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MULTI-TRACER SYSTEM FOR MEASURING VENTILATION RATES AND VENTILATION EFFICIENCIES IN LARGE MECHANICALLY-VENTILATED BUILDINGS

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Publication Date

1985-09-01

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APPLIED SCIENCE DIVISION

Presented at the AIC Conference, Het Meerdal, Netherlands, September 16-19, 1985

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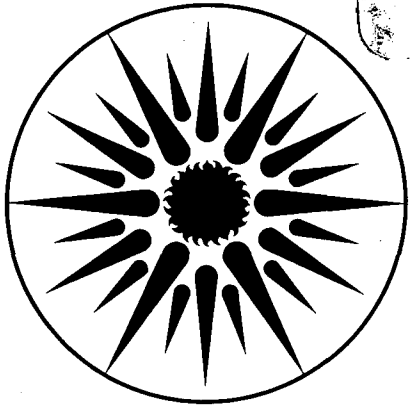

APPLIED SCIENCE DIVISION

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

DISCLAIMER

To be presented at the AIC Conference,
September 16-19, 1985,
Het Meerdal, Netherlands.

LBL-20209
EEB-Vent. 85-15

Multi-Tracer System For Measuring Ventilation Rates and Ventilation Efficiencies in Large Mechanically-Ventilated Buildings

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September 1985

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

SYNOPSIS

Measurement of air exchange rates, ages of air, and nominal and local ventilation efficiencies in large buildings is often complicated by the building size and compartmentalization, and by the presence of multiple ventilation systems. To allow characterization of the ventilation process in such buildings, a unique experimental system, that employs multiple tracer gases, is being developed at Lawrence Berkeley Laboratory. The tracer gases are sulfur hexafluoride and five halocarbons. The system is designed to be non-obtrusive, highly automated, and relatively easy to install in buildings. Included in the system is a programmable tracer-gas injector that automatically initiates and terminates the process of tracer injection. One injector will be used for each tracer gas. Another component of the system is a programmable sampler that collects up to 15 small samples of air; these samples can be stored and analyzed at a later time in the laboratory. One sampler will be placed at each sampling location. Because each tracer gas injector and sampler is a stand-alone device, long runs of tubing are not required to inject tracer or take samples. The concentrations of tracer gas in the samples are determined using a gas chromatograph with an electron capture detector.

This paper first provides background information on the ventilation of large buildings and a discussion of age of air and ventilation efficiency. Various tracer gas techniques are briefly reviewed and equations to analyze the tracer gas data from the step-up and decay techniques are presented. The experimental system is described in detail and the results of two tests of system performance are presented. In these tests, four of the six tracer gases yielded the same result (i.e., air exchange rate, age of air, or ventilation efficiency) within approximately 15 percent. In an experiment conducted in a well-mixed test space, these four tracer gases also yielded an air exchange rate, or age of air, that differed by no more than 12 percent from a reference measurement made with an orifice plate flow meter. Further work is required to increase the accuracy of our measurements with the other two tracer gases.

1. INTRODUCTION

1.1 Ventilation Systems

Large buildings almost always contain a mechanical ventilation system and some also have provisions for natural ventilation (e.g., openable windows). Uncontrolled infiltration (air leakage) can also be significant in these buildings. Several independent or semi-independent mechanical ventilation systems may be present in a single building. A number of ventilation system designs are in common use; only features that are common in many of these designs and that are especially relevant to this paper are described here.

The airflow configuration of a typical large-building ventilation system is shown in Figure 1. The air supplied to the building is generally a mixture of outside air and a larger amount of recirculated air. When heating or cooling loads are high because of high or low outdoor temperatures, the entry rate of outside air may be adjusted to a minimum value in order to save energy. Conversely, when outdoor air is at a temperature that makes it useful for cooling, the supply air may be entirely outdoor air. The position of the three major dampers in the system, which determines the flow rates of outside air and exhaust air, is regulated automatically in response to thermal loads and outdoor temperature. Some ventilation systems also contain variable air volume (VAV) control units, which regulate the flow of supply air out of a group of supply diffusers in response to thermal loads in the region served by the diffusers.

It is important to recognize that actual ventilation systems are much more complex than indicated by the simple diagram in Figure 1. Actual systems generally contain a complex system of ductwork and dampers, large numbers of supply diffusers and exhaust registers, heating and cooling coils, filters, and a complex control system that regulates supply air temperature and humidity and air flow rates.

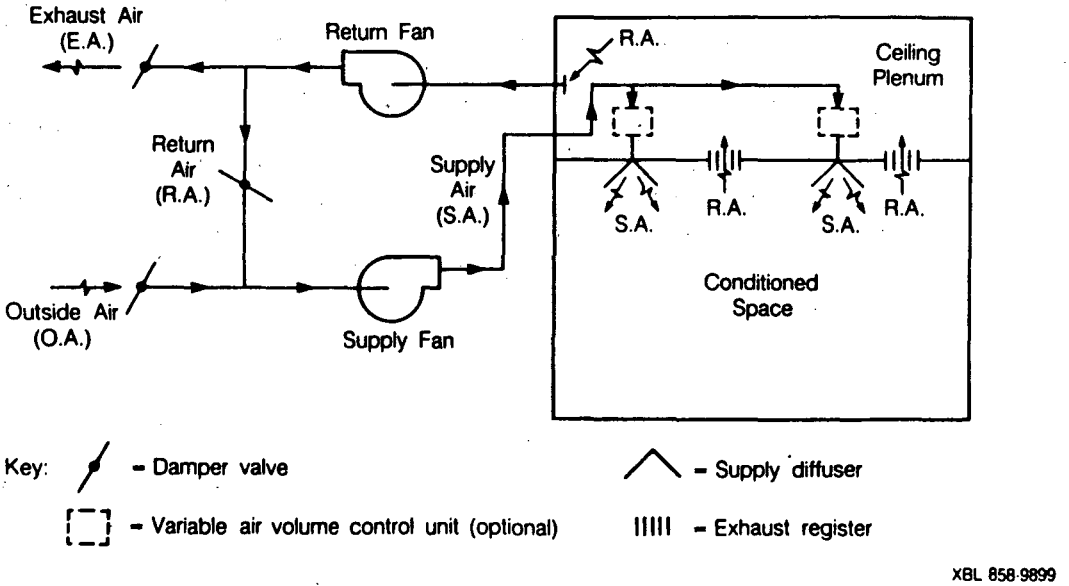


Figure 1. Simplified schematic diagram of air flow pathways in typical large-building ventilation systems.

1.2 Air Exchange Rate, Age of Air, and Ventilation Efficiencies

The objectives of the ventilation process in a large building are to remove or supply heat and moisture and to remove indoor-generated pollutants from the building. These objectives are accomplished by conditioning (e.g., heating or cooling) of the recirculated air and by exchange of indoor air with outside air. Numerous factors affect the performance and efficiency of the ventilation process. In this paper we are concerned primarily with the following factors: 1) the nominal air exchange rate; 2) the overall pattern of air flow between supply diffusers and exhaust registers; and 3) the spatial pattern (e.g., evenness) of outside air distribution throughout the building.

The nominal air exchange rate is simply the rate at which outside air enters the building divided by the indoor volume. A nominal time constant or turnover time can be computed by taking the inverse of the nominal air exchange rate.

The second parameter, the overall airflow pattern, is more difficult to describe. The pattern of airflow can, in theory, vary from one extreme, in which much of the air exiting the supply diffusers rapidly short-circuits to the exhaust registers, to the other extreme where the flow between supply and exhaust approaches a piston-type or displacement flow. Between these extremes is perfect mixing of the indoor air. The benefit of displacement flow and disadvantage of short-circuiting is perhaps best understood if one considers a hypothetical room throughout which pollutants or heat are generated uniformly. In the case of displacement flow, the air exiting the room will contain pollutants (or heat if the room is being cooled) at a concentration that is higher than the average within the room. Conversely, with a less-efficient short-circuiting flow pattern, the exiting air will have a lower pollutant concentration or temperature than the average within the room.

The performance index that characterizes the overall airflow pattern is the nominal ventilation efficiency. The most unambiguous, but unfamiliar, interpretation of this parameter is provided by Sandberg and Sjoberg in their paper that applies age distribution theory to ventilated buildings.[1] In this theory, the age of an infinitesimal parcel of air is the elapsed time since that parcel entered the building and the nominal ventilation efficiency equals the turnover time (described above) divided by the mean age of all air parcels within the building. Because the turnover time equals the age of air within the building for the reference case of perfect mixing, the nominal ventilation efficiency also equals this reference case age of air divided by the actual mean (spatial average) age of air within the building. The theoretical maximum value of nominal ventilation efficiency is two for a perfect displacement flow, the theoretical minimum is zero for complete short-circuiting, and this nominal efficiency equals

unity with perfect mixing.

Sandberg et al.[2] and others[3-5] have shown in laboratory and field experiments that the nominal ventilation efficiency can vary widely, from substantially below unity to substantially above unity, and that efficiency depends on such factors as the relative positioning of supply diffusers and exhaust registers, the type of supply diffuser, the relationship between supply and exhaust temperature, the nominal air exchange rate and the geometric configuration (e.g., number of rooms) of the ventilated space. However, the applicability of available data on ventilation efficiency for the majority of large buildings is uncertain. Previous studies of ventilation efficiency were conducted with ventilation systems that did not recirculate indoor air, which contrasts with the typical system in a large building. In addition, the majority of available data are based on laboratory experiments with supply air that was warmer than the indoor air (i.e., when the building was being heated). In many large buildings, the supply air is often cooler than the indoor air (i.e., supply air is used for cooling). Virtually no measurements of nominal ventilation efficiencies have been made large, mechanically-ventilated buildings.

The third factor of interest is the spatial pattern of outside air distribution throughout the building. The pattern of outside air distribution is influenced by several characteristics of the ventilation system including the balancing of air flow through various sections of supply ductwork and supply diffusers, the degree of mixing between the outside air and recirculated air, and the modulation of air flow by the VAV control units. In buildings with multiple ventilation systems, the various systems may also supply different amounts of outside air to the zones they serve. The degree of short-circuiting in various regions of the building, as noted above, is one final parameter that will influence the distribution of outside air.

The appropriate performance index for outside air distribution patterns is the local ventilation efficiency. Again, age distribution theory provides the most unambiguous interpretation of the performance index[1]. The local ventilation efficiency is the turnover time, which equals the age of all air within the building if the air is perfectly mixed, divided by the age of air at a specific point within the building. By comparing local ventilation efficiencies measured at different locations, the evenness of ventilation can be assessed[4].

Each of the parameters described above, nominal air exchange rate and mean and local ages of air and ventilation efficiencies, can be measured using tracer gases. Various tracer gas techniques are reviewed in the next section and expressions for computing the age of air and ventilation efficiency are given. Finally, in the remainder of the paper,

a multi-tracer experimental system being developed at Lawrence Berkeley Laboratory (LBL) is described in detail.

2. TRACER GAS TECHNIQUES

A variety of tracer gas techniques can be employed to assess ventilation system performance in a large building. In this paper, these techniques are divided into two categories: transient techniques and the constant injection rate technique.

2.1 Transient Tracer Gas Techniques

Tracer decay: The most common transient technique is the tracer gas decay[6-8]. With outside air dampers closed, a volume of tracer gas is released, usually at a number of locations, within the building. After mixing between the tracer and the indoor air has occurred for a period of time, outside air dampers are opened and fresh tracer-free air is brought into the building. The dilution of indoor air with outside air causes indoor tracer concentrations to decrease or decay. Tracer concentrations are monitored as a function of time at various locations within the building and in the exhaust ductwork. Two methods of data analysis can be employed. In the first, the natural log of tracer gas concentration is plotted versus time, and the slope of the straight line that is the best fit to the data is computed and used as a measure of ventilation rate. If the slope is computed from the latter linear portion of the decay curve, it is an appropriate indicator of the overall ventilation rate (i.e., nominal air exchange rate multiplied by nominal ventilation efficiency). However, it has been shown clearly that the slopes of decay curves are poor indicators of local ventilation rates[9] if there is a substantial amount of air exchange between the different points or zones of measurement. In fact, under such circumstances the slopes measured at different locations will, in theory, eventually become equal[2,9].

The second method of analyzing tracer gas decay data is to apply age distribution theory[1]. The mean age of air ($\bar{A}$) within the room or zone and the local age of air (A_p) at point p can can be computed using the equations:

$$\bar{A} = (Q/V) \int_0^\infty \tau \, C_e(\tau) / C_e(o) \, d\tau, \text{ and} \qquad (1)$$

$$A_p = \int_0^\infty C_p(\tau) / C_p(o) \, d\tau \qquad (2)$$

where $C(\tau)$ is a tracer gas concentration at time τ, subscript e refers to the exhaust duct, V is the indoor volume, and Q is the entry rate of outdoor air. The nominal air exchange rate

(Q/V) and its inverse the turnover time (V/Q) are computed with the equation

$$Q/V = C(o) \; / \int_o^\infty C_e(\tau)\, d\tau \qquad (3)$$

which is easily derived from mass balance considerations. The turnover time (V/Q) also equals the age of air in the exhaust duct (A_e); therefore, it can also be computed directly from Equation 2. The nominal and local ventilation efficiencies, ϵ_n and ϵ_p, are then calculated using the expressions

$$\epsilon_n = (V/Q) \; / \; \bar{A}, \text{ and} \qquad (4)$$

$$\epsilon_p = (V/Q) \; / \; A_p \; . \qquad (5)$$

A major constraint associated with usage of equations 1-3 above is that the tracer must be uniformly mixed throughout the building at the start of the decay. The tracer decay technique has been employed in 38 commercial buildings by our colleagues at LBL[8] and in the majority of these buildings, especially those with multiple ventilation systems, satisfactory mixing could not be achieved. Therefore, the requirement of initial mixing limits the usefulness of the decay technique in large buildings.

Tracer step-up: A second transient technique, referred to as the step-up method, involves continuous injection of tracer into the stream of outside air that enters the building. The injection is continued until steady state concentrations are achieved. Tracer concentrations are measured as a function of time in the building and at points within the HVAC system. The step-up technique is analogous to a tracer gas decay. In the decay technique the indoor air is uniformly labeled with tracer gas and in the step-up technique the incoming outside air is uniformly labeled with tracer gas. The mean and local ages of air from a step-up are computed with the expressions[1]:

$$\bar{A} = (Q/V) \int_o^\infty \tau \; (1 - C_e(\tau) \; / \; C_e(\infty))\, d\tau, \text{ and} \qquad (6)$$

$$A_p = \int_o^\infty (1 - C_p(\tau) \; / \; C(\infty))\, d\tau \qquad (7)$$

and the entry rate of outside air (Q) is computed with

$$Q = \dot{m} \; / \; C_e(\infty) \qquad (8)$$

where $\dot{m}$ is the injection rate of tracer gas into the incoming outside air. The indoor volume (V) is determined from physical measurements and ventilation efficiencies are computed from Equations 4 and 5. Alternately, the turnover time (V/Q), which equals A_e, can be computed directly from Equation 7 and then the ventilation efficiencies from Equations 4 and 5. A disadvantage of the step-up technique is that only the air entering the building through the HVAC system can be labeled with tracer gas, i.e., infiltrating air can not be labeled. However, the infiltration rate can be determined by comparing the steady state concentration of tracer in the incoming outside air to the steady state concentration in the exhaust. An important advantage of the step-up method is that initial mixing of tracer throughout the building is not required, however, the tracer must mix well with the outside airstream and good mixing may be difficult to achieve in some ventilation systems. In a building with multiple ventilation systems, and air flow between the zones served by separate systems, it is necessary to have the same concentration of tracer in each stream of outside air, which is impractical, or to use a unique tracer in each system.

Tracer pulse: A third transient technique, which is only mentioned here, is to suddenly release a fixed volume or pulse of tracer in the incoming outside air. Expressions for the entry rate of outside air and mean and local ages of air and ventilation efficiencies are provided by Sandberg and Sjoberg[1].

2.2 Constant Injection Rate Technique

An alternative to transient techniques, which require tracer concentrations to be measured as a function of time, is to employ a constant injection rate technique[10] which relies on measurements of time-averaged tracer concentration. Typically, tracer is injected continuously at a controlled and known rate for an extended period of time (e.g., several days) into the supply airstream(s) or at a number of locations within the building and some technique is used to measure the time-averaged tracer concentration at several points within the building. If the building has multiple ventilation systems a unique tracer should be used with each system. The data are generally analyzed using a single-zone or multi-zone steady-state mass balance model to compute the entry rate of outside air and, if multiple tracers are employed, to compute rates of air flow between zones. An assumption implicit in the steady-state models is that the air within each zone is perfectly mixed. In addition, the measurement period should be much greater than the amount of time required to achieve steady state tracer concentrations, which is roughly three to four turnover times. The constant injection rate technique is best suited for buildings that have a nearly constant or slowly-changing ventilation rate. An assessment should be made of the errors that result from using this technique over an extended period of time in buildings with large deviations from steady state, such as nightly shutdowns of the HVAC

system.

The primary advantages of the constant injection rate technique are that only a simple experimental system need be deployed in the building, such as the convenient passive tracer gas sources and samplers developed at Brookhaven National Laboratory[11], and that the average ventilation rate for an extended period of time can be measured in a single experiment. The nominal ventilation efficiency and local age of air or ventilation efficiency cannot be measured using the constant injection rate technique because the data analysis is based on the assumption of perfect mixing within each zone and ventilation efficiencies result from imperfect mixing.

3. MULTI-TRACER EXPERIMENTAL SYSTEM

The remainder of this paper describes a multi-tracer experimental system under development at LBL and summarizes the results of experiments conducted to verify system performance. The design objectives were as follows: 1) a flexible system that can be utilized for a variety of tracer gas techniques without major modifications; 2) a system that can measure ventilation efficiencies and local ages of air within a zone; 3) a system that can be deployed rapidly in a building; 4) a system suitable for use during periods of building occupancy; and 5) a system suitable for use in buildings with multiple ventilation systems. We plan to use this multi-tracer system to study ventilation system performance in a substantial number of large mechanically-ventilated buildings and to assess the impacts of changes to ventilation systems. Some of these future studies will be conducted as part of more comprehensive investigations of ventilation and indoor air quality in large buildings.

The experimental system consists of six tracer gases and instrumentation for measuring tracer gas concentrations, stand-alone tracer gas injection systems, and stand-alone samplers. In buildings with six or fewer ventilation systems, the step up or constant injection rate techniques can be employed by injecting a different tracer gas into each ventilation system. The injection of each tracer gas will be controlled by a distinct stand-alone injection system placed in the building near the point of injection. The stand-alone samplers will also be placed at various locations within the building near to points where the time-history of tracer gas concentration is required. These samplers collect and store small air samples taken at different times during an experiment (e.g., every 15 minutes during a step up experiment). The concentration of each tracer gas in the samples can then be determined in the laboratory after completion of the experiment.

3.1 Tracer Gases and Tracer Gas Measurement System

Selection of tracer gases: Selection of tracer gases was a

major early consideration. Suitable tracers must be non-toxic, chemically unreactive in buildings, naturally present in buildings only at concentrations that are low compared to those encountered during experiments, readily available at an acceptable cost considering the amount of tracer required, and not prone to substantial physical adsorption on indoor surfaces. Another consideration is whether the tracer is a gas or liquid at normal indoor temperature and pressure; liquids are more conveniently stored, but gases are more easily injected into the building at a controlled rate and may be less prone to physical adsorption. The measurement process also imposes important constraints on tracer selection. Measurement of tracer concentration over approximately two orders of magnitude, is highly desirable. The time required to separate and analyze a mixture of tracers must be reasonable (e.g., less than about ten minutes). Finally the cost of the measurement system is a major consideration.

The two groups of tracers that were considered are: 1) a set of four perfluorocarbon tracers (PFTs) used routinely at Brookhaven National Laboratory[10,11], and 2) sulfur hexafluoride plus selected halocarbons. The PFTs can be utilized at very low concentrations[11] (parts per trillion) due to their extremely low background concentrations. Generally to collect sufficient PFT for analysis, the PFT from a volume of air is adsorbed and thus concentrated onto a solid sorbent[11]. The PFTs are then thermally desorbed from the sorbent just prior to analysis in the laboratory. An expensive analytical system (approximately $30,000) is required to desorb the PFTs from the solid sorbent and determine the amount of each PFT desorbed. If PFTs were used in the parts per billion concentration range, a less expensive analytical system might be suitable, however, this alternative is impractical because of the high cost of PFTs, 100 to 500 $/kg[12] (45 to 225 $/lb). The fact that PFTs are liquids at room temperature makes storage convenient, however, an automated system for evaporation and injection of PFTs at a controlled rate posed a difficult design challenge considering the extremely small quantities of liquid required.

Because of the considerations regarding the use of PFTs noted above, and the expectation that a system of more than four tracers could be developed, we selected sulfur hexafluoride (SF_6) and several halocarbons as a preferred group of tracers for our application. Each of the tracers selected is a gas at typical indoor temperature and pressure. SF_6 has been used routinely as a tracer in large buildings[6-8] and three halocarbons have also been previously used as tracers in buildings[13]. After preliminary experimentation with a large number of halocarbons, a group of five (R-13B1, R-115, R-12, R-12B1, and R-114) plus SF_6 were selected. The chemical formula, approximate cost, and other relevant data on these tracers are given in Table 1. We intend to conduct our experiments so that the peak concentration of R-13B1, R-115, R-12, and R-114 is 1000 parts per billion (ppb) and the peak

concentration of SF_6 and R-12B1 is 100 ppb. In buildings with substantial leakage of refrigerants from refrigeration equipment, one may encounter substantial background concentrations of R-12 and R-115. We have taken air samples from several buildings, and in one building, specifically chosen because its mechanical system had a large refrigerant leak, the concentration of R-12 was approximately 225 ppb, which is sufficiently high to prohibit our use of R-12 as a tracer in this building.

Table 1. Selected Properties of Gaseous Tracers

Refrigerant Number*	Chemical Name	Chemical Formula	Molecular weight	Boiling Point (°C)	TLV (PPM)+	U.L. Safety Group**	Approx. Cost ($/Kg)++
---	Sulfur Hexafluoride	SF_6	146.1	-64	1000	-	12
13B1	Bromotrifluoromethane	$CBrF_3$	148.9	-58	1000	6	21
115	Chloropentafluoroethane	$CClF_2CF_3$	154.5	-39	1000	-	19
12	Dichlorodifluoromethane	CCl_2F_2	120.9	-30	1000	6	5
12B1	Bromochlorodifluoromethane	$CBrClF_2$	165.4	-4	--	-	12
114	1,2-dichlorotetrafluoroethane	$CClF_2CClF_2$	170.9	+4	1000	6	11

* Refrigerant number designation of the American National Standards Institute.

\+ Threshold Limit Value published by the American Conference of Governmental Industrial Hygienists.

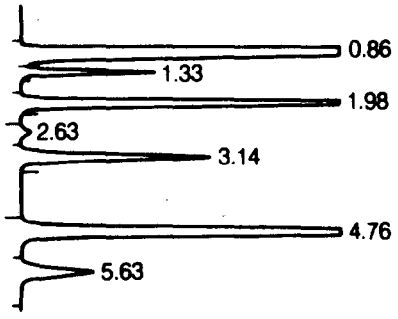
** Underwriters Laboratories safety Group 6 is for "gases or vapors which in concentrations up to at least about 20 percent by volume for durations of exposure of about 2 hours do not appear to produce injury".

++ Costs vary widely depending on purity and quantity purchased.

Tracer gas analysis: A microprocessor-controlled instrumentation system is used to determine the amount of each tracer present in small air samples. This system consists of a Hewlett Packard (HP) 5890A Gas Chromotagraph (GC) with an electron capture detector and a ten-port sampling valve with a 0.25 cc sample loop, a HP 3392A Integrator, and a HP 19405A Sample Event Control Module which controls operation of the sampling valve. This instrumentation system costs approximately $14,000. The carrier gas is a mixture of 7% methane and 93% argon. A standard backflushing procedure, with a 0.15 m (0.5 ft) pre-column and 2.4 m (8 ft) main column, is employed to prevent extraneous high-retention-time gases within the sample from entering the main column. Backflushing is initiated 0.75 min after injecting the contents of the sample loop into the pre-column. Both columns

contain Chromosil 310, 60/80 mesh packing in a stainless steel tube with an outer diameter of 0.32 cm (0.125 in). The flow rate of carrier gas is maintained at 20 cc/min. The initial oven temperature of 35°C is maintained for 2.75 min after which the oven temperature is increased at a rate of 30°C/min to a maximum of 60°C. The entire cycle is completed in approximately eight minutes.

Figure 2 shows a typical chromatogram, a tabulation of retention times and areas under each peak based on the printout of the HP 3392A Integrator, and additional information for characterizing each peak. The sensitivity of the electron capture detector to each tracer can be computed from the information given. The printed output of the integrator is also recorded on magnetic tape and subsequently read into a mainframe computer system. Calibration is accomplished by injecting and analyzing six to eight mixtures of calibration gas with known concentrations of each tracer. Because the calibration curves are not entirely linear, a third degree polynomial is fit to the calibration data using a curve fitting routine available on the mainframe computer system.



Retention Time (min)	Area	Component	Conc. (ppb)
0.86	1.9700E+07	Air	—
1.33	529140	SF_6	5
1.98	3098700	R-13B1	50
2.63	74651	R-115	50
3.14	1426800	R-12	50
4.76	7478000	R-12B1	50
5.63	657790	R-114	50

XBL 858-9897

Figure 2. Example chromatogram and table of information that characterizes each peak.

Tracer gas safety considerations: It was stated above that a suitable tracer must be non-toxic. However, any tracer can be hazardous to health if sufficiently high concentrations are encountered. A more precisely-stated requirement is the following: the investigators must be sure that normal usage of the tracer gas, and feasible accidents, will not harm any of the building occupants. In the following paragraphs we discuss briefly the safety of our selected tracer gases and tracer gas technique. However, until this issue is reviewed by qualified experts, no definitive conclusions should be made by the reader regarding the safety of these tracers or our procedures.

Included in Table 1 are two safety-related parameters. The first of these is the Threshold Limit Value-Time Weighted Average (TLV) published by the American Conference Governmental Industrial Hygienists (ACGIH). The TLV is defined by the ACGIH as follows: "time-weighted average concentration for a normal 8-hour work day and a 40-hour work week to which nearly all workers may be repeatedly exposed, day after day, without adverse affect". The maximum TLV established by the ACGIH is 1000 parts per million (ppm) even when no harm is expected from exposures to concentrations much higher than 1000 ppm. For all of the tracers except R-12B1, the TLV is 1000 ppm which is 1000 to 10,000 times greater than the maximum concentrations that will be encountered in our experiments. No TLV has been published for R-12B1. In his review of fluorocarbon toxicity, Clayton[14] indicates that R-12B1 should be less toxic than R-12B2, for which the TLV equals 100 ppm or 1000 times greater than the maximum concentration of R-12B1 expected in our experiments. However, Clayton indicates that R-12B1 should be more toxic than R-13B1 for which the TLV is 1000 ppm. Other information on the toxicity of R-12B1 is provided by Beck et al.[15] who exposed various animals to R-12B1. Most of the experiments involved concentrations in the range of 1 to 30 percent and significant adverse effects were noted, however, no adverse effects were noted when rats were exposed to 3300 ppm of R-12B1 (i.e., 33,000 times our maximum) 6 hr/day, 5 days/week, for three weeks.

The second safety-related parameter in Table 1 is the Underwriters Laboratories (U.L.) safety group. Three of the tracers have been assigned to Group 6 which is for "gases or vapors which in concentrations up to about 20 percent by volume for durations of exposure of about 2 hours do not appear to produce injury". A concentration of 20 percent is 200,000 times greater than the one ppm maximum of our experiments. U.L. has not assigned a safety group number for SF_6, R-115, or R-12B1.

Based on these two safety-related parameters, exposure of building occupants to maximum concentrations of tracer gas of 1000 ppb or 100 ppb, depending on the tracer, does not appear to be of concern. However, an accidental rapid release of a large amount of tracer gas from a pressurized cylinder into a small room could result in tracer concentrations much higher than 1000 ppb. To preclude this possibility, we have designed a tracer injection system (described later) that eliminates the need for pressurized cylinders in the building and that limits the maximum quantity of each tracer within the building to approximately 100 liters.

A third safety-related issue is the thermal decomposition of the halocarbon tracers. It is known that halocarbons can decompose to toxic products (phosgene, halogens, and halogen acids) if heated to high temperatures such as those

encountered in gas flames or at the surface of electric heating elements[16]. Neither open flame gas heaters nor a substantial quantity high-temperature electric heating are generally present in the buildings we plan to study; when present we will avoid usage of the tracer system. Another concern is the possibility of decomposition of the tracers when they pass through burning tobacco. Hanst et al.[17] determined that R-11 and R-22 did not decompose when 2000 ppm of these gases passed through a lighted cigarette within their detection limit of 0.1%. However, we have identified no analogous experimental data for the five selected halocarbons tracers. Based on some preliminary calculations we believe that decomposition of these tracers in burning tobacco is unlikely to be a problem. Further analysis is warranted before these tracers are used routinely.

One should place our safety concerns into proper perspective. We are trying to be extremely careful. It is our impression (as yet unconfirmed) that many industrial workers and others including smokers, are routinely exposed to these halocarbon gases in concentrations and for a duration that greatly exceed those in our experiments without any apparent adverse affects.

3.2 Programmable Stand-Alone Sampler

Real time analysis of tracer gas concentrations during an experiment, by placing the GC in the building and drawing samples to the GC through sample tubing run to various locations within the building, is generally not a practical alternative when multiple tracer gases are employed. For example, the time required to analyze a single sample with our system is eight minutes. If measurements are required at ten locations, and often monitoring at more than ten locations is desirable, data could be obtained from each location only once every 80 minutes, which is too infrequent for any transient tracer gas technique. Even without this constraint, we would have decided against real-time analysis and multi-point sampling using sample tubing because of the large amount of time and labor required to set up the GC in the building and string the sampling tubes out of the way of building occupants.

To meet our sampling requirements we designed the programmable stand-alone sampler depicted in Figure 3. The sampler utilizes a 34-port, 16-position valve (Valco Instruments Multiposition Valve with ST type flowpath) mounted on a Valco electric actuator. The valve has an inlet port, an outlet port and a pair of ports at each of the 16 positions. A six position version of the valve is shown schematically in Figure 4. In each valve position, a different sample collection loop can be purged and filled with a sample. In our experiments a 2.1 m (7 ft) length of copper tubing, with outer and inner diameters of 0.32 cm (0.125 in) and 0.165 cm (0.065 in.), respectively, is used as the sample collection

loop; a shorter piece of tubing with a larger inner diameter may be used in the future. Since one pair of valve ports must always be open to the inlet and outlet of the valve, a sixteen position valve can store only fifteen samples. A small pump is used to draw air through the valve.

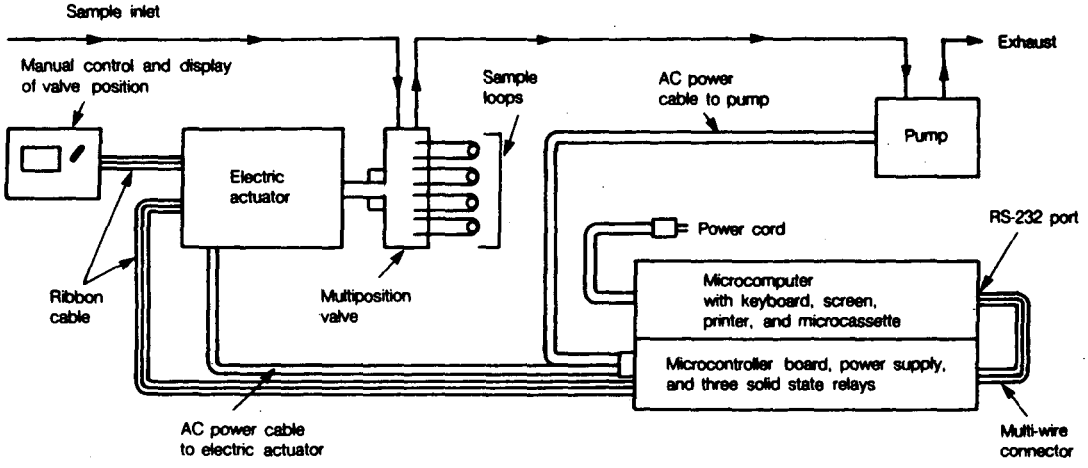


Figure 3. Schematic diagram of automated stand-alone sampler. The actual sampler contains 15 sample collection loops.

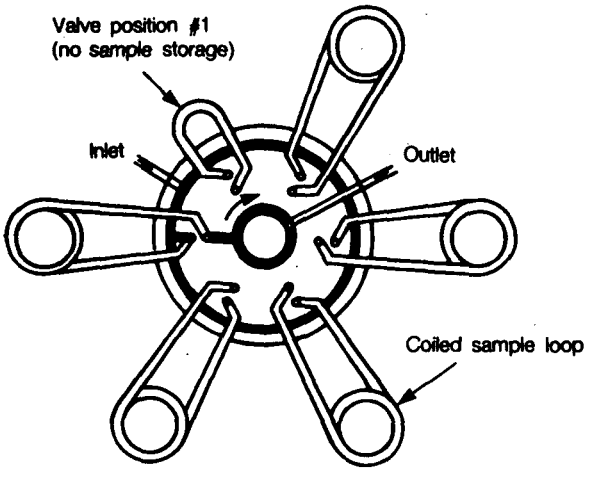


Figure 4. Schematic diagram of flow path in six position valve. A-16 position valve is used in sampler.

The multiposition valve is positioned by the electric actuator. During normal operation a sampler control system (described later) uses binary coded decimal (BCD) logic to position the electric actuator, and thus the valve, in the desired position. The valve can also be stepped to the next position or moved to position #1 manually, using a toggle switch.

The sampler control system consists of an Epson HX20 microcomputer, communicating via its serial RS 232 port with a small microcontroller board (Basicon MC-1N). The microcontroller board, along with a power supply and three miniature solid-state relays are installed in a small metal housing attached to the underside of the HX20. The microcontroller board has three eight bit binary ports which sends control signals to the electric actuator, senses actuator position and controls the solid state relays. One of the relays controls the pump, one turns the electric actuator on and off, and the remaining relay is a spare. A BASIC program burned into read-only memory of the microcontroller allows communication with the Epson HX20. The Epson microcomputer is also programmable in BASIC, keeps track of date and time with a real time clock, and contains a built-in keyboard, liquid-crystal display screen, printer, and micro-cassette tape system.

To minimize programming or operator errors when numerous samplers are deployed, a single micro-cassette tape can be used to load programs or control data files into each sampler. An appropriate operating procedure is the following. Prior to the experiment a control data file is loaded into the Epson and also printed on the Epson's printer. The valve is automatically rotated to position #1, which does not contain a sample loop, and all solid state relays are switched to the off position. A few minutes before the first sample is required, the electric actuator is turned on, the valve is rotated to position #2 and the pump and actuator are turned on. During the following few minutes the sample loop and the short length of tubing leading from the sampler to the desired sampling location is purged of the previous sample. At the desired sample collection time, the valve is rotated to position #3 and the pump is turned off. This basic procedure is repeated until all samples are taken. A record of all valve operations and changes in state of the relays can be printed on the Epson's printer or recorded on magnetic tape. The system is highly flexible; the sample loops can be filled in any desired sequence and at any desired time in the future. By repositioning the pump, the sampler can also automatically inject samplers into the GC for analysis.

The multiposition valve with sample collection loops connected is easily removed from and reinstalled on the electric actuator. Thus, by purchasing more than one multiposition valve for each sampler, the sampler can be reused before or during analysis of the previous samples. However,

the $375 price of the multiposition valve makes the purchase of more than a few valves for each sampler prohibitively expensive. The total cost of all major components of a sampler with a single multiposition valve, excluding a case to house the components (which has not yet been selected), is approximately $2000.

Mixtures of calibration gases containing all six tracer gases have been stored in the sample loops connected to a multiposition valve for as long as three weeks. Within the precision of our measurement system (approximately five percent) the concentration of each tracer within these sample loops has remained constant except in a few instances that we attribute to procedural errors. Longer-term tests of tracer storage are planned.

3.3 Tracer Gas Injection System

To complete our experimental system a subsystem for injection of tracer gases is required. We have designed a simple stand-alone automated injection system that is well suited for the step-up tracer gas technique. A separate injection system will be utilized for each tracer gas. The major components are depicted in Figure 5. As shown, a peristaltic pump (Cole Parmer Masterflex) draws tracer gas from a 100 liter gas storage bag (Calibrated Instruments) and pumps this tracer through a length of injection tubing. The rotational speed of the peristaltic pump is regulated within ±1% of the digital set point (according to manufacturers specifications) with a variable speed drive (Cole Parmer Ismatec No. T-7610-30). Because several different size peristaltic pumps can be mounted on the variable speed drive, and two pumps can be mounted simultaneously, the rate of tracer gas injection can be varied over a wide range (approximately 1 to 1200 cc/min). Starting and stopping of the drive is under control of a programmable timer. The optional integrating flowmeter placed downstream of the pump (Singer Model DTM-115-3), with a manufacturers rated accuracy of ±2% and a resolution of 10 cc, can be read before and after each experiment to determine the total amount of tracer injected during the experiment. The system should be calibrated by measuring flow rate versus the digital set point on the variable speed drive with a highly accurate flow meter (for example, the Mast Development Co. Model 832 electronic bubble flowmeter). The cost of all major system components, excluding a housing, is approximately $1900.

The 100 liter volume of tracer in the gas storage bag should be sufficient for the majority of experiments and two or more bags can be connected together if desired. The bag holds sufficient tracer to maintain 100 ppb of tracer in the supply air of a large ventilation system (47 m^3/s or 100,000 cfm) for a period of six hours with 100% outside air. In more typical situations, with smaller ventilation systems and/or less than 100% outside air, a 100 liter bag will hold enough

tracer for more than a single experiment. The seven-layer bag is fairly rugged but should be protected by some type of enclosure. The bag with enclosure will occupy a comparable volume to a large pressurized cylinder of tracer gas, but is lighter and thus easier to carry. The bag is also less hazardous than a pressurized cylinder of tracer gas.

This tracer injection system, without an integrating flow meter or a programmable timer, has been used to inject tracer gas in five experiments. During each experiment, the tracer injection rate was measured periodically with an electronic bubble flow meter. Except for two unexplained high readings of flow rate during one experiment, the measurements indicate that this system injects tracer at a highly stable rate (i.e., 2% maximum variation in injection rate).

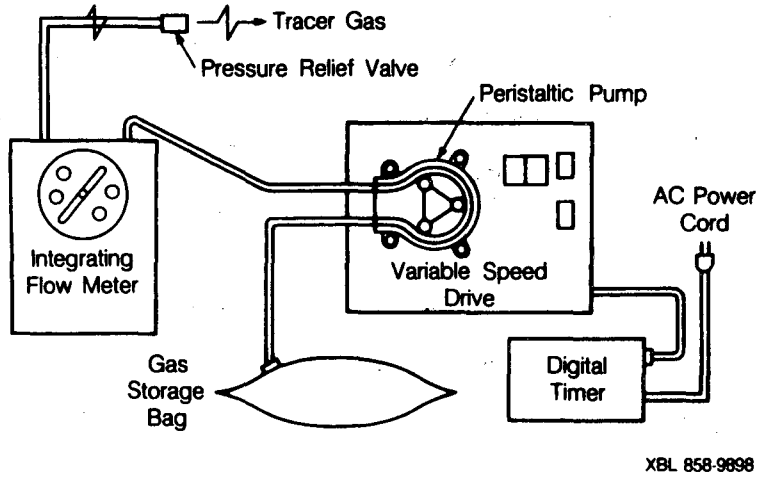


Figure 5. Schematic diagram of tracer gas injection system.

4. VALIDATION OF PERFORMANCE

A tracer gas intercomparison is an important test of any multi-tracer system. When a mixture of the tracer gases is utilized in the same experiment, the data from each tracer gas should yield the same nominal air exchange rate, ages of air, and ventilation efficiencies. Discrepancies could result from such factors as substantial adsorption of one or more of the tracers on indoor surfaces, inaccuracies in sampling, loss of tracer during storage of samples, and inaccurate analysis of tracer concentrations. Highly consistent results from a tracer gas intercomparison do not, however, ensure that the results are accurate because the same error(s) could occur with each tracer. Therefore, the performance of a tracer gas system should also be tested in a building with good mixing

and a known air exchange rate. Each type of test has been performed with our multi-tracer system and the results are described in the remainder of this section.

To conduct the tests we utilized the following procedure in two different buildings. The 100 liter gas storage bag was filled with a mixture of the tracers. (Note that in normal operation each storage bag would be filled with a single tracer.) A step-up experiment was then performed using a single injection system to inject the mixture of tracers into the building at a controlled rate. The injection rate was monitored using a bubble flow meter. After steady-state tracer concentrations were achieved, tracer injection was stopped and a tracer decay ensued. The stand-alone sampler was not used in these experiments; instead the GC was located within the building and samples of air were drawn to the GC from a single location through a small-diameter copper tube. A data point was taken every ten minutes. The GC was calibrated prior to each experiment, and prior to the first experiment we determined that there were negligible tracer losses in the copper sample tubing. Data from the HP Integrator was recorded on magnetic tape and processed on a mainframe computer after completion of the experiments.

The experimental procedure was first employed in a two-room test space of a research house (experiment #1) with a total internal volume of 69.1 m^3 (2400 ft^3). The two rooms were connected by an open door. Indoor surfaces consisted of plasterboard and plywood on walls and ceilings, a carpeted floor in one room and a vinyl tile floor in the other. A variety of furnishings were also placed within the rooms. To ensure good mixing, the air within the test space was vigorously mixed with five oscillating fans, eight wall-mounted fans, and a large ceiling fan. Tracer gas was injected at the back side of two oscillating fans and air samples were withdrawn from a location in the open doorway. Air was exhausted mechanically through a duct that penetrated the ceiling of one room and the flow rate of this exhaust airstream was monitored with an orifice plate flowmeter[18]. By combining the flow rate measurement with a physical measurement of test-space volume the actual air exchange rate of the test space can be determined with an estimated uncertainty of ±5%.

The second experiment was performed at Building 50E at Lawrence Berkeley Laboratory, which is a single-story structure with a floor area of 931 m^2 (10,000 ft^2) and an estimated volume of 2620 m^3 (92,600 ft^3). The building is furnished in a typical manner for office buildings. Much of the building is subdivided into office cubicles with fabric-covered dividers. In addition, a number of more formal offices, with walls that extend to the ceiling and closable doors, are present around the perimeter of the building. A single constant-volume HVAC system serves the building with both supply diffusers and exhaust registers located at ceiling

level. An open entry way connects Building 50E to the remainder of the Building 50 complex which is served by other HVAC systems. The mixture of tracer gases was injected into the outside air duct and samples were drawn into the GC from the exhaust air duct. The outside air, return-air, and exhaust-air dampers were disconnected from their actuators during the experiment so that no automatic modulation of damper positions was possible.

Table 2 gives the local age of air measured in Experiment #1 at the Research House. Because the concentration of R-12B1 exceeded the maximum calibration gas concentration of 100 ppb, a local age from the R-12B1 data can only be computed using the latter portion of the R-12B1 decay curve. Ideally, the data from each tracer gas should yield the same local age of air; the step-up and decay procedure should yield the same local age; and, assuming we were successful in obtaining good mixing during this experiment, all the ages of air calculated from tracer gas data should equal the reference measurement of age of air (i.e., the inverse of the nominal air exchange rate) made with the orifice plate flow meter. If one excludes the results obtained with R-12B1, the different tracer gases yield the same local age of air within ten percent. If the R-12B1 result is included, the maximum deviation between tracer

Table 2. Local Age of Air from Experiment #1 Performed in Well-Mixed Test Space of a Research House.

Tracer Gas	Tracer Gas Step-up A_p^* (min)	Tracer Gas Decay A_p (min)
SF_6	55	64+
R-13B1	53	63+
R-115	52	58+
R-12	52	60+
R-12B1	--	69**
R-114	52	64+

* A_p is the age of air at the measurement point calculated from equation 2 or 7 as appropriate.

\+ Data analysis performed assuming time zero (see Equation 2) corresponds to time of first data point after tracer injection ceased.

** Data analysis performed assuming time zero (see Equation 2) corresponds to time of first data point after R-12B1 concentration fell below maximum of calibration range.

Note: Meaurement of air flow rate and volume of test space yield an age of air of 59 minutes with an estimated uncertainty of ±5%.

gases is 14 percent. Compared to the decay data, the step-up data yields 11 to 21 percent lower ages of air, perhaps because of physical adsorption of tracer gases on indoor surfaces or systematic errors in our determination of tracer gas concentrations. An encouraging result is that the reference measurement of age of air, made with the orifice plate flow meter, falls between the step-up results and the decay results. The maximum deviation from the reference measurement is 17 percent (12 percent if the R-12B1 data are excluded).

Table 3 presents the local and mean (spatial-average) ages of air and the corresponding ventilation efficiencies based on the tracer gas data of Experiment #2 performed in Building 50E. The correspondence of the results from four of the tracer gases (R-13B1, R-115, R-12, and R-114) is quite good, however, the SF_6 and R-12B1 data yield substantially different results. We believe that the discrepancies with these two tracer gases may be due, in large part, to inaccuracy in our analysis of tracer gas concentrations. The calibration curves for these two tracers were not as smooth as the calibration curves for the other four tracers. Improved calibration gas mixtures and

Table 3. Ages of Air and Ventilation Efficiencies from Experiment #2 Performed in Building 50E.

Tracer Gas	Tracer Gas Step-up				Tracer Gas Decay			
	A_p* (min)	ϵ_p+ (-)	$\bar{A}$** (min)	ϵ_n++ (-)	A_p* (min)	ϵ_p+ (-)	$\bar{A}$** (min)	ϵ_n++ (-)
SF_6	31	1.44	21	2.05	39	1.00	45	0.87
R-13B1	36	1.03	33	1.13	39	1.00	42	0.92
R-115	35	1.01	31	1.14	37	1.00	38	0.98
R-12	39	0.98	38	0.99	40	1.00	50	0.80
R-12B1	47	0.85	50	0.81	47	1.00	82	0.58
R-114	37	0.97	36	1.00	39	1.00	41	0.95

* A_p is the age of air at the measurement point, which was the exhaust duct, calculated from Equations 2 or 7 as appropriate.

\+ ϵ_p is the local ventilation efficiency at the measurement point, calculated from Equation 5.

** $\bar{A}$ is the mean (i.e., room-average) age of air calculated from Equation 1 or 6 as appropriate.

++ ϵ_n is the nominal ventilation efficiency calculated from Equation 4.

increasing the maximum concentration of these two tracers by a factor of two or three may reduce these discrepancies in the future. The mean ages of air and nominal (i.e., spatial-average) ventilation efficiencies vary more widely between tracer gases than their local counterparts because the mean parameters are more highly affected by the shape of the step-up or decay curves and are, therefore, more difficult to measure accurately. The local ages of air and local ventilation efficiencies from the step up correspond very well with those from the decay for all tracer gases except SF_6. However, the step up yields 13 to 27 percent lower mean ages of air and 5 to 22 percent higher nominal ventilation efficiencies than the decay, excluding the SF_6 and R-12B1 data. One cannot draw firm conclusions from correspondence between results of the step up and the decay because the overall airflow pattern and even the nominal air exchange rate may have actually changed during the experiment. The step up was performed during the day when the building was occupied and the decay was performed during the evening and night-time hours. In addition, we have no data to confirm that the tracers were fully mixed with the air at the start of the decay. A final interesting observation based on Table 3, is that the four closely corresponding tracer gases indicate that the nominal ventilation efficiency during the experiment was within 15 percent of unity.

The fourth table lists the flow rates of outside air and nominal air exchange rates determined from the tracer gas data of Experiment #2, and our estimate of the indoor volume. If one excludes the SF_6 and R-12B1 data, the correspondence between different tracer gases and between step-up and decay is good (i.e., the maximum difference between any two numbers is 14 percent). Even the SF_6 and R-12B1 results are in reasonable agreement with the results of the other tracer gases.

Table 4. Flow Rate of Outside Air (Q) and Nominal Air Exchange Rates (Q/V) from Experiment #2 Performed in Building 50E.

	Tracer Gas Step-up		Tracer Gas Decay	
Tracer Gas	Q^* (m^3/h)	Q/V^+ (h^{-1})	Q^{**} (m^3/h)	Q/V^{++} (h^{-1})
SF_6	3580	1.36	4030	1.54
R-13B1	4250	1.61	4050	1.54
R-115	4510	1.72	4240	1.62
R-12	4160	1.58	3920	1.49
R-12B1	3930	1.50	3320	1.27
R-114	4380	1.67	4050	1.54

* From Equation 5.

\+ From Equation 5 and estimate of indoor volume of 2624 m^3.

** From Equation 3 and estimate of indoor volume of 2624 m^3.

++ From Equation 3.

5. SUMMARY

A unique multi-tracer experimental system that utilizes up to six tracer gases, sulfur hexafluoride and five halocarbons, is being developed. This system is intended primarily for measurements of air exchange rate, ages of air, and ventilation efficiencies in large mechanically-ventilated buildings. Tracer gas concentrations are determined using a gas chromatograph with an electron capture detector. So that tracer-gas concentrations can be monitored at numerous locations and with sufficient frequency for transient tracer gas techniques, a programmable stand-alone sampler has been designed that collects up to 15 small air samples. The samples can be stored and analyzed in the laboratory after the experiment has been completed. A simple programmable stand-alone tracer gas injection system that injects tracer gas at a highly stable rate has also been designed and tested. One injection system will be used for each tracer gas and one sampler will be employed near each sampling location.

Two tests of the system, excluding the sampler, have been completed. Each test included both a tracer gas step-up and a tracer decay. Four of the six tracer gases yielded the same result (e.g., age of air) within approximately 15 percent. These four tracers also yielded an air exchange rate, or age of air, that differed by no more than 12 percent from a reference measurement made in a well-mixed test space with an orifice plate flow meter. Further work is required to increase the accuracy of our measurements with the remaining two tracers and to verify system performance in general.

6. ACKNOWLEDGEMENTS

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

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