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FIELD MEASUREMENTS OF VENTILATION AND VENTILATION EFFECTIVENESS IN AN OFFICE/LIBRARY BUILDING

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ABSTRACT

Mechanical ventilation system performance involves the provision of adequate amounts of outdoor air, uniform distribution of ventilation air within the occupied space, and the maintenance of thermal comfort. Standardized measurement techniques exist to evaluate thermal comfort and air exchange rates in mechanically ventilated buildings; field techniques to evaluate air distribution or ventilation effectiveness are still being developed. This paper presents field measurements of air exchange rates and ventilation effectiveness in an office/library building in Washington, DC. The tracer gas decay technique was used to measure whole building air exchange rates. Ventilation effectiveness was investigated at several locations within the building through the measurement of local tracer gas decay rate and mean local age of air. The ventilation effectiveness measurements serve as an investigation of the applicability of the measurement procedures employed, providing insight into the measurement issue of establishing initial conditions, the spatial variation in tests results within a building, and the repeatability between tests.

1. INTRODUCTION

The James Madison Memorial Building of the Library of Congress, located in downtown Washington DC, has had a history of indoor air quality complaints by the building occupants. These complaints include stale, "dead" and uncomfortable air, poor air circulation, warm temperatures, and physical discomfort such as headaches, drowsiness, nausea, and sinus irritation. In an attempt to determine whether these complaints are related to the ventilation system performance and contaminant concentrations in the building, the Center for Building Technology of the National Institute of Standards and Technology (NIST) conducted an evaluation of the building's ventilation and air quality characteristics. This evaluation included measurements of building air exchange rates, ventilation effectiveness, and the concentrations of selected indoor air pollutants.

Indoor air quality complaints have become more common, or at least more publicized, in recent years. Whether or not air quality within office buildings has actually worsened, the awareness of building occupants and managers with respect to these problems has increased. Although there has been insufficient research to establish the causes of many indoor air quality complaints, several have been suggested including the reduction of building air exchange rates. In fact, air exchange rates and other ventilation system performance parameters have not been well characterized in mechanically ventilated office buildings. Therefore, general statements about air exchange rates in buildings, including trends over time, can not be supported [1].

The investigation of the Madison Building conducted by NIST included the evaluation of the ventilation system performance and the measurement of indoor contaminant concentrations. Whole building air exchange rates were measured with the tracer gas decay technique, using an automated measuring system. The assessment of ventilation effectiveness involved the measurement of local tracer gas decay rates and the mean local age of air. In addition, the concentrations of selected pollutants were measured in the building. This report presents the results of the air exchange rate and ventilation effectiveness measurements in the building. In addition, the relationship between the indoor carbon dioxide concentration and the building air exchange rate is examined. Additional information describing the building and preliminary results of the study are available in Reference 2.

2. BUILDING AND VENTILATION SYSTEM DESCRIPTION

The Madison Building was constructed during the 1970s and first occupied in 1979. It is a nine-story building with two basement levels and a ground level that is partially below grade. The building contains primarily office space, along with several other facilities including meeting rooms, auditoriums, library material storage areas, a print shop and preservation laboratory on the ground level, a loading dock on the ground level, and an underground garage. There is a tunnel on the ground floor connecting the Madison Building to the other buildings of the Library of Congress. The total floor area of the building is about 164,400 m^2.

The mechanical ventilation system of the Madison Building consists of 44 air handlers in the penthouse mechanical room and ten additional air handlers in four subbasement mechanical rooms. The portion of the building served by the penthouse air handlers constitutes the bulk of the building volume, while the subbasement air handlers serve only a small fraction of the building volume, most of which is unoccupied. Each floor of the building is divided into eight zones, and each of the eight building zones is associated with a bank of air handlers in the penthouse mechanical room. These zones are not isolated from each other in terms of airflow, with interior air being able to flow between these zones through hallways, from room to room, and within open office spaces that are in more than one zone.

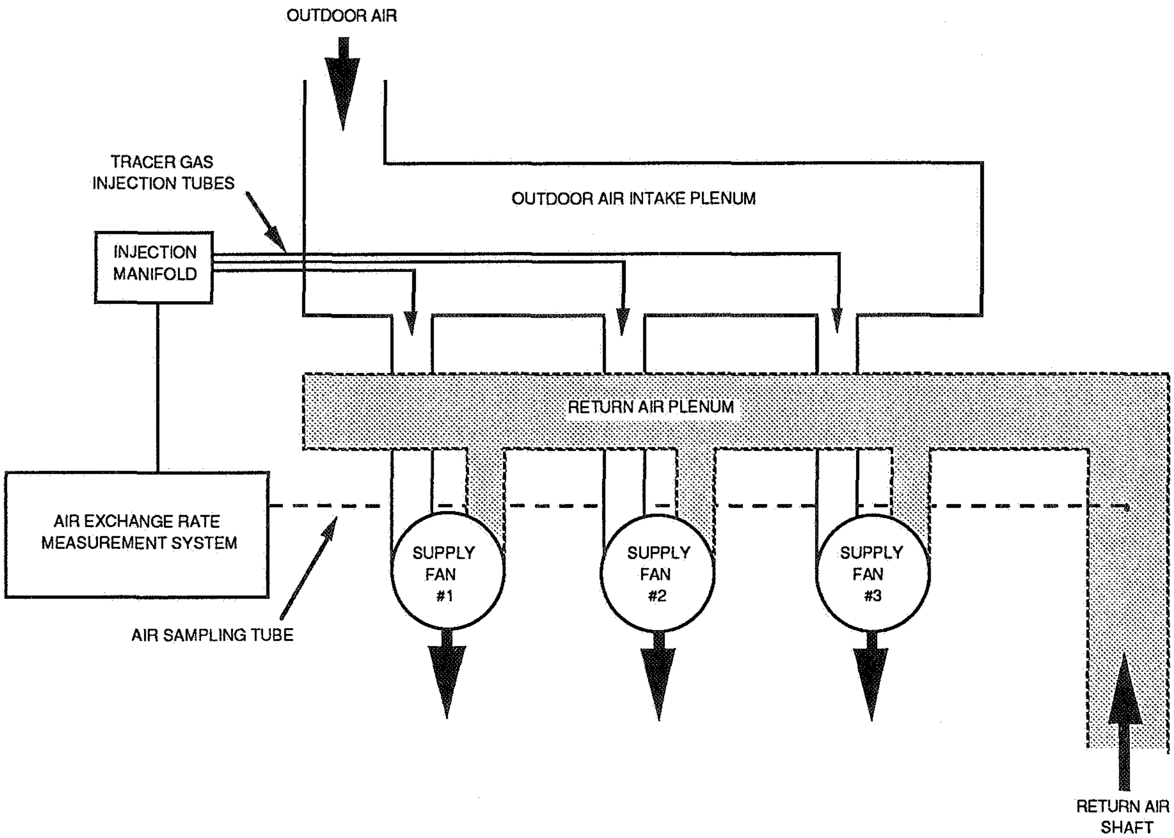

Figure 1 Schematic of Air Handling System

Figure 1 is a schematic of the air handling system for one of the eight building zones. Each zone is associated with an outdoor air intake plenum and a return air shaft. There are four to eight air handlers associated with each zone (only three are shown in the figure), with any given air handler serving from one to nine of the building floors. These air handlers all have variable air volume (VAV) supply fans and maintain constant outdoor air intake rates through the control of dampers in the

3. DESCRIPTION OF MEASUREMENTS

There are many factors related to the performance of building ventilation systems, but standardized measurement techniques and procedures exist to evaluate only some of these performance parameters in the field. Of particular interest is the development of measurement techniques to quantify the uniformity of air distribution or ventilation effectiveness in mechanically ventilated office buildings. Existing techniques to measure ventilation effectiveness have been successfully applied in laboratory facilities and in some field applications, but experience in modern, North American office buildings is limited. In this investigation, whole building air exchange rates were measured using the tracer gas decay technique, a standardized procedure. Ventilation effectiveness was evaluated using the tracer gas decay technique to measure the local tracer gas decay rate and the mean local age of air.

3.1 Whole Building Air Exchange Rates

Whole building air exchange rates were measured in the Madison Building using the tracer gas decay technique. This procedure has been used in thousands of residential buildings and many office buildings [1,4] and is described in ASTM Standard E741 [5]. The tracer gas decay technique is used to determine the rate at which outdoor air enters a building, including both intentional outdoor air intake through the air handling systems and unintentional infiltration through leaks in the building envelope. Regardless of common design expectations of minimal infiltration rates in mechanically ventilated office buildings, these two components of air exchange can be comparable in magnitude [6,7]. The air exchange rate of a building depends on a variety of factors including the design, installation and operation of the mechanical ventilation system and its controls, the airtightness of the building envelope, the interior configuration of the building, and outdoor weather conditions. Due to the complexity of air exchange in mechanically ventilated buildings, it is necessary to make many air exchange rate measurements in order to understand the air exchange characteristics of a building.

The tracer gas measurements of air exchange rates in the Madison Building employed an automated measuring system that enables the collection of large amounts of data under a range of outdoor weather and building operation conditions. The automated measuring system has been used previously to provide continuous measurements of building air exchange rates [4] and employs sulfur hexafluoride (SF_6) as the tracer gas. The microcomputer-based system controls tracer gas injection and air sampling, records SF_6 concentrations, and monitors and records outdoor weather, indoor temperature and fan operation status. A gas chromatograph equipped with an electron capture detector is used to measure SF_6 concentrations in a range of about 5 to 300 parts per billion (ppb) with an accuracy of roughly 1%.

In tracer gas tests, the manner in which the tracer gas is injected into the building and the locations at which the tracer gas concentrations are measured are necessarily based on the layout of the building and its air handling systems. In the Madison Building both the tracer gas injection and the air sampling strategies are based on the division of the building into the eight zones. Tracer gas was injected into the eight outdoor air intake plenums associated with the eight building zones, and the SF_6 concentration was monitored in each of the eight return air shafts and at an outdoor location. Figure 1 depicts the injection and sampling scheme for one building zone. A tracer gas injection tube carries a metered amount of tracer gas from the automated system to each of the eight outdoor air intake plenums, where the injection tube is connected to an injection manifold containing a flowmeter for each air handler in that outdoor air intake ducts of each fan. These intake dampers are modulated based on the output of an airflow monitor in the outdoor air intake duct. Supply air is delivered to the occupied space through ducts that run vertically through ventilation chases and horizontally through the plenums above the suspended ceilings on each floor. The return air from the occupied space flows into the suspended ceiling plenum on each floor through return air openings in the suspended ceiling. This return air then flows through the plenum and into the vertical return air shafts. The return shaft of each zone is connected to a return air plenum in the penthouse that serves the air handlers for that zone, enabling the recirculation of return air. There are no return fans in the building and no provisions for spilling excess return air, therefore all of the return air is recirculated. The air handling systems in the Madison Building operate 24 hours a day, throughout the year. There is a nighttime setback in the supply air static pressure setpoint, but the outdoor air intake rate is constant.

The air handling systems in the Madison Building are different from the systems that are typically employed in modern, North American office buildings. In order to protect library materials from degradation by outdoor air pollutants, the outdoor air brought into the buildings is cleaned and filtered. In order to limit the infiltration of unfiltered outdoor air, the outdoor air intake rate is carefully controlled to maintain the building at a positive pressure relative to the outdoors. The ventilation systems are operated at the same outdoor air intake rate 24 hours a day in order to provide constant protection of the library materials. In typical office building ventilation systems, outdoor air intake rates are not monitored and controlled as carefully as they are in the Madison Building. The ventilation systems in most office buildings are designed to bring in minimum levels of outdoor air during very cold and very hot weather to reduce the space conditioning load. Larger amounts of outdoor air are brought in during mild weather for cooling, employing a so-called economizer cycle. Therefore, in typical office buildings the air exchange rate varies by a factor of 5 or more depending on the outdoor weather, time of day and season of the year. In addition, office building ventilation systems are generally shut down during evenings and weekends.

The supply airflow rate capacity for the Madison Building's air handlers is about 850 m^3/s, and the minimum outdoor air intake rate is 170 m^3/s. These airflow rates can be converted to air changes per hour (ach) by dividing them by the building volume. Based on the gross building volume (the gross floor area of the building multiplied by the ceiling height, including the height of the return air plenum) the supply airflow rate capacity corresponds to about 5 ach, and the design outdoor air intake rate corresponds to 1.05 ach. The actual interior volume of the building is less than the gross volume due to the volume associated with interior partitions, furniture and other items. The volumetric airflow rates should be divided by this lower volume, which will increase the corresponding air change rates. An appropriate factor by which to reduce the gross volume is not available, but the correction to the air change rates is probably no more than 10 or 20%. ASHRAE Standard 62 [3] recommends a minimum ventilation rate in office space of 10 L/s per person. This value can be converted to air changes per hour by dividing by the volume associated with a single person. Assuming an occupant density in office space of 7 people per 100 m^2 (the default value contained in ASHRAE Standard 62) and a ceiling height of 3.5 m, 10 L/s per person converts to 0.72 ach. This conversion should also be corrected to account for the volume occupied by interior furnishings, but as stated above the correction is probably not large. The outdoor air intake rate specified in the mechanical ventilation system design for this building is almost 50% above the recommendation in ASHRAE Standard 62-1989.

zone. An injection line runs from the outlet of each flowmeter to each air handler in the zone. Thus, when tracer gas is injected into one of the eight zones, it is released into all the air handlers of that zone for the same length of time, at flow rates that are based on the volume served by each individual air handler.

Tracer gas was injected into 39 of the the 44 penthouse air handlers every three hours at a rate that was based on achieving an initial concentration of about 150 ppb in the building. After the injection, the tracer gas concentration was monitored at the nine air sample locations, with each location being sampled once every ten minutes. With the building fans operating 24 hours a day, eight tracer gas decay tests were conducted each day. The tracer gas concentration data were analyzed to determine the decay rate for each of the eight returns, and these eight decay rates were averaged to estimate the whole building air exchange rate. The accuracy of this air exchange rate determination depends on the uniformity of the tracer gas concentration within the building. The measurement error is estimated to be about 10%.

3.2 Ventilation Effectiveness

It is valuable to compare measurements of whole building air exchange rates to design values and ventilation standards, but these air exchange rates do not provide an indication of how this ventilation air is distributed within a building. Although the air exchange rate may be adequate on a whole building scale, there may be areas within the building with inadequate outdoor air supply due to nonuniform ventilation air distribution among the spaces within the building or due to poor mixing of this ventilation air within these spaces. Nonuniform air distribution, i.e., the existence of rooms or locations within rooms that are less well ventilated than other portions of the building, have been suspected as being responsible for some air quality complaints. There are no standardized measurement procedures for quantifying the uniformity of air distribution or ventilation effectiveness in mechanically ventilated office buildings. Therefore, the effects of nonuniformities in air distribution on air quality have not been demonstrated. However, based on the potential importance of air distribution, ventilation effectiveness measurement techniques for field application are being developed and studied [8-11].

Ventilation effectiveness was evaluated in the Madison Building in two series of tests, the first presented in Reference 2 and the second described in this paper. These evaluations consisted of measurements of local tracer gas decay rate and mean local age of air. In order to make these measurements, a uniform tracer gas concentration is established throughout the building. The first series of tests employed a pulse injection of tracer gas followed by a mixing period to achieve these initial conditions. In the second series of tests, tracer gas was injected at a constant rate until the concentration in the building attained equilibrium. A series of air samples was then taken at selected locations within the occupied space during the subsequent tracer gas decay. In order to assess local tracer gas decay rates, the tracer gas concentrations at each location are fit to an equation of the form:

$$C_i(t) = C_{oi}e^{-\lambda_i t} \tag{1}$$

$C_i(t)$ is the concentration at location i measured at time t, and C_{oi} and λ_i are determined from the curve fit. C_{oi} is the calculated the tracer gas concentration location i at t=0, though in general it will not equal the measured concentration at t=0 as explained below. In the first series of tests, t=0 corresponds to the time at which the pulse injection is complete. In the second series of tests, t=0 corresponds to the time at which the constant injection of tracer gas is stopped. λ_i is the tracer gas decay rate at the location in units of air changes per hour, although it is not generally equal to the air exchange rate at the location being tested. The value of λ_i is equal to the building air exchange rate only when the tracer gas concentration is uniform throughout the building during the decay. Based on multi-zone building airflow theory, the tracer gas concentration at all locations in the building will decay according to Equation 1 after a sufficient length of time (assuming that none of the locations are in spaces do not exchange air with the rest of the building). Regardless of the degree of mixing within the building, the values of λ_i will eventually be the same throughout the building and the values of C_{oi} will vary within the building [12]. C_{oi} is therefore a calculated concentration that characterizes a particular location and does not correspond to the actual initial concentration, which should be the same throughout the building. The calculated value of C_{oi} will be higher at locations that are less well ventilated and can be considered an indicator of ventilation effectiveness. There are no straightforward relationships between the values of C_{oi} and the airflow rates within a building except in very simple situations [13]. In real buildings, the values of C_{oi} can only be used as a qualitative indicator of ventilation effectiveness, with higher values corresponding to poor ventilation air distribution. There are some practical considerations regarding the use of C_{oi} as a measure of ventilation effectiveness. If one does not wait long enough before fitting the data to Equation (1), the values of λ_i will vary among locations and C_{oi} may not be a useful indicator of ventilation effectiveness. Also, variation in C_{oi} can occur due to a nonuniform distribution of the initial tracer gas injection.

Measurements of the mean local age of air were also made in the building as a measure of ventilation effectiveness. Mean local age has been proposed for quantifying ventilation effectiveness and has provided useful results in both laboratory and field tests [8,10]. However, complications exist when applying the measurement procedures in large, mechanically ventilated office buildings [9], and research is needed to examine the applicability of this approach in the field. The mean local age of air at a location i within a building τ_i is defined as the average amount of time that has elapsed since the air at that location has entered the building. If the ventilation air within a building is uniformly distributed to all spaces and the air within each space is perfectly mixed, then the local age will be the same throughout the building and equal to the inverse of the building air exchange rate. The inverse of the building air exchange rate is defined as the nominal time constant of the building τ_n. If there is nonuniform ventilation air distribution within a building, then those locations with poor ventilation air distribution will have ages of air that are higher than the building average. There are several definitions of ventilation effectiveness based on comparisons of τ_i to τ_n or to the building average age of air. In this paper, the ventilation effectiveness ε_i is defined as τ_n divided by τ_i. When the ventilation air distribution is perfectly uniform, $\varepsilon_i = 1$ at all locations in the building. When there is nonuniform ventilation air distribution, locations in so-called stagnant zones, which are effectively bypassed by the ventilation air, will have local ages of air that are relatively large and values of ε_i significantly less than 1.

To measure the mean local age of air, one establishes a uniform tracer gas concentration within the building and monitors the decay in tracer gas concentration at specific locations. The mean local age of air at location i is then defined as:

$$\tau_i = \frac{1}{C_{oi}} \int_0^{\infty} C_i(t)dt \qquad (2)$$

Two techniques for evaluating this integral were employed in the Madison Building, the first based on an average concentration determined by slowly filling an air sample bag at a constant rate during the test. The integral was also determined numerically from the discrete tracer gas concentration measurements made during the decay.

Reference 2 reports on the first series of measurements of local tracer gas decay rate and mean local age of air at 56 locations in the Madison Building. In these tests the initial conditions of uniform tracer gas concentration were achieved by a pulse injection of tracer gas lasting about 5 minutes followed by a period of about 30 minutes for the tracer gas to mix with the interior air. After the mixing period, five air samples were collected at each test location at roughly 20 minute intervals. Ten tests were conducted, one in the morning and one in the afternoon on five consecutive days. During each test, five to seven locations were monitored. One location was included in eight of the ten tests to provide an indication of the repeatability of the test results.

Another series of ventilation effectiveness measurements was conducted in the building more recently. In these measurements, the initial conditions were achieved by injecting tracer gas into the building supply fans at a constant rate until the concentration within the building attained equilibrium. In these tests the tracer gas injection lasted for at least five hours. After equilibrium was established, six air samples were collected at selected locations within the occupied space at approximately 20 minute intervals, with the first air sample taken before the injection was stopped. These measurements were made at 22 locations within the building, with each location tested three times.

4. RESULTS AND DISCUSSION

4.1 Whole Building Air Exchange Rates

Whole building air exchange rates were measured in the Madison Building from the end of January 1989 through March 1990, with a total of about 1300 individual measurements. Figure 2 is a plot of the building air exchange rates measured during the day versus the indoor-outdoor air temperature difference. These data indicate that the building air exchange rates are essentially constant over a wide range of temperature difference. The mean daytime air exchange rate is 0.82 ach with a standard deviation of 0.05 ach. The nighttime air exchange rates are similarly constant and have a mean of 0.76 ach with the same standard deviation. These standard deviations are less than the measurement uncertainty of 10%. Therefore, the outdoor air intake controls are performing as intended, i.e., the building air exchange rate is constant. There are very small variations over the day that appear to be related to the total supply airflow rate, with higher supply airflow rates corresponding to slightly higher air exchange rates.

Figure 3 is a plot of the daytime air exchange rates against Julian day, showing a slight decrease in air exchange rate over the measurement period. The variation in air exchange rate is not large relative to the measurement uncertainty of roughly 10%. This figure shows the minimum ventilation recommendation in ASHRAE Standard 62-1989, i.e., 10 L/s per person, corresponding to an air exchange rate of 0.72 ach, and the building's design minimum outdoor air intake rate, 1.05 ach. All of the measured air exchange rates are below the design value, and almost all are above the ASHRAE recommendation. These air exchange rates are similar in magnitude to those measured in other U.S. office buildings [1].

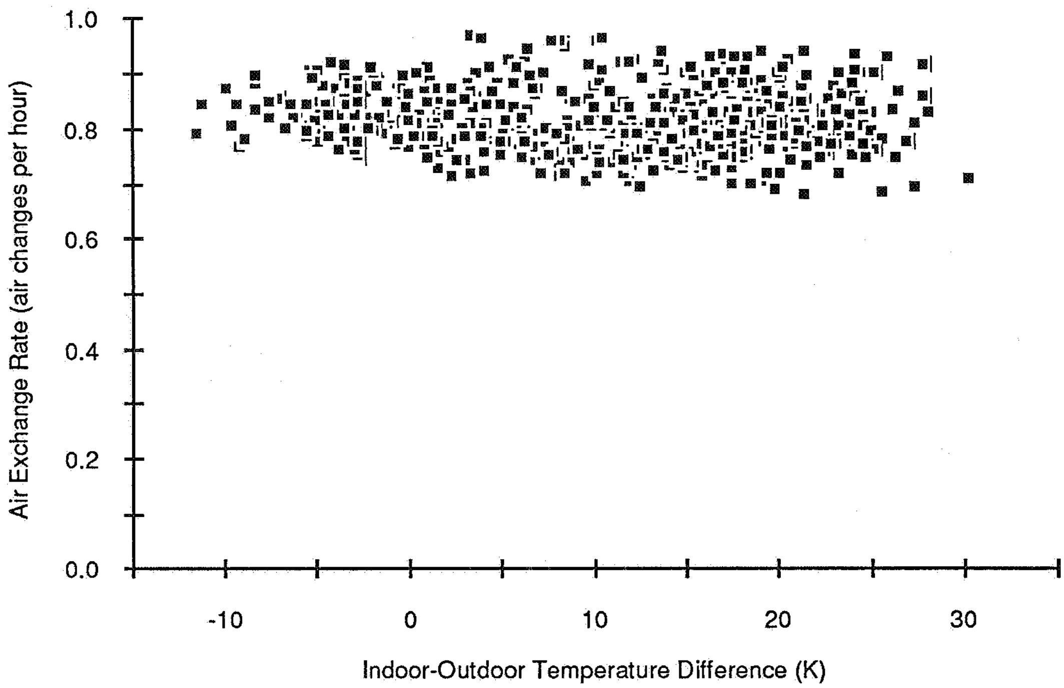

Figure 2 Daytime Air Exchange Rate versus Temperature Difference

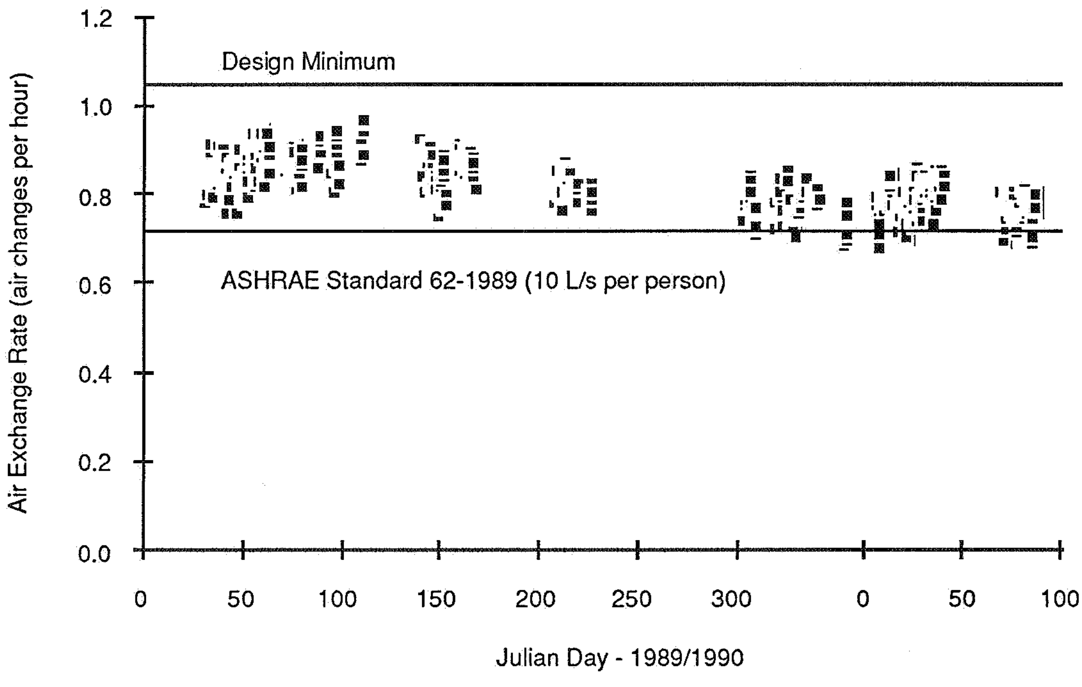

Figure 3 Daytime Air Exchange Rate versus Julian Day

4.2 Ventilation Effectiveness

Given the current status regarding the measurement of ventilation effectiveness in mechanically ventilated buildings, the ventilation effectiveness measurements in the Madison Building must be considered an investigation of the practicality of making these measurements in the field and the usefulness of results. In addition to providing insight into the applicability of the procedures, the measurements in the Madison Building enable the examination of three issues regarding the evaluation of ventilation effectiveness. Another issue addressed by both series of tests is the spatial variation in ventilation effectiveness measurement results, since this variation provides an indication of the uniformity of ventilation air distribution within a building. However, because there have been few field measurements of ventilation effectiveness, it is difficult to relate the magnitude of spatial variation to the uniformity of air distribution. Finally, measurements were made eight times at a single location in the first series of tests and three times at each location in the second series. Therefore, these results provide information on the repeatability of the test results.

4.2.1 Results of Previous Measurements

The results of the first series of ventilation effectiveness measurements are presented in detail in Reference 2. During each test, the local decay rate and the local age of air was measured at five to seven locations within the occupied space. The results of each test include the whole building tracer gas decay rate λ, the calculated value of the initial tracer gas concentration C_o averaged over the eight building returns, and calculated values of the initial concentration C_{oi}, the tracer gas decay rate λ_i, the mean local age of air τ_i, and the ventilation effectiveness ε_i at each location.

The ratio of the local tracer gas decay rate to the whole building decay rate, i.e., λ_i/λ, was calculated for each location. According to multi-zone building airflow theory, this ratio will equal one at all locations in the building after a sufficient length of time [12]. The average of these ratios for all the tests is 0.99 with a standard deviation of 0.05. Given that the local decay rates are basically uniform, a value of the ratio of the local C_{oi} to the whole building C_o that is close to 1.0 indicates good ventilation air distribution at this location. Those locations with poor mixing of the ventilation air will have a value of C_{oi} that is greater than C_o. The average value of C_{oi}/C_o for all the tests is 0.94 with a standard deviation equal to 0.09. Due to a lack of experience with these measurements, it is not possible to relate the magnitude of the variation in C_{oi} within the building to the uniformity of air distribution, but the results are consistent with good ventilation effectiveness. The predominance of values of C_{oi} less than C_o and the variation in C_{oi} throughout the building could also be caused by nonuniformities in the initial tracer gas concentration within the building. The eight tests conducted at the same location in the building provide an indication of the repeatability of the test results. The standard deviation of C_{oi}/C_o for the eight measurements at this location is 5% of the mean. Therefore, the variation in C_{oi}/C_o within the building is somewhat larger than the variation at a single location.

The mean local age of air was determined at the same locations at which the local tracer gas decay rates were measured. Two procedures were used, the first based on the average tracer gas concentration at each test location determined by filling an air sample bag at a constant rate during the test. The second determination was based on a curve fit to the tracer gas concentrations measured every 20 minutes during the test. If the air within the building was perfectly mixed and the measurement results had no errors, then the values of τ_i would be the same throughout the building and their inverses equal to the whole building air exchange rate. The ventilation effectiveness ε_i (equal to τ_n/τ_i) will then equal one throughout the building. Given the simultaneous measurement of τ_i at several locations in the building, the magnitude of the standard deviation of the values of τ_i at the various measurement locations relative to their mean value serves as a measure of the uniformity of ventilation air distribution. For the ten tests, the ratio of the standard deviation of τ_i to its mean ranged from 2% to 7%, with an average of 4%. The ventilation effectiveness values for all the tests range from 0.94 to 1.23, with an average value of 1.01, indicative of uniform ventilation air distribution. The spatial variation in the ventilation effectiveness ε_i is identical to the variation in τ_i. As in the case of the local decay rate measurements discussed above, there is insufficient experience with ventilation effectiveness measurements to determine how these results relate to the uniformity of air distribution within the building. The eight tests conducted at a single location provide an indication of the repeatability of the test results. The standard deviation of ε_i at this location is 5% of the mean value when determined from the average concentrations and 4% when determined numerically. Therefore, the variation in ε_i throughout the building is similar in magnitude to the variation at this single location.

It is difficult to interpret the results of the first series of ventilation effectiveness measurements in the Madison Building due to a lack of measurements in other buildings for comparison. The predominance of values of ε_i close to one is indicative of uniform air distribution in the building. The variation in both C_{oi}/C_o and ε_i throughout the building is similar in magnitude to the variation in repeated measurements at the same location. While no firm statements can be made regarding the uniformity of air distribution, these results are consistent with uniform ventilation air distribution and good air mixing within the space. The uniformity of the tracer gas concentrations during the decays, both within the occupied space and within the return air shafts, is also consistent with good ventilation effectiveness.

4.2.2 Results of Second Series of Measurements

In the second series of tests three measurements were conducted at three groups of locations, and the results of the nine tests are presented in the Table 1. The first column in the table gives the test location with the first number in the location designation indicating the building floor. The next two columns contain the initial concentrations at each location. C'_{oi} is the concentration measured just before the injection was stopped, and C_{oi} is the concentration determined from a curve fit to the five concentrations measured during the tracer gas decay (Equation 1). C_{oi} was evaluated from this curve fit at the time the injection was stopped. The local decay rate λ_i in air changes per hour, given in the fourth column of the table, is also determined from this curve fit. The inverse of λ_i is also included in the table. The local age of air in hours is presented in the last two columns of the table and is determined in two ways. τ'_i is based on the measured value of the initial concentration C'_{oi}, and τ_i is based on the calculated value C_{oi}. The results of each test are summarized for each of these parameters as the mean value for all locations in the test, the standard deviation and the ratio of the standard deviation to the mean. The table also shows the measured whole building air exchange rate for each of the tests.

Table 2 presents the measured values of ventilation effectiveness ε_i for the tests, where ε_i is defined here as τ_n/τ_i. The value of τ_i is used in this definition rather than τ'_i, because C_{oi} provides a more reliable estimate of the initial tracer gas concentration than C'_{oi}. The measured values of ε_i range from 0.85 to 1.13 with an average value of 0.98, indicative of uniform ventilation air distribution. The measured values of ε_i are summarized in Table 2 along with the mean, standard deviation and their ratio for each test. The mean and standard deviation of ε_i are also given for each location.

As discussed above, these experiments enable the examination of the establishment of initial conditions, the spatial variation in the test results and repeatability of the results at a single location. The measurement of local tracer gas decay rates and mean local ages of air using the tracer gas decay technique requires the establishment of a uniform tracer gas concentration throughout the building being tested, and establishing these initial conditions is extremely challenging in the field. The approach taken and the subsequent success will be determined to a large degree by the layout of the building and its air handling systems, the manner in which the ventilation system operates and the experience of the person conducting the test. In the case of the Madison Building, the ability to obtain the desired initial conditions is greatly facilitated by the building air handlers operating 24 hours a day, the air exchange rate being constant, and the recirculation of large volumes of return air.

The spatial uniformity of the initial tracer gas concentration can be characterized by the ratio of the standard deviation of the initial concentrations at the various test locations to the mean concentration. The initial concentrations C'_{oi} can be measured directly at each location or determined by the curve fits to the concentrations C_{oi} measured at each location during the tracer gas decay. In the first series of tests, the concentration that was used for assessing the uniformity of the initial conditions is the concentration calculated at the time of the first air sample of the test. The ratios of the standard deviation to the mean initial concentration for the ten tests are as follows: 0.068, 0.073, 0.072, 0.079, 0.030, 0.102, 0.090, 0.074, 0.112 and 0.085. The average of these ratios is 0.078. In the second series of tests, the concentration used for assessing the uniformity of the initial conditions is that calculated at the time that the tracer gas injection was stopped. These calculated concentrations C_{oi} are in the third column of Table 1. The ratios of the standard deviation to the mean initial concentrations for these nine tests range from 0.075 to 0.139, and the average of these ratios is 0.101. Thus, the initial concentrations are somewhat less uniform for the constant injection tests than for the pulse injection tests. One reason for the difference is that tracer gas was injected into 39 air handlers in both series of tests, and despite much effort the balancing of the tracer gas injections among the air handlers was not perfect. This injection imbalance led to spatial variation in tracer gas concentration in the building after the pulse injection and during the so-called equilibrium conditions of the constant injection tests. About 30 minutes elapsed between the time of the pulse injections and the time of the first air samples, while only 10 to 20 minutes elapsed before the first samples in the constant injection tests. The different amounts of time for tracer gas mixing allowed the spatial differences in concentration to diminish more in the pulse tests than in the constant injection tests.

These results provide some insight into the problem of establishing a uniform tracer gas concentration within a building when conducting ventilation effectiveness measurements. In general, the pulse injection approach takes less time than constant injection. Depending on the mixing characteristics of the building, the pulse injection approach will take less than one hour for injection and mixing. The constant injection approach takes about four times the nominal building time constant τ_n (τ_n equals the inverse of the building air exchange rate) to reach equilibrium. Depending on the building air exchange rate, the time to reach equilibrium can take from two hours to more than twelve hours. The long time period to reach equilibrium will present a problem when the ventilation system operation varies over this time period. Another important factor for either injection procedure is the ability to balance the tracer gas injection among a building's air handlers. Either procedure requires that the tracer gas be injected into each air handler at a rate that results in approximately the same tracer gas concentration throughout the building. Adjusting or balancing the tracer gas injection rates for multiple air handlers can be an extremely difficult and time-consuming task, depending on the number of air handlers and the complexity of the ventilation system zoning in the building. In general, many iterations of injection, assessing the concentration response and adjusting the injection airflow rates will be required in a building before an adequately balanced injection is achieved. The process of setting the injection rates in the Madison Building took several weeks. In either injection procedure, small imbalances in the injection rates can be overcome during a mixing period. If mixing within the building is poor or the ventilation air distribution is nonuniform, the mixing period can make the tracer gas concentration less uniform in either procedure. The degree of mixing within the building is very important in establishing the desired initial conditions. If mixing is rapid and thorough, it will decrease the mixing time required in the pulse injection procedure, and the faster pulse injection approach should be used. If the mixing is slow and incomplete, the pulse injection procedure may be inappropriate and the constant injection procedure should be used with no mixing period.

The evaluation of ventilation effectiveness in a building is based in part on the spatial uniformity of the test results, as measured by the local age of air τ_i and ventilation effectiveness ε_i. Locations with poor ventilation effectiveness will generally be characterized by larger values of τ_i and smaller values of ε_i than locations with good air distribution. The measured values of these two quantities are presented in Tables 1 and 2 for the nine tests conducted in the Madison Building. In the case of the local age of air τ_i, the variation among the measurement locations for each test ranges from 3% to 10% with an average value of 5%. The variation in the ventilation effectiveness ε_i among the test locations is almost identical. Because there have been few field measurements of ventilation effectiveness, the significance of this amount of variation can not be related to the uniformity of air distribution or the extent of mixing within the building. Measurements in additional buildings are required to determine the magnitude of the measurement error associated with these quantities. Because the Madison Building appears to be characterized by good mixing and uniform air distribution, the spatial variation in these results may serve as a useful baseline for the magnitude of variation in the measured values of these quantities.

The repeatability of ventilation effectiveness measurements at any particular location is another important measurement issue. Three ventilation effectiveness measurements were made at each location in the second series of tests in order to provide some insight to this question. The last two columns of Table 2 present the mean and standard deviation of ε_i at each location for the three measurements. The variation among the three measurements at each location, about 5%, is similar in magnitude to the variation among the different locations in each test.

5. VENTILATION AND CARBON DIOXIDE CONCENTRATIONS

The maximum whole building CO_2 concentration was determined for each working day in the Madison Building. The mean daily peak concentration was 512 ppm, the standard deviation was 30 ppm, and the largest daily peak was 605 ppm. ASHRAE Standard 62-1989 recommends that the CO_2 concentration be maintained below 1000 ppm, and therefore the whole building average CO_2 concentrations in the Madison Building are well below the ASHRAE maximum.

In a building with constant occupancy, the daily maximum in the CO_2 concentration is related to the building air exchange rate. The relationship between CO_2 concentration and air exchange rate has been discussed extensively in Reference 14. This reference contains a plot of daily maximum CO_2 concentration versus daily average air exchange rate for three mechanically ventilated office buildings. This plot is reproduced in Figure 4 with the addition of the Madison Building data. The solid line in the figure is the equilibrium CO_2 concentration as a function of air exchange rate based on the following assumptions: an occupant density of seven people per 100 m^2 of floor area, a ceiling height of 3.5 m (including the return air plenum), an outdoor CO_2 concentration of 300 ppm, and a CO_2 generation rate of 5.2×10^{-6} m^3/s per person. The data in the figure deviate from the equilibrium curve because the CO_2 concentrations in these buildings do not attain equilibrium. This is due to the fact that CO_2 generation rates (proportional to occupancy levels) are not constant for sufficient lengths of time to attain equilibrium. The deviation between the measured peak CO_2 concentrations and the calculated equilibrium concentrations is greater at lower air exchange rates because it takes longer to reach equilibrium at lower air exchange rates. These data confirm the inappropriateness of using CO_2 concentrations to determine building air exchange rates. The Madison Building data are clustered closely together in this plot, because the air exchange rates in the building do not vary. The relation between CO_2 concentration and air exchange rate in the Madison Building is similar to that observed in other office buildings.

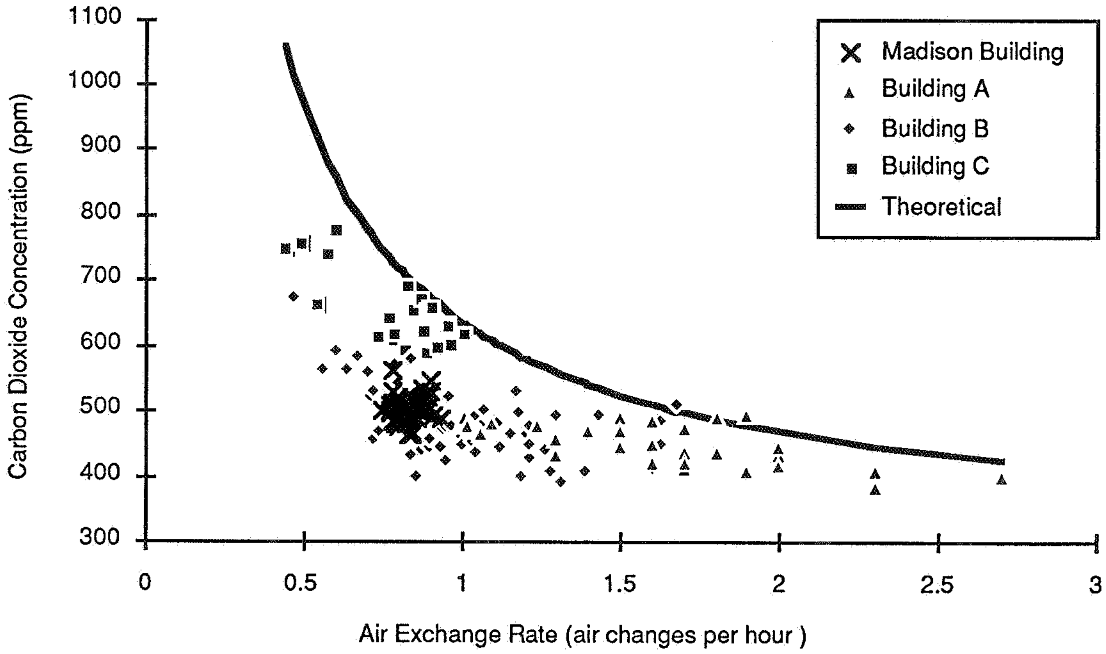

Figure 4 Carbon Dioxide Concentration versus Air Exchange Rate

6. SUMMARY

The ventilation assessment of the Madison Building study included the measurement of whole building air exchange rates for over a year and the application of two techniques to evaluate ventilation effectiveness. The whole building air exchange rates measured during occupied hours had an average value of 0.82 air changes per hour (ach) with little variation over the entire period of measurement. The air exchange rates measured at night were slightly lower. The daytime air exchange rates are generally above the ventilation recommendation in ASHRAE Standard 62-1989 (0.72 ach) and below the design air exchange rate for the building (1.05 ach). The measurements of whole building average CO_2 concentrations yielded an average value of the daily peak concentration of 512 ppm on working days, well below the recommended maximum in ASHRAE Standard 62-1989 of 1000 ppm. The relationship between CO_2 concentration and building air exchange rate is consistent with the relationship seen in other office buildings.

The results of the ventilation effectiveness measurements of local tracer gas decay rate and mean local age of air are consistent with good distribution of the outdoor air by the ventilation system and good mixing within the space. The average of the measured values of ventilation effectiveness is close to 1. The spatial variation in these quantities within the building is about 5%, as is the repeatability of the measurement results at the same location.

Valuable experience with the application of ventilation effectiveness measurement techniques was gained in this building. Even though several characteristics of this particular building made the measurements much easier than they might have been in a more typical office building, the measurements were still very involved and time consuming. The feasibility of measuring ventilation effectiveness and interpreting the results is in general problematic, and may very well be impractical in many buildings. Additional experience with the application of these measurement techniques in mechanically ventilated office buildings is needed in order to develop a reliable procedure for measuring ventilation effectiveness and the ability to interpret the results in terms of the adequacy of ventilation air distribution.

7. ACKNOWLEDGEMENTS

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Table 1 Ventilation Effectiveness Measurement Results

Test	Location	Initial Concentration (ppb) Measured C'_{oi}	Calculated C_{oi}	Local Decay Rate (hr^{-1}) λ_i	$1/\lambda_i$	Age of Air (hours) Based on C'_{oi} τ'_i	Based on C_{oi} τ_i
#1	Building Air Exchange Rate = 0.83/hr						
	6U4	54.1	50.5	0.79	1.27	1.19	1.27
	6V14	59.2	63.1	0.70	1.43	1.52	1.43
	6F12	56.8	58.9	0.83	1.21	1.26	1.21
	5D4	79.6	76.5	0.94	1.06	1.02	1.06
	5M8	65.2	64.2	0.82	1.22	1.20	1.22
	5S4	62.7	55.3	0.76	1.31	1.16	1.31
	5R13	58.3	55.7	0.76	1.32	1.27	1.32
Mean		62.2	60.6	0.80	1.26	1.23	1.26
Standard Deviation		7.8	7.8	0.07	0.10	0.14	0.11
Std Dev/Mean		0.13	0.13	0.09	0.08	0.11	0.08
#2	Building Air Exchange Rate = 0.81/hr						
	6U4	62.1	62.7	0.84	1.19	1.20	1.19
	6V14	72.1	71.4	0.78	1.28	1.26	1.27
	6F12	56.0	63.4	0.82	1.22	1.38	1.22
	5D4	74.9	80.9	0.87	1.15	1.24	1.14
	5M8	64.8	61.6	0.86	1.16	1.11	1.17
	5S4	57.8	55.0	0.79	1.27	1.21	1.27
	5R13	53.7	60.4	0.79	1.27	1.42	1.26
Mean		63.1	65.1	0.82	1.22	1.26	1.22
Standard Deviation		7.5	7.9	0.03	0.05	0.10	0.05
Std Dev/Mean		0.12	0.12	0.04	0.04	0.08	0.04
#3	Building Air Exchange Rate = 0.76/hr						
	6U4	72.4	68.1	0.72	1.39	1.31	1.39
	6V14	85.2	84.9	0.73	1.37	1.37	1.37
	6F12	67.1	77.0	0.69	1.45	1.66	1.45
	5D4	89.1	90.9	0.78	1.28	1.31	1.29
	5M8	80.9	67.3	0.77	1.30	1.08	1.30
	5S4	67.5	59.4	0.72	1.39	1.22	1.39
	5R13	64.4	68.3	0.69	1.45	1.55	1.46
Mean		75.2	73.7	0.73	1.38	1.36	1.38
Standard Deviation		9.1	10.3	0.03	0.06	0.18	0.06
Std Dev/Mean		0.12	0.14	0.04	0.04	0.13	0.04
#4	Building Air Exchange Rate = 0.74/hr						
	4X17	92.9	77.8	0.77	1.30	1.09	1.30
	4P12	63.3	66.7	0.72	1.39	1.47	1.39
	4W4	63.2	60.9	0.77	1.30	1.25	1.30
	4E7	77.7	77.5	0.83	1.20	1.20	1.20
	2D4	61.9	64.5	0.75	1.33	1.40	1.34
	2E7	72.5	61.3	0.76	1.32	1.12	1.32
	2G16	67.0	68.4	0.72	1.39	1.43	1.40
	2S16	57.9	61.4	0.70	1.43	1.51	1.42
Mean		69.6	67.3	0.75	1.33	1.31	1.33
Standard Deviation		10.6	6.5	0.04	0.07	0.15	0.07
Std Dev/Mean		0.15	0.10	0.05	0.05	0.12	0.05
#5	Building Air Exchange Rate = 0.80/hr						
	4X17	87.8	69.8	0.79	1.27	1.00	1.26
	4P12	63.9	64.5	0.73	1.37	1.39	1.38
	4W4	70.5	70.3	0.77	1.30	1.30	1.30
	4E7	79.0	81.0	0.83	1.20	1.23	1.20
	2D4	72.3	68.2	0.75	1.33	1.25	1.33
	2E7	57.0	60.6	0.73	1.37	1.45	1.37
	2G16	71.9	77.0	0.71	1.41	1.51	1.41
	2S16	69.8	70.3	0.74	1.35	1.36	1.35
Mean		71.5	70.2	0.76	1.33	1.31	1.33
Standard Deviation		8.6	6.0	0.04	0.06	0.15	0.06
Std Dev/Mean		0.12	0.09	0.05	0.05	0.11	0.05

Table 1 Ventilation Effectiveness Measurement Results (continued)

		Initial Concentration (ppb)		Local Decay Rate (hr^{-1})		Age of Air (hours)	
		Measured	Calculated			Based on C'_{oi}	Based on C_{oi}
Test	Location	C'_{oi}	C_{oi}	λ_i	$1/\lambda_i$	τ'_i	τ_i
#6	Building Air Exchange Rate = 0.76/hr						
	4X17	87.6	76.6	0.84	1.19	1.05	1.20
	4P12	60.9	67.3	0.77	1.30	1.44	1.30
	4W4	68.7	70.0	0.83	1.20	1.23	1.21
	4E7	74.1	74.3	0.76	1.32	1.31	1.31
	2D4	62.5	68.6	0.78	1.28	1.41	1.28
	2E7	61.7	68.8	0.80	1.25	1.40	1.25
	2G16	71.1	84.5	0.84	1.19	1.42	1.19
	2S16	68.3	69.7	0.80	1.25	1.28	1.25
Mean		69.4	72.5	0.80	1.25	1.32	1.25
Standard Deviation		8.2	5.4	0.03	0.05	0.12	0.04
Std Dev/Mean		0.12	0.07	0.04	0.04	0.09	0.03
#7	Building Air Exchange Rate = 0.71/hr						
	3T17	75.6	73.8	0.70	1.43	1.40	1.44
	3G17	68.7	77.8	0.72	1.39	1.58	1.40
	3G11	77.1	79.9	0.71	1.41	1.47	1.42
	3E9	84.2	82.4	0.77	1.30	1.27	1.29
	3G5	77.7	92.7	0.72	1.39	1.67	1.40
	1K4	79.6	78.9	0.70	1.43	1.41	1.42
	1H17	62.8	66.6	0.70	1.43	1.52	1.43
Mean		75.1	78.9	0.72	1.40	1.47	1.40
Standard Deviation		6.6	7.4	0.02	0.04	0.12	0.05
Std Dev/Mean		0.09	0.09	0.03	0.03	0.08	0.03
#8	Building Air Exchange Rate = 0.73/hr						
	3T17	71.2	72.5	0.56	1.79	1.81	1.78
	3G17	78.7	83.9	0.63	1.59	1.70	1.60
	3G11	82.8	89.3	0.74	1.35	1.46	1.35
	3E9	78.6	82.5	0.74	1.35	1.42	1.35
	3G5	84.5	94.9	0.65	1.54	1.73	1.54
	1K4	71.7	81.1	0.72	1.39	1.56	1.38
	1H17	67.0	77.0	0.65	1.54	1.76	1.53
Mean		76.4	83.0	0.67	1.51	1.63	1.50
Standard Deviation		6.0	6.9	0.06	0.15	0.14	0.15
Std Dev/Mean		0.08	0.08	0.09	0.10	0.09	0.10
#9	Building Air Exchange Rate = 0.77/hr						
	3T17	62.0	68.2	0.74	1.35	1.48	1.35
	3G17	67.3	75.6	0.81	1.23	1.39	1.24
	3G11	71.2	75.2	0.79	1.27	1.33	1.26
	3E9	65.6	63.7	0.76	1.32	1.28	1.32
	3G5	68.5	78.2	0.73	1.37	1.56	1.37
	1K4	61.4	63.8	0.74	1.35	1.41	1.36
	1H17	59.1	62.1	0.73	1.37	1.43	1.36
Mean		65.0	69.5	0.76	1.32	1.41	1.32
Standard Deviation		4.0	6.2	0.03	0.05	0.09	0.05
Std Dev/Mean		0.06	0.09	0.04	0.04	0.06	0.04

Table 2 Summary of Ventilation Effectiveness Measurements

Location	Ventilation Effectiveness, ε_I			Mean	Standard Deviation
	Test #1	Test #2	Test #3		
6U4	0.95	1.04	0.95	0.98	0.05
6V14	0.85	0.97	0.96	0.93	0.07
6F12	1.00	1.01	0.91	0.97	0.06
5D4	1.13	1.08	1.02	1.08	0.06
5M8	0.99	1.06	1.01	1.02	0.03
5S4	0.92	0.97	0.95	0.95	0.03
5R13	0.91	0.98	0.90	0.93	0.04
Mean	0.96	1.02	0.96		
Standard Deviation	0.09	0.04	0.05		
Std Dev/Mean	0.09	0.04	0.05		
	Test #4	Test #5	Test #6		
4X17	1.04	0.99	1.10	1.04	0.05
4P12	0.97	0.91	1.01	0.96	0.05
4W4	1.04	0.96	1.09	1.03	0.06
4E7	1.13	1.04	1.00	1.06	0.06
2D4	1.01	0.94	1.03	0.99	0.05
2E7	1.02	0.91	1.05	1.00	0.07
2G16	0.97	0.89	1.11	0.99	0.11
2S16	0.95	0.93	1.05	0.98	0.07
Mean	1.01	0.94	1.05		
Standard Deviation	0.06	0.05	0.04		
Std Dev/Mean	0.06	0.05	0.04		
	Test #7	Test #8	Test #9		
3T17	0.98	0.77	0.96	0.90	0.12
3G17	1.01	0.86	1.05	0.97	0.10
3G11	0.99	1.01	1.03	1.01	0.02
3E9	1.09	1.01	0.98	1.03	0.06
3G5	1.01	0.89	0.95	0.95	0.06
1K4	0.99	0.99	0.95	0.98	0.02
1H17	0.98	0.90	0.95	0.95	0.05
Mean	1.01	0.92	0.98		
Standard Deviation	0.04	0.09	0.04		
Std Dev/Mean	0.04	0.10	0.04		

Discussion

Paper 43

D.Harrje (DTH Consultant, USA)

Since the constant injection at 39 air handlers had 5 hours to equilibrate shouldn't this approach be better at achieving the uniform concentration desired?

A.Persily (NIST, USA)

In order for the constant injection approach to result in a uniform tracer gas concentration throughout the building, the injection rate into each air handler must be proportional to the volume served by that air handler. In practice this is very difficult to establish. Any difference in the ratio of injection rate to space volume among the air handlers will result in non-uniform tracer gas concentrations regardless of how long one waits.

J.Axley (MIT, USA)

I would like to reiterate the sources of error in determining vent effectiveness in the field that you mention and establish an additional source. You noted that the reliability of the test depends on one's success in establishing initial conditions which in turn depend on a) the building flow/air distribution character and b) the injection strategy used to establish these initial conditions. An additional source of error is related to the skill of the experimentalist - to establish some sense of this aspect I only remind the attendees here today that you were dealing with 39 air handlers and would ask you to simply describe the size of these air handlers and the building volume they served so that scale of the experimental challenge can be established.

A.Persily (NIST, USA)

I regret having not communicated the difficulty associated with making those measurements, which were in part due to the complexity of the air handling systems. The air handlers were indeed quite large; most of them had supply air capacities greater than 20 m3/s (40,000 cfm) and served volumes larger than 14,000 m^3. In fact there are several aspects of this building that facilitated the measurements: 24 hour fan operation constant outdoor air intake, fairly uniform ventilation air distribution to the spaces, and good mixing in the spaces. Even under these fortunate circumstances, the measurements were still quite difficult. In other buildings the measurements will generally be even more difficult if they are indeed at all practical.

Earle Perera (BRE, UK)

Is this the experience with the "pulse decay" technique in real buildings?

A.Persily (NIST USA)

We have made measurements in a mechanically ventilated office building and they were presented in a paper by James Axley and myself at the 9th AIVC Conference. In these measurements we idealized the building as three zones and learned several lessons regarding practical measurement issues. First, one can start the integration period somewhat after the tracer gas injection and avoid some problems associated with the mixing of the tracer. Also, the integration can end before the concentrations get too low and accuracy becomes a problem. In the zone of injection one can determine the integral by filling an air sample container at a constant rate thereby avoid ing measurement inaccuracies associated with determining very high concentrations.

J Van der Maas (LESO, Switzerland)

The ventilation effectiveness seems to vary only 10-20%, how do you expect this to explain the complaints from occupants?

A Persily (NIST, USA)

The ventilation effectiveness measurement results do not explain the occupant complaints nor do the measured ventilation rates. Other factors must be causing the occupants' dissatisfaction with the environment. Additional measurements have been made in the building which may explain the complaints and these will be reported on in the future.