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A Review of Tracer-Gas Techniques for Measuring Airflows in Buildings

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ABSTRACT

This paper describes tracer gas measuring techniques that have been used to characterize ventilation and air infiltration in buildings, with an emphasis on recent developments and applications in large industrial and commercial structures. Fundamentals and applications are presented for both single and multiple tracer gas methods. In addition to techniques suitable for detailed characterization of building airflows, procedures and equipment appropriate to surveying large numbers of buildings are also discussed. Illustrative examples of the various measuring techniques as well as discussion of their advantages and disadvantages are provided. A detailed bibliography is also included to facilitate a more thorough examination of the topics discussed.

INTRODUCTION

This paper provides a review of tracer gas measuring techniques for characterizing infiltration and ventilation rates in buildings. While there have been previous reviews of tracer gas measuring techniques, this paper concentrates on more recent developments and emphasizes the study of large buildings. Many examples of the application of these techniques are also presented.

The following section of the paper provides a brief discussion of the fundamentals of tracer gas measurement including the mass balance theory on which the measurements are based and the three basic approaches, i.e., decay, constant concentration, and constant injection. Multi-chamber theory and applications are also discussed. The third section is on single tracer techniques for the study of large buildings, including both mechanically and naturally ventilated enclosures. The application of the tracer gas decay technique in office buildings is presented as an example, along with other large building applications. The use of the constant injection technique for pressure testing office buildings is also presented. Multiple tracer techniques are discussed in the fourth section as a means of characterizing ventilation in multi-chamber structures and studying interzonal airflow rates. The last section discusses low-cost tracer gas measuring techniques that are useful for the study of large numbers of buildings.

FUNDAMENTALS OF TRACER GAS MEASUREMENTS

Tracer gases have been used to measure air infiltration and ventilation characteristics of buildings for about 30 years, and the various procedures have been discussed previously (Sherman et al. 1980; Hunt 1980; Harrje et al. 1981). Desirable properties of tracer gases have been considered by Honma (1975) and by Hunt (1980), and include detectability, nonreactivity, nontoxicity, and a relatively low concentration in the ambient air. Several techniques used to measure tracer gas concentration are listed in Table 1, along with some of

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the gases appropriate to each method. Tracer gases measured with electron capture detector gas chromatography are commonly used for measurements in large buildings, primarily due to cost considerations, as discussed below; however, measurements have been performed in large buildings using infrared absorption (Potter et al. 1983; Zuercher and Feustel 1983) and flame ionization gas chromatography (Prior et al. 1983).

There are three basic tracer gas techniques: (1) decay; (2) constant concentration; and (3) constant injection. To understand these methods, one employs a mass balance of the tracer gas released within the building. Assuming that the tracer gas mixes thoroughly and instantaneously within the structure, the mass balance equation is

$$V\dot{C}(t) = F(t) - q(t)\,C(t) \tag{1}$$

where V is the building volume, C is the tracer gas concentration (dimensionless), $\dot{C}$ is the time derivative of concentration, q is the volumetric airflow rate out of the building, F is the volumetric tracer gas injection rate, and t is time. The outdoor tracer gas concentration is assumed to equal zero.

The air exchange or infiltration rate I is given by

$$I(t) = q(t)/V \tag{2}$$

where I is in air changes per hour (h^{-1}). The solution to Equation 1 is given by

$$C(t) = C_o \exp\left(- \int_o^t (q(s)/V)\, ds \right) + (1/V) \int_o^t Q(t,t_1)\, F(t_1)\, dt_1 \tag{3}$$

where

$$Q(t,t_1) = \exp\left(- \int_{t_1}^t (q(y)/V)\, dy \right)$$
$$C_o = C(0). \tag{4}$$

In all of the tracer gas techniques, a variety of difficulties and uncertainties can arise in the measurements. They include loss of tracer by means other than leakage, for instance, condensation, chemical reaction, or solution in water. Another problem is imperfect mixing of the tracer gas with the interior air. Equation 1 assumes the tracer gas concentration within the building is uniform and can be characterized by a single value. If this is not true, then measurement errors will result. Some problems of imperfect mixing may be overcome through appropriate multi-point injection strategies.

Decay

The simplest tracer gas technique is the tracer gas decay method, which has been discussed previously by Lagus (1980). This technique is also the subject of a standardized measurement procedure (ASTM 1983). After an initial tracer injection into the structure, there is no source of tracer gas, hence F(t)=0 and Equation 3 becomes

$$C(t) = C_o \exp\left(- \int_o^t (q(s)/V)\, ds \right). \tag{5}$$

Equation 5 can be solved exactly to yield the average infiltration rate from 0 to t,

$$\bar{I}_t = (1/t) \ln \left((C_o/C(t) \right) \tag{6}$$

This technique requires only the measurement of relative tracer gas concentrations, as opposed to absolute concentrations, and the analysis required to determine I is straightforward. The measuring equipment can be located within the structure, or building air samples containing tracer may be collected in suitable containers and analyzed off-site (Grot 1980; Harrje et al. 1982).

Constant Concentration

The constant concentration technique requires the use of automated instrumentation to simultaneously analyze the tracer gas concentration and inject an appropriate quantity of tracer gas to maintain a constant concentration within a building. This technique has been applied by Collet (1981). For constant concentration, i.e., $\dot{C}(t) = 0$, Equation 1 reduces to reduces to

$$C(t) = F/q \tag{7}$$

However, since mixing of the tracer gas within a volume takes a finite amount of time, $\dot{C}(t)$ is never really equal to zero unless $I(t)$ is constant. $\dot{C}(t)$ may be close to zero if $I(t)$ is a slowly changing function of time, and an appropriate injection strategy is employed. Hence, Equation 7 is not an exact mathematical solution and measurements based on this equation will be subject to errors. The magnitude of these errors have not been well examined. An advantage of the constant concentration technique is that it can be used to measure simultaneously the infiltration rates into different zones of a building, as described below in the discussion on multi-chamber measurement.

Constant Injection

The third tracer gas technique is referred to as the constant injection technique in which $F(t)$ = constant. If I is also assumed to be constant, then Equation 3 yields

$$C(t) = (F/q) + (C_o - F/q)\exp(-It). \tag{8}$$

After a sufficiently long time, the transient dies out, i.e., C attains equilibrium, and one obtains the simple constant injection equation,

$$C(t) = F/q \tag{9}$$

This relation is valid only for cases in which the infiltration rate is constant, thus the results obtained with this technique are exact only when the system is in equilibrium. Otherwise, the results will be subject to errors, with the magnitude of these errors depending on the extent of the departure from equilibrium.

Multi-Chamber Approach

Most of the previous discussion applies to structures which are modelled as a single zone. In many cases this assumption is inappropriate and a multi-chamber model must be used (Sinden 1978). A variety of multichamber measuring techniques exist, involving tracer decay, constant concentration, or constant injection techniques, and the use of one or several tracer gases.

The equations describing the multichamber case are similar to Equation 1, except for the addition of airflow between chambers. A mass balance for each chamber yields,

$$V_i\dot{C}_i = \sum_{j=1}^{N} q_{ij}\,(C_j - C_i) - q_{io}C_i + F_i \tag{10}$$

where V_i is the volume of the ith chamber, C_i is the tracer gas concentration in that same chamber, $\dot{C}_i$ is its derivative with respect to time, q_{ij} is the airflow rate from the jth to the ith chamber, q_{io} is the airflow rate from the ith chamber to outside and $q_{ii} = 0$. Note that, as in the case of Equation 1, we are assuming that the outdoor tracer gas concentration is zero. For each tracer gas that is used, there will be another set of these equations, again, one equation for each zone.

The tracer gas decay method can be applied to a multi-chamber building model in order to determine all of the q_{io} and q_{ij}. This is done by releasing a different tracer in each chamber and montioring the concentration response of each tracer in all of the chambers. In order for this technique to provide all the airflows of interest and not yield degenerate equations, the division of the building into chambers, the injection strategy, and the initial conditions must be appropriate.

Alternatively, one can determine all of the q_{io} by applying the constant concentration method simultaneously in all chambers. $\dot{C}_i(t) = 0$ and $C_i(t) = C_i$ for all i, and therefore

$$F_i = q_{io}\,C_i. \tag{11}$$

From this equation one obtains a value of q_{io} for each chamber. The total infiltration rate for the entire building I is determined by simply adding together all of the q_{io}.

SINGLE TRACER TECHNIQUES FOR LARGE BUILDINGS

This section reviews techniques that employ a single tracer gas to measure infiltration and ventilation in large buildings, arbitrarily defined as structures with floor areas greater than about 5000 ft^2 (500 m^2). These buildings may have mechanical ventilation systems or they may be naturally ventilated. The types of large buildings that have been studied include office buildings, industrial buildings such as warehouses and airplane hangers, stores, shopping centers, and institutional facilities such as schools and hospitals. Most of the measurements in large buildings have employed the tracer gas decay method, and this particular application is discussed below. Several other examples of field applications of tracer gas measurement are also presented. The use of a constant injection technique to measure airflow rates in the pressurization testing of buildings is also discussed.

Tracer Gas Decay in Large Buildings

The basic approach of tracer gas decay measurements in large buildings is the same as that described earlier. The tracer gas is released into the building and allowed to mix thoroughly with the interior air. The decay in the tracer gas concentration is monitored over time, and the infiltration rate is determined from the decay rate. Several characteristics of large buildings influence the manner in which the decay method is applied to these structures. First, because of the large building volumes, the quantity of tracer gas required for a test and its cost become important. The expense depends on the cost per ft^3 (m^3) of tracer gas, the building volume, and the magnitude of measurable tracer gas concentrations. Table 2 shows the range in the maximum building volume that can be measured for one dollar's worth of tracer gas (1985 prices). These volumes range from about 4000 ft^3 (400 m^3) for helium in the 300 parts per million (ppm) range, to about 10^6 ft^3 (10^5 m^3) for carbon dioxide and nitrous oxide. The ability to measure SF_6, $CBrF_3$ and PDCH in the range of parts per trillion (ppt) yields measurable volumes of 10^8 to 10^{10} ft^3 (10^7 to 10^9 m^3) per dollar's worth of tracer gas. From this table it is apparent that tracer gases such as SF_6, refrigerants, and perfluorocarbons analyzed at ppt, or even parts per billion, are most appropriate for large buildings.

The mixing of the tracer gas injection in these large building volumes is an important issue. Mixing by diffusion alone is a slow process; however, even in naturally ventilated buildings, there are significant convective mixing mechanisms. In mechanically ventilated buildings the air distribution system can be used to mix the tracer gas, but it can still take 15 minutes to an hour. In naturally ventilated buildings, tracer gas mixing is a more difficult problem. If the building interior is open with few internal partitions, then the gas will mix with the air, although it can take several hours. Fans can be used to mix the tracer, but they will alter interior air movement patterns, which may affect the building infiltration rate. The fans may be used to obtain an initially uniform concentration, and then be turned off during the decay. The attainment of a uniform concentration can also be assisted by injecting the gas at several locations. The only way to determine if good mixing has been achieved is to measure the tracer gas concentration at several locations within the building.

In mechanically ventilated buildings, fan operation and damper position are important issues. Most of these buildings have automatic control systems, which turn fans on and off, modulate airflow rates, and adjust exhaust, recirculation, and supply damper positions. Thus, to conduct meaningful tracer gas measurements and interpret the results, one must be aware of the fan operating schedules and ventilation control strategies. Procedures intended to provide long-term averages of infiltration rates must be designed with reference to the fact that fans turn off, damper positions change, and the amount of outside air intake varies greatly, even within a single day.

Finally, one may make either long-term, continuous measurements in a building or only a small number of individual tests. Long-term studies are useful for examining the dependence of air leakage on weather and the performance of ventilation control systems. When making long-term measurements, one's equipment, sensors, and air-sampling lines must be unobtrusive with regard to the building occupants and the automatic operation of building equipment.

Tracer Decay Measurements in Office Buildings

In this section we discuss the application of tracer gas measurements in mechanically ventilated office buildings, along with other examples of infiltration measurements in a variety of large buildings. The example of measurements in a mechanically ventilated office building involves the use of automated equipment to conduct long-term, continuous measurements of infiltration and ventilation (Grot et al. 1980; Grot 1982). The tracer gas equipment is generally located in the building's mechanical equipment room where the main air handlers are located. Figure 1 is a schematic of such a building with the mechanical equipment room located in a penthouse. Most office buildings have separate air handlers, for spaces such as lobbies, which may be located some distance from the main mechanical equipment room. Such an air handler is shown in the figure. In order to obtain a uniform tracer gas concentration throughout the building, one must inject tracer into all the supply fans. This requires the installation of injection tubing from the measuring equipment to each supply fan.

As seen in Figure 1, the tracer gas concentration is measured at several locations within the building in order to verify that the tracer is indeed well mixed. For example, one may sample in the building's main return duct, on individual floors, and in the return ducts of any other air handlers. One installs air-sample tubing connecting the measuring equipment to each of the sampling locations and uses pumps to bring the air to the measuring equipment. The individual floor sampling locations can be in the return air plenums immediately upstream of the return air shafts. In order for these sampling locations to give meaningful concentration measurements, the air handlers must be operating. Since building geometry and air-handler arrangements vary greatly among buildings, tracer injection and air-sampling locations are different for each building.

In office buildings there are two types of measurements that are of interest, referred to here as ventilation and infiltration. Ventilation rates refer to measurements made when the building HVAC system is operating normally under occupied conditions. In this case the various spill and intake dampers open or close as the control system dictates in response to inside and outside temperature and humidity and time of day. Infiltration rates refer to the measurements obtained when the spill and intake dampers are closed (including any minimum outside air dampers) and the fans are running. These test results give an indication of the airtightness of the building envelope. The operation of the fans during these measurements is necessary for mixing and may have an effect on the test results.

Short-term measurements can also be made in office buildings using injection and sampling by hand. The tracer is injected into the supply fans and air is collected in containers at locations throughout the building. The tracer gas concentrations in these containers are then determined at some later time. This "manual" technique has a shorter setup time than the automated procedure described above, but each infiltration measurement must be made by hand.

Long-term automated infiltration and ventilation measurements have been made in ten mechanically ventilated office buildings (Grot 1982; Grot and Persily 1983), among other studies. In these tracer gas decay tests, hourly average infiltration and ventilation rates were measured for hundreds of hours in each building and the results were related to inside-outside temperature difference and wind speed. The infiltration rates of the different buildings were found to exhibit varying degrees of weather dependence, and there was a range in the airtightness of the building envelopes.

The tracer gas decay technique has been applied in an 11-story office building, employing hand injection of the tracer gas and sampling of the interior air with polyethylene bottles (Harrje et al. 1982). The tracer gas concentration in the bottles was later determined at a central location. The air was sampled on four different floors and in the main return duct of the air handler. Only a small number of measurements were made in the building, but the results demonstrated the utility of this "air sample container" technique in large buildings.

A small number of industrial buildings have also been studied with the tracer gas decay technique. These buildings are often characterized by large open volumes, such as warehouses, where tracer gas mixing can take a long time and is assisted by multi-point injection and the use of fans. In a study of three large, naturally ventilated single-zone structures in England, a fan was used to mix the tracer gas (Waters and Simons 1984). A uniform tracer gas concentration throughout the space was generally obtained within about 20 or 30 minutes after injection, although some spatial variation did remain. A series of tracer gas decay measurements in airplane hangers has also been conducted (Ashley and Lagus 1984).

There are other examples of the use of tracer gas in large buildings (Potter et al. 1983; Zuercher and Feustel 1983). In one particular application, a constant injection scheme with gas bag sampling of the interior air was applied to a laboratory building (Freeman et al. 1983). In these measurements, tracer gas was injected at a constant rate at 12 locations and the equilibrium tracer gas concentration was determined from air sample bags filled at 12 other locations. This "bag sample equilibrium" method was compared to measurements based on tracer gas decay, and the agreement was good when mixing was thorough.

Pressurization Testing of Large Buildings

The constant injection technique has been used to measure airflow rates in the evaluation of the airtightness of large building envelopes using pressurization testing. In pressurization testing, a fan induces a large pressure difference across the building envelope, and the airflow rate required to induce the pressure difference is measured. The airflow rate associated with a specific inside-outside pressure difference is a measure of the airtightness of the building shell. The airflow can be induced with a large fan, which is brought to the building for the test, or with the building's air-handling equipment. Various means exist for measuring the airflow rate through the fan, but a constant injection tracer gas method has been used in some cases. This is a simple technique, which does not require the duct lengths and flow straighteners associated with other flow-measuring techniques.

To measure the airflow rate with the constant injection tracer gas method, tracer gas is injected into the airstream at a constant and known rate. The tracer injection is generated using a compressed gas cylinder with a flowmeter such as a critical orifice, a float-type rotameter, or an electronic flow controller. The tracer concentration is then measured as far downstream as possible from the injection point. Under conditions of perfect mixing of the tracer gas and the airflow, the airflow rate can be determined from the tracer injection rate and the measured concentration (see Equation 9).

Several large industrial buildings have been pressure tested using a fan brought to the buildings and employing the flow-measuring technique described above (Lundin 1984). Figure 2 shows a schematic of the flow-measuring equipment used in these tests. The same flow-measuring procedure was applied to seven modern office buildings in which the building supply fans were used to pressurize the structure (Persily and Grot 1984a). Figure 3 shows a schematic of the test arrangement including the fan operating conditions, damper positions, tracer gas injection location, and tracer gas concentration measurement point.

MULTIPLE TRACER TECHNIQUES

The above tracer gas measurement techniques generally employ a single zone model of a building. In some cases, a single zone is not adequate to model a building's infiltration characteristics, or one is interested in the airflows between the various zones of a building. In these cases, multi-chamber building models and multiple tracer gas measurement techniques are used. The use of multiple tracer techniques for building airflow studies began in the middle seventies. Multiple tracer measurements often involve the use of gas chromatographs designed to determine simultaneously the concentration of the different gases; however, separate continuous infrared analyzers have also been successfully used for simultaneous analysis of SF_6, CO_2 and N_2O (Perera et al. 1983).

An illustration of the simultaneous chromatographic separation of six refrigerants is provided in Figure 4. Note that the time for a single measurement of the six gases is on the order of ten minutes. A throughput time of this magnitude may preclude the use of a single gas chromatograph in a constant concentration measurement. If one desires analysis times on the order of minutes, it is necessary to have several gas chromatographs available.

Multiple tracer gas measuring systems have been developed using both decay and constant injection techniques. In decay measurements, a tracer or several tracers are released at various locations as pulses, and their concentrations are monitored in the various zones over time. Several measurement systems employing the decay method have been developed, including those of Prior et al. (1983) and Irwin et al. (1984). Both systems employ gas chromatograph electron capture detectors, to measure refrigerants in the first system and perfluorocarbon tracers in the latter. I'Anson et al. (1982) also employs a decay system involving refrigerant tracers. In Figure 5 we show representative data from their paper in which two tracers are used to study the airflow between the upper and lower levels of a building. The refrigerant $C_2Cl_2F_4$ is injected downstairs and CCl_2F_2 upstairs. The movement of tracer between the zones and the subsequent decay is evident in the data. Analysis of these data yields the airflow rates between the two zones and from each zone to the outside.

A constant injection technique has been employed by Dietz and Cote (1982) and Dietz et al. (1984a) using several perfluorocarbon tracers and passive samplers. In these measurements a different tracer is released at a constant rate into each zone and the average concentration in all zones is determined over the measurement period. From the injection rates and the average concentrations, one determines the airflows of interest. Figure 6 is an example of measured airflows for a two-zone case using this technique (Dietz et al 1984a).

There have been other multiple tracer studies including those of Foord and Lidwell (1973 and 1975) studying ventilation rates and interzonal airflows in hospitals. Lagus (1977) suggested the use (shown in Figure 7) of multiple tracer gases in multi-story buildings for evaluating simultaneously infiltration rates on individual floors and airflow rates between floors by injecting a different tracer on each of three adjacent floors. Lagus (1982a, 1982b) has used multiple tracers to study ventilation effectiveness and hazardous containment integrity of forced ventilation systems within a chemical process, industrial plant environment. A similar approach has been used to demonstrate the degree of ventilation/isolation of a process control computer room in a pulp mill (Lagus 1981). Figure 8 shows an example of a constant injection measurement of ventilation and interzonal airflows in two adjacent, negative pressure laboratory rooms (Lagus 1984). The two laboratories are under negative pressure (as shown in the figure), and a different tracer gas is injected into each laboratory at a constant rate. The equilibrium tracer concentrations in each zone are also shown in the figure. The measured airflow rates agree well with the ventilation rates measured by tracer decay. In addition, note the flow of the refrigerant $CBrF_3$ into the lower laboratory. This evidence of undesired airflow between the laboratories led to the laboratory owner taking remedial action.

In many of these applications, it should be noted that one does not require the full solutions to Equation 10 to obtain useful information. For instance, documentation of ventilation-induced isolation, demonstration of ventilation-induced hazardous containment integrity, and characterization of inadvertant recirculation are examples of the information obtainable without resorting to a full solution of Equation 10.

LOW-COST TRACER GAS TECHNIQUES

The various tracer gas measuring techniques described above involve bringing sophisticated equipment for measuring tracer gas concentrations to the building under investigation. Long-term measurements require one to leave this equipment in the building for extended periods of time. These studies provide immediate results and much detail, but they occupy expensive equipment and require highly skilled professionals for installation. Several low-cost tracer gas measuring techniques have been developed, which are useful for surveying the air leakage characteristics of large numbers of buildings. In addition, the field procedures can be handled by less well trained people. These techniques provide less information than long-term studies, but in some cases the data collected are adequate. The low-cost procedures generally involve some device for on-site air sampling, with the tracer gas concentration of the air sample being subsequentially determined at some central location. Thus, a single tracer gas measuring device can be used to obtain infiltration measurements in many buildings. Most of these techniques have been applied to homes, but they can also be used in large buildings.

Decay Methods

Low-cost tracer gas decay techniques are based on the same principles as other decay methods, and have been described previously (Grot 1980; Harrje et al. 1982; Tamura and Evans 1983). They involve injection of the tracer gas into the building at an appropriate location, or locations, to facilitate the achievement of a uniform tracer gas concentration throughout the structure. After sufficient time is allowed for this mixing, air-sample containers are filled at roughly equal time intervals. The containers are then sent to a central laboratory where the tracer gas concentration of each sample is measured. From the decay rate of the tracer gas concentration, one determines the average air infiltration rate during the measurement period. The tracer gas injection and the air sampling require careful attention by the field personnel, but the procedures themselves are not difficult. A variety of specific containers have been used including 30.5 in^3 (500 mL) flexible polyethylene bottles (Harrje et al. 1982), 600 in^3 (10 L), five-layer air sample bags (Grot 1980; Persily and Grot 1984b), and 1.2 in^3 (20 mL) evacuated blood sample tubes (Tamura and Evans 1983).

These low-cost decay methods have generally been applied to homes, but larger buildings have also been tested. A study of an 11-story office building using the "bottle technique" has been mentioned earlier (Harrje et al. 1982).

The low-cost of these techniques has enabled several surveys of the air-leakage characteristics of large numbers of homes. In these surveys a small number of tracer gas decay tests are conducted in each home under a range of outside weather conditions. One study measured air infiltration rates in over 200 homes in low-income areas of the U.S. (Grot and Clark 1979). Another survey examined more than 50 passive solar homes (Persily and Grot 1984b). The low-cost of these measuring techniques enables the testing of large numbers of homes spread over a large geographical area with a single tracer gas concentration measuring device.

Constant Injection Methods

Low-cost air infiltration measuring techniques based on the constant injection of tracer gas into a building have been developed. In these procedures, a tracer gas is injected at a constant rate and the interior air is continuously sampled to determine the average tracer gas concentration in the building over the sampling period. The average concentration and the injection rate are combined to determine the average infiltration rate over this same time period. In the low-cost versions of this technique, relatively simple devices are used for tracer gas injection and air sampling, while the tracer gas concentration of the air sample is determined with equipment at a central facility.

One version of the constant injection technique is the average infiltration monitor (AIM) developed at the Lawrence Berkeley Laboratory (Harrje et al. 1981). This system employs suitcase-sized injectors and samplers to enable unattended measurement of long-term average infiltration rates. The injector contains a pump that slowly releases the tracer gas at a constant rate into the building. The sampler slowly fills a sample bag to obtain the average tracer gas concentration during the measurement period. The concentration in the sample bag is later determined at a central location. Another technique employs small passive injectors and samplers in a similar procedure. The Brookhaven National Laboratory Air Infiltration Monitoring System (BNL/AIMS) employs perfluorocarbon tracer gases (PFT) which diffuse out at at a known and constant rate from a fluoroelastomer plug impregnated with the tracer (Dietz and Cote 1982; Dietz et al. 1984a, 1984b). The passive sampler is a small capillary adsorption tube, which collects the PFT from the building interior during the test. The sampler is later analyzed to determine the average tracer gas concentration in the building and, hence, the average air infiltration rate.

The application of these constant injection, long-term averaging techniques to large buildings requires that several tracer sources be used and that they are well-distributed throughout the building. Several samplers are also required. In mechanically ventilated office buildings, the intermittent operation of fans and changing damper positions must be considered when using these techniques.

CONCLUSIONS

In this paper we have attempted to describe recent applications of tracer gas measuring techniques to characterize infiltration and ventilation in buildings, with particular attention given to large buildings. There are presently a large variety of ways to study air exchange in buildings, and a range in experimental cost, complexity, and completeness of the data obtained.

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TABLE 1
TRACER GASES AND MEASURING TECHNIQUES

Technique	Gases
Thermal Conductivity Detector	H_2, He, CO_2
Electron Capture Gas Chromatograph	SF_6, Refrigerants, Perfluorocarbons
Flame Ionization Gas Chromatograph	C_2H_6
Infrared Absorption	CO, CO_2, SF_6, N_2O, C_2H_6, CH_4

TABLE 2
RELATIVE GAS COSTS TAKING DETECTABILITY INTO ACCOUNT

Gas	Detectable Concentration (ppm)	Gas Volume Per Dollar		Maximum Measureable Volume Per Dollar	
		ft3	(m3)	ft3	(m3)
He	300	1.4	(0.13)	4×10^3	(4×10^2)
CO_2	1	7.0	(0.65)	6×10^4	(6×10^5)
N_2O	1	2.4	(0.22)	2×10^6	(2×10^5)
SF_6*	5×10^{-6}	0.13	(1.2×10^{-2})	2×10^{10}	(2×10^9)
"	5×10^{-3}	"	"	2×10^7	(2×10^6)
"	1	"	"	1×10^5	(1×10^4)
$CBrF_3$	5×10^{-5}	3.7×10^{-2}	(3.4×10^{-3})	7×10^8	(7×10^7)
PDCH**	5×10^{-6}	3.0×10^{-3}	(2.8×10^{-4})	6×10^8	(6×10^7)

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* The three detectable concentration levels for SF_6 are based on different concentration measuring devices. 5×10^{-6} is based on electron capture gas chromatography with a measurement time of about 5 minutes. 5×10^{-3} is also based on electron capture detection with a one minute measurement time. 1 ppm is based on detection with IR adsorption.

** perfluorodimethylcyclohexane

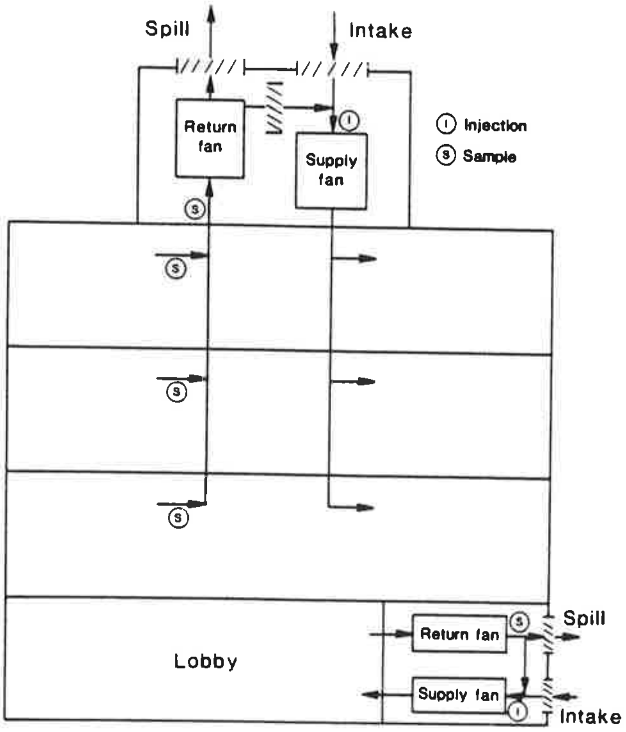


Figure 1. Schematic of tracer gas measurement in a mechanically ventilated building

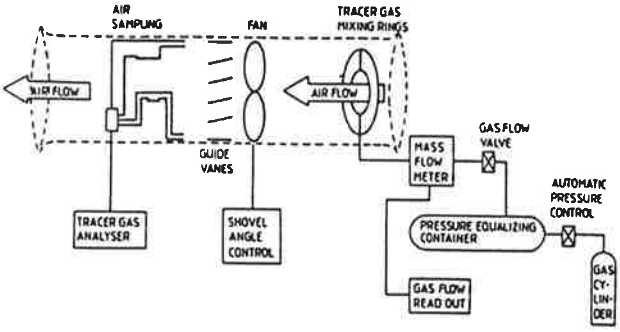


Figure 2. Schematic of constant injection flow measurement system (Lundin 1984)

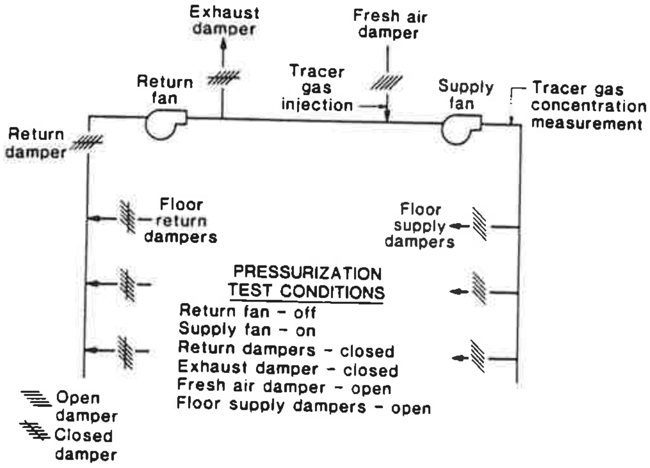


Figure 3. Schematic of building pressurization test arrangement

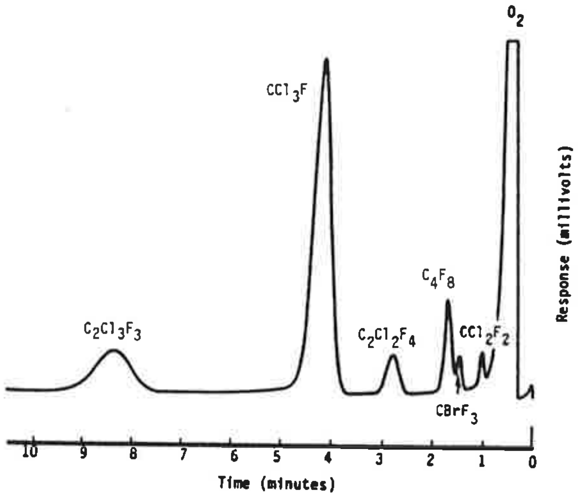
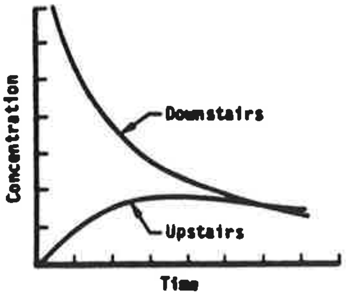
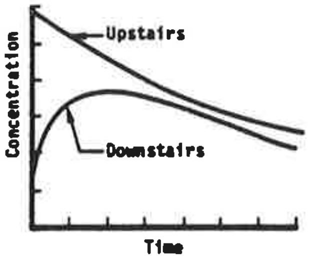


Figure 4. Multiple tracer gas chromatograph separation



Concentration of $C_2Cl_2F_4$ against time, upstairs and downstairs



Concentration of CCl_2F_2 against time, upstairs and downstairs.

Figure 5. Representative two tracer data (I'Anson et al 1982)

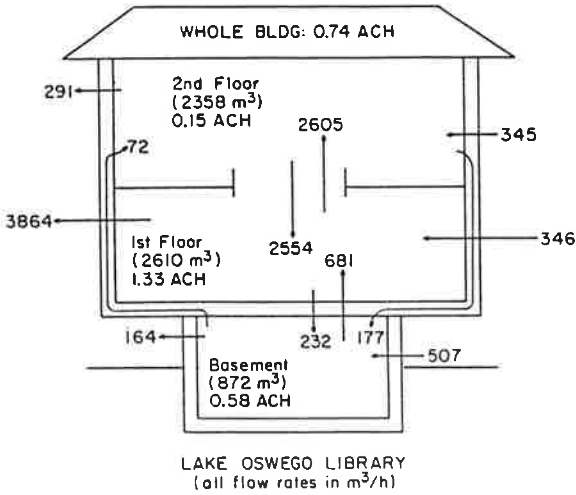


Figure 6. Flow rates measured in multi-tracer tests (Dietz et al 1984a)

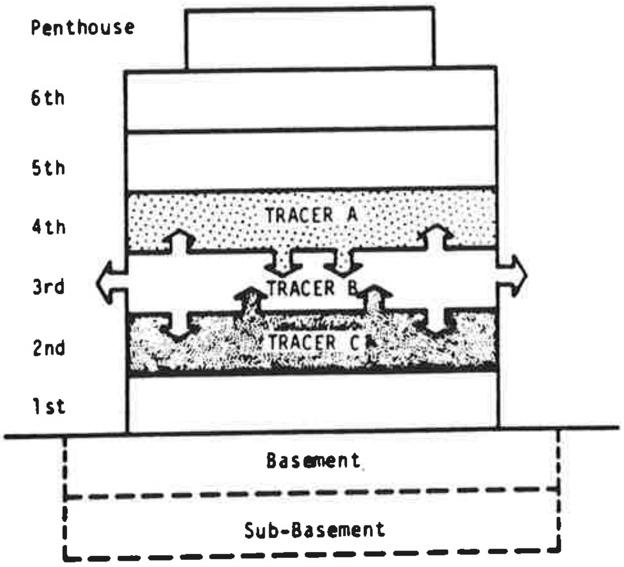


Figure 7. Multi-tracer "sandwich" tests

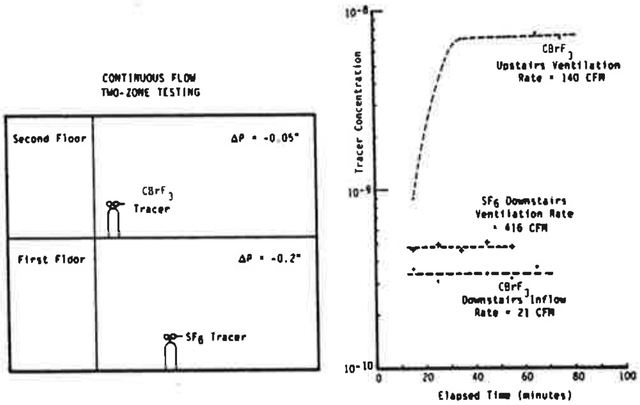


Figure 8. Constant flow experiment to determine ventilation and interzone flow rates (Lagus 1984)