasion because it required a great deal of time to perform a traverse of the main outdoor air intake ducts. During the traverses of the main outdoor air intake ducts, the supply airflow rate rarely remained constant, interfering with several attempts to make these measurements.

Ventilation Rate per Person

Three methods were used to determine the outdoor air intake rate per person: tracer gas decay, peak CO_2 levels, and direct measurement of the total supply airflow rate multiplied by the percent outdoor air intake rate (multiplicative method). The measurement of peak CO_2 levels was performed using the automated CO_2 system, CO_2 detector tubes, and air sample bags filled using a portable pump and analyzed with the automated CO_2 analyzer. The determination of the per-person ventilation rate by the multiplicative method employed the various methods to determine percent outdoor air intake described previously. The tracer gas and CO_2 methods determine the ventilation rate due to both mechanical ventilation and envelope leakage. The multiplicative method accounts for only outdoor air intake through the mechanical system.

Whole-building ventilation rates determined using the tracer gas decay method were based on the average of the decay rates measured in the return air ducts of the three main air handlers. In order to convert whole-building ventilation rates in air changes per hour to ventilation rate per person, the whole-building air change rate is multiplied by the building volume and divided by the number of building occupants, which is approximately 2000. The building volume was determined from a scale set of drawings, and the number of occupants was obtained from a computerized personnel directory.

Building ventilation rates were also estimated by measuring equilibrium or peak values of CO_2 inside the building and the outdoor concentration. This method is based on a mass balance of CO_2 within the building with a constant ventilation rate, a uniform and constant CO_2 generation rate inside the building (that is, constant occupancy), and a constant outdoor CO_2 concentration [9]. Under these assumptions the building ventilation rate is related to the equilibrium CO_2 concentration inside the building by

$$Q_p = G_p/(C_{eq} - C_o) \tag{3}$$

where

Q_p = per-person building ventilation rate (m^3/s per person),
G_p = per-person CO_2 generation rate (assumed equal to 5.3×10^{-6} m^3/s per person),
C_{eq} = indoor CO_2 concentration at equilibrium, and
C_o = outdoor CO_2 concentration.

This method is also based on the assumption that the CO_2 concentration is the same throughout the building and that it has attained equilibrium. The uncertainty of the ventilation rate per person determined using Eq 3 is given by Eq 4 and depends on the uncertainty in the measured indoor and outdoor CO_2 concentrations, ΔC_{eq} and ΔC_o. However, Eq 4 does not account for the uncertainty in the CO_2 generation rate:

$$\Delta Q_p = Q_p \frac{(\Delta C_{eq}^2 + \Delta C_o^2)^{1/2}}{C_{eq} - C_o} \tag{4}$$

Determination of the ventilation rate per person using CO_2 detector tubes is also based on Eq 3 and the associated assumptions. Detector tubes were used to measure ventilation rates per person on January 15 and 16, 1992. On the 15th, concentrations were measured in the return air ducts of the three main air handlers, and on the 16th they were measured in several locations within the occupied space.

Peak CO_2 measurements were performed within the occupied space using portable hand-held sample pumps and air sample bags and the infrared CO_2 detector of the automated CO_2 system. This was done only on January 16, 1992 at the same time that the CO_2 detector tube measurements were being performed. Samples were collected over a period of about one hour, which spanned the time at which the peak indoor concentration was expected to occur. The expected peak time was based on the automated CO_2 data collected the previous day and verified by the automated data collected during the test. Typically, the CO_2 concentration reached a peak at around 11:00 a.m. Air samples were collected at three locations on floors 1 through 7, and an average of these sample concentrations was used as the equilibrium concentration. Outdoor air samples were also collected before and after the interior samples were collected, and the average of these values was used in the calculation.

When determining ventilation rates per person using the multiplicative method, supply airflow rates were measured using a hot-wire anemometer in the supply fan housings. Percent outdoor air intake rates were measured using the SF_6 and CO_2 automated systems, CO_2 detector tubes, and direct airflow measurements of the minimum outdoor air intake fans. The latter case corresponds to the direct measurement of the outdoor air intake rate at the minimum outdoor air handler units. The uncertainty in ventilation rates per person, ΔQ_p, determined using the multiplicative method is dependent on the uncertainty of the supply airflow rate measurement, ΔQ_S, the uncertainty of the percent outdoor air intake measurement, $\Delta\%OA$, and is given by

$$\Delta Q_p = \frac{\left[\left(\Delta Q_S \cdot \frac{\%OA}{100}\right)^2 + \left(\frac{\Delta\%OA}{100} \cdot Q_S\right)^2\right]^{1/2}}{\text{Number of occupants}} \tag{5}$$

CO_2 Buildup Analysis

While the peak CO_2 measurement technique requires steady-state conditions to exist, one can also analyze the buildup in CO_2 concentrations to determine ventilation rates. The buildup method is based on the transient analysis of CO_2 as the concentration increases or builds up in the morning. The technique is based on a single-zone mass balance expressed in volumetric terms as

$$V\,dC/dt = Q(C_o - C) + G \tag{6}$$

where

V = building volume,
C = interior CO_2 concentration,
t = time,
Q = airflow rate into and out of building,
C_o = outdoor CO_2 concentration, and
G = generation rate of CO_2 within the building.

Assuming that Q, C_o, and G are constant, and setting C' equal to the difference between the indoor and outdoor CO_2 concentration, the solution to Eq 6 can be expressed as

$$C' = C'_{eq} + (C'_{init} - C'_{eq})e^{-It} \tag{7}$$

where

C'_{eq} = equilibrium value of C', G/Q,
C'_{init} = $C - C_o$ at $t = 0$, and
I = Q/V, building air change rate.

Based on the time history of the CO_2 concentration inside the return air ducts, nonlinear regression techniques were used to solve for the parameters C'_{eq}, C'_{init}, and I. The value of I can be converted to the ventilation rate per person based on the building volume and the number of occupants. In addition, an average CO_2 generation rate per person can be determined by

$$G_p = C'_{eq}IV/(\text{Number of occupants}) \tag{8}$$

Results

Whole-Building Air Change Rates

The automated tracer gas system was used to measure whole-building air change rates in a previous study from September 1987 to July 1989 [2] and in the present study from July 1991 to January 1992. This enabled an assessment of changes in the operation and performance of the ventilation system since the previous study was performed. Figure 1 shows the

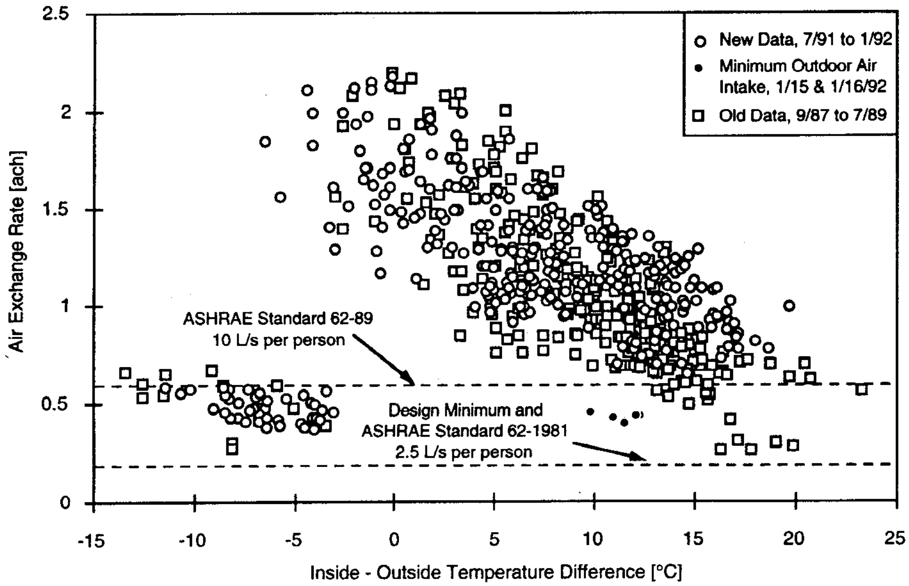

FIG. 1—*Building air change rates for old and new data.*

whole-building air change rates as determined by the automated SF_6 system for the old and new sets of data. The new data are very similar to the data collected in the previous study, indicating that for these weather conditions, that is, outdoor temperatures between 12 and 32°C (54 and 90°F), the building ventilation system is operating as it was during the period of September 1987 to July 1989. These two data sets provide the first opportunity to assess changes in the ventilation characteristics of a building over such a long period of time.

Figure 1 also shows the design minimum air change rate and the air change rates corresponding to the minimums recommended in ASHRAE Standard 62-1981 (2.5 L/s per person, 5 cfm per person) and ASHRAE Standard 62-1989 (10 L/s per person, 20 cfm per person) based on the building occupancy of 2000 people. The average air change rate measured using tracer gas decay under minimum intake for the new data set is 0.45 ACH, about twice the design minimum of 0.19 ACH. The maximum measured air change rate shown in Fig. 3 is 2.2 ACH, about one half of the design capacity.

Direct Measurement of Ventilation System Airflows

Direct measurements of system supply and outdoor airflow rates were made during the weeks of August 6, 1991 and January 13, 1992. The results are presented in Tables 1 and 2 respectively. These tables list the date and time the measurements were performed, the measurement location, the measurement instrument used, the design airflow rate capacity at that location in the system, and the percent difference from design (% DIFF DESIGN = (measured flow − design flow)/design flow) of each measured airflow rate. Measurement locations in individual supply air submain ducts are denoted by their diameters in Table 1. Because the supply fans modulate supply airflow based on cooling demand, the measured supply airflow rates are not expected to equal their design capacities unless the fan is running at full capacity. The minimum outdoor air handler units (AHU-10,11&12) are always run at full capacity; therefore, the differences between the measured and design values are of in-

TABLE 1—*Direct airflow measurements (week 1).*

Date	Time	Fan System	Measurement Location	Measurement Method	Design Flow Rate [L/s]	Measured Flow Rate [L/s]	% DIFF DESIGN	% DIFF METHOD
8/6/91	9:30	SFC12	OA Duct	hot wire	53081	46520	-12%	4%
8/6/91	9:30	SFC12	OA Duct	pitot	53081	48285	-9%	
8/6/91	11:00	SFC12	fan box	hot wire	53081	56397	6%	3%
8/6/91	11:00	SFC12	fan box	vane	53081	58050	9%	
8/6/91	11:00	AHU-10		hot wire	1982	2156	9%	
8/6/91	14:30	SFC12	1.12 m OD	hot wire	16416	11124	-32%	16%
8/6/91	16:00	SFC12	1.12 m OD	pitot	16416	13090	-20%	
8/6/91	15:00	SFC12	1.42 m OD	hot wire	29840	21887	-27%	7%
8/6/91	16:00	SFC12	1.42 m OD	pitot	29840	23406	-22%	
8/6/91	16:00	SFC12	fan box	hot wire	53081	57605	9%	7%
8/6/91	16:00	SFC12	fan box	vane	53081	61839	16%	
8/6/91	15:00	AHU-10		pitot	1982	2425	22%	
8/6/91	16:40	SFC56	0.76 m OD	hot wire	6603	6759	2%	2%
8/6/91	16:40	SFC56	0.76 m OD	pitot	6603	6628	0%	
8/6/91	16:30	SFC56	1.22 m OD	hot wire	20069	17130	-15%	10%
8/6/91	16:30	SFC56	1.22 m OD	pitot	20069	15465	-23%	
8/6/91	16:50	SFC56	1.42 m OD	hot wire	27433	25880	-6%	3%
8/6/91	16:50	SFC56	1.42 m OD	pitot	27433	25037	-9%	
8/6/91	16:40	SFC56	Duct Total	hot wire	54105	49754	-8%	5%
8/6/91	16:40	SFC56	Duct Total	pitot	54105	47121	-13%	
8/6/91	17:00	SFC56	fan box	hot wire	54105	57387	6%	1%
8/6/91	17:00	SFC56	fan box	vane	54105	58050	7%	
8/7/91	9:20	SFC12	1.12 m OD	hot wire	16416	12923	-21%	26%
8/7/91	8:30	SFC12	1.12 m OD	pitot	16416	9924	-40%	
8/7/91	9:30	SFC12	1.42 m OD	hot wire	29840	22004	-26%	15%
8/7/91	8:40	SFC12	1.42 m OD	pitot	29840	18877	-37%	
8/7/91	8:30	SFC12	OA Duct	hot wire	53081	45243	-15%	18%
8/7/91	10:00	SFC12	OA Duct	pitot	53081	53946	2%	
8/7/91	10:15	AHU-10		hot wire	1982	2375	20%	4%
8/7/91	10:15	AHU-10		pitot	1982	2473	25%	
8/7/91	14:40	SFC56	0.76 m OD	hot wire	6603	6575	0%	0%
8/7/91	13:20	SFC56	0.76 m OD	pitot	6603	6583	0%	
8/7/91	14:50	SFC56	1.22 m OD	hot wire	20065	15761	-21%	6%
8/7/91	13:50	SFC56	1.22 m OD	pitot	20065	16703	-17%	
8/7/91	15:15	SFC56	1.42 m OD	hot wire	27433	22921	-16%	15%
8/7/91	13:40	SFC56	1.42 m OD	pitot	27433	26544	-3%	
8/7/91	14:50	SFC56	Duct Total	hot wire	54105	45257	-16%	10%
8/7/91	13:40	SFC56	Duct Total	pitot	54105	49831	-8%	
8/8/91	9:20	SFC12	1.12 m OD	hot wire	16416	9724	-41%	
8/8/91	9:30	SFC12	1.42 m OD	hot wire	29840	19925	-33%	
8/8/91	9:25	SFC56	Duct Total	hot wire	54105	48209	-11%	
8/8/91	10:35	SFC34	Duct Total	hot wire	47856	35020	-27%	
8/8/91	11:30	AHU-12		hot wire	1982	1838	-7%	
8/8/91	12:00	SFC56	fan box	vane	54105	59813	11%	
8/8/91	12:05	SFC56	Duct Total	hot wire	54105	43939	-19%	
8/8/91	14:25	SFC56	fan box	vane	54105	56088	4%	
8/8/91	16:30	SFC56	fan box	vane	54105	58750	9%	
8/8/91	16:40	SFC56	Duct Total	hot wire	54105	44471	-18%	
8/8/91	14:30	AHU-12		pitot	1982	2101	6%	

terest. The airflow rate of AHU-10 was measured six times and always yielded a higher airflow rate than the design value of 2000 L/s (4200 cfm). Measured values were on the average 20% higher than the design capacity. AHU-11 was measured three times, and the airflow rates were approximately 20% lower than design. AHU-12 was measured five times and yielded airflow rates within 7% of the design capacity.

The difference between measurements taken at the same location with different instruments was divided by their mean value and is presented in the column labeled "%DIFF

TABLE 2—*Direct airflow measurements (week 2).*

Date	Time	Fan System	Measurement Location	Measurement Method	Design Flow Rate [L/s]	Measured Flow Rate [L/s]	% DIFF DESIGN
1/14/92	10:50	SFC12	fan box	hot wire	53081	30534	-42%
1/14/92	11:00	SFC34	fan box	hot wire	47856	35041	-27%
1/14/92	10:40	SFC56	fan box	hot wire	54105	28847	-47%
1/14/92	13:40	SFC56	fan box	hot wire	54105	29605	-45%
1/14/92	16:10	SFC12	fan box	hot wire	53081	28499	-46%
1/14/92	16:00	SFC34	fan box	hot wire	47856	35544	-26%
1/14/92	16:20	SFC56	fan box	hot wire	54105	26386	-51%
1/15/92	9:25	SFC12	fan box	hot wire	53081	57157	8%
1/15/92	9:40	SFC34	fan box	hot wire	47856	38591	-19%
1/15/92	9:15	SFC56	fan box	hot wire	54105	51522	-5%
1/15/92	15:00	SFC12	fan box	hot wire	53081	28356	-47%
1/15/92	15:50	SFC34	fan box	hot wire	47856	22849	-52%
1/15/92	16:10	SFC56	fan box	hot wire	54105	24948	-54%
1/16/92	8:15	SFC12	fan box	hot wire	53081	54329	2%
1/16/92	8:30	SFC34	fan box	hot wire	47856	37538	-22%
1/16/92	8:00	SFC56	fan box	hot wire	54105	40171	-26%
1/16/92	11:50	SFC12	fan box	hot wire	53081	56048	6%
1/16/92	12:00	SFC34	fan box	hot wire	47856	42268	-12%
1/16/92	11:40	SFC56	fan box	hot wire	54105	56058	4%
1/16/92	14:15	SFC12	fan box	hot wire	53081	55201	4%
1/16/92	14:30	SFC34	fan box	hot wire	47856	38847	-19%
1/16/92	14:00	SFC56	fan box	hot wire	54105	55965	3%
1/15/92	13:50	AHU-10		hot wire	1982	2441	23%
1/16/92	9:30	AHU-10		hot wire	1982	2560	29%
1/15/92	11:30	AHU-11		hot wire	1982	1556	-22%
1/16/92	8:40	AHU-11		hot wire	1982	1589	-20%
1/16/92	11:40	AHU-11		hot wire	1982	1644	-17%
1/15/92	14:15	AHU-12		hot wire	1982	1865	-6%
1/16/92	9:10	AHU-12		hot wire	1982	1864	-6%
1/16/92	11:30	AHU-12		hot wire	1982	1838	-7%

METHOD" in Table 1. The comparisons are made between the hot-wire measurements which are presented in the same row as the %DIFF METHOD and the measurement which appears in the row below the hot-wire value. Airflow rates measured using the hot-wire anemometer and the pitot tube, and the hot-wire anemometer and vane anemometer, were generally within 10% of each other.

In order to evaluate the measurement of the same airflow rate at different locations, measurements of the West air handler system (SFC-5&6) taken inside the cold supply fan box were compared with the sum of the individual airflow rates measured in the three submain ducts of the West system. The difference between these measurements divided by the average measured airflow rate ranged from 15% to 30%.

Percent Outdoor Air Intake Rate

Percent Outdoor Air: SF_6 and CO_2 Automated—Percent outdoor air intake rates, based on data collected with the SF_6 tracer gas system during the previous study, were determined for the Center air handling system for the period of September 1987 to July 1989 and are presented in Fig. 2 along with the new measurements. An average maximum outdoor air intake rate of 83% occurred when outdoor temperatures were between 15% and 25°C (59°F and 77°F), and a minimum of about 8% occurred when the outdoor temperature was above about 25°C (77°F). Due to the operation of the economizer cycle, the percent outdoor air intake was modulated when the outdoor temperature was below 12°C (54°F).

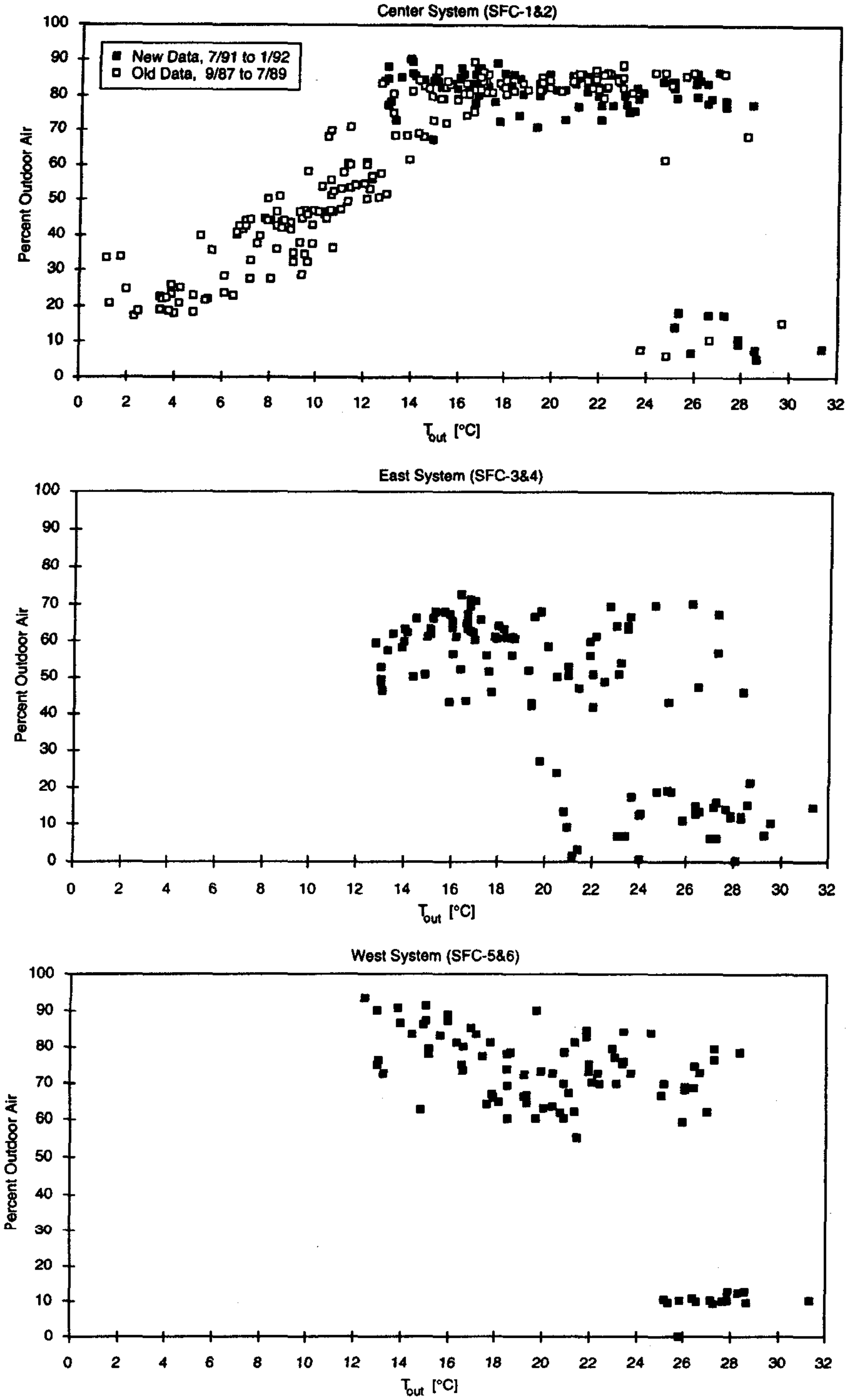

FIG. 2—*Percent outdoor air intake (SF_6 automated).*

For this study, percent outdoor air intake was continuously monitored using both the automated SF_6 tracer gas system and the automated CO_2 system simultaneously. Figure 2 shows percent outdoor air intake rates for all three main fan systems as determined by the automated SF_6 system. Figure 3 shows percent outdoor air intake measured with the automated CO_2 system. All three fan systems have approximately the same minimum outdoor air intake rate of about 10% compared to a design value of 4%. The average maximum rates of the Center, East, and West systems (SFC-1&2, SFC-3&4, and SFC-5&6) are 82%, 60%, and 74% respectively based on the SF_6 data.

Percent Outdoor Air: CO_2 Detector Tubes—The results of the percent outdoor air intake determinations based on CO_2 detector tube measurements are presented in Table 3, which gives the individual detector tube readings divided by the number of pump strokes used to take the sample. The percent outdoor air based on the readings obtained by each individual are shown, along with the mean and standard deviation of these three readings. The averages of the concentration readings taken by the three people were also used to calculate the percent outdoor air intake rates given in bold in Table 3. The values to the right of the bold values are the measurement uncertainties given in percent outdoor air. The determinations on August 8, 1991 and January 15, 1992 were all done by a single person, and uncertainty estimates are shown for each value of percent outdoor air.

The percent outdoor air calculations based on one individual's readings are quite variable and subject to significant uncertainty. This uncertainty is due to the low resolution of the detector tubes used in this study, the difficulty in reading the tubes, and calibration errors. In some cases the single-person results were quite unreasonable, that is, less than 0% or greater than 100%.

Percent Outdoor Air: Direct Airflow Measurement—Percent outdoor air intake rates were determined under both minimum and maximum percent outdoor air intake conditions during the first week of direct airflow measurements and under minimum outdoor air intake conditions during the second week. These values of percent outdoor air intake were determined by dividing the airflow rate measured in the outdoor air intake ducts by the supply airflow rate, with both values being obtained by duct traverses. Table 4 lists the results of these determinations along with the mixed-air damper status for the fan system being measured as obtained from the HVAC control system. Very few measurements were made with the mixed-air dampers open because of difficulties in accessing some of the ductwork and due to the modulation of the mixed-air damper positions during traverses.

Ventilation Rate Per Person

Ventilation Rate Per Person: SF_6 Automated—Table 5 shows the whole building air change rate determined by the tracer gas decay method and the ventilation rate per person based on the measured air change rate, 2000 building occupants, and a building volume of 114 000 m^3 (4 030 000 ft^3). The measurement uncertainty associated with the ventilation rate as determined by the tracer gas decay method is approximately 10% of the indicated values. The values obtained during minimum outdoor air intake were approximately 8 L/s (16 cfm) per person which is higher than the recommended minimum outdoor air intake given in ASHRAE Standard 62-1981 (2.5 L/s per person, 5 cfm per person) and slightly lower than the value in ASHRAE Standard 62-1989 (10 L/s per person, 20 cfm per person). These measurements include both intentional outdoor air intake through the ventilation system and unintentional air leakage through the building envelope.

Ventilation Rate Per Person: Peak CO_2 Automated—Building ventilation rate estimates based on equilibrium analysis were determined using the peak values of the average building CO_2 concentration. These concentrations were measured in the return ducts of the main air

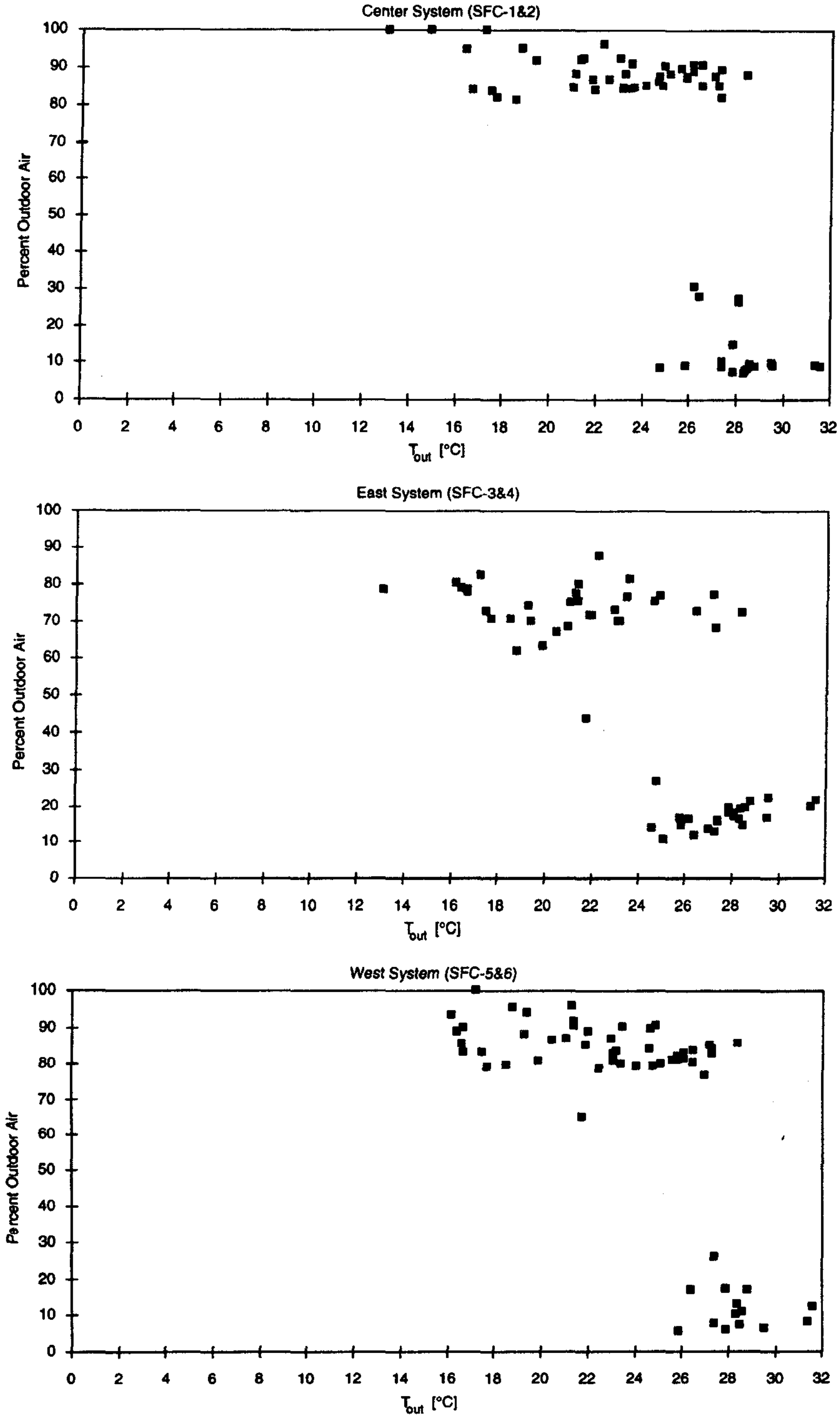

FIG. 3—*Percent outdoor air intake (CO_2 automated).*

TABLE 3—*Percent outdoor air by CO_2 detector tubes.*

Date	Time	System	CO_2 Concentrations			%OA	Person
			Supply	Return	Outdoor		
8/6/91	10:10	SFC12	467	533	417	57%	1
			467	567	417	67%	2
			317	433	300	87%	3
						70%	<-- Avg
						13%	<--Std
		Avg-->	417	511	378	**71%**	± 43%
8/6/91	10:40	SFC12	467	533	417	57%	1
			467	567	433	75%	2
			433	500	400	67%	3
						66%	<-- Avg
						7%	<--Std
		Avg-->	456	533	417	**67%**	± 48%
8/7/91	8:30	SFC12	417	500	417	100%	1
			417	500	433	125%	2
			383	467	400	125%	3
						117%	<-- Avg
						12%	<--Std
		Avg-->	406	489	417	**115%**	± 100%
8/7/91	10:35	SFC12	467	500	467	100%	1
			467	500	500	ERR	2
			433	500	433	100%	3
						ERR	<-- Avg
						ERR	<--Std
		Avg-->	456	500	467	**133%**	± 237%
8/7/91	13:30	SFC56	400	500	433	150%	1
			400	500	467	300%	2
			400	500	400	100%	3
						183%	<-- Avg
						85%	<--Std
		Avg-->	400	500	433	**150%**	± 126%
8/7/91	15:30	SFC56	667	767	467	33%	1
			733	700	433	-12%	2
			667	700	433	12%	3
						11%	<-- Avg
						19%	<--Std
		Avg-->	689	722	444	**12%**	± 17%
8/8/91	11:00	SFC56	667	600	417	-36%	± 27%
8/8/91	11:30	SFC56	567	700	467	57%	± 23%
8/8/91	17:25	SFC56	550	750	525	89%	± 28%
8/8/91	18:05	SFC56	550	600	500	50%	± 53%
1/15/92	11:00	SFC12	900	1067	475	28%	± 8%
1/15/92		SFC34	967	1067	475	17%	± 8%
1/15/92		SFC56	1000	1267	475	34%	± 6%
1/15/92	14:00	SFC12	933	1125	454	29%	± 7%
1/15/92		SFC34	983	1050	454	11%	± 8%
1/15/92		SFC56	1050	1483	454	42%	± 5%

handlers using the automated CO_2 system. Table 6 shows the calculated ventilation rate per person based on Eq 3, the measurement uncertainty in the calculated ventilation rate, and the building air change rate corresponding to this ventilation rate. Under minimum percent outdoor air intake, the peak CO_2 method yielded a ventilation rate of about 15 L/s (30 cfm) per person and about 50 L/s (100 cfm) per person under maximum percent outdoor air intake conditions.

The measurement uncertainties shown in Table 6 are based on the accuracy of the infrared CO_2 monitor utilized by the automated system and the propagation of uncertainty in Q_p given by Eq 4. The uncertainties given in the table do not include other sources of error such as in the number of building occupants, variations in the number of building occupants during the measurements, variations in the ventilation rate, non-constant outdoor CO_2 concentrations, nonuniformities in the CO_2 concentrations within the building, and the indoor CO_2 concentration not being at equilibrium.

Ventilation Rate Per Person: Peak CO_2 Detector Tubes—Peak CO_2 was measured with detector tubes on January 15 and 16, 1992. Measurements were performed in the three main return air ducts on the 15th and in several locations in the office space on the 16th. The

TABLE 4—*Percent outdoor air by direct flow method.*

Date	Time	System	% Outdoor Air by Direct Flow Method	Mixed-air Damper Status [%open]
8/6/91	10:10	SFC-1&2	87%	100%
	10:40	SFC-1&2	87%	100%
	16:40	SFC-5&6	3%	0%
8/7/91	15:00	SFC-5&6	4%	0%
8/8/91	11:30	SFC-5&6	3%	0%
	16:30	SFC-5&6	4%	0%
1/15/92	9:25	SFC-1&2	4%	5%
	9:40	SFC-3&4	4%	0%
	9:15	SFC-5&6	4%	0%
1/16/92	8:00	SFC-1&2	5%	4%
	8:15	SFC-3&4	4%	0%
	8:30	SFC-5&6	5%	0%
1/16/92	11:50	SFC-1&2	5%	4%
	12:00	SFC-3&4	4%	0%
	11:40	SFC-5&6	3%	0%
1/16/92	14:15	SFC-1&2	4%	4%
	14:25	SFC-3&4	4%	0%
	14:05	SFC-5&6	4%	0%

calculated ventilation rates per person under minimum outdoor air intake conditions were approximately 9 L/s (18 cfm) per person on both days with an associated uncertainty of approximately 8% of the measured value.

Ventilation Rate Per Person: Peak CO_2 Air Sample Bags—Peak CO_2 was determined in the office space on January 16, 1992 using air sample bags and the infrared CO_2 analyzer of the automated system. The interior sample concentrations ranged from 450 to 1200 ppm, and the outdoor concentration was approximately 550 ppm. The ventilation rate per person based on the average of these interior measurements was approximately 16 L/s (32 cfm) per person. For comparison, a value of 13 L/s (26 cfm) per person was obtained using the automated CO_2 system to measure the return air concentrations at the main air handlers. The uncertainties associated with these ventilation rates are approximately 5% of the measured values.

Ventilation Rate Per Person: Multiplicative Method—Table 7 displays the results of the determinations of per-person ventilation rate based on the multiplicative method during the week of January 13, 1992. Of particular interest are the four sets of measurements performed under minimum outdoor air intake conditions. Excellent agreement was obtained between the per-person ventilation rates at minimum intake as determined using the percent outdoor air intake rates based on the automated SF_6 and automated CO_2 systems and the results obtained based on SF_6 decay. The ventilation rates per person obtained by the direct measurement of the minimum outdoor air intake fan airflow rates were approximately one-half the rates obtained using the multiplicative methods based on the automated SF_6 and CO_2 systems. Results based on the CO_2 detector tubes were inconsistent with the results of the

TABLE 5—*Ventilation rate per person (SF_6 automated).*

Date	Hr	SF_6 Decay		
		ach	per person	
			[L/s]	[cfm]
7/26/91	9	1.7	27	57
7/29/91	9	1.8	29	62
7/30/91	9	1.8	29	61
7/31/91	9	2.0	32	67
7/31/91	15	0.5	8	16
8/01/91	9	1.9	30	63
8/12/91	9	1.7	27	57
8/12/91	17	0.5	8	17
8/13/91	9	1.9	30	64
8/14/91	9	1.8	28	59
8/14/91	16	0.6	9	19
8/15/91	9	2.1	33	71
8/15/91	15	0.6	9	19
8/16/91	10	1.6	25	52
8/19/91	9	1.9	31	65
8/19/91	15	0.6	9	19
8/20/91	9	1.8	29	61
8/20/91	15	0.6	9	18
8/21/91	8	1.6	26	54
8/21/91	15	0.6	9	20
1/15/92	11	0.4	7	15
1/16/92	11	0.4	7	14

other methods. The relative uncertainties associated with these ventilation rates are dependent upon the uncertainty in the percent outdoor air intake measurement technique used.

CO_2 Buildup Analysis

The buildup analysis was performed with the data collected on January 15 and 16 under minimum outdoor air intake conditions between 9:00 and 11:00 a.m. The results are presented in Table 8. A plot of the data collected on January 15 along with the nonlinear curve fit to the data is shown in Fig. 4. Table 8 lists the air change rate and the per person CO_2 generation rate based on the curve fit and the whole-building air change rate determined by SF_6 decay.

Discussion

Measurement Results

Direct Measurement of Ventilation System Airflows—In making direct measurements of ventilation system airflow rates using duct traverses, the impact of practical considerations on the use of these techniques was noted. As expected, the physical configuration of the HVAC system and the manner in which it is operated can limit which airflows can be measured, when they can be measured, and the accuracy of the measurements. None of the airflow rate measurement locations were consistent with handbook recommendations for pitot

TABLE 6—*Ventilation rate per person (peak CO_2 automated).*

Date	Hr	Peak CO_2 Automated per person [L/s]	[cfm]	% Uncertainty	ach
7/26/91	9	50	106	17%	3.2
7/26/91	14	41	87	14%	2.6
7/29/91	9	45	96	15%	2.9
7/29/91	15	15	33	5%	1.0
7/30/91	9	49	103	16%	3.1
7/30/91	16	21	44	7%	1.3
7/31/91	9	52	111	18%	3.3
7/31/91	15	18	38	6%	1.1
8/01/91	9	54	115	18%	3.4
8/12/91	9	43	90	14%	2.7
8/12/91	17	37	78	12%	2.3
8/13/91	9	45	95	15%	2.8
8/13/91	14	40	84	13%	2.5
8/14/91	9	45	95	15%	2.8
8/14/91	16	20	41	7%	1.2
8/15/91	9	47	100	16%	3.0
8/15/91	15	15	31	5%	0.9
8/16/91	10	45	95	15%	2.8
8/19/91	9	43	92	14%	2.7
8/19/91	15	20	43	7%	1.3
8/20/91	9	52	109	17%	3.3
8/20/91	15	17	37	6%	1.1
8/21/91	8	49	103	16%	3.1
8/21/91	15	18	37	6%	1.1
8/22/91	9	45	95	15%	2.8
8/22/91	15	16	34	5%	1.0
1/15/92	11	14	30	5%	0.9
1/16/92	11	13	27	4%	0.8

tube or hot-wire traverses [*7,10*]. All of the traverse locations represented a compromise with recommended practice, but the results obtained appeared to be consistent and reasonable. In some cases, ducts of interest were entirely inaccessible. Along with these physical constraints, there are also time constraints associated with these airflow measurements. Throughout the course of a day, changes in system demands affect system airflow rates. This effect

TABLE 7—*Ventilation rate per person (multiplicative method).*

Date	Time	%OA	Ventilation Rates [L/s per person] Total Supply x %OA: CO_2 Auto	CO_2 Tube	SF_6 Auto	Direct Flow	SF_6 Decay
1/14/92	16	max	34	--	30	--	--
1/15/92	9	min	6	20	7	3	7
1/15/92	16	max	28	10	25	--	16
1/16/92	8	min	7	--	6	3	7
1/16/92	12	min	7	--	5	3	7
1/16/92	14	min	6	--	5	3	7

TABLE 8—*Ventilation rate per person (CO_2 buildup).*

Date	Time	Regression Results		SF_6 Decay
		I [ach]	G_p [m^3/s per person]	[ach]
1/15/92	9:00-11:00	0.59	4.06×10^{-6}	0.44
1/16/92	9:00-11:00	0.40	3.48×10^{-6}	0.43

was particularly evident during the first week of measurements when the weather was quite warm, that is, near to the temperature at which the main outdoor air intake (mixed-air) dampers close due to the operation of the economizer cycle. Under these conditions, the building operated with the mixed-air dampers wide open until the outdoor air temperature increased to the level at which these dampers shut and the intake was reduced to its minimum value. Several duct traverses were interrupted by this sudden change in airflow rate. Such system effects can sometimes be anticipated, but this requires an understanding of how the system is intended to work and, more importantly, how the system is actually working.

The measurements of ventilation system airflow rates using pitot tube, hot-wire anemometer, and vane anemometer duct traverses were generally consistent with each other even though the duct configurations were not consistent with standard recommendations. Measurements of the same airflow rate using these different devices were generally within 10% of each other.

Percent Outdoor Air Intake Rate—Table 9 compares the results of the measurements based on SF_6 and CO_2 balances. Percent outdoor air intake rates based on the automated SF_6 and CO_2 test results are generally in good agreement with each other as seen in Figs. 2 and 3. All three fan systems have approximately the same minimum outdoor air intake rate of about 10% compared to the design value of 4%. As seen in Table 9, the determination of percent outdoor air intake based on detector tube readings was often quite inaccurate, particularly at low values of percent outdoor air intake.

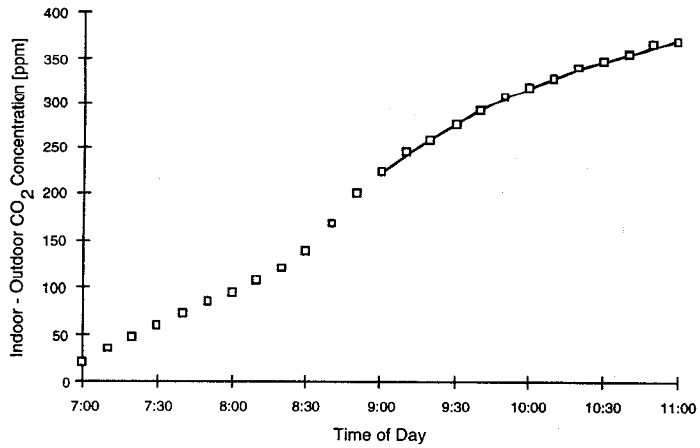

FIG. 4—*Nonlinear curve fit of CO_2 buildup data (1/15/92).*

TABLE 9—*Comparison of percent outdoor air measurements by method.*

Date	Time	System	Percent Outdoor Air			
			CO_2 Tubes (1 person)	CO_2 Tubes (3 person)	CO_2 Auto	SF_6 Auto
8/6/91	10:10	SFC-1&2	57%	71%	87%	--
	10:40	SFC-1&2	57%	67%	82%	--
8/7/91	8:30	SFC-1&2	100%	115%	90%	--
	10:35	SFC-1&2	100%	133%	90%	--
	13:30	SFC-5&6	150%	150%	88%	--
	15:40	SFC-5&6	33%	12%	11%	--
8/8/91	11:00	SFC-5&6	-36%		8%	--
	11:30	SFC-5&6	57%		12%	--
	17:25	SFC-5&6	89%		13%	--
	18:05	SFC-5&6	50%		11%	--
1/15/92	9:25	SFC-1&2	28%		7%	11%
	9:15	SFC-5&6	34%		8%	16%
1/15/92	13:50	SFC-1&2	29%		10%	11%
	14:10	SFC-3&4	11%		10%	10%
	14:00	SFC-5&6	42%		9%	16%
1/16/92	8:00	SFC-1&2	--		8%	5%
	8:15	SFC-3&4	--		14%	7%
	8:30	SFC-5&6	--		13%	14%
1/16/92	11:50	SFC-1&2	--		8%	8%
	12:00	SFC-3&4	--		9%	9%
	11:40	SFC-5&6	--		9%	12%
1/16/92	14:15	SFC-1&2	--		6%	4%
	14:25	SFC-3&4	--		12%	6%
	14:05	SFC-5&6	--		7%	12%

The CO_2 detector tubes used in this study did not yield reliable measurements of percent outdoor air intake due to the difficulty in obtaining consistent readings and the low resolution of the tubes. The single-person CO_2 tube method yielded results which were as much as several hundred percent different from the values obtained by the other tracer gas methods. For example, on August 8, 1991 and January 15, 1992 the automated SF_6 and CO_2 systems yielded percent outdoor air intake rates under minimum outdoor air intake conditions of approximately 10%, while the CO_2 tube method yielded results from −36% to 89%.

As compared with the CO_2 concentration measurements using the automated system, the measurements of CO_2 concentrations with detector tubes in this study were associated with significant measurement uncertainties. Large variations between readings taken by individuals occurred because the line separating the reacted and nonreacted chemical is diffuse, making it difficult to read the tubes consistently. Graduations on the tubes are in increments of 500 ppm, which is very coarse for resolving concentrations typical of indoor and outdoor air.

The three-person method seemed to be useful only to determine a rough estimate of percent outdoor air intake, but it still yielded some unreasonable results. Percent outdoor air values obtained using the three-person CO_2 detector tube sampling method correlated better with the outdoor air damper status than the values obtained by the single-person method, which did not correlate at all.

The percent outdoor air intake rates measured with the direct flow technique under minimum outdoor air intake conditions were approximately 5%, which is about one-half the intake rates determined with the automated SF_6 and CO_2 systems. The reason for this difference is that the direct airflow measurements accounted only for intake through the minimum outdoor air intake fans and did not account for leakage of outdoor air through the mixed-air dampers when they were in the fully closed position. This damper leakage was verified by performing velocity measurements in the economizer outdoor air intake ducts under minimum outdoor air intake conditions when the mixed-air dampers were closed. Based on these results it is seen that under minimum outdoor air intake conditions, outdoor air leakage through the mixed-air dampers is approximately equal to the intentional minimum outdoor air intake rate.

Ventilation Rate per Person—Table 10 presents per-person ventilation rates from SF_6 decay and peak CO_2 concentrations determined with the automated CO_2 measurement system. Under minimum outdoor air intake conditions, the CO_2-based values are roughly twice those determined by SF_6 decay. At higher air change rates, as expected, the difference is not quite as large, though still significant. Under minimum percent outdoor air intake the tracer gas decay method yielded a ventilation rate of approximately 8 L/s (16 cfm) per person and the peak CO_2 method yielded about 15 L/s (30 cfm) per person. Under maximum outdoor air intake conditions the tracer gas decay method yielded about 30 L/s (60 cfm) per person and the peak CO_2 method about 50 L/s (100 cfm) per person.

As seen in other studies [9], overprediction by the peak CO_2 approach appears to occur because the CO_2 concentrations are not at equilibrium at the time of the measurements. This and most other office buildings are only occupied by an approximately constant number of people at best from about 9:00 a.m. until 12:00 noon and from 1:00 p.m. until 5:00 p.m. In the test building, this period of constant occupancy is further shortened by the implementation of flex-time schedules. Under constant occupancy, three hours are required to reach 95% of the steady-state concentration at an air change rate of 1.0 ACH and approximately

TABLE 10—*Comparison of ventilation rate per person measurements by method.*

Date	Hr	SF_6 Decay L/s per person	Peak CO_2 Auto L/s per person
7/26/91	9	27	50
7/29/91	9	29	45
7/30/91	9	29	49
7/31/91	9	32	52
7/31/91	15	8	18
8/01/91	9	30	54
8/12/91	9	27	43
8/12/91	17	8	37
8/13/91	9	30	45
8/14/91	9	28	45
8/14/91	16	9	20
8/15/91	9	33	47
8/15/91	15	9	15
8/16/91	10	25	45
8/19/91	9	31	43
8/19/91	15	9	20
8/20/91	9	29	52
8/20/91	15	9	17
8/21/91	8	26	49
8/21/91	15	9	18
1/15/92	11	7	14
1/16/92	11	7	13

six hours at a rate of 0.5 ACH. Therefore, in this and other office buildings, it is unlikely that the peak CO_2 concentration is an actual equilibrium value, leading to overpredictions of per-person ventilation rates based on peak CO_2 analysis.

The limited number of ventilation rate per-person determinations based on peak CO_2 measured with detector tubes agreed with the SF_6 measurements, but this agreement was fortuitous. The peak CO_2 approach with detector tubes has the same tendency to overpredict based on the use of pre-equilibrium concentrations. However, inaccuracies in the CO_2 concentration measurements using the detector tubes just happened to balance out the pre-equilibrium overprediction.

Under minimum outdoor air intake, the multiplicative method of determining ventilation rate per person using percent outdoor air based on the automated SF_6 and CO_2 measurements agreed with the ventilation rate per person based on SF_6 decay. This is interesting because the multiplicative method does not account for envelope infiltration, while the SF_6 decay method does. The ventilation rate per person based on direct airflow rate measurement accounts for only intake through the minimum outdoor air intake fans, and the results of these determinations were about one-half the results based on SF_6 decay. Based on these results, the amount of envelope infiltration appears to be minimal under conditions of minimum outdoor air intake. However, there appears to be outdoor air leakage into the building through the mixed-air dampers at a rate approximately equal to the intake through the minimum outdoor air intake fan, and this is the reason for the agreement between the multiplicative and tracer gas decay methods.

Measurement Issues

The approaches to ventilation assessment studied in this project have both advantages and disadvantages. The amount of effort associated with each technique, and the completeness and quality of the information obtained, is in general a function of the building being studied and the resources available to those performing the assessment. Building layout and HVAC system configuration are two important factors that impact the required level of effort. Additional resource requirements including the initial cost of the measurement equipment; the cost associated with installation, calibration, and maintenance; the number of measurements to be conducted; and the time for data analysis. The number of measurements is an important consideration when deciding between an automated monitoring system and a manual approach. This decision must involve a balance between the amount of time required to make the manual measurements and the installation time of an automated system. A discussion of some of these measurement issues follows, including estimates of the level of effort associated with each technique.

SF_6 Automated and CO_2 Automated—The initial setup of the automated SF_6 and CO_2 systems for measuring the concentrations at the main air handlers required about 10 person-weeks. However, these systems were installed for a different project, and if they were installed to conduct this study alone the installation would have required only about four person-weeks. Once the system was installed, the automated measurements required little effort to keep them running. Maintaining these systems involves calibrating the detectors; maintaining the sample pumps, valves, and controllers within the systems; changing diskettes used to store the data; and replacing compressed gas cylinders. Calibration of the SF_6 system takes about one hour, and the CO_2 system about 15 min. The CO_2 system does not require a tracer gas injection system, is easier and quicker to calibrate, and requires less maintenance than the SF_6 system.

Direct Flow—Direct airflow measurements require a detailed inspection of the HVAC system in order to identify the most suitable measurement locations. Once these locations are determined, the layout of traverse points must be determined and holes drilled in the ducts if necessary. As is often the case, traverse locations for performing these measurements in accordance with recommended practice [*7*] were unobtainable in this HVAC system. Traverses were performed in the only accessible locations with several different instruments, and the various approaches and measurement locations yielded similar results. Total supply airflow rates measured by performing duct traverses of the submain ducts of all three systems, some of which were inaccessible, required approximately 120 min to perform, whereas measurements taken inside all three fan boxes required only about 40 min to perform. Duct traverse measurements required about 60 min for all three minimum outdoor air intake fans.

CO_2 Tubes—Each measurement performed with a detector tube required approximately 10 min using three pump strokes per sample. A total of 60 min was required to measure per-person ventilation rates, based on peak CO_2 concentrations, at all three main air handlers. A similar amount of time was required to determine the percent outdoor air intake for the three air handlers. CO_2 detector tubes have the advantages of being portable and not requiring any installation time. The manufacturers of the CO_2 detector tubes used in this study state that their tubes require no calibration; however, the tubes which were used in this study often disagreed with values determined with the infrared monitor used in the automated system. Results based on the CO_2 tube measurements are subject to user interpretation and can yield very unreliable results when compared with a calibrated CO_2 monitor. This study was based on the use of only one brand of detector tube. There are other manufacturers of CO_2 detector tubes, and a more detailed study of some of these tubes is presented in Ref *11*.

CO_2 Sample Bags—Air sample bags and portable pumps have the advantage over an automated system of requiring no installation time, except perhaps the drilling of access holes in the ductwork. In these tests, it took about one minute to collect the air samples and another minute to measure the CO_2 concentration. Another option is to use a portable CO_2 monitor at the measurement site. The monitor must be calibrated periodically, requiring about 15 min. This calibration time is relatively insignificant with performing a large number of measurements.

CO_2 Buildup—This method was based on data collected by the automated CO_2 sampling system. Because the data were collected automatically, the time required for this method was primarily associated with the nonlinear regression analysis. The buildup method also requires that the CO_2 concentration data fit the model given by Eq 7. The limited amount of data analyzed in this study fit the model well, but as seen in other studies, this is not always the case [*9*].

Conclusions

This study of ventilation assessment in an office building concentrated on two issues, changes in building ventilation characteristics over time and a comparison of different approaches to ventilation evaluation. In the study, whole-building air change rates were measured over several months using the tracer gas decay technique. The results of these measurements were compared with a similar data set collected about three years earlier, and the comparison showed no significant changes in the ventilation rates of this building over time. The measured ventilation rates were always above the design minimum of 3 L/s (6 cfm) per person, in compliance with the recommendations of ASHRAE Standard 62-1981, the standard on which the design was based. The minimum ventilation rates were below the minimum levels recommended in ASHRAE Standard 62-1989 of 10 L/s (20 cfm) per person.

Ventilation rates per person ranged from about 7 L/s (14 cfm) per person to about 36 L/s (72 cfm) per person. Also, the measured air change rates indicate that the outdoor air intake controls are operating in accordance with design.

The measurements of ventilation system airflow rates using duct traverses showed that the minimum outdoor air intake was within 10% or 20% of design for the three minimum outdoor intake fans. Although the traverse locations were not in accordance with standard recommendations, the results of traverses using pitot tubes, hot-wire anemometers, and vane anemometers were generally within 10% of each other. In conducting these measurements, several logistical difficulties were identified such as inaccessible ductwork and modulations in system airflow rates during the traverses.

The percent outdoor air intake at the building air handlers was determined reliably using SF_6 and CO_2 balances in the supply, return, and outdoor airstreams. However, when CO_2 detector tubes were used to perform these balances, the percent outdoor air determinations were inaccurate and unreliable. These problems were due to the inaccurate determinations of CO_2 concentration using the detector tubes. The determination of percent outdoor air by dividing the outdoor air intake rate measured at the minimum outdoor air intake fans by the measured supply airflow rate yielded values approximately one-half those obtained from the tracer gas mass balance under minimum intake conditions. This difference is due to outdoor air leakage at the mixed-air dampers under minimum outdoor air intake.

Ventilation rates per person were determined from whole building SF_6 decay tests and equilibrium analysis of peak CO_2 concentrations. The values obtained from the peak CO_2 analysis were about 50% to 100% above the values obtained from SF_6 decay, depending on the ventilation rate. This overestimation presumably occurred because CO_2 concentrations in this building did not attain equilibrium due to insufficiently long periods of constant CO_2 generation, that is, constant occupancy. When the percent outdoor air was determined by an SF_6 or CO_2 mass balance and multiplied by the supply airflow rate, the resultant ventilation rate was in good agreement with the rate obtained by SF_6 decay.

All of these approaches to ventilation evaluation have certain advantages and disadvantages, but none of them yields a complete characterization of the ventilation system performance. In order to obtain a complete understanding, a combination of methods must be considered and a certain investment of resources is required. In many situations, resource limitations result in the ability to perform only a partial evaluation of ventilation. With proper planning and careful consideration, however, a partial evaluation can still yield useful and reliable information.

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Discussion

Stephen N. Flanders[1] *(written discussion)*—How was the SF_6 tracer gas distributed in the building and how was the uniformity of concentration tested?

W. S. Dols (authors' closure)—Tracer gas was injected into the supply airstreams of the three main air handlers which serve the entire building. Each air handler serves a zone which is approximately one third of the total building volume. Each of these zones is made up of one third of floors 1 through 7. Because the three zones are about the same size, tracer gas was injected at approximately equal rates and allowed to mix for about twenty minutes prior to calculating the decay rates in the return airstreams of the three main air handlers. Uniformity of tracer gas was verified by sampling the return airstreams and selected locations within the occupied space every ten minutes during the decay.

David Saum[2] *(written discussion)*—How typical is this building? Have there been any air quality complaints?

W. S. Dols (authors' closure)—There are many different types of office buildings and mechanical ventilation systems, and this variety makes it difficult to describe the test building or any other building as typical. The test building was certainly not unusual.

Aside from a few isolated complaints primarily associated with thermal comfort, there haven't been any major indoor air quality complaints in this building.

[1] USA CRREL, Hanover, NH 03755.
[2] Geomet Technologies, Germantown, MD 20874.