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Air Change Effectiveness Measurements in Two Modern Office Buildings

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Abstract

Local age of air and air change effectiveness were determined in two office buildings using tracer gas techniques to study the applicability of the associated measurement procedures in mechanically ventilated office buildings. Measurement issues examined include the establishment of a uniform tracer gas concentration at the start of the test and the relationship of ventilation system configuration and system operation to the test procedure. Air change effectiveness was determined at locations in the occupied space based on the local age of air at that location and the age of air in the corresponding ventilation system return duct. Values of the air change effectiveness in the occupied space were generally close to one, which is consistent with good mixing of the ventilation air within the occupied space. Deviations from 1.0, on the order of 10%, did occur, but given the limited experience with these measurement procedures in the field it is not clear whether these deviations are significant. These tests provide data on air change effectiveness to supplement the limited database on mechanically ventilated office buildings in the U.S. In addition, the experience obtained with the measurement procedures will assist in the development of a standardized approach to measuring air change effectiveness in the field.

KEY WORDS:
Air change effectiveness, Building performance, Commercial building, Indoor air quality, Mechanical ventilation, Office building, Tracer gas, Ventilation, Ventilation effectiveness.

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Introduction

Ventilation systems are designed and operated to provide adequate amounts of outdoor air, to distribute this outdoor air throughout the occupied space, and to maintain thermal comfort. There are numerous design features and performance parameters relevant to these goals. Ventilation effectiveness has been described in general terms as the ability of a ventilation system to meet its design objectives (Persily, 1992). Specific definitions of ventilation effectiveness also exist that address air mixing within ventilated spaces. Discussions of ventilation effectiveness within ventilated spaces have concentrated on two issues, the mixing of ventilation air within the space and the removal of internally generated contaminants. Much of the activity in this area is based on concerns that significant quantities of supply air may flow directly into the return or exhaust vents without reaching the occupied space, so-called "short-circuiting." In such situations, appropriate amounts of outdoor air may not be delivered to the occupied portions of the space and internally generated contaminants may build up to undesirable levels.

The ability to evaluate the existence of short-circuiting in the field and to assess the performance of innovative approaches to air distribution is limited by a lack of validated measurement procedures to assess ventilation effectiveness. A variety of procedures have been suggested, and some laboratory and field applications of these procedures have been conducted. Of these various definitions of ventilation effectiveness, air change effectiveness based on the measurement of the age of air is one of the more promising for use in the field (Sandberg, 1983; Sandberg and Sjöberg, 1983; Seppänen, 1986). Using this approach, the air change effectiveness measurements conducted to date in U.S. office buildings indicate good mixing of the ventilation air within ventilated spaces (Fisk et al., 1991a; Persily and Dols, 1991). While these measurement results have not re-

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on each of the five upper floors. The fans serving the two below-grade floors have a design capacity of 3.4 m^3/s (7,200 cfm), yielding 13.6 m^3/s (28,800 cfm) on each of the below-grade floors. The supply airflow rate capacity of the atrium air handlers is 6.8 m^3/s (14,400 cfm). The design minimum outdoor air intake specifications for each floor of the building are: 3.6 m^3/s (7,600 cfm) on levels one through five, 2.7 m^3/s (5,700 cfm) for the basement, 1.8 m^3/s (3,800 cfm) for the sub-basement, and 1.4 m^3/s (3,000 cfm) for the atrium.

In summary, the mechanical ventilation system consists of 30 supply fans with a total capacity of 126 m^3/s (267,000 cfm), corresponding to 3.5 air changes per hour (ach). The exhaust airflow capacity for the building, consisting mainly of toilet exhausts, is 9.1 m^3/s (19,300 cfm). The design value for minimum outdoor air intake for the building is 23.9 m^3/s (50,600 cfm), corresponding to 0.66 ach. The conversion of the design minimum outdoor air intake rate to air changes per hour is approximate since it is based on the gross building volume, uncorrected for the volume occupied by furniture, walls and other items. The minimum outdoor air intake rates for the individual floors are: 0.77 ach on levels two through five, 0.66 on level one, 0.62 ach on the basement, and 0.44 ach on the sub-basement and the atrium. ASHRAE Standard 62-1989 (ASHRAE, 1989) recommends a minimum ventilation rate of 10 *l*/s (20 cfm) per person for office space. Based on an occupancy of seven people per 100 m^2 (1000 ft^2) and a ceiling height of 3.5 m (11.5 ft), including the return air plenum, the ASHRAE recommendation corresponds to 0.72 ach. The occupant densities in the atrium and the sub-basement are much lower than in the rest of the building. In addition, the ceiling height is much greater in the atrium. Therefore, the ASHRAE recommendation corresponds to an air change rate in the atrium that is well below 0.72 ach on the sub-basement level and in the atrium. The air change rate based on the minimum outdoor air intake rate specifications for the other floors of the building are essentially the same as the rate based on the minimum recommendation in ASHRAE Standard 62-1989.

Portland Building

The Portland building is a seven-story office building with a one-story basement and a two-story underground parking garage. The building was constructed during 1986 and 1987, and occupancy began late in 1987. The conditioned office space within the building has a floor area of about 34,600 m^2 (372,000 ft^2) and a conditioned volume of about 134,000 m^3 (4.73×10^6 ft^3). A more detailed description of the building, with floor plans and air handler schematics, is contained in Grot et al. (1989). The building consists primarily of open office space, with 1.5 m (5 ft) high partitions separating the individual work stations. The building also contains some private offices and conference rooms enclosed by floor-to-ceiling walls.

A penthouse mechanical room houses the main HVAC systems, consisting of three large, dual-duct variable air volume (VAV) systems, one serving seven floors of the center of the building and the others serving the east and west sides. There are also several smaller air handling systems located on and serving the basement level. Each of the three main air handling systems consists of two "cold" supply fans that work in parallel, one "hot" supply fan that only operates when needed, a return fan and a minimum outdoor air fan. VAV terminal units are distributed throughout the floors, with single duct units in the interior connected to the cold deck and dual-duct units in the exterior connected to both the hot and cold decks. The building air handlers employ an economizer cycle, in which outdoor air is used to cool the building when the outdoor air temperature is above freezing and below the return air temperature.

The design supply air capacity of each system is 47.2 m^3/s (100,000 cfm), and the capacity of each minimum outdoor air intake fan is 2.0 m^3/s (4,200 cfm), which is about 4% of the supply air capacity. The exhaust airflow capacity for the building, consisting mainly of toilet exhausts, is 6.6 m^3/s (14,000 cfm). Based on the building volume, the maximum supply airflow capacity is 3.8 ach, and the minimum design outdoor air intake rate is 0.16 ach. This building was designed to comply with ASHRAE Standard 62-1981, which contained a minimum outdoor air intake requirement of 2.5 *l*/s (5 cfm) per person in smoke-free office space (ASHRAE, 1981). Based on an occupancy of seven people per 100 m^2 (1000 ft^2) and a ceiling height of 3.5 m (11.5 ft), including the return air plenum, this requirement corresponds to an air change rate of approximately 0.18 ach in an office building, slightly above the design minimum. The conversion of the minimum outdoor intake specifications to an air change rate is an approximate calculation given the uncertainty in the building volume, and the 0.02 ach difference between the air change rate based on the building design and ASHRAE Standard 62-1981 is not significant. ASHRAE Standard 62-1989 contains a minimum outdoor air requirement for office space of 10 *l*/s (20 cfm) per person (ASHRAE, 1989) which corresponds to an air change rate of about 0.72 ach.

Measurement Procedures

This section describes the procedures used to measure the local age of air and to determine air change effectiveness. The measurement procedures are described both in general terms and specifically as applied in these buildings.

Background

The measurements in these two buildings employed the tracer gas decay technique to measure the age of air (Sandberg, 1983; Sandberg and Sjöberg, 1983; Seppänen, 1986). The local age of air is defined as the average amount of time that has elapsed since the air molecules at a specific location entered the building. The local age of air is denoted by τ_i, and the average value of the local age of air for all points in a particular space is denoted by $\langle\tau\rangle$. The inverse of the building air change rate is referred to as the nominal time constant of the building τ_n. There are several definitions of air change effectiveness based on comparisons of τ_i, $\langle\tau\rangle$ and τ_n. The local air change effectiveness characterizes the air change effectiveness at a specific location and is defined as

$$\varepsilon_i = \tau_n / \tau_i. \tag{1}$$

The mean air change effectiveness of a building or a space η is a measure of the overall air distribution pattern for the building or space and is given by

$$\eta = \tau_n / \langle\tau\rangle. \tag{2}$$

The tracer gas techniques used to measure the age of air are described in detail elsewhere (Sandberg, 1983; Sandberg and Sjöberg, 1983). One technique involves injecting tracer gas at a constant rate into the building supply airstream and monitoring the tracer gas concentration build-up in the space and the exhaust, the so-called "step-up" approach. In the "decay" technique one starts with a uniform tracer gas concentration in the space, and then monitors the decay in tracer gas concentration within the space and the exhaust or return air.

If the air within a space is perfectly mixed, then the local age of air τ_i will be the same throughout the space and equal to the inverse of the air change rate, i.e., τ_n. The value of $\langle\tau\rangle$ will also equal τ_n. The local air change effectiveness ε_i at all locations within the space and the mean air change effectiveness η for the space will equal one. In the idealized case of pure piston flow through the space, τ_i will be minimized near the supply and maximized near the exhaust. The mean age of air for the space $\langle\tau\rangle$ will be exactly equal to $\tau_n/2$, and therefore η will equal 2, its maximum possible value. The local air change effectiveness ε_i will be above one near the supply and below one near the exhaust. If there is non-uniform air distribution within a space, those locations with poor ventilation air distribution will have local ages of air that are higher than the space average. Locations in the so-called "stagnant" regions will have values of τ_i that are relatively large and values of ε_i significantly less than one, a generally undesirable situation. With significant stagnation in a space, the value of η for the space will be below one.

The measurement of local age of air and air change effectiveness using tracer gas techniques is straightforward in laboratory test rooms, and a significant amount of work has been done to advance the understanding of ventilation system performance (Sandberg, 1983; Seppänen, 1986; Fisk et al., 1991a). However, the application of these techniques in the field is more complicated, and research is currently under way to investigate the applicability of these approaches in the field (Fisk et al., 1991b; Persily and Dols, 1991).

There are several issues that complicate tracer gas measurements of age of air in the field. One issue is whether the test involves tracer gas injection and concentration monitoring in an entire building or in a specific zone within a building. Testing a single zone in a building is complicated because the decay (or build-up) in tracer gas concentration within a zone is affected by both outdoor air ventilation and interzone airflow. There is no way to separately account for the effects of outdoor airflow and interzone airflow on the test results. Therefore, single zone tests are not generally reliable, unless the zone is isolated from the rest of the building, and this isolation can be demonstrated. A measurement involving tracer gas injection into an entire building, even if the concentration measurements are primarily in a single zone, avoids interzone airflow problems. In a whole building test, one cannot separate the outdoor airflow into a zone due to the ventilation system from the outdoor air provided via other spaces, but the test results do account for all of the outdoor airflow.

In the build-up technique, only the outdoor air entering the building through the air handlers is tagged with tracer gas, and therefore the age of air measurements only account for air that has entered through the air handlers. The decay technique accounts for outdoor air brought in by the air handlers and outdoor air entering due to envelope infiltration. There is a practical difficulty with the build-up technique in buildings with multiple air handlers. To apply the build-up technique, tracer gas must be injected into all the air handlers so that the equilibrium tracer gas concentration in all the supply ducts is the same. It is very difficult to select the tracer gas injection rates for all the air handlers so that all of the supply air concentrations are the same at the end of the build-up period. In the build-up technique, the tracer gas injection rates cannot be adjusted during the build-up. Depending on the number of air handlers, and the manner in which they are operated, it may be impossible to employ the build-up technique in some buildings.

The tracer gas decay procedure for measuring the age of air requires initial conditions of a uniform tracer gas concentration throughout the building. Achieving these initial conditions can be quite difficult in the field, given the complexity of office building layouts, ventilation system configurations, and system operation schedules. One strategy for achieving a uniform concentration in a building is to inject tracer gas at a constant rate into each air intake until equilibrium conditions have been attained. In general, many hours are required to reach equilibrium, during which the tracer gas injection rates into the air handlers will probably need to be adjusted. This process can be quite involved and time consuming, and it may not be possible to obtain a sufficiently uniform tracer gas concentration in some buildings. It is not yet clear how uniform the concentrations within the building must be in order to obtain reliable results. Additional field testing is required to develop strategies for achieving the desired initial conditions and to determine the degree of concentration uniformity that is required.

Another issue affecting field measurements is the fact that the operation of the ventilation system changes in response to weather, interior loads, and the time of day. Beside impacting the ability to achieve a uniform tracer gas concentration in the building, these changes in outdoor air intake rates and supply airflow rates may also affect the test results. The effects of system modulation on the test results are not predictable, given the limited amount of field experience. Sometimes the HVAC control system can be adjusted to keep the outdoor air intake percentage or flow rate constant during the test. However, such an adjustment may cause the system to operate in ways that were never intended, leading to test results of questionable validity.

When measuring the local age of air at a particular location, the results are influenced by both the air mixing within the space and the uniformity of the distribution of supply air to that space. As pointed out by Fisk et al. (1991a), comparing the value of τ_i to the nominal time constant of the building τ_n, as in the definition of the local air change effectiveness ε_i in Equation (1), does not enable one to distinguish between the effects of mixing and distribution. In order to assess the within-space mixing, Fisk proposes comparing the value of τ_i to the age of air measured at the return vent(s) serving the space. The values of the age of air at return vents and within other return airstreams can also be used to assess the uniformity of ventilation air distribution within the building. In fact, age of air measurements in return ducts may prove to be a more practical and useful approach to ventilation assessment than the determination of air change effectiveness.

Even with these questions regarding age of air measurements in the field, this approach to assessing ventilation effectiveness holds a great deal of promise. Before this approach is generally applicable in the field, additional tests are needed to develop experience with its use and to assess its feasibility over a range of buildings and ventilation system types. Conducting these tests will enable the development of estimates of the experimental errors, including the repeatability of the test results.

A study by Persily and Dols (1991) provides some indication of the repeatability of the test results. In this study, the local age of air was measured at a single location eight times during one week and three times at twenty-two additional locations in a building with a fixed rate of outdoor air intake. The standard deviation of the local age of air measured eight times at the single location was about 5% of the mean value. For the twenty-two locations tested three times each, the standard deviation of the age of air ranged from 2% to 11% of the mean, with an average value of 8%. Additional demonstrations in the field will improve the ability to determine measurement errors and to deal with the realities of complex building and ventilation system configurations and operating schedules as they impact issues of tracer gas injection, achieving a uniform concentration within the building and air sampling.

Application

The measurements in both buildings employed an automated tracer gas measurement system. This microcomputer-based measuring system has been used previously to make continuous measurements of building air change rates, using sulfur hexafluoride (SF_6) as the tracer gas. The 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 5%. Networks of air sample and tracer gas injection tubing were installed in each building for use in conjunction with the automated systems for these and other tests. These tubing networks enable the automated injection of tracer gas into the air handlers and air sampling throughout the building, with air sample locations in the air handlers and in the occupied space. These installations are described in Persily et al. (1991) and Grot et al. (1989) for the Overland and Portland buildings respectively.

In tracer gas measurements of air change effectiveness, the manner and locations in which the tracer gas is injected into the building and the locations at which it is sampled necessarily depend on the layout of the building and its ventilation systems. The tests described in this paper employed the tracer gas decay technique, in which one establishes initial conditions of a uniform tracer gas concentration throughout the building and then monitors the decay in tracer gas concentration at each measurement location. The specific injection strategies employed in each building are described in the sections that follow, but the basic procedure is to inject tracer gas at a constant rate until a uniform concentration is achieved throughout the building. Depending on the air change rate of the building, it takes several hours for the indoor tracer gas concentration to reach equilibrium. When equilibrium has been achieved the tracer gas concentration will be uniform throughout the building, regardless of the air distribution and mixing patterns within the building. Any concentration differences at equilibrium will be due to differing amounts of infiltration airflow into different zones. Based on a mass balance analysis of the constant injection of tracer gas, it will take three time constants τ_n to reach 95% of the equilibrium concentration and four time constants to reach 98% of equilibrium, assuming the outdoor airflow rate into the building Q is constant. τ_n, the nominal time constant of the building, is equal to the inverse of the air change rate Q/V where V is the building volume. For example, at an air change rate of 1 ach it will take three hours to reach 95% of equilibrium and four hours to reach 98%. At 0.5 ach, it will take six and eight hours to reach 95% and 98% respectively.

An alternative to using a constant injection of tracer gas to reach equilibrium is to employ an initial injection of tracer gas at an elevated level and then to reduce the injection rate to a level that will provide the desired equilibrium concentration. When injecting tracer gas into a building at a constant rate q, the build-up in concentration is given by the following equation:

$$C(t) = C_{eq}(1 - e^{-t/\tau_n}) \tag{3}$$

If the tracer gas injection rate q is constant, then the equilibrium tracer gas concentration is given by

$$C_{eq} = \frac{q}{Q}. \tag{4}$$

If instead tracer gas is injected at a rate k·q, where k is a constant greater than one, then the concentration in the building will build up more quickly. After some appropriate time T, the injection rate is reduced to the original target level of q. Employing appropriate values of the injection adjustment k and the injection reduction time T can greatly reduce the time required to achieve an equilibrium concentration. The use of this alternative approach in the field is complicated by the fact that an accurate value of Q, and therefore C_{eq}, is not available before a test. Therefore, optimal combinations of k and T that will minimize the time required to reach C_{eq} cannot be accurately determined beforehand. However, an initially elevated injection rate can still be used to decrease the time to reach equilibrium. After the injection rate is reduced, some time will still be required for the tracer gas concentration to equilibrate. Based on repeated applications of this injection procedure in a given building, improved estimates of k and T can be used in subsequent tests.

In general, the tracer gas injection locations are based on the layout of the building and its ventilation systems, with tracer gas injection into each air handling system generally required. In the tests of these two buildings, tracer gas concentrations were automatically monitored at selected locations within the building during the injections to provide feedback on the concentration response within the building. The locations at which the concentration is monitored depends on the layout of the building and its ventilation systems and on the tracer gas injection locations. When injecting into more than one location, some adjustment of the injection flow rates is required so that all portions of the building attain the same equilibrium concentration. These adjustments, and the subsequent stabilization of concentration, cause the time required to reach a uniform concentration in the building to be even longer than a specific multiple of τ_n. Depending on the building, it may take eight hours or more to reach a uniform concentration, and the degree of uniformity achievable in a given building may be limited. In this study, the uniformity target for the tracer gas injection was that the measured concentrations in all the return air sample locations be within 10% of their mean value for one hour.

Once a uniform tracer gas concentration is attained in the building, the injection is stopped and air sampling for tracer gas concentration analysis is conducted at selected points in the building and its ventilation systems. Based on the measured concentrations during the tracer gas decay, the age of air at a given location is determined from the following equation:

$$\tau_i = \frac{1}{C_{i,0}} \int_0^\infty C_i(t)\,dt \qquad (5)$$

where $C_i(t)$ is the tracer gas concentration at time t and $C_{i,0}$ is the concentration at $t=0$, the time at which the tracer gas injection is stopped. In these tests, the integral in Equation (5) was evaluated based on numerical integration of the concentrations measured at 10 minute intervals using the automated tracer gas monitoring system.

The nominal time constant τ_n for the building was determined based on the equilibrium tracer gas concentration and the tracer gas injection rate, as given by the following formula:

$$\tau_n = \frac{C_{eq}\,V}{q} \qquad (6)$$

where C_{eq} is the building average of the equilibrium tracer gas concentration, V is the building volume and q is the tracer gas injection rate. The equilibrium concentration was determined by averaging the tracer gas concentrations in the building returns after equilibrium conditions had been established. The average was calculated from the return concentrations measured over one hour. In the calculations of τ_n, the conditioned building volume was used without any correction for the volume displaced by walls, furnishings and other building elements. The use of such a gross building volume introduces a positive bias into the calculations of τ_n that may be on the order of 10%. Additional research is needed to provide a more reliable means of determining actual building volumes for use in these calculations.

Overland Building

The decentralized ventilation system layout of the Overland building divides the building into 15 zones, the east and west sides of the seven floors plus the atrium. Each of these zones has its own air handling system. In order to achieve a uniform tracer gas concentration in the building, SF_6 was injected into each air handler at a constant rate. Control system setpoints were adjusted to maintain a constant outdoor air intake percentage during the tests, but these percentages still changed during some of the tests. In those cases when the outdoor air intake rate changed, either the test was cancelled for the day or the test was extended to allow the establishment of a new equilibrium concentration. During the injection, the tracer gas concentrations in each of the 15 zones' return airstreams were monitored every 10 minutes with the automated system. After about two time constants the injection rates were adjusted to compensate for nonuniformities in the tracer gas concentration among the returns. In some cases, additional adjustments in the injection rates were required. The goal of the injection procedure was that these 15 return air concentrations be within 10% of their mean value for at least one hour. In most of the tests, the establishment of these conditions required at least 8 hours. In many of the tests the injection was started the previous evening, and during the following morning the tracer gas injection rates were adjusted to meet the uniformity criteria.

Once the tracer gas concentration was uniform, the tracer gas injection was stopped and the decay in concentration over time was monitored at selected locations in the building. Five tests were conducted in the Overland building. In tests A and B, the decay was monitored in the same 15 return airstreams that were monitored during the injection. In the others tests, the age of air measurements focused on locations within the occupied space on either the west (Tests C and E) or east sides of the building (Test D). In tests C through E, the age of air was measured in the return airstreams on the designated side of the building and in selected locations in the occupied space at a height of about 1.5 m (5 ft) above the floor. Both the return and the occupied space locations were sampled using the automated system, with the concentration measured every 10 minutes at each location. For tests C through E, the air was sampled in the 15 returns during the tracer gas injection. After equilibrium had been attained, the sample locations were changed to the return and space locations on one side of the building. The equilibrium tracer gas concentrations were then monitored at each of the new sample locations for about one hour before the injection was stopped.

Portland Building

The ventilation system layout of the Portland building divides the building into three zones: center, east and west. Each of these zones consists of all seven floors within that portion of the building, and a separate air handling system serves each of the three zones. Control system setpoints were adjusted to maintain a constant outdoor air intake percentage during the tests. In order to achieve a uniform concentration within the building, tracer gas was injected into the three main air handlers at an elevated level for about one-half hour. After this initial injection period, the tracer gas injection rate was reduced to a level estimated to induce the desired equilibrium concentration. In some cases, further adjustments in the injection rates were required after the injection rate reduction. During the injection, the tracer gas concentrations in each of the three return airstreams (center, east and west) and about 15 locations within the occupied space were monitored every 10 minutes with the automated system. The goal of the injection procedure was to maintain the tracer gas concentrations in the three main returns within 10% of their mean value for at least one hour. The establishment of these conditions required about six hours.

Once the tracer gas concentration was uniform, the tracer gas injection was stopped and the decay in concentration over time was monitored at selected locations in the building. Four tests were conducted in the Portland building. In all of the tests, the decay was monitored in the return airstreams of the three main air handlers and in selected locations within the occupied space.

Results

Overland Building

The results of the measurements in Overland are presented in Tables 1 through 5 for Tests A through E. During these tests, the outdoor air intake damper controls were adjusted so that the outdoor air intake percentage for each air handler was fixed during the test. During Test A, the outdoor air intake percentage ranged from 0 to 50% for the individual air handlers. In Tests B through D, the percentage ranged from 0 to 10% among the air handlers, and in Test E all of the air handlers were operating with no outdoor air intake.

Tables 1 and 2 present the results for Tests A and B, in which the age of air was measured in the building's fifteen return airstreams. In these tables the first column contains the location of the measurement, the second column contains the initial tracer gas concentration $C_{i,0}$ at each location, and the third column contains the age of air in the return airstream, designated as τ_r. The fourth column contains the air change effectiveness in the return airstream, defined here as the nominal time constant τ_n divided by τ_r. The mean and standard deviation of $C_{i,0}$ and the value of τ_n are presented at the bottom of the tables.

As mentioned earlier, these measurements require initial conditions of a uniform tracer gas concentration throughout the building. As seen in Tables 1 and 2, the value of $C_{i,0}$ varies among the fifteen airstreams. The standard deviation of $C_{i,0}$ in the first test is 10% of the mean value and 19% in the second test. In the tests in this building, it was difficult to adjust the injection rates so that the tracer gas concentration on Level B2 was the same as the value throughout the rest of the building. This difficulty is evident in Test B, where the initial concentration on the east side of Level B2 is about one-half of the concentration in the rest of the building and the initial concentration on the west side is about 30% above the building mean. Neglecting the B2 returns, the standard deviation of $C_{i,0}$ is 9% of the mean in Test A and 10% of the mean in Test B. Based on the air handling system layout in this building, it was necessary to control and adjust 15 tracer gas injection rates in order to achieve a uniform tracer gas concentration throughout the building. This injection procedure made it extremely difficult to achieve a uniform concentration. Based on the measurements in the 15 return airstreams shown in Tables 1 and 2, the equilibrium concentrations in about two-

Table 1 Results of Overland Test A

Location	$C_{i,0}$ (ppb)	Age of air (hours) Return, τ_r	Air change effectiveness τ_n/τ_r
5th floor, west return	117	1.82	0.63
4th floor, west return	101	0.52	2.19
3rd floor, west return	105	0.87	1.31
2nd floor, west return	112	2.49	0.46
1st floor, west return	94	1.56	0.73
B1 floor, west return	105	0.90	1.27
B2 floor, west return	78	0.82	1.39
5th floor, east return	97	1.87	0.61
4th floor, east return	106	0.74	1.54
3rd floor, east return	101	0.79	1.44
2nd floor, east return	95	0.85	1.34
1st floor, east return	88	0.94	1.21
B1 floor, east return	93	0.84	1.36
B2 floor, east return	93	1.28	0.89
Atrium	115	1.44	0.79

τ_n = 1.14 hours
$C_{i,0}$: Mean = 100 ppb, Standard deviation = 10 ppb
τ_r: Mean = 1.18 hours, Standard deviation = 0.55 hours

Table 2 Results of Overland Test B

Location	$C_{i,0}$ (ppb)	Age of air (hours) Return, τ_r	Air change effectiveness τ_n/τ_r
5th floor, west return	58	2.03	0.95
4th floor, west return	60	2.92	0.66
3rd floor, west return	62	2.26	0.85
2nd floor, west return	72	3.57	0.54
1st floor, west return	70	2.70	0.71
B1 floor, west return	69	2.38	0.81
B2 floor, west return	92	2.66	0.72
5th floor, east return	67	1.73	1.10
4th floor, east return	62	1.92	1.00
3rd floor, east return	66	1.49	1.29
2nd floor, east return	83	2.30	0.83
1st floor, east return	78	1.54	1.25
B1 floor, east return	71	2.37	0.81
B2 floor, east return	33	1.77	1.08
Atrium	75	2.32	0.83

τ_n = 1.92 hours
$C_{i,0}$: Mean = 68 ppb, Standard deviation = 13 ppb
τ_r: Mean = 2.26 hours, Standard deviation = 0.56 hours

thirds of the return airstreams were within 10% of the mean value for the building. While additional study is required to determine if 10% is an appropriate limit for concentration uniformity, it is encouraging that this degree of uniformity was achievable under such difficult circumstances.

Examining the values of the local age of air in the returns τ_r in Tables 1 and 2, there is significant variation among the return airstreams. This variation reflects zonal differences in the outdoor air intake rate of the air handling systems, in the envelope infiltration rates, and in the extent of ventilation air mixing within the space. Based on the results of Tests C and D in the building (discussed later), ventilation air mixing does not appear to impact the values of τ_r. Therefore, the variation in τ_r between the zones is due to differences in the outdoor airflow rate into the zones. Some of the differences in air intake may be intentional, while some of the variation may be due to improperly functioning airflow rate controls. The value of the air change effectiveness in the last column is a measure of the amount of outdoor airflow into each zone as compared to the building average. Return airstreams with a value of the air change effectiveness less than one have an age of air that is above the building average, i.e., an outdoor airflow that is below the building average. For Test A the average value of τ_r is equal to 1.18 hours, which is very close to the value of τ_n, 1.14 hours. For Test B, the average value of τ_r is 2.26 hours and the value of τ_n is 1.92 hours. The standard deviation of the values of τ_r for the two tests are 0.55 and 0.56 hours respectively. If there was significant short-circuiting of the occupied space by the ventilation air, then τ_n would be less than τ_r, with the magnitude of the difference depending on the extent of the short-circuiting. The fact that the air change effectiveness in the occupied space is close to one, as discussed below for Tests C and D, does not support this explanation of the difference observed in Test B. The reason for the difference between τ_n and τ_r in Test B is not clear, but measurement error probably accounts for some of the difference.

Tests A and B were conducted to demonstrate procedures used to measure τ_r, as these values are needed as reference values when measuring the age of air within the occupied space of the building. Due to the measured variations in the outdoor airflow rates to the fifteen building zones, it is inappropriate to compare the age of air at a location within the occupied space to the nominal time constant of the building τ_n. In order to assess mixing of the ventilation air within the occupied space, these local ages of air should be compared to the age of air in the return airstream of the zone in which the local age is measured. The values of τ_r are also of interest for their value in characterizing differences in the outdoor airflow to the different zones of the building.

Tables 3 through 5 present the results of the age of air measurements in the occupied space in the Overland building. The first column contains the location of the measurement, with the first seven rows containing the results for the return airstreams on one side of the building. The lower group of rows contains the measurement locations within the occupied space, described by the building floor and the column number. These column numbers refer to floor plans contained in Persily et al. (1991). The second column of these tables contains the initial tracer gas concentration $C_{i,0}$ at each location. The next two columns contain the age of air at the measurement locations, with values obtained in the return airstreams designated as τ_r and values obtained in the

Table 3 Results of Overland Test C

Location	$C_{i,0}$ (ppb)	Age of air (hours)		Air change effectiveness	
		Return τ_r	Space τ_i	Return τ_n/τ_r	Space τ_r/τ_i
5th floor, west return	60	2.01	--	0.92	--
4th floor, west return	60	2.48	--	0.74	--
3rd floor, west return	57	2.11	--	0.87	--
2nd floor, west return	62	3.61	--	0.51	--
1st floor, west return	57	2.77	--	0.66	--
B1 floor, west return	74	2.24	--	0.82	--
B2 floor, west return	73	2.75	--	0.67	--
5th floor, column W20	92*	--	1.46	--	1.38
5th floor, column W15	95*	--	1.34	--	1.50
4th floor, column W20	19*	--	3.53	--	0.70
4th floor, column W15	69	--	2.05	--	1.21
3rd floor, column W15	81*	--	1.54	--	1.37
3rd floor, column U22	58	--	2.13	--	0.99
2nd floor, column W15	70	--	3.35	--	1.08
2nd floor, column U22	62	--	3.76	--	0.96
1st floor, column M22	62	--	2.77	--	1.00
B1 floor, column Q18	74	--	2.36	--	0.95

* Value of $C_{i,0}$ is more than 20% different from mean value of equilibrium concentration.
τ_n = 1.84 hours
Equilibrium concentration in returns = 62 ppb
τ_r/τ_i: All data: Mean = 1.11 hours, Standard deviation = 0.25 hours
Neglecting * data: Mean = 1.03 hours, Standard deviation = 0.10 hours

occupied space designated as τ_i. The last two columns contain the air change effectiveness. For the return airstreams, the air change effectiveness is defined as it was in Tables 1 and 2. For the occupied space locations, the air change effectiveness is defined as the age of air in the corresponding return airstream τ_r divided by τ_i. The mean value of the equilibrium concentration in the fifteen building returns, the value of τ_n and other summary statistics are given at the bottom of the tables.

The degree of uniformity of $C_{i,0}$ among the returns for Tests C through E is similar to that obtained in Tests A and B. However, the values of $C_{i,0}$ at the occupied space locations exhibit much more variation. As described earlier, the tracer gas concentrations at the occupied space locations were not monitored until the return airstream concentrations had equilibrated. When the air sample locations were changed to the occupied space locations, concentration nonuniformities were sometimes revealed, but no additional adjustments were made in the tracer gas injection rates to the various zones. Locations with values of $C_{i,0}$ that are marked with the symbol * are outside the range of +/- 20% of the mean value of the equilibrium concentration in the ventilation system return ducts.

For the occupied space locations, most of the values of the air change effectiveness are within 10% of 1.0. As discussed earlier, the air change effectiveness equals 1.0 at all locations in the building under conditions of perfect mixing of the ventilation air. Given the limited amount of field testing that has been performed to date, it is not yet possible to reliably estimate measurement errors and to state how large a deviation from 1.0 is significant. Based on existing experience, measurement errors are estimated to be at least 10% (Fisk et al., 1991a; Persily and Dols, 1991). The average values of the air change effectiveness in the occupied space for Tests C, D and E are 1.11, 1.19 and 1.03 respectively. The standard deviations of the values for these three tests are 0.25, 0.17 and 0.13. For Test C, eliminating the measurements for which $C_{i,0}$ was more than 20% from the building average brought the mean value closer to 1.0, i.e., 1.03, and reduced the standard deviation to 0.10. For the other two tests, eliminating these measurements had a less pronounced effect. More importantly, the fact that the values of air change effectiveness are close to 1.0 is consistent with good mixing of the ventilation air within the occupied space. If the age of air within the occupied space had been referenced to the nominal time constant of the building rather than the age of air in the return, the air change effectiveness values would have covered a much wider range and may have been misinterpreted. When local age of air is compared with the

Table 4 Results of Overland Test D

Location	$C_{i,0}$ (ppb)	Age of air (hours)		Air change effectiveness	
		Return τ_r	Space τ_i	Return τ_n/τ_r	Space τ_r/τ_i
5th floor, east return	41	2.01	--	0.88	--
4th floor, east return	48	2.07	--	0.86	--
3rd floor, east return	45	1.87	--	0.95	--
2nd floor, east return	67	2.48	--	0.71	--
1st floor, east return	57	1.69	--	1.05	--
B1 floor, east return	71	2.73	--	0.65	--
B2 floor, east return	71	2.84	--	0.62	--
5th floor, column G15	57	--	1.49	--	1.35
5th floor, column R7	51	--	1.67	--	1.20
4th floor, column G15	49*	--	1.79	--	1.16
4th floor, column R7	15*	--	1.64	--	1.26
3rd floor, column G15	64	--	1.30	--	1.44
3rd floor, column J7	45*	--	1.99	--	0.94
2nd floor, column G15	79*	--	2.40	--	1.03
2nd floor, column J7	66	--	2.36	--	1.05
1st floor, column J7	57	--	1.24	--	1.36
B1 floor, column L15	74	--	2.57	--	1.06

* Value of $C_{i,0}$ is more than 20% different from mean value of equilibrium concentration.

τ_n = 1.77 hours

Equilibrium concentration in returns = 62 ppb

τ_r/τ_i: All data: Mean = 1.19 hours, Standard deviation = 0.17 hours

Neglecting * data: Mean = 1.24 hours, Standard deviation = 0.17 hours

nominal time constant, the resultant air change effectiveness combines the effect of nonuniform outdoor air distribution to the different zones of the building and the effects of mixing within the space. While both effects are of interest, one needs to look at them separately in order to evaluate and understand the ventilation system performance in terms of air distribution.

Portland Building

Tables 6 through 9 present the results of the age of air measurements in the Portland building for Tests A through D. During these tests, the outdoor air intake damper controls were modified so that the intake percentage for each air handler was constant. In Tests A and B, the air handlers were operating at minimum outdoor air intake, about 10%. In Tests C and D, the outdoor air intake percentage was about 30%.

The first column contains the location of the measurement, with the results presented in three groups based on the three zones in the building. Return fans #6, #7 and #8 correspond to the center, east and west portions of the building respectively. The occupied space locations in each group are in the zones served by the designated return fan. These return fans serve all seven floors of the building. The column numbers used in identifying the measurement locations refer to floor plans contained in Grot et al. (1989). The second column of these tables contains the initial tracer gas concentration $C_{i,0}$ at each location. The next two columns contain the age of air at the measurement locations, with values obtained in the return airstreams designated as τ_r and values obtained in the occupied space designated as τ_i. The last two columns contain the air change effectiveness. For the return airstreams, the air change effectiveness is defined as the nominal time constant of the building τ_n divided by age of air in the corresponding return airstream τ_r. For the occupied space locations, the air change effectiveness is defined as the age of air in the corresponding return airstream τ_r divided by τ_i. The mean value of the equilibrium concentration in the three building returns, the value of τ_n and other summary statistics are given at the bottom of the tables.

Because the Portland building has three central air handlers that serve all seven floors of the building, and because the center, east and west zones communicate freely on the floors, it was much easier to achieve a uniform tracer gas concentration in this building than in the Overland building. Locations with values of $C_{i,0}$ that are marked with the symbol * are outside the range of +/- 20% of the mean value of the equilibrium concentration in the building returns. One such location exists in each of the last three tests in Portland, as opposed to three or four in each of the Overland tests.

Table 5 Results of Overland Test E

Location	$C_{i,0}$ (ppb)	Age of air (hours)		Air change effectiveness	
		Return τ_r	Space τ_i	Return τ_n/τ_r	Space τ_r/τ_i
5th floor, west return	88	4.07	--	0.81	--
4th floor, west return	89	4.29	--	0.77	--
3rd floor, west return	87	4.01	--	0.82	--
2nd floor, west return	92	4.65	--	0.71	--
1st floor, west return	108	3.52	--	0.93	--
B1 floor, west return	81	4.01	--	0.82	--
B2 floor, west return	77	4.00	--	0.82	--
5th floor, column W20	84	--	4.73	--	0.86
5th floor, column W15	81	--	4.02	--	1.01
4th floor, column W20	89	--	4.03	--	1.06
4th floor, column W15	86	--	4.20	--	1.02
3rd floor, column W15	115*	--	3.68	--	1.09
2nd floor, column W15	86	--	4.74	--	0.98
1st floor, column M22	104*	--	3.85	--	0.91
1st floor, guard desk	29*	--	2.67	--	1.32
B1 floor, column W17	84	--	3.80	--	1.05

* Value of $C_{i,0}$ is more than 20% different from mean value of equilibrium concentration.
τ_n = 3.29 hours
Equilibrium concentration in returns = 84 ppb
τ_r/τ_i: All data: Mean = 1.03 hours, Standard deviation = 0.13 hours
Neglecting * data: Mean = 1.00 hours, Standard deviation = 0.07 hours

For the occupied space locations, the values of the air change effectiveness are all within 15% of 1.0. The average values for Tests A, B, C, and D are 0.93, 1.03, 1.00 and 1.05 respectively. The standard deviations of the values for these four tests are 0.10, 0.10, 0.14 and 0.11. Neglecting the measurements for which $C_{i,0}$ was more than 20% from the building average reduces the standard deviations for the last three tests to 0.06, 0.11 and 0.10. The fact that the values of air change effectiveness are close to 1.0 is consistent with good mixing of the ventilation air within the occupied space.

The fact that the air change effectiveness values for the occupied space locations were based on the age of air in the return air as opposed to the nominal time constant of the building raises two important issues. First, the nominal time constant τ_n was less than the average age of air in the return airstreams by 9%, 15%, 16% and 4% in tests A, B, C and D respectively. A similar difference was noted in the Overland building tests. If there was significant short-circuiting of the occupied space by the ventilation, then a difference would be expected, with its magnitude dependent on the extent of the short-circuiting. The fact that the air change effectiveness in the occupied space is close to one does not support this explanation. The reason for the difference between τ_n and τ_r is not clear, but uncertainty in the value of the building volume used to calculate τ_n may be one source in the Portland building.

As discussed earlier, there is some uncertainty in the building volume due to the volume displaced by walls, interior furnishings and other building elements. However, if the gross conditioned volume was decreased to account for the displaced volume, then τ_n would have been even smaller that the mean of τ_r. A potential explanation for the difference between τ_n and τ_r in Portland is that the large penthouse, with a volume of about 26,000 m^3 (910,000 ft^3), may exchange a significant amount of air with the occupied portion of the building. If air flows up to the penthouse and some of that air returns to the building, then a portion of the penthouse volume should be included in the total building volume used to calculate τ_n. A larger value of the building volume would increase the value of τ_n, lessening the systematic difference between τ_n and τ_r.

Another issue in this building is that although we are using τ_r for the appropriate zone to calculate the air change effectiveness in the occupied space, this value is based on a return duct that serves all seven floors of the building. Differences between the floors in the amount of outdoor air delivered by the ventilation system or in the levels of infiltration are not accounted for in using this value of τ_r. The lack of a value of τ_r for each individual floor may account for some of the variability in air change effectiveness among the occupied space locations.

Table 6 Results of Portland Test A

Location	$C_{i,0}$ (ppb)	Age of air (hours) Return τ_r	Space τ_i	Air change effectiveness Return τ_n/τ_r	Space τ_r/τ_i
Return fan #6	102	2.12	--	0.95	--
7th floor, column Q14	111	--	2.40	--	0.88
6th floor, column Q14	103	--	2.45	--	0.87
5th floor, column Q14	106	--	2.37	--	0.89
4th floor, column Q14	104	--	2.30	--	0.92
3rd floor, column Q14	101	--	2.44	--	0.87
2nd floor, column Q14	97	--	2.48	--	0.85
1st floor, column Q14	100	--	2.77	--	0.77
Return fan #7	105	2.23	--	0.90	--
7th floor, column M22	106	--	2.52	--	0.88
5th floor, column M22	106	--	2.20	--	1.01
3rd floor, column M22	106	--	2.35	--	0.95
Return fan #8	106	2.29	--	0.88	--
7th floor, column V4	115	--	2.25	--	1.02
5th floor, column V4	98	--	2.08	--	1.10
3rd floor, column V4	108	--	2.09	--	1.10

τ_n = 2.01 hours

Equilibrium concentration in returns = 104 ppb

τ_r/τ_i: All data: Mean = 0.93 hours, Standard deviation = 0.10 hours

Summary and Discussion

The measurements of air change effectiveness in the Overland and Portland buildings serve as a field demonstration of age of air measurement procedures. They have provided additional experience with the measurement procedures and additional building performance data. Several important issues were addressed that need to be understood in order to develop a standardized measurement procedure.

In using the tracer gas decay technique, the ability to achieve a uniform tracer gas concentration is critical. In these tests, the equilibrium tracer gas concentration was generally within 10% of the mean value throughout the building, though some larger differences did occur. Attaining uniformity required up to eight hours or more and involved adjusting the HVAC system controls to keep the outdoor air intake rate as constant as possible. Unexpected modulations in the outdoor air intake rate or inabilities to attain equilibrium for other reasons caused some tests to be aborted. The impacts of modifying the HVAC controls on the test results are not known. In a given building, the system operation characteristics under which reliable measurements can be conducted may be severely limited. An alternative injection strategy to achieve equilibrium in a shorter period of time was employed in the Portland building. This approach of using an elevated injection rate for a short period of time, followed by a reduction in the injection rate to a level consistent with the target equilibrium concentration, did reduce the time to achieve acceptable equilibrium. However, the air handler layout and zoning in the Overland building was too complex to employ this injection procedure, and presumably this would be the case in other buildings. It is anticipated that buildings will be encountered in which the ability to achieve a uniform tracer gas concentration will be severely limited.

The issue of what value should serve as a reference when computing air change effectiveness from the age of air in the occupied space has been addressed before (Fisk et al., 1991a). The use of the nominal time constant of the building τ_n is inappropriate because its use combines the effects of nonuniform outdoor air delivery throughout the building with the effects of nonuniform ventilation air mixing within the occupied space. It is more appropriate to use a value of the age of air in the return air for the space in question. The ventilation system layout and zoning will affect exactly where the return age of air can be measured. In the Overland building, the age

Table 7 Results of Portland Test B

Location	$C_{i,0}$ (ppb)	Age of air (hours)		Air change effectiveness	
		Return τ_r	Space τ_i	Return τ_n/τ_r	Space τ_r/τ_i
Return fan #6	79	2.13	--	0.89	--
7th floor, column Q14	73	--	2.06	--	1.03
6th floor, column Q14	78	--	2.11	--	1.01
5th floor, column Q14	67	--	2.32	--	0.92
4th floor, column Q14	79	--	2.08	--	1.02
3rd floor, column Q14	69	--	2.23	--	0.96
2nd floor, column Q14	79	--	2.10	--	1.01
1st floor, column Q14	70	--	2.24	--	0.95
Return fan #7	70	2.25	--	0.84	--
7th floor, column M22	70	--	2.25	--	1.00
5th floor, column M22	73	--	2.24	--	1.00
3rd floor, column M22	64	--	2.41	--	0.93
1st floor, column M22	80	--	2.07	--	1.09
Return fan #8	67	2.35	--	0.81	--
*7th floor, column V4	90	--	1.77	--	1.33
5th floor, column V4	77	--	2.10	--	1.12
3rd floor, column V4	70	--	2.17	--	1.08
1st floor, column V4	75	--	2.29	--	1.03

* Value of $C_{i,0}$ is more than 20% different from mean value of equilibrium concentration.
τ_n = 1.90 hours
Equilibrium concentration in returns = 72 ppb
τ_r/τ_i: All data: Mean = 1.03 hours, Standard deviation = 0.10 hours
Neglecting * data: Mean = 1.01 hours, Standard deviation = 0.06 hours