DETERMINING DELIVERED QUANTITIES OF OUTSIDE AIR: CO_2 TRACER GAS, OR BOTH?

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INTRODUCTION

As part of an indoor air quality investigation protocol, a major focus is frequently a determination of the quantities of outside air (OA) actually being delivered to the occupants of a building. This quantity of OA being delivered to the occupants is a function of both the quantity of OA taken in at the OA dampers and the effectiveness of the HVAC system in delivering this air to the people. In this paper, *the ratio of the air quantity entering the OA dampers and the outside air quantity delivered to the occupants is referred to as the ventilation efficiency (others have suggested this be called ventilation performance).* Often, it is desirable to know this ventilation efficiency in order to determine if improvements in the delivery efficiency are warranted. Measurement of both the delivered quantities of outside air and the efficiency of the ventilation system is especially important in light of various protocols for design options, which are contained in proposed ASHRAE Standard 62-1981R, "Ventilation for Acceptable Indoor Air Quality."

The two principal tools currently utilized for evaluating the quantity of outdoor air (OA) delivered to the occupants of a building are the measurement of carbon dioxide (CO_2) concentrations and the measurement of tracer decay rates using sulfur hexafluoride. These two methods have also been utilized by the authors and other researchers to assess the efficiency of outside air delivery. Each of these techniques has its own set of advantages and disadvantages, but the performance of the two together tends to cancel out some of the weaknesses of each. Therefore, whenever possible, the authors have performed both procedures side by side to maximize the precision and the accuracy of the results. This paper discusses some of the issues raised by the results that have been obtained and presents suggestions for minimizing errors in the interpretation of the test results.

INFORMATION THAT CAN BE DERIVED FROM CARBON DIOXIDE TESTING

CFM Outside Air Per Person

A ventilation rate determination using CO_2 measurements compares the indoor concentrations with outdoor concentrations and assumes that the increase in indoor values is due to the buildup of CO_2 expired due to respiration by the building occupants. This relationship is detailed in Appendix D of ASHRAE Standard 62-1981 (ASHRAE 1981). An advantage of this technique is that relatively few measurements, obtained during the typical peak late-morning or mid-afternoon occupancy period, can provide a determination of the quantity of ventilation air being provided at the time of measurement. The results express the ventilation rate in terms of cubic feet per minute of outdoor air per person (cfm of OA per person), which is then directly comparable with the recommended minimum OA quantities published in ASHRAE Standards 62-1981 and 1981R (ASHRAE 1981, 1986), which are currently being adopted or considered by states such as Maine and New Jersey (State of Maine 1988; State of New Jersey 1988).

Ventilation Efficiency (Performance)

Although the determination of cfm of OA delivered per person is very useful, it is not sufficient for the scope of many evaluations. For instance, in order to compare the quantity of OA delivered with the quantity of OA that is measured to be entering the OA intake of the HVAC system, the delivered quantities need to be expressed in terms of just cfm of OA. The cfm of OA at the air intake is often determined by flow measurements, while the delivered quantity is the product of the CO_2-derived cfm/person value and the total number of people present at the time of the test measurements. Thus, in actual testing situations, it is necessary to know exactly how many people are present in the space at the time of the CO_2 measurements to convert the results from cfm/person values to cfm values. For small buildings with populations up to 30 or so people, this rarely presents a problem, but for large buildings with 300 people or so, the ability to count the number of people is much more difficult. Techniques for estimating this population are, of course, possible. As part of building surveys, we have measured not only CO_2 concentrations, but potential number of people per office and actual number of people per office. Then, assuming that the 20% of the "random" offices surveyed are typical of the rest of the building, we can estimate the total building population. This then yields the OA quantity in terms of cfm.

CFM Outside Air Per Square Foot

Dividing cfm of OA value by the area involved yields another important evaluation criterion, cfm of OA per ft^2. Corporate and lease ventilation standards are often expressed in terms of minimum quantities of cfm of OA per ft^2. This contrasts with ventilation standards, which have assumed human beings to be the principal or exclusive polluters in offices and similar spaces. This type of cfm/ft^2 approach has recently been presented as an important criterion by Fanger (1988).

For typical office environments (as defined by ASHRAE 62-1981R), with seven people per 1000 ft^2 area, the proposed ASHRAE minimum ventilation rate value of 20 cfm of OA per person is equivalent to 0.14 cfm of OA per ft^2 of office space. This outdoor air delivery rate can be contrasted with total air delivery rates for ventilation and air conditioning, which are typically around 1.0 to 1.2 cfm per ft^2 of office space.

Building Volume Air Changes Per Hour of Outside Air

In addition to expressing the ventilation rate in terms of cfm of OA per person or per ft^2, the ventilation rate can also be expressed as the number of air changes per hour (ach). In the authors' opinion, it is this expression of the ventilation rate that most accurately represents the rate at which air contaminants generated within the building envelope are diluted and removed from the space. This is also the format for the results from tracer decay ventilation testing.

For the ASHRAE-defined typical office, with 20 cfm/person, seven people per 1000 ft^2 and total ceiling heights of about 10 ft, the outdoor air ventilation rate would be 1.0 ach. Factored into this calculation is the empirical result, from the authors' experiences with tracer gas studies, that the net effective volume can be estimated as being 85% of the gross volume of the space.

POSSIBLE INTERPRETATION DISCREPANCY (CO_2 MEASUREMENTS)

These distinctions in expressing ventilation rates in units of cfm OA/person, cfm OA/ft², and ach OA become especially important in *atypical* office-type spaces, which are often found in a variety of office building types. For example, in one evaluation of a complaint building, with total ceiling heights of 18 ft, utilizing the CO_2 approach, data were collected which yielded a peak average indoor concentration of 713 ppm with 425 ppm outdoor conditions, yielding a ventilation rate of 36.5 cfm of OA per person. For the measured population estimate of 300 people, this represented 10,950 cfm of OA. Tracer gas testing conducted at the same time yielded a value of 0.65 ach. When this ach was applied to the area of 60,000 ft² and an estimated effective volume of 972,000 ft³, it yielded 10,530 cfm of OA. Both of these values (in cfm) are very similar and can be expressed as 0.18 cfm of OA per ft². The question remains, however, as to which criterion is the one to use in recommending a ventilation rate sufficient to prevent complaints of inadequate ventilation. In this situation, it is the ventilation rate expressed in terms of ach that is most directly concerned with the rate at which air contaminants such as environmental tobacco smoke (ETS) or other internally generated pollutants are diluted and removed from this space by OA.

The determination of the most appropriate ventilation goal and the criteria of meeting that goal, i.e., cfm/person, cfm/ft², or ach, can have a profound effect on the age of the air within the building, resulting air quality in the space, and the amount of outside air needed to provide acceptable air quality. Further research is needed related to the most appropriate evaluation criteria for the delivery of outside air to the breathing zone, or occupied zone, and the appropriate terminology for specifying the ventilation rate.

CARBON DIOXIDE MEASUREMENT AS A DIAGNOSTIC TOOL

Limitations of Carbon Dioxide Testing Alone

Measurements of CO_2 concentrations at different indoor locations can point out localized variations in ventilation rates throughout a building. Measurements comparing the concentrations in the supply ductwork and the return ductwork as well as the occupied spaces can characterize the ratio of outdoor air to recirculated air leaving the HVAC equipment. Measurements obtained in the early morning can document the persistence of air contaminants from the evening before where the building occupancy extends beyond the operation of the ventilation system. Early morning measurements can also assess the impact of air contaminants from parking garages.

The measurement of CO_2 concentrations has also been used by the authors to detect the presence of inadequately vented combustion appliances, i.e., a poorly vented gas-fired hot water heater affecting a university classroom building. The interference of CO_2 from sources other than the occupants, such as the unaccounted-for presence of the products of combustion, can lead to very erroneous ventilation rates. This was reported in the case of an investigation of a warehouse/showroom that was heated with direct-fired gas heaters.

Therefore, in order to trust the results from a CO_2 analysis, one must be certain that there are no products of combustion entering the building or mechanical systems. A potentially limiting aspect of the CO_2 approach is the precision of the sampling technique used. CO_2 detector tubes have a relative standard deviation of 10% and detectors based on CO_2 absorbance in the infrared band typically display their results to only the nearest 50 ppm. A display reading of 850 ppm could therefore actually be 826 ppm or 874 ppm. Taking into consideration the combined uncertainties of detector results and the number of people present in the building typically leads to cfm of OA results being stated as a range of values with expected upper and lower bounds.

Another disadvantage of this approach is the requirement for a sufficient density of people, within a small enough volume, in order to obtain a measurable increase in indoor concentrations as compared with outdoor concentrations. The extreme example of this is when we have been called upon to evaluate a building that has been evacuated and is devoid of the products of human respiration. This situation then requires the use of tracer testing for a ventilation rate evaluation.

VENTILATION INFORMATION THAT CAN BE DERIVED FROM TRACER TESTING

Building Volume Air Changes Per Hour of Outside Air

As already mentioned, the tracer decay testing approach yields its results in terms of ach. This approach is based on measuring the rate of decrease of a tracer, such as sulfur hexafluoride, that has been uniformly dispersed throughout the space under investigation. If the space under investigation is behaving as a single, well-mixed chamber, the measurements will yield a straight line on a semi-log plot (ASTM 1983). The slope of this plotted line is equivalent to the ventilation rate and can be expressed in terms of ach. Calculations are based on the relative changes in tracer concentration and do not require an absolute calibration of the analysis equipment. (See Figures 1 and 2 for typical tracer plots.) As with the CO_2 assessment approach, the quantity of OA often needs to be expressed in terms of just cfm of OA in order to evaluate the performance of the HVAC system. To convert tracer-determined ventilation rates (expressed in terms of ach) to cfm values, it is necessary to multiply the ach values by the volume into which the tracer has been disbursed. This tracer mixing volume, or effective volume, will be somewhat less than the gross physical volume of the structure due to the presence of furnishings, equipment, and stagnant zones either in corners of the occupied space or due to a large return air plenum above a suspended ceiling. This volume can be determined from procedures that require a very precise determination of the rate of tracer release and the absolute quantity of the tracer measured (ASHRAE 1985). In the authors' experience, typical conventionally designed office spaces are in fact well mixed, with typically 85% of the air being recirculated during the air-conditioning or heating mode. The assumption of a clearly defined single zone, however, varies from case to case. The potential uncertainty as to the volume for the dispersal of the tracer leads to results being stated as a range of values with expected upper and lower bounds. The actual shape of the tracer decay plot is an additional source of both useful information to characterize the behavior of the ventilation system and uncertainty as to the ventilation rate. Slopes that deviate from linearity (on a semi-log plot) indicate variations from the well-mixed case; slopes with the appearance of an increasing slope with time are representative of displacement or plug flow; while slopes with the appearance of a decreasing slope with time are representative of incomplete mixing and zones of stagnation. It is only when the plotted slope is linear that the ventilation rate can be determined with absolute certainty.

Most building investigations do not have the budgets to support the precise determination of the effective volume of the tracer dilution; thus, an estimate based on the gross volume is more typically used. Our experience indicates that estimates of effective volume that are 85% of the gross volume yield reasonable results. This is an area in which more research would be very useful.

POSSIBLE INTERPRETATION DISCREPANCY (TRACER GAS MEASUREMENTS)

Overestimation of ACH (Between Zone Mixing)

Cross-contamination between different zones of a complicated HVAC system can lead to erroneous results, i.e., in one example, one part of the building was being impacted by air contaminants being generated in another part of the building. The airflow relationship was such that the air being delivered to the space being evaluated had already traveled through another occupied part of the building. Tracer decay testing performed only in this space of interest failed to take this into consideration and initially yielded an outside air ventilation rate much higher than was actually being provided. Multiple tracer gas tests with releases occurring in different HVAC zones and transport evaluation being conducted or the use of CO_2 testing (with a sufficient density of people) were required to yield accurate representative results. In this particular situation, the evaluation included several locations within a building complex. The complex consisted of two adjacent buildings that had been interconnected. The direct release of the tracer into the occupied area of the smaller of the two original buildings, with 4100 ft² per floor (the adjoining building has 16,500 ft² per floor), yielded a linear decay rate equivalent to 4.3 ach. For the estimated volume of this space, this represented 2320 cfm of OA. The CO_2 test results, however, based on 700 ppm indoors and 400 ppm outdoors with 17 people present in the space, yielded a ventilation rate of 35 cfm per person or a total of 595 cfm of OA. An additional tracer test of the same study area, but with the tracer being released into the HVAC system located in the larger building three floors above, yielded a tracer decay rate equivalent to 1.1 ach. This 4100 ft² area had a total ceiling height of 9.3 ft, leading to a gross volume of 38,100 ft³. Using the previously mentioned relationship of the effective volume for occupied office spaces being 85% of the gross volume, the net volume is 32,400 ft³ and the 1.1 ach yields an effective ventilation rate of 594 cfm of OA, which is the same result as that from the CO_2 calculation.

This example also points out that with both assessment approaches, it is crucial to be familiar with the design of the HVAC system as well as the intended modes of operation and the need to be aware of any changes in the operation of the system which could affect the quantity of OA being delivered throughout the testing period.

COMPARATIVE ADVANTAGES AND DISADVANTAGES OF EACH APPROACH

In using the carbon dioxide measurement approach, the accuracy of the result is limited by the precision of both the CO_2 measurement device and the counting of the number of people actually present in the building during the CO_2 measurements. In using the tracer decay approach, the accuracy of the result is limited by the accuracy of the estimate of the effective volume of the space under investigation and the linearity of the semi-log plot of the tracer decay values. In both of these approaches, the results are typically presented as being between a given upper and lower bound. The performance of both of these assessments together can reduce these bounds.

The authors have been known to say that "most buildings are similar but each building is unique." Some of these unique situations point out the strengths and weaknesses of these two investigatory approaches. For example, the results from one unusual office building, with a height of 18 ft from floor to roof deck, where both procedures were used, are presented in Table 1.

In this table, the range of values for the tracer testing results reflects estimates of the effective volume ranging from 80% to 95% of the gross volume. The range for the CO_2 results reflects the ±25 ppm aspect of the detector device. In this table, each test refers to a different zone of the building, with the exception of Tests 6 and 7, which are for the

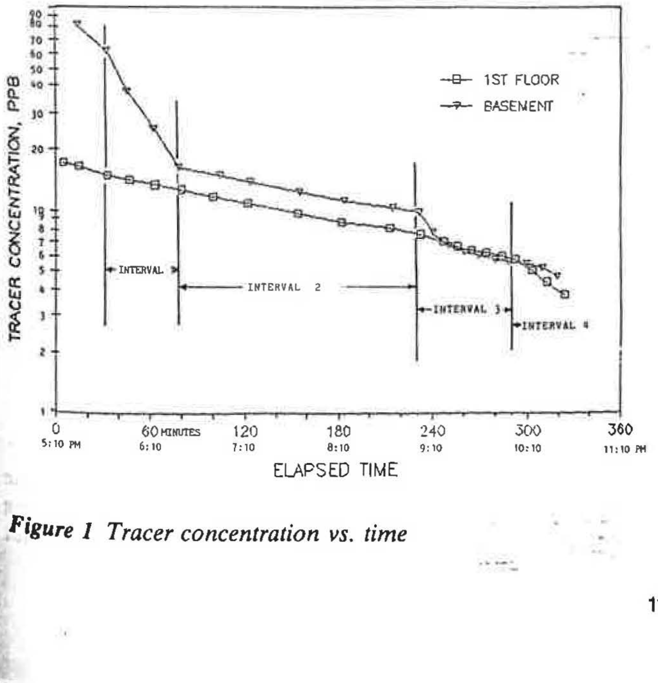

Figure 1 Tracer concentration vs. time

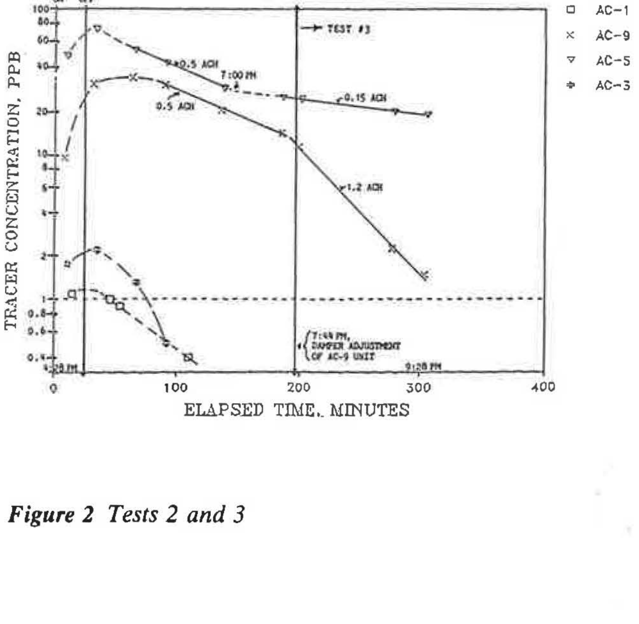

Figure 2 Tests 2 and 3

TABLE 1

Comparison of Outdoor Air Quantities from Tracer Testing and CO_2 Testing

Test Zone	CFM from Tracer Decay	CFM from CO_2 Test	CFM from Combination
1	9340–11100	10,100–12,000	10,100–11,100
2	3060– 3630	1900– 3800	3060– 3630
3	1770– 2100	630– 840	?
4	1000– 1700	1470– 1960	1470– 1700
5	250– 1100	700– 1050	700– 1050
6	820– 960	980– 1180	970
7	1730– 2050	1960– 2940	1960– 2050

same zone, but with the OA dampers in different positions. In five of these seven examples, the combination of the results from the two evaluation techniques reduces the uncertainty of the determined cfm of OA quantites. In one example, the range for the tracer results fell entirely within the range of results from the CO_2 evaluation. In test zone 3, however, the ranges of expected results did not overlap. This space, in addition to being a candidate for testing, was a laboratory space, with fume hood exhausts and a low population density. Another confounding aspect of this space was the presence of a lot of equipment, which would be expected to reduce the effective volume. This provides an explanation as to why the tracer results exceed the CO_2 results.

VENTILATION EFFICIENCY EVALUATIONS (VENTILATION PERFORMANCE)

One reason the OA quantities presented in Table 1 were expressed as cfm values and not as ach or cfm/person values is that they were to be compared with the amount of OA determined to be entering the HVAC system. There needs to be greater recognition of the fact that measurement of the quantity of OA measured as entering the air intakes of an HVAC system does not necessarily reflect the quantity of OA delivered to the building occupants. In the authors' experience, diffuser sizing and appropriate supply and return location is very important in order to minimize complaints of drafts and noise and to promote good mixing. With supply and return systems of conventional design (both in the ceiling), good mixing is important in order to minimize inefficiencies in the HVAC distribution system and the poor operational economics caused by the short-circuiting of supply and return airstreams. Rather large inefficiencies of outside air and cooling air distribution have been observed in several conventional-type office/research buildings evaluated by the authors. These data are presented in Table 2.

In this data set, the evaluation of the OA quantity entering the HVAC system at the air intakes was either determined by direct measurement of the air volume or by combination of the measurement of total flow at each air-handling unit plus an apportionment by enthalpy balance to determine the percentage of the total flow consisting of outdoor air. The evaluation of the "delivered" OA quantity was determined from measurements of carbon dioxide in the occupied spaces in combination with population counts as an assessment of the number of people present in the building at the time of these CO_2 measurements. These CO_2 concentrations yield a value for effective ventilation rates expressed in terms of cfm/person. Since it is the number of people actually present that is the source of the CO_2, the actual number of people present in the building needs to be determined to convert this ventilation rate into a quantity that can be expressed in units of cubic feet of OA per minute (cfm).

TABLE 2

Comparison of Range of Measured Outdoor Air Volumes into the HVAC System and Delivered to Building Occupants

Test Location	%OA	Measured OA, CFM Into System	CO_2-Determined CFM to People	Ventilation Performance
A	50	90,600	12,600–17,400	14–19%
B	44–67	50,000–80,000	20,200–25,750	40–52%
C	40(avg)	38,000–38,500	9150–11,400	24–30%
D	30–60	38,200	12,200–15,200	32–40%
E	28	31,000	7200–12,000	23–39%
F	19	18,700	7000–14,750	37–79%
G	15	18,000	9900–13,800	55–77%

NOTE: Each test location represents approximately 125,000 ft^2 of space.

Since the absolute number of people in the building was not determined with certainty, a range of expected minimum and maximum values is used to bracket the expected result. The lower bound was determined from a count of people present vs. the desks per office as part of the building survey. This ratio of percent of people present was then applied to the total reported population. In case the census undercounted the actual number of people, the upper bound for this range assumed that 80% of the potential number of people were present even if fewer were counted. In this data set, the range of people present varied widely, from population counts below 40% up to 80%. This cfm/person term is therefore multiplied by the range of the number of people present at the time of the building survey to yield values of the absolute quantity of OA, expressed in cfm.

Limited information available on other buildings, outside of this particular study, suggests that losses of 25% of this OA can normally be expected. Distribution inefficiencies are important both from an economy of operation perspective as well as because they interfere with the delivery of OA to the building as a block from actually getting to where the people are. Typical causes of distribution inefficiencies are:

1) leakage from the supply air ductwork directly to the return air plenum,
2) poor mixing due to short-circuiting of low-velocity discharges across the ceiling and back to the return plenum without penetrating to the occupied zone, and
3) the delivery of OA to unoccupied areas in the building.

With respect to this last item, for instance, for the building data presented in Table 2, the total area occupied by people typically represented only 60% of the gross areas of the building. The extent that a portion of the outdoor air delivered to the building is going to unoccupied areas would explain a portion of the difference between the OA quantities measured to be entering the building as compared with being delivered to the building occupants' offices.

Other contributing factors might be that there are imbalances of makeup air between adjoining buildings, which may also account for a decrease in the delivery efficiency. In a building that is not operated under slight positive pressure, uncontrolled infiltration into the building shell could increase the OA for ventilation without increasing the quantity measured at the OA dampers.

INFILTRATION

The issue of infiltration is of special interest because the determination of the quantity of OA delivered to the building occupants, either by the CO_2 or tracer technique, does not differentiate between OA delivered by the mechanical ventilation system and that entering the building due to infiltration through the building shell. Assessing the magnitude of the infiltration component is achieved in combination with other aspects of the building evaluation. Infiltration, if it is occurring, is dependent on two conditions: the presence of leakage sites in the building shell and the existence of areas in the building that are at negative pressure with respect to the outdoors. While it can be expected that there will always be some leakage sites, the building typically should be operating at a slight (0.05 of water column) positive pressure with respect to the outdoors. The identification of leakage sites is achieved by the use of air current tubes, which provide a visual indication of local air movement. Once a leakage site is detected, the direction of air movement will indicate the pressure relationship at that location. This, in turn, indicates whether infiltration is occurring or if the building is being maintained at a positive pressure with respect to the outdoors as it should be. Since infiltrating air does not receive the benefit of filtration, a clue that infiltration is occurring is the presence of dust on surfaces, especially on VDT screens. This assumes that the ductwork is clean and that there are adequate filters in place.

Quantification of the amount of infiltration entering the building, if it is significant, can be determined by subtracting the OA quantity measured as entering the HVAC system from the amount of OA determined to be delivered to the building occupants. Another approach is to perform a tracer evaluation with the OA dampers closed. The ventilation rate occurring under this condition will be primarily due to infiltration. There may, however, be some leakage past the OA dampers.

From an economics of operation standpoint, good delivery efficiencies should be pursued. Reducing these inefficiencies would allow many buildings to more often meet ASHRAE outside air guidelines over a greater range of operating conditions, allowing this to be accomplished with significantly less outside air being brought into the HVAC system, and with less total air movement required. An expected side benefit is an increased ability to deliver more of the installed cooling capacity to the occupied spaces.

CONCLUSIONS

We have presented information that can be derived from the measurement of the amount of outside air delivered to the occupants and discussed many of the pitfalls evaluators should be cautious of. Done correctly, a ventilation assessment can point out whether or not there is a need for improvement in a ventilation system. Performed without a clear understanding of the limitations of the methods, the HVAC system, and the needs of the occupancy of the building, the results can lead to a serious misinterpretation of what is actually happening within a building system.

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DISCUSSION

Carl N. Lawson, LRW Engineers, Tampa, FL: Were any of your tests conducted in the breathing zones of the areas of concern? Do you feel the supply air distribution gives the best results in determining the outdoor air quantities? Why?

W.A. Turner, Harriman Associates, Auburn, ME: All tests were conducted in the breathing zone of the occupants, i.e., typically 4 to 6 ft off the floor. Testing is also conducted at supply diffusers and return grilles. No, supply air only tells you what is entering the occupied space, if the air turnover rate is low, or if occupancy is high. It will seldom be representative of the breathing zone of the occupants.

John A. Tiffany, UMDNJ-RWJ Medical School; NIOSH Educational Resource Center, Piscataway, NJ: Do you ever suggest using grab samples for CO_2 measurement (due to its inaccuracy and no long-term measurement factor)?

Turner: I do not use short-term grab samples to make economic or health decisions for a client. Measurements must be well understood in conjunction with an understanding of what the HVAC system is or is not doing. The investigator must understand how the changes in the ventilation system operation would be expected to affect the measurements.

P.E. McNall, Phoenix Engineers, Overland Park, KS: What are the specifics of how to measure in the breathing zone? Where is it done and for how long?

Turner: When we measure in the breathing zone, we attempt to measure between approximately 4 ft and 6 ft off the floor. With a CO_2 instrument, we would measure until a stable reading is reached, typically 2 to 3 minutes. With an SF_6 sample, we would collect the sample over a 30-second time period, typically. In both cases, we try not to disturb the normal activities of the occupants.