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# SIMULTANEOUS MEASUREMENTS OF INFILTRATION AND INTAKE IN AN OFFICE BUILDING

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## ABSTRACT

The net air change rate of a mechanically ventilated building is determined by a complex interaction of the exterior environment, the building envelope, the mechanical ventilation system, and the building's interior configuration. The resultant air change rate includes both intentional outdoor air intake through the air handlers and uncontrolled air infiltration through the building envelope. The outdoor air intake rates are determined by the building control system through fan speeds and damper positions in response to changing exterior conditions and internal loads. In the design and operation of ventilation systems, the envelope infiltration rates are assumed to be negligible. In addition, the outdoor air intake rates, as well as airflow rates through the fans, are assumed to equal their design values. In reality, the phenomena of air exchange in mechanically ventilated buildings is not well understood and these assumptions may not always be valid. Pressure differences across the building envelope induced by weather conditions and ventilation system operation may lead to significant amounts of uncontrolled air infiltration through leaks in the building envelope. Also, outdoor air intake rates and other ventilation system airflow rates may be quite different from their design values.

Tracer gas decay measuring techniques exist to determine whole building air exchange rates. This paper presents two new measuring techniques to determine simultaneously both the amount of air exchange due to intentional outdoor air intake and the amount due to uncontrolled envelope infiltration. One of these techniques was applied to a new office building as a demonstration of the procedure, and to investigate the air exchange characteristics and mechanical ventilation system performance in this particular building. Using a tracer gas measuring technique in combination with multithermistor airflow-rate measuring systems, intake and infiltration rates were measured under a range of weather conditions and outdoor air intake rates. The results indicate that the outdoor air intake rates for this building are often well below their design values, a significant percentage of the net air exchange rate of the building is due to envelope leakage, and the amount of envelope leakage is dependent primarily on the outdoor air intake rate.

## INTRODUCTION

The phenomena of airflow into and within mechanically ventilated office buildings has been studied for many years due to concerns regarding energy consumption, thermal comfort, and, more recently, indoor air quality. The airflow characteristics of such buildings are extremely complex, involving the interaction of the exterior environment, the building envelope, interior partitions, and the mechanical ventilation system. The current design and operation of such buildings are based on several assumptions that have been difficult to test. These assumptions include the existence in modern, mechanically ventilated office buildings of only a small amount of uncontrolled air leakage through the building envelope, i.e., infiltration. These infiltration rates are generally assumed to be essentially zero with the mechanical ventilation systems operating, due to a combination of airtight envelope construction and mechanically

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induced pressurization of the building interior. Because of the very low infiltration rates, intentional intake through the air handling system is assumed to dominate the total building air exchange rate. In addition, these buildings have control systems that are assumed to operate the mechanical ventilation system in a specific manner. This operation includes maintaining a minimum amount of outdoor air intake, keeping the supply fan airflow rate a certain amount above the return airflow rate to maintain building pressurization, and adjusting the positions of the outdoor air intake, spill, and recirculation dampers when the system is in an economizer cycle. Even under ideal circumstances, these can be difficult conditions to maintain given the airflow measurement and control mechanisms that exist in many air handling systems. The situation is worse when there are shortcomings in the design, installation, operation, or maintenance of the mechanical ventilation system and controls. Recent research has indicated that maintaining building pressurization is often a problem, that fixed intake dampers do not necessarily provide constant outdoor air intake when the supply airflow rate varies (Atkinson 1986), and that tuning mechanical ventilation system controllers is a more difficult task than is generally acknowledged (Pinnella et al. 1986).

The application of existing measuring techniques has led to the questioning of some of the above assumptions, and the use of multizone airflow models has allowed the study of situations in which the assumptions may be in error. Tracer gas decay measurements in large, mechanically ventilated office buildings have revealed air exchange rates as large as 1.0 air changes per hour in some buildings with no intake through the air handling systems. Measured values of air exchange rates with intentional outdoor air intake were, in some cases, not much larger than the air exchange rates with no intake, suggesting that weather-induced envelope leakage may be a significant fraction of the total air exchange rate. Design values of outdoor air intake rates under conditions of minimum outdoor air intake correspond to about 0.7 air changes per hour, but values as low as 0.1 air changes per hour have been measured. Ventilation measurements have also revealed a difference between the expected and the actual dependence of air exchange rates on outdoor conditions, due to excessive envelope air leakage and/or poor control system performance (Persily and Grot 1985a; Grot and Persily 1986).

The application of a multizone airflow model to mechanically ventilated office buildings has quantified the potential impact on net air exchange rates of excessive envelope leakiness and inadequate control of mechanical airflow rates (Persily and Grot 1985b). This modeling revealed that existing envelope airtightness levels can lead to envelope infiltration rates that are similar in magnitude to outdoor air intake rates. Such excessive envelope leakiness makes it difficult to control the building air exchange rate, even under conditions of moderate wind speed and indoor-outdoor temperature difference. The modeling also revealed that the existence of an imbalance between the supply and return airflows leads to significant additional envelope infiltration. Thus, the limited measurements and modeling done to date have suggested the importance of further investigations of the assumptions of minimal infiltration and proper control system performance, along with their impacts on building air exchange rates in mechanically ventilated office buildings.

This paper presents new measuring techniques to simultaneously determine a building's envelope infiltration rate and outdoor air intake rate in order to examine some of these assumptions and to further our understanding of air exchange in mechanically ventilated buildings. One of these techniques is applied to a new office building to obtain measurements of total air exchange, infiltration, intake, and fan airflow rates under a range of weather conditions and outdoor air intake control modes.

## MEASUREMENT TECHNIQUES

The measurement techniques described in this section enable the simultaneous measurement of a building's total air exchange rate and the rate of outdoor air intake through the air handling system, and the determination of their difference, the rate of uncontrolled air infiltration through the building envelope. These quantities can be measured using two different techniques, a steady-state, constant injection tracer gas procedure and a procedure combining tracer gas decay and airflow-rate measuring stations. Both techniques, along with the associated measuring equipment, are described in this section.

The constant injection procedure is illustrated in Figure 1. In this schematic, $Q_{OA}$ is the rate of intentional outdoor air intake through the air handling system, $Q_{RC}$ is the recirculation airflow rate, and $Q_{SU}$ is their sum, the supply airflow rate. $Q_{IN}$ is the rate of uncontrolled air leakage into the building through the building envelope, and $Q_{EX}$ is the sum of the uncontrolled air leakage out through the building envelope and the airflow out of intentional openings such as bathroom exhausts. $Q_{RE}$ is the return airflow rate and $Q_{SP}$ is the airflow rate through the spill dampers.

In the constant injection measurement procedure, one injects tracer gas at a constant rate q into the supply airstream as indicated in Figure 1. In this procedure, the value of the outdoor air tracer gas concentration must be constant, and for many tracer gases it will equal zero. The equations below are developed under the assumption that the value of the outdoor concentration is zero, but an alternative set of equations can be easily developed for an outdoor concentration that is nonzero but constant. During the test, one measures the return air tracer gas concentration $C_R$, the supply air concentration $C_S$, and the mixed-air concentration $C_M$. $C_M$ must be measured some distance downstream of the location where the recirculation air meets the new outdoor air in order to provide the two airstreams an opportunity to mix. Similarly, $C_S$ must be measured downstream of the tracer gas injection location, after the tracer mixes with the supply airstream. The tracer gas mixing can be enhanced by releasing the tracer at several locations across a supply duct crossection. In employing this measuring procedure one must wait for the tracer gas concentrations to reach steady-state conditions, which can take several hours depending on the net ventilation rate of the building, the amount of recirculation of the return air, and the extent of air mixing within the building.

Based on the tracer gas injection rate q (in units of volumetric flow rate), and the equilibrium values of the supply-, return- and mixed-air tracer concentrations, one can determine the values of $Q_{OA}$, $Q_{IN}$, $Q_{RC}$, and $Q_{SU}$ as follows. The value of $Q_{SU}$ is determined from the increase in concentration across the tracer gas injection in the supply airstream according to

$$C_S - C_M = q/Q_{SU}. \quad (1)$$

Based on a mass balance of tracer gas at the point where the recirculation air mixes with the outdoor air, one obtains $Q_{RC}$ from the following equation:

$$Q_{RC}C_R + Q_{OA}C_{out} = Q_{SU}C_M. \quad (2)$$

Assuming the outdoor concentration of tracer gas $C_{out}$ is zero, Equation 2 can be rearranged to yield

$$Q_{RC} = (C_M/C_R)Q_{SU}. \quad (3)$$

The outdoor air intake rate $Q_{OA}$ can be determined from the values of $Q_{SU}$ and $Q_{RC}$ and a mass balance of airflows where the outdoor and recirculation air mix, i.e.,

$$Q_{OA} = Q_{SU} - Q_{RC}. \quad (4)$$

The rate of envelope infiltration $Q_{IN}$ can be determined by tracer gas and airflow mass balances on the total building system:

$$(Q_{OA} + Q_{IN})\ C_{out} + q = (Q_{EX} + Q_{SP})\ C_R \quad (5)$$

and

$$Q_{EX} + Q_{SP} = Q_{OA} + Q_{IN}. \quad (6)$$

Again assuming $C_{out}$ equals zero, Equations 5 and 6 can be combined to yield

$$Q_{OA} + Q_{IN} = Q_{AE} = q/C_R. \quad (7)$$

$Q_{AE}$ is the total air exchange rate of the building. Based on the value of $Q_{OA}$ obtained from Equation 4, Equation 7 can be used to determine $Q_{IN}$. The determination of these airflows requires several hours for the concentrations to reach equilibrium, and the damper positions and fan airflow rates must be essentially constant during the measurement. When these conditions are altered, one must again wait for equilibrium to determine the quantities of interest at the new airflow conditions.

Alternatively, one may use a tracer gas decay/airflow-rate measuring station procedure to determine these same quantities. In this procedure one conducts a tracer gas decay test to determine the total air exchange rate of the building, while simultaneously measuring the supply airflow rate with an appropriate airflow-rate measuring device. The tracer gas measurement involves injecting a small amount of tracer into the building, generally into the building supply airstream, waiting for the tracer to mix thoroughly with the interior air, and monitoring the decay rate of the tracer gas concentration over time. The decay rate of the tracer concentration is used to determine the building air exchange rate: $Q_{AE} = Q_{OA} + Q_{IN}$. During the tracer gas decay measurement, an airflow-rate measuring station is used to determine the supply airflow rate. From these measurements, one can determine all of the quantities of interest.

During the tracer gas decay, one determines the building air exchange rate by monitoring the return-air tracer concentration $C_R$, which decreases according to the following equation:

$$C_R = C_{Ro}e^{-I_r t} \qquad (8)$$

where t is time, $C_{Ro}$ is the return air tracer gas concentration at t=0, and $I_r$ is the slope of $\ln C_R$ versus time. $I_r$ is equal to $Q_{AE}$ divided by the building volume V. In this measurement procedure, one also monitors the supply air tracer gas concentration $C_S$, which is given by

$$C_S = C_{So}e^{-I_s t} \qquad (9)$$

where $C_{So}$ is the supply-air concentration at t=0 and $I_s$ is the slope of $\ln C_S$ versus time. Theoretically, $I_s$ equals $I_r$; however, measurement errors can lead to differences between these two quantities.

Given constant intake and recirculation rates, the ratio of $C_R$ and $C_S$ will be constant and can be used to determine the percent of outdoor air intake, i.e., $Q_{OA}/Q_{SU}$. This determination employs mass balances of tracer gas and airflow at the point where the recirculation and outdoor air intake airflows mix. These mass balances take the forms of Equations 3 and 4. In this procedure, $C_M$ is equal to $C_S$, and these two equations can be combined to yield

$$Q_{OA}/Q_{SU} = 1 - (C_S/C_R) \qquad (10)$$

At this point one employs the airflow-rate measuring station to determine $Q_{SU}$. Such a station can consist of multipoint arrays of pitot tubes, thermistors or hot wire anemometers, or other airflow-rate measuring devices. Other airflow rates, such as the return and spill airflows, can also be measured if desired. Whatever airflow-rate measuring devices are used, they must be employed properly, i.e., factors such as lengths of upstream ductwork must be considered. In some ventilation systems it may be very difficult to employ an airflow-rate measuring device in a manner yielding reliable measurements.

From the measured values of $Q_{SU}$ and Equation 10, one determines $Q_{OA}$. From the value of $Q_{AE}$ determined from the tracer gas decay, one determines $Q_{IN}$ (= $Q_{AE} - Q_{OA}$). As in the case of the constant injection tracer gas procedure, the damper positions and fan airflow rates must be essentially constant during the measurement.

Both the constant injection procedure and the tracer gas decay/airflow-rate measuring station procedure are somewhat limited when there are multiple air handlers serving building zones that exchange air with one another. Only if there is no mixing between zones can the above analysis be used in each zone to separately determine the envelope infiltration rate into that zone. In the more general case of nonzero mixing between zones, the tracer gas decay/airflow-rate measuring procedure can only be used to determine the outdoor air intake rate into each zone and the tracer gas decay rate for each zone. If there is sufficient mixing between zones, then the tracer gas decay rate will be identical for all the zones and equal to the total building air exchange rate. Even if the mixing is not perfect, the volume-weighted average tracer gas decay rate for all the zones will be a good approximation to the total building air exchange rate. Based on the measured outdoor air intake rates for all the zones and the total building air exchange rate, one can determine the total building envelope infiltration rate.

## BUILDING DESCRIPTION

The building involved in these tests was built in 1984 and has three floors that are identical except for the locations of partitions and entrances (see Figure 2). The building has a large atrium with a glass facade and skylighted roof, and the building interior contains a U-shaped corridor, designed as a light slot with large skylights. The corridor is conditioned, while the atrium is not. The conditioned floor area is $1.30 \times 10^5$ ft$^2$ ($1.21 \times 10^4$ m$^2$) and the volume is $1.65 \times 10^6$ ft$^3$ ($4.68 \times 10^4$ m$^3$). The all-electric building has a variable-air-volume (VAV) air distribution system with separate air handlers serving the east and west sides of the building. The two sides of the building are open to each other through hallways and open-plan office space. The building has a ducted supply air network above a suspended ceiling and employs the space above this suspended ceiling as a return air plenum. During the tests described in this paper, the suspended ceiling had been installed in only half of the building. Openings to the two return air shafts (east and west) on each floor are shown in Figure 2. These are the only connections between each floor's ceiling return plenum and the return fans.

Figure 3 is a schematic of one of the air handling systems. These VAV systems are designed to supply fixed temperature air to the conditioned spaces throughout the year, with exceptions as discussed later. The amount of air supplied to the offices is varied by the thermostatically controlled VAV boxes to maintain the thermostat set point; perimeter boxes include hot-water coils for use in winter. The supply fan airflow rate is modulated by variable inlet vanes in response to the supply duct static pressure resulting from the positions of the VAV box dampers. The amount of outdoor air intake is varied, depending on the particular control mode that is in effect as described below and summarized in Table 1.

In normal operation, the amount of outdoor air intake is modulated in order to maintain the supply air temperature at an adjustable set point specified by design as 55 F (13$^{o}$C) and raised by the building superintendent to 60 F (16$^{o}$C). The minimum outdoor air intake dampers, shown in Figure 3, do not modulate and are always open to insure adequate ventilation. The design minimum outdoor airflow is 10,000 cfm (4.7 m$^3$/s) for both the east and west side systems. The sum of 20,000 cfm (9.4 m$^3$/s) meets ASHRAE ventilation requirements (ASHRAE 1981), assuming full occupancy and the presence of smokers, and corresponds to 0.73 air changes per hour for this building. When additional outdoor air is brought into the building through the main intake dampers to maintain the supply air temperature, the outdoor air intake is said to be in the "main" mode of control (often referred to as an economizer cycle). The airflow rate of this additional outdoor air is controlled by modulating the main outdoor air intake, spill, and recirculation dampers, maintaining a 10,000 cfm (4.7 m$^3$/s) difference between the supply and return airflow rates on each side of the building. The supply and return airflow rates that are input to the control system are based on single point pitot tubes within the ductwork.

In this building, a special intake control mode, referred to here as "minimum," takes effect when the outdoor air temperature is less than a set point of 38 F (3.3$^{o}$C). In the minimum mode, the minimum intake dampers remain open and the main intake dampers are closed. The minimum mode was developed because the building was proving difficult to heat, and the prevention of high levels of outdoor air intake at low outdoor air temperatures would reduce the heating load. When the outdoor air intake control is in this minimum mode, the spill and main intake dampers are closed, and the recirculation dampers are open. The supply air temperature is not controlled, and will generally rise above the 60 F (16$^{o}$C) set point. As with the main mode, the proper outdoor airflow is provided by adjusting the inlet vanes on the return fans such that the return airflow-rate on each side is 10,000 cfm (4.7 m$^3$/s) less than the supply airflow rate. The supply airflow-rate is still controlled from the supply duct static pressure, which is in turn determined by the positions of the VAV box dampers within the building. The return fan controller is effective only when the supply airflow-rate exceeds about 30,000 cfm (14.3 m$^3$/s) for a single fan.

During morning warmup periods the air handlers and the VAV induction box fans distribute heated air in a "recirculation" mode. Both the minimum and main outdoor air dampers are closed and each supply fan/return fan pair receives the same signal from its supply duct static pressure sensor; the supply and return fans should be moving about the same amount of air, neglecting any differences in their response to this identical static pressure signal. Whether or not the intake control is in the recirculation mode is based on the return air temperature. The transition from morning warmup (recirculation) in the winter to either the main mode or minimum mode occurs when the return air temperature rises above an adjustable set point; the time at which this happens may be before or after the occupants arrive. If the recirculation mode set point temperature is set too low, i.e., well below the inside thermostat set point, the minimum and possibly the main dampers will open prior to occupant arrival. Outdoor air will then be brought into the building, causing the building to warm up more slowly and to require more heat. But if the recirculation set point temperature is above the thermostat set point, the recirculation mode may still be in effect when the occupants arrive and there will be no outdoor air intake. The building superintendent did not want to go into the main or minimum modes prematurely because the building was difficult to heat, and therefore set the controller to stay in the recirculation mode until the return air temperature exceeded 70 F (21$^{o}$C). Because the recirculation mode was frequently in effect when occupants were in the building, the superintendent disconnected a subset of the minimum outdoor air dampers and left them permanently open to insure some outdoor air intake. This mode of outdoor air intake control, essentially recirculation with a subset of the minimum outdoor air intake dampers open, is referred to as the "subminimum" mode. On some days with extremely low outdoor air temperatures, the building remained in the subminimum mode for the entire day.

Thus there are four basic modes of outdoor air intake: recirculation, subminimum, minimum and main, in order of increasing amounts of outdoor air intake. These four control modes are summarized in Table 1.

## EXPERIMENTAL DETAILS

The measurements in the office building employed the tracer gas decay/airflow-rate measuring station procedure and occurred during the winter of 1985/86. The equipment required for these tests included a gas chromatograph equipped with an electron capture detector for measuring the concentration of the tracer gas (sulfur hexafluoride, $SF_6$), an air sampling system for directing air from the air sampling locations to the $SF_6$ monitor, a microcomputer for controlling the equipment and for data acquisition, and a series of multithermistor, airflow-rate measuring stations. The gas chromatograph/electron capture detector was calibrated in the range of 5 to 150 parts per billion (ppb) using prepared mixtures of $SF_6$ in air. The $SF_6$ concentration determined with this device is accurate within $\pm 3\%$ in the concentration range employed during the measurements. The air sampling system consisted of air sample tubes, pumps, and an air sampling manifold. Nylon air sampling tubes ran from each sample point to an air sample pump that operated continuously during the test. The airflow rate through the pumps was large enough such that the transit time from each sample point to the measuring equipment was only a few seconds. An air sampling manifold was used to enable selection among the various air sampling locations and to direct the appropriate air sample to the $SF_6$ monitor. The microcomputer-based data acquisition and control system enabled the tracer gas decay measurements to be automated by controlling the tracer gas injection and directing the air samples from the various sampling locations to the tracer gas detector. The microcomputer system also did preliminary data reduction and stored the data for later analysis.

The multithermistor airflow-rate measuring stations were commercially available devices. The thermistors are surrounded by flow straighteners and are arranged on a 0.5-ft (0.15-m) grid. The airflow-rate measurement is based on the fact that the voltage required to maintain each thermistor at a fixed temperature increases with the heat transfer coefficient, which in turn increases with the speed of the airstream flowing past the thermistor. A separate, shielded thermistor is used to compensate for changes in the airstream temperature. The associated electronics produce a 0-5 VDC signal linearly proportional to air speed, with an accuracy, claimed by the manufacturer, of $\pm 1\%$ from 60 to 2500 fpm (0.3 to 12.7 m/s). The airflow measuring stations were calibrated at the manufacturer's laboratory over a range of 1100 to 2500 fpm (5.6 to 12.7 m/s). Sources of error for these devices include nonuniform temperature profiles across the airstream, deposits on the thermistors that could change their heat transfer coefficient, inaccuracies in the voltage dividing network that converts the output voltage to a level that is compatible with the microcomputer-controlled data-acquisition system, and the existence of swirling and recirculation in the airstream due to system effects and other peculiarities of the installation.

In the tracer gas decay tests, the tracer gas was injected into both the east and west supply air systems every three hours. After an initial mixing period, the tracer gas concentration was monitored in the supply and return ducts on both sides of the building. The tracer gas concentration was determined at each of these four locations every ten minutes. These concentrations were recorded by the data acquisition and control system, along with the air temperatures in the east and west supply and return ducts, the air temperature within the building, the outdoor air temperature, and the wind speed and direction. A separate data-acquisition system recorded hourly averages of the airflow rates measured by the multithermistor arrays. Six different airflow rates were monitored, including the supply, return and spill airflows on the east and west sides of the building. Only the supply is needed to determine the quantities discussed in the section on theory, but the additional airflows provide other useful information.

The analysis of the tracer gas data involved fitting the concentrations at the four supply and return locations to equations of the forms of Equations 8 and 9 for each three-hour decay period. The curve fitting included only those data recorded after the east and west return concentrations were sufficiently close to each other to indicate good mixing of the tracer gas injection. The natural logarithm of each of the four different concentrations was regressed against time to obtain the tracer gas decay rate corresponding to that location in units of air changes per hour, along with an estimate of the uncertainty associated with each decay rate.

The decay rates based on the supply and return air concentrations for each side of the building were then averaged to determine the decay rate for that side of the building. These zonal decay rates were then averaged to determine the total building air exchange rate. The total building air exchange rates were determined with an average uncertainty of 5% of their measured values. The average difference between the east and west tracer gas decay rates was 14%, and the tracer gas concentrations on the two sides of the building were generally within 10% of each other during the decays. These indications of good mixing within the building imply that the average of the east and west tracer gas decay rates is a good measure of the total building air exchange rate.

In order to calculate $Q_{OA}$ with Equation 10 for each side of the building, the measured values of $C_S$ and $C_R$ were fit to Equations 8 and 9. The supply and return concentrations were calculated using these curve fits at 10-minute intervals over the same time period as the tracer gas decay. The ratios of $C_S$ and $C_R$ were then determined at each of these times and averaged. These ratios were determined for each three hour decay period with an average uncertainty of about 1% of their values.

During the tracer gas decay, hourly average airflow rates determined by the multithermistor airflow-rate measuring devices were recorded by the associated data-acquisition system. These hourly averages were averaged over each three-hour decay period to determine the supply and return airflow rates on the east and west sides of the building. The uncertainty in these airflow rates, based on the standard deviations of these averages, was about 5%. Thus for each tracer gas decay the following quantities were determined: the total building air exchange rate, the ratio of $C_S$ and $C_R$ on each side of the building, and the volumetric supply and return airflow rates on the east and west sides. Using the techniques outlined earlier in the theory section, these quantities were used to determine the outdoor air intake rates for the east and west sides, the rate of uncontrolled air infiltration through the total building envelope, and other quantities of interest. The average uncertainty in the east and west intake rates was about 5%, while the uncertainty in the total building infiltration rates was about 10%.

## RESULTS AND DISCUSSION

The results of these measurements can be examined in terms of two different aspects of the building's air exchange. First, there is the question of control system performance, i.e., one may examine the outdoor air intake as a function of outdoor temperature. The building control system is designed to determine this airflow rate as described earlier, and the measurement results can be examined to determine if the actual values of the outdoor air intake rates correspond to their design values. The second aspect of the building's air exchange is the amount of uncontrolled envelope infiltration that occurs under various conditions of mechanical system operation and weather.

### Control of Outdoor Air Intake Rates

The data obtained in these measurements allow us to evaluate the performance of this building's control system in determining the outdoor air intake rate. As discussed earlier there are four basic modes of outdoor air intake control (see Table 1): "main," in which the main outdoor air intake dampers are open and modulate to maintain the supply air temperature at a fixed set point; "minimum," in which only the minimum outdoor air intake dampers are open and the supply air temperature is not controlled; "recirculation," in which no outdoor air intake dampers are open and the supply and return airflow rates are approximately the same; and "subminimum," which is similar to the recirculation mode except that a subset of the minimum intake dampers are open. No measurements were made in the recirculation mode and thus only the main, minimum and subminimum modes were studied. These three modes of operation are evident in Figure 4, which is a plot of the percent of outdoor air intake ($Q_{OA}/Q_{SU}$) on the east side of the building versus outdoor temperature. The data points were separated into the three modes of operation by examining the data in this plot, spill airflow-rate measurements, and supply air temperatures. The data in Figure 4 are obtained from only the tracer gas decay data without relying on the airflow-rate measuring stations. Figure 5 is a plot of the outdoor air intake rate on the east side versus outdoor air temperature, and the determination of these rates does require the airflow rate measuring stations.

In the subminimum mode, with only a subset of the minimum dampers open and the same signal being sent to the supply and return fans, there is very little variation in the outdoor air intake rate with outdoor temperature. The supply air temperature increases as the outdoor temperature rises and is typically between 65 F and 68 F (18$^{\circ}$C and 20$^{\circ}$C), as opposed to the supply air temperature set point of 60 F (16°C). An increased supply air temperature has the intended advantage of reducing the building heating load, however, the warmer supply air may adversely affect the performance of the air diffusers within the building. The air intake rate in the subminimum is less than one-half of the design level (10,000 cfm (4.7 $m^3/s$)) shown in Figure 5. The potential air quality impact of these low intake rates is lessened because there is air infiltration in addition to air intake, although there is no control of the amount of such infiltrating air or its distribution within the building. In addition, building occupancy was about 30% of the level for which the air intake rate was designed, although there had been no modifications to the system to account for this level of occupancy. About half of the subminimum mode data were collected when the building was unoccupied.

Figures 4 and 5 show that the subminimum mode occurs even in relatively warm winter weather, above 32 F (0°C). These points exist because subminimum intake may occur during morning warmup, when return temperatures may be low even for mild outdoor temperatures. Also, the subminimum mode can occur in the middle of the day when building internal gains are small due to cloudy weather and low occupancy levels. The warm weather subminimum mode data were obtained during a weekend experiment when the ventilation system was running and the heat pumps were disabled.

In the minimum mode, with the main outdoor air intake dampers fixed in the closed position and the minimum dampers wide open, there is substantial variation in the outdoor air intake rate. According to design there should be a constant difference between the supply and return airflow-rates in the minimum mode, equal to the minimum outdoor air intake rate. For values of outdoor temperature less than 28 F (-2°C), the outdoor air intake rate is fairly constant and well below the design minimum. For those points in the minimum mode with an outdoor temperature greater than about 32 F (0°C), the intake rate is close to the design minimum. As discussed earlier, the building superintendent employed a control scheme that switched from the main mode to minimum at an outdoor air temperature set point of 38 F (3°C). The data in Figures 4 and 5 show that the main mode continued down to 28 F (-2°C). The reason for the existence of main mode points at an outdoor temperature below 38 F (3°C) is not clear but may involve an error in the outdoor temperature sensor or a change in the outdoor temperature setpoint controlling the transition from the minimum to the main mode. The points in the minimum mode have a supply air temperature of 62-64 F (17-18°C), lower than in the subminimum mode but higher than the 59 F (15°C) recorded in the main mode. As mentioned earlier, a higher supply air temperature in the minimum mode will reduce the heating load of the building, but may adversely affect the performance of the building's air diffusers. There may be an opportunity to save energy through the use of intake control modes that allow increased supply air temperatures, but the effects on air distribution and thermal comfort within the occupied space need to be examined.

In the main mode, the east outdoor air intake rate climbs above the design minimum at about 27 F (-3°C), where an energy balance (Norford et al. 1986) shows that the design minimum air intake rate, mixed with the return airflow rate corresponding to the VAV boxes at their minimum setting, produces 59 F (15°C) supply air. At higher outdoor temperatures, more air intake is needed to maintain a fixed supply air temperature. For the main mode of intake, the outdoor air intake rates are generally well above the design minimum level.

The outdoor air intake rate is determined not only by damper position but also by the pressure difference across the intake dampers. In the minimum and subminimum modes, with fixed damper positions, the outdoor air intake rate is determined by the difference between the supply and return airflow rates. The difference between the supply and return airflow rates for the east side is plotted against outdoor temperature in Figure 6. In the subminimum mode, both the difference between the supply and return airflows, as well as their actual values, are nearly constant and their difference is well below its design value corresponding to minimum outdoor air intake. The minimum mode data show a large amount of variation. At low outdoor air temperatures, the difference in airflows is fairly constant and well below design. Larger differences exist when the outdoor air temperature rises above 32 F (0°C), corresponding to larger outdoor air intake rates. For the warm-weather minimum-mode points, the return airflow remained nearly constant and the supply airflow-rate increased significantly relative to the cold weather minimum points. This phenomenon of low supply minus return airflow-rates during cold weather may be due to the inability of the return fan controller to track the supply fan when the supply airflow is below a cutoff thought to be about 30,000 cfm (14.3 $m^3/s$). Although in the minimum and subminimum modes one would expect the outdoor air intake rate to equal the difference between the supply and return airflow rates, examination of Figures 6 and 7 reveal that this is not the case. Sources of this discrepancy may be measurement error and leakage across the spill air dampers. In the main mode, the difference in supply and return airflows is closer to the design value, indicating better control and performance.

The outdoor air intake data on the west side of the building are shown in Figure 7 and do not exhibit the clear division into the three intake modes that is seen on the east side. The west side intake rates are almost all less than the design value of 10,000 cfm (4.7 $m^3/s$), even with the main intake dampers open. One reason for the greater variation in the west side intake data as compared to the east side is a dependence of the west side intake rate on the east side intake rate. Figure 8 is a plot of west intake versus east intake, in which a sawtooth pattern is evident. For east side intake rates less than about 9500 cfm (4.5 $m^3/s$), corresponding to the subminimum and minimum modes of operation, there is a strong correlation between the east and west intake rates. When the east main dampers are open, corresponding to east intake rates greater than about 9500 cfm (4.5 $m^3/s$), the west side intake rate decreases significantly and then renews its positive correlation with east intake. The decrease in west side intake when the east main dampers are open is also evident in Figure 7. The reason for the drop in west intake is not clear, but may be due to the removal of internal heat gains on the west side of the building by outdoor air brought into the east side supply airstream. Because the east intake rate in the main mode is generally so much larger than the west intake rate, and because of the apparently good mixing between the two sides of the building, this may be a reasonable explanation.

Infiltration as a Fraction of Total Air Exchange

By simultaneously measuring the rates of uncontrolled air infiltration and outdoor air intake through the air handlers, we are able to examine the impact of such infiltration on the building's total air exchange rate for a variety of conditions. One important factor affecting the amount of infiltration turns out to be the outdoor air intake rate. Figure 9 is a plot of the air exchange rate of the whole building versus the total building outdoor air intake rate. The data in this figure can be divided into three regions. In region 1 the outdoor air intake rate is less than or equal to about 8500 cfm (4.0 $m^3/s$). In region 2 the outdoor air intake rate is greater than 8500 cfm (4.0 $m^3/s$) and the east main dampers are closed, and in region 3 the east main intake dampers are open.

In region 1 the slope of the plot of total air exchange rate versus outdoor air intake rate is almost flat, i.e., the total air exchange rate is essentially independent of the amount of outdoor air intake. If there were no envelope infiltration, then this plot would have a slope of one and an intercept of zero. The fact that the slope of the data in region 1 of Figure 9 is essentially flat implies that the envelope infiltration rate decreases as the outdoor air intake rate increases. This phenomena can be explained by considering the design goal of pressurizing the building interior, thereby eliminating envelope infiltration. The fact that there is significant envelope infiltration at low values of outdoor air intake is probably due to a leaky building envelope in combination with the insufficient difference between supply and return airflow rates, i.e., low outdoor air intake rates. Very low intake rates occur when the ventilation system is in the subminimum and minimum modes, where the return fan does not track the supply fan at the design airflow rate difference and, as shown in Figure 6, the measured airflow difference is in fact only half the design value. Low values of the supply minus return airflow rates means that the return airflow is relatively large, inhibiting the effort to pressurize the building interior relative to the outdoor. Insufficient airflows to maintain pressurization lead to envelope infiltration as weather-induced pressure differences overcome these lower-than-intended, intentional pressures. Also, excessive return airflows can lead to significant depressurization of the return air plenum and outdoor airflow directly into this plenum. All of these problems are aggravated by an excessively leaky building envelope. Whole building pressurization measurements of this building have revealed that the building envelope is not particularly airtight (Norford et al. 1985). As the outdoor air intake rate is increased, the return airflow rate is better able to track the supply, the building's interior pressurization becomes more successful, and the envelope infiltration rate decreases.

In region 2 the slope of total air exchange versus outdoor air intake is almost one, implying that the envelope infiltration rate in this region is essentially constant. The fact that the infiltration rate changes very little with intake rate implies that the interior pressurization is equally successful throughout this region. The residual infiltration is due to leaks in the building envelope and improper tracking of the supply fan by the return fan.

In region 3 the east main outdoor air intake dampers are open. There is a step increase in the total air exchange rate, and the slope of total air exchange versus intake is 2.0. Therefore, when the east outdoor air intake dampers open, there is a significant increase in the whole building envelope infiltration rate. The reason for this additional infiltration is not clear but may involve an imbalance between the supply and return airflows related in some manner to the opening of the east side main intake dampers. One possible mechanism for this imbalance involves a decrease in west supply airflow when the east main intake dampers open because the outdoor air in the east supply airflow cools the west as well as the east side of the building. If the west return fan airflow does not decrease with the west supply airflow, because the tracking controller is below its operating range or the return fan inlet vanes are already nearly closed, building pressurization decreases and envelope infiltration increases.

### Summary

The results of these measurements are summarized to some extent by Table 2. This table shows the total air exchange rate, intake rate, infiltration rate, and percent of total exchange due to infiltration for the whole building. These values are shown for the three modes of intake control, i.e., main, minimum, and subminimum. Only those points for which both sides of the building were in the same mode were used in calculating the averages shown in the table. In the subminimum mode, the total air exchange rate is slightly more than half of the design intake rate, while the actual intake rate is less than one-quarter of the design value. In the minimum mode, the total air exchange rate is similar to the value in the subminimum mode, but more of the total exchange is due to intake. The intake rate is still less than one-half of its design value. In the main mode of intake control the total air exchange rate is well above the design value of outdoor air intake. The amount of air exchange due to infiltration and intake are roughly the same, slightly less than the design minimum intake value. Thus, the amount of air intake through the air handlers is below design in all three modes of intake control. The infiltration through the envelope constitutes a significant fraction of the total air exchange in all the modes.

These results point out several shortcomings in the operation of this building's mechanical ventilation system. One problem is inadequate amounts of outdoor air intake due in part to an inability of the return fan to track the supply fan at low supply airflow rates. Also, because of return fan tracking problems, the building is not operating in a pressurized mode as designed, leading to increased envelope infiltration rates. Lower infiltration rates would enable better control of the building's air exchange rate and would mean more of the air exchange takes place through the ventilation system, providing the ability for controling its distribution within the building. Better ventilation control could also reduce the occurence of excessive ventilation which for this building would result in significant energy savings (Norford et al. 1986).

## CONCLUSIONS

These measurements of outdoor air intake and envelope infiltration rates have demonstrated the usefulness of these new measuring techniques, and have provided a unique data set to study several aspects of this building's mechanical ventilation system performance. Measurements of the outdoor air intake rates were made for three modes of intake control, i.e., main, minimum, and subminimum. Although no variation in the intake rate is expected in the minimum mode, such a variation was observed. This variation occurred because the return fan could not properly track the supply fan at low supply airflow-rates. Also, some occurrences of the so-called minimum intake control mode were observed for outdoor temperatures that should have invoked the main control mode. These points could have been in the minimum mode because of a inaccurate outdoor air temperature sensor or because of a change in the transition set point. The measured intake rates on the east side of the building were found to be well below their design value in the minimum and subminimum control modes. The west side intake rates were below the design minimum in all modes of intake control, even the main mode. Again, these low outdoor air intake rates may be due to supply airflow rates that are too low for the return fan to track properly. The examination of the envelope infiltration rates revealed that, at very low intake rates, envelope infiltration constituted more than one-half of the total air exchange rate. As the outdoor air intake rate increased, the envelope infiltration rate decreased both in absolute terms and as a fraction of the total air exchange rate. This decrease is probably due to more successful building pressurization at the higher intake rates, in conjunction with larger supply airflow-rates that the return fan is better able to track. Leaks in the building envelope also make the maintenance of building pressurization difficult. Finally, when the east main outdoor air intake dampers were open, the west intake rate decreased dramatically and the building's envelope infiltration rate increased such that it was roughly the same as the total intake rate. The west intake probably decreased because the high rate of east intake air cooled both sides of the building, thereby decreasing the need for west supply airflow. The increased envelope infiltration rate may be due to a return fan tracking problem on the west side, but additional measurements are required to verify this hypothesis.

In addition to revealing these many interesting features about this building's mechanical ventilation system performance, these results have demonstrated the usefulness of the measurement techniques. The application of these procedures in other buildings will undoubtedly reveal other interesting aspects of the performance of mechanical ventilation systems and increase our understanding of the complex process of air exchange in mechanically ventilated buildings.

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TABLE 1

Outdoor Air Intake Control Modes

| | Intake Control Mode | | | |
|---|---|---|---|---|
| | Main | Minimum | Recirculation | Subminimum |
| Damper Positions | | | | |
| Spill | Modulating | Closed | Closed | Closed |
| Recirculation | Modulating | Open | Open | Open |
| Intake | Minimum dampers open. Main dampers modulating | Minimum dampers open | All Closed | Subset of Minimum Dampers Open |
| Design Outdoor Air Intake Rate | Variable | 10,000 cfm (4.7 $m^3/s$) per side | None | Unknown <10,000 cfm (4.7 $m^3/s$) per side |
| Supply Minus Return Airflow Rate | 10,000 cfm (4.7 $m^3/s$) per side | 10,000 cfm (4.7 $m^3/s$) per side | Same static pressure signal to supply and return fans. Nominally same airflow through each fan. | |
| Supply Air Temperature Control | 60 F (16°C) | None | None | None |

For return air temperatures below 70 F (21°C), the intake control is in the subminimum mode. For return temperatures above 70 F (21°C), the intake control is in the main or minimum mode, depending on the outdoor air temperature. For outside air temperatures above 38 F (3.3°C), the intake control is in the main mode, and for outdoor temperatures below 38 F (3.3°C), the intake control is in the minimum mode.

TABLE 2

Summary of Results

| Intake Control Mode | Total Air Exchange Rate cfm ($m^3/s$) | Outdoor Air Intake Rate cfm ($m^3/s$) | Infiltration Rate cfm ($m^3/s$) | Infiltration Divided by Total Exchange Rate |
|---|---|---|---|---|
| Subminimum | 10,800 (5.1) | 4,700 (2.2) | 6,100 (2.9) | 58% |
| Minimum | 11,200 (5.3) | 7,600 (3.6) | 3,600 (1.7) | 31% |
| Main | 36,200 (17.1) | 18,200 (8.6) | 18,000 (8.5) | 49% |

The design minimum outdoor air intake rate is 20,000 cfm (9.4 $m^3/s$), or 0.73 air changes per hour.

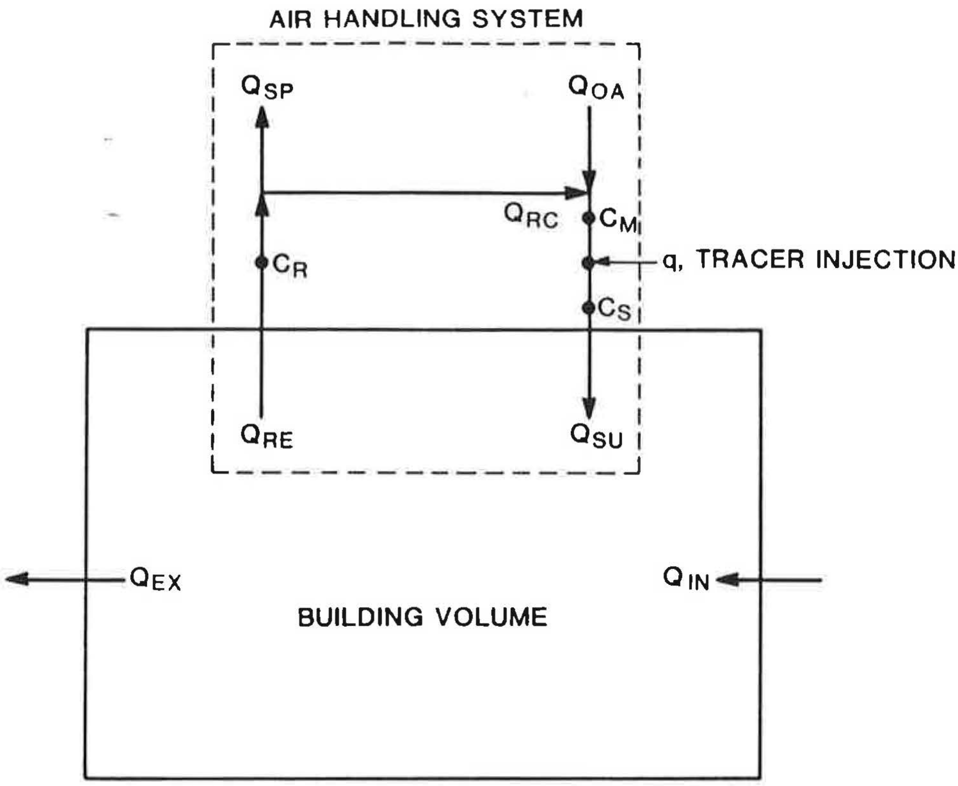


*Figure 1. Schematic of constant injection measurement procedure*

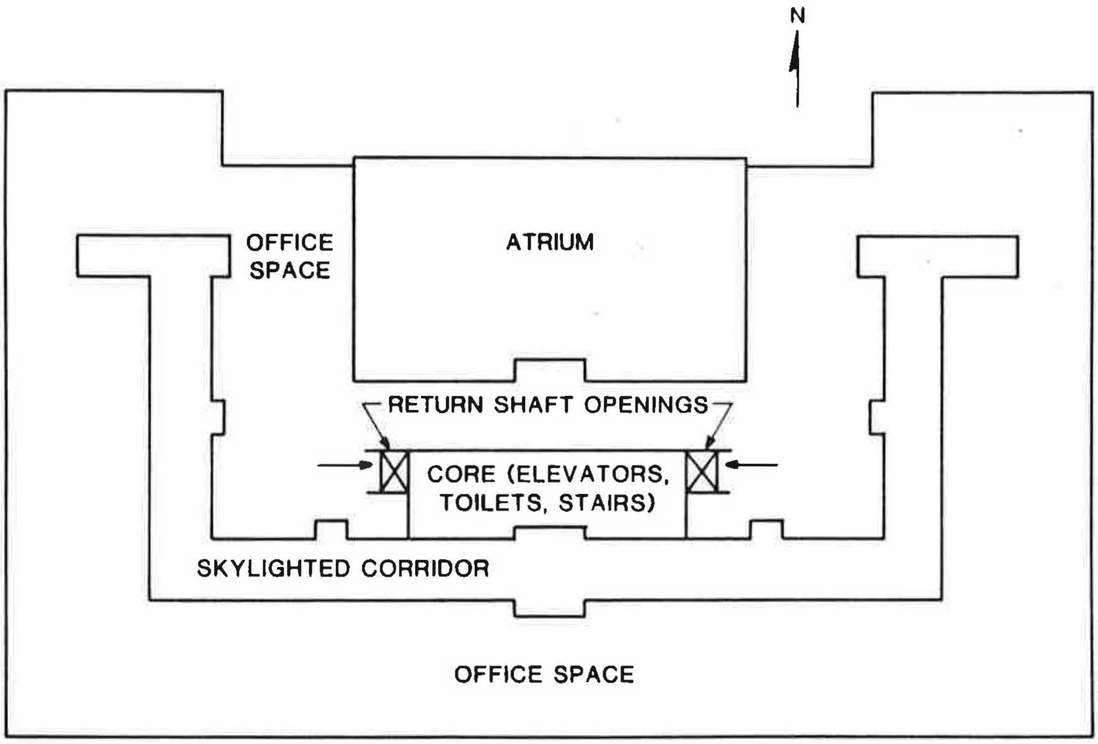


*Figure 2. Schematic of office building*

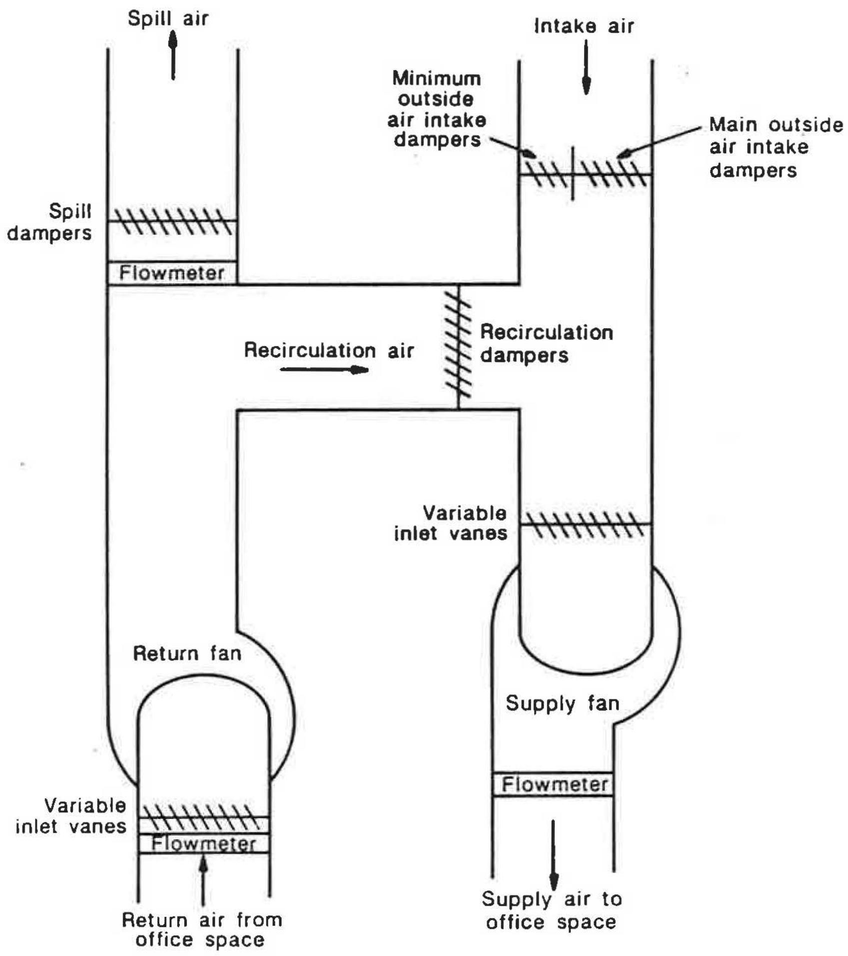


*Figure 3. Schematic of ventilation system*

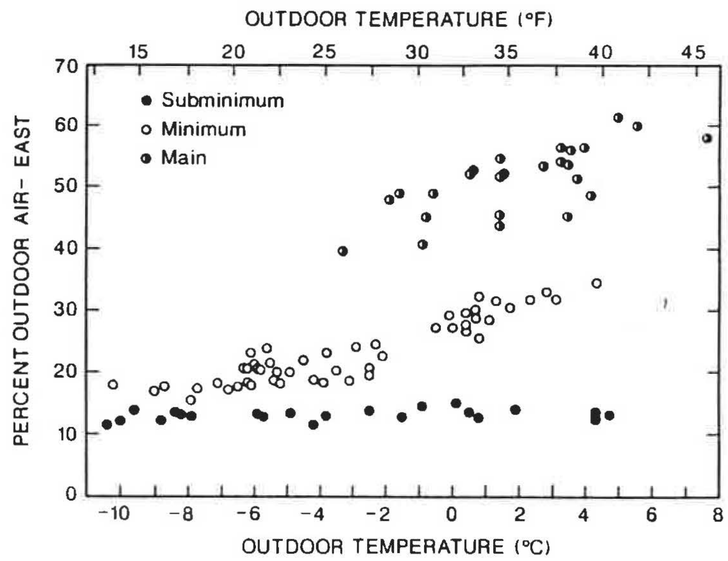


*Figure 4. Percent east outdoor air intake air vs. outdoor temperature*

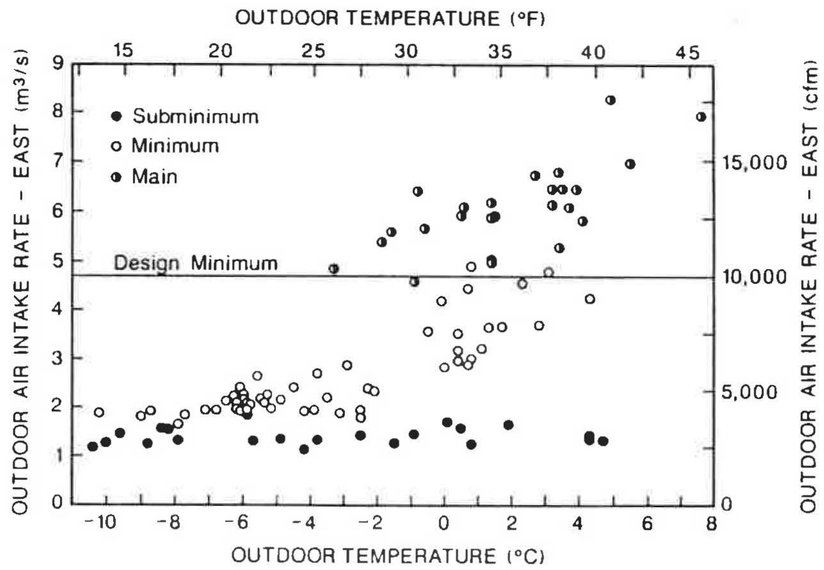


*Figure 5. East outdoor air intake vs. outdoor temperature*