VENTILATION STRATEGIES AND MEASUREMENT TECHNIQUES
6th AIC Conference, September 16-19 1985, Netherlands

PAPER 26

VENTILATION SYSTEM PERFORMANCE EVALUATION USING TRACER GAS TECHNIQUES

A.K. PERSILY and R.A. GROT

Center for Building Technology
National Bureau of Standards
U.S. Department of Commerce
Gaithersburg, Maryland 20899 USA

SYNOPSIS

Based on current concerns regarding indoor air quality and energy use, there is a need for in situ techniques for evaluating buildings' infiltration and ventilation characteristics. The U.S. National Bureau of Standards has developed and employed equipment and techniques for such evaluation. The measurement of whole building leakage and ventilation rates has been reported on previously.

Additional procedures are presented here for a more complete evaluation of the ventilation system operation and the distribution of air within the building. The measurements reveal both the amount of outside air infiltrating through the envelope and the amount of intentional intake through the air handlers. Tracer gas techniques to study the uniformity of air distribution throughout a building are also discussed.

These in situ evaluation techniques are described and results from their application are presented. The measurements reveal that, in some cases, a significant amount of a building's net ventilation rate is due to envelope leakage as opposed to intentional outside air intake through the air handling system. Also, air distribution inadequacies are often encountered in buildings, leading to effective ventilation rates of occupied zones which are less than intended or advised.

1. INTRODUCTION

The infiltration and ventilation characteristics of mechanically ventilated buildings are areas of increasing importance. The performance of the ventilation system and the air leakage characteristics of the building envelope impact upon energy use, thermal comfort, and indoor contaminant levels. The use of new ventilation system and envelope designs, and attempts to decrease energy use, have additional effects on ventilation. This situation leads to a need for in situ measurement techniques to evaluate the infiltration and ventilation performance of buildings. The factors which require evaluation include envelope airtightness, mechanical ventilation rates, and interior air distribution or ventilation effectiveness. Basically, one needs to evaluate the design and performance of the building envelope and mechanical ventilation system as they relate to the goals of providing a safe and comfortable environment for the building occupants without an excessive expenditure of energy.

A variety of tracer gas measurement techniques already exist to characterize building infiltration and ventilation, and new techniques are being developed.[1] Single tracer gas decay techniques have been developed and employed for determining whole building infiltration and ventilation rates, and these have been reported on previously.[2-4] These techniques are used to study the weather dependence of infiltration and ventilation rates, but do not distinguish between envelope leakage and intentional outside air intake. More recently, techniques have been developed to study the performance of ventilation systems including the separation of envelope leakage rates from intentional outside air intake rates, and the determination of the rates of recirculation of return air and total airflow through the ventilation system. In addition, techniques to quantify interior air distribution performance or ventilation effectiveness are also being developed. This paper discusses these tracer gas techniques for the characterization of ventilation and infiltration in mechanically ventilated office buildings. Past work involving single tracer gas decay is briefly summarized. Single tracer measurement techniques, developed more recently, to determine ventilation system performance and ventilation effectiveness are also presented along with some preliminary results of their application. In general, the material in this paper concerns modern mechanically ventilated office buildings, but much of the discussion is relevant to other building types.

2. WHOLE BUILDING DECAY MEASUREMENTS

Various tracer gas decay techniques have been applied to mechanically ventilated office buildings to measure infiltration and ventilation rates. NBS has employed an automated system to collect a large amount of data in about one dozen office buildings.[2-5] The measurement technique and results have been reported on previously, and are described briefly below.

2.1 Measurement Technique

The measurement system employs the tracer gas decay technique, using sulfur hexafluoride (SF_6) as the tracer and measuring its concentration with an electron capture detector gas chromatograph. The system is completely automated with a microcomputer controlling tracer injection, air sampling, and concentration measurement, performing data analysis, and recording the infiltration rates and weather conditions. The system operates totally unattended for periods of several weeks and yields continuous measurements of hourly, average air exchange rates. It is typically deployed in a building for several weeks during each season of the year in order to obtain measurements under a wide range of weather conditions.

In the tracer gas decay method it is important to begin the concentration decay with a uniform tracer gas concentration throughout the building. This can be ensured by using injection strategies appropriate to the building and verified by sampling at several locations in the building. Most large buildings have several main air handlers which serve the bulk of the building, and the tracer must be injected into the supply duct of each one to get the tracer throughout most of the building volume. Buildings often also have smaller air handlers for spaces such as lobbies, and tracer must also be released into the supply ducts of these systems. Such a multi-point injection strategy distributes the tracer throughout the building. After the tracer gas injection, one must wait for the tracer to mix with the interior air until a uniform concentration is obtained. The operation of the air handlers assists in mixing the tracer, but it can still take from twenty minutes to one hour to obtain a sufficiently uniform tracer gas concentration. It is necessary, however, to verify that the concentration is indeed uniform. This is done by sampling the tracer concentration at several locations within the building. In actual installations, these sampling locations have generally included return air shaft openings on each floor of the building, main return ducts of large air handlers, and return ducts of any smaller air handlers. The specific locations for tracer injection and air sampling depend on the building layout and air handling system design.

The past studies of office buildings have included measurements of both ventilation and infiltration. Ventilation rates refer to measurements made with the building HVAC system operating normally under occupied conditions. In this case the spill and intake dampers open and close as the control system dictates, in response to inside and outside temperature and humidity, and time of day. Infiltration refers to uncontrolled air leakage through the building envelope. These measurements are made with the spill and intake dampers closed (including minimum outside air dampers), all local exhausts off, and the air handlers running. These test results provide an indication of the airtightness of the building envelope. The operation of the fans during these measurements is necessary for mixing and may affect the test results through local pressurization and depressurization within the building, or through leakage across the intake and exhaust dampers. In several cases these dampers have been sealed with polyethylene, and the infiltration rates were no different than those measured without the dampers sealed.

2.2 Measurement Results

The results of the past measurements have provided a great deal of information with regard to infiltration and ventilation characteristics of office buildings. The infiltration measurements have shown a range in the air exchange rates of buildings, and varying degrees of weather dependence of the infiltration rates for the various buildings studied. In several recently constructed office buildings, the measured infiltration rates ranged from about 0.1 to 0.7 exchanges per hour, except under extremely windy conditions. These infiltration rates, which consume energy even when the building is unoccupied, account for 20 to 60% of the buildings' design heating load.[5] Some of the buildings' infiltration rates show significant dependence on inside-outside temperature difference and wind speed, while others were insensitive to weather conditions. No correlations between building characteristics, such as height, and the extent of weather dependence were observed.

The ventilation measurements have also revealed important findings. The measured ventilation rates were found to vary with weather conditions due primarily to the effect of the control systems and, to a lesser degree, due to uncontrolled infiltration. Typically the buildings have low ventilation rates under heating and cooling conditions when the control system brings in a minimum amount of outside air in order to control the space conditioning load. These minimum rates range from about 0.2 to 0.6 exchanges per hour, except under extreme weather conditions. During mild weather, outside air is used to cool the buildings and large ventilation rates are induced. This pattern of low ventilation rates under heating and cooling conditions and higher rates during mild weather was exhibited in almost all of the buildings studied by NBS.[4]

The ability to determine actual building ventilation rates and compare them to design values and recommended outside air intake levels is an important feature of whole building ventilation measurements. If the measured ventilation rates are extremely low, the air quality within the building may be compromised, but if they are too high an excessive amount of energy will be used. The measured minimum ventilation rates in several office buildings were compared to the recommendations of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 62-1981[6] for office spaces with smoking present. Roughly one-third of the buildings were found to be ventilated at rates significantly above the standard, one-third were close to the standard, and one-third were ventilated at rates lower than the standard recommends. In two of the buildings, the measured rates were less than 50% of the ASHRAE recommendations.[4] The existence of such low ventilation rates has important implications for building operation, and points out the value of and need for in situ measurement of ventilation rates.

The ventilation data also revealed the importance of uncontrolled air leakage through the building envelope as a component of the net ventilation rate. Under conditions of minimum intentional outside air intake, the measured net ventilation rate of several buildings was found to increase with temperature difference. This occurs because temperature dependent infiltration increases and becomes comparable in magnitude to the intentional ventilation rate. Also, high net ventilation rates due to the influence of wind-induced infiltration were also observed. Several buildings exhibited this property of weather induced infiltration being a significant, or even predominant, portion of the net ventilation rate. Thus, the measurements revealed that modern office building envelopes are not necessarily airtight, and under extreme weather conditions there is little control of the net ventilation rate. Such uncontrolled leakage occurs continuously, and can account for a significant waste of energy and adversely affect thermal comfort.

In the ventilation measurements discussed above, there were also indications of nonuniform air distribution within the buildings. One example in a 26-story office building in Newark, New Jersey has been described previously.[3] In this building the SF_6 concentration was sampled on several floors of the building, and the results were quite similar on all floors except for two. On these two floors the initial SF_6 concentration was significantly less than in the rest of the building, as was the decay rate. This indicates that the supply airflow rate for these floors was proportionally less than for the rest of the building, and therefore these floors have lower ventilation rates. Other examples of such large scale variations in internal air distribution and local ventilation rates have been observed, and similar problems are suspected to exist within individual rooms. When specific areas suffer from poor air distribution, they may have indoor air quality problems even if the whole building or room is adequately ventilated. Tracer gas measurement techniques to quantify air distribution are discussed below.

3. VENTILATION EFFECTIVENESS

The NBS ventilation measurements, and other experience, has pointed out the potential for inadequate air distribution within mechanically ventilated buildings. In order to quantify building or room air distribution, the concept of ventilation effectiveness has been developed. Several definitions and associated measurement procedures exist and have been applied in experimental studies.[7-10] In this section existing definitions of ventilation effectiveness are discussed, along with practical considerations affecting their use in mechanically ventilated office buildings. A more detailed discussion of ventilation effectiveness definitions and their application to mechanically ventilated buildings is presented in reference 11.

3.1 Definitions of Ventilation Effectiveness

Several definitions and theoretical frameworks have been used to discuss ventilation effectiveness. One group of ventilation effectiveness definitions, referred to here as "concentration efficiencies," are based on relations between pollutant or tracer gas concentrations in the supply air, the exhaust air, and at locations within the ventilated space.[7-9] A steady-state concentration efficiency has been defined, which is measured with a tracer gas by injecting the gas at a constant, known rate into the zone being studied and waiting until the concentrations reach equilibrium. The injection strategy, including the location of the source and whether it is diffuse or a point, depends on the nature of the pollutant one wishes to simulate. There are also transient ventilation efficiencies, which are measured by starting with the tracer gas distributed within the space and no tracer gas sources. Various transient efficiencies are defined based on the ratio of the exhaust concentration to the concentration at some location within the occupied space. These definitions include the ratio of the instantaneous exhaust concentration to the instantaneous concentration in the space, and the ratio of the integrals of these concentrations over time.

Age distributions and residence times, concepts employed in chemical reactor engineering, have also been applied to the study of ventilation effectiveness.[8,10] Ventilation effectiveness definitions based on age distributions involve average ages of interior air and residence times of contaminants. To determine ventilation effectiveness, these ages are compared to their values under conditions of perfect mixing within the ventilated space or pure piston flow through the space. Various tracer gas measurement strategies are used to determine these age distribution efficiencies. These involve tracer gas injection at a constant rate into the room or supply airstream, and pulses into these same locations. The time responses of the exhaust and/or room concentrations are then used to determine the age or residence time of interest.[8,10-11]

Both concentration and age distribution efficiencies have been applied in experimental work in laboratory test facilities.[7-9] These rooms have reconfigurable supply and exhaust opening positions, and controllable supply air temperature, ventilation rates, and internal thermal loads. The rooms are essentially airtight with airflow in and out of the space occuring only through the ventilation system. In these tests, various measures of ventilation effectiveness have been determined under a range of conditions. These experiments have been extremely useful in studying the occurrence of short-circuiting between the supply and return air vents, stratification of room air, and the performance of alternative ventilation strategies.

Ventilation Effectiveness Measurement in Buildings

While the experimental study of ventilation effectiveness in test rooms has been useful, it is also important to measure ventilation effectiveness in actual buildings. The application of the tracer gas measurement procedures discussed above is difficult in real buildings for various reasons discussed in this section. One problem is the difficulty in defining and measuring the exhaust concentration. Most modern office buildings, especially in the U.S., employ ceiling return plenums. The exhaust air vents are simply openings in the dropped ceiling through which room air flows into the plenum space, mixes with return air from other locations on the same floor, and flows to an opening in the return air shaft. There are generally only one or two return air shaft openings per floor, and therefore a well-defined exhaust concentration measurement point exists only for whole floors or large portions of floors. To measure the exhaust concentration for a smaller area, even a single room, one must sample the air at several return air openings into the ceiling plenum. This procedure can be impractical in many cases due to the large number of measurement points and limitations of the measuring equipment.

Depending on the particular measure of ventilation effectiveness being employed, and the size and arrangement of the space being studied, the required tracer gas injection may be difficult to achieve. The application of certain measures of ventilation effectiveness in a large area of a building requires a diffuse tracer gas injection in the lower, occupied zone of the ventilated space. The diffuse injection of tracer throughout a large area at a rate that is uniform in units of tracer gas flow rate per floor area may be difficult.

Another problem in measuring ventilation effectiveness in buildings is associated with the difference between an airtight test room and a ventilated space in an actual building. In the laboratory test facilties discussed above, air enters only through supply vents and leaves only through the exhausts, leading to well-defined supply and exhaust airstreams and concentrations. In this situation all quantities of interest (airflow rates, mixing factors, residence times, and ventilation efficiencies) can be determined with a single tracer gas in a straightforward manner. In real buildings, the space under study is subject to additional airflows to and from adjacent interior spaces and in and out through exterior walls. The supply and exhaust concentrations are no longer well characterized, and the existence of the additional airflows greatly complicates the situation. Even if one determines a value of the ventilation effectiveness, the results are no longer related to the quantities of interest.

Finally, almost all procedures for measuring ventilation effectiveness assume there is no recirculation of the return air. However, ventilation systems operate with 100% outside air intake only during limited periods of time. To study the ventilation system performance of actual buildings under realistic operation, modifications to existing ventilation effectiveness measurement procedures must be made to deal with recirculation. In addition, to characterize the ventilation effectiveness for large zones within a building or for whole buildings, one must deal with the fact that these spaces are often served by more than one air handler. These air handlers may be moving different amounts of total air and outside air. All of the above factors make the measurement of ventilation effectiveness in actual buildings difficult, but in many cases procedures can be employed to evaluate the ventilation system performance.

4. VENTILATION SYSTEM CHARACTERIZATION PROCEDURES

In this section ventilation system performance evaluation procedures for use in real buildings are presented, along with some preliminary results from their application in a three-story office building. A technique for measuring system flows and envelope leakage simultaneously is described, followed by a discussion of procedures to measure ventilation effectiveness.

4.1 System Flow Measurement

The whole building ventilation measurement results discussed previously revealed the fact that uncontrolled air leakage could be an important part of a building's net ventilation rate. In order to simultaneously measure this air leakage rate and the rate of intentional outside air intake, one can employ a constant injection tracer gas technique. This procedure is illustrated in the schematic in figure 1. In this schematic Q_{OA} is the rate of intentional outside air intake, 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 in through the building shell, and Q_{EX} is the sum of the uncontrolled air leakage out through the building shell 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. Tracer gas decay tests determine the sum of Q_{OA} and Q_{IN}, but their individual values are important in evaluating the ventilation system operation and the airtightness of the building envelope.

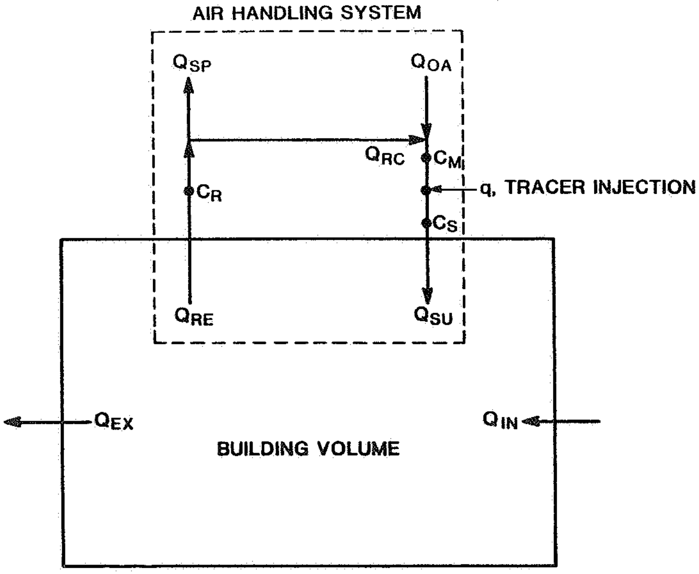

Figure 1 Schematic of Ventilation Evaluation Procedure

In this measurement procedure, one injects tracer at a constant rate into the supply airstream as indicated in figure 1. One then measures the return air 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 where the recirculation air meets the new outside 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 cross-section. Under conditions of good mixing, the value of Q_{SU} can be determined from the tracer gas injection rate q and the difference between C_S and C_M. To make this determination, one must wait for steady-state conditions, which can take several hours depending on the net ventilation rate and the extent of mixing within the building. From various mass balances of the airflows and tracer gas, one can determine the values of Q_{OA}, Q_{RC}, Q_{SU}, and Q_{IN} from the three concentrations and the tracer injection rate. In this analysis it is convenient to define two ratios,

$$R = C_M/C_R = Q_{RC}/Q_{SU} \tag{1}$$

and

$$L = C_R/C_S = Q_{SU}/(Q_{EX} + Q_{RE}) \tag{2}$$

R, the recirculation fraction, is the percentage of return air which is recirculated. L is called the leakage fraction.

In addition to the requirement of good mixing in measuring the values of C_M and C_S, there is another complication in the general case in which a building is served by more than one air handler. In this situation, it is desirable that the value of C_S be the same for all the air handlers. For a given tracer gas injection rate, the value of C_S depends on R, L, and Q_{SU}, and these may certainly vary among the air handlers. Some guesswork is involved in determining the appropriate values of the tracer injection rate q for each air handler, and trial runs may be necessary to achieve satisfactory tracer injection rates.

4.2 Ventilation Effectiveness Measurement

Despite the difficulties involved with making ventilation effectiveness measurements in real buildings, there is a need to quantify air distribution characteristics. The procedure discussed in the last section to determine system flows can be extended to study ventilation effectiveness. This is done by analyzing the tracer gas concentrations as the system approaches equilibrium and, again, during the decay after the tracer gas injection is turned off.

There have been only a few cases of ventilation effectiveness measurement in real buildings.[10,12] The work in reference 10, done at the Norwegian Institute of Technology, involved the determination of residence times in a 400 m^2 room in a hotel in Trondheim, Norway. The room was considered to be isolated from the rest of the building in terms of airflow and was ventilated with no recirculation, avoiding some of the difficulties discussed earlier. A constant flow of tracer gas was introduced into the supply air and the tracer concentration was monitored in the supply, exhaust, and at a location within the room. During the build-up in tracer, the local mean age of the air at a specific point in the room τ_i and internal mean age for the entire space $\{\tau_i\}$ are given by

$$\tau_i = \int_0^\infty [1 - (C_i(t)/C_i(\infty)] \, dt \tag{3}$$

and

$$\{\tau_i\} = (1/\tau_n) \int_0^\infty [1 - (C_e(t)/C_e(\infty)]t \, dt \tag{4}$$

$C_i(t)$ is the tracer concentration at the point in question, and τ_n is the inverse of the air exchange rate of the space. τ_i can be conveniently determined by filling an air sample container at the location of interest from the time the injection starts until the concentration attains equilibrium. The determination of $\{\tau_i\}$ requires the continuous monitoring of $C_e(t)$. Both τ_i and $\{\tau_i\}$ can also be determined from the concentration decay after the injection is stopped with expressions similar to equations (3) and (4). Skaret and Mathisen point out that when there is envelope leakage the decay results are more reliable because during buildup all the incoming air cannot be labelled with the tracer gas.[10] Based on the ages in equations (3) and (4) one defines a mean air exchange efficiency as

$$\{\eta_a\} = \tau_n/2\{\tau_i\} \tag{5}$$

This efficiency attains a maximum value of 1.0 under conditions of pure piston flow through the space and equals 0.5 under perfect mixing. The existence of stagnant zones within the space yields a value less than 0.5. Local conditions are characterized by the local air exchange efficiency

$$e_a = \{\tau_i\}/\tau_i \qquad (6)$$

If the local interior air age is less than the room average age, a generally favorable situation at that location, then e_a has a value greater than one. These quantities were determined for the hotel space in Trondheim using this procedure on two different occassions. The values of $\{\eta_a\}$ were 0.59 and 0.58, and the local air exchange efficiencies were 0.87 and 1.24.[10] This room had a displacement type ventilation system, which is consistent with values of $\{\eta_a\}$ above 0.5.

The definitions in equations (3) and (4) are appropriate for the case of a building ventilated with 100% outside air, but we also require techniques when there is recirculation of return air. One option is to employ these definitions with no modifications, ignoring the fact that there is recirculation. The values of $\{\eta_a\}$ and e_a will then reflect more complete mixing than is actually occurring within the building. The values of these measures of ventilation effectiveness will be affected by the amount of recirculation occurring, regardless of the actual air distribution characteristics within the building. Alternatively, a measure of ventilation effectiveness that is not affected by the amount of recirculation is required. This analysis is more involved than for the case of 100% outside air intake and is not yet available.

While the analysis techniques to determine building average and local internal ages with nonzero recirculation have not been completed, some interesting relations have been developed. For example, the average age of the air leaving the building, i.e. the return air, can be determined when there is recirculation. In the case of 100% outside air intake, this average residence time τ_r is equal to τ_n regardless of the flow pattern within the building. When there is less than 100% outside air intake, one may still determine this average residence time. To do so, one considers the average time for the ventilation air to make a circuit of the building from the supply fan back to the return fan, τ_s. τ_s is equal to the building volume V divided by the supply airflow rate Q_{SU}. The average age of the return air is then given by

$$\begin{aligned}\tau_r &= (1-R)\tau_s + R(1-R)2\tau_s + \ldots + R^{n-1}(1-R)n\tau_s + \ldots \\ &= \tau_s/(1-R)\end{aligned} \qquad (7)$$

As expected, when there is 100% recirculation (R=0), $\tau_r=\tau_s=\tau_n$. One can also determine τ_s by analyzing the values of C_R and C_M during the concentration buildup and decay. The values of C_S are not used because they rise quickly during buildup and typically exhibit more scatter than C_R and C_M, making their analysis difficult. Also, the values of C_M and C_S are identical during the decay. During the buildup the concentrations are given by

$$\begin{aligned}C_R(n\tau_s) &= (q/Q_{SU})\ [\ L + RL^2 + \ldots + R^{n-1}L^n\ ] \\ &= (q/Q_{SU})\ L\ [1-(RL)^n]/(1-RL)\end{aligned} \qquad (8a)$$

$$C_M(n\tau_s) = (q/Q_{SU}) [RL + R^2L^2 + \ldots + R^nL^n]$$

$$= RC_R(n\tau_s) \tag{8b}$$

During the decay, the concentrations are given by

$$C_R(t + \tau_s) = RL\ C_R(t) \tag{9a}$$

$$C_M(t + \tau_s) = RL\ C_M(t) \tag{9b}$$

Given the average age of the return air τ_r and the recirculation fraction R, the average age of the supply air is given by

$$\tau_{su} = R\tau_r = R\tau_s/(1-R) \tag{10}$$

This equation, and equation (7), are only true after many system time constants τ_s have elapsed. Earlier in the fan operation schedule, one must account for the age of the building air when the fans are turned on. Depending on the values of R and τ_s, it may take several hours for the supply air are τ_{su} to approach the value given in equation (10). If T is the average age of the building air when the fans are turned on, then the supply air age after n time constants τ_s have elapsed is given by

$$\tau_{su}(n\tau_s) = TR^{n+1} + R\tau_s/(1-R) \tag{11}$$

For example, consider the case in which the average building air age is 10 hours when the fans come on in the morning, R=0.75, and τ_s=0.5 hr. The equilibrium value of τ_{su} in equation (10) is 1.5 hr, but it takes 5 hours before the actual value of τ_{su} is less than 2 hours. Thus, the supply air age varies through the day and is strongly dependent on fan operation schedules. Note that all of the above discussion neglects the age of the air in the breathing zone of the occupants, which may be much older than the supply air for some interior airflow patterns.

4.3 Measurement Results

In order to investigate the applicability of the techniques discussed above, experiments were conducted in a three-story office building in Plainsboro, New Jersey. This privately owned building was completed in the fall of 1984, and an overhead view of its floor plan is shown in figure 2. The building dimensions are roughly 90 by 55 m, including an unconditioned atrium. The volume of the conditioned space is 46,000 m^3 and the floor area is 12,000 m^2. A skylighted corridor, extending all three stories, is isolated from the office space except for glass panels and doorways. There are two air handlers, serving the east and west sides of the building. Openings to each fan's return air shaft are shown in the figure, and these are the only connections between the entire floor's ceiling return plenum and the return fans. Note that the return air from office space near the bottom of the figure must go all the way around the skylighted corridor to reach the return shaft. The layout of this building suggests the potential for air distribution problems, making this building an interesting candidate for ventilation effectiveness tests.

In these tests, a known flow of tracer gas was injected into the main supply duct of each air handler and the concentrations C_M, C_S and C_R, as shown in figure 1, were monitored over time for each air handler. Once steady-state was achieved, the injection was stopped and the decay in the concentrations were monitored. During the buildup, and during the decay, air sample bags were filled at six locations on the first floor, as noted in figure 2. All six locations were at approximately desktop height. The tests were carried out on two consecutive days. The results of the steady-state evaluation of system flows are shown in table 1. This table lists the equilibrium values of the concentrations, the recirculation and leakage ratios (R and L), and the calculated values of Q_{SU}, Q_{OA} and Q_{IN}. Based on the differences between the east and west sides observed on 6/13, the tracer injection rates were adjusted on 6/14 and the equilibrium values of the concentrations on the two sides of the building were closer together. The values of R, L, and the airflow rates are quite similar for the two days. As noted in figure 1, Q_{OA} is the rate of intentional outside air intake through the air handlers and Q_{IN} is the rate of uncontrolled air leakage through the building shell. Table 1 shows that this uncontrolled leakage constitutes about two-thirds of the net outside air ventilation rate. This is not expected since the building is intended to be operated at a slight overpressure of the interior, which should cause Q_{IN} to equal zero.

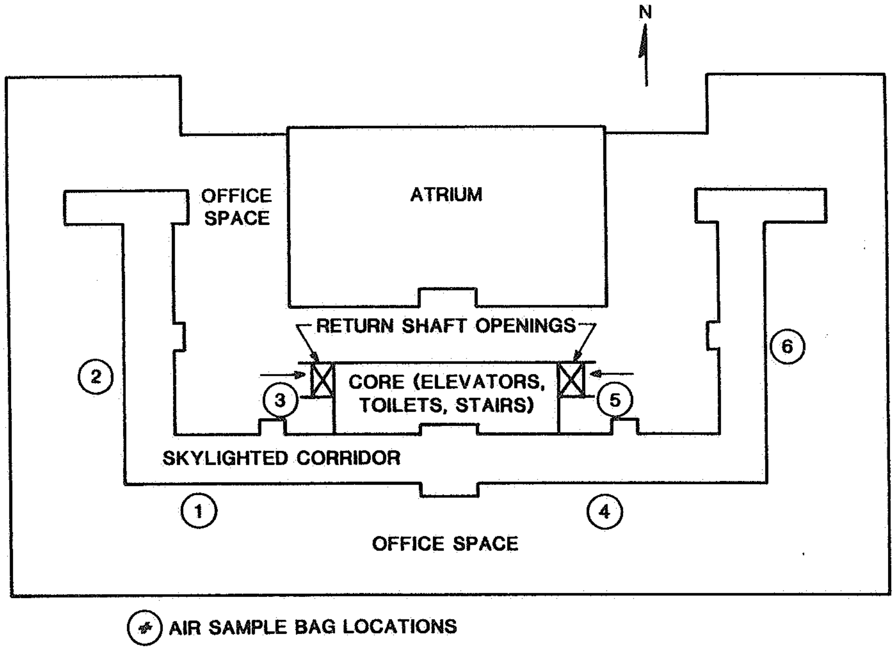

Figure 2 Schematic of Test Building

The values of τ_i and $\{\tau_i\}$ from equations (3) and (4) were determined for the two days of testing in this same building, and are given in table 2. The values of τ_n in this table (the inverse of the air exchange rate) is based on the net ventilation rate of the building, $Q_{IN}+Q_{OA}$. The fact that more outside air enters the building through the envelope than through the ventilation system may make the analysis procedure inapplicable. It will at least make the decay results more accurate than the buildup results, as pointed out by Skaret and Mathisen.[10] The values of $\{\tau_i\}$ are calculated using equation (4) during the buildup and a variation of this equation during decay. While the values determined during the decay are almost twice those from the buildup period, the values are similar over the two tests. The values of $\{\eta_a\}$ are also given in the table. On both nights the west-buildup value of $\{\eta_a\}$ is greater than its theoretical maximum of 1.0, but the buildup values are expected to be less reliable. The averages of the east and west down values are 0.41 and 0.44 for the two tests, corresponding to less than perfect mixing. The fact that the down values on the west side are greater than 0.5, corresponding to displacement flow, may or may not be significant. It is doubtful that the west side of the building performs like a displacement system and the east side does not. Table 2 also presents values of τ_i (equation (3)) determined at the six locations in figure 2 using air sample bags. With only a few exceptions, the values at each location are somewhat similar over the two days and for both the up and down data. The value of e_a (equation (6)) based on these values of τ_i are also given and no consistent patterns are evident. The values of the average concentrations over buildup and decay, and the concentrations at the steady-state, at the six different locations were suprisingly similar. This implies relatively good mixing on the floor and no significant differences for locations 3 and 5, which are directly below the return shaft openings.

	C_S	C_R	C_M	R	L	Q_{SU}	Q_{OA}	Q_{IN}	$Q_{IN}/(Q_{OA}+Q_{IN})$
6/13/85									
EAST	82.5	60.1	45.2	.75	.73	10.7	2.7	4.0	60%
WEST	100.1	70.4	57.3	.81	.70	7.0	1.3	3.0	70%
6/14/85									
EAST	76.9	54.7	39.9	.73	.71	10.8	2.9	4.4	60%
WEST	86.8	61.2	48.5	.79	.71	6.6	1.4	2.7	66%

Concentrations in pbb, flows in m^3/s.

Table 1 Results of System Flow Measurements

The results of the residence time analysis are presented in table 3. As mentioned earlier, the average time for the ventilation air to make a circuit of the building τ_s can be determined in more than one ways. τ_s is equal to V/Q_{SU}, and this quantity is given in the table for the east and west side of the building and for the building as a whole. Alternatively, τ_s can be determined during the buildup from equation (8) and during the decay from equation (9). These values for the two sides of the building are also given in table 3. While the values of V/Q_{SU} for the east and west sides are quite different, the values of τ_s based on equations (8) and (9) are essentially the same for both sides of the building. This may be due to mixing between the two sides of the building. Also, the values of τ_s based on the decay data are larger than those based on buildup. However, the average of the decay and buildup values are very close to the whole building values of V/Q_{SU}.

	6/13/85				6/14/85			
	East		West		East		West	
τ_n(minutes)	57		89		53		93	
	Up	Down	Up	Down	Up	Down	Up	Down
$\{\tau_i\}$(min)	55	113	37	79	43	116	29	73
$\{n_a\}$	.52	.25	1.2	.56	.62	.23	1.6	.64
τ_1(min)	55	--			50	109		
τ_2	93	105			76	80		
τ_3	65	99			27	--		
τ_4			39	--			40	75
τ_5			71	--			68	88
τ_6			60	--			61	77
e_{a1}	1.00	--			.86	1.06		
e_{a2}	.59	1.08			.57	1.45		
e_{a3}	.85	1.14			1.59	--		
e_{a4}			.95	--			.73	1.00
e_{a5}			.52	--			.43	.83
e_{a6}			.62	--			.48	.95

Table 2 Internal Air Age Results

	6/13/85			6/14/85		
	East	West	Whole Building	East	West	Whole Building
V/Q_{SU}	36	55	43	35	58	44
τ_s Buildup (eq (8))						
Return	39	37		38	40	
Mixed	43	39		42	40	
τ_s Decay (eq (9))						
Return	53	52		52	48	
Decay	50	48		49	46	

Table 3 Residence Time Results (minutes)

5. CONCLUSIONS

In this paper we have discussed existing and recently developed tracer gas techniques for the in situ evaluation of ventilation system performance. Past work on whole building infiltration and ventilation measurement was discussed and the major findings reviewed. The use of tracer gas to measure ventilation effectiveness in mechanically ventilated buildings was also discussed. While techniques exist for such measurements under conditions of 100% outside air intake, the evaluation of systems operating with recirculation is more difficult. Techniques appropriate to this latter situation are not yet available, but some limited evaluation is possible. Measurement procedures are also described to separately measure the intentional outside air intake through the air handlers and the amount of uncontrolled air leakage through the building shell. The results of the application of these techniques in a three-story office building are presented and discussed.

6. ACKNOWLEDGEMENTS

This research was supported by the U.S. Department of Energy.

7. REFERENCES

1. LAGUS, P. and PERSILY, A.K., "A review of tracer-gas techniques for measuring airflows in buildings," ASHRAE Transactions, Vol.91, Part 2, 1985.

2. GROT, R.A., "The air infiltration and ventilation rates in two large commercial buildings," in proceedings of DOE/ASHRAE conference, Thermal Performance of the Exterior Envelopes of Buildings II, Las Vegas, Nevada, 1982, ASHRAE SP 38.

3. GROT, R.A. and PERSILY, A.K., "Air infiltration and air tightness tests in eight U.S. office buildings," in Air Infiltration Reduction in Existing Buildings, proceedings of the Fourth Air Infiltration Centre Conference, Elm, Switzerland, 1983.

4. PERSILY, A.K. and GROT, R.A., "Ventilation measurements in large office buildings," ASHRAE Transactions, Vol.91, Part 2, 1985.

5. GROT, R.A., PERSILY, A.K., CHANG, Y.M., FANG, J.B., WEBER, S. and GALOWIN, L.S., "The application of measurement methods for the evaluation of the thermal integrity of the building envelope of eight federal office buildings," NBSIR 85-3147, National Bureau of Standards, 1985.

6. "Ventilation for acceptable indoor air quality," ASHRAE Standard 62-1981, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., 1981.

7. SANDBERG, M., "What is ventilation efficiency?," Building and Environment, Vol.16, No.2, 1981.

8. SANDBERG, M., "Ventilation efficiency as a guide to design," ASHRAE Transactions, Vol.89, Part 2, 1983.

9. SKARET, E. and MATHISEN, H.M., "Ventilation efficiency - a guide to efficient ventilation," <u>ASHRAE Transactions</u>, Vol.89, Part 2, 1983.

10. SKARET, E. and MATHISEN, H.M., "Test procedures for ventilation effectiveness field measurements," proceedings of the International Symposium on Recent Advances in the Control and Operation of Building HVAC Systems, Trondheim, Norway, 1985.

11. PERSILY, A.K., "Ventilation efficiency in mechanically ventilated office buildings," NBSIR 85-3208, National Bureau of Standards, 1985.

12. OFFERMANN, F.J., FISK, W.J., GRIMSRUD, D.T., PEDERSEN, B., and REVZAN, K.L., "Ventilation efficiencies of wall-or-window mounted residential air-to-air heat exchangers," <u>ASHRAE Transactions</u>, Vol.89, Part 2, 1983.