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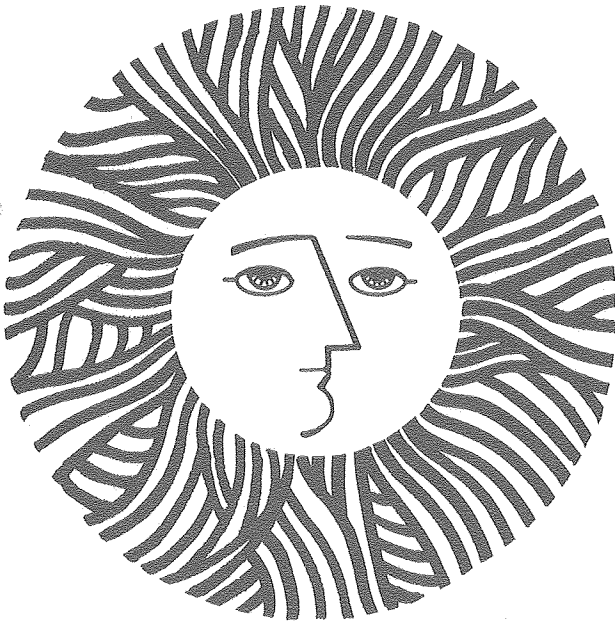
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Occupant-generated CO<sub>2</sub> as an Indicator of Ventilation Rate

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April 1980

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## ABSTRACT

Ventilation rates in buildings are generally determined by means of tracer-gas techniques that permit calculation of the number of air changes per hour occurring in a given area, or, alternatively, by measuring the actual air flow in the ventilation ducts. There are difficulties associated with both of these methods. In this study in a San Francisco office building, we used occupant-generated CO<sub>2</sub> as an indicator of the actual ventilation rate. Two techniques were employed, a decay method and an integral method and, in both cases, measurements were conducted simultaneously at several locations. The decay method compared favorably with the conventional measurement methods in both the all-outside-air and recirculation modes, whereas the integral method showed a considerable deviation from the other methods in the recirculation mode. Both techniques show promise of being suitable methods for measuring ventilation rate in commercial or institutional buildings.

Keywords: buildings, carbon dioxide, indoor air quality, office building, tracer gas, ventilation



# Occupant-Generated CO<sub>2</sub> as an Indicator of Ventilation Rate

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## INTRODUCTION

In response to national efforts to conserve energy, new construction in both the residential and non-residential sectors now incorporate features designed to reduce infiltration and ventilation rates and thereby lower heating and cooling requirements.<sup>1,2</sup> One of the ramifications of reducing infiltration and ventilation rates, however, is that indoor air quality may deteriorate, compromising the health and comfort of building occupants.<sup>3</sup> At Lawrence Berkeley Laboratory (LBL), we have initiated a broad-scale program to assess the impact of ventilation-related energy conservation measures on indoor air quality. There are two approaches to evaluating the quality of indoor air in institutional and commercial buildings: the first is to directly measure the concentrations of indoor air pollutants and the second is to infer the quality of the indoor air by measuring the ventilation rate.

In this paper we describe two methods of measuring ventilation rates in occupied buildings. Both methods use occupant-generated CO<sub>2</sub> as an indicator of the ventilation rate at the stratum of the occupied space where occupants breathe the air. We will confine the present discussion to non-residential buildings, although these methods are also suitable for use in residential buildings where CO<sub>2</sub> may be generated by combustion appliances such as gas stoves.

In both methods to be described, the concentration of CO<sub>2</sub> generated by occupants is measured simultaneously in several locations throughout



the building. This procedure permits making time-integrated calculations of ventilation rate. Precise measurement of the ventilation rate at the occupied stratum in a room becomes particularly important if both outside air and total air-circulation rates are reduced, because such a reduction may aggravate the problem of delivering the contaminant-diluting ventilation air to the breathing level of the inhabitants of the conditioned space. As ventilation rates are lowered, CO<sub>2</sub> levels rise and, thus, the accuracy of the measurement techniques increases.

Two frequently used methods of determining ventilation rate rely on tracer-gas techniques or air-flow measurements within ventilation air ducting systems. In the first method, a gas, such as sulfur hexafluoride (SF<sub>6</sub>), ethane (C<sub>2</sub>H<sub>6</sub>), or nitrous oxide (N<sub>2</sub>O) is injected into the space and measured (concentration in ppm of air) as a function of time. If the tracer gas is well mixed throughout the space, the number of air changes per hour (ach) is obtained from the slope of the exponential decay curve plotted on a semi-logarithmic scale. To convert this air-change rate to a volume-flow rate, the mixing volume -- which may or may not be the total room volume -- must be known. Other problems associated with injecting these gases into occupied spaces have to do with properties of the gas used. SF<sub>6</sub> is heavier than air and requires fans to ensure thorough mixing<sup>4</sup>. In the case of C<sub>2</sub>H<sub>6</sub>, special handling is required to avoid an explosion which might occur if the ethane concentration exceeds 3%<sup>5</sup>. Because of the potential health hazard to occupants, N<sub>2</sub>O cannot be used at concentrations greater than 25 ppm<sup>6</sup>. When using these gases for such experimental purposes, permission should be obtained from the building manager. It is obvious that using occupant-generated CO<sub>2</sub> as a tracer gas avoids most or all of the above problems

and, from any vantage point,<sup>7</sup> is considerably more convenient.

The second method, measuring air flow in ventilation ducts, has the advantage of providing direct-source ventilation rates. A major disadvantage, however, is that duct measurements do not necessarily correlate with actual air flows in the conditioned space or at the breathing stratum of the occupied space. For example, there may be ventilation air losses from the air-distribution system and ineffective and/or unequal distribution of ventilation air within the occupied space or spaces. Further, supply and return air ducts in mechanical ventilation systems are often inconveniently located, making it difficult to perform accurate measurements. Even when accurate measurements can be made in the distribution system, the ventilation rate determined from these measurements, as noted above, is not necessarily a measure of the actual ventilation rate experienced by the building occupants. In contrast, using the CO<sub>2</sub> generated by the occupants themselves assures that we can determine the "effective" ventilation rate for the occupied stratum of the conditioned space.

#### EXPERIMENTAL SITE CHARACTERISTICS

During the fall of 1979, we monitored CO<sub>2</sub> concentration in the eight-story San Francisco Social Services (SFSS) Building. The building had been occupied for one year at the time of our studies. It operates two separate mechanical ventilation systems, one for the first floor and another for the second through eighth floors. On the first floor, where our monitoring was conducted, the ventilation system mixes outside air with recirculated air which is then passed through an air-conditioning unit. Air from this unit is transmitted to induction terminal devices,

some of which have heating coils, located above the ceiling of the conditioned space. Return and recirculated air enters this plenum above the ceiling through slots in the lighting fixtures. Air from this plenum is then induced to recirculate back into the occupied space, returned to the air conditioning unit, or exhausted from the building.

In this study, the quality of the outside air and the air in the first-floor applicant interview area was monitored continuously. The interview area is almost triangular in shape and contains a large waiting room and several office cubicles with partitions approximately seven feet high. Smoking is permitted in the office cubicles. The dimensions of the area are 30.5m X 27.5m X 39.6m (100ft X 90ft X 130ft) with a 3.35m (11 ft) high ceiling. The area tested (~20% of the total first-floor space) had a volume of  $1,405\text{m}^3$  ( $50,000\text{ft}^3$ .) Each of three selected locations within this test area was sampled sequentially at ten-minute intervals.  $\text{CO}_2$  concentration was measured with an infrared absorption instrument, and occupancy was determined every hour on the hour by visually counting the number of people in the test sector.

Tests of ventilation rates were made with the air-conditioning unit in both a recirculation mode (15% outside air) and an all-outside-air mode. In the recirculation mode the  $\text{CO}_2$  concentrations throughout the first floor varied by as much as 20%, being highest in the heavily populated waiting room.

## METHODOLOGY

### 1. Ventilation Rate by $\text{CO}_2$ Measurement

Tracer-Gas Decay Method -- Our first method of calculating the ventilation rate is based on routine tracer-gas decay methods. Assuming that the mixture of CO<sub>2</sub> and room air is homogeneous when the generation of CO<sub>2</sub> ceases, the concentration C<sub>i</sub>(t), falls exponentially according to the equation:

$$C_i(t) - C_o = (C_1 - C_o) e^{-Qt} \quad (1)$$

where

C<sub>i</sub> = inside concentration of CO<sub>2</sub>

C<sub>o</sub> = outside concentration of CO<sub>2</sub>

C<sub>1</sub> = initial indoor concentraion of CO<sub>2</sub>

Q = outside air ventilation rate (hr<sup>-1</sup>)

Solving for Q, the air exchange rate, we have:

$$Q = \frac{1}{(t_2 - t_1)} \left[ \ln (C_1 - C_o) - \ln (C_i(t) - C_o) \right] \quad (2)$$

Integral Method -- Equation (3) models the air flow into and out of a space of volume V, where CO<sub>2</sub> is being generated at the rate G by each of N people:

$$\frac{d}{dt} (C_i V) = GN - (C_i - C_o) Q \quad (3)$$

where

V = volume of space where CO<sub>2</sub> concentration is measured (m<sup>3</sup>)

N = number of people in volume V

G = average CO<sub>2</sub> generation rate of people in space in m<sup>3</sup>/h/person

In the above equation, it is assumed that CO<sub>2</sub> is homogeneous in the space and does not diffuse to other spaces surrounding the space of volume V. Rearranging and expressing equation (3) in integral form yields:

$$\int_{t_1}^{t_2} Q(C_1 - C_o) dt = \int_{t_1}^{t_2} GN(t) dt - \int_{C_1}^{C_2} V dC_1 \quad (4)$$

If one chooses times t<sub>1</sub> and t<sub>2</sub> such that C<sub>1</sub>=C<sub>2</sub> then the third integral will equal zero and equation (5) results:

$$Q = \frac{G \int_{t_1}^{t_2} N(t) dt}{\int_{t_1}^{t_2} [C_1(t) - C_o] dt} \quad (5)$$

The ventilation rate can be calculated by integrating the occupancy and concentration functions over the chosen time period and using the appropriate CO<sub>2</sub> generation rate, G.

## 2. Ventilation Rate by Air-Flow Measurements

Air velocity was measured, using a hot-wire constant-temperature anemometer, at the return air connection to the air-conditioning unit and in the mixed air chamber upstream from the cooling coil. In each case, the average velocity was multiplied by the associated area to determine the air-flow quantity. The return air flow was deducted from the total air flow to determine the outside air flow.

### RESULTS

Fig. 1 illustrates the time dependence of occupancy and CO<sub>2</sub> concentration in the waiting room on a day when the ventilation system was in the all-outside-air mode. The CO<sub>2</sub> concentration was found to vary slightly (~10%) among the three indoor locations where CO<sub>2</sub> was continuously monitored. The outside CO<sub>2</sub> concentration was found to be essentially constant (~325 ppm).

Fig. 2 illustrates the time dependence of occupancy and CO<sub>2</sub> concentration in the waiting room on a day when the ventilation system was in the constant recirculation mode with both the outside and return air dampers in fixed positions. In general, CO<sub>2</sub> concentration follows occupancy patterns rather well.

Decay Method -- As is evident in Figs. 1 and 2, CO<sub>2</sub> concentration drops sharply when occupants leave the area at the end of the day. When the indoor CO<sub>2</sub> concentration, minus the outdoor CO<sub>2</sub> concentration, C<sub>o</sub>, is plotted against the time of day (beginning at 5 p.m., the end of occupancy for this area) on semi-logarithmic graph paper, a straight-line fit can be obtained as shown in Fig. 3. The slope of this straight line

is the air-exchange rate. Fig. 3 is a plot of  $\text{CO}_2$  decay for September 18, 1979 and corresponds to the tail portion of Fig. 2, corrected for outside  $\text{CO}_2$  concentration. The air-exchange rate for that particular day, determined in this manner, was 0.38 ach. For the five days (September 17-21) when the  $\text{CO}_2$  decay rate was determined in the above manner, the average air-exchange rate was 0.44 ach. Four of the five measurements ranged between 0.38 and 0.42 ach and the fifth measurement was 0.57 ach. During all of these days, the ventilation system was in the recirculation mode. On September 20, The Research Corporation of New England (TRC) performed a tracer-gas measurement, injecting  $\text{SF}_6$  into the supply air duct and measuring its concentration in the test area every ten minutes (by gas chromatography) for a one-hour period. A ventilation rate of 0.55 ach was obtained by this method. The LBL measurement on September 20, was 0.39 ach.

When the ventilation system was in the all-outside-air mode (September 25-28), the concentration of  $\text{CO}_2$  was significantly lower than when in the recirculation mode. As a result, the measurement of the  $\text{CO}_2$  decay rate was more difficult to obtain. In order to gather enough data to accurately plot the  $\text{CO}_2$  decay curve over a short time period, we monitored  $\text{CO}_2$  concentration at one location continuously instead of sequentially sampling for ten minutes at each of four locations. Fig. 4 shows the  $\text{CO}_2$  decay curve and a straight-line "best fit" for the time period between 5:00 and 5:30 p.m. on that test day (September 27). The resulting air-exchange rate was 2.4 ach. TRC performed  $\text{SF}_6$  decay measurements under the same ventilation conditions and obtained a ventilation rate of 2.3 ach on September 27, and an average ventilation rate of 2.4 ach (range 2.2 to 2.7 ach) for the four days. TRC measurements were made by

releasing SF<sub>6</sub> at several locations in the interview area and mixing it by means of fans, as well as by releasing SF<sub>6</sub> into the supply air duct.

Integral Method -- Equation (3) was used to calculate ventilation rate using the data presented in Figs. 1 and 2. The lower and upper limits, t<sub>1</sub> and t<sub>2</sub> respectively, were chosen so that C<sub>1</sub> = C<sub>2</sub>. The generation rate of CO<sub>2</sub> was taken to be 0.021 m<sup>3</sup>/h/person (0.74ft<sup>3</sup>/h/person), an average for sedentary people and people performing desk work<sup>8</sup>. The area

under each curve was separately calculated and  $\int_{t_1}^{t_2} C_o dt$  was subtracted from  $\int_{t_1}^{t_2} C_i(t) dt$ .

For Fig. 1, the following was obtained:

$$Q = \frac{0.021 \text{ m}^3/\text{h}/\text{person} \times (611.5 \text{ person hrs.})}{3,332 \times 10^{-6} \text{ hrs.}} = 3,865 \text{ m}^3/\text{h} = 2,274 \text{ cfm}$$

Therefore, for the all-outside-air mode we find the outside-air ventilation rate to be 3,865 m<sup>3</sup>/h (2.73 ach) by this method. This can be compared to 2.43 ach as determined by the CO<sub>2</sub> decay method.

Similarly, for the recirculation mode, we analyzed Fig. 2 and found that

$$Q = .021 \frac{\text{m}^3/\text{h}/\text{person} \times (558 \text{ person hrs.})}{9,595 \times 10^{-6} \text{ hrs.}} = 1,221 \text{ m}^3/\text{h} = 718 \text{ cfm}$$

The CO<sub>2</sub> decay method yielded an average air-exchange rate of 0.44 ach (618 m<sup>3</sup>/h) for this ventilation mode.



The results of air-flow measurements in the ventilation ducts are shown in Table 1. The outside air ventilation rate in the all outside air mode is seven times that in the recirculation mode.

#### DISCUSSION

When the ventilation system is in the all-outside-air mode, there is good agreement among the methods used to calculate ventilation rate. As can be seen in Table 1, less ventilation air actually reaches the occupied stratum than air-flow measurements in the ducts would indicate. Distribution losses in the ventilation ducting system may account for the lower ventilation rates predicted by the other calculation methods.

In the recirculation mode, the agreement between the CO<sub>2</sub> decay method and air-flow measurements in the ducts is very good; with the CO<sub>2</sub> integral method, however, it is not. The SF<sub>6</sub> and CO<sub>2</sub> decay measurements differ by about 20%, a larger differential than we expected. On the other hand, only one SF<sub>6</sub> measurement was taken in this ventilation mode, and the one-hour measurement period may not have been long enough to establish an equilibrium situation throughout the first floor.

In the same ventilation mode, the CO<sub>2</sub> integral method of calculation yielded a ventilation rate twice as high as that obtained by the CO<sub>2</sub> decay method or by the air-flow measurements. A possible explanation for this result is that, in the recirculation mode, unequal CO<sub>2</sub> concentration between the test area and other spaces on the first floor led to transfer of CO<sub>2</sub> from the test area and increased its loss rate beyond that which would result from outside-air dilution alone. At the end of the day, when the CO<sub>2</sub> decay measurements were taken, the air throughout

the first floor would have reached a more homogeneous condition so that the CO<sub>2</sub> decay measurement would produce a more accurate indication of ventilation rate.

If we select 3,400 m<sup>3</sup>/hr (2,000 cfm) as the rate at which ventilation air is supplied to the test area in the all-outside-air mode, then we find that the ventilation rate ranges from 34 to 57 m<sup>3</sup>/h (20-33 cfm) per person during periods of high occupancy. Similarly, if we choose 620 m<sup>3</sup>/h (360 cfm) as the rate at which ventilation air is supplied to the test area in the recirculation mode, we find a ventilation rate of 6-10 m<sup>3</sup>/h (4-6 cfm) per person during high occupancy periods. Under maximum occupancy conditions (~100 occupants) occupant density in the test area is one person per 14 m<sup>3</sup> (500 ft<sup>3</sup>). Typically, the design criteria for occupant density in office areas is one person per 28 m<sup>3</sup> (1,000 ft<sup>3</sup>).

#### CONCLUSIONS

The CO<sub>2</sub> decay method of measuring ventilation rate compares favorably with both SF<sub>6</sub> tracer-gas measurements and with air-flow measurements in the ducts. This method should be applicable to any commercial or institutional building where most of the occupants leave at approximately the same time and occupant density is reasonably homogeneous. When outside-air ventilation rates are low, as in energy-conserving buildings, CO<sub>2</sub> concentrations rise and, thus, the CO<sub>2</sub> decay method is more easily applied. The integral method of determining ventilation rate appears to be satisfactory in the all-outside-air mode but overestimates the ventilation rate in the recirculation mode, perhaps because of the presence of CO<sub>2</sub> gradients. In addition, there is always some

uncertainty in fixing the value of G (CO<sub>2</sub> generation rate), and this factor will affect the calculation of ventilation rate.

Indoor air-quality studies performed by LBL<sup>9,10</sup> have confirmed that CO<sub>2</sub> concentration is a good indicator of indoor air quality in many non-residential buildings. Under contract to LBL, Honeywell, Inc., is now testing an automatic variable ventilation control system based on CO<sub>2</sub> detection at a junior high school in the Minneapolis area.<sup>11</sup> We believe that significant energy savings can result when ventilation systems are designed to be responsive to occupancy/activity levels rather than to fixed standards based on maximum occupancy code requirements.

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Table 1

## Summary of Ventilation Rate Measurements: SF Office Building

Mode	<u>Calculation Method</u>			Velometer in Ducts
	CO <sub>2</sub> decay	SF <sub>6</sub> decay <sup>a</sup>	CO <sub>2</sub> Integral	
All outside air	3,434 (2,020) <sup>b</sup>	3,365 (1,980)	3,865 (2,274)	4,490 (2,642) <sup>c</sup>
Recirculation	609 (358)	782 (460)	1220 (718)	621 (365) <sup>d</sup>

<sup>a</sup> Measured by TRC.

<sup>b</sup> m<sup>3</sup>/h (cfm).

<sup>c</sup> An 8-point traverse was taken in the supply air duct

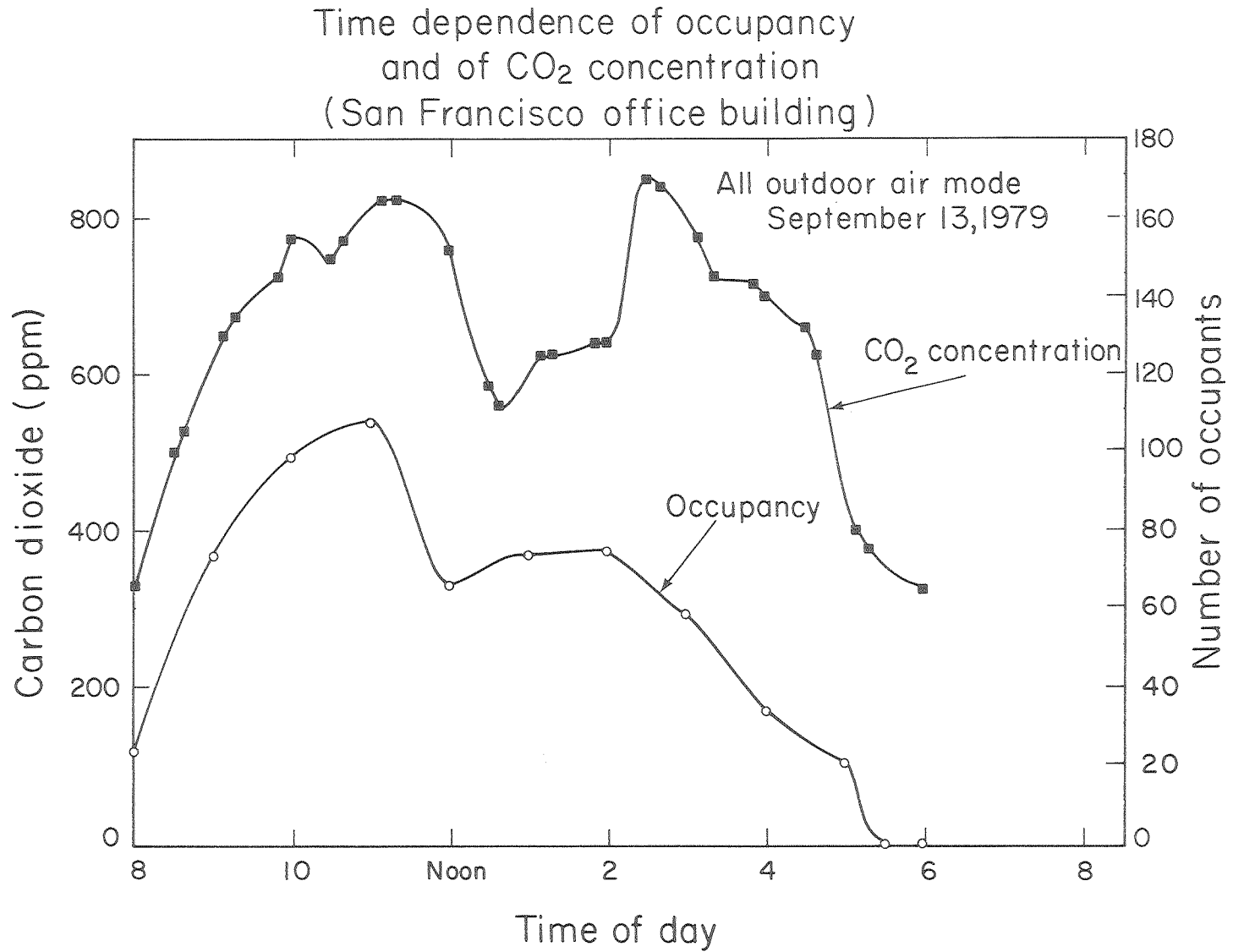
<sup>d</sup> A 32-point traverse was taken in the supply air duct and a 12-point traverse in the return air duct.

## Acknowledgments

We wish to thank James Berk, James Koonce, and Rodger Young of LBL's Ventilation and Indoor Air Quality group for their assistance in carrying out the measurements reported here. Dick Duffee and Paul Jann of The Research Corporation of New England were very helpful in supplying us with their SF<sub>6</sub> tracer measurement results. We are especially grateful to Peter Warren of the Building Research Establishment in Watford, England for several informative discussions concerning the CO<sub>2</sub> integral method of measuring ventilation rate.

Figure Captions

- Figure 1 Time dependence of carbon dioxide concentration and occupancy in the waiting room of the San Francisco Social Services Building. The ventilation system is in the all-outside-air mode.
- Figure 2 Time dependence of carbon dioxide concentration and occupancy in the waiting room of the San Francisco Social Services Building. The ventilation system is in the recirculation mode.
- Figure 3 Carbon dioxide decay curve for the recirculation mode.
- Figure 4 Carbon dioxide decay curve for the all-outside-air mode.

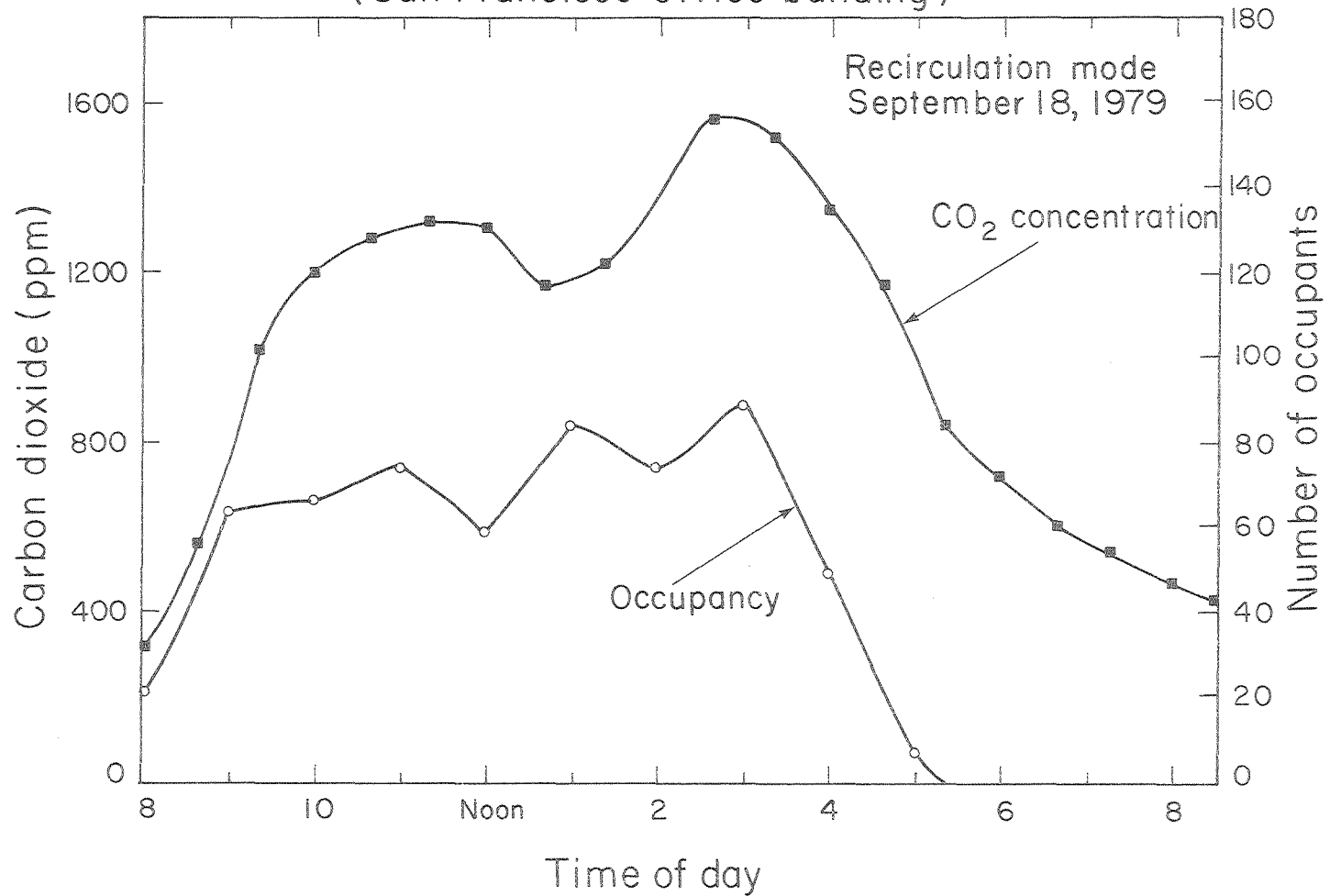


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Figure 1 Time dependence of occupancy and of carbon dioxide concentration in the waiting room of the San Francisco Social Services Building. The ventilation system is in the all-outside-air mode.

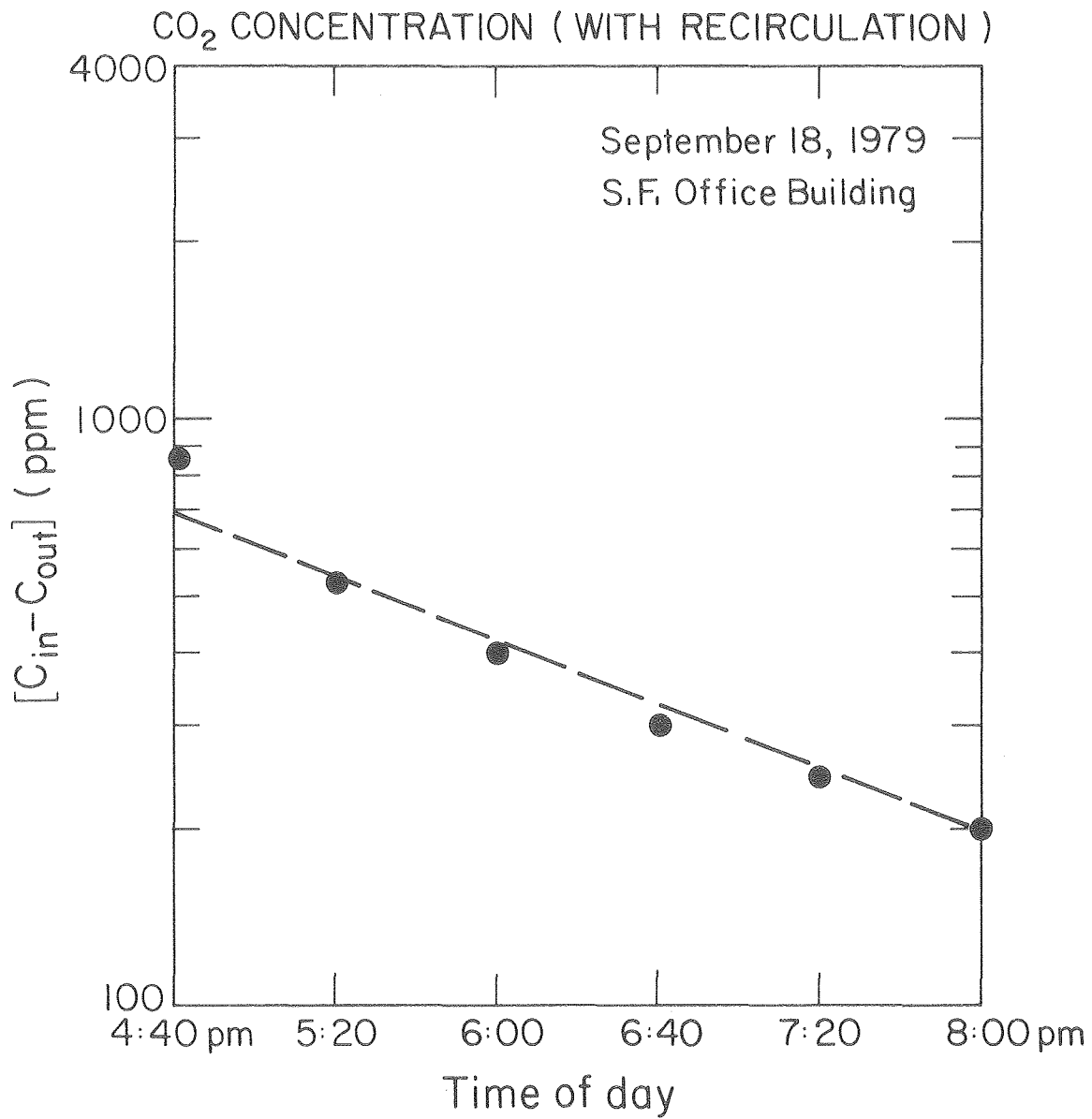


Time dependence of occupancy  
and of CO<sub>2</sub> concentration  
(San Francisco office building)



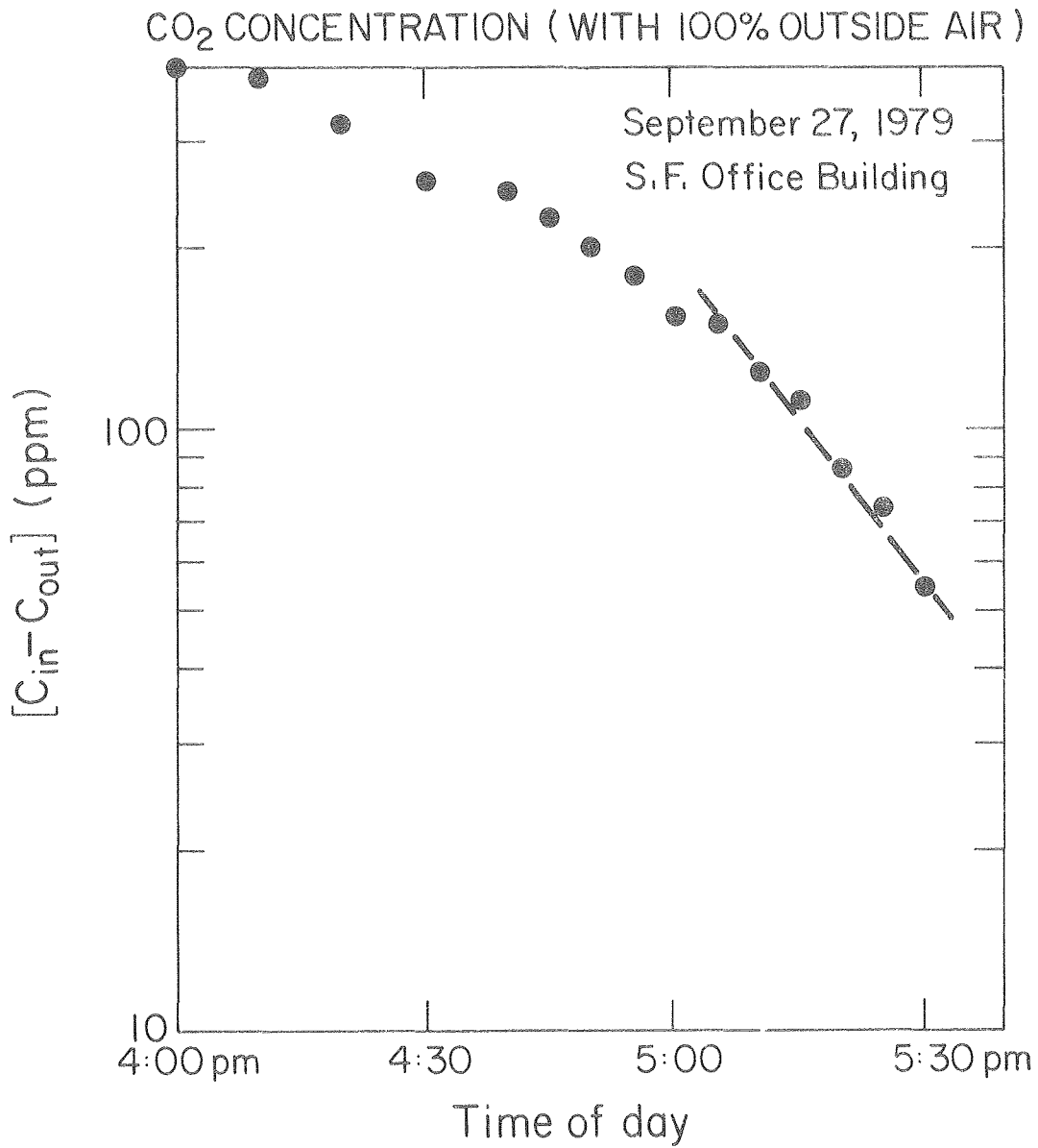
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Figure 2 Time dependence of occupancy and of carbon dioxide concentration in the waiting room of the San Francisco Social Services Building. The ventilation system is in the recirculation mode.



XBL 7910-4478

Figure 3 Carbon dioxide decay curve for the recirculation mode.



XBL 7910-4477

Figure 4 Carbon dioxide decay curve for the all-outside-air mode.