

Protocol for Measuring the Air Change Rate in Non-residential Buildings

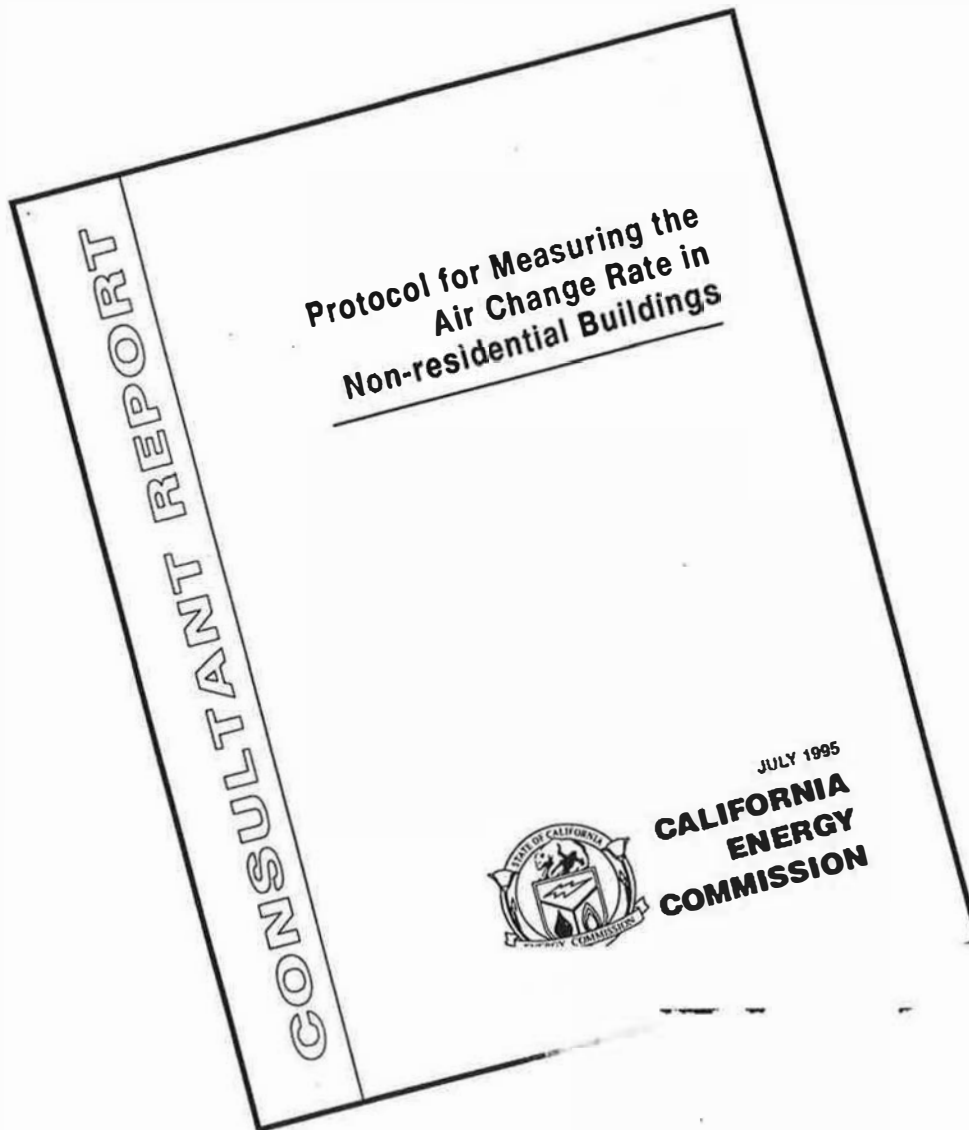
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1 Summary of Measurement Techniques

This report describes various measurement protocols to be used in the measurement of air change rates in non-residential buildings. The measurement protocols are based on the use of tracer gas techniques. Tracer gas techniques are the only accurate methods which can be used to measure the quantity of outside air being supplied to a building.

The purpose of the measurement protocol is to formulate a test procedure by which the air change rates in non-residential buildings can be measured in a study which is to determine the effects of various California Energy Codes on the air change rates of non-residential buildings. The test protocol is designed to be carried out over a one or two day period by a team of field technicians experienced with tracer gas measurements, field data collection in buildings and building HVAC systems. The protocol is designed so that measurements are non-intrusive to the occupants of the buildings. The buildings will be tested under at least two operating conditions: (1) the normal occupied operating conditions of the building for the existing occupancy and weather conditions during the tests, and (2) the minimum outside air operating setting possible for the building's HVAC control system. This report describes three tracer test methods: the tracer decay method, the constant injection method and the buildup/decay method. If only the tracer decay method is used, the building will be evaluated under two additional operating conditions when the building is not occupied: (3) the condition with the building exhaust fans off and all air intakes sealed and building's HVAC system fans operating, and (4) the condition with all HVAC system and exhaust system fans off. The results of the tests will produce (1) the total air change rate of the building during the conditions of the tests, (2) the air change rate due to the operation of the building's HVAC system, (3) the air change rate due to air infiltration and leakage, and (4) the percent of outside air supplied by the building's HVAC system.

In the evaluation of the performance of ventilation systems, tracer gas methods can be also be used for

- Measuring airflow rates in ducts
- Evaluating ventilation effectiveness

It is not the intention of this test protocol to describe how these two additional measurements should be accomplished. Tracer gas methods may be used to measure the air flow through HVAC systems and fans if these flows are required to determine four required measurement results and more traditional air testing and balancing procedures are not practical, feasible or accurate for the building being tested.

The buildings to be tested are from four climate zones in the State of California: the northern coastal region, the northern interior valley region, the southern coastal region and the southern interior valley region. Twelve buildings from each climate region are to be tested in the initial field phase of this project. The types of buildings to be tested are: office buildings, retail establishments and schools. The sample of buildings in each region is to be divided into two groups: one group of eight buildings consisting of small retail and office buildings and schools and a second group consisting of large retail and office buildings. Candidate buildings for the field phase of this project have been selected under a previous contract to the California Energy Commission.

Basic Principles of a Tracer Gas Measurement

A basic tracer gas test is performed by introducing a gaseous tracer not normally present in either the interior air of the building or the exterior ambient air into a building and measuring its rate of buildup and/or decay. For most North American buildings, a tracer gas test is the only accurate method to determine the total outside air intake to a building. There are several reasons for this: 1) most North American buildings mix the outside air with recirculated air from the building and provide no access to measure the outside air directly using standard air testing and balancing procedures, 2) much of the outside air supplied to even a mechanically ventilated building comes through paths other than the mechanical system's ducts such as windows, leakage of the envelope, doorways and other entrance ways, 3) short circuiting and by-passing of the mechanically supplied outside air often occurs and 4) there is often unintentional reentrainment and recirculation of exhausted building air. A properly performed tracer test can overcome these shortcomings.

The basis of a tracer gas test is the principle of conservation of mass: the conservation of mass for the air entering and leaving a building and the conservation of mass for the tracer specie introduced into the building. Tracer gas evaluations are usually performed using one of three methods: 1) The tracer decay method in which tracer is injected once into the building for a short period of time, allowed to mix with the building air and its rate of decay measured. The tracer decay method produces a direct measurement of the building's air change rate. With proper sampling, the percent of outside air in the HVAC system's supply air can also be determined during a tracer decay test. 2) The constant injection method in which tracer is injected continuously using a metering device and the buildup of tracer is measured until an equilibrium value is obtained. This method produces a direct measure of the total outside air flow rate for the building. With proper sampling, this method can also produce a direct measurement of the mechanical system's supply air flow rate, the percent of outside air in the supply air and the air infiltration to the building's occupied zone measured as a percent of the mechanical system's supply air flow rate. 3) The constant concentration method in which a feedback control strategy is used to control the injection of tracer so that the concentration in the building remains constant. This method can provide the total outside air flow rate to individual zones of the building. It requires however sophisticated tracer monitoring and injection equipment and is usually often used for research purposes. It should be noted that none of the above methods requires, if proper data analysis techniques are used, that the outside air flows are constant during the test. However, this assumption is usually made. In addition to the three methods listed above, this report also discusses a hybrid of the tracer decay and constant injection method, called here the buildup/decay method. In this method a constant metered injection of tracer is performed for a period of time and the buildup of tracer monitored. The injection is then turned off and the decay of tracer measured. This method overcomes some of the traditional shortcomings of the tracer decay and constant injection method and produces both a direct measurement of the air change rate, outside air flow rate and with proper sampling the percent of outside air in the supply air, the percent of air infiltration and the HVAC system's supply air flow rate. The choice of which method to use depends of the building's configuration and the availability of accurate tracer gas metering equipment and monitoring equipment. For buildings with many isolated zones, air change rates of less than one air change per hour, or buildings without mechanical ven-

tilation, the tracer decay method is the only practical method. For buildings with few (less than four) zones and high air change rates the constant injection or the buildup/decay method will produce more information in a shorter period of time.

Characteristics of a Desirable Tracer Gas

Though in principle any gaseous substance not normally found in the area being measured can be used as a tracer gas, the desirable properties of a substance used as a tracer in occupied buildings are that it be:

- Non-toxic and non-allergenic at the levels used
- Chemically inert, odorless and tasteless
- Non-flammable and non-explosive
- Not naturally present in the building nor as a normal constituent of air
- Easily transported and dispersed as an atmospheric gas
- Easily and economically measured with high reliability
- Measurable by established experimental techniques which preclude interference with air
- Commercially available.

Physical Properties of a Tracer Gas

Historically, helium, hydrogen, methane, carbon dioxide, carbon monoxide, nitrous oxide and even radioactive gases have been used as tracers for ventilation and airflow studies. Currently, the most commonly used tracers are sulfur hexafluoride, halogenated refrigerant compounds and perfluorocarbons. These gases are electronegative tracer gases which can be detected by electron capture gas chromatographs. They have most of the properties of an ideal tracer. They can be detected from the parts per million range to the parts per trillion range. There are several methods which can be used to measure tracer concentrations. These are listed in Table 1.1. In selecting a tracer gas detector and designing one's measurement procedure several characteristics of the detector need to be considered including the range of detectable concentrations, the device's analysis time, the required airflow rate of the sampling device, and the need for expendable supplies such as compressed gas or other chemicals. Table 1.2 gives the relative costs for several tracer gases. As can be seen by examining the data in Table 1.2, very large volumes can be measured at reasonable cost if gas detection equipment with measurement capabilities in the ppb or ppt range are used. Note that the column labelled "Detectable Concentration" should not be interpreted as "minimum detectable concentrations" as reported by some manufacturers but as the value at which accurate measurements (5 percent or less) can be made. The authors have successfully performed ventilation tests in buildings which have volumes over 10 million cubic feet. Table 1.3 lists the currently used tracer gases which can be used to measure airflows in large buildings at modest costs by using small quantities of tracer.

Instrumentation Required

Figure 1.1 outlines the instrumentation required to perform a tracer gas test of a building ventilation system. The basic instrumentation and materials required to perform tracer gas evaluation of ventilation systems are 1) suitable quantities of tracer gases, 2) a tracer gas concentration measuring device, 3) air sampling and sample collection system, 4) tracer gas injection systems and 5) a data acquisition and control system. The sophistication of the system depends on the application. It can be as simple as series of air sampling containers and syringes with all analysis done in a laboratory off-site or as complicated as automated micro-processor controlled injection, multi-point sampling, data analysis and recording system used to generate data unattended over long periods of time.

In general, the evaluation of building ventilation systems requires the measurement of tracer concentrations over time at several locations in the building. This requires an air sampling system or network (Figure 1.2). The complexity of this sampling network can vary from simple manual collection systems using syringes or air sample bags to complex permanently or semi-permanently installed network of tubing, sampling manifolds and sample pumps which bring air samples from remote locations to a central point. In mechanically ventilated buildings, the building air handling system can be used as a sampling network. The decision on which type of system to use depends on the goals, resources and accuracy required by the investigation and the complexity of building being evaluated. If one requires only a one-time evaluation of a system, manual collection of data is usually the most cost effective, though in complex facilities this procedure is labor intensive.

A method for the injection of tracer into a building is also required. In mechanically ventilated buildings the injection is usually accomplished using the building air handling systems (Figure 1.2). The tracer is injected into each air supply system. In complex, compartmentalized buildings individual injections into each zone of the building is often the only method which can be used for injection of tracer. It should be emphasized that the injection of tracer into the building must be planned carefully if uniform initial concentrations are to be obtained in a reasonable length of time. This is often overlooked in the technical literature where emphasis is usually given to mixing devices such as circulating fans. The steps in planning an injection strategy for an investigation are: calculate the volume of each separate zone of the building, determine which zones are served by which air handling systems, determine the target concentration desired and calculate the quantity of tracer needed to reach the target concentration. In manual injection, it is good practice to use partial injections of the tracer in many locations in the volume being studied in order to obtain uniform mixing quickly. When using the building ventilation system, inject the tracer over a period of at least five minutes unless one is performing pulse tests. Certain safety considerations should also be considered. The indoor air quality concentrations should not be exceeded for the tracer used. This means that one should keep the level of a tracer to less than 1/10th the TLV and it is good practice to keep it below 1/100th the TLV. If automated injection systems are used, a safe design requires that 1/10th the TLV not be exceeded even if all tracer in the container is released at once. Information which can be calculated from a tracer gas evaluated of a building ventilation system is shown in Figure 1.3.

Table 1.1
Tracer Gases and Measurement Techniques

<u>Technique</u>	<u>Gases</u>
Thermal Conductivity Detector	Hydrogen Helium Carbon Dioxide
Electron Capture Gas Chromatograph	Sulfur Hexafluoride Halogenated Compounds Perfluorocarbons
Flame Ionization Gas Chromatograph	Ethane Methane
Infrared Absorption	Carbon Monoxide Carbon Dioxide Sulfur Hexafluoride Nitrous Oxide Ethane Methane

Table 1.2
Relative Tracer Gas Costs for a Tracer Decay Test Taking Detectability and Ambient Levels into Account

Gas	Working Concentration (ppm)	Gas Volume Per Dollar		Maximum Measurable Volume Per Dollar	
		ft ³	(m ³)	ft ³	m ³
He	7500	1.4	(0.13)	16	1.6
CO ₂	2000	7.0	(0.65)	3500	350
N ₂ O	25	2.4	(0.22)	8·10 ⁴	(8·10 ³)
SF ₆	5·10 ⁻³	0.13	(1.2·10 ⁻²)	2.6·10 ⁷	(2.6·10 ⁶)
"	25	"	"	7200	720
CBrF ₃ [*]	5·10 ⁻³	3.7·10 ⁻²	(3.4·10 ⁻³)	7·10 ⁶	(7·10 ⁵)
PDCH ^{**}	5·10 ⁻³	3.0·10 ⁻³	(2.8·10 ⁻⁴)	6·10 ⁶	(6·10 ⁵)

^{*} bromotrifluoromethane (Freon 13B1)

^{**} perfluorodimethylcyclohexane

Working Concentration is Target Level for the Start of a Tracer Decay Test

Table 1.3. Electronegative Tracer Gases

Name	Symbol	Trade Name
Dibromodifluoromethane	CF_2Br_2	Freon 12B2
Trichlorofluoromethane	CFCl_3	Freon 11
1,1,1,-Trichlorotrifluoroethane	$\text{C}_2\text{Cl}_3\text{F}_3$	Freon 113
Bromotrifluoromethane	CF_3Br	Freon 13B1
Octafluorocyclobutane	C_4F_8	Freon C-318
Dichlorodifluoromethane	CCl_2F_2	Freon 12
1,2-Dichlorotetrafluoroethane	$\text{C}_2\text{Cl}_2\text{F}_4$	Freon 114
Chlorodifluoromethane	CHClF_2	Freon 22
Chloropentafluoroethane	CClF_2CF_3	Freon 115
Bromochlorodifluoromethane	CBrClF_2	Freon 12B1
Sulfur Hexafluoride	SF_6	
Perfluorodimethylcyclohexane		PDCH
Perfluoromethylcyclohexane		PMCH
Perfluoromethylcyclopropane		PMCP
Perfluorodimethylcyclobutane		PDCB

General Tracer Measurement System

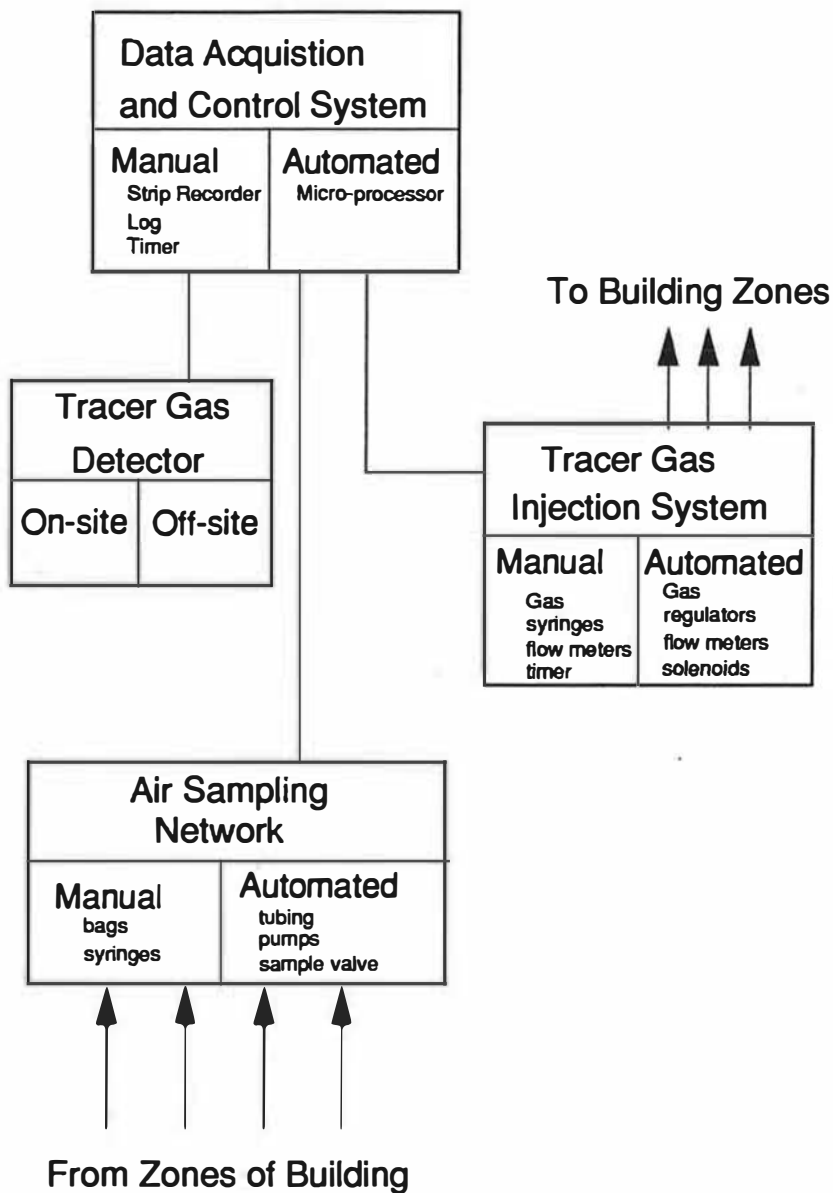
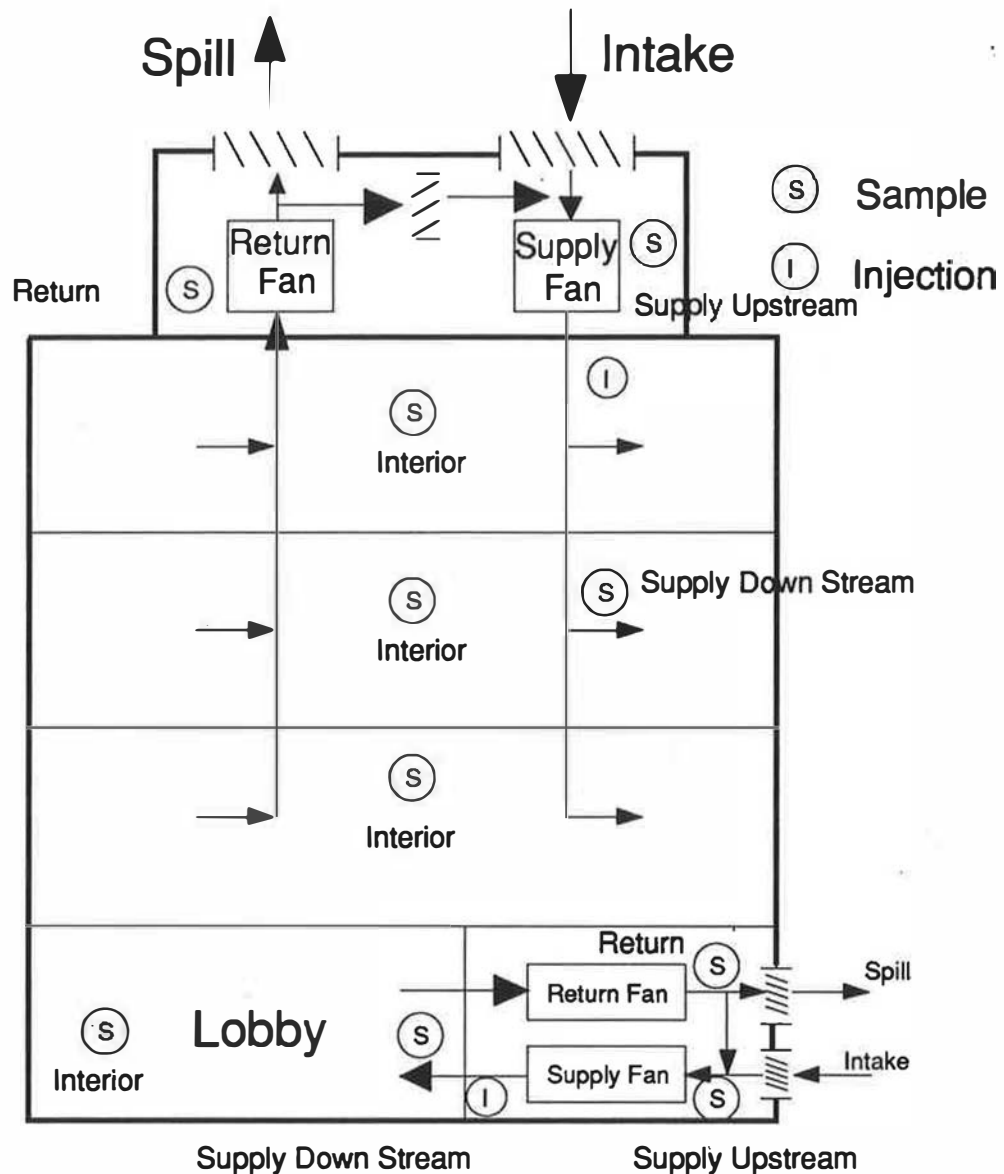


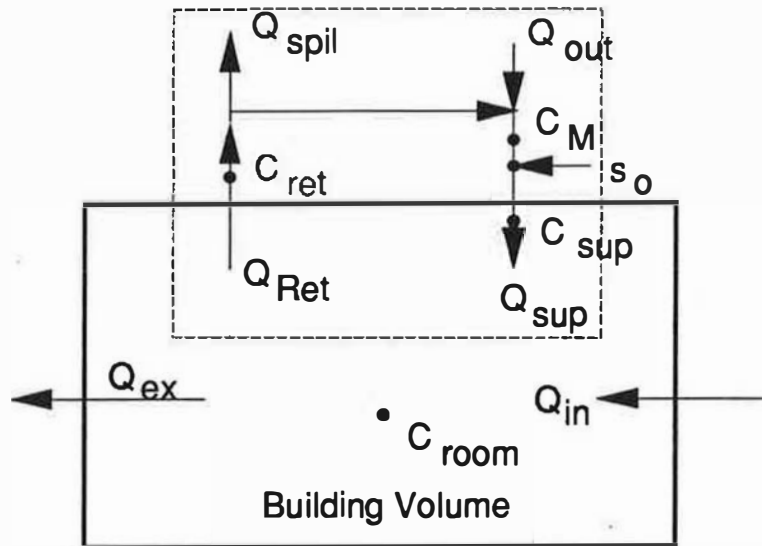
Figure 1.1 A Schematic of the Instrumentation Required for a Tracer Measurement of Building Air Change Rate



Schematic of Building Ventilation System

Figure 1.2 A Schematic of a HVAC System Used for Tracer Sampling and Injection in a Large Building

Air Handling System with recirculation



Equations

Percent Outside Air

$$\% = 1 - \frac{C_M}{C_{Ret}}$$

Air Infiltration

$$Q_{in} = Q_{sup} \left(\frac{C_{sup}}{C_{room}} - 1 \right)$$

Supply Airflow

$$Q_{sup} = \frac{s_o}{C_{sup} - C_M}$$

Figure 1.3 A Schematic of a Zone of a Building Served by an Air Handler. The equation for the air infiltration is only valid after equilibrium has been obtained.

2 Theoretical Basis for Techniques

The theoretical assumptions which form the basis for tracer gas testing of single zone buildings can be explained by studying Figure 2.1. In this situation, there is one well mixed zone in which air is entering through known or unknown flow paths at a flow rate Q_{in} and exiting the space through known or unknown flow paths at a flow rate Q_{out} . If a tracer gas is introduced into the space, the basic equation for a tracer gas concentration $C(t)$ in the zone is given by the conservation of mass of the tracer in the zone:

$$\frac{d}{dt}(\rho V C) = C_0 Q_{in} - C Q_{out} + s \quad (2.1)$$

where

ρ is the density of air in the zone (moles of air per m^3)

V is the volume of the zone in m^3 .

C is the concentration of the tracer per unit mass of air (moles of tracer gas per mole of air)

C_0 is the concentration of tracer in the region exterior to the zone in the same units as C

Q_{in} is the mass flow rate of air into the zone from the exterior (moles of air per second)

Q_{out} is the mass flow rate of air out of the zone (moles of air per second)

s is the generation rate of tracer in the zone (moles of tracer per second)

The basic assumptions leading to the derivation of equation (2.1) are:

- The tracer gas in the zone is well mixed and therefore can be represented by a concentration density independent of the spatial position in the room.

Note: This assumption can be relaxed somewhat to the assumption that the average concentration in the zone is the same as the average value of the tracer in the airflows out of the zone

- The air in the room is of uniform density which is independent of the spatial position in the room.

Note: To this point, no assumption has been made as to the temporal dependence of the quantities in equation (2.1). That is ρ , C , C_0 , Q_{in} , Q_{out} , s and even V are arbitrary functions of time as long as the above two assumptions are satisfied. Useful and accurate information can be obtained from tracer gas experiments without restrictive assumptions on the temporal dependence of these quantities.

The second basic equation for analyzing tracer gas data is the equation for conservation of mass for air flowing into and out of the zone. Under the second assumption of equation (2.1), the conservation of mass for air flowing into and out of a zone is:

$$\frac{d}{dt}(\rho V) = Q_{in} - Q_{out} \quad (2.2)$$

In the common situation of constant temperature, pressure and zone volume, equation (2.2) is nothing more than a statement that the flows into the zone are equal to the flows out of the zone. Equations (2.1) and (2.2) have been written in mass units: flow in mass per unit time and concentrations in mass of tracer per mass of air. This is the simplest form of the equations when temperature and pressure are not constant or when the exterior temperature is different from the interior temperature. It is also in the authors' opinion, the easiest way to make temperature and pressure corrections when such precision is required; however in most investigations little error is introduced by using volume flows rates (cfm) or volume concentrations. If the left hand side of equation (2.1) is differentiated by parts and equation (2.2) substituted for $\frac{d}{dt}(\rho V)$, equation (2.1) reduces to

$$\rho V \frac{dC}{dt} = (C_0 - C)Q_{in} + s \quad (2.3)$$

Equation (2.3) is the fundamental equation of tracer gas test methods in a single well mixed zone.

There are several quantities of interest which can be determined by tracer gas experiments:

- The air change rate $\lambda(t)$ defined as

$$\lambda = \frac{Q_{in}}{\rho V}$$

- The air inflow rate $Q_{in}(t)$

Equation (2.3) can be put into several different forms depending on which quantity is to be measured and the type of tracer experiment (decay test, constant injection or constant concentration) to be performed.

Determination of the Air Change Rate λ

Equation (2.3) can be solved for λ to yield

$$\lambda(t) = -\frac{d}{dt}(\ln \hat{C}) + \frac{\hat{s}}{\rho V \hat{C}} \quad (2.4)$$

where

$$\hat{s} = s - \rho V \frac{dC_0}{dt}$$

$$\hat{C} = C - C_0$$

Though in principle, equation (2.4) can be used to estimate $\lambda(t)$, in practice accurate determination of the derivative of the concentration from experimental data is not possible. In practice one is also usually interested in the average air change rate over a period of time (t_1, t_2) . Integrating equation (2.4) over the interval (t_1, t_2) leads to the equation:

$$\lambda_{av}(t_1, t_2) = \frac{1}{t_2 - t_1} \ln \left(\frac{\hat{C}(t_1)}{\hat{C}(t_2)} \right) + \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \frac{s(\tau) d\tau}{\rho(\tau) V(\tau) \hat{C}(\tau)} \quad (2.5)$$

where

$$\lambda_{av}(t_1, t_2) \equiv \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \lambda(\tau) d\tau$$

Equation (2.5) can be used to determine the building air exchange rate in all three tracer test methods. All quantities on the right hand side of equation (2.5) are measurable during a tracer test. However, each tracer test method is designed to simplify the form of equation (2.5) and it is the simplified forms which are usually used in the analysis of tracer data. Equation (2.5) is useful in assessing errors caused by the lack of fulfillment of the assumptions of each test procedure: the effect of small leaks of tracer in a tracer decay test, the error caused by unsteady flows or lack of equilibrium in the constant injection test and the error caused by deviations in the zone concentration from the target concentration in the constant concentration method.

The Tracer Decay Method.

For the tracer decay method, after injection, the tracer injection rate $s = 0$. The exterior tracer concentration must also be constant (for a properly selected tracer, it is zero). In this case the equation (2.5) reduces to the following simple relationship for the building air change rate which occurred in the time period (t_1, t_2) :

$$\lambda_{av}(t_1, t_2) = \frac{1}{t_2 - t_1} \ln \left(\frac{\hat{C}(t_1)}{\hat{C}(t_2)} \right) \quad (2.6)$$

In practice, tracer decay data are usually analyzed by plotting the logarithm of the concentration versus time and portions of the data for which the decay is linear are analyzed statistically by fitting a straight line to the data. That the resulting plot is a straight line requires the added assumption that the flow rates are constant. This is not required for the use of equation (2.6); however it is necessary to assure that the lack of a logarithmic decay, if it does occur, is not due to poor initial mixing or the invalidity of the single zone assumption.

Constant Injection Method

In the constant injection method, tracer gas is injected into a test volume at a constant injection rate s_0 and the tracer concentration is monitored until an equilibrium value C_∞ is reached. Equations (2.5) and (2.6) then reduce to the following simple expression for the ventilation or airflow rate into the test volume:

$$q_{in} = \frac{s_0}{(C_\infty - C_0)} \quad (2.7)$$

Equation (2.7) is also used to determine ventilation flow rates in ducts, though the derivation in this case is different and requires the assumption the tracer concentration is uniform across a duct cross-section. It must be emphasized that equation (2.7) is valid only for steady flows. If fluc-

tuations in the flow are observed (by noticing oscillations in the tracer concentration), equation (2.5) can be used to obtain the average flow rate during a period of time or to estimate the error caused by using equation (2.7).

Multi-Chamber Theory

In some investigations, a single zone model of a building is not adequate and a multi-chamber or multi-zone approach must be used. Figure 2.2 depicts the air and tracer gas fluxes for three interacting zones. The theory behind multi-chamber methods is complex and it is only outlined here. The mass balance for a tracer in the i th zone is given by the equations:

$$\frac{d\rho_i V_i C_i}{dt} = -Q_i^{(out)} C_i + \sum_{j \neq i} Q_{ij} C_j + s_i \quad i = 1 \dots N \quad (2.8)$$

where $Q_i^{(out)}$ is the sum of all flows out of the i th zone and Q_{ij} is the flow to the i th zone from the j th zone. In the above equations, the exterior is denoted by the subscript 0 and N is the number of zones.

Using the conservation of mass for the airflows, equations (2.8) can be written as

$$\rho_i V_i \frac{dC_i}{dt} = -Q_{i0}(C_i - C_0) + \sum_{\substack{j \neq i \\ j \neq 0}} Q_{ij}(C_j - C_i) + s_i \quad i = 1 \dots N \quad (2.9)$$

Equation (2.9) is the basis for most multi-zone and multi-tracer methods. For multi-tracer methods, an equation of the form of (2.8) or (2.9) is formed for each tracer gas used in each zone. In principle, in a building with N zones, a properly designed experiment with N tracers can determine all interzonal airflows and the airflows to and from the exterior for each zone (that is, there are N^2 equations for N^2 unknowns). The simplest multi-tracer test is done by injecting a different tracer at a constant injection rate into each zone and waiting until equilibrium is reached. Therefore the derivatives on the left hand side of equation (2.9) are zero. In the case of strongly interacting zones, this interaction sometimes leads to poorly conditioned equations which are difficult to solve accurately.

To avoid ill-conditioned equations, the system of equations (2.9) is often integrated over a period of time (t_1, t_2) , assuming that the airflows are constant, to produce

$$\rho_i V_i (C_i(t_2) - C_i(t_1)) = -Q_{i0} \int_{t_1}^{t_2} (C_i(t) - C_0(t)) dt + \sum_{\substack{j \neq i \\ j \neq 0}} Q_{ij} \int_{t_1}^{t_2} (C_j(t) - C_i(t)) dt + \int_{t_1}^{t_2} s_i(t) dt \quad (2.10)$$

Equations (2.10) are the bases of the so-called integral-pulse method (see Persily and Axley [1990]) in which pulses of tracer are injected into each zone. One advantage of this method is that all quantities appearing in equations (2.10) can be measured simply without resorting to the mathematical evaluation of the integrals. The integrals of the concentrations are determined using standard integral sampling techniques such as filling air sample bags at a constant rate over the time period of the test. The integral of the injection source rate is the total quantity of tracer injected during the time of the test.

Constant Concentration Method

In a multi-chamber test, if a method can be found to keep the concentrations in all interior zones the same, the derivatives on the left hand side of equation (2.9) are zero as are the terms in the summation on the right hand side. Equations (2.9) then yield the following simple expression for the flow of exterior air into the zone:

$$Q_{i0}(t) = \frac{s_i(t)}{(C_{target} - C_0)} \quad (2.11)$$

where $Q_{i0}(t)$ is the airflow rate into the space from the exterior, C_{target} is the controlled level of tracer and $s_i(t)$ is flow rate of tracer required to maintain the target concentration at the time t . Sophisticated micro-processor controlled systems have been designed by various research laboratories to make constant concentration measurements.

Single Zone Model

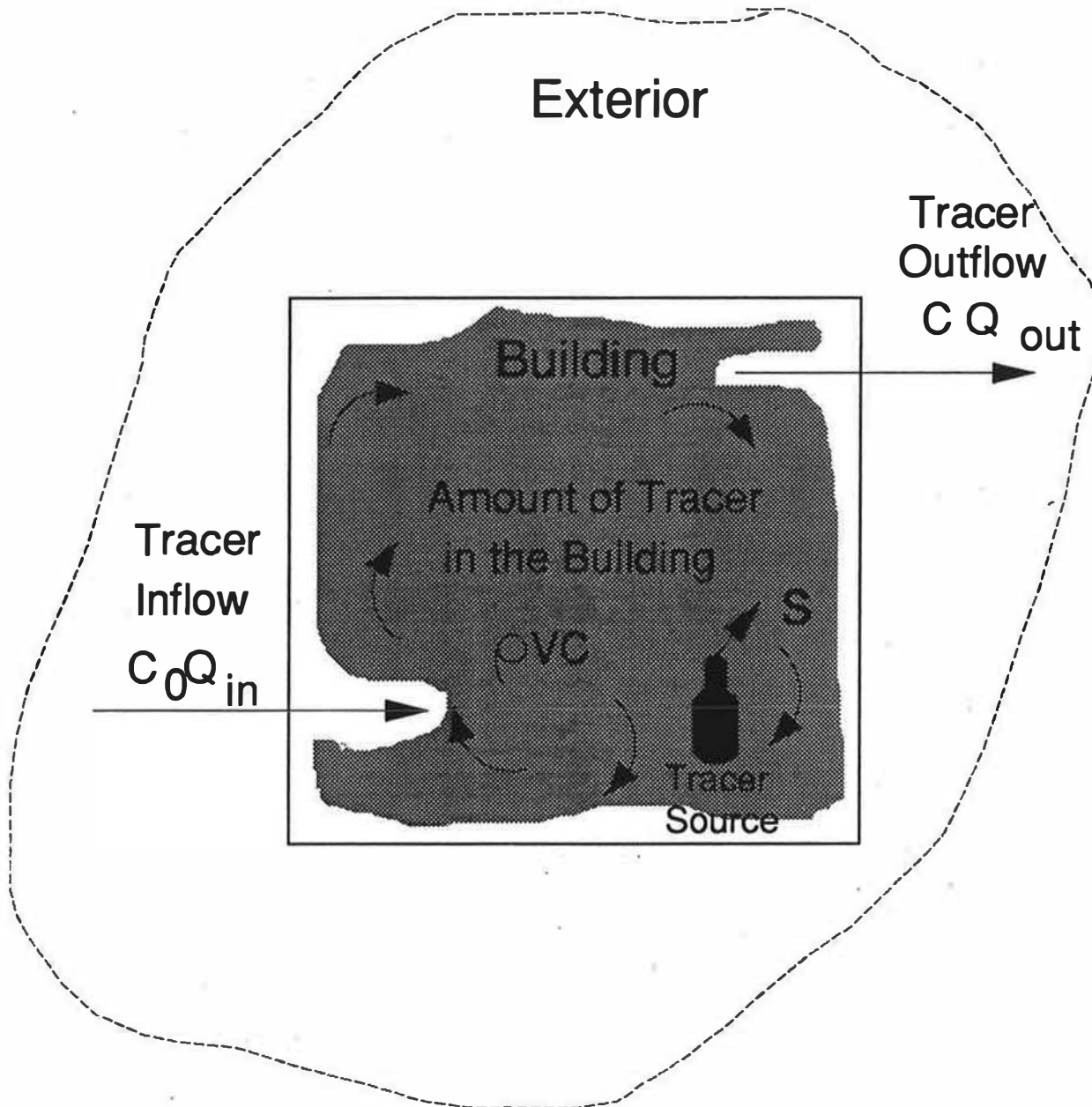


Figure 2.1. Single Zone Model for Tracer Experiments

Multi-Zone Model

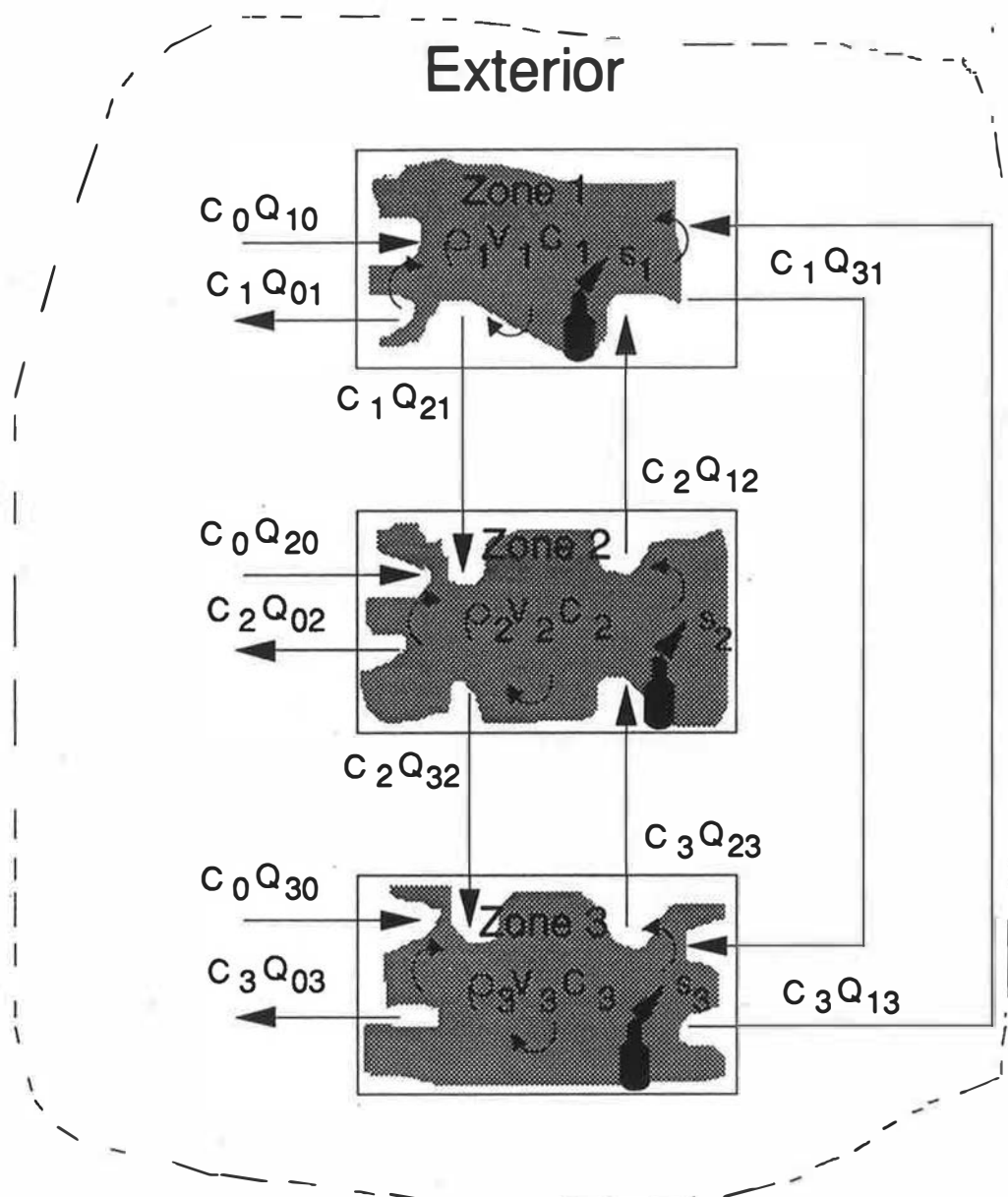


Figure 2.2. Multi Zone Model for Multi-Chamber Test

3 Initial Procedures for Arranging Building Data Collection

3.1 Initial Phone Contact Procedure

In obtaining information on the buildings the three categories of responses were: 1) those that agreed to participate in the testing phase; 2) those that required more information before agreeing to participate in the testing and 3) those that initially refused to participate. The buildings will initially be selected using technical and statistical requirements without regard to the initial response. Each contact person for the building will be phone interviewed as follows depending on the initial response of the first survey.

Phone Contact for those that participated before and agreed to test.

Hello, May I please speak to _____ (contact, this information should be available from the last phone contact), (if this person is not available I would say " can I please speak to the person that took his/her place of the supervisor").

(person is on the phone). Hi, my name is _____ and I'm calling from ACCI and we are working with Lagus Applied Technology on a California Energy Commission project having to do with non-residential outdoor air change rates. You may remember a couple months ago participating in a phone survey and answering some basic questions regarding the characteristics of your building, and at that time you had agreed to participate in the actual testing. It is now time to schedule testing for your building.

The purpose of this test is to determine if the HVAC system is providing adequate outside air, a test to certify that the system is functioning according to specifications, a test that will verify that the system is properly balanced. The California Energy Commission is obtaining this information on California buildings to determine if the recent modifications in the California Energy Codes affected the amount of outside air delivery to buildings. All information and test results will be kept in strict confidence. You may if you wish receive a copy of the results for your building.

We have preliminary data on the building and the air conditioning and heating systems. We need to verify the information is correct and to schedule the outside air change rate tests that will be conducted on your building.

We find faxing a copy of this data works best. You can review it, make changes, and fax it back. Along with this fax will be a few dates for you to choose from. It is important to verify one of these dates as soon as possible as we will be scheduling sites in groups by geographic location. If none of these dates will work, please let me know as soon as possible so we can decide on another mutually acceptable date, a weekend would be okay.

After this date is scheduled I will need to talk to the person that will be allowing the testing team access to the building. Depending on the size of your building, testing usually take 8-12 hours and there will be little or no interference with the normal operation and use of the building.

Phone Contact for those that wanted more information and who said no

Hello, May I please speak to _____ (contact, this information should be available from the last phone contact), (if this person is not available I would say "can I please speak to the person that took his/her place of the supervisor").

(person is on the phone). Hi, my name is _____ and I'm calling from ACCI and we are working with Lagus Applied Technology on a California Energy Commission project having to do with non-residential outdoor air change rates. A few months ago you were contacted to see if you were interested in participating in this study and were asked some basic questions on the building, at that time you indicated that you wanted more information about the study and the purpose. The purpose of this test is to determine if the recent changes in the California Energy Codes have affected the adequacy of the amount of outside air being supplied to the building. Your building was selected because the data on your building indicate (chose one) 1) that the building was built before the Energy Code modification took effect and will serve as base line data for the study, 2) that the building was constructed according to the new energy codes. I would like to clarify the nature of this study: 1) All information and test results are strictly confidential and the building will not be identified with the results -- even to the California Energy Commission. 2) If you wish, the test results will be made available to you. The tests will show if the HVAC system is providing adequate outside air, if it is functioning according to design and if it has been properly balanced and adjusted. This information may be useful to you or your maintenance staff. 3) Most of the testing is done in mechanical equipment rooms with some minimal air sampling in selected interior spaces and there will be little or no disruption to the occupants of the building. We are willing to perform the test out-of-hours or on weekends if you feel that testing is too intrusive.

What I would like to do is fax you a description of the testing procedures and a list of the equipment that may be used at your facility. After you have had time to review this information, I would like to call you back so we can discuss any concerns you may have and to answer any questions. We feel it be of great benefit to participate, not just for research data, but to also verify that your facility is ventilated properly, economically and provides adequate outside air for the building occupants.

3.2 Information Requirements for Contact Person before Testing Begins

After the contact person has agreed to the testing the following information will be provided before testing begins:

- 1.) The date and duration of the planned tests
- 2.) The name and phone number of the test coordinator and the names of the test specialists who will perform the tests.
- 3.) A summary of the test plan and what modifications will be done to the HVAC system. An explanation of the rationale for the modifications to be made. A list of equipment and supplies which will be used during the test and the procedure to be used to return the system to its original conditions if modifications are required.

4.) Requirements for access to the building and assistance required by the test team from the building staff. Compensation which will be made for this assistance.

5.) The date the test results will be available if desired.

6.) The name and phone number of a team person with whom the test results can be discussed.

After completion of the tests, a thank-you letter will be written to the contact person.

3.3 Procedures for Minimizing the Disruption of Occupants during Data Collection

The protocol developed in this report results in a test method which will have almost no impact on the operation of the building or its occupants. It is possible to perform these tests in a manner in which the occupants are unaware that anything but normal HVAC testing and balancing is being performed. The following procedures will be used to minimize the disruption of the building occupants.

1.) Testing equipment will be installed and removed from the building during out-of-hours.

2.) Testing equipment will be installed in mechanical equipment rooms, maintenance areas, an unoccupied space or off-site if required in that order of preference.

3.) The HVAC system will only be operated during occupied hours in a manner which can provide the design comfort conditions and minimum required ventilation. Tests which require special modifications to the HVAC system will be performed out-of-hours.

4. Only minimal interior space air sampling will be used. This will require only the presence a data collection specialist in the occupied space once every twenty minutes for a period of about one minute during the testing phase. Air samples will be drawn either manually in a plastic syringe or an air sample bag using a personal sampling pump if the presence of a syringe is offensive to the occupants. It should be noted that it is easy to conceal both the syringe or air sample bag in a container so that its nature is hidden from the occupants.

4 Procedures for Gathering Information on Building Configuration

The following data will be gathered on each building by the following procedure: First, the data obtained in the previous phase of this project will be examined to determine if any of the data is missing and the accuracy of the data in the existing data base on the building will be verified by sending a copy to the contact person. If data is missing for the data base, the contact person will be asked if he/she is willing to provide the data. If the contact person is not willing to provide the data, the data will be gathered during the building test by a data collection specialist. In all cases, before the test starts, a data collect specialist will check the accuracy of the data.

4.1 General Building Description

Building Name
Location of Building
Date of Construction

Gross Area
Number of Floors Above Grade
Number of Floors Below Grade
Number of Zones
Usage of the Building
 Percent retail
 Percent office
 Percent Education
 Percent Computer
 Percent Recreation
Number of Occupants
Number of HVAC Systems
Location of Mechanical Equipment
Does the building have operable windows
Does there exist a simplified sketch of the building in the form of floor plans, exit routes, etc.

4.1.1 Zone Data

Gross Area
Location in Building
Date of Construction
Number of Floors Above Grade
Number of Floors Below Grade
Number of Occupants
Usage of the Zone
 Percent retail
 Percent office
 Percent Education
 Percent Recreation
 Percent Computer
Description of Mechanical System
Description of Exhaust Systems
Connections to Adjacent Zones

4.2 Mechanical System Description

Type of Heating system and fuel used.
Type of cooling system
Does the building have an energy management center
Supply fan rated capacity
Return fan rate capacity
Economizer cycle
Type of damper control for outside air
Number and capacity of exhaust fans

4.3 Information on Operation and Maintenance of HVAC System

Schedule of operation of the HVAC system for weekdays, weekends and holidays. Schedule of operation of the building exhaust fans. Date of last test and balancing. Date of last modification to the system. Schedule for cleaning and changing filters.

5 Air Change Test Procedures

This section details the procedures recommended for preparing the system for ventilation system measurements, collection of general ambient environmental parameters, and restoration of the system to its original condition.

5.1 Set-up Procedures and Requirements

The tracer gas monitoring equipment will be installed in the building during out-of-hours in either a mechanical room, a maintenance area, an unoccupied office or off-site as mutually agreed to by the test coordinator and the building contact person. No equipment or supplies will be installed in any other area of the building. All injection and sample tubing will only be installed in the mechanical equipment rooms or service areas and will not be visible to the building occupants. This installation should be done on the day prior to the data collection.

5.2 Mechanical System Operation During Testing

In general, during the course of the actual tests to evaluate the ventilation characteristics of the building, the technicians responsible for preparing the building should help ensure that steady-state operation of the ventilation system is maintained. No mechanical or electrical modifications should be made to the system during the course of the test. The test coordinator should be notified immediately if any changes are inadvertently made to the system which would possibly invalidate the test data. Equipment which should be monitored include

- Status of the building's heating and cooling systems
- Status of the building's air handlers
- Position of outside air dampers
- Position of fire and zone isolation dampers
- Status of building exhaust systems
- Operation of windows
- Operation of exterior doors
- The status of emergency exhaust and pressurization systems

Conditions of the above parameters will be determined at the beginning and end of each test and once an hour during the test. This will be by visual inspection and the status of each system will be recorded in the log book. If the building has a computerized control or monitoring system, its log will be requested from the building engineer. The reading of any HVAC system gages and monitors which indicate the status of the above parameters will be recorded during these inspections.

5.2.1 Normal Operation

Normal operation of the HVAC systems, exhaust systems and building's windows and doors for the weather conditions and occupancy occurring during the test will be tested. No special preparation of the systems is necessary, however it is important to monitor that all systems are operating correctly, and that no abnormal or atypical conditions occur during the test.

5.2.2 Placement of System in Minimum OA Operation

The HVAC system will be placed in the minimum outside air operating state which can be achieved by the building's control system for the occupied building as the HVAC system is currently adjusted and balanced. The building exhaust fans will operate as normal for minimum operating conditions. Operable windows will be closed. The specific method used to place the HVAC system in its minimum OA operating condition depends on the design of the system. For systems without an economizer cycle, the minimum damper positions which the building operating staff uses will be used. For systems with economizers, there are three methods which can be used to place the HVAC system in its minimum OA operating position: use the building energy management system if one exists, heat or cool the outside air sensor to "fool" the building control system, or to physically place the system in its minimum design position. The method used for placing a building in its minimum OA operating state will be recommended by the mechanical engineer and control engineer on the project team after studying the HVAC system's design documentation.

5.2.3 Placement of System in Zero OA Operation

The HVAC system will be placed in the minimum outside air operating state which can be achieved by the building's control system for the occupied building as the HVAC system is currently adjusted and balanced. Minimum outside air dampers will be closed. The building exhaust fans will be turned off. Operable windows will be closed. The building will be unoccupied during this period except for the required test personnel.

5.2.4 System and Exhausts Off

The HVAC systems will be turned off and all exhaust fans will be turned off and all intake dampers closed. Operable windows will be closed. The building will be unoccupied during this period except for the required test personnel.

5.3 Tracer Gas Injection Methods

There are two basic tracer gas injection methods which will be used during the testing: pulse injection using syringes (for the tracer decay test) and metered injection using a flow controller and an electronic flow meter. During injection and for a mixing time of at least 20 minutes after the end of the injection, the HVAC system fans will be used to mix the injected tracer.

5.3.1 Tracer Decay Method

For the tracer decay method either pulse injection using syringes or metered injection using a flow controller and an electronic flow meter can be used. The selection depends on the configuration and size of the building and its HVAC system. Pulse injection can be done in either the interior space of the zone to be tested or into the air stream of the HVAC system serving the space. For space less than 20,000 square feet, syringe injection is usually preferred. For large zones, metered injection into the HVAC system over a period of 10 minutes is usually the simplest method. The following method should be used to calculate the amount of tracer to be injected. This procedure is embedded in the software of the AUTOTRAC tracer monitor to be used on the project and also included in the data analysis software AUTOTRAC for IBM compatible computer and in the Lotus 123 tracer gas spreadsheet template TRDECAY.WK3.

Step 1. Select a target concentration C_{arg} (in ppb) to be achieved after the injection. The target concentration for AUTOTRAC is approximately 30 ppb. It is important not to inject too much tracer into a zone with a low air change rate. It is best to inject too little tracer and then inject additional tracer later than to over-saturate a zone.

Step 2.) Calculate the quantity of tracer, Q_p (in cc) required by a pulse injection to achieve this target if there is no loss of tracer due to outside air exchange.

$$Q_p = 28.317 \cdot C_{arg} \cdot Vol \cdot 10^{-6}$$

where Vol is the zone's volume in cubic feet.

Step 3.) If any estimate, Ach_{est} , of the zone's air change rate is available, correct for the loss of tracer during the mixing period.

$$Q = Q_p \cdot \exp^{Ach_{est} \cdot \frac{t_{mix}}{60}}$$

where

Q is the quantity of tracer to injection in cc

t_{mix} is the mixing time in minutes

If metered injection is to be used, calculate the injection flow rate σ (in lpm) using

$$\sigma = \frac{Q}{1000 \cdot t_{dur}}$$

where

t_{dur} is the duration of the metered injection in minutes.

5.3.2 Constant Injection Method

For the constant injection method, metered injection using a flow controller and an electronic flow meter must be used. The following method should be used to calculate the

injection flow rate, σ of tracer to be injected. This procedure is embedded in the software of the AUTOTRAC tracer monitor to be used on the project and included in the data analysis software AUTOTRAC for IBM-compatible computer.

Step 1. Select a target concentration C_{targ} (in ppb) to be achieved after the injection. The target concentration for AUTOTRAC is approximately 30 ppb. It is important not to inject too much tracer into a zone with a low air change rate. It is best to inject too little tracer and then inject additional tracer later than to over-saturate a zone.

Step 2.) Estimate the zone's air change rate, Ach_{est} , and correct for the loss of tracer during the injection period.

Calculate the injection flow rate σ (in lpm) using

$$\sigma = \frac{28.317 \cdot Vol \cdot Ach_{\text{est}} \cdot C_{\text{targ}} \cdot 10^{-9}}{60}$$

where

Vol is the zone in cubic feet

5.3.3 Buildup/Decay Method

For the tracer buildup/decay method, metered injection using a flow controller and an electronic flow meter must be used. The following method should be used to calculate the injection flow rate, σ of tracer to be injected. This procedure is embedded in the software of the AUTOTRAC tracer monitor to be used on the project and included in the data analysis software AUTOTRAC for IBM-compatible computer.

Step 1. Select a target concentration C_{targ} (in ppb) to be achieved after the injection. The target concentration for AUTOTRAC is approximately 30 ppb. It is important not to inject too much tracer into a zone with a low air change rate. It is best to inject too little tracer and then inject additional tracer later than to over-saturate a zone.

Step 2.) Calculate the quantity of tracer, Q_p (in cc) required by a pulse injection to achieve this target if there is no loss of tracer due to outside air exchange.

$$Q_p = 28.317 \cdot C_{\text{targ}} \cdot Vol \cdot 10^{-6}$$

where Vol is the zone's volume in cubic feet.

Step 3.) Estimate the zone's air change rate, Ach_{est} , and correct for the loss of tracer during the injection period.

$$Q = Q_p \cdot \exp^{Ach_{\text{est}} \cdot \frac{t_{\text{dur}}}{60}}$$

where

Q is the quantity of tracer to injection in cc

t_{dur} is the injection time in minutes (about 90 minutes)

Calculate the injection flow rate σ (in lpm) using

$$\sigma = \frac{Q}{1000 \cdot t_{dur}}$$

5.4 Tracer Gas Sampling Methods

The use of a tracer gas monitor such as AUTOTRAC, which is based on an electronic capture detector, allows methods of air sampling which obtain air samples as little as 10cc. This permits the use of syringes to manually draw air samples from a space or the use of low flow sampling pumps. For the test in this project, for each zone air samples will be drawn (see Figure 1.2) from the HVAC system return, downstream of the injection of tracer in the HVAC supply, upstream of the injection of the tracer in the HVAC supply (constant injection test or buildup/decay test) and at 2 to 5 interior space sample locations. If a building has no HVAC system, additional interior space samples will be taken.

5.4.1 Occupied Space Sampling Methods

For the air sampling of occupied spaces, manual air sampling will be done using either syringes (60cc plastic syringes with air tight caps) or air sample bags (the container sampling method in ASTM E741 tracer gas standard). The samples will be taken at 20 minutes intervals. For the tracer decay test, sampling will begin 20 minutes after the end of the injection of tracer. Five air samples will be taken at each sample location. For the constant injection and the buildup/decay method, sampling will begin 20 minutes after the start of the metered injection. For the constant injection test a total of 10 samples taken at 20-minute intervals will be obtained at each sampling location. For the buildup/decay method, six samples will be taken at 20 minute intervals during the buildup phase and four additional samples during the decay phase.

The air sampling technique used for interior paces will be the spacial averaging technique of filling the air sample syringe or air sample bag over a period of about one minute while walking through the space to be sampled.

5.4.2 HVAC System Sampling Methods

For obtaining air samples from the sample locations in the HVAC system, the sampling method used for the occupied space can be used if the sample locations are readily accessible. However, it is usually preferable to install sample tubing in the HVAC system and using air sample pumps to withdraw samples from pump air stream. Syringe samples can be taken from the sample pumps. It is planned to install in each mechanical equipment room, an dual head air sample pump with two four position sample valves for this purpose. The sample interval for the HVAC system will be the same as that for the occupied space. For a building with only one mechanical room and no more than three zones, the AUTOTRAC tracer monitor is capable of automatically taking the samples from the HVAC systems.

For air-stream sampling, a spatially averaged sample will be obtained using either a sample manifold or a integrated syringe system obtained by moving the syringe across the cross-section area of the air stream. At one instance of time, five syringe samples, one from the center and four from each quarter diagonal location, will be obtained cross the air stream to check the mixing of tracer in the air-stream. For the constant injection method and buildup/decay method these samples will be taken immediately before the injection of tracer is ceased. For the tracer decay method, these samples will be taken forty minutes after the end of the injection of tracer.

5.5 Additional Measurements

Ambient environmental data will be monitored and recorded during the course of the ventilation rate measurements. Data to be collected include ambient temperature, ambient atmospheric pressure, and ambient relative humidity. To ensure accurate data, temperature measurement devices shall be sufficiently shielded to exclude the effects of direct sunlight, and undesirable convective effects from potentially hot surfaces such as black roof surfaces and hot exhaust sources. One measurement of each ambient parameter will be made each hour during the tests. The time of day of these measurements should be recorded in the log book. Measurement of external wind speeds will be made only if the nearest official meteorological station is not representative of the wind conditions experienced by the tested building. A brief visual inspection of the immediate area surrounding the building will be made to ensure that there are no sources of contaminants which might pose a threat to the air intakes of the building. At each interior location at which a tracer measurement is made, the interior temperature and relative humidity will be measured when the air sample is taken. These temperatures and humidity will be recorded in the data log when the tracer concentrations are recorded.

5.6 Data Analysis and Verification

This section explains the data analysis and verification to be used for the analysis of the tracer concentration data. The analysis schemes described in this section are implemented in various software which Lagus Applied Technology has developed: 1) the tracer Monitor **Autotracer** embedded software version 1.00 uses the analysis methods explained in this section in either its manual or automatic air change mode to calculate the air change rate, outside air flow rate and the percent of outside air in the supply air; 2) the Lotus 123 spreadsheets templates **TRDECAY** and **TRCONST** will perform the tracer decay and constant injection analysis and 3) the MS-DOS program **AUTOTRAC** performs all these modes of data analysis. For each of these methods, the data analyst need only input the tracer concentrations and times of the sample according to the instructions for these analysis programs.

5.6.1 Tracer Decay Method

The data from a tracer decay test will be analyzed using regression analysis to determine the best logarithmic decay which fits the data for a zone. The data for each zone of the building, for each of the three test periods: the building under normal operation, the HVAC systems operating at minimum OA conditions and the building at zero OA conditions will be analyzed using the following equations. This procedure can be implemented

in the field using a IBM compatible laptop computer. It can be carried out using manual entry of the data in the Lotus 123 spreadsheet using the template **TRDECAY.WK3** (see Appendix VI) or using the data analysis program **AUTOTRAC** recording and analyzing the data using the RS232C interface of the tracer gas monitor AUTOTRAC (see Appendix VII).

The following steps are required to calculate the air change rate for each sample location in each zone of the building:

Take the natural log of each concentration reading forming the array of values y_i , $i=1,N$, where N is the number of tracer concentration readings.

$$y_i = \ln C_i \quad (5.1)$$

From the corresponding array x_i of elapsed times in hours from the end of the tracer injection for each tracer concentration reading.

$$x_i = t_i - t_e \quad (5.2)$$

Calculate the averages y_{av} and x_{av} of the arrays y and x :

$$y_{av} = \frac{1}{N} \sum_{i=1,N} y_i \quad (5.3)$$

$$x_{av} = \frac{1}{N} \sum_{i=1,N} x_i \quad (5.4)$$

Calculate the sum of the squares, σ_y and σ_x , of the deviations of y and x from the averages and the sum of the products, σ_{xy} of the deviation of x and y from their average values

$$\sigma_y = \sum_{i=1,N} (y_i - y_{av})^2 \quad (5.5)$$

$$\sigma_x = \sum_{i=1,N} (x_i - x_{av})^2 \quad (5.6)$$

$$\sigma_{xy} = \sum_{i=1,N} (x_i - x_{av})(y_i - y_{av}) \quad (5.7)$$

The best estimate of the air change rate, Ach , of the zone is the slope of the regression of y and x :

$$Ach = -\frac{\sigma_{xy}}{\sigma_x} \quad (5.7)$$

The initial concentration resulting from the injection can be determined from the intercept of the least squares fit

$$C_0 = e^{(y_{av} + Ach \cdot x_{av})} \quad (5.8)$$

The goodness of the fit can be determined from

$$ss = \frac{1}{N-2} \sum_{i=1, N} (y_i - \ln C_0 + Ach \cdot x_i)^2 \quad (5.9)$$

The R-squared of the fitted equation is given by

$$R^2 = 1 - \frac{ss}{\sigma_y} \quad (5.10)$$

The standard error, δAch , in the air change rate is given by

$$\delta Ach = \frac{\sqrt{ss}}{\sigma_x} \quad (5.11)$$

The standard error, δC_0 in the initial concentration is given by

$$\delta C_0 = C_0 \cdot \sqrt{ss \left(\frac{1}{N} + \frac{x_{av}}{\sigma_x} \right)} \quad (5.12)$$

5.6.2 Constant Injection Method

If equilibrium is reached in a constant injection test, then the analysis of the data reduces to calculating the average value of the equilibrium values of the interior concentrations of a zone and determining the outside air flow rate using equation (2.7). In general, equilibrium may not be obtained or it is difficult to assess whether equilibrium has been obtained. The following general analysis method will produce a good estimate of the equilibrium concentrations if equilibrium has not been obtained and reduces to the equilibrium value if equilibrium has been obtained. This method is based on the rigorous integral solution (2.5) to the tracer specie conservation of mass equation assuming that the injection flow rate is constant.

If one defines the average outside air flow rate F_{OA} (in cfm)

$$F_{OA}(t_1, t_2) \equiv \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} Q_{in}(\tau) d\tau \quad (5.13)$$

and multiplies equation (2.5) by the volume of the zone, the average outside air flow rate can be determined by

$$F_{OA} = 10^9 \frac{\sigma}{28.317 \cdot C_{\infty}} \quad (5.14)$$

where

σ is the tracer injection flow rate in lpm
the time t is expressed in minutes

and C_{∞} is defined as

$$\frac{1}{C_{\infty}} = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \frac{d\tau}{C(\tau)} + \frac{1}{C_p} \ln \left(\frac{C(t_1)}{C(t_2)} \right) \quad (5.15)$$

where C_p is given by

$$C_p = \frac{28.317 \cdot \sigma \cdot (t_2 - t_1)}{Vol} \quad (5.16)$$

where

Vol is the volume in cubic feet.

$C(t)$ is the tracer concentration in the zone at time t in ppb (parts per billion)

It should be noted that C_p is the tracer concentration which would have occurred in the zone if all the tracer had been injected as a pulse and allowed to mix.

For discrete samples C_i , t_i ($i = 1$ to N) C_{∞} can be approximated by

$$\frac{1}{C_{\infty}} = \left(\frac{1}{C} \right)_{av} + \frac{1}{C_p} \ln \left(\frac{C_I}{C_N} \right) \quad (5.17)$$

where

$$\left(\frac{1}{C} \right)_{av} = \frac{1}{(t_N - t_I)} \sum_{i=I+1}^N \left(\frac{1}{C_{i-1}} + \frac{1}{C_i} \right) \cdot \frac{(t_i - t_{i-1})}{2} \quad (5.18)$$

The error in determining the equilibrium concentration is determined from

$$\delta \left(\frac{1}{C_{\infty}} \right) = \sqrt{Var \left(\frac{1}{C} \right) + \frac{1}{C_p^2} \left(\left(\ln \left(\frac{C_I}{C_M} \right) \right)^2 \left(\frac{\delta C_p}{C_p} \right)^2 + \left(\frac{\delta C_I}{C_I} \right)^2 + \left(\frac{\delta C_M}{C_M} \right)^2 \right)} \quad (5.19)$$

where

$\delta \sigma$ is the uncertainty in the injection flow rate

δVol is the uncertainty in the zone volume

δC_I is the uncertainty in C_I

δC_M is the uncertainty in C_M

and $Var \left(\frac{1}{C} \right)$ is the variation in the inverse of the concentration readings

$$Var\left(\frac{1}{C}\right) = \frac{1}{(t_M - t_I)} \sum_{i=I+1}^M \frac{(t_i - t_{i-1})}{2} \left[\left(\frac{1}{C_i} - \left(\frac{1}{C} \right)_{av} \right)^2 + \left(\frac{1}{C_{i-1}} - \left(\frac{1}{C} \right)_{av} \right)^2 \right] \quad (5.20)$$

and

$$\frac{\delta C_p}{C_p} = \sqrt{\left(\frac{\delta \sigma}{\sigma} \right)^2 + \left(\frac{\delta Vol}{Vol} \right)^2} \quad (5.21)$$

The uncertainty in the determination of the outside air flow δF_{OA} is given by the equation

$$\frac{\delta F_{OA}}{F_{OA}} = \sqrt{\left(\frac{\delta \sigma}{\sigma} \right)^2 + \left(\frac{\delta C_{\infty}}{C_{\infty}} \right)^2} \quad (5.22)$$

where δC_{∞} is given by

$$\delta C_{\infty} = \delta \left(\frac{1}{C_{\infty}} \right) C_{\infty}^2 \quad (5.23)$$

5.6.3 Buildup/Decay Method

For the buildup/decay method, the data collected after time t_M that the injection of tracer has ended is analyzed per the method in section 5.6.1 to give the air change rate Ach and its statistics. The data during the buildup could be analyzed as explained in section 5.6.2 for the constant injection data; however, if the airflows are constant during the test, the following analysis is preferable.

For a constant air change rate and constant injection, equation (2.7) reduces to

$$C(t) = C_{\infty} + (C_{\infty} - C_I) \exp^{-Ach \cdot (t - t_I)} \quad (5.24)$$

where

t_I is a time at mixing has occurred

C_I is the tracer concentration at t_I

For each sample, i , between t_I and t_M calculate C_{∞}^i

$$C_{\infty}^i = \frac{C_i + C_I \exp^{-Ach \cdot (t_i - t_I)}}{(1 - \exp^{-Ach \cdot (t_i - t_I)})} \quad (5.25)$$

Then calculate C_{∞} as the average

$$C_{\infty} = \frac{1}{(M - I + 1)} \sum_{i=I}^M C_{\infty}^i \quad (5.26)$$

then outside airflow rate, F_{OA} , is given by

$$F_{OA} = \frac{\sigma}{28.317 \cdot C_{\infty}} \quad (5.27)$$

and the uncertainty, δF_{OA} , in the outside airflow rate is given by equation (5.22) with δC_{∞} given by

$$\delta C_{\infty} = \frac{1}{(M-1)} \sum_{i=1}^M (C_i - C_{\infty})^2 \quad (5.28)$$

5.7 Field Data Reporting Format

This sections contains the field data report forms to be used in collection of the data for the tracer gas tests.

5.7.1 Building Configuration Data

GENERAL BUILDING INFORMATION:		
BUILDING NAME	<input type="text"/>	
LOCATION OF BUILDING	<input type="text"/>	
GROSS AREA	<input type="text"/>	
NUMBER OF FLOORS ABOVE GRADE	<input type="text"/>	
NUMBER OF FLOORS BELOW GRADE	<input type="text"/>	
NUMBER OF ZONES	<input type="text"/>	
NUMBER OF OCCUPANTS	<input type="text"/>	
BUILDING USAGE	<input type="text"/>	
NUMBER OF HVAC SYSTEMS	<input type="text"/>	
LOCATION OF MECHANICAL EQUIPMENT	<input type="text"/>	
ZONE DATA:		
ZONE NAME	<input type="text"/>	
GROSS AREA	<input type="text"/>	
LOCATION IN BUILDING	<input type="text"/>	
NUMBER OF FLOORS	<input type="text"/>	
NUMBER OF OCCUPANTS	<input type="text"/>	
TYPE OF MECHANICAL SYSTEM:		
	ZONE NAME	NO. OF SYS
1. CONSTANT VOLUME, SINGLE ZONE	<input type="text"/>	<input type="text"/>
2. VARIABLE AIR VOLUME	<input type="text"/>	<input type="text"/>
3. MULTIZONE	<input type="text"/>	<input type="text"/>
4. DUAL DUCT	<input type="text"/>	<input type="text"/>
5. OTHER	<input type="text"/>	<input type="text"/>
REMARKS:		

Figure 5.1 Field Data Report Forms for Building and Zone Configuration

5.7.2 HVAC System Data

(1) CONSTANT VOLUME, SINGLE ZONE SYSTEM

MFG. & MOD. NO. RATED CFM O.A. DAMPER: FIXED MODULATING %M.O.A. ECONOMIZER: YES NO RETURN/EXHAUST FAN: CFM HP INTERLOCK

IS THE RETURN/EXHAUST SYSTEM COMMON TO ALL ZONES

YES NO LOCATION OF RETURN AIR DUCT OR OPENINGS

TYPICAL CONSTANT VOLUME, SINGLE ZONE SYSTEM CONFIGURATION:

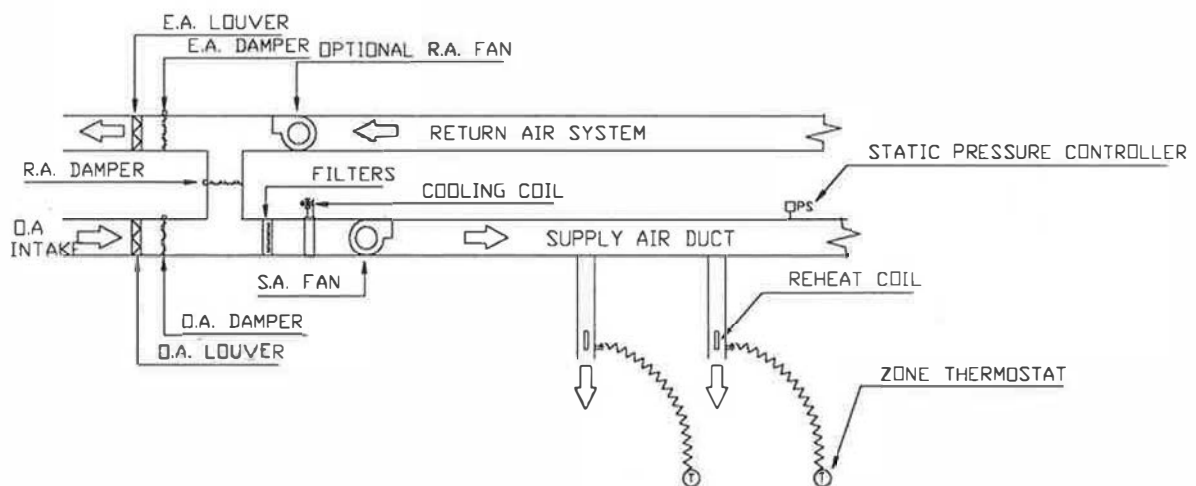


Figure 5.2 Field Data Report Form for Constant Volume Single Zone System

(2) VARIABLE AIR VOLUME SYSTEM

MFG. & MOD. NO. RATED CFM D.A. DAMPER: FIXED MODULATING %M.O.A. ECONOMIZER: YES NO RETURN/EXHAUST FAN: CFM HP INTERLOCK

IS THE RETURN/EXHAUST SYSTEM COMMON TO ALL ZONES

YES NO LOCATION OF RETURN AIR DUCT OR OPENINGS

TYPICAL VARIABLE VOLUME SYSTEM CONFIGURATION:

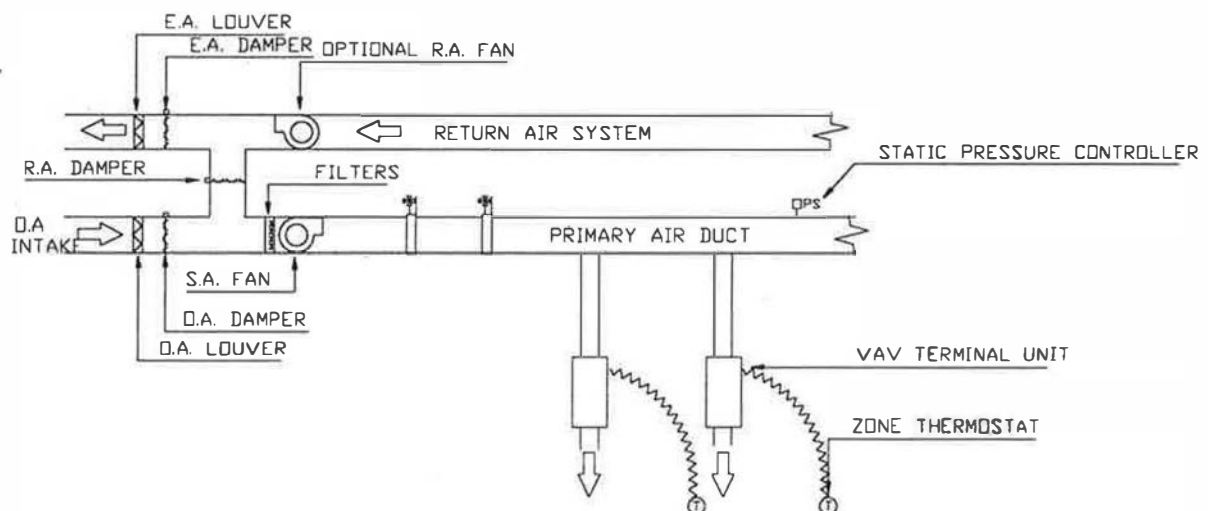


Figure 5.3 Field Data Report Form for Variable Volume System

(3) MULTIZONE SYSTEM

MFG. & MOD. NO. RATED CFM O.A. DAMPER: FIXED MODULATING %M.O.A. ECONOMIZER: YES NO RETURN/EXHAUST FAN: CFM HP INTERLOCK

IS THE RETURN/EXHAUST SYSTEM COMMON TO ALL ZONES

YES NO LOCATION OF RETURN AIR DUCT OR OPENINGS

TYPICAL MULTIZONE SYSTEM CONFIGURATION:

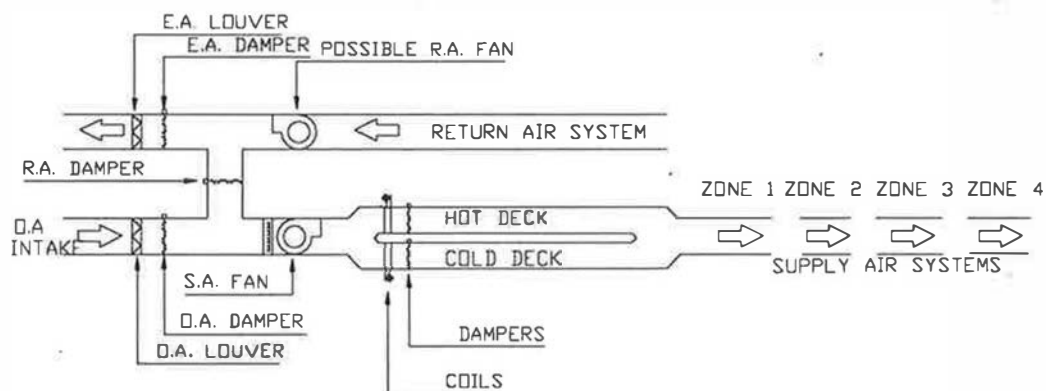


Figure 5.4 Field Data Report Form for Multizone System

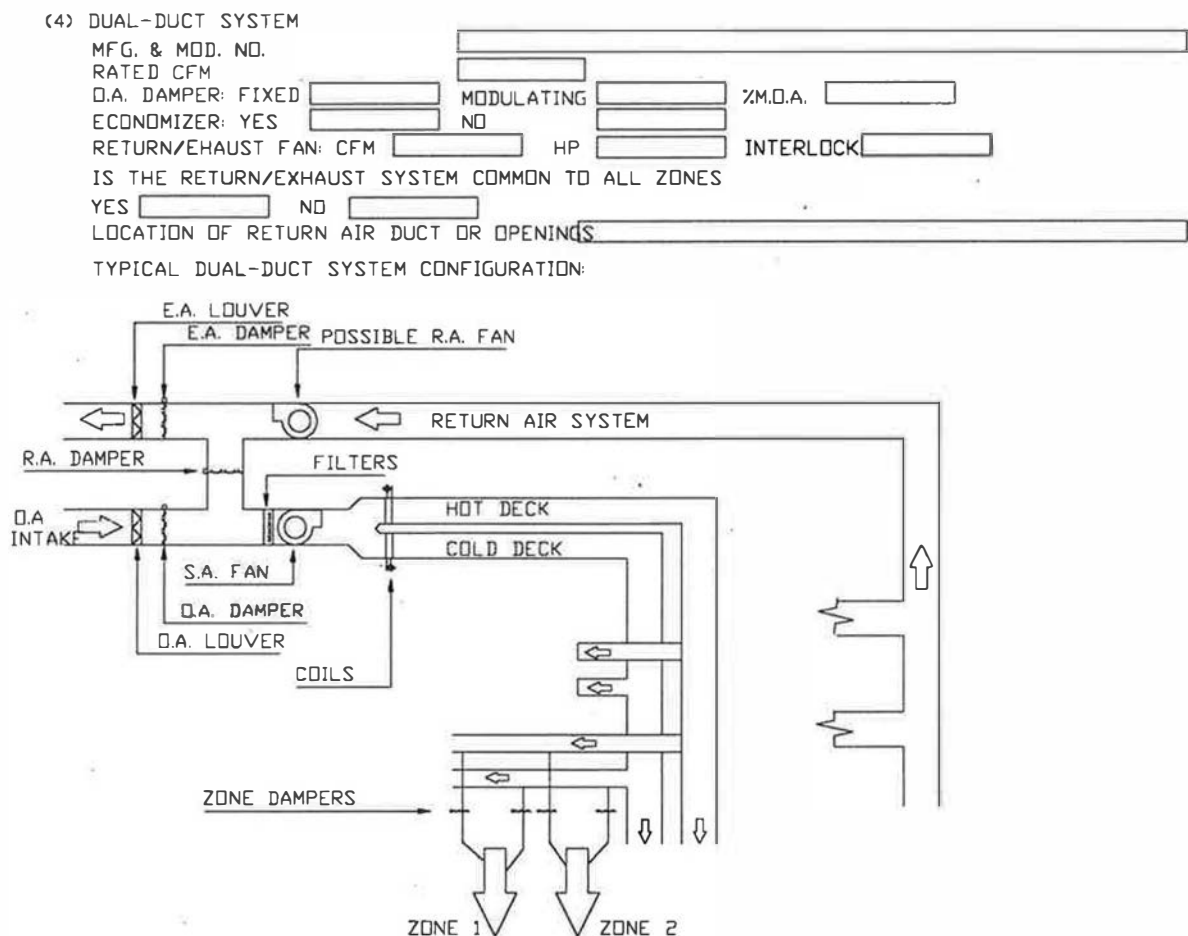


Figure 5.5 Field Data Report Form for Dual Duct System

(5) OTHER SYSTEM

MFG. & MOD. NO.

RATED CFM

D.A. DAMPER: FIXED MODULATING %M.O.A.

ECONOMIZER: YES NO

RETURN/EXHAUST FAN: CFM HP INTERLOCK

IS THE RETURN/EXHAUST SYSTEM COMMON TO ALL ZONES

YES NO

LOCATION OF RETURN AIR DUCT OR OPENINGS

SKETCH OF OTHER SYSTEM:

Figure 5.6 Field Data Report Form for Other Systems

5.7.3 Tracer Injection DataTracer Injection Data Form

Building Name: _____
Zone Name: _____
Date: _____
Test Condition: _____

Type of Injection: _____
Time Injection Started _____
Target Concentration: _____ ppb
Duration of Injection: _____ seconds
Percent of Tracer: _____ %
Injection Flow Rate _____ lpm cc/min
Quantity Injected _____ liter cc

5.7.4 Tracer Sampling DataLocation Tracer Concentration Data Form

Building Name: _____

Zone Name: _____

Location: _____

Date: _____

Test Condition: _____

Test Data

Sample	Time	Concentration ppb	Injection On/Off	Invalid	Temperature °F	Humidity %
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						

5.7.5 Environmental DataEnvironmental Data Form

Building Name: _____

Date: _____

Time	Exterior Temperature °F	Relative Humidity %	Wind Speed mph	Wind Direction Degrees

5.8 Procedures for Returning the Building to Original Condition

The procedure for returning the system to its original condition shall be dictated by the functional changes as noted in the log book during system preparation. During the restoration period, a systematic approach will be taken to address specific tasks to be completed, as noted in the log book check list. It is the responsibility of the test technicians to record in the log book check list as individual items are addressed, red tags are removed, and the system parameters are returned to their original condition. The tags will be removed only after the system parameters are returned to their original condition. Before the ventilation test is considered complete, all items in the check list shall be denoted as successfully completed by indication of the responsible technician's signature. Thus, it is ensured that all facility-specific changes detailed during the preparation procedure shall be addressed before the system is considered returned to its initial state. The test coordinator shall verify that all tasks indicated on the check list have been signed-off.

6 Equipment List and Specifications

The following is a list of equipment which will be required for each building. Certain equipment in this list is required for spare parts and/or contingency.

Tracer Gas Monitor - SF6, AUTOTRAC Model 101. Range 0.5 ppb to 50 ppb, 5% of reading accuracy, 3% of reading repeatability; printer interface, 9 sample ports, RS232 interface. Capable of manual or automatic sample analysis. Internal calculation of air change rate, outside air flow rate and percent of outside air in either manual or automated mode. MS-DOS (IBM) compatible 3.5 inches 1.44 megabyte floppy disk. One required.

Printer - Centronics interface, Hewlett-Packard PCL-5 compatible. One required

Laptop MS-DOS computer - 286/386 laptop computer with VGA screen, RS232 COM port capable of running Lotus 123 version 3.1. 4 megabytes of memory. One required.

Carrier Gas Cylinder with regulator - P-5 (argon with 5% methane) ultra-high purity with two stage regulator, shutoff valve and 1/4" swagelok quick connect. Minimum cylinder size 30 cu. ft.

Lecture bottle of SF6 with regulator, shutoff valve and septum. One required if syringe injection used.

Injection Syringes:

- 10 cc syringe - glass
- 20 cc syringes - plastic
- 60 cc syringes - plastic

Cylinder diluted SF6 - 150 cu. foot cylinder of 10 percent SF6 in air for metered injection - 1% accuracy, with tow stage regulator. One required per mechanical room if metered injection is used

Mass Flow controller with mass flow meter - range 0 to 5 lpm, accuracy 2 % of full scale. One required per zone for constant injection or buildup/decay test.

Stationary dual head sample pump - range 0 to 30 SCFH sample flow rate equipped with two 4 position sample values. One required per mechanical room or per four HVAC systems.

60cc sample syringes with caps - 5 per sample location per test for decay test, 10 per sample location per test for constant injection or buildup/decay test. Preprinted labels should be prepared for each syringe.

carrying case for sample syringes - either a brief case or plastic tool box, one per data collection specialist.

1/4" polyethylene injection tubing - one 500 foot coil reserve.

1/4" polyethylene sample tubing - two 500 foot coil reserve.

1/4" copper tubing - two 50 foot coils - reserve.

1/8" nylon tubing - 1000 foot coil - reserve

1/8" copper tubing - 50 foot coil - reserve

Swagelok fittings:

2 male quick connectors - spare part

10 1/8" unions - spare part

5 1/8" tees - spare part

20 1/8" ferrule set - spare part

10 1/8" unions - spare part

5 1/4" tees - spare part

20 1/4" ferrule set - spare part

5 1/8" to 1/4" union - spare part

5 1/4" to 3/8" union - spare part

Mechanical and electrical service tool kit:

cylinder bottle wrench

set of open end wrenches.

Set of socket wrenches

wire cutters.

hammer

1/4" electrical drill

set of drill bits

hacksaw with metal blades

sheet metal cutter

2 adjustable wrenches

electrical tape (2 rolls)

duct tape (2 100 feet rolls)

digital multi-meter.

100 ty-wraps 6" long.

two cylinder table clamps.

Personal air sample pump: battery operated, flow one liter per minute. Optional equipment.
Used if air sample bags are required for interior sampling.

Digital Thermometer/Humidity Meter. 2 ° F accuracy, 2% RH accuracy. One required for data analyst plus one for each data collection specialist.

Wind speed and direction indicator. accuracy 1 mph, threshold 0.5 mph wind speed. 15 degrees wind direction resolution . Required if nearest weather station is not representative of wind conditions for the building.

Recording Equipment

- 10 3.5" computer disks with labels
- log book
- spare pens and pencils
- set of magic markers
- yellow and red marking tape
- tie on labels

Table and chairs:

A table approximately 30 by 72 inches and two chairs for the tracer monitoring equipment, laptop computer and printer. The preferred location for this equipment is a mechanical equipment room; however any small room (at least 10 feet by 10 feet) which is air conditioned can be used. It is possible to use a room which is not in the building tested if travel time to the building is less than five minutes.

7 Time and Personnel Requirements for Different Types of Buildings and HVAC Systems

The basic time and personnel requirements for performing the tracer gas tests can be determined from the following data:

- 1.) Setup time for the tracer gas equipment is approximately two man-hours.
- 2.) Preparation time for injection and sample in one mechanical room is approximately two man-hours.
- 3.) A tracer decay test with five different air samples taken at 20 minute intervals at each location, 10 minute injection duration and 20 minute mixing period, requires approximately two and one half hours. A continuous injection test or a buildup/decay test requires about four hours per test condition.
- 4.) Placing a building in a special operating condition requires about one hour.
- 5.) A tracer gas data analyst can analyze and record accurately one sample every two minutes.
- 6.) One data collection specialist is required per 10 sample locations.
- 7.) Approximately two hours are required for removing the equipment from the building and returning the HVAC system to its original condition.

7.1 Single-zone HVAC System Building

A small building with a one or two HVAC systems can be tested using one tracer gas analyst and one data collection specialist. The test would require approximately 12 to 16 hours. It would be best to start the test late on the first day and test throughout the second day until data for all conditions are collected.

7.2 Multi-zone HVAC Systems

A large building with three or more HVAC systems will require one tracer gas specialist and mechanical system technician for full duration of the setup, testing and restoration phases - approximately 16 to 24 hours. It is best that these two specialists arrive early on the first day and brief the building's engineering staff, install the tracer gas equipment and obtain a familiarity with the building. On the second day, one or two additional data collection specialists will be required to gather the air sample data. On the second day, only a part of the air samples will be analyzed; enough to ensure that the tests are progressing correctly. The remaining samples will be analyzed on the third day by the tracer gas specialist. On the third day, the mechanical system technician will verify that the HVAC system has been restored to its original condition and assist in the removal of the equipment from the building.

8 Calculational Procedures

The tracer tests on each building will produce air change rates for each zone of the building under two or four operating conditions depending on the tracer test method used:

1.) Normal Operation

The results of the data analysis will yield

Ach^{ZN} - The total air change rate under normal operation

F_{OA}^{ZN} - The total outside air flow rate under normal conditions

$OA_{\%}^{ZN}$ - The percent of outside air in the supply air under normal conditions

OA_{per}^{ZN} - The total outside air flow rate per person under normal operations conditions

For Constant Injection and the Buildup/Decay Test

Ach_I^{ZN} - The infiltration component of the air change rate under normal operations conditions

Ach_{Mech}^{ZN} - The mechanical system component of the air change rate under normal operations conditions

2.) Minimum Operation

Ach_M^Z - The total air change rate under minimum operation

F_{OA}^{ZM} - The total outside air flow rate under minimum conditions

$OA_{\%}^{ZM}$ - The percent of outside air in the supply air under minimum operating conditions

OA_{per}^{ZM} - The total outside air flow rate per person under minimum operations conditions

For Constant Injection and the Buildup/Decay Test

Ach_I^{ZM} - The infiltration component of the air change rate under normal operations conditions

Ach_{Mech}^{ZM} - The mechanical system component of the air change rate under normal operations conditions

3.) Closed Operation (Tracer Decay Test)

Ach_C^Z - The total air change rate under closed operations

4.) System Off (Tracer Decay Test)

Ach_O^Z - The total air change rate with the system off.

In the tracer decay test, the air change rate under closed operation will be considered as the infiltration air change rate of the zone when the HVAC systems are operating. This air change rate consists of both building envelope air leakage and duct leakage occurring when the HVAC systems are operating and pressurizing the building. The air change rate with the system off is the infiltration air change rate due to the leakage of the building envelope with the building pressurized by the stack and wind pressures across the building envelope.

In the tracer decay test, the ventilation component of the air change rate will be calculated for both normal operation and minimum operation by subtracting the air change rate measured under closed operation from the total air change rate measured for normal and minimum operation.

For the tracer decay test, the ventilation air change rate under normal operation ACH_{Mech}^{ZN} :

$$Ach_{Mech}^{ZN} = Ach_N^Z - Ach_C^Z$$

The ventilation air change rate under minimum operation ACH_{Mech}^{ZM} :

$$Ach_{Mech}^{ZM} = Ach_M^Z - Ach_C^Z$$

The zone results will be reported in the Zone Data Report Sheet.

For each zone, bar graphs will be produced to graphically show: 1.) the design air change rate, 2.) the ASHRAE-62-1989 required air change rate, 3.) the measured total air change rate, 4.) mechanical system component of the air change rate 5.) and the infiltration component of the air change rate for normal and minimum operating conditions.

8.1 Tracer Decay Method

A tracer decay test will be performed for each zone of the building with the building under normal operation, with the HVAC system in its minimum operation, with the dampers closed and with the HVAC system off. The duration of each test will be approximately one and a half to two hours. For each of these four operational conditions the following data analysis will be carried out.

For Each Zone, the test will produce tracer Decay Concentrations (N samples, $N \geq 5$) to be measured for

Return Air	C_i^R at time t_i^R , $i = 1$ to N
Supply Air	C_i^S at time t_i^S , $i = 1$ to N
Interior Space M Locations	C_j^I at time t_j^I , $j = 1$ to M , $i = 1$ to N
$M \geq 4$	

From the zone data

1.) Calculate Ach^R , Ach^S and Ach^I by regression for the return air, supply air and each interior location using regression.

For each location report:

- Ach - the air change rate
- δAch - the error in the air change rate
- R^2 - the R-squared of the fit
- Std. error of fitted line
- C_0 - the initial tracer concentration when injection stopped
- δC_0 - the std. error in the initial concentration

Graphical Results

Produce a decay plot for each location

2.) From the composite data set consisting of the data from the return and the interior locations (C_i^R at time t_i^R , C_j^I at time t_j^I , $j = 1$ to M , $i = 1$ to N) calculate the zone air change rate, Ach_z , by regression, eliminating any outliers. This composite data set provides a good check of the mixing of the tracer throughout the zone and also the best estimate of the zone's air change rate. Poor mixing will be reflected in a poor R-squared for this data set and large uncertainties in the initial tracer concentration and zone air change rate.

For zone report:

- Ach^Z - the air change rate
- δAch^Z - the error in the air change rate
- R^2 - the R-squared of the fit
- Std. error of fitted line
- C_0^Z - the initial tracer concentration when injection stop
- δC_0^Z - the std. error in the initial concentration

Graphical Results

Produce a decay plot for the zone

This plot will show all tracer data for the return, supply and each interior location.

The composite regression line and the regression line of the supply air data. If the ACH of a location is an outlier (significantly different from the ACH^Z of the zone), this line should also be shown and a different symbol used for these data.

3.) Calculate F_{OA}^Z the Outside Airflow Rate for the Zone in cfm

$$F_{OA}^Z = \frac{Ach^Z \cdot Vol^Z}{60}$$

where

Vol^Z is the volume of the zone in ft^3 .

and the error δF_{OA}^Z

$$\delta F_{OA}^Z = \frac{\delta Ach^Z \cdot Vol^Z}{60}$$

4.) Calculate the OA_{per}^Z , Outside Airflow per person, for the zone

$$OA_{per}^Z = \frac{Ach^Z \cdot Area_{per} \cdot H}{60}$$

where

Ach^Z is the zone air change rate

$Area_{per}$ is the area per person (ft^2)

H is the ceiling height of the zone (ft)

and the std error δOA_{per}^Z

$$\delta OA_{per}^Z = \frac{\delta Ach^Z \cdot Area_{per} \cdot H}{60}$$

5.) Calculate $OA_{\%}^Z$, the percent of outside air in the supply air

$$OA_{\%}^Z = 100 \cdot \left(1 - \frac{C_0^S}{C_0^R} \right)$$

where

C_0^S is the initial supply air tracer concentration from regression

C_0^R is the initial return air tracer concentration from regression

and $\delta OA_{\%}^Z$ the error in the

$$\delta OA_{\%}^Z = OA_{\%}^Z \cdot \sqrt{\left(\frac{\delta C_0^R}{C_0^R}\right)^2 + \left(\frac{\delta C_0^S}{C_0^S}\right)^2}$$

8.2 Constant Injection Method

A constant injection test will be performed for each zone of the building with the building under normal operation and with the HVAC system in its minimum operating condition. The duration of each test will be approximately two and a half to three hours. For each of these two operational conditions the following data analysis will be carried out.

For Each Zone, the test will produce tracer concentrations (N samples, $N \equiv 10$) to be measured for

Return Air	C_i^R at time t_i^R , $i = 1$ to N
Downstream Supply Air	C_i^{DS} at time t_i^{DS} , $i = 1$ to N
Upstream Supply Air	C_i^{US} at time t_i^{US} , $i = 1$ to N
Interior Space M Locations $M \equiv 4$	C_i^j at time t_i^j , $j = 1$ to M , $i = 1$ to N

For each location in the zone, one should perform the analysis of section 5.6.2 to produce the equilibrium concentrations and their uncertainties:

Return Air	C_{∞}^R and δC_{∞}^R
Downstream Supply Air	C_{∞}^{DS} and δC_{∞}^{DS}
Upstream Supply Air	C_{∞}^{US} and δC_{∞}^{US}
Interior Space M Locations $M \equiv 4$	C_{∞}^j and δC_{∞}^j $j = 1$ to M

The interior equilibrium concentrations should be averaged to produce

Average Interior	C_{∞}^{int} and δC_{∞}^{int}
---------------------	--

where the uncertainty in the interior equilibrium concentration is the variation of the interior location equilibrium concentrations. This procedure will produce a measure of the mixing of tracer in the zone.

From these data for the zone, the total outside air flow rate in cfm is given by the equation:

$$F_{OA}^Z = 10^9 \frac{\sigma}{28.317 \cdot C_{\infty}^{int}}$$

The supply flow rate is given by

$$F_s^Z = \frac{\sigma}{28.317 \cdot (C_{\infty}^{DS} - C_{\infty}^{US})}$$

The mechanical system component of the outside air flow rate is

$$F_{Mech}^Z = F_s^Z \cdot \left(1 - \frac{C_{\infty}^{US}}{C_{\infty}^R} \right)$$

The infiltration component of the outside airflow rate is

$$F_{OA_{Mech}}^Z = F_s^Z \cdot \left(1 - \frac{C_{\infty}^{int}}{C_{\infty}^{DS}} \right)$$

The corresponding air change rates are determined by dividing airflow rates by the zone volume and multiplying by 60:

$$Ach^Z = 60 \cdot \frac{F_{OA}^Z}{Vol}$$

$$Ach_{Mech}^Z = 60 \cdot \frac{F_{OA_{Mech}}^Z}{Vol}$$

$$Ach_{inf}^Z = 60 \cdot \frac{F_{infOA}^Z}{Vol}$$

The uncertainties in the above quantities follow by applying standard error analysis to the above equations.

8.3 Combined Constant Injection/Decay Method

A buildup/decay test will be performed for each zone of the building with the building under normal operation and with the HVAC system in its minimum operating condition. The duration of each test will be approximately two and a half to three hours. For each of these two operational conditions the following data analysis will be carried out.

For Each Zone, the test will produce tracer concentrations (N samples, $N \geq 10$) to be measured for

Return Air C_{∞}^R and δC_{∞}^R

Downstream Supply Air	C_{∞}^{DS} and δC_{∞}^{DS}
Upstream Supply Air	C_{∞}^{US} and δC_{∞}^{US}
Interior Space M Locations $M \cong 4$	C_{∞}^j and δC_{∞}^j $j = 1$ to M

The sample $i = 1$ to I will be considered buildup data, the sample $i = I$ to N will be considered decay data, where $I \cong 6$.

For each location in the zone, perform the data analysis of section 5.6.3 producing at each location a local air change rate and a local equilibrium concentration. Use the analysis in section 8.3 above on the air change rates. Use the analysis of section 8.4 on the equilibrium concentrations using the effective volume of the zone calculated by dividing the outside air flow rate multiplied by 60, by the total air change rate for the zone.

8.4 Calculation of Building Results from the Zone Results

From the results of the zone calculation, calculate the building results

1.) Calculate ACH, the air change rate of the building

$$ACH = \frac{\sum_{Z=1}^{NZ} (ACH^Z \cdot Vol^Z)}{Vol}$$

where

Vol is the total volume of the building

NZ is the number of zones in the building

and δACH for the building

$$\delta ACH = \sqrt{\sum_{Z=1}^{NZ} \left(\frac{\delta ACH^Z \cdot Vol^Z}{Vol} \right)^2}$$

2.) Calculate F_{OA} , the total outside airflow rate of the building

$$F_{OA} = \sum_{Z=1}^{NZ} F_{OA}^Z$$

and δF_{OA} , the error in the total outside airflow rate

$$\delta F_{OA} = \sqrt{\sum_{Z=1}^{NZ} (\delta F_{OA}^Z)^2}$$

3.) Calculate OA_{per} , the outside airflow per person for the building

$$OA_{per} = \frac{\sum_{Z=1}^{NZ} (OA_{per}^Z \cdot NP_Z^Z)}{NP}$$

where

NPZ is the number of occupants in the zone Z

NP is the total number of occupants in the building

and δOA_{per} , the error in the building airflow per person

$$\delta OA_{per} = \sqrt{\sum_{Z=1}^{NZ} \left(\frac{\delta OA_{per}^Z \cdot NP_Z^Z}{NP} \right)^2}$$

4.) Calculate $OA_{\%}$, the percent of outside air supplied by the building supply air

$$OA_{\%} = \frac{\sum_{Z=1}^{NZ} (OA_{\%}^Z \cdot F_s^Z)}{F_s}$$

where

F_s^Z is the supply airflow rate to the zone Z

F_s is the total supply airflow rate to the building (the sum of the F_s^Z)

and $\delta OA_{\%}$, the error in the percent of outside air supplied to the building

$$\delta OA_{\%} = \sqrt{\sum_{Z=1}^{NZ} \left(\frac{\delta OA_{\%}^Z \cdot F_s^Z}{F_s} \right)^2}$$

These building calculations will be performed for each of the test conditions and for the total air change rate, the mechanical system component air change rate and the infiltration component of the air change rate.

9 Report Presentation Format for Measured and Calculated Data

The report for a building test will consist of the following forms:

- 1.) A Building Report Data Form (Figure 9.1)
- 2.) A bar graph presentation of the results for normal operation and minimum operation.
- 3.) For each zone
 - 3.a) A Zone Report Data Form (Figure 9.2)
 - 3.b) A bar graph presentation of the zone results for normal operation and minimum operation

- 3.c) A composite tracer decay, tracer buildup or tracer buildup/decay graph for all interior points and the return air sample. This graph will show the measured data and the theoretical graph of the fitted results
- 3.d) For each sample location
 - 3.d.1) The appropriate test location data form (decay, constant injection, buildup/decay (Forms sections 9.1, 9.2 and 9.3 respectively)
 - 3.d.2) A tracer decay, tracer buildup or tracer build-up/decay graph for the location showing the tracer concentrations and the theoretical graph of the fitted results
- 4.) Copies of the Field Data Forms
 - 4.1) Building and Zone Configuration Sketches
 - 4.2) HVAC System Data Forms
 - 4.1) HVAC System Log
 - 4.2) Weather Data
 - 4.3) Injection Field Data Forms
 - 4.4) Tracer Concentration Field Data Forms
 - 4.5) Record of Equipment Calibration
 - 4.6) Copy of test log.

The building data are to be reported in the Building Report Data Form in Figure 9.1 and the zone data are to be reported in the Zone Report Data Form in Figure 9.2.

Figure 9.1 Building Report Data Form

California Energy Commission Non-Residential Building Air Change Study Building Data Report				
Date of Test _____				
Building ID _____				
Building Type _____			Year of Construction _____	
Building Size (ft ²) _____			Number of Floors _____	
Building Classification _____			Climate Zone _____	
Number of Zones _____			Number of Occupants _____	
Design Ventilation Rate (ACH) _____	ASHRAE 62-89 Vent. Rate (ACH) _____			
Energy Code Applicable _____			Type of HVAC System _____	
Air Change Rates				
	Normal Operation	Minimum Operation		
Total Air Change Rate				
Ventilation Air Change Rate				
Infiltration Air Change Rate				
Test Data Summary				
	Normal Operation	Minimum Operation	Dampers Closed	System Off
Exterior Temperature (°F)				
Wind Speed (mph)				
Wind Direction				
Interior Temperature (°F)				
Air Change Rate (ACH)				
Std. Err. Air Change Rate (ACH)				
Outside Airflow Rate (cfm)				
Std. Err. Outside Airflow Rate (cfm)				
OA per person (cfm/person)				
Std. Err. OA per person (cfm/person)				
HVAC System Airflow Rate (cfm)				
Percent Outside Air (%)				

Figure 9.2 Zone Report Data Form

California Energy Commission Non-Residential Building Air Change Study Zone Data Report				
Date of Test _____				
Building ID _____				
Zone ID _____				
Building Type _____			Year of Construction _____	
Building Size (ft ²) _____			Number of Floors _____	
Building Classification _____			Climate Zone _____	
Number of Zones _____			Number of Occupants _____	
Design Ventilation Rate (ACH) _____			ASHRAE 62-89 Vent. Rate (ACH) _____	
Energy Code Applicable _____			Type of HVAC System _____	
Air Change Rates				
	Normal Operation	Minimum Operation		
Total Air Change Rate				
Ventilation Air Change Rate				
Infiltration Air Change Rate				
Test Data Summary				
	Normal Operation	Minimum Operation	Dampers Closed	System Off
Exterior Temperature (°F)				
Wind Speed (mph)				
Wind Direction				
Interior Temperature (°F)				
Air Change Rate (ACH)				
Std. Err. Air Change Rate (ACH)				
Outside Airflow Rate (cfm)				
Std. Err. Outside Airflow Rate (cfm)				
OA per person (cfm/person)				
Std. Err. OA per person (cfm/person)				
HVAC System Airflow Rate (cfm)				
Percent Outside Air (%)				

The following is a brief description of the data fields in the building and zone data reports.

Data Field	Description
Building ID	Building Identification Code
Building Type	Type of Building by Usage: Office/Educational/Retail
Year of Construction	Year of Construction. For the Building, the year in which the original construction was completed. For a zone, the year the zone was constructed.
Building Size	Gross area of buildings.
Number of Floors	Number of floors above grade
Building Classification	Classification of the building for the purposes of this study: Large/Small
Climate Zone	Climate Zone in which the building is located. For the purposes of this study the climate zones are: North Coastal, North Interior Valley, South Coastal and South Interior Valley
Number of Zones	Number of independent zones of the building studied
Number of Occupants	Number of Occupants in the building or zone
Energy Code Applicable	The California energy code to which the building or zone was required to meet.
Design Ventilation Rate	The minimum ventilation for which the building was originally designed.
ASHRAE 62-1989 Ventilation Rate	The minimum ventilation rate which the ASHRAE Standard 62-1989 "Ventilation for Acceptable Indoor Air Quality" requires for the building or zone
Date of Test	Date on which the test was performed.
Normal Operation	Data collected during the normal operation of the HVAC systems, exhaust systems and building for the weather conditions and occupancy occurring during the test.
Minimum Operation	Data collected when the HVAC systems and dampers are placed by the building control system in their minimum positions allowed for an occupied building. Building exhaust system should be in their normal operating mode for minimum conditions.
Dampers Closed	Data collected with the HVAC outside air dampers closed and the building exhaust systems off. The building is unoccupied. Data collected in this test phase represents the air infiltration component of the building air change rate.

Description of Report Data Fields (continued).

Data Field	Description
System Off	Data collected with the HVAC and building exhaust systems off and building dampers in their normal off position. (Note: special zones such as computer rooms will not be shut off). Data collected in this phase represents the air change rate during out-of-hours.
Exterior Temperature	The average exterior temperature during the tests.
Wind Speed	The average wind speed during the tests.
Wind Direction	The average wind direction during the tests.
Interior Temperature	The average exterior temperature during the tests. For the whole building, this is the volume weighted average of the occupied zone temperatures.
Air Change Rate	The air change rate determined by the test data.
Std. Error Air Change Rate	The standard error in the air change rate as determined by the test data.
Outside Airflow Rate	The equivalent outside airflow rate due to the measured air changed rate.
Std. Err. Outside Airflow Rate	The standard error in the equivalent outside airflow rate due to the error in the measured air changed rate.
OA per person	The outside airflow rate per person using the normal number of people in the building.
Std. Err. OA per person	The error in the outside airflow rate per person using the normal number of people in the building.
HVAC System Airflow Rate	The total HVAC system air supply flow rate.
Percent Outside Air	The percent of outside air in the HVAC system supply air.

9.1 Tracer Decay Method Data Form**Tracer Decay Test**Location Data Analysis Report

Building Name: _____

Zone Name: _____

Location: _____

Date: _____

Test Condition: _____

Air Change Rate: _____ ACH

Initial Concentration: _____ ppb

 R^2 : _____

Std. Error of Fit: _____

Temperature: _____ °F

Relative Humidity: _____ %

Test Data

Sample	Time	Concentration ppb	Invalid	Temperature °F	Humidity %
1					
2					
3					
4					
5					
6					

9.2 Constant Injection Method Data Form**Constant Injection Tracer Test**Location Data Analysis Report

Building Name: _____

Zone Name: _____

Location: _____

Date: _____

Test Condition: _____

Equil. Concentration: _____ ppb

Temperature: _____ °F

Relative Humidity: _____ %

Test Data

Sample	Time	Concentration ppb	Injection On/Off	Invalid	Temperature °F	Humidity %
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						

9.3 Combined Constant Injection/Decay Method Data Form

Tracer Buildup/Decay Test

Location Data Analysis Report

Building Name: _____
 Zone Name: _____
 Location: _____
 Date: _____
 Test Condition: _____

Air Change Rate: _____ ACH
 Initial Concentration: _____ ppb
 R^2 : _____
 Std. Error of Fit: _____
 Equil. Concentration: _____ ppb
 Temperature: _____ °F
 Relative Humidity: _____ %

Test Data

Sample	Time	Concentration ppb	Injection On/Off	Invalid	Temperature °F	Humidity %
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						

10 Summary of the Steps in Performing a Tracer Test Evaluation of a Building

Steps in the performance of a tracer gas test are:

1. Pre-Test Preparations
2. Performance of the Test
3. Analysis of the Data
4. Preparation of the Test Report

10.1 Pre-Test Preparations

The preparations required for a tracer gas test of building or a building ventilation system are not very different than the preparations of any building field test. It is more economical to spend some time obtaining basic information on the building, the building HVAC systems and plan a test strategy before arriving at the site. However, one should not go to the other extreme of spending too much time and effort attempting to obtain exact engineering data where it probably does not exist. The amount of effort and time required for test preparations depends on the complexity of the building to be tested. Complexity does not necessarily relate to size. The types of questions which should initially be asked are: what is the size of the building, is it a single building or a complex, the number of stories, the interior configuration (open office space or compartmentalized), the number of HVAC systems, their type, where they are located and what they serve and are there any special areas of concern or problems and what parts of the building will not be accessible for testing or entry. The information required for the pre-test preparations will initially come from the data in the CEC data base on the building. This data will be examined by a project engineer to assess its completeness. The initial contact interviewer will be informed of the need for additional information on the building. The contact person will be asked of their willingness to provide this information either over the phone or by fax. Information and actions which should be addressed before testing are:

10.1.1 Determine the type of building to be tested

One should have a reasonably clear understanding of the type of building which is to be tested. Much of the information can be obtained without the need for a site visit before testing. However, in a complicated facility, a site visit may be the most efficient way to plan a test and minimize the costs. The author will usually ask some general questions about the buildings: its size, the number of floors, the number of HVAC systems serving the building and their type, and the number of mechanical equipment rooms in the building and the nature of the interior configuration of the building (individual rooms or an open plan architecture). If the building is small (less than 2000 square meters) and has only a couple of HVAC systems, no more information is usually required to plan the test unless there are some special circumstances which must be considered. If building is larger than 2000 square meters, one should request a set of HVAC system drawings for the mechanical rooms and typical areas served, a HVAC system schedule which lists the fans and their capacities, and some architectural drawings which give the overall configu-

ration of the building and typical floor and area layouts (in complex facilities, one really does not want the architectural drawings, but floor diagrams used to orient visitors, show locations of major departments, emergency exit plans and/or sales or rental literature which have already reduced the information to an understandable form.). Even if these drawings are not needed before the testing, it is good practice to have them available during the test.

10.1.1.1 Estimate the building volume or size

One should obtain an estimate of the size and volume of the building. At the planning stage, if one is to err, one should err on the high side. In a complex building, one can spend many hours taking dimensions off drawings to obtain an accurate estimate of the building size and volume. For the interpretation of certain test results, this may be necessary at the data analysis stage; however for the planning of a test, a reasonable estimate can be obtained by multiplying the gross area of the building by the height of a typical floor, taking in account special areas such as atria, auditoria and manufacturing and laboratory areas which may have non-typical heights or shapes.

10.1.1.2 Determine the Type and the Number of HVAC Systems and Exhaust Systems Serving the Building

One needs a clear understanding of the type, configuration and number of HVAC systems serving the building, where they are located, if they are accessible and what sections of the building they serve. It is necessary to understand how each HVAC system is controlled and what its operating schedule is. One should advise the system operator as to when the systems should be turned on and off. One should attempt to obtain technical information on the capacity of the fans, whether the system has both supply and return fans, if the systems are single zone or multi-zone and if any are variable volume systems. One should determine how many exhaust systems the building has and their operating schedule.

10.1.1.3 Determine the Number of Zones Which Should be Tested

The building must be divided into air zones for the purpose of performing a tracer test. These zones do not always coincide with thermal zones. In general, for a tracer test, a zone is part of a buildings which is isolated from other parts of the buildings. All parts of a building on a common return air system are considered to be in one zone. Similarly, areas of the building without physical barriers (for example open office areas) for the purpose of a tracer test are considered as one zone. For each zone, the HVAC systems which serve the zone must be identified.

10.1.2 Establish a Test Plan

The preparation of a test plan entails the following:

Determine the number of sampling points in each zone.

Determine the quantity of tracer gas to be injected and the method to be used for the injection of the tracer gas.

Determine the configurations of the HVAC System to be tested.

Determine the tracer test methods to be used.

Determine what other measurements should be made in conjunction with the tracer measurements.

Plan the test sequence.

Determine equipment requirements.

Determine supplies needed.

Determine personnel required.

10.2 Performance of a Tracer Gas Test

10.2.1 Equipment Setup

Determine a location in the building for the equipment.

In the following order:

Install the tracer gas monitor, turn on and allow it to stabilize. Be sure to fasten securely the carrier gas cylinder and check all carrier gas lines for leakage.

Install HVAC system injection tubing and injection equipment if required. If metered injection is to be used, secure all tracer gas cylinders and check all injection gas regulators and fittings for leakage.

Install HVAC system sample tubing and pumps on the return and supply air streams if required. Check the sample pumps for faulty check valves and broken diaphragms. Check connections for leakage. Label all sample lines using the zone and location name.

Install wind monitoring equipment.

Determine location for exterior temperature and humidity measurements.

10.2.2 Calibration of the Instrumentation

Before the start of the first test condition, the tracer gas equipment should be calibrated. For the AUTOTRAC monitor the internal automated calibration feature should first be used. If another monitor is used, readings of with 0.5, 1.0, 2.0, 10.0 and 20.0 ppb nominal 2% traceable calibration gases should be made and recorded in a calibration log.

10.2.3 Building Preparation

The building and its HVAC system should be inspected to insure that all air handlers, heating/cooling equipment and exhaust fans are in the appropriate operating condition for the test. Air dampers, windows and doors should be checked.

Each member of the test team and the building engineer staff should be instructed to their proper role during the test.

Equipment which has been modified especially for the test should be red tagged and the modification recorded in the test log.

10.2.4 Injection of the Tracer Gas

Tracer gas should be injected into each zone of the building according to the building test plan. The injection data form for each zone should be filled in accordance with the method of injection used.

10.2.5 Sampling the Building for Tracer Concentration

Tracer gas samples should be obtained at each sample location in the building according to the test plan. For manually obtained samples, the syringe or air sample bag should be labeled and the information on the labels entered and checked for accuracy and completeness. At the end of a sample sequence, the samples should be brought to the tracer gas analyst and logged into the data log. The tracer gas analyst will analyze the samples per the test plan. For a tracer decay test, after analyzing the first sample from each return of each zone, he will inform the test coordinator if sufficient or excessive tracer has been injected into the building. If insufficient tracer has been injected, the test should be aborted and additional tracer injected into the zones. If excessive tracer exists, additional samples will be drawn at twenty minute intervals until five valid samples are obtained.

10.2.6 Preparation for Next Test Condition or Return Building to Its Original Condition

After completion of a test, the test team will meet and discuss any difficulties which occurred during the previous test. The roles of each person will be reviewed for the next test. After the last test, the building will be returned to its original condition. The red tags will be removed from each modified building or HVAC system component and brought to the test coordinator. The test coordinator will verify that the proper restoration has occurred. He will discuss with the representative of the building what has been done to put the building back in its original condition.

10.2.7 Removal of Equipment from the building

After returning the building to its original condition. The test equipment will be packed and removed from the building. All areas used by the test personnel should be left neat and orderly. All trash generated during the test should be removed from the building.

10.3 Data Analysis

Much of the preliminary data analysis will be carried out on site as the test is progressing. If it is not possible to analyze all data as the test progresses, all data from the return air samples should be analyzed on-site during the tests to assess the validity of the test data. Next all upstream supply air samples should be analyzed. Then all samples from selected interior locations should be analyzed.

10.4 Preparation of Building Report

The building test report will be completed according to section 9. Field analysis of the data will be checked during the preparation of the building report including an assessment of the accuracy of the test results.

Appendix I. Error Analysis for Various Techniques for Determining the Quantity of Outside Air

This appendix discusses an error analysis for various methods which can be used for estimating the amount of outside air being supplied to a building. Typical errors which can occur when using each of the methods are presented graphically.

Percent of Outside Air Methods

In the percent of outside air method, the amount of outside air delivered to a building or zone of the building is determined by measuring the air supply flow rate F_s using either such standard techniques as velocity traverses, flow hood, averaging flow meters or by using a tracer dilution technique and using the percent of outside air, P , in the supply stream, determined either the temperature method, the carbon dioxide method or a tracer gas method. The rate of outside air delivered to the space is then given by

$$F_o = P \cdot F_s \quad (\text{AI.1})$$

The percent of outside air is determined by using either a energy or mass balance. Of these three techniques, the temperature method is the one with the most hidden assumptions (it neglects radiation effects, other heat losses and gains, transient effects, solar heating of air intake surfaces and the fact that most digital thermometers have at least one more display digit than their accuracy or precision warrant).

The percent of outside air, P , in the supply stream is determined by one of the following equations depending on the method used:

Temperature Method

$$P = \frac{T_R - T_S}{T_R - T_O} \quad (\text{AI.2})$$

where

T_R is the return air stream temperature
 T_S is the supply air stream temperature
 T_O is the outside air temperature

Carbon Dioxide Method

$$P = \frac{C_R - C_S}{C_R - C_O} \quad (\text{AI.3})$$

where

C_R is the return air stream carbon dioxide concentration
 C_S is the supply air stream carbon dioxide concentration
 C_O is the outside air carbon dioxide concentration

Tracer Gas Method

$$P = 1 - \frac{C_S}{C_R} \quad (\text{AI.4})$$

where

C_R is the return air stream tracer concentration

C_S is the supply air stream tracer concentration

and it is assumed that C_O , the outside tracer concentration is zero. This should be verified experimentally.

The tracer gas and the carbon dioxide method are really the same method and based on the same physical principle: conservation of mass. To the author's knowledge, there is only one hidden assumption: that either *tracer or carbon dioxide concentration is uniform across the ducts and intakes* or that the *air velocity is constant across the duct*. Either of these assumptions can be verified experimentally and errors due to these effects can be estimated and corrected for if required. The experimental techniques employed normally attempt to make the tracer concentration uniform. The tracer gas method assumes that there is no tracer in the outside air. If re-entrainment occurs, then the above equation gives the effective outside air percent.

Standard error analysis for the above set of equations yields the following uncertainties in the estimate of the amount of outside air delivered:

$$\frac{\delta F_O}{F_O} = \sqrt{\frac{\delta F_S^2}{F_S^2} + \frac{\delta P^2}{P^2}} \quad (\text{AI.5})$$

where

δF_O is the error in the quantity of outside air delivered

δF_S is the error in the measured air supply rate

δP is the error in the percent of outside air

The error in the percent of outside air can be determined by performing a standard error analysis on the above equations:

Temperature Method

If absolute temperature sensors are used:

$$\frac{\delta P}{P} = \frac{1}{T_R - T_O} \sqrt{\frac{(1-P)^2}{P^2} \delta T_R^2 + \frac{1}{P^2} \delta T_S^2 + \delta T_O^2} \quad (\text{AI.6})$$

For thermometers with a precision δT , the relative error in the percent of outside air reduces to (from the above equation for absolute temperature sensors):

$$\frac{\delta P}{P} = \frac{\delta T}{T_R - T_O} \sqrt{2 \cdot \frac{(1-P+P^2)}{P^2}} \quad (\text{AI.7})$$

Figure AI.1 shows the type of accuracy one can expect using typical digital thermometers (1°C precision) and typical duct flow measurement methods (10 percent accuracy). For a typical US design ventilation system, it requires about 20 percent to 30 percent outside air to satisfy ASH-RAE Standard 62-1989. Therefore it requires inside-outside temperature differences approaching 30°C to obtain better than 20 percent accuracy using typical test and balance equipment. EPA Indoor Air Quality Guide for Building Managers states that a condition to use the temperature method is that "There is at least a several degree temperature difference between the building interior and the outdoors." It is authors' opinion that this statement should be reworded to state that "all hell should freeze over before one uses the temperature method" unless one uses specially designed and calibrated differential temperature measuring instrumentation.

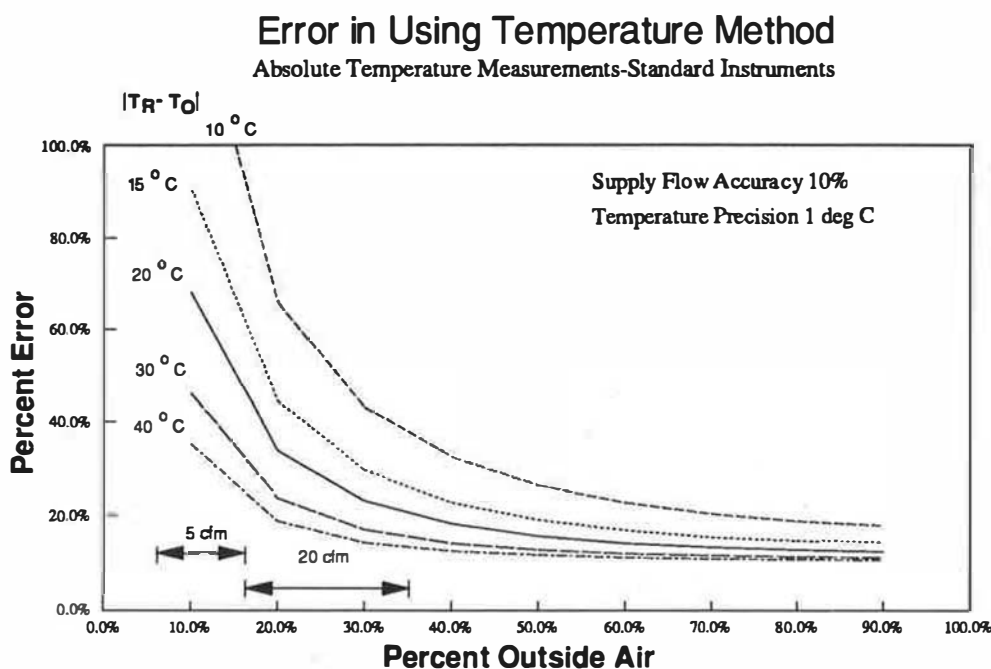


Figure AI.1 Error in Using Temperature Method to Determine Quantity of Outside Air Supplied Using Standard Digital Thermometers

It is possible with special calibration to obtain thermometers with a precision of 0.3°C . If these are used in conjunction with precision duct flow measurement techniques, better accuracy can be obtained. Figure AI.2 shows these accuracies.

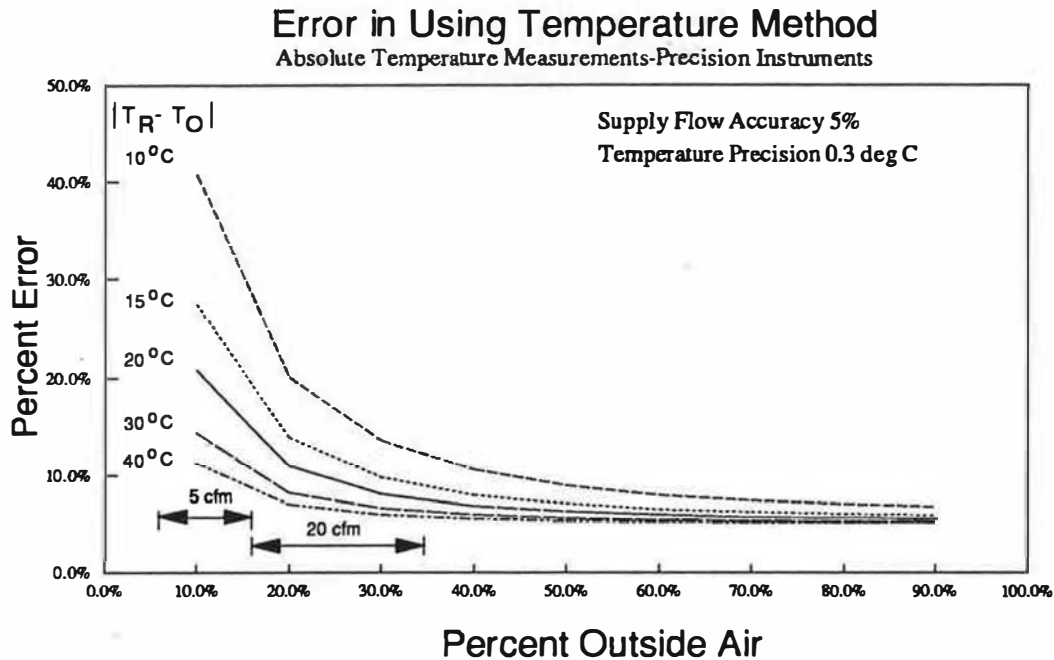


Figure AI.2 Error in Using Temperature Method to Determine Quantity of Outside Air Supplied Using Precision Calibrated Thermometers

It is also possible to use differential thermometers such as thermopiles. If differential temperature sensors are used error in the determination of the percent of outside air is:

$$\frac{\delta P}{P} = \sqrt{\left(\frac{\delta T_{RS}}{T_{RS}}\right)^2 + \left(\frac{\delta T_{RO}}{T_{RO}}\right)^2} \quad (\text{AI.8})$$

where

$$T_{RS} = T_R - T_S$$

$$T_{RO} = T_R - T_O$$

For a differential thermometer with a precision of δT , equation (AI.8) becomes

$$\frac{\delta P}{P} = \frac{\delta T}{T_{RO}} \sqrt{1 + \frac{1}{P^2}} \quad (\text{AI.9})$$

Figure AI.3 shows the accuracies obtained using standard 1°C precision differential thermometers and 10 percent flow accuracies. Figure AI.4 shows the accuracies using a precision (0.3°C) differential thermometer and a 5 percent duct flow measurement.

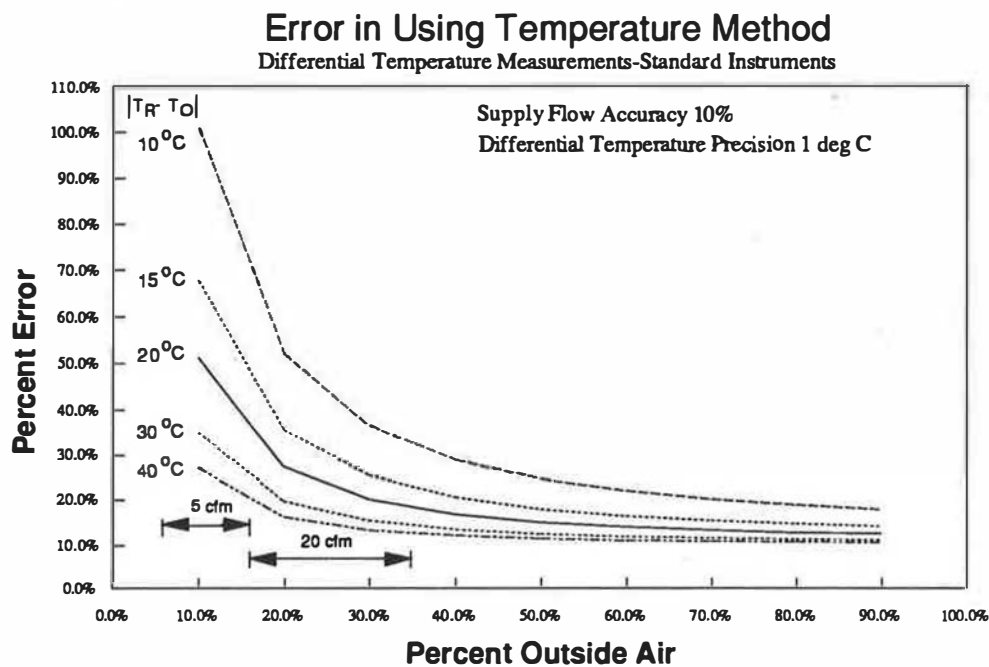


Figure AI.3 Error in Using Temperature Method to Determine Quantity of Outside Air Supplied Using Standard Differential Thermometers

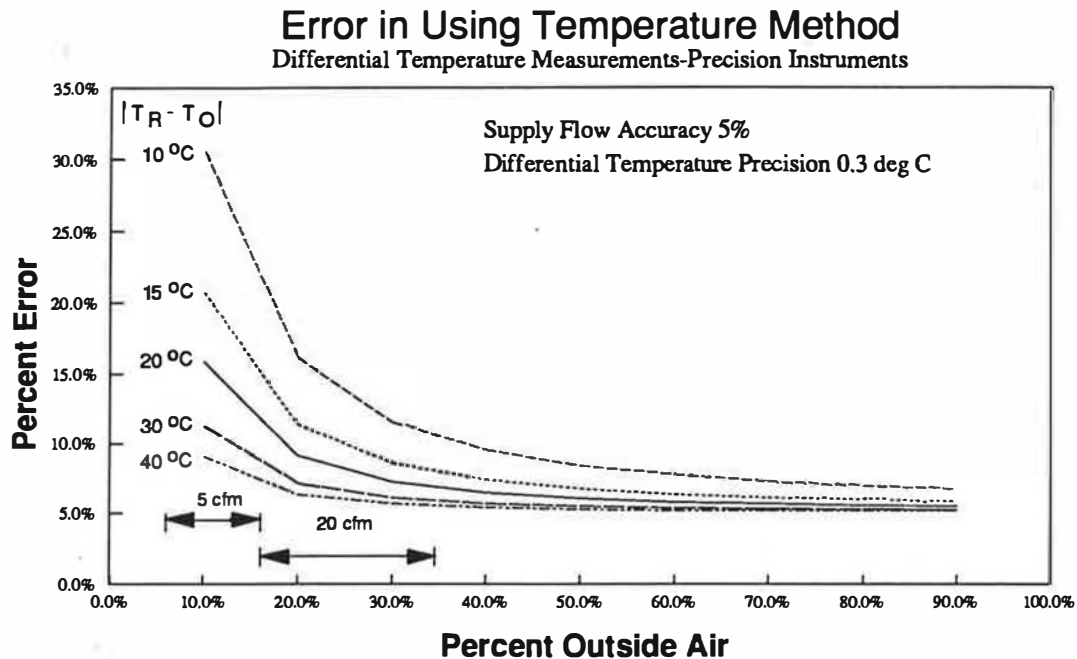


Figure AI.4 Error in Using Temperature Method to Determine Quantity of Outside Air Supplied Using Precision Differential Thermometers

Carbon Dioxide Method

An error analysis of the use of Carbon Dioxide to measure the percent of outside air gives the following expression for the error in the percent of outside air:

$$\frac{\delta P}{P} = \frac{1}{C_R - C_O} \sqrt{\frac{(1-P)^2}{P^2} \delta C_R^2 + \frac{1}{P^2} \delta C_S^2 + \delta C_O^2} \quad (\text{AI.10})$$

For a monitor which has an absolute precision of δC (a percent of full scale specification) the above equation yields the following expression for the relative error in the percent of outside error:

$$\frac{\delta P}{P} = \frac{\delta C}{C_R - C_O} \sqrt{2 \cdot \frac{(1-P+P^2)}{P^2}} \quad (\text{AI.11})$$

Typical low cost Carbon Dioxide monitors (sample tube are even worse) have a precision of 100 ppm and a full scale of 2000 ppm. Figure AI.5 shows the accuracy one can expect when using such an instrument to measure the percent of outside air. Notice that the errors in the method are greater than 40 percent in typical situations. This instrumentation is not capable of accurately measuring the quantity of outside air delivered to a zone. It is possible to obtain carbon dioxide monitors which can be calibrated to about 10 ppm. These monitors are not low cost and careful

field calibration is required. Figure AI.6 shows the percent error in estimating the quantity of outside air delivered using precision CO₂ monitors. Such instrumentation is capable of determining the quantity of outside air delivered to about 15 percent if the difference between the inside CO₂ concentration and the outside CO₂ concentration is greater than 700 ppm.

Error in Using CO₂ Method

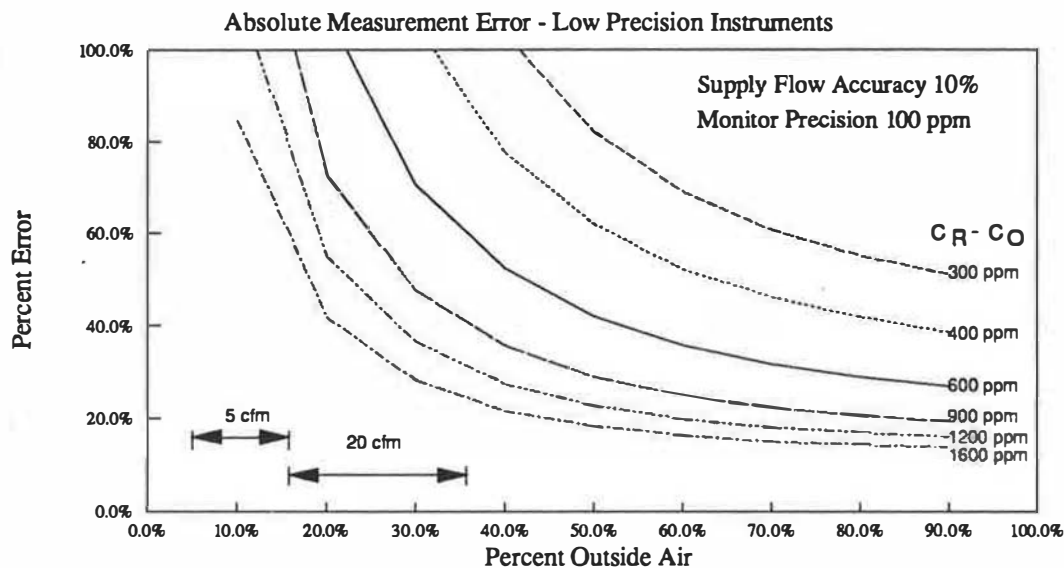


Figure AI.5 Error in Using Carbon Dioxide Method to Determine Quantity of Outside Air Supplied Using Typical Low Precision Monitors (100 ppm precision, Full Scale of 2000 ppm)

Error in Using CO₂ Method

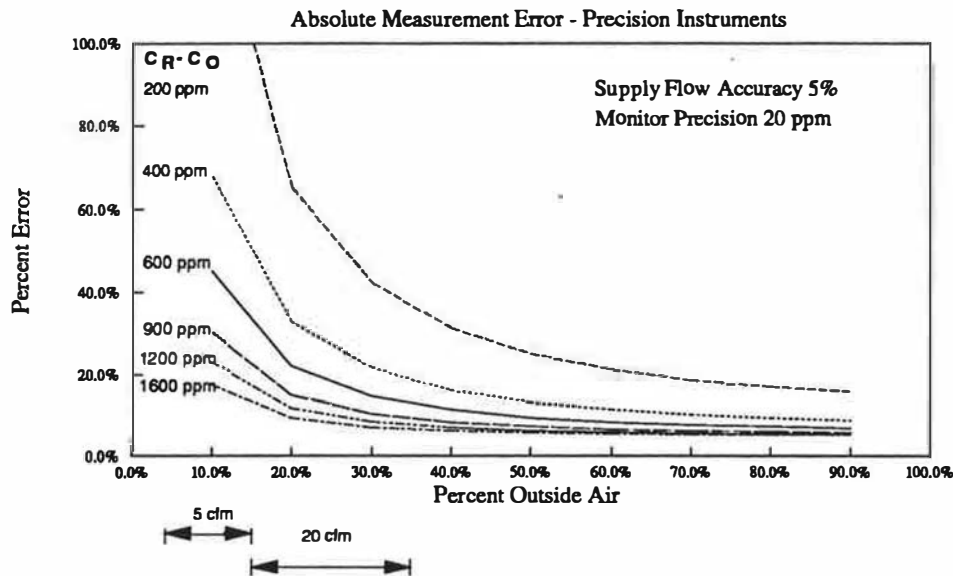


Figure AI.6 Error in Using Carbon Dioxide Method to Determine Quantity of Outside Air Supplied Using High Precision Monitors (10 ppm precision, Full Scale of 2000 ppm)

Tracer Gas Method

An error analysis of the equation for determining the percent of outside air using a tracer gas which is not present in the outside air yields the following equation for the relative error in the percent of outside air:

$$\frac{\delta P}{P} = \frac{1}{C_R} \sqrt{\frac{(1-P)^2}{P^2} (\delta C_R)^2 + \frac{1}{P^2} (\delta C_S)^2} \quad (\text{AI.12})$$

For a tracer gas monitor which has an error proportional to the reading (this is true for gas chromatographs) this equation reduces to:

$$\frac{\delta P}{P} = \sqrt{2} \frac{(1-P)}{P} \left(\frac{\delta C}{C} \right) \quad (\text{AI.13})$$

Error in Using Tracer Gas

Gas Chromatograph (% of reading error)

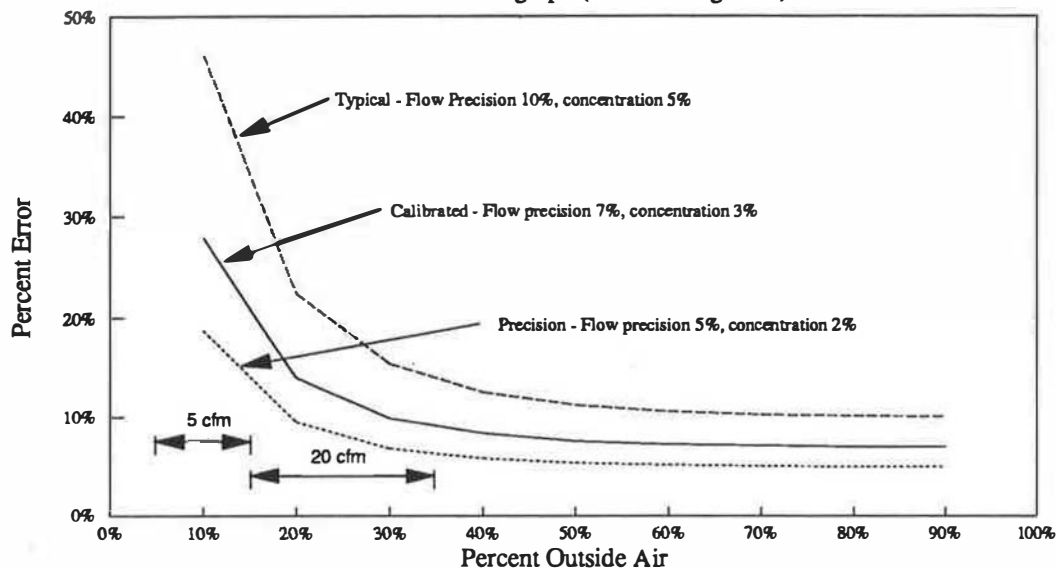


Figure AI.7 Error in Using Tracer Gas Method to Determine Quantity of Outside Air Supplied Using Various Precision Chromatographs

Error Analysis for the Tracer Dilution Methods for Measuring Outside Air

It has been shown by several authors, (Grot and Lagus, 1990) that in general for a single zone tracer gas measurement, the total outside airflow Q can be determined from the following equation

$$Q_{av}(t_2, t_1) = \frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} \frac{\sigma(\tau)}{C(\tau)} d\tau + \frac{V}{(t_2 - t_1)} \ln \left(\frac{C_1}{C_2} \right) \quad (\text{AI.14})$$

where

- $Q_{av}(t_2, t_1)$ is the average outside airflow in the time interval (t_1, t_2)
- $\sigma(t)$ is the injection flow rate at time t ,
- $C(t)$ is the tracer concentration at time t ,
- V is the volume of the zone tested.

The three standard tracer dilution methods: the tracer decay method, the constant injection method and the constant concentration method control the injection rate of tracer, σ , such that the evaluation of equation (AI.14) simplifies.

Tracer Decay

For the tracer decay test $\sigma(t) = 0$ identically after the initial injection of tracer into the space and equation (AI.14) reduces to

$$Ach(t_2, t_1) = \frac{1}{(t_2 - t_1)} \ln \left(\frac{C_1}{C_2} \right) \quad (\text{AI.15})$$

where $Ach(t_2, t_1)$ is the average air change rate in the time period (t_1, t_2)

$$Ach(t_2, t_1) = \frac{Q(t_2, t_1)}{V}$$

If one performs a standard error analysis of equation (AI.15), one obtains the following uncertainty in the air change rate:

$$\delta Ach = \frac{1}{(t_2 - t_1)} \sqrt{\left(\frac{\delta C_2}{C_2} \right)^2 + \left(\frac{\delta C_1}{C_1} \right)^2} \quad (\text{AI.16})$$

where

δAch is the uncertainty in the air change rate

δC_2 is the uncertainty in $C(t_2)$

δC_1 is the uncertainty in $C(t_1)$

There are two general classes of tracer monitor used for determining the tracer concentrations in the building: instruments, such as those based on infrared absorption, which have an error which is a percentage of full scale (a fixed precision) and instruments, such as gas chromatographs, which have over a wide range have a percent of reading error (a relative precision).

Instruments with Percent of Full Scale Error

For an instrument which has a fixed precision, δC , equation (AI.16) reduces to

$$\delta Ach = \frac{\delta C}{C_1} \sqrt{1 + \left(\frac{C_1}{C_2} \right)^2} \quad (\text{AI.17})$$

Equation (AI.17) has been used to infer that the tracer decay method using equation (AI.15), though an unbiased estimate of the average air change rate, is inaccurate and that the optimal time interval for the test is $1/Ach$. If one solves (AI.15) for the ratio C_1/C_2 and substitutes the result in (AI.17), one arrives at the following expression for the relative error in the air change rate determination *using instruments with a fixed precision*:

$$\frac{\delta Ach}{Ach} = \frac{\delta C}{(t_2 - t_1) \cdot C_1 \cdot Ach} \sqrt{1 + \exp(2 \cdot Ach \cdot (t_2 - t_1))} \quad (\text{AI.18})$$

Figure AI.8 shows the percent error in using equation AI.15 with fixed precision instruments to obtain an unbiased estimate of the air change rate.

Tracer Decay Error

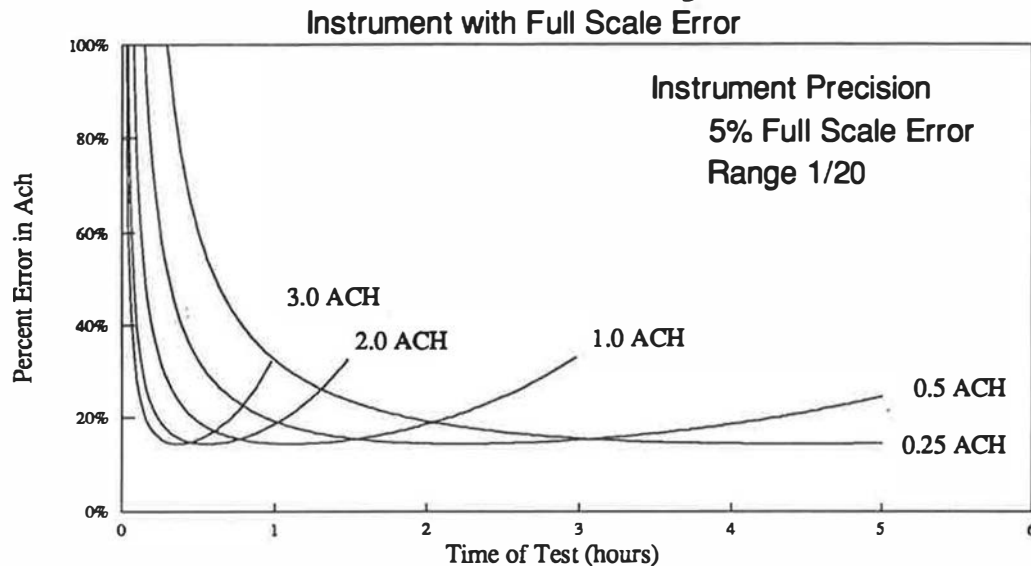


Figure AI.8 Percent Error in Determining the Air Change Rate Using Fixed Precision Instruments which have a Percent of Full Scale Error. Curves are drawn only for concentrations in the range of the instrument.

Instruments with a Percent of Reading Error

For instruments with a percent of reading error over its measurement range

$$\frac{\delta C_1}{C_1} = \frac{\delta C_2}{C_2} \equiv \frac{\delta C}{C}$$

equation AI.16 reduces to

$$\delta ACh = \frac{\sqrt{2}}{(t_2 - t_1)} \frac{\delta C}{C} \quad (\text{AI.19})$$

Figure AI.9 shows the percentage error in the determination of the air change rate using equation (AI.15) using an instrument, such as a gas chromatograph, which has a percent of reading error. The curves in figure AI.9 assume a measurement range of 50 to 1 which is very conservative of most gas chromatographs (some models of gas chromatographs with electron capture detectors have measurement ranges in excess of 500 to 1).

Tracer Decay Error

Instrument with 5 Percent of Reading Error

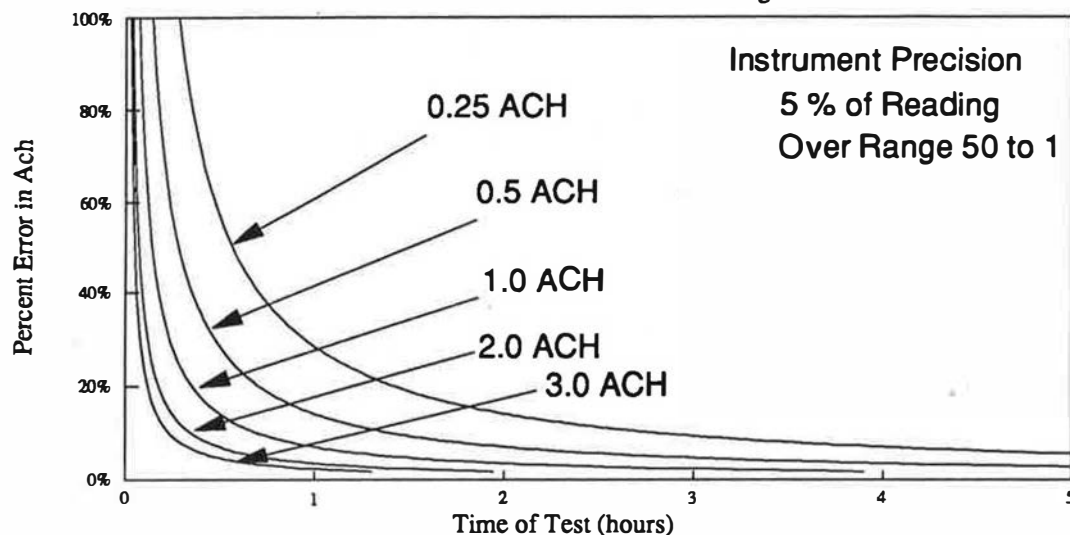


Figure AI.9 Percent Error in Determining the Air Change Rate Using Instruments which have a Percent of Reading Error. Curves are drawn only for concentrations in the range of the instrument (50 to 1).

Equation (AI.12) and the curves of Figure AI.8 are the reasons that Sherman (which the authors of reference Roulet et al. parrot) makes the catchy statement "such is the price of an unbiased estimate." Sherman and reference [2] fail to mention what the errors would be if one uses a percent of reading instrument. The reference Roulet et al. correctly states in its review of instruments that gas chromatographs have an error which is a percent of reading and that this error can be as low as 2 or 3 percent of reading with proper calibration. Equation (AI.19) and the curves of Figure AI.9 show that, with a gas chromatograph, the use of equation (AI.15) can produce both an unbiased and accurate estimate of the average air change rate if one stays within the range of measurement of the instrument. The curves of Figure AI.9 are similar to those that Hunt published in his review article on tracer methods in 1980.

Constant Injection Method

For the constant injection tracer method, the injection flow rate $\sigma(t)$ is held at a constant rate σ and one allows the tracer concentration in the space to build up to an equilibrium value. For the constant injection method, equation (AI.15) reduces to

$$Q_{av}(t_2, t_1) = \sigma \left[\frac{1}{C} \right]_{av} + \frac{V}{(t_2 - t_1)} \ln \left(\frac{C_2}{C_1} \right) \quad (\text{AI.20})$$

where
$$\left[\frac{1}{C} \right]_{av} \equiv \frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} \frac{d\tau}{C(\tau)}$$

For a constant injection measurement, one waits for some time interval (t_1, t_2) the beginning and end concentrations C_1 and C_2 are approximately equal. In such a situation equation (AI.20) reduces to

$$Q_{av}(t_2, t_1) = \sigma \left[\frac{1}{C} \right]_{av} \quad \text{when } C_2 \equiv C_1 \quad (\text{AI.21})$$

It should be noted that equation (AI.21) does not require the assumption of steady state airflows. One must, however, properly evaluate the average of $1/C(t)$ over the time period. Do not assume that it is the inverse of the average concentration unless steady state has been achieved.

Performing a standard error analysis of equation (AI.20) for the case when $C_2 \equiv C_1$ leads to the following error in determining Q when using equation (AI.21):

$$\frac{\delta Q}{Q} = \sqrt{\left(\frac{\delta \sigma}{\sigma} \right)^2 + \left(\frac{\delta C}{C_{av}} \right)^2 \left(\alpha^2 + \frac{2V^2}{(t_2 - t_1)^2 Q^2} \right)} \quad (\text{AI.22})$$

where C_{av} is the average concentration in the time period.

The α

$$\alpha^2 = \frac{\text{Var} \left[\frac{1}{C} \right]}{\left(\delta C \left[\frac{C_{av}}{C} \right] \right)^2} \equiv \frac{\text{Var}[C]}{(\delta C)^2}$$

$$\text{where } \text{Var}[f] \equiv \frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} (f(\tau) - f_{av})^2 d\tau$$

is a measure of the lack of obtaining a steady state value compared to the precision of the concentration measurement. In most cases, this expression is unity. In this case equation (AI.22) becomes:

$$\frac{\delta Q}{Q} = \sqrt{\left(\frac{\delta \sigma}{\sigma} \right)^2 + \left(\frac{\delta C}{C_{av}} \right)^2 \left[1 + \frac{2V^2}{(t_2 - t_1)^2 Q^2} \right]} \quad (\text{AI.23})$$

$$\text{when } \alpha^2 \equiv 1$$

Figure AI.10 shows the percent error in determining the airflow rate Q by the constant injection method.

Constant Injection

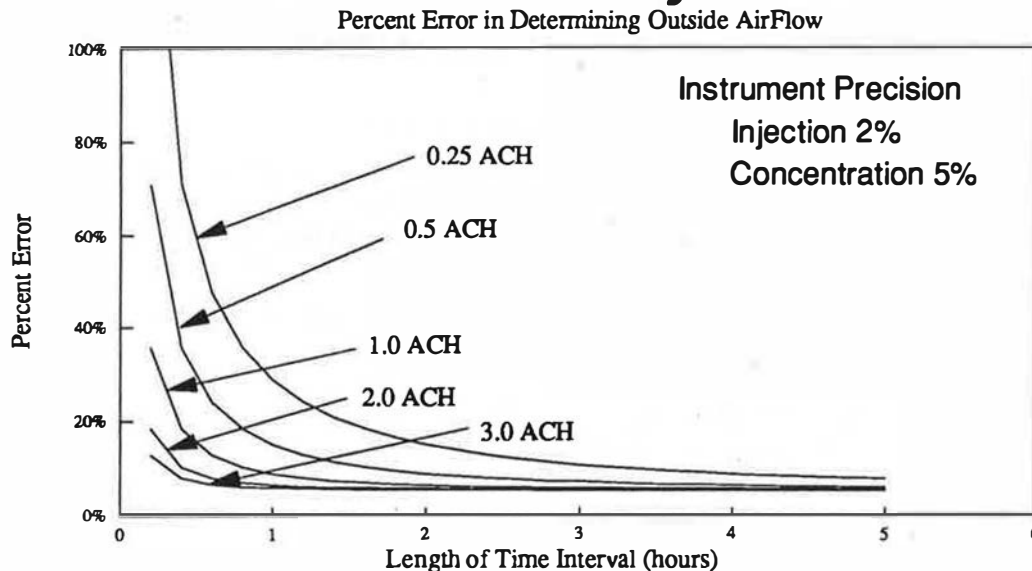


Figure AI.10 Percent Error in Determining the Airflow Rate Using the Constant Injection Method as a Function of the Length of the Period of Averaging. Note: the above curves also represent the error in determining the average airflow as a function of the length of the period of averaging for the constant concentration method. See the next section.

As Figure AI.10 shows, at low air change rates, it is necessary to obtain an average approximation to "steady" state for a period of several hours to obtain acceptable precision. In other words, once one judges that "steady state" has occurred to within the precision of the measurement, one should wait a time of at least $1/\text{ACH}$ to obtain an accurate estimate of the airflow rate. It should be noted that it takes a time of approximately $3/\text{ACH}$ for near equilibrium to occur. Therefore, to obtain an accurate airflow using the constant injection tracer dilution test requires a time period of approximately $4/\text{ACH}$.

Constant Concentration

In the constant concentration tracer dilution method, one attempts to control the injection of tracer into the zone such that tracer concentration in the zone is constant, C_{avg} . The constant concentration method is the most difficult to carry out in the field and the most difficult to correctly analyze. If one selects a time period (t_1, t_2) such that $C_1 \equiv C_2$ then equation (AI.14) reduces to

$$Q_{\text{av}}(t_2, t_1) = \left[\frac{\sigma}{C} \right]_{\text{av}} \equiv \sigma(t_2, t_1) \cdot \left[\frac{1}{C} \right]_{\sigma_{\text{av}}} \quad (\text{AI.24})$$

In equation (AI.24), $\sigma(t_2, t_1)$ is the amount of tracer gas injected in the period (t_1, t_2)

and

$$[f]_{\sigma_{av}} \equiv \frac{1}{\sigma(t_2, t_1)} \int_{t_1}^{t_2} f(\tau) \sigma(\tau) d\tau$$

is the σ weighted average of the function $f(t)$ in the period (t_1, t_2) .

It should be noted that equation (AI.24) does not require the assumption of steady state airflows or perfect control. One must, however, properly evaluate the σ weighted average of $1/C(t)$ over the time period. Do not assume that it is the total amount of tracer injected divided by the average concentration unless good control of the concentration has been achieved.

Performing a standard error analysis of equation (AI.20) for the case when $C_2 \equiv C_1$ leads to the following error in determining Q when using equation (AI.24):

$$\frac{\delta Q}{Q} = \sqrt{\left(\frac{\delta \sigma}{\sigma(t_2, t_1)}\right)^2 + \left(\frac{\delta C}{C_{\sigma_{av}}}\right)^2 \left(\alpha^2 + \frac{2V^2}{(t_2 - t_1)^2 Q^2}\right)} \quad (\text{AI.25})$$

where $C_{\sigma_{av}}$ is the σ weighted average concentration in the time period.

The parameter α

$$\alpha^2 = \frac{\text{Var}_\sigma\left[\frac{1}{C}\right]}{\left(\delta C\left[\frac{C_{\sigma_{av}}}{C}\right]_{\sigma_{av}}\right)^2} = \frac{\text{Var}_\sigma[C]}{(\delta C)^2}$$

$$\text{where } \text{Var}_\sigma[f] \equiv \frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} (f(\tau) - f_{\sigma_{av}})^2 \sigma(\tau) d\tau$$

is the σ weighted variance of f

is a measure of the lack of obtaining perfect target concentration control compared to the precision of the concentration measurement. In most cases, this expression is unity. In this case equation (AI.24) becomes:

$$\frac{\delta Q}{Q} = \sqrt{\left(\frac{\delta \sigma}{\sigma(t_2, t_1)}\right)^2 + \left(\frac{\delta C}{C_{\sigma_{av}}}\right)^2 \left[1 + \frac{2V^2}{(t_2 - t_1)^2 Q^2}\right]} \quad (\text{AI.26})$$

when $\alpha^2 \equiv 1$

It should be noted that the equations for the constant concentration method are identical to the constant injection method if one replaces all averages and variances with σ weighted averages and variances. Therefore, figure AI.10 also represents the error in the constant concentration method of obtaining an unbiased estimate of the average airflow over a period (t_1, t_2) for which $C_1 \equiv C_2$. Thus one can obtain accurate estimates of the airflow rate in the constant concentration method only if one averages the results for a period greater than $1/Ach$.

Appendix II. Instructions for the Use of the Lotus 123 Spreadsheet Template TRDECAY.WK3 for Analyzing Tracer Decay Data

Instructions for TRDECAY.WK3 Tracer Decay Spreadsheet Template

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These instructions for the use of TRDECAY.WK3 spreadsheet template assume a basic familiarity with Lotus 1-2-3 on the part of the user.

No explanation of Lotus 1-2-3 commands is given!

These instructions assume some knowledge of tracer testing.

All concentration units are assumed to be parts per billion (ppb).

TRDECAY.WK3 is a Lotus 1-2-3 version 3.1 spreadsheet template for analyzing tracer decay data for a single zone. If more than one zone is to be analyzed, multicopies of the spreadsheet can be loaded using the File Open (/FO) command. Multicopies must have different names. TRDECAY.WK3 uses the WYSIWYG.PLC addin for Lotus 1-2-3. This is loaded automatically when TRDECAY.WK3 is retrieved using the File Retrieve (/FR) command and selecting TRDECAY.WK3.

On loading, the automatic macro {0} is called. This macro will check to see if WYSIWYG.PLC is loaded. If it is not loaded, WYSIWYG.PLC is loaded. If the filename in the range location "filename" is "trdecay", you will be asked to input another filename. The macro will save the spreadsheet under the new filename. If the title of the spreadsheet in range location "title" is blank, you will be asked to input a title for the zone.

There are several ways in which data can be entered in the spreadsheet. It should first be noted that most of the spreadsheet is protected and direct entry of data is allowed only in a limited number of locations. Most of the entry of data should be done through the input macros: (Alt-I, Alt-R, Alt-D, Alt-T, Alt-F) or the Main Menu (Alt-M).

In its simplest use, only the date, time and entry columns of the table labelled concentrations need be filled in. The spreadsheet will begin calculating the air change rate and plot the data as soon as a sufficient number of points are entered.

However, if the user wishes to also determine the quantity of outside air delivered to the zone, the quantity of outside air per occupant or to determine the amount of tracer to inject into the zone, either by means of a metered amount using a flow meter or a syringe release, the other sections of the spreadsheet should be filled in

Procedure for inputting data:

- 1.) Select units (physical and for injection quantities). (optional - default SI)
- 2.) Input dimensions of zone. (optional)
- 3.) Input injection parameters. (For most situations, input the target concentration and the duration of injection if a flow meter is used. The spreadsheet will calculate the amount of tracer to be injected and the flow rate to use.)
- 4.) Set the calibration factor (default is 1) for Model 215BGC (ALT-C).
- 5.) Set the Range used on the Model 215BGC (ALT-B).
- 6.) Input tracer data (time and readings).
- 7.) Save spreadsheet!

Steps 1, 2, and 3 are done using the main menu (ALT-M) macro.

To input data, position cell pointer to table labelled "Concentrations" under the column labelled date.

Positioning the cell pointer can be done using the cursor movement keys {Up}, {Down}, {RIGHT}, {LEFT}, {PgUP}, {PgDn}, {End}, {Home} or the macros ATL-N which will position the cursor for the next time entry and ALT-Q which will position the cursor for the next concentration entry.

Position the cell pointer to the first blank row in the date column.

Enter the date. The date does not have to be entered in the other rows unless the test lasts into the next day. Format (MM/DD/YY)

Enter the time of each reading in column labelled time. (Format HH:MM)

Enter the reading in the columns labeled Entry #1 and Entry #2 or #3

if more than one reading of each sample is desired. The entry of a Model 215BGC reading can be either direct if no conversion to concentration is needed, or using either ALT-I (the general input macro) or ALT-R (the Model 215BGC reading macro). The ALT-I macro requires the input of the Model 215BGC reading, the dilution factor

used (for syringe or bag samples that require diluting to obtain an on-scale reading) and the Range Scale of the Model 215BGC (A,B,C,D,E). For the dilution factor, input 2 for a one half dilution (50%), 3 for a one third dilution (33.3%) etc. The default dilution factor is 1 and the default range scale of the Model 215BGC is the C range. The dilution factor can be set with ALT-D. The range scale of the Model 215BGC can be set with the ALT-B macro. ALT-R requires only the input of the reading from the Model 215BGC and uses the previous values of the dilution factor and the range. For most applications ALT-I is used once to establish the dilution factor and the range of the Model 215BGC and then ALT_R is used until either the dilution factor or range is changed. ALT-I and ALT-R calculate

$$\text{conc} = \text{reading} * \text{scale} * \text{dilution} * \text{calib_factor}$$

where scale = (4.0, 2.0, 1.0, 0.4, 0.2) for ranges (A, B, C, D, E).

If a new calibration factor is required ALT-C should be used to change the the calibration factor. It is assumed that the C Range is used for calibration.

Repeat the above steps for each sample taken.

The "Valid" column is used to exclude a sample from the points used to calculate the air change rate. To exclude a point, type an "X in the "Valid" column. To include the point again, erase the the the "X using /RE~.

The macro ALT-N can be used to positon the cell pointer to the next location for the time of reading data entry.

The macro ALT-Q can be used to position the cell pointer to the next location for a Model 215BGC reading data entry.

An example spreadsheet EXDECAY.WK3 is included with TRDECAY.WK3.

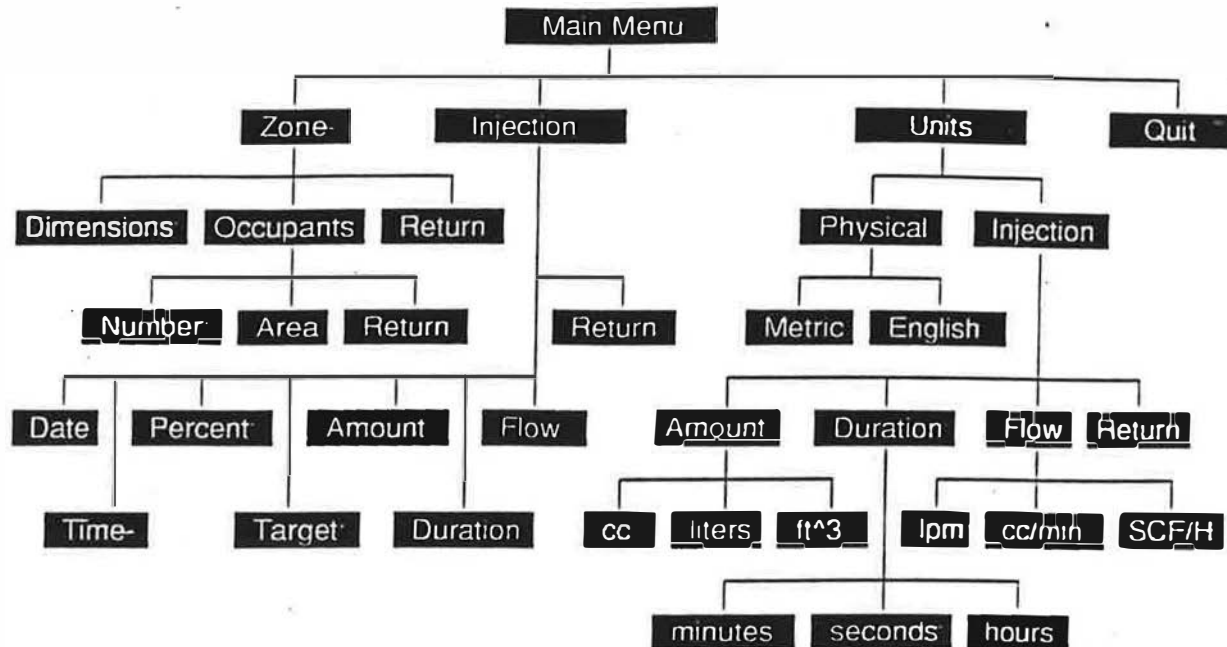
The spreadsheet is limited to 11 readings as supplied. If one wishes to increase the number of entries, globally disable the protection of the spreadsheet (/WGPD~) and position the cell pointer to a point in column A in the middle of the table, insert the number of additional rows needed, and copy the formula from a row of the table to the added rows, in all columns A through AC.

These instructions can be printed using WYSIWYG (:PG).

Description of Macros:

- ALT-A Internal use. Test for WYSIWYG.PLC addin and loads in not active.
- ALT-B Select Range of Model 215BGC (A,B,C,D,E)
- ALT-C Input of calibration concentration and reading. Calculates calibration factor.
- ALT-D Change dilution factor.
- ALT-F Input file name.
- ALT-G Display graph of tracer decay
- ALT-I General input of readings, dilution factor and range and puts the calculated tracer concentration in current cell. Result stored in current cell.
- ALT-M Produces the main menu for entry of zone data, injection data and the selection of units.
- ALT-N Positions cell pointer to next position for time entry.
- ALT-Q Positions cell pointer to next data entry position.
- ALT-P Prints report using WYSIWYG.PLC print routine.
- ALT-R Input of readings. Calculates tracer concentration using previous dilution factor and range setting.
- ALT-S Saves spreadsheet as the file listed in "filename".
- ALT-T Input of title for zone.
- ALT-X Saves current spreadsheet and loads a new one.

Description of Main Menu (ALT-M)



Menu items can be selected by either using the cursor keys to highlight an item and typing enter, or by typing the first letter of the item

Menu Item

Zone

Entry for input of zone data.

Dimensions

Input of physical dimensions of zone:

Height of floor

Width of floor

Length of floor

Number of floors

Will calculate volume and area of zone.

 $\text{area} = \text{num_of_floors} * \text{length} * \text{width}$ $\text{volume} = \text{area} * \text{height}$

Occupants

Entry for input of occupant data.

Number

Number of occupants in zone.

Area

Floor area for each occupant (if not inputted, will be determined from number of occupants and the area of the zone)

Return

Return to zone menu

Return

Return to main menu.

<u>Menu Item</u>	(CONTINUED)
Injection	Entry for input of tracer injection parameters.
Date	Date of injection. Use MM/DD/YY format.
Time	Time of Injection. Use HH:MM format.
Percent	Percent of tracer in injection gas. Use percent format, e.g. 10%.
Target	Tracer target level desired. If target is specified and amount not specified, amount will be calculated. If amount is specified and target not specified, then target will be calculated.
Amount	Amount of tracer to be injected. Units can be cc, liters or ft ³ . See Units-Injection-Amount item below. If duration and time are specified and amount not specified, then amount will be determined from duration and time of injection.
Duration	Duration of injection. If not specified and flow rate of injection is specified, will be determined for amount and flow rate. Units are minutes, hours or seconds. See Units-Injection-Duration item below.
Flow	Injection flow rate of tracer gas. If not specified, will determined from amount and duration of injection if duration is specified.
Return	Return to main menu.
Units	Entry for selecting units.
Physical	Entry to select metric or english units for zone dimensions.
Metric	Select metric units for zone dimensions (meters).
English	Select english units for zone dimensions (feet).
Injection	Select units for injection quantities.
Amount	Entry to menu to select units for amount of tracer injected.
cc	Amount into be expressed in cc.
liters	Amount to be expressed in liters.
ft ³	Amount to be expressed in cubic feet.
Duration	Entry to menu to select injection duration units.
minutes	Duration of injection to be expressed in minutes.
seconds	Duration of injection to be expressed in seconds.
hours	Duration of injection to be expressed in hours.
Flow	Entry to menu to select units for injection flow rate.
lpm	Injection flow rate to be expressed in liters per minute.
cc/min	Injection flow rate to expressed in cc per minute.
SCF/H	Injection flow rate to be expressed in cubic feet per hour.
Return	Return to Units Menu
Return	Return to main menu
Quit	Exit main menu and return to spreadsheet.

Lagus Applied Technology Tracer Decay Test Spreadsheet

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Title: Office Building 101File: EXDECAY

Units
metric

Zone Dimensions	
Volume	336 m ³
Area	120 m ²
Floor Height	2.8 m
Number of Floors	1
Num. of Occupants	10
Area per Occupant	12 m ²

Tracer Injection	
Date	06/20/92
Time	23:00
% SF6	1.00%
Amount	504 cc
Duration	10 minutes
Flow Rate	0.050 lpm

Target Concentration
15.000 ppb

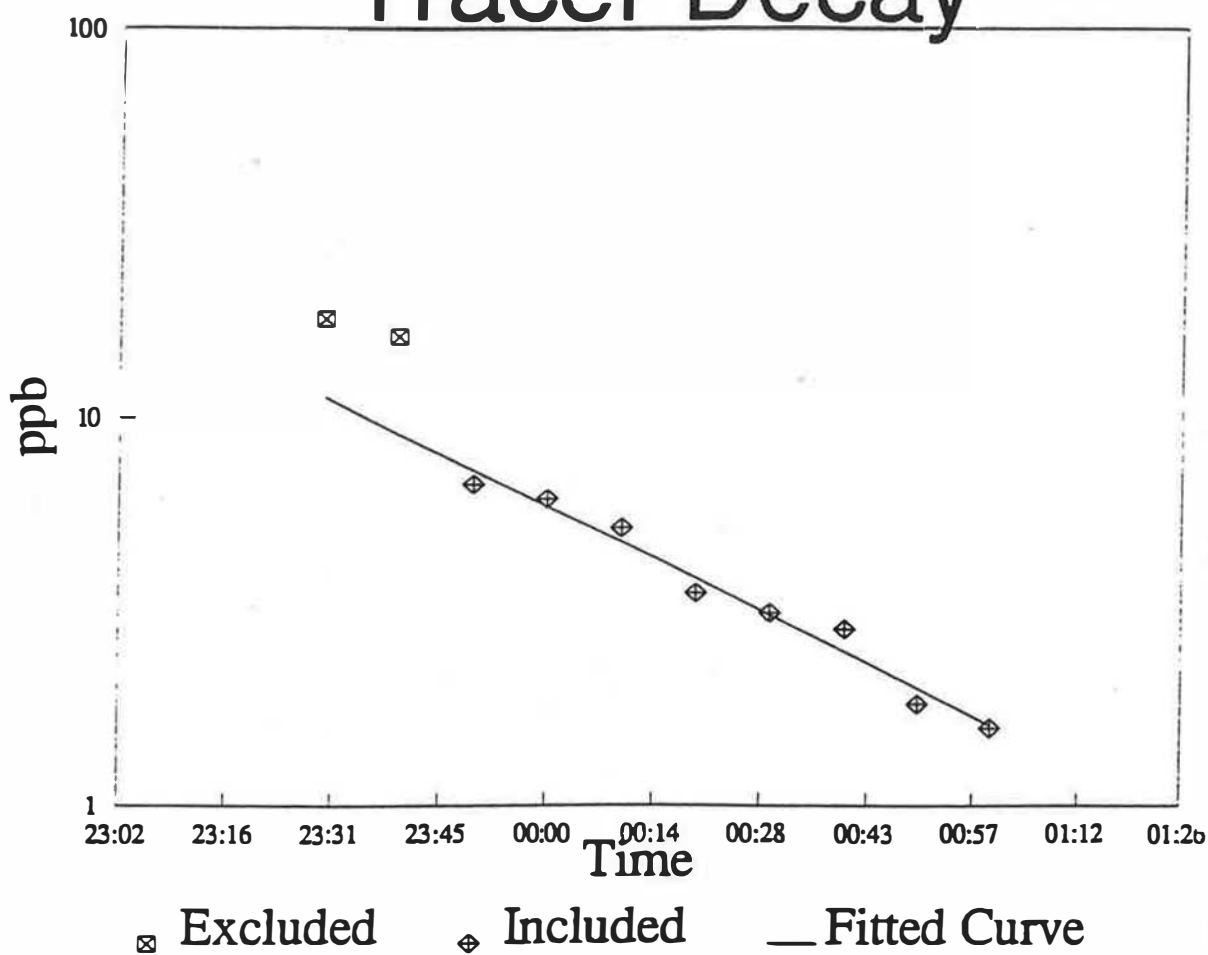
Sample	Date	Time	Concentrations			Valid
			Average ppb	Variance ppb	Entry 1 ppb	
1	06/20/92	23:30	17.912	0.000	17.912	X
2		23:40	16.049	0.000	16.049	X
3		23:50	6.735	0.000	6.735	
4	06/21/92	00:00	6.162	0.000	6.162	
5		00:10	5.159	0.000	5.159	
6		00:20	3.487	0.000	3.487	
7		00:30	3.105	0.000	3.105	
8		00:40	2.818	0.000	2.818	
9		00:50	1.815	0.000	1.815	
10		01:00	1.576	0.000	1.576	
11						

Results

Air Change Rate	0.52 ach
Std Error ACH	0.03 ach
R**2	0.97522
Std Error of Fit	0.09143
Initial Conc.	11.265 ppb
Std Err C0	0.947 ppb

Total lps	48.5567
Error lps	3.16021
lps per person	4.86
Error lps per person	0.02

Tracer Decay



Office Building 101

Appendix III. Instructions for the Use of the Lotus 123 Spreadsheet TRDUCT.WK3 for Analyzing Duct Flow Data

Instructions for TRDUCT.WK3 Tracer Duct Flow Spreadsheet Template

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These instructions for the use of TRDUCT.WK3 spreadsheet template assume a basic familiarity with Lotus 1-2-3 on the part of the user.

No explanation of Lotus 1-2-3 commands is given!

These instructions assume some knowledge of tracer testing.

All concentration units are assumed to be parts per billion (ppb).

TRDUCT.WK3 is a Lotus 1-2-3 version 3.1 spreadsheet template for analyzing tracer buildup data for a single duct. If more than one duct is to be analyzed, multicopies of the spreadsheet can be loaded using the File Open (/FO) command. Multicopies must have different names. TRDUCT.WK3 uses the WYSIWYG.PLC addin for Lotus 1-2-3. This is loaded automatically when TRDUCT.WK3 is retrieved using the File Retrieve (/FR) command and selecting TRDUCT.WK3.

On loading, the automatic macro {0} is called. This macro will check to see if WYSIWYG.PLC is loaded. If it is not loaded, WYSIWYG.PLC is loaded. If the filename in the range location "filename" is "trduct", you will be asked to input another filename. The macro will save the spreadsheet under the new filename. If the title of the spreadsheet in range location "title" is blank, you will be asked to input a title for the zone.

There are several ways in which data can be entered in the spreadsheet. It should first be noted that most of the spreadsheet is protected and direct entry of data is allowed only in a limited number of locations. Most of the entry of data should be done through the input macros: (Alt-I, Alt-R, Alt-D, Alt-T, Alt-F) or the Main Menu (Alt-M).

In its simplest use, only the date, time and entry columns of the table labelled concentrations need be filled in. The spreadsheet will begin calculating the duct flow rate and plot the data as soon as a sufficient number of points are entered.

Procedure for inputting data:

- 1.) Select units (physical and for injection quantities).
- 2.) Input injection parameters. (For most situations, input the target concentration, the injection flow rate and the percent of tracer in the injection gas. The spreadsheet will estimate a duct flow rate. This estimate flow rate should be less than the anticipated duct flow rate. If not, reduce the injection flow rate.)
- 3.) Set the calibration factor (default is 1) for Model 215BGC (ALT-C).
- 4.) Set the Range used on the Model 215BGC (ATL-B).
- 5.) Input tracer data (time and readings).
- 6.) Save spreadsheet!

Steps 1, 2, and 3 are done using the main menu (ALT-M) macro.

To input data, position cell pointer to table labelled "Concentrations" under the column labelled date.

Position the cell pointer to the first blank row in the date column.

Enter the date. The date does not have to be entered in the other rows unless the test lasts into the next day. Format (MM/DD/YY)

Enter the time of each reading in column labelled time. (Format HH:MM)

Enter the reading in the columns labeled Entry #1 and Entry #2 or #3

if more than one reading of each sample is desired. The entry of a Model 215BGC reading can be either direct if no conversion to concentration is needed, or using either ALT-I (the general input macro) or ALT-R (the Model 215BGC reading macro). The ALT-I macro requires the input of the Model 215BGC reading, the dilution factor used (for syringe or bag samples that require diluting to obtain an on-scale reading) and the Range of the Model 215BGC (A,B,C,D,E). Input 2 for a one half dilution (50%), 3 for a one third dilution (33.3%) etc. The default dilution factor is 1 and the default Range Scale of the Model 215BGC is the C Range.

The dilution factor can be set with ALT-D. The range scale of the Model 215BGC can be set with the ALT-B macro. ALT-R requires only the input of the reading from the Model 215BGC and uses the previous values of the dilution factor and the range. For most applications ALT-I is used once to establish the dilution factor and the range of the Model 215BGC and

then ALT-R is used until either the dilution factor or range is changed. ALT-I and ALT-R calculate the tracer concentration using the dilution factor, range setting and the calibration factor established by the ALT_C macro.

$$\text{conc} = \text{reading} * \text{scale} * \text{dilution} * \text{calib_factor}$$

where scale = (4.0, 2.0, 1.0, 0.4, 0.2) for ranges (A, B, C, D, E).

Repeat the above steps for each sample taken.

If a new calibration factor is required ALT-C should be used to change the the calibration factor. It assumes that a C Range reading is used for calibration.

The "Valid" column is used to exclude a sample from the points used to calculate the duct flow rate. To exclude a point, type an "X" in the "Valid" column. To include the point again, erase the the the "X" using /RE~.

The macro ATL-N can be used to positon the cell pointer to the next location for the time of reading data entry.

The macro ATL-Q can be used to position the cell pointer to the next location for a Model 215BGC reading data entry.

A sample duct spreadsheet EXDUCT.WK3 is included on the disk.

These instructions can be printed using WYSIWYG.PLC print command (:PG).

Description of Macros:

ALT-A Internal use. Test for WYSIWYG.PLC addin and loads in not active.

ALT-B Select Range of Model 215BGC (A,B,C,D,E)

ALT-C Input of calibration concentration and reading. Calculates calibration factor.
The calibration assumes a C Range reading.

ALT-D Change dilution factor.

ATL-F Input file name.

ALT-G Display graph of tracer concentration in duct versus time.

ALT-I General input of readings, dilution factor and range and puts the calculated
tracer concentration in current cell. Result stored in current cell.

ALT-M Produces the main menu for entry of zone data, injection data and the selection
of units.

ALT-N Positions cell pointer to next position for time entry.

ALT-Q Positions cell pointer to next data entry position.

ALT-P Prints report using WYSIWYG.PLC print routine.

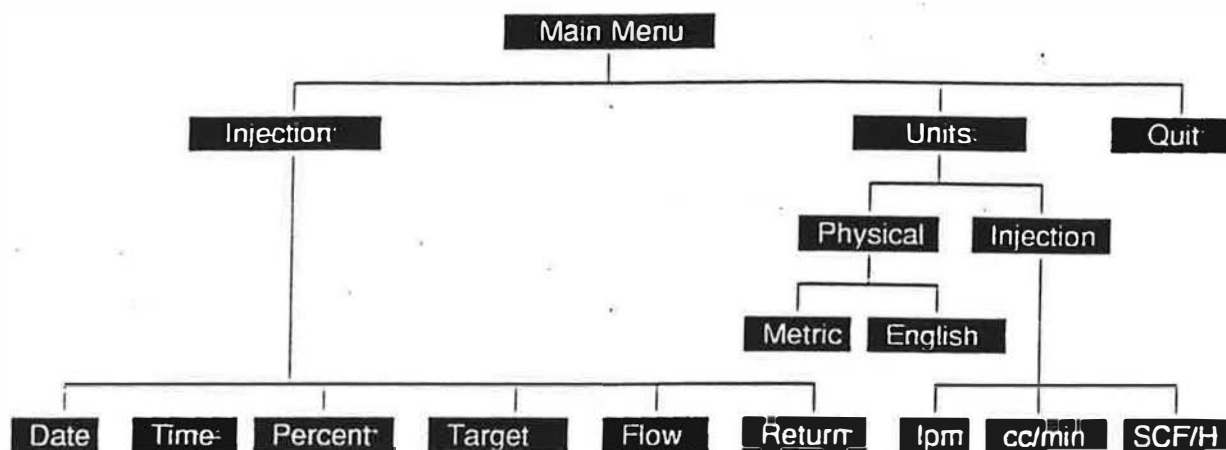
ALT-R Input of readings. Calculates tracer concentration using previous dilution factor
and range setting.

ALT-S Saves spreadsheet as the file listed in "filename".

ALT-T Input of title for zone.

ALT-X Saves current spreadsheet and loads a new one.

Description of Main Menu (ALT-M)



Menu items can be selected by either using the cursor keys to highlight an item and typing enter, or by typing the first letter of the item

Menu Item

Injection	Entry for input of tracer injection parameters.
Date	Date of injection. Use MM/DD/YY format.
Time	Time of Injection. Use HH:MM format.
Percent	Percent of tracer in injection gas. Use percent format, e.g. 10%.
Target	Tracer target level desired.
Flow	Injection flow rate of tracer gas.
Return	Return to main menu.
Units	Entry for selecting units.
Physical	Entry to select metric or english units for zone dimensions.
Metric	Select metric units for zone dimensions (meters).
English	Select english units for zone dimensions (feet).
Injection	Select units for injection quantities.
lpm	Injection flow rate to be expressed in liters per minute.
cc/min	Injection flow rate to expressed in cc per minute.
SCF/H	Injection flow rate to be expressed in cubic feet per hour.
Return	Return to Units Menu
Return	Return to main menu
Quit	Exit main menu and return to spreadsheet.

Lagus Applied Technology
Tracer Duct Flow Test Spreadsheet

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Title: Test Example

File: EXDUCT

Units
metric

Tracer Injection	
Date	06/20/92
Time	00:00
% SF6	1.00%
Flow Rate	1.000 lpm

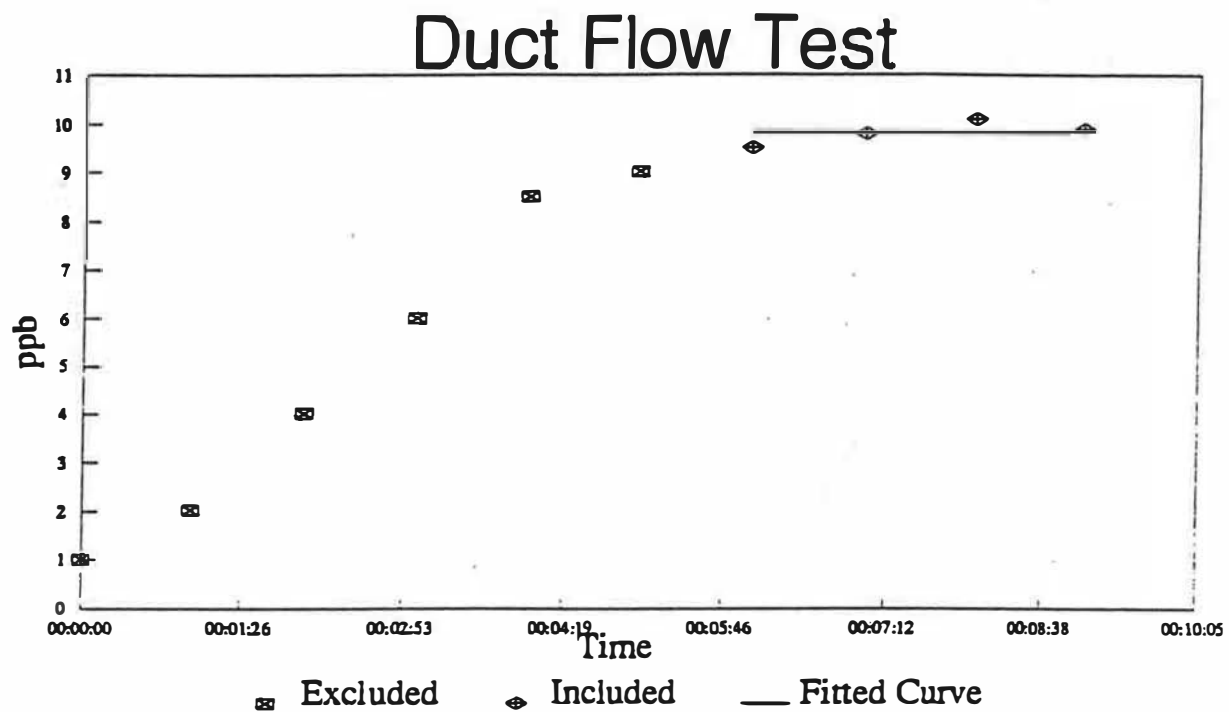
Target Concentration
10.000 ppb

Target Duct Flow
16.6667 m ³ /s

Sample	Date	Time	Concentrations			Valid
			Average ppb	Variance ppb	Entry 1 ppb	
1	06/20/92	00:01	1.000	0.000	1.000	X
2		00:02	2.000	0.000	2.000	X
3		00:03	4.000	0.000	4.000	X
4		00:04	6.000	0.000	6.000	X
5		00:05	8.500	0.000	8.500	X
6		00:06	9.000	0.000	9.000	X
7		00:07	9.500	0.000	9.500	
8		00:08	9.800	0.000	9.800	
9		00:09	10.100	0.000	10.100	
10		00:10	9.900	0.000	9.900	
11						

Results

Duct Flow Rate	16.9718 m ³ /s
Std Error of Duct Flow Rate	0.43521 m ³ /s



Test Example

Appendix IV. Questionnaire to be Used to Obtain Additional Information**Proposed Telephone Questionnaire****1. Introduction**

Good morning/afternoon. My name is _____ and I'm calling for the California Energy Commission. The California Energy Commission is currently studying commercial buildings in California in particular the quality of air within these buildings. Could you connect me with the person who is most familiar with the building at: (INSERT ADDRESS). This might be a building Engineer, facilities Engineer, operations or energy manager.

If necessary, prompt again " Would you connect me with the correct person.

2. Upon Being Connected

Good morning/afternoon. My name is _____ and I'm calling for the California Energy Commission. The California Energy Commission is conducting a study of the Indoor Air Quality (IAQ) of commercial buildings in California and I need to speak with the person who is most familiar with plant operations at: (INSERT ADDRESS). This might be the building Engineer, Facilities Engineer operations or energy manager.

3. Study Explanation

The study is being conducted to obtain basic information about the characteristics of buildings in California including information about heating, ventilation and cooling systems. The survey takes a few minutes to complete and is completely confidential.

4. First, I would like to confirm some basic information. Is this building located at: (INSERT ADDRESS).

1. YES

2. NO

4a. (If NO) Could you tell me the building address please?**5. And could I have your name and title please?****6. What year was the building built?****7. Can you tell be the total amount of enclosed floor space of the building in square feet?****8. How many floors are above grade?****9. How many floors are below grade?****10. How many people are in the building?****11. What is the building used for?****12. Does the building have and air conditioning/cooling system?**

1. YES.

2. NO.

13. What type or types of air conditioning systems are in this building? Pick from the selections below.

1. CONSTANT VOLUME/SINGLE ZONE
2. VARIABLE AIR VOLUME
3. MULTIZONE
4. DUAL DUCT
5. ZONE

(Go to the sheet that has the HVAC system picked above and fill in the information provided by the client).

i.e. Manufacturer & Model No., rated CFM, O.A. damper position, location of return air, etc.

14. Does your HVAC system use an economizer cycle?
(and economizer cycle uses the dampers to take advantage of the ambient air temperature).

1. YES.
2. NO.
3. Don't Know(DK), Not Sure(NS)

15. How many air handling units (AHU) are in the building?

1. # of units
2. DK/NS

16. How many zones are in the building?

1. # of zones
2. DK/NS

17. Does the building have a filtration system as part of the building HVAC system?

1. YES.
2. NO.
3. DK/NS

18. (If yes) Does this filtration system use mechanical, electrostatic or gaseous filters?

1. MECHANICAL
2. ELECTROSTATIC
3. GASEOUS
4. OTHER
5. DK/NS

19. Does this building have general exhaust systems such as rest room exhaust. Note this does not include mechanical room or electrical room exhaust.
20. Do you have an HVAC operations and maintenance (O&M) protocol?
21. For the next phase of this study, buildings will be randomly chosen so that on-site measures of ventilation can be conducted. Should your building be chosen for Phase II of the study, someone will be calling you back within the next couple of months. For right now, I just need to note whether you would have any objections to allowing your building's ventilation to be measured sometime in the future?
 1. NO OBJECTIONS
 2. HAS OBJECTIONS
22. (If respondent has objections) What would be your objections? (Open-ended answer).

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