EFFECTIVE VENTILATION

9th AIVC Conference, Gent, Belgium
12-15 September, 1988

Paper 9

COMMERCIAL BUILDING VENTILATION MEASUREMENTS USING MULTIPLE TRACER GASES

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SYNOPSIS

A unique multiple tracer experimental system has been developed and utilized within commercial buildings to monitor ventilation rates, air exchange efficiency, ages of air (at multiple indoor locations), flow rates of supply and outside air, and percent outside air in supply airstreams. The multiple tracer technique also makes it possible to determine the fractions of air at a monitoring point that entered the building through a particular air handler and by infiltration. To label the incoming air, a distinct tracer gas is injected at a constant rate into each outside air or supply airstream. Cart-mounted gas chromatographs are placed in mechanical rooms and monitor tracer gas concentrations versus time in the major airstreams of the air handlers. Small "local samplers" placed at various indoor locations are utilized to monitor local ages of air. Age distribution theory is applied to determine ages of air; however, the standard methods of applying this theory are modified to process the multiple tracer data. The experimental system, methods of data analysis and the results of studies in both a twelve-story building and a complex of three interconnected two-story office buildings are presented. Rates of outside air supply per occupant were comparable to or above the minimum rate of 10 *l*/s-occupant specified in the draft revised version of the ASHRAE ventilation standard. Within regions of these buildings that are served by a single air handler that supplies a mixture of outside and recirculated indoor air, the measured ages of air varied by 30% or less from the region-average age. Monitoring at different heights above floor level provided no evidence of either a short-circuiting or displacement flow pattern within rooms. The age of air varied more substantially between physically isolated regions of a building, regions served by different air handlers, and over time. In the complex of three buildings, air exchange efficiency values were close to 0.5 suggesting relatively uniform mixing of air in regions served by a single air handler. In the other building, air was supplied and removed from physically-separated regions, and the air exchange efficiency was 0.7.

1.0 INTRODUCTION

Researchers in the U.S. have reported the results of measuring the nominal ventilation rate, i.e., outside air supply rate per unit building volume, in approximately 50 U.S. commercial buildings.[1,2] The nominal ventilation rate, and parameters that can be derived from the nominal ventilation rate, are sufficient for characterizing the rate of ventilation only in buildings where the air is thoroughly mixed. Data that indicate the extent to which air is mixed in commercial buildings are largely unavailable. Mixing may depend on building size, internal configuration, the number and type of air handlers, and numerous other factors. When the indoor air is not fully mixed, indoor air quality and building energy consumption are influenced by such factors as local ventilation rates or ages of air, the extent and direction of interzonal air flow, the pattern of air flow between locations of air supply and removal, and the associated values of air exchange efficiency. We have obtained this detailed information on ventilation as well as more traditional information on building ventilation by labeling each airstream of entering outside air with a distinct tracer gas, appropriate monitoring of tracer gas concentrations, and specific procedures of data analysis. We describe our technical approach, methods of evaluating the data, and the results from two buildings.

2.0 TECHNICAL APPROACH

2.1 Tracer Decay

A tracer gas decay is the most common method of monitoring ventilation within large buildings. Ideally, the indoor air is uniformly labeled with a tracer gas at some point in time (so that tracer concentrations are nearly identical throughout the building) and tracer gas concentrations are measured as a function of time as they decrease (decay) because of the entry of tracer-free outside air. Sandberg[3] and others have described data analysis procedures for determining nominal and local ages of air (where "local" refers to a location within the building), local ventilation rates, and air exchange efficiencies from the tracer gas data when a single tracer gas is employed. There are limitations to the information obtained from a tracer gas decay; for example, a tracer decay conducted with a single tracer gas does not provide information on interzonal air flow. In addition, in many large buildings with multiple air handling units (AHUs), obtaining satisfactory initial mixing of the tracer gas with the indoor air is very difficult[1] -- in such instances, local ages of air, local ventilation rates, and air exchange efficiencies values cannot be determined.

2.2 Multiple Tracer Step-up

This research effort is based largely on another tracer gas technique called a multiple tracer step-up. Each stream of outside air that enters the building through an AHU is labeled uniformly with a distinct tracer gas by injecting the tracer gas into this airstream at a constant rate. Tracer gas concentrations are monitored as a function of time in the major ducts of the AHUs and, if sufficient monitoring equipment is available, in other exhaust airstreams such as bathroom exhausts. Injection is continued until concentrations in the return/exhaust ducts and in other exhaust ducts are stable (i.e., no longer increasing more than five to ten percent per hour). The time-average and steady state tracer concentrations of all the tracer gases are monitored at numerous locations within the occupied space. This multiple tracer step-up technique is usually impractical in buildings with more than three or four outside air intakes because of limitations in the number of tracer gases and limited monitoring equipment.

Many AHUs do not contain an outside air duct -- instead the outside air passes through the outside air dampers and immediately into a mixing box where mixing between the outside air and recirculated indoor air occurs (see Fig. 1). In this type of AHU, a tracer gas is usually injected into the supply airstream (the mixture of outside and recirculated air). If the outside air and recirculated air mix thoroughly, this method is functionally identical to injecting tracer directly into the stream of outside air; although a slightly different method of data analyses is required.

2.3 Monitoring System

The tracer gases, sulfur hexafluoride (SF_6) and four halocarbons [bromotrifluoromethane (R-13B1), chloropentafluoromethane (R-115), dichlorodifluoromethane (R-12), and 1,2 -dichlorotetrafluoroethane (R-114)], were selected based on a consideration of toxicity, cost, and the ease of simultaneous measurements of tracer gas concentrations with a single instrument. Maximum tracer gas concentrations are approximately 200 parts per billion (ppb) for SF_6, 500 ppb for R-13B1, and 1000 ppb for the other tracers. These tracer gases may decompose, yielding toxic decomposition products, if they pass through a flame or burning tobacco, or contact a very hot surface (e.g., electric resistance heating element). Based on our recent experimental studies and calculations[4] tracer gas decomposition should not be a problem in typical commercial buildings if tracer gas concentrations are limited to the maximum values noted above and there are not unusual sources of tracer decomposition. However, we suggest further studies of this issue before these tracers are used at much higher concentrations in occupied buildings.

The major components of the monitoring system can be deployed as indicated in Fig. 1. Cart-mounted gas chromatograph systems (GCs) each with an electron capture detector, signal integrator, computer data logger, and pumps and valves for sampling from three locations are usually

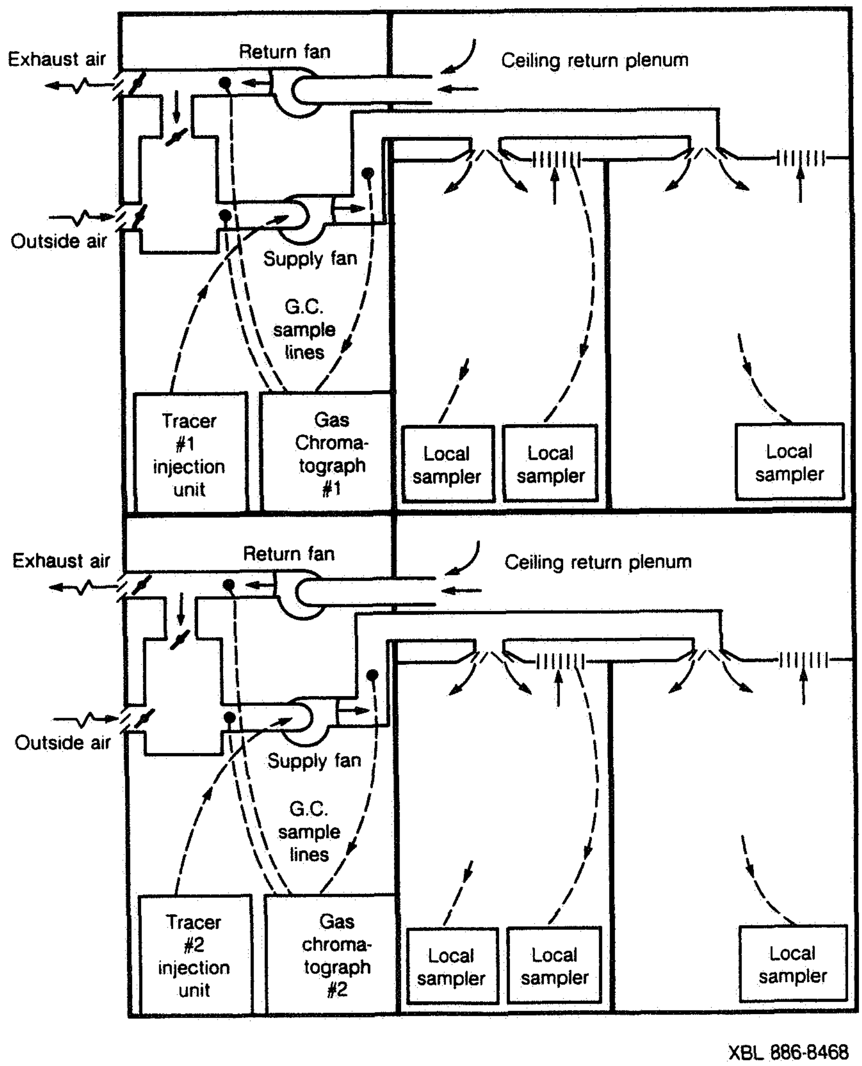

Figure 1. Schematic diagram showing major components of monitoring system and locations of tracer injection and sampling.

deployed in the mechanical rooms. A sample containing the first four tracer gases listed above is analyzed in approximately 4.5 minutes with the GC oven at a constant 35°C. To include measurements of the fifth tracer gas (R-114) requires eight minutes and a variable oven temperature. Approximately ten gas standards are used to calibrate the GCs -- these gas standards are stored in sample bags and calibration is performed at the monitoring site. The major equipment items, GC operational procedures, and verifications of the system have been described previously.[5] Samples are drawn to the GCs through copper tubing usually from the major return/exhaust ducts and from the supply ducts upstream and downstream of the points of tracer injection as illustrated in Fig. 1. If substantial air exits the building through the bathroom exhaust ducts or other exhausts, the GCs or local samplers (described below) can also sample air from these ducts. With three GC systems, we can obtain near real-time data from up to nine locations.

The tracer injection systems, also described previously,[5] consist of peristaltic pumps with variable speed drives that draw pure tracer gas from approximately 100-liter multiple layer bags. These bags of pure tracer are placed in a plastic can to prevent damage. A flow meter system, consisting of three different size rotameters (calibrated with a bubble flow meter), a valve to select the desired rotameter, and pressure gages is included between the bag of pure tracer and the peristaltic pump. Tracer injection rates can be varied over approximately two orders of magnitude. Prior to an actual test, the mixing of the tracer in the stream of outside air or supply air must be checked -- this can be accomplished by manually taking multiple point syringe samples from the supply duct. To improve mixing of the tracer with the airstream, we sometimes inject tracer at multiple points using a 3 m long tube containing ten 0.34 mm diameter holes along its length.

To characterize ventilation at specific indoor locations, local samplers are deployed throughout a building. These samplers consist of a case, a small peristaltic pump, a one to three meter long sample line, a one-liter multiple layer sample bag with a septa fitting, an elapsed time indicator, and a programmable timer. During a test, these units collect a sample of air/tracer at a constant rate; thus, the concentrations of tracer gas in the sample bag equal the time-average concentrations during the period of sampling. The final (steady state) tracer gas concentrations at the sampling location are also required as indicated in the subsequent section on data analysis. Therefore, when tracer concentrations are stable, as determined from the real-time measurements, a sample is collected in a disposable syringe at the sampling location. In general, these local samplers plus syringe samples are used to characterize ventilation at approximately the breathing level of a sitting person in various work spaces; however, they can also sample from many other locations of interest such as supply diffusers, return grills, exhaust ducts, and outside-air intake grills. Starting and stopping of the local samplers is controlled with the programmable timers. Between tests, we check sample bags for leaks, either flush out the bag with air or pump down the bags in a vacuum chamber, fill the bags with tracer-free air, and check for any residual tracer gas in the bags. The bags are evacuated prior to installation in the local samplers.

2.4 Monitoring Procedure

The details of the monitoring procedure depend on the building characteristics and the specific goals of a test. In general, the following basic procedure is employed: (1) the GCs are calibrated and real time sampling by the GC systems is initiated; (2) the injection of all tracers is started simultaneously (allowing for the time required to purge the flow meter and injection lines of air); (3) the local samplers are started when tracer injection is initiated; (4) real time data are monitored to determine when tracer concentrations are stable; (5) once concentrations are stable, the local samplers are stopped and syringe samples are collected; and (6) the bag and syringe samples are manually injected into the GCs for analysis.

The entry rates of outside air should be as stable as possible during a test; otherwise, tracer gas concentrations will not stabilize and interpretation of the data is difficult. Many air handlers contain an economizer which automatically regulates damper positions and, thus, the proportions of outside air and recirculated air in the supply airstream. Tests should be conducted during weather conditions (for example, hot weather) when the economizers are not adjusting the outside air entry rates. Another option is to reset the economizer control systems so that damper positions are fixed during the test. We usually try to conduct tests with dampers in the minimum outside air and 100% outside air positions. In addition, operable windows and doors to outside should be closed during a test, particularly when an evaluation of the mechanically-supplied ventilation is desired.

3. DATA EVALUATION

3.1 Single-tracer Step-up

Standard equations based on the application of age distribution theory[3] to air within buildings can be utilized if a building has only one AHU, the infiltration rate is small compared to the rate of mechanical ventilation, and a single tracer step-up technique is employed. For example, the local age (LA) of a sample of air at location l, where age is the amount of time elapsed since the air entered the building, can be computed using the equation -

$$LA = \int_0^\infty \left[1 - C_l(t)/C_l(\infty)\right]dt \qquad (1)$$

where t refers to time since the start of tracer injection, $C_l(t)$ is the tracer concentration at time t, and $C_l(\infty)$ is the steady-state tracer concentration. The reciprocal of the local age of air exiting the building equals the nominal ventilation rate[3], i.e., outside air entry rate per unit building volume, which is often called the air exchange rate.

With a single tracer step-up, calculations similar to those described in the next section, can be used to determine selected air flow rates, the percent of outside air in the supply airstream, and the fraction of air at a location that enters by infiltration.

3.2 Multiple Tracer Step-up

3.2.1 Nomenclature

An extensive system of nomenclature is required to describe the methods of analysis of multiple tracer data. The primary variables are as follows:

C = tracer gas concentration;

C_{eff} = effective concentration of tracer gas in stream of outside air;

LA = local age of a tracer or of air labeled by the tracer;

$\dot{M}$ = volumetric tracer injection rate;

P = percent of outside air in the supply airstream;

Q = flow rate of air;

V = volume of building or zone;

Z = fraction of air sample that entered through a particular AHU or by infiltration; and

ϵ_a = air exchange efficiency.

The primary variables may require up to three indices. For example, consider the variable *C(i,l,t)*, where:

i = a tracer or AHU code: 1 = SF_6, 2 = R-13B1, 3 = R-115, 4 = R-12, INF = infiltration, T = total, i.e., all tracers plus infiltration; i also refers to the AHU into which tracer i is injected;

l = location

- S_i = supply duct of AHU i,
- O_i = outside air "duct" of AHU i,
- R_i = return/exhaust "duct" of AHU i,
- RC_i = recirculation "duct" of AHU i,
- M_i = mixture of return and outside air in AHU i upstream of the point of tracer gas injection;
- E_i = exhaust "duct" of AHU i;
- Zone = a zone of a building; and

t = time since start of injection ($t = \infty$ when tracer concentrations have reached steady-state and $t = \bar{t}$ is the average with respect to time between $t = 0$ and $t = \infty$).

Where possible, one or more of the indices are omitted, for example, Z and LA are not a function of time and, if flow rates are stable, Q is only a function of location.

3.2.2 Standard AHU Information

Assuming that tracers are injected into the supply airstreams as illustrated in Fig. 1 and that tracer gas concentrations in the outside air are negligible, air flow rates and percent outside air can be computed with the following equations which are based on simple mass balances:

$$Q(S_i) = \dot{M}(S_i)/[C(i,S_i,\infty) - C(i,M_i,\infty)], \qquad (2)$$

$$P(S_i) = [1 - C(i,M_i,\infty)/C(i,R_i,\infty)]100\%, \quad (3)$$

$$Q(O_i) = P(S_i)Q(S_i)/100\%, \text{ and} \quad (4)$$

$$Q(RC_i) = Q(S_i)C(i,M_i,\infty)/C(i,R_i,\infty). \quad (5)$$

In some AHUs, accurate measurement of tracer gas concentrations in the mixture of outside and recirculated air is difficult because these two airstreams may not mix fully prior to passing through the supply fan. Drawing a sample from multiple locations within the mixed airstream can improve measurement accuracy.

3.2.3 Sources of Air

To calculate the fraction of a sample of air that entered the building through each air handler or by infiltration, one must first determine the effective concentration of tracer gas in each entering stream of outside air. This effective outside-air tracer concentration is the concentration that would result if the tracer was actually injected into the outside air. Assuming tracer injection as illustrated in Fig. 1, the effective outside air concentration is determined from the equation

$$C_{eff}(O_i) = \dot{M}(S_i)/Q(O_i)$$

$$= C(i,R_i,\infty)[C(i,S_i,\infty) - C(i,M_i,\infty)]/[C(i,R_i,\infty) - C(i,M_i,\infty)]. \quad (6)$$

If tracer is actually injected into the stream of outside air and the resulting tracer concentration is measured, the effective concentration simply equals the measured concentration.

The fraction $[Z(i,l)]$ of the air within an air sample (collected at location l and at time infinity) that entered the building through a particular AHU is indicated by the ratio

$$Z(i,l) = C(i,l,\infty)/C_{eff}(O_i). \quad (7)$$

If $Z(i,l)$ equals unity, all of the air at location l must have entered through AHU i. A value of $Z(i,l)$ less than unity indicates that some of the air entered through another AHU or by infiltration. The fraction of the air that entered by infiltration $Z(\mathrm{INF},l)$ is

$$Z(\mathrm{INF},l) = 1 - \sum_i Z(i,l). \quad (8)$$

The uncertainty in measured values of $Z(\mathrm{INF},l)$ can be considerable because this parameter is typically based on the difference between unity and an imperfectly known number or sum with a value close to unity. In addition, if the tracer gas concentrations at location l have not reached steady-state, despite stable exhaust and return concentrations, $Z(\mathrm{INF},l)$ will be overestimated.

3.2.4 Age of Air

The total age of air at a location should be determined by summing the products of all individual ages and the corresponding values of Z. However, we do not obtain any information on the age of air that enters by infiltration since this air is not labeled with a tracer gas. Thus, the following approximate equation is used to compute the total local age $[LA(T,l)]$

$$LA(T,l) = \sum_i \left[LA(i,l) Z(i,l) / \sum_i Z(i,l) \right]. \tag{9}$$

Implicit in Eqn. 9, is an assumption that the age of air that entered by infiltration equals the weighted (by Z) average age of air that enters through the AHUs. In most instances, this assumption should cause only small errors in the total local age of air.

When real time data are collected at location l, the local age of the air supplied by a particular AHU, $LA(i,l)$ in Eqn. 9, is determined by the integration given in Eqn. 1. When a local sampler and final syringe sample are employed, the sampler "performs" the integration and the following equation is used

$$LA(i,l) = t(\infty)[1 - C(i,l,\bar{t})/C(i,l,\infty)] \tag{10}$$

where $t(\infty)$ is the time when the sampler operation is terminated and $C(i,l,\bar{t})$ $C(i,l,\infty)$ equal the concentrations of tracer in the bag and syringe samples, respectively.

3.2.5 Local Ventilation Rate

A local ventilation rate can be defined to be the reciprocal of the local age of air. This parameter does not contain new information but may be more readily accepted since many in the ventilation field are familiar with ventilation rates and unfamiliar with ages of air. If the air within the building is thoroughly mixed, the local ventilation rate equals the nominal ventilation rate.

3.2.6 Air Exchange Efficiency

Various parameters are used to indicate the effectiveness or efficiency of ventilation based on the data obtained with tracer gases.[3,6] The air exchange efficiency[6] ϵ_a is based on a ratio of the nominal building or zone ventilation time constant $[V/Q(O)]$, i.e., the reciprocal of the nominal air exchange rate, to the spatial average age of all air within the building or zone, designated $\langle LA(T,ZONE) \rangle$, i.e.,

$$\epsilon_a = V/Q(O)/[2 < LA(T, ZONE) >]. \quad (11)$$

The nominal time constant equals the age of air exhausted from the building or zone[3], *LA(T,E)*, and the age of air within the building is estimated by averaging the age measured at a finite number of measurements; thus, the following equation is used

$$\epsilon_a = LA(T,E)/[2\overline{LA(T,ZONE)}]. \quad (12)$$

A higher age in the air that exits the building compared to the age of air in the occupied regions of the building is generally desirable since "older" air is likely to contain a higher concentration of pollutants. The factor of two in the denominators of Eqns. 11 and 12 causes the air exchange efficiency to equal 0.5 when the indoor air is perfectly mixed. The theoretical upper limit of this parameter is unity for a perfect displacement (piston-like) flow between the location of air supply and removal. The numerator of Eqn. 12 should, in theory, equal the average age of all air that exists the building. In many large buildings, air may exit via several routes such as the main AHU return/exhaust ducts, bathroom exhausts, other exhausts, and exfiltration. Monitoring in every exhaust stream may be impractical; thus, the local age of air exhausted must be estimated using the best information obtainable. The age in the denominator of Eqn. 11, i.e., the spatial average (mean) age of air within a building, can be computed using only measurements of tracer concentration in the exhausted air[3]; however, we do not use this method of calculation because, in a previous investigation,[5] measurements of this mean age were significantly less precise than measurements of local age.

4.0 MEASUREMENT ACCURACY

We have not determined the accuracy of our measurements of all the parameters described in the previous section. Measurement accuracy will depend on both the accuracy of individual measurements and the validity of the assumptions that underlie the data analysis (for example, the assumptions of a stable outside air flow rate and that outside air and recirculated air mix fully). A few comments can be provided on measurement accuracy. In a previous study (and we have improved GC calibration procedures since this study), data from the different tracer gases yielded the same local age of air within 10%. When the tracers were used in a well mixed chamber with a known (physically-measured) ventilation rate, the maximum deviation between the known and tracer-gas-based ventilation rates was 12%. Finally, different local samplers deployed at the same location generally yield the same local age within approximately 5%.

5.0 RESULTS FROM TWO BUILDINGS

5.1 Building A

Building A is an office building with twelve stories plus a basement and 213 office workers. This building is owned by a county within California and was constructed in 1962. The total floor area, excluding the basement, a large first-floor meeting room, and exterior stairwells, is approximately 4450 m^2 with each floor approximately 34 m long and 13 m wide. Windows cannot be opened by the occupants. The layout of the major AHUs is shown in Fig. 2. One main AHU, designated AHU2, serves floors 1 through

6 and 8 through 12 and supplies air at a constant rate to the building perimeter through perimeter induction units. At the induction units, the air supplied by AHU2 to a particular floor mixes (by entrainment) with indoor air from the same floor and passes through heating/cooling coils. The mixture of outside and indoor air is discharged vertically upward through perimeter supply grills located approximately 1 m above floor level. Other AHUs, that operate intermittently, supply air to a basement-level interview room and a large first-floor meeting room. Each of these AHUs draws air from the same outside-air duct. The air that passes through the supply fans of these air handlers is intended to be 100% outside air; however, some indoor air may be drawn into these supply fans due to reverse-direction flow through the other non-operating supply fans and the associated supply and return duct work. An independent AHU (not shown on Fig. 2) serves the seventh floor which is occupied at all times. In addition, there is a small AHU located in the ceiling plenum at the north end of each floor (also not shown of Fig. 2). Some of the ceiling-plenum AHUs only recirculate and condition the indoor air via ceiling mounted supply diffusers in the office areas and a ceiling mounted return grill at the north end of the floor (see Fig. 3). Other ceiling-plenum AHUs have a small outside air intake. The only mechanical exhaust from the building (except for an exhaust on Floor 7) is via a roof-top exhaust fan that draws air from bathrooms and custodial rooms located at the north end of the building.

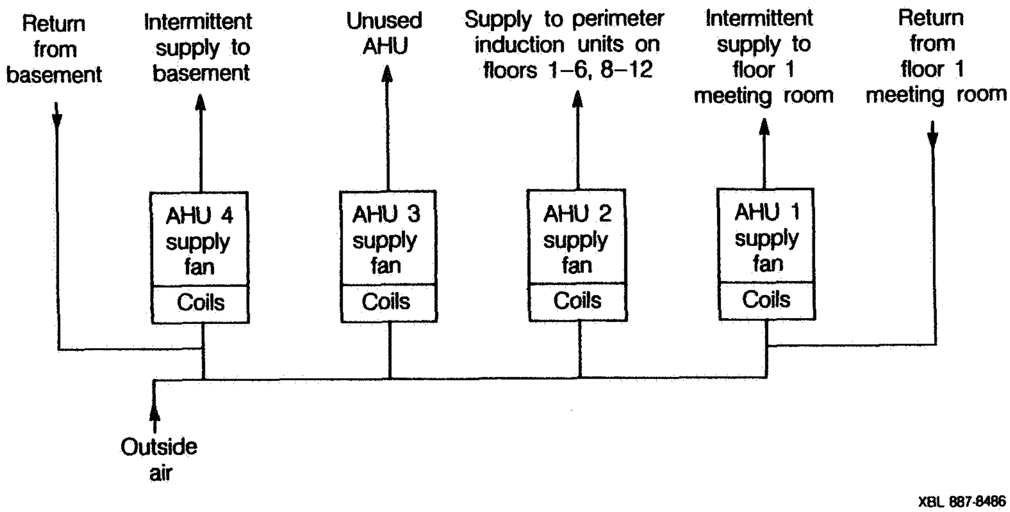

Figure 2. Layout of air handling units in Buidling A.

To study ventilation, a single tracer gas was injected at a constant rate into the entering outside airstream, just upstream of the supply fan of AHU2. Tracer concentrations were measured as a function of time in the supply airstream of AHU2, the outlet of the roof-top exhaust fan, and at three indoor locations. Local samplers were deployed at 14 indoor locations.

In a preliminary test, we determined that more than 25% of the air on several floors served by AHU2 entered the building either via infiltration or the small outside-air intakes of the ceiling plenum AHUs. The age of the air supplied by AHU2 was measured at a central location on five floors and varied from 1.0 to 1.9 h. The flow rate of air through AHU2 ranged between 6.1 and 6.9 m^3/s on the three days of monitoring with an average flow rate of 6.4 m^3/s. A flow rate of 6.9 m^3/s is provided in the building specifications. Dividing the average measured flow rate by the internal volume on the eleven floors directly served by AHU2 (1360 m^3 per floor) yields a supply flow rate per unit volume of $1.5h^{-1}$. Dividing by the total building volume, since all areas received some air from AHU2 either directly or via internal air flow, yields a supply flow rate per unit volume of $1.2h^{-1}$. These supply flow rates per unit volume may be significantly greater than the nominal air exchange rate because the air supplied by AHU2 was not entirely outside air (see the previous comment on reverse-direction air flow).

Following the preliminary test, we conducted detailed (multi-point) investigations of ventilation at the fifth and sixth floor where greater than 80% of the air was supplied by AHU2. Fig. 3 shows a floor plan of the fifth floor on which the measured fractions of air supplied by AHU2 and the measured ages of air are indicated. On this floor, there are only two isolated rooms -- a private office and a computer room -- the remainder of the floor space is subdivided by approximately 1.5-m high fabric-covered dividers. The data from the 12 measurement locations in the office area, which include data from three different heights above floor level, are remarkably uniform. The percent of air supplied by AHU2 ranges from 89% to 91% and the age of this air ranges from 1.1 h to 1.3 h. The age at three different heights above floor level is identical within measurement accuracy. The 0.8-h age of air that exits a perimeter supply register, which compares to an age of zero in incoming outside air and an average age of 1.2 h indoors, indicates that this supply air is approximately 35% outdoor air and 65% recirculated indoor air. A bathroom, custodial room, and elevator lobby are located at the north end of the floor and are physically isolated from the office area (where air is supplied) by walls and closed doors. Air flows into this north end region through a grill and then into the bathroom and custodial room exhaust grills and the return grill of the ceiling plenum AHU. The ages of air (supplied by AHU2) at the bathroom exhaust grill and the return grill of the ceiling-plenum AHU are 1.6 h and 1.5 h, respectively, which is significantly greater than the 1.2-h average age in the office space. One might expect a similar high age of air in the elevator lobby; however, the measured age is 1.2 h. The air exchange efficiency, based on the ages of air in the office region and the age at the bathroom exhaust grill, is 0.7. This high air exchange efficiency, greater than the 0.5 value that occurs with perfect mixing of indoor air, is probably due to the substantial physical isolation of the fifth floor exhaust grills from the office area where air is supplied.

The outside air flow rate to the fifth floor can be estimated by multiplying the indoor volume, after subtracting 15% for furnishings, with the reciprocal of the local age of air measured at the bathroom exhaust grill. The result is an outside air supply rate of 0.20 m^3/s. With 21 occupants on the fifth floor, the estimated outside air supply per occupant is 9.5 *l*/s-occupant. For comparison, the current ASHRAE Ventilation Standard 62[7], entitled "Ventilation for Acceptable Indoor Air Quality," specifies a minimum outside air supply of 2.5 *l*/s-occupant in office areas where smoking is prohibited and 10 *l*/s-occupant in office areas with smoking. The draft revised version[8] of this standard specifies a minimum of 10 *l*/s-occupant for all office areas.

Fig. 4 shows a floor plan of the sixth floor with the percents of air supplied by AHU2 and the ages of this air indicated on the figure. Unlike the fifth floor, the perimeter region of the sixth floor is subdivided into private offices; however, the data from the office area on this floor (i.e., excluding the elevator lobby, bathroom, and north end hallway) are still relatively uniform. The age of air varies from 0.9 h to 1.4 h with an average age of 1.1 h. There appears to be a trend toward higher ages at the north-end of this office area but the data are not conclusive. As on the fifth floor, the ages of air at the bathroom exhaust grill (1.6 h) and the return grill of the ceiling plenum AHU (1.5 h) are significantly higher than the average age in the office space (1.1 h). The 1.2 h age of air across the hall from the bathroom exhaust grill (actually the grill through the bathroom door) is low compared to the nearby measured ages and we are unable to provide a satisfactory explanation. The air exchange efficiency of 0.7 is the same as on the fifth floor. Again, this high air exchange efficiency is probably due to the substantial physical isolation of the exhaust grills from the office area.

The rate of outside air supply to the sixth floor and the outside air flow per occupant were estimated in the manner described previously -- the results are 0.20 m^3/s and 9.5 l/s-occupant.

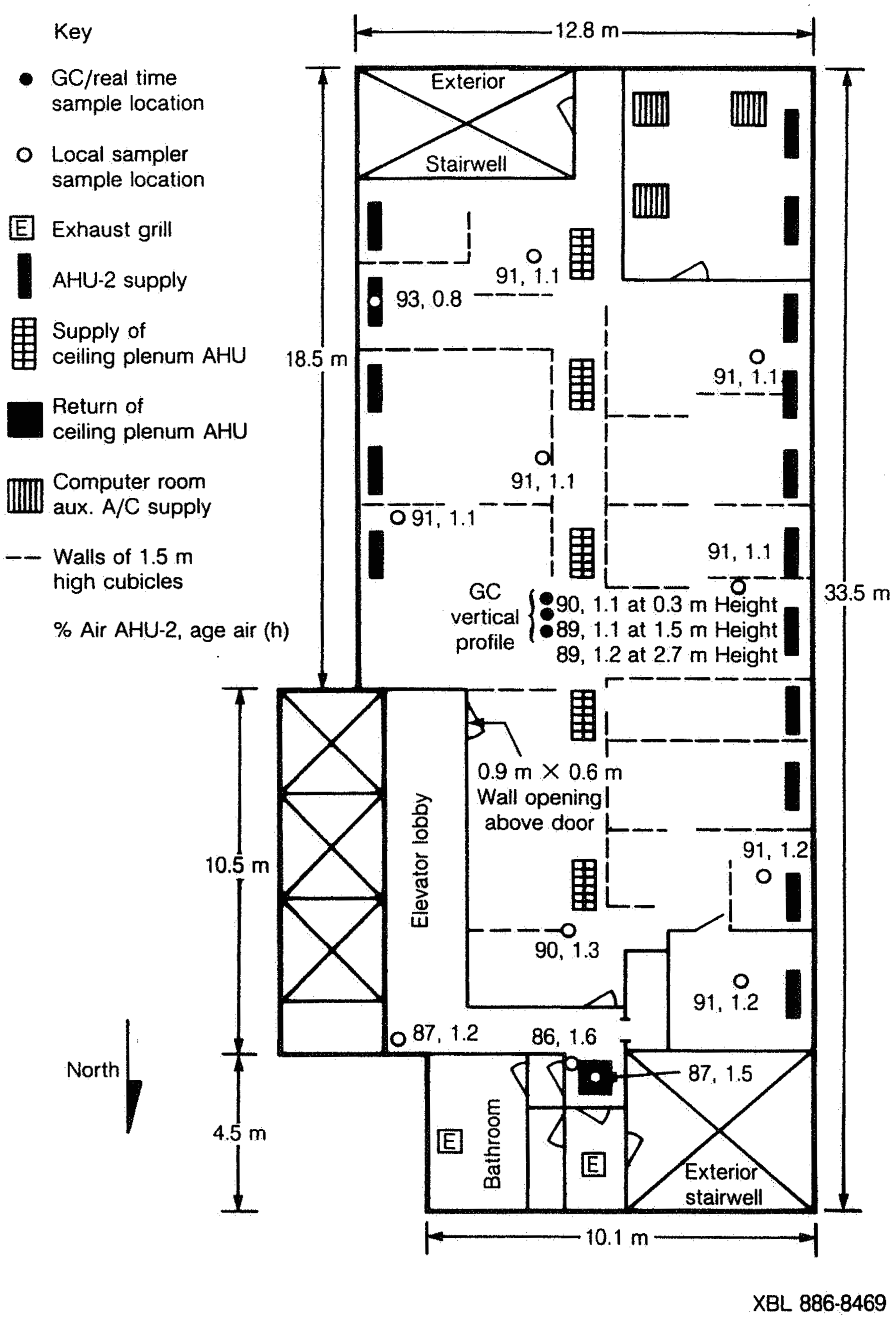

Figure 3. Plan view of fifth floor of Building A showing the fractions and ages of air supplied by AHU2.

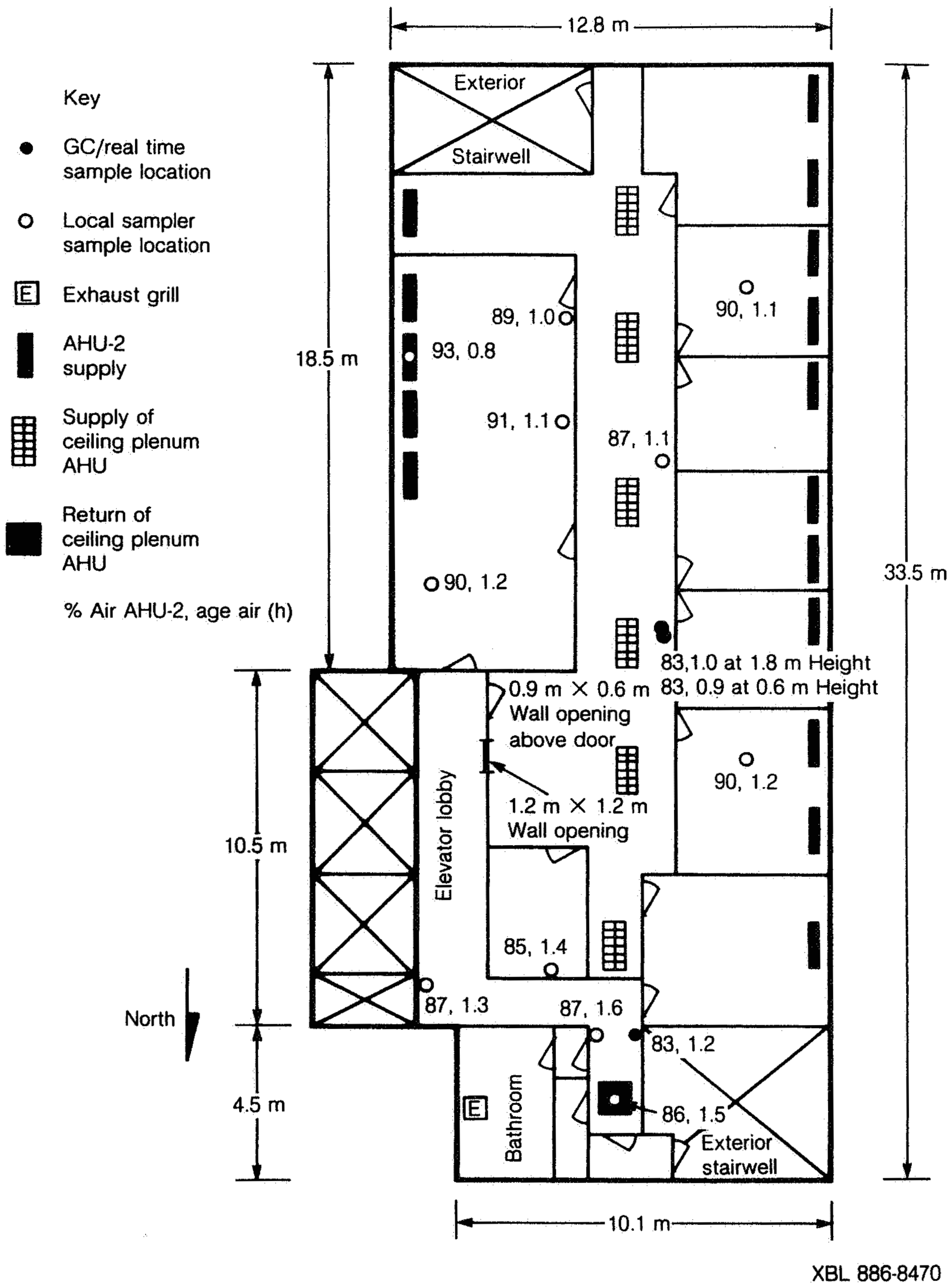

Figure 4. Plan view of sixth floor of Building A showing the fractions and ages of air supplied by AHU2.

5.2 Building B

Building B is actually a complex of three interconnected, privately-owned, two-story office buildings located in Palo Alto, California and constructed in 1977. The three buildings within this complex, designated Buildings 2, 3, and 4 or B2, B3, and B4, have unopenable windows, 284 total occupants, and floor areas of 2140, 2280, and 2420 m^2, respectively. Open hallways connect the second floor of B2 with the first floor of B3 and the second floor of B3 with the first floor of B4. Each building is highly subdivided into one-to-three person private offices -- there are few open areas or cubicles. One variable air volume (VAV) AHU serves B2 and B3 and a different VAV AHU serves B4. The AHUs have the general configuration shown in Fig. 1. Air is supplied through circular ceiling-mounted diffusers and returned through return grills in the suspended ceiling (the return air passes through the plenum above the suspended ceiling). Virtually every office has both a supply diffuser and return grill. Each AHU has a simple economizer system so that either a minimum amount or 100% outside air is supplied to the building depending on the outdoor temperature. Separate exhaust fans draw air at a constant rate from the bathrooms and one print room and exhaust this air to outside.

Ventilation was studied on three days during a period of hot weather when the economizer systems set the dampers so that a minimum amount of outdoor air was drawn into the buildings (i.e., recirculation of indoor air was maximized). A different tracer was injected upstream of each supply fan and tracer concentrations were monitored as a function of time at the locations indicated schematically in Fig. 1. Local samplers were deployed at 13 indoor locations including perimeter offices, interior offices, and the hallway that connects B3 and B4.

Table 1 provides the measured (at mid-afternoon) flow rates of the supply and outside airstreams, the same flow rates normalized by building volumes, the percents of outside air in the supply airstreams (% OA), and the outside air flow rates per occupant for the complex of three buildings. The measured supply flow rates on August 3 are within 6% of the flow rates given in the specifications for the AHUs. On the other days, supply flow rates were lower, possible due to milder weather. The % OA varies between 17% and 31%. In the B4 AHU, the % OA is relatively constant; thus, the total supply of outside air to B4 appears to decrease (and increase) with the supply air flow rate. The previously described ASHRAE ventilation standards do not specify a minimum % OA but instead a minimum flow rate of outside air per occupant. The measured outside air entry rates per occupant in the Building B complex of 16 to 19 *l*/s-occupant are substantially above the rates specified in the current and draft revised version of ASHRAE Standard 62. However, the occupant density is low, approximately four occupants per 100 m^2 floor area, compared to the 7.5 occupant per 100 m^2 floor area value listed in the ASHRAE standard for design purposes if actual occupancy cannot be predicted.

Approximately 75% of the air in B2 and B3 entered (from outside) through the AHU that serves these buildings, 5 to 10% of the air entered through the B4 AHU, and 15 to 25% of the air entered by infiltration. Approximately, 90% to 95% of the air in B4 was supplied by the B4 AHU with the remaining air entering via infiltration and through the B2 and B3 AHU. Thus, the flow rates of air between B4 and adjoining B3 were small compared to the rates of outside air entry.

Due to the low rate of interzonal air flow, considering B4 as one zone and B2 and B3 (denoted B2/B3) as another zone, each zone contained only a single tracer gas at sufficiently high concentrations for accurate calculations of age of air. Therefore, the ages of air in B2/B3 are based only on the tracer gas injected into the B2/B3 AHU and the ages of air in B4 are based only on the tracer gas injected into the B4 AHU. (Very similar, but possibly less accurate, ages of air result if concentrations of both tracer gases are used to compute each age.) Within each zone, the measured local ages of air vary by 25% or less from the average local age. However, we monitored at only thirteen indoor locations and probably did not determine maximum and minimum ages of air. The highest measured age of air is in the hallway that connects B3 and B4. On August 7, the age of air was monitored at both the breathing level and ceiling-level return grill of Room

3-217 -- the identical ages measured indicate that the air within the room was probably well mixed. The relatively uniform ages and sources of air within each zone may be due, in part, to the high fractions of recirculated air in the supply airstreams (all three tests were conducted with minimum outside air and maximum recirculation) and to the large number of supply and return grills.

Information on the source and age of air and the local ventilation rates at each measurement location is provided in Table 2. We first consider the sources of air.

Table 1. Percent outside air and supply and outside air flow rates in Building B -- a complex of three interconnected buildings. One variable-air-volume (VAV) AHU serves Buildings 2 & 3 and a different VAV AHU serves Building 4. AHU dampers were automatically adjusted to bring a minimum amount of outside air into the buildings.

Date	8/3/87	8/5/87	8/7/87
Building 2 & 3 AHU*			
% outside air (%)	17	29	31
Supply air flow (m^3/s)	19.3	12.2	9.9
Supply air flow per unit building volume (h^{-1})	5.7	3.6	2.9
Outside air flow (m^3/s)	3.3	3.5	3.1
Outside air flow per unit building volume (h^{-1})	1.0	1.0	0.9
Building 4 AHU*			
% outside air (%)	22	24	24
Supply air flow (m^3/s)	9.3	5.9	6.0
Supply air flow per unit building volume (h^{-1})	5.0	3.2	3.2
Outside air flow (m^3/s)	2.0	1.4	1.4
Outside air flow per unit building volume (h^{-1})	1.1	0.8	0.8
Building 2 & 3 & 4 AHUs*			
Outside air flow per occupant (*l*/s-occ.)+	19	17	16

* with these variable-air-volume AHUs, supply air flow rates and, to a lesser extent, outside air flow rates varied over time; the results in this table are based on data collected between 14:30 h and 15:15 h

\+ based on number of employees (261) and visitors per day (23) during July, 1987

Ages of air varied more substantially between the two "zones" which are served by different air handlers. On August 3 and 5, ages of air in B4 were approximately 40% higher than ages of air in B2/B3. In B2/B3, the age of air also varied substantially between days, possibly due to large variations in the amount of air supplied by the VAV control units.

Table 2. Source and age of air in Building B -- a complex of three interconnected buildings served by two variable air volume air handling units. On all three days of monitoring, August 3, 5, and 7, 1987, AHU dampers were automatically set to bring a minimum amount of outside air into the buildings.

Location Bldg-Room	% Air From Bldg. 2 & 3 AHU (%)			% Air From Bldg. 4 AHU (%)			% Air From Infiltration (%)			Total Age of Air (h)			Local Vent Rate (h^{-1})		
	8/3	8/5	8/7	8/3	8/5	8/7	8/3	8/5	8/7	8/3	8/5	8/7	8/3	8/5	8/7
2-255	78	77	72	8	4	4	14	19	24	1.0	1.3	1.6	1.0	0.8	0.6
2-102A	76	75	73	8	4	3	16	21	24	1.0	1.3	1.6	1.0	0.8	0.6
2-118	77	78	76	8	4	4	15	18	20	0.9	1.2	1.9	1.1	0.8	0.5
2-221	76	72	73	8	5	4	16	23	23	0.8	0.9	1.4	1.2	1.1	0.7
3-217	73	71	71	10	6	4	17	23	25	0.8	0.9	1.5	1.2	1.1	0.7
3-217 RG*	--	--	71	--	--	4	--	--	25	--	--	1.5	1.0	--	0.7
3-132	78	79	--	9	5	--	13	16	--	1.0	1.2	--	--	0.8	--
3-234	70	68	67	14	8	6	16	24	27	1.1	1.2	1.7	0.9	0.8	0.6
3-107	78	78	74	8	5	4	14	17	22	1.0	1.5	1.5	1.0	0.7	0.7
2 & 3 Avg.+	76	75	72	9	5	4	15	20	24	1.0	1.2	1.6	1.0	0.8	0.6
2 & 3 AHU RD$	72	80	69	9	6	5	19	14	26	1.1	1.2	1.5	0.9	0.8	0.7
4-221	2	5	2	96	91	88	2	4	10	1.4	1.6	1.7	0.7	0.6	0.6
4-244	2	5	2	96	90	88	2	5	10	1.5	1.7	1.6	0.7	0.6	0.6
4-107	3	5	2	96	90	89	1	5	9	1.3	1.6	1.7	0.8	0.6	0.6
4-151	3	6	2	96	88	86	1	6	12	1.5	1.8	1.8	0.7	0.6	0.6
4-123B	--	5	2	--	89	88	--	6	10	--	1.5	1.7	--	0.7	0.6
4-Avg.+	2	5	2	96	90	88	2	5	10	1.4	1.7	1.7	0.7	0.6	0.6
4-AHU RD$	4	5	2	95	89	89	1	6	9	1.3	1.7	1.7	0.7	0.6	0.6
3 & 4 Hall	3	6	11	95	86	74	2	8	15	1.5	2.4	2.6	0.7	0.4	0.4

* RG = return grill
+ average of results measured with local samplers located within building
$ RD = main AHU return/exhaust duct, ages are based on integration of tracer concentration versus time

The ages of air in the return/exhaust ducts were always within 10% of the corresponding average local age within the zones, yielding air exchange efficiency values identical (within estimated measurement accuracy) to the 0.5 value that occurs with complete mixing of the indoor air.

5.0 CONCLUSIONS

A unique multiple tracer monitoring system, together with some new methods of data analysis, have proven useful for detailed studies of ventilation within commercial buildings. Traditional information, such as flow rates of air in the air handling units can be obtained as well as information on the sources and ages of air at multiple indoor locations, the amounts of infiltration and interzonal air flow, and the air exchange efficiency. The results of investigations in two buildings are presented. Rates of outside air supply per occupant were comparable to or above the minimum rates specified in ASHRAE Standard 62. Within regions of these buildings that are served by a single air handler that supplies a mixture of outdoor and recirculated indoor air, the measured ages and sources of air varied by 30% or less from the region-average values. Monitoring at different heights above floor level provided no evidence of either short circuiting or displacement flow patterns within a room; however, the air supplied to these rooms was always a mixture of outdoor and recirculated air. Age of air varied more substantially between physically-isolated regions of a building (e.g., different floors with no mechanical recirculation between the floors) and between regions served by different air handlers. In one complex of buildings, air exchange efficiency values were close to 0.5, suggesting relatively uniform mixing of the indoor air in regions served by a single air handler. In another building, air was supplied and removed from physically-isolated regions, and the air exchange efficiency was 0.7. Monitoring (currently underway) in additional buildings is required before general conclusions can be drawn regarding these aspects of ventilation in commercial buildings.

6.0 ACKNOWLEDGMENTS

Dr. Jehuda Binenboym, Hossein Kaboli, Brian Weber, and Al Robb contributed to the development and evaluation of the multiple tracer measurement system.

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Systems, Building Systems Division of the U.S. Department of Energy under contract No. DE-AC03-76SF00098.

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Discussion

Paper 9

M. Holmes (Arup Research and Development, London, UK) It is interesting that your building A (induction system) is typical of the type that can give rise to sick buildings in the UK - was this the reason for the study? Could you also give an idea of how long it takes to set up and carry out a test on a building of this type?

W.J. Fisk (Lawrence Berkeley Laboratory, USA) The building was chosen because it was available and because it has a ventilation system which is not common in the US. In building B, which is more complex than building A, approximately one man-week was required to set up instrumentation and perform some preliminary checks. A single test requires about 7 - 11 hours of effort by two people, however data collection occurs for only about 3 - 4 nominal time constants. Another couple of man-days are required to remove equipment.

M. Sherman (Lawrence Berkeley Laboratory, USA) (a) Your data seemed to suggest that the variation of ventilation rate over time is small. Is this correct? (b) If ventilation rates are reasonably constant is it possible to make the same type of measurements with single tracer gas equipment by making repeated tests in different configurations?

W.J. Fisk (Lawrence Berkeley Laboratory, USA) (a) Except for indicating the ventilation rates on different days, I did not provide data on ventilation rate as a function of time. In building A the mechanical system does not regulate the rate of supply of outside air, and in building B the systems were continually supplying a minimum amount of outside air because of the hot weather. It is possible that some variations did occur however, but they were not investigated. In the general case ventilation rates may vary substantially with time due to operation of economiser systems. (b) I would not recommend repeated use of a single tracer gas in different configurations because: (i) the time required to conduct such tests would be excessive (ii) ventilation rates or air flow patterns might vary between the different single-tracer tests and cause the investigations to draw incorrect conclusions.

R. Anderson (Solar Energy Research Institute, USA) Your measurements in building A suggest that the flow is locally well mixed, with an overall plug flow pattern between supply and exhaust which results in a high air exchange efficiency. In your opinion will this system provide better air quality than building B which has local exhausts and a lower value of air exchange efficiency?

W.J. Fisk (Lawrence Berkeley Laboratory, USA) In building A the age of air in the office areas on a floor where occupants spend the greatest amount of time is lower than it would be if the air on the entire floor was perfectly mixed. Thus the flow patterns in building A should improve the air quality in the office area. However measurements of ventilation rates and airflow patterns do not directly indicate air quality, hence I have no way of comparing the air quality in the two buildings.