A STUDY OF VENTILATION AND CARBON DIOXIDE IN AN OFFICE BUILDING

Steven J. Nabinger **Andrew K. Persily, Ph.D.** *Member ASHRAE* **W. Stuart Dols**

ABSTRACT

Ventilation rates and indoor carbon dioxide levels were monitored for two years in a new office building near St. Louis, Missouri. These measurements were made to assess the operation and performance of the ventilation system in this building and to investigate the relationship between indoor carbon dioxide levels and air change rates. Ventilation rates were measured with the tracer gas decay technique using an automated measuring system. Indoor carbon dioxide concentrations were also measured with an automated system. The ventilation rates exhibited a dependence on outdoor temperature that was expected based on the heating, ventilating, and air-conditioning (HVAC) system's controls. The air change rates under conditions of minimum outdoor air intake were about 0.5 air changes per hour (ach), which is lower than both the air change rate corresponding to the building design value for minimum outdoor air intake and the rate that corresponds to the recommended minimum outdoor airflow per person in ASHRAE Standard 62-1989. The indoor carbon dioxide concentrations were generally lower than the 1,000-ppm guideline in Standard 62. The relationship between the indoor carbon dioxide levels and the building air change rates was similar to that seen in other office buildings. These results are presented as part of a discussion on the use of equilibrium analysis of carbon dioxide concentrations to determine building air change rates. This discussion points out limitations in the use of equilibrium analysis of carbon dioxide concentrations in office buildings.

INTRODUCTION

As part of a long-term study of ventilation and indoor air quality in new office buildings, an environmental performance evaluation was conducted in a new office building in Overland, Missouri. This evaluation involved an assessment of the thermal integrity of the building envelope, long-term monitoring of ventilation system performance, and measurement of indoor levels of selected pollutants, including carbon dioxide, carbon monoxide, formaldehyde, radon, and volatile organic compounds (VOCs) (Persily et al. 1991, 1992). Ventilation rates and carbon dioxide levels were monitored for about one week during each season of one year, and an occupant questionnaire was administered and concentrations of selected air pollutants were measured. As a result of these efforts, ventilation rates and carbon dioxide concentrations were measured in this building for a period of two years, from November 1990 to November 1992.

This paper presents the results of these ventilation and carbon dioxide (CO_2) measurements. In this effort, automated tracer gas and CO_2 monitoring systems were employed to measure whole-building air change rates and CO_2 concentrations. The following results are discussed in this paper: (1) the relationship between the building air change rate and indoor/outdoor temperature difference, (2) the average and maximum CO_2 concentrations in the HVAC return ducts and occupied spaces, and (3) the relationship between the maximum daily CO_2 concentration and building air change rate.

BUILDING AND HVAC DESCRIPTION

The test building is located in Overland, Missouri, about four miles west of St. Louis. Construction of this building began in 1988 and occupancy began late in 1990. The building consists of seven floors—levels 1 through 5 above grade and levels B1 and B2 below grade. A photograph of the building is shown in Figure 1. The building has a total floor area of about 35,100 m^2 (378,000 ft^2) and a volume of about 130,000 m^3 (4,590,000 ft^3). This building is connected to an older building by doorways on levels B1, 1, and 3. The older building was not involved in the tests. Most of the test building consists of open office space that is divided into smaller cubicles by 1.5 m (5 ft) high partitions. The building also contains a limited number of private offices, conference rooms, and classrooms with floor-to-ceiling walls. The floor plan for a typical upper floor of the building is shown in Figure 2. The building is basically square, with a skylit atrium extending from the first floor. Stairways are located in each corner of the building. Mechanical rooms are located in the east and west corners, and restrooms are located in the north and south corners. Passenger elevators and a freight elevator are located in the

Steven J. Nabinger and **W. Stuart Dols** are mechanical engineers and **Andrew K. Persily** is a group leader in the Building and Fire Research Laboratory at the National Institute of Standards and Technology, Gaithersburg, MD.

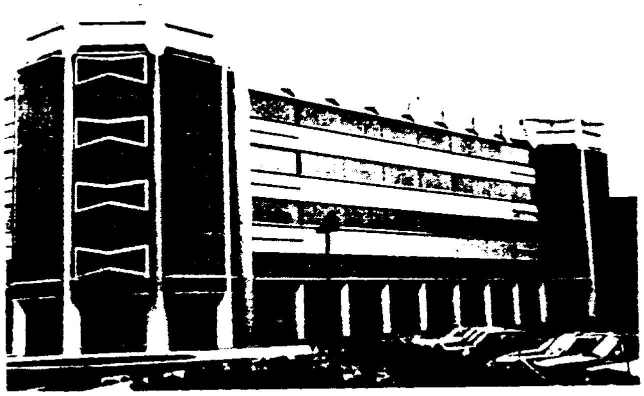

Figure 1 *Photograph of the Overland building.*

south corner of the building. A detailed description of the building, including floor plans, is contained in Persily et al. (1991).

The HVAC system is a variable-air-volume (VAV) system and utilizes unpowered VAV terminal units in the interior zones of the building and fan-powered terminal units in the perimeter zones. The terminal units do not have a nonzero minimum damper position setting. The building ventilation system is zoned horizontally, with air-handling equipment located in two mechanical rooms on each floor of the building. Each mechanical room contains two air handlers that are connected to a common supply duct system serving either the east or west side of the building. A separate mechanical room serves the atrium. A schematic of a typical mechanical room is shown in Figure 3. Each fan serving levels 1 through 5 has a design supply air capacity of 4,600 L/s (9,700 cfm), yielding a total supply capacity of 18,400 L/s (39,000 cfm) for each floor. The fans serving levels B1 and B2 have a design supply air capacity of 3,400 L/s (7,200 cfm), yielding a capacity of 13,600 L/s (28,800 cfm) on each of these floors. The supply airflow rate capacity of the atrium air handlers is 6,800 L/s (14,400 cfm). The minimum outdoor air intake specifications for the various levels are 3,600 L/s (7,600 cfm) per floor on levels 1 through 5; 2,700 L/s (5,700 cfm) on level B1; 1,800 L/s (3,800 cfm) on level B2; and 1,400 L/s (3,000 cfm) for the atrium. There is some uncertainty in these supply and minimum outdoor airflow design values due to incomplete documentation of the HVAC design.

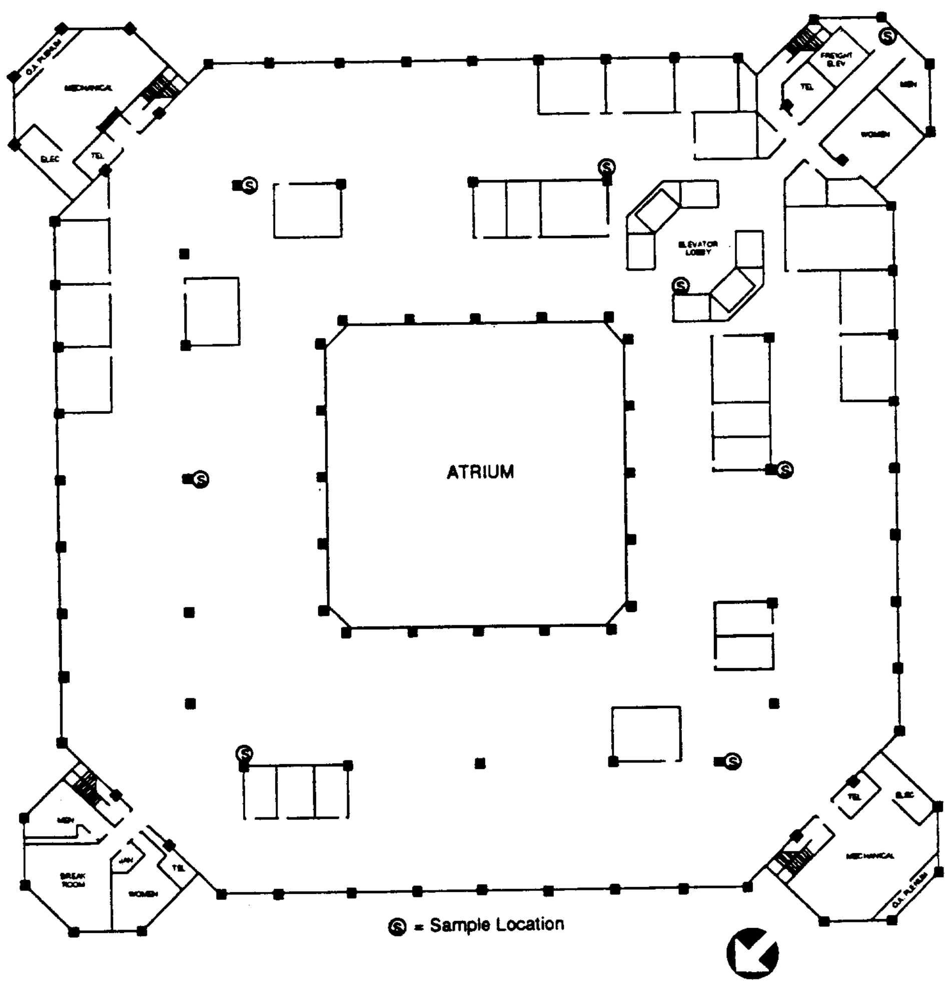

Figure 2 *Typical floor plan.*

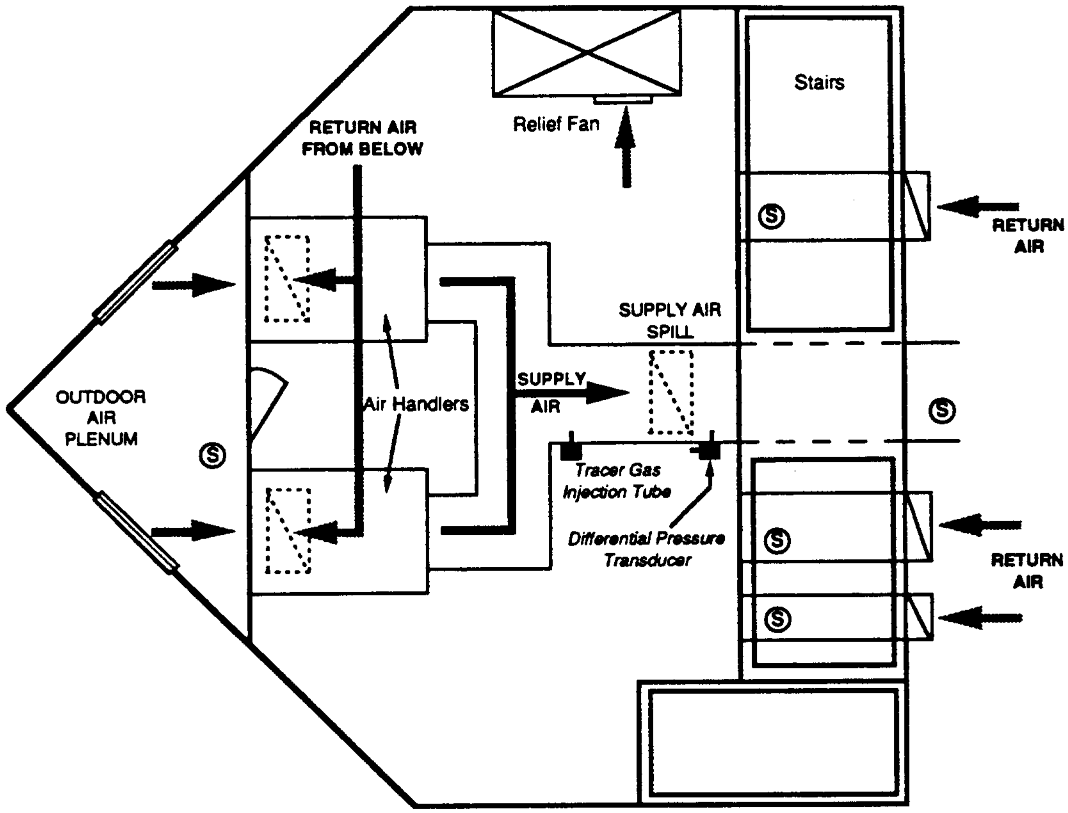

Figure 3 *Typical mechanical room.*

In each air-handling system, outdoor air is brought in through an outdoor air plenum located upstream of the air handlers. A return air damper is located in the bottom of the duct that connects the outdoor air plenum to the air handlers. Return air from the occupied space flows directly into the mechanical room from the return air plenum and through this damper when it is open. Therefore, the mechanical rooms are part of the return air system.

In summary, the mechanical ventilation system for the building consists of 30 supply fans with a total capacity of 126,000 L/s (267,000 cfm), or 3.5 air changes per hour (ach). The design value for minimum outdoor air intake for the building is 23,900 L/s (50,600 cfm), corresponding to 0.66 ach. The conversion of the minimum outdoor air intake rate to air changes per hour is approximate since it is based on the gross building volume, uncorrected for the volume occupied by walls and furniture. The minimum outdoor air intake rates for the individual floors are 0.77 ach on levels 2 through 5, 0.66 ach on level 1, 0.62 ach on level B1, and 0.44 ach on level B2 and in the atrium. ASHRAE Standard 62-1989 (ASHRAE 1989) recommends a minimum ventilation rate of 10 L/s (20 cfm) per person for office space. Assuming an occupant density of seven people per 100 m^2 (1,000 ft^2) of floor area and a ceiling height of 3.5 m (11.5 ft), including the return air plenum, the ASHRAE recommendation corresponds to 0.72 ach. The occupant densities in the atrium and on the B2 level are much lower than in the rest of the building. In addition, the ceiling height is much higher in the atrium. Therefore, the ASHRAE recommendation corresponds to an air change rate that is well below 0.72 ach on the B2 level and even lower in the atrium. The air change rate based on the minimum outdoor air intake rate specifications for levels B1 through 5 is essentially the same as the rate based on the minimum recommendation in ASHRAE Standard 62-1989.

MEASUREMENT PROCEDURES

Three microcomputer-based data acquisition and control systems were used to monitor air change rates and carbon dioxide concentrations in this building: two tracer gas systems for measuring building air change rates and one system for monitoring CO_2 concentrations. These automated systems, as well as other equipment employed in the environmental monitoring, were located in a diagnostic center in the building. Figure 4 is a photograph of the diagnostic center. A detailed description of the diagnostic center is given in Persily et al. (1992).

Building Air Change Rates

Whole-building air change rates were measured using the tracer gas decay technique. This procedure has been used in thousands of residential buildings and many office buildings (Persily and Grot 1985a; Persily 1989) and is described in ASTM test method E-741 (ASTM 1993). The

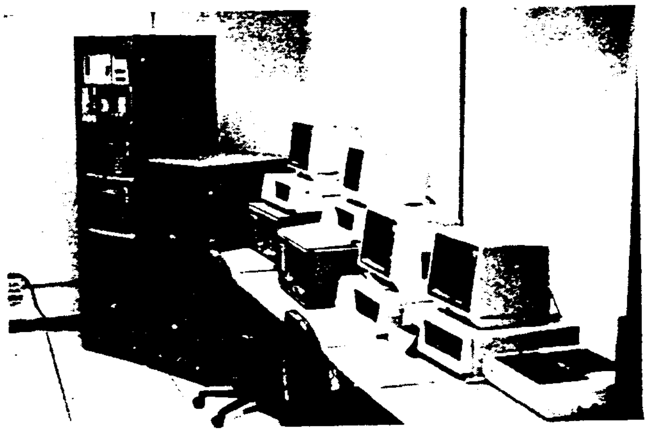

Figure 4 *Photograph of the diagnostic center.*

tracer gas decay technique determines the rate at which outdoor air enters a building, including both intentional outdoor air intake through the air-handling systems and unintentional infiltration through leaks in the building envelope. Despite common expectations of minimal infiltration rates in mechanically ventilated office buildings, these two components of air change can be comparable in magnitude (Persily and Grot 1985b; Persily and Norford 1987). The air change rate of a building depends on a variety of factors, including the design, installation, and operation of the mechanical ventilation system; the airtightness of the building envelope; the interior configuration of the building; outdoor weather conditions; and the ventilation system controls. Due to the complexity of air change in mechanically ventilated buildings, many air change rate measurements under a range of conditions are required for an understanding of the air change characteristics of a building.

In the tracer gas decay technique, a tracer gas is released into a building and mixed with the interior air. Once the tracer gas concentration within the building is spatially uniform, the decay in concentration is monitored over time. The rate of decay of the logarithm of concentra-concentration is equal to the air change rate of the building during the test period, in units of building volumes per unit time (generally ach). The tracer gas decay technique is based on an assumption that the tracer gas concentration within the building can be characterized by a single value. If this condition of uniform concentration is not achieved, then the measurement results will be in error. The ASTM test method requires that the concentration within the building be uniform within 10%. A uniform tracer gas concentration can be facilitated by using tracer gas injection strategies that distribute the tracer gas throughout the building volume. The mixing of the interior air by the building's air-handling systems also assists in achieving a uniform tracer gas concentration. The uniformity in concentration must be verified by sampling the concentration at several locations within the building.

Measurements of the building air change rate were made with two automated tracer gas systems that employed sulfur hexafluoride (SF_6) as the tracer gas. Each system consisted of a microcomputer-based data acquisition and control system and a gas chromatograph (GC) equipped with an electron capture detector. The electron capture detectors are capable of determining SF_6 concentrations over a range of about 5 to 300 parts per billion (ppb) with an uncertainty of about 5% of the reading. The timing of the injection of the tracer gas, as well as the amount of tracer gas injected into each zone, were controlled by one of the microcomputers. The same microcomputer also monitored fan status, indoor and outdoor temperatures, and wind speed and direction. Certain data, including tracer gas concentrations, temperatures, wind speed and direction, and the number of seconds per hour that each fan operated, were stored on a floppy disk. The system was capable of operating unattended for up to one month.

In tracer gas tests, the manner in which the tracer gas is injected into the building and the locations at which the tracer gas concentrations are measured are necessarily based on the layout of the building and its air-handling systems. In these tests, both the tracer gas injection and the air-sampling strategy were based on the division of the Overland building into 15 zones—2 on each level and the atrium. Tracer gas was injected into all 15 of the building's air handlers every three hours and allowed to mix for a period of 20 to 30 minutes to obtain a uniform concentration throughout the building. The tracer gas injection rates were calculated based on a target concentration of 150 ppb throughout the building. Because the building's ventilation system was used to distribute and mix the tracer gas, the measurements could only be performed when the ventilation system was on. The system operated only about 12 hours a day; therefore, four decay tests were conducted on each day.

The tracer gas concentration was monitored at 19 locations within the building and at an outdoor location, with the concentrations measured at each location every 10 minutes. The sampling locations included the return airstreams on each floor of the building, the atrium return air duct, a mixture of air samples from the same location within the occupied space on levels 2 through 5, a location on the second level of the old building (the same as the first level of the new building), a central location within the occupied space on each level, and an outdoor location on level 5. The locations in the occupied spaces were on structural columns, about 1.5 m (5 ft) above the floor. Figure 5 is a photograph of a sample location in an occupied space.

The tracer gas concentration data from the building returns were analyzed to determine the tracer gas decay rate on each building level and in the atrium. As mentioned earlier, the tracer gas decay technique requires that the tracer gas concentration be uniform within the space being evaluated. In whole-building tests, this requirement will be valid if the concentration is uniform throughout the entire building. If the building is composed of multiple spaces, the single-zone assumption can also be met if the concentration is uniform within these individual spaces and there is no airflow between them. In the case of multiple isolated

Figure 5 *Photograph of an air sample location.*

spaces, the tracer gas decay rate for each space is the outdoor air change rate for that space. Individual floors in the Overland building have their own ventilation systems and are relatively isolated in terms of airflow compared to a central system that serves several floors. In addition, the tracer gas concentrations were uniform on the individual floors within 10%. Although there were some differences in the tracer gas decay rates and concentrations on the individual floors, the interzonal differences were ignored based on the isolation of the zones from each other and the level of concentration uniformity among the zones. Therefore, in order to determine the whole-building air change rate, the individual floor and atrium tracer gas decay rates were averaged using a weighting based on their volumes. The whole-building air change rate values are estimated to be accurate within about 10%.

Measurements of whole-building air change rates started in November 1990 and continued through November 1992. The results constitute a data set of more than 1,000 measured air change rates along with the corresponding weather and fan operation conditions. By analyzing the measurement results, one can determine how the building air change rates compare to the design ventilation rates and how they are affected by weather conditions.

Carbon Dioxide Concentrations

Another automated system was used to continuously monitor carbon dioxide concentrations in the building. CO_2 was monitored with an infrared absorption analyzer having a range of 0 to 2,500 parts per million (ppm) and an uncertainty of ±0.5% of full scale. This monitor was connected to 10 of the 20 locations monitored by the tracer gas system. The CO_2 concentration was determined at each of the 10 locations once every 10 minutes.

The indoor and outdoor concentrations of carbon dioxide were monitored starting in November 1990; however, the building was not fully occupied until October 1991. Initially, the indoor samples included the return air from each of the seven levels and the atrium, along with a sample consisting of a mixture of air from an occupied-space location on each of the four uppermost levels of the building. At the end of August 1991, monitors for the two basement-level return air samples, the atrium, and the space average were disconnected in order to monitor concentrations at individual occupied-space locations on the four upper levels of the building. In August 1992, the sample locations were changed again to monitor the returns, the atrium, and selected supply ducts.

RESULTS

This section presents the results of the ventilation and carbon dioxide measurements performed between November 1990 and November 1992. Only a portion of the building was occupied in November 1990, with full occupancy occurring during October 1991. Therefore, neither the thermal loads nor the HVAC operation were at their design levels prior to November 1991.

Building Air Change Rates

The results of the tracer gas decay measurements of ventilation for the full two-year test period are presented in Figure 6. These data indicate ventilation rates ranging from about 0.3 to 2.6 ach, depending on the level of outdoor air intake by the air handlers, which, in turn, correlates with the indoor-outdoor temperature difference. The horizontal axis in this figure is the indoor-outdoor temperature difference and is presented in reverse order, with higher values (cold outdoor temperatures) on the left and lower values (warm outdoor temperatures) on the right. This HVAC system utilizes an economizer cycle that controls the amount of outdoor air intake based on the indoor and outdoor air temperatures. When the outdoor air temperature is below a setpoint value, the economizer is set to minimum outdoor air intake to protect the HVAC equipment from freezing and to avoid heating more outdoor air than is necessary. This condition is presented in Figure 6 in the temperature difference range from 35°C to 20°C (19°F to 11°F). When the outdoor air temperature rises above the economizer shut-

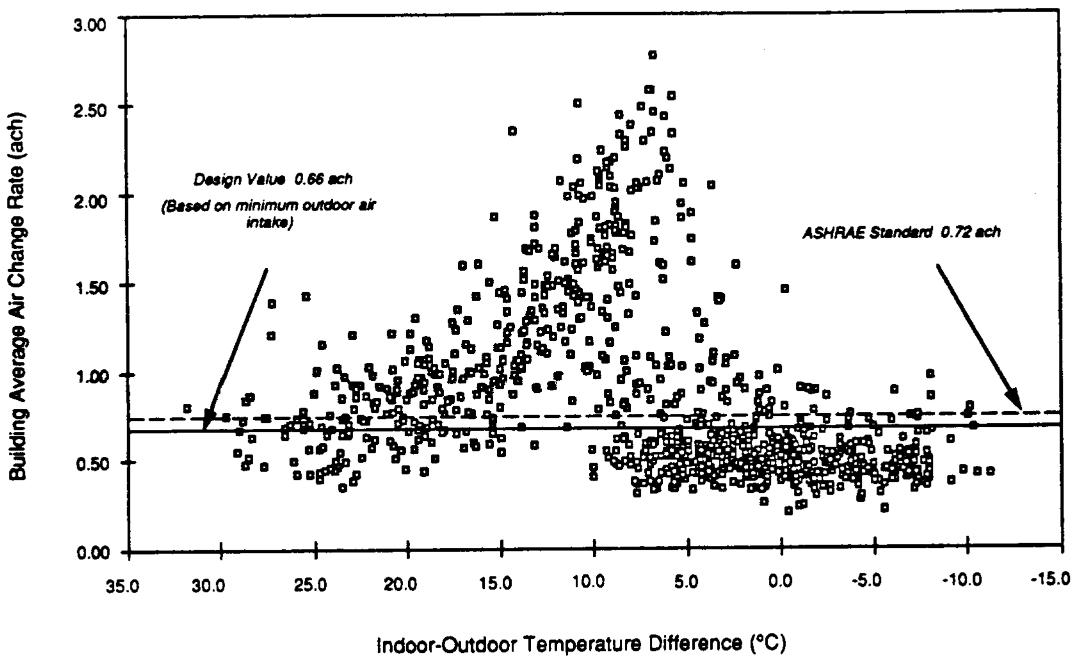

Figure 6 *Building air change rate as a function of indoor-outdoor temperature difference.*

off temperature, the economizer control modulates the outdoor air intake and return air dampers such that the mixture of the two airstreams is at the desired supply air temperature. As the outdoor air gets warmer, more outdoor air is required to cool the building's return air to the desired supply air temperature, and the economizer incrementally opens the outdoor intake dampers. This mode of operation is indicated in Figure 6 by the higher air change rates at temperature differences between 20°C (11°F) and about 5°C (3°F); the air change rate increases as the indoor-outdoor temperature difference decreases. The outdoor air intake continues to increase with outdoor temperature until the outdoor air temperature is so high that it is more economical to cool the building's return air than the outdoor air. When this situation exists, the outdoor air intake dampers are closed to their minimum position. This trend is shown by the lower ventilation rates for indoor-outdoor temperature differences below 5°C (3°F).

Not all of the variation in ventilation rate is due to the position of the outdoor air intake damper; some of the variation is due to the control of the supply static pressure in this VAV HVAC system. Also, there is no significant difference in the air change rates measured before full occupancy and those measured afterward. It is interesting to note that the minimum ventilation rate under cold outdoor conditions is higher than the minimum measured during warm weather. The exact cause for this difference has not been determined, but it may be due to increased air infiltration through the building envelope due to the larger stack-driven pressure differences during colder weather. Pressure testing of the building envelope showed that the building was quite leaky, supporting this explanation (Persily et al. 1991).

As discussed earlier, the minimum outdoor air recommendation in ASHRAE Standard 62-1989 of 10 L/s (20 cfm) corresponds to about 0.72 ach in an office building, and the building design value for minimum outdoor air intake corresponds to about 0.66 ach. Some of the measured air change rates, particularly those measured during warm weather minimum outdoor air intake, fall below these two reference values. Whole-building ventilation rates below ASHRAE recommendations and below building design values have been noted in other buildings. The range and weather dependency of the ventilation rates in this building are similar to those seen in other office buildings (Persily 1989).

Carbon Dioxide Concentrations

The major indoor source of CO_2 in this building is people; therefore, the data collected under partially occupied conditions were not particularly revealing. Daily maximum CO_2 concentrations were in the 400 to 500 ppm range during this period, with higher concentrations on the partially occupied B1 and B2 levels. Starting early in December 1990, people began moving into the upper levels of the building and, although not fully occupied, the daily maximum CO_2 concentrations ranged from 600 ppm to as high as 800 ppm on some of the floors. During partial occupancy, the building ventilation system was operating with outdoor air intake, but its operation may not have reflected its intended operation under full occupancy because of the reduced thermal loads.

CO_2 measurements under full occupancy conditions (November 1991 to November 1992) revealed daily maximum values between 400 and 1,100 ppm in the return ducts and between 400 and 1,400 ppm in the occupied space. These values are based on the highest single reading for each non-holiday weekday. Typically, instantaneous daily peak values in the returns ranged from 450 to 750 ppm, with an average value of 600 ppm; in the space, they ranged from 500 to 850 ppm, with an average value of 630 ppm. On a few isolated occasions, concentrations in the returns were as high as 1,100 ppm; in the space, they were as high as 1,400 ppm. These elevated concentrations occurred when the ventilation system was not operating according to design (i.e., not all of the air handlers were operating). In general, the carbon dioxide concentrations measured within the occupied space (about 1.5 m [5 ft] above the floor) and in the ventilation system returns were within 50 ppm of each other. The lack of a significant difference between the CO_2 concentrations in the occupied space and in the returns is consistent with good mixing of the ventilation air. Measurements of ventilation effectiveness in this building, performed using the tracer gas decay technique to measure the age of air, are also consistent with good mixing of the ventilation air within the occupied space (Persily et al. 1994).

Hourly average CO_2 concentrations were also determined for each sample location. Daily maxima of the hourly average concentrations typically ranged from 450 to 700 ppm in the returns and from 500 to 800 ppm in the space. As was the case with the instantaneous measurements, there were a few isolated occasions when hourly average concentrations were as high as 850 ppm in a return and 1,000 ppm in the occupied space.

RELATIONSHIP BETWEEN INDOOR CARBON DIOXIDE CONCENTRATION AND VENTILATION RATE

The use of indoor carbon dioxide concentrations to determine building air change rates has been proposed as an easy and inexpensive alternative to traditional methods of airflow rate measurement (such as pitot tube traverses) and more advanced techniques (such as tracer gas decay testing). While previous studies have cast doubt on the applicability of this technique in office buildings (Persily and Dols 1990; Dols and Persily 1992; Persily 1993), the data collected in Overland offer another opportunity to investigate the relationship between carbon dioxide and air change rate and to evaluate the use of indoor CO_2 as a means of measuring air change rates.

Theory of Equilibrium Analysis

The most commonly proposed technique for using indoor carbon dioxide levels to determine building air change rates is referred to here as *equilibrium analysis*. This technique is based on a mass balance of carbon dioxide in the building or space in question. This mass balance is expressed in volumetric terms as

$$V\,dC/dt = Q(C_o - C(t)) + G(t) \tag{1}$$

where

V = building or space volume,
$C(t)$ = indoor CO_2 concentration at time t,
Q = volumetric airflow rate into (and out of) the building or space,
C_o = outdoor CO_2 concentration, and
$G(t)$ = generation rate of CO_2 in the building or space at time t.

The air change rate, I, is equal to Q divided by V and has units of inverse time, generally expressed as ach. In Equation 1, it is assumed that the CO_2 concentration in the building or space can be characterized by a single concentration value, sometimes referred to as a single-zone or good mixing assumption. If this equation is being applied to only a portion of the building, e.g., an individual room, it is only valid if the space is isolated from the rest of the building or if there is no difference in CO_2 concentration between the space and the rest of the building. In addition, density differences between the indoor and outdoor air are ignored in Equation 1.

If one assumes that the airflow rate (Q), the generation rate (G), and the outdoor concentration (C_o) are constant, then Equation 1 can be solved as follows:

$$C(t) = C_o + G/Q + (C(0) - C_o - G/Q)\,e^{-It} \tag{2}$$

where $C(0)$ is the indoor concentration of CO_2 when time t equals zero. If the generation rate is constant for a sufficient period of time, the last term on the right side of Equation 2 attains a value of essentially zero, and the airflow rate can be expressed as

$$Q = G/(C_{eq} - C_o) \tag{3}$$

where C_{eq} is the equilibrium CO_2 concentration, which can be expressed as $C_o + G/Q$. Equation 3 can also be expressed in terms of the outdoor airflow rate per person and the CO_2 generation rate per person. Such a presentation is contained in Appendix D of ASHRAE Standard 62-1989.

While Equation 3 is valid given the assumptions above, these assumptions are not necessarily valid in the field. Furthermore, in many discussions of the equilibrium approach, these important assumptions are not acknowledged. The most important and most neglected assumption is that the indoor carbon dioxide concentration is at equilibrium. Based on Equation 2, the time required to reach equilibrium is dependent only on the air change rate (I). Figure 7 is a plot of the calculated buildup of indoor CO_2 concentration for several different air change rates. The figure shows that at low air change rates it takes many hours for the indoor CO_2 level to reach steady state. At an air change rate of 0.25 ach (corresponding to about 3 L/s [6 cfm] per person, not uncommon in office buildings under minimum outdoor air intake [Persily 1989]), it takes 12 hours of constant occupancy to reach 95% of the equilibri-

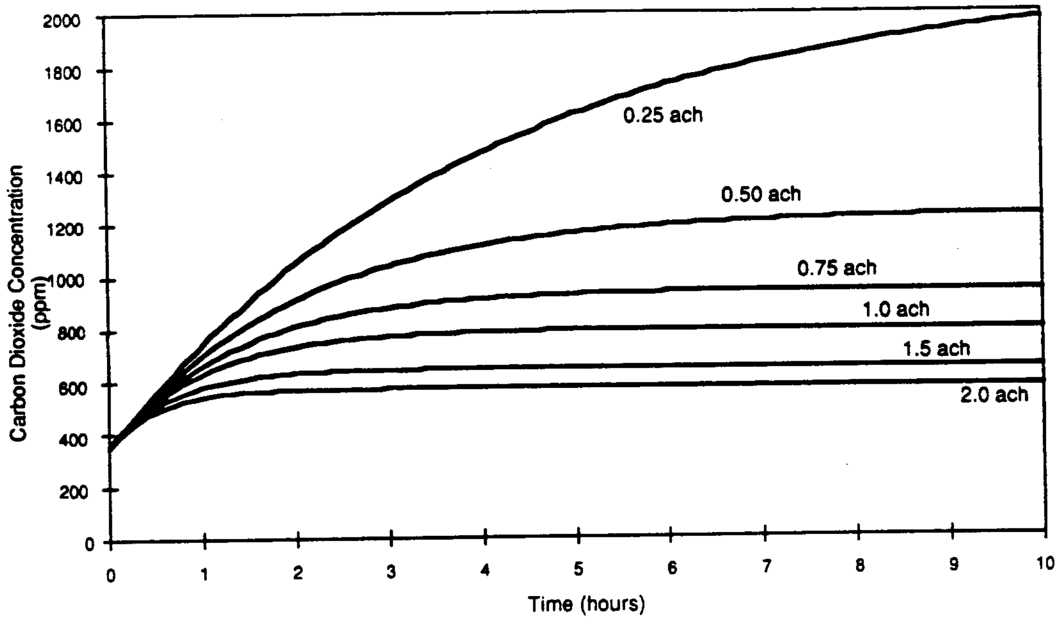

Figure 7 *Carbon dioxide buildup as a function of air change rate.*

um CO_2 concentration. At 0.75 ach (corresponding to approximately 10 L/s in an office building and more typical of office building ventilation rates), it takes four hours for the indoor CO_2 concentration to reach 95% of its steady-state value. At high air change rates—well above 1 ach—equilibrium is reached in three hours or less.

While the time required to reach equilibrium depends only on the air change rate, the actual equilibrium concentration depends on the CO_2 generation rate per person and the building volume per person. In Figure 7, the generation rate per person is assumed to equal 5.3×10^{-6} m^3/s (0.011 cfm), and the outdoor concentration equals 350 ppm. The volume per person is based on a ceiling height of 3 m (9.8 ft) and an occupant density of 7 people per 100 m^2 (1,000 ft^2).

The calculations used to develop Figure 7 are based on a constant CO_2 generation rate, i.e., a constant level of building occupancy. In many office buildings, the occupancy patterns do not provide CO_2 generation rates for long enough periods of time for the CO_2 concentration to reach equilibrium, particularly at low air change rates. Unless equilibrium conditions exist, the use of Equation 3 is not valid and will generally lead to significant overestimation of the ventilation rate. The amount of overestimation depends on the air change rate of the building, with more significant errors at lower air change rates.

Presentation of Results

Figure 8 is a plot of maximum CO_2 levels versus air change rate for the Overland building and four other office buildings. In this plot, each point corresponds to a single day on which the building was occupied (i.e., no weekends or holidays). The maximum concentrations are the maximum one-hour building average concentrations that occurred during each day. The air change rate is the average value calculated for that portion of the day during which the building was occupied. Only data for days on which the building air change rate was relatively constant are included in the plot. The data from the Overland building only include days after the building was fully occupied. The theoretical line on the plot is the equilibrium concentration as a function of the air change rate. The values on this line are based on the following assumptions: a constant air change rate, an occupant density of 7 people per 100 m^2 (1,000 ft^2) of floor area, a ceiling height of 3.5 m (11.5 ft), a constant outdoor CO_2 concentration of 350 ppm, and a CO_2 generation rate of 5.3×10^{-6} m^3/s (0.011 cfm) per person. The ceiling height includes the return air plenum.

The measured data deviate significantly from the curve, with the measurements generally falling below the theoretical curve. Part of the reason for the offset is the particular values assumed for the CO_2 generation rate, the outdoor concentration, and the volume per person, as these values will vary from building to building and even from day to day. Each building actually has its own equilibrium curve based on the values appropriate for that building. However, the measurements will generally still deviate from this curve. The primary reason for the deviation from theory is that the CO_2 concentrations in these buildings have not attained equilibrium. For a given building, the deviations between the measured maximum concentrations and the theoretical equilibrium values are greater at lower air change rates because it takes longer to reach equilibrium at lower values of ach. Examining the data for an individual building, it is evident that the deviation from the theoretical curve is greater at lower air changes rates.

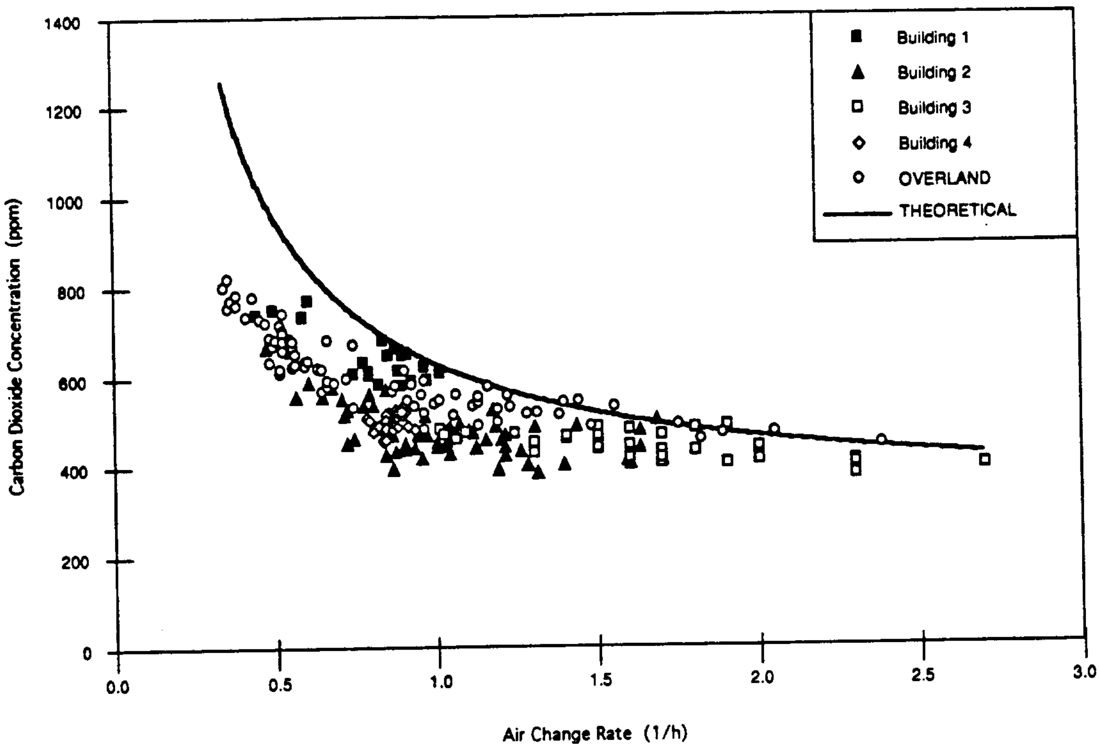

Figure 8 *Maximum carbon dioxide concentration vs. air change rate.*

Short-circuiting of supply air to the returns cannot explain the data in Figure 8 for two reasons. First, the measured difference between the CO_2 concentrations in the occupied space and in the returns was on the order of 50 ppm, which is too small to account for the difference from the equilibrium curve. Second, as mentioned earlier, the results of the ventilation effectiveness measurements in the Overland building did not indicate the existence of short-circuiting in the building (Persily et al. 1994).

The data from Overland cover the entire range of measured air change rates in Figure 8 and are consistent with the data from the other buildings. The maximum CO_2 concentration at 1 ach is about 200 ppm below the equilibrium value, while the maximum concentration at 0.5 ach is about 400 ppm less. If one used the equilibrium curve to predict the air change rate from the measured maximum CO_2 concentration, significant errors would have resulted. For example, a measured value of 700 ppm would correspond to about 1.2 ach based on equilibrium analysis, while the air change rate was actually about 0.5 ach.

The data in Figure 8 demonstrate the difficulties with using equilibrium analysis to determine ventilation rates in office buildings. In addition to the problems associated with the use of pre-equilibrium concentrations, the approach also requires an accurate estimate of the CO_2 generation rate within the building, a constant and known outdoor concentration, and a constant building air change rate. To determine the CO_2 generation rate, one requires an accurate value for the number of building occupants and the average CO_2 generation rate per occupant, neither of which is necessarily easy to determine accurately. Also, outdoor CO_2 concentrations can be more variable than is generally recognized. While equilibrium analysis is based on a constant ventilation rate, outdoor airflow rates generally change during the day in mechanically ventilated office buildings based on the actions of the the HVAC controls. Finally, equilibrium analysis assumes that the indoor CO_2 concentration can be characterized by a single value, i.e., that the concentration is uniform within the building. This uniformity requirement may or may not be fulfilled, depending on the distribution of the people and the outdoor distribution air within the building.

These arguments against the use of Equation 3 in office buildings based on the violation of the equilibrium and other assumptions do not necessarily apply to all conditions and all buildings. The accuracy of this approach ultimately depends on the appropriateness of the required assumptions. In buildings with higher air change rates and longer periods of constant occupancy, the equilibrium assumption is more likely to be valid. However, based on the results obtained to date, the technique of equilibrium analysis does not appear to be applicable to office buildings at typical air change rates.

SUMMARY

This paper has described air change rate and indoor carbon dioxide concentration measurements in a new office building. These measurements were made for about two years, providing insights into the ventilation characteristics of the building that would not have been possible with a more limited assessment protocol. The whole-building air change rates, measured with an automated tracer gas decay procedure, ranged from 0.3 to 2.6 ach. As expected, these air change rates exhibited a dependence on the indoor-outdoor air temperature difference based on economizer control of the outdoor air intake rate. Under minimum outdoor air intake, the whole-building air change rates were less than the air change rate that corresponds to the building design value for minimum outdoor air and less than the rate that corresponds to the recommendations contained in ASHRAE Standard 62-1989. The range of air change rates measured in this building was similar to that seen in other office buildings (Persily 1989). Daily peak carbon dioxide levels were typically between 500 and 800 ppm, with a few instances of higher concentrations when the ventilation system was not operating according to design (i.e., some of the air handlers were off).

In comparing daily peak carbon dioxide concentrations with the whole-building air change rates, the expected relationship was evident. At lower air change rates, higher CO_2 levels were observed. As seen in other buildings, the peak CO_2 level could not be predicted by simple equilibrium analysis because the assumptions on which this analysis are based were not valid. In particular, the CO_2 generation rate, i.e., the building occupancy level, was not constant long enough for equilibrium conditions to be established except perhaps at high air change rates. As a result, the daily maximum CO_2 concentration was significantly less than the calculated equilibrium concentration, with larger differences at lower air change rates. The inappropriateness of equilibrium analysis has also been observed in other office buildings (Persily and Dols 1990). These results reinforce the fact that indoor CO_2 concentrations cannot be used to reliably determine air change rates in office buildings using the equilibrium approach. This approach may be appropriate in other building types with longer periods of constant occupancy, but the appropriateness of the assumptions of equilibrium analysis must still be carefully assessed.

ACKNOWLEDGMENTS

This work was supported by the Public Buildings Service of the General Services Administration through an interagency agreement with the National Institute of Standards and Technology. The authors wish to express their appreciation to Monte Findley, John Brumley, and Dan Frank along with the rest of the GSA staff in Overland.

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