



Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution¹

This standard is issued under the fixed designation E741; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers techniques using tracer gas dilution for determining a single zone's air change with the outdoors, as induced by weather conditions and by mechanical ventilation. These techniques are: (1) concentration decay, (2) constant injection, and (3) constant concentration.

1.2 This test method is restricted to any single tracer gas. The associated data analysis assumes that one can characterize the tracer gas concentration within the zone with a single value. The zone shall be a building, vehicle, test cell, or any conforming enclosure.

1.3 Use of this test method requires a knowledge of the principles of gas analysis and instrumentation. Correct use of the formulas presented here requires consistent use of units, especially those of time.

1.4 Determination of the contribution to air change by individual components of the zone enclosure is beyond the scope of this test method.

1.5 The results from this test method pertain only to those conditions of weather and zonal operation that prevailed during the measurement. The use of the results from this test to predict air change under other conditions is beyond the scope of this test method.

1.6 The text of this test method references notes and footnotes which provide explanatory material. These notes and footnotes (excluding those in tables and figures) shall not be considered requirements of this test method.

1.7 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

¹ This test method is under the jurisdiction of ASTM Committee E06 on Performance of Buildings and is the direct responsibility of Subcommittee E06.41 on Air Leakage and Ventilation Performance.

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2. Referenced Documents

2.1 ASTM Standards:²

D4480 Test Method for Measuring Surface Wind by Means of Wind Vanes and Rotating Anemometers³

E260 Practice for Packed Column Gas Chromatography

E631 Terminology of Building Constructions

E779 Test Method for Determining Air Leakage Rate by Fan Pressurization

E1186 Practices for Air Leakage Site Detection in Building Envelopes and Air Barrier Systems

2.2 ASHRAE Documents:⁴

ASHRAE Handbook of Fundamentals Chapter 23

ASHRAE Standard 62

3. Terminology

3.1 Definitions:

3.1.1 For definitions of general terms related to building construction used in this test method, refer to Terminology E631.

3.2 Definitions of Terms Specific to This Standard:

3.2.1 *air change flow, Q , n* —the total volume of air passing through the zone to and from the outdoors per unit time (m^3/s , m^3/h , ft^3/h).

3.2.2 *air change rate, A , n* —the ratio of the total volume of air passing through the zone to and from the outdoors per unit of time to the volume of the zone ($1/\text{s}$, $1/\text{h}$).⁵

3.2.3 *envelope, n* —the system of barriers between a conditioned building zone and the outdoors.

² For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For Annual Book of ASTM Standards volume information, refer to the standard's Document Summary page on the ASTM website.

³ Withdrawn. The last approved version of this historical standard is referenced on www.astm.org.

⁴ Available from American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. (ASHRAE), 1791 Tullie Circle, NE, Atlanta, GA 30329, <http://www.ashrae.org>.

⁵ A common way of expressing air change rate units is ACH = air changes per hour = $1/\text{h}$.

3.2.3.1 *Discussion*—This includes exterior doors, windows, roofs, walls, floors and ductwork. It excludes interior partitions, ducts, and so forth, that separate conditioned zones.

3.2.4 *tracer gas, n*—a gas that is mixed with air and measured in very small concentrations in order to study air movement.

3.2.5 *tracer gas analyzer, n*—a device used to measure the concentration of tracer gas in an air sample.

3.2.6 *tracer gas concentration, C, n*—the ratio of the quantity of tracer gas in air to the quantity of that air (moles/mole or m^3/m^3).

3.2.7 *single zone, n*—a space or set of spaces wherein the concentration of a tracer gas is maintained uniformly throughout and that only exchanges air with the outside.

3.2.7.1 *Discussion*—Multizone buildings are difficult to treat as single zones and meet the uniformity of tracer gas concentration required in this test method. Single zones within multizone buildings are difficult to isolate such that they exchange air only with the outside and not to other zones within the building via ventilation ducts, electrical conduits, elevator shafts, stairs, and other pathways.

3.3 Symbols:

3.3.1 Variables:

<i>A</i>	= air change rate (1/s, 1/h).
<i>C</i>	= concentration (dimensionless).
<i>CONF</i>	= confidence limit value (units of the variable measured).
<i>d</i>	= desired precision (dimensionless).
<i>ESE</i>	= estimated standard error.
<i>i</i>	= location number.
<i>k</i>	= constant.
<i>n</i>	= number of data points.
<i>N</i>	= number of sampling locations in the zone.
<i>Q</i>	= flow (m^3/s , m^3/h , ft^3/h).
<i>s</i>	= sample standard deviation (units of the variable estimated).
<i>t</i>	= a specific time (s, h).
<i>T</i>	= a period of time (s, h).
<i>V</i>	= volume (m^3 , ft^3).
α	= probability (dimensionless).
ϵ	= error (units of the variable estimated).
<i>v</i>	= coefficient of variation (dimensionless).

3.3.2 Superscripts:

'	= value at the end of the test.
–	= mean value.

3.3.3 Subscripts:

<i>A</i>	= pertaining to air change rate.
<i>avg</i>	= average.
<i>bias</i>	= pertaining to bias.
<i>C</i>	= pertaining to concentration.
<i>est</i>	= estimated.
<i>GA</i>	= pertaining to the gas analyzer.
<i>i</i>	= pertaining to time or location.
<i>inj</i>	= pertaining to the injection period.

<i>lower</i>	= lower limit.
<i>meas</i>	= pertaining to the measurement.
<i>mix</i>	= pertaining to the mixing period.
<i>precis</i>	= pertaining to precision.
<i>rep</i>	= pertaining to replicates.
<i>sample</i>	= pertaining to a discrete tracer gas or air sample.
<i>target</i>	= pertaining to the desired level of tracer gas.
<i>test</i>	= pertaining to the test period.
<i>twt</i>	= weighted according to tracer gas flow.
<i>tracer</i>	= pertaining to the tracer gas.
<i>upper</i>	= upper limit.
<i>vol</i>	= pertaining to the volume of the zone.
<i>zone</i>	= pertaining to the zone under study.
<i>1</i>	= first occurrence under discussion.
<i>2</i>	= last occurrence under discussion.

3.3.4 Other Notations:

Δt	= time interval between periodic samples.
(<i>t</i>)	= function of time.
(<i>t, i</i>)	= function of time, <i>t</i> , and location, <i>i</i> .
<i>t</i> (<i>n</i> ,	= <i>t</i> -distribution value for <i>n</i> degrees of freedom
$1-\alpha$)	and a two-sided probability of α .

4. Summary of Test Method

4.1 This test method uses the measurement of tracer gas dilution to determine air change within a building or other enclosure that is characterized as a single zone. The measurement of the concentration, and sometimes the volume rate of the tracer gas that is injected into the zone, allows calculation of the volume rate of outgoing air from the zone. From this, one can infer the volume rate of incoming air. Three techniques are presented: (1) concentration decay, (2) constant injection, and (3) constant concentration. Each technique employs specific tracer gas injection and sampling strategies. Other techniques exist but are beyond the scope of this test method. **Table 1** summarizes the three techniques.

4.2 *Choice of Technique*—In choosing a technique for measuring air change, consider the quantity to be measured, the comparative capabilities of the techniques, and the complexity of the required equipment.

4.2.1 *Air Change Quantity to Be Measured*—Choose between direct measurement of air change rate or air change flow. Conversions between rate and flow and vice versa are subject to the precision and bias of the measurement of the zone volume. To obtain air change rate directly, use the tracer gas decay technique. To obtain air change flow, use the constant injection or constant concentration techniques.

5. Significance and Use

5.1 *Effects of Air Change*—Air change often accounts for a significant portion of the heating or air-conditioning load of a building. It also affects the moisture and contaminant balances in the building. Moisture-laden air passing through the building envelope can permit condensation and cause material degradation. An appropriate level of ventilation is required in all buildings; one should consult **ASHRAE Standard 62** to determine the ventilation requirements of a building.

5.2 *Prediction of Air Change*—Air change depends on the size and distribution of air leakage sites, pressure differences

TABLE 1 Summary of Air Change Measurement Techniques

NOTE 1—*Speed of Measurement*—A one-time measurement of air change is most quickly acquired with the concentration decay technique and least quickly with the constant concentration technique.

NOTE 2—*Time-Varying Air Change*—The constant concentration and constant injection techniques may be useful for measuring air change rates that vary with time.

NOTE 3—*Complexity of Zone Geometry*—Whereas all the techniques require uniform tracer gas concentration, the constant concentration technique may be useful to achieve this in a zone with complex geometry.

NOTE 4—*Equipment Complexity*—The complexity of the required equipment is lowest for the tracer gas decay technique and highest for the constant concentration technique.

Technique	Type of Air Change Measurement	Steady-State Assumption Required?	Volume Control of Tracer Gas	Concentration Measurement Relative To
Concentration Decay—Section 8				
Average	Rate	No	Approximate initial target	Other samples
Regression	Rate	Yes	Approximate initial target	Other samples
Constant Injection—Section 9				
Average	Flow	No	Flow rate to within 2 %	Absolute standard
Constant Concentration—Section 10				
	Flow	No	Mean concentration within 2 % of target	Absolute standard

induced by wind and temperature, mechanical system operation, and occupant behavior. Air change may be calculated from this information, however, many of the needed parameters are difficult to determine. Tracer gas testing permits direct measurement of air change.

5.3 Utility of Measurement—Measurements of air change provide useful information about ventilation and air leakage. Measurements in buildings with the ventilation system closed are used to determine whether natural air leakage rates are higher than specified. Measurements with the ventilation system in operation are used to determine whether the air change meets or exceeds requirements.

5.4 Known Conditions—Knowledge of the factors that affect air change makes measurement more meaningful. Relating building response to wind and temperature requires repetition of the test under varying meteorological conditions. Relating building response to the ventilation system or to occupant behavior requires controlled variation of these factors.

5.5 Applicability of Results—The values for air change obtained by the techniques used in this test method apply to the specific conditions prevailing at the time of the measurement. Air change values for the same building will differ if the prevailing wind and temperature conditions have changed, if the operation of the building is different, or if the envelope changes between measurements because of construction or deterioration. To determine air leakage sites, follow Practice E1186.

5.6 Fan Pressurization—A related technique (Test Method E779) uses a fan to pressurize the building envelope. Measurements of corresponding air flows and pressure differences across the envelope characterize envelope airtightness as either the air leakage rate under specified induced pressure differences or the equivalent leakage area of the envelope. These factors permit modeling natural air change due to wind and

temperature differences. However, direct measurement of natural air change is not possible with Test Method E779. Test Method E779 permits comparison of different buildings, isolation of leakage sites, and evaluation of retrofit measures.

6. Apparatus

6.1 The apparatus includes means for distributing the tracer gas, means for obtaining air samples, a gas analyzer to measure tracer gas concentration in the air samples, and other measurement devices.

6.2 Tracer Gas—See Appendix X1 for information on tracer gases and equipment used to measure their concentrations. Appendix X1 also contains tracer gas target concentration levels and safety information.

6.2.1 Tracer Gas Concentration Standard—A known concentration of tracer gas in air.

6.3 Tracer Gas Injection and Distribution Apparatus—There are several means for releasing the appropriate volume of tracer gas and distributing it in the zone.

6.3.1 Tracer Gas Metering and Injection Devices—These include (1) a graduated syringe or other container of known volume with a means for controlled release of its contents and (2) a compressed tracer gas supply with a critical orifice, a critical orifice metering valve, an electronic mass flow controller, or other tracer gas flow rate measurement and control device.

6.3.2 Tracer Gas Distribution Devices—These include (1) fans that permit good mixing of tracer gases injected manually within the zone (oscillating or hassock fans, or, ducted forced air systems can serve this purpose), (2) tubing networks that dispense tracer gas via manifolds and automated valves and (3) pressure-operated valves that stop the flow from a tubing network when the tubing is not pressurized. (Note that leaks in tubing networks release tracer gas at unintended locations.)

6.4 Tracer Gas Sampling Apparatuses—Examples include containers for manual sampling and automatic samplers that employ containers or networks.

6.4.1 Materials for Sampling Apparatuses—Select and check materials used in tracer gas sampling systems carefully for their reactivity and absorption of the tracer gas in use. Depending on the tracer gas, desirable materials include glass, copper, and stainless steel. Metal foil is appropriate for flexible containers. Other acceptable materials include polypropylene, polyethylene, and nylon. Materials that absorb tracer gas degrade the accuracy of the measurement. Other materials release substances that interfere with tracer gas analyzer accuracy. Depending on the tracer gas, materials to avoid include soft plastics, like vinyl and TFE-fluorocarbon.

6.4.2 Manual Samplers—These include syringes, flexible bottles, or air sample bags with a capacity of at least three times the minimum sample size of the gas analyzer used. These containers shall have an airtight seal to assure that the sample is not diluted or contaminated. Each container shall have a label that keys it to a record of the time and location that it was used. Do not reuse sample containers without first confirming that they are not contaminated with tracer gas.

6.4.3 Automatic Samplers—These apparatuses comprise either a sampling network or automated samplers.

6.4.3.1 Sampling Networks—These include (1) tubing, (2) a manifold or selection switch (the manifold receives, combines, and averages equal flows from individual legs of the network; the selection switch, often solenoid-driven, permits sampling of individual legs of the network), and (3) a pump that draws air samples through the network at a rate that minimizes delays between the time air samples leave the zone and the time they reach the gas analyzer.

6.4.3.2 Automated Samplers—These self-contained units, such as syringe samplers, are programmed to draw air samples at defined time intervals. Place such devices at different locations throughout the zone to be evaluated when required.

6.5 Gas Analyzer—This device shall be suited for the tracer gas used and the concentrations within the zone studied. It shall be properly calibrated and have a precision⁶ of better than $\pm 5\%$ at concentrations employed in the tracer gas study. See **Appendix X2** for calibration information.

6.6 Ancillary Measurement Devices:

6.6.1 Portable Meteorological Station—This records wind speed and direction and outdoor temperature. Meteorological data collected at a local weather station are acceptable.

6.6.2 Temperature Measurement—Use a thermometer or record the output of thermocouples, thermistors, resistance thermal devices (RTDs), and so forth.

6.6.3 Timing Device—This provides a common standard for all events relating to the measurement procedure, including gas injection times, sampling times, and meteorological driving forces. The timing device shall determine time differences between events within a 1 % uncertainty.

6.7 Data Acquisition and Control System—This equipment is optional for all but the constant concentration technique.

6.7.1 Data Acquisition—Appropriate interfaces provide temperature, wind speed, wind direction, and tracer gas concentration data to a computer or other machine-readable data storage unit.

6.7.2 Control of Processes—A computer uses current tracer gas concentration information to control metering and switching equipment to deliver tracer gas to the appropriate parts of the network. When a feedback process controls gas concentrations, based on gas concentration measurements, an algorithm that minimizes deviation from the target concentration is required. A digital optimal adaptive proportional control algorithm has been used effectively for constant concentration measurements (1).⁷

7. Hazards

7.1 Safety is the responsibility of the user of this test method. Tracer gases have safe maximum concentration limits due to health and, in some cases, explosiveness. **Table X1.1** presents, as a guide, the maximum allowable concentration in air for some tracer gases that have been used for air change measurements. The tracer gas supplier's material safety data sheet also provides information about health, fire, and explosion hazards.

7.2 Health Limitations—Use the current OSHA information on the permissible exposure limit (PEL) to determine the maximum safe concentration for the tracer gas chosen for the test. Use a concentration that is at most one tenth of the maximum safe concentration. Avoid using tracer gases for which no OSHA PEL exists.

NOTE 1—Special circumstances may cause one tenth of PEL to be too high a concentration. For example, the heat of a lit cigarette decomposes some tracer gases into potentially hazardous by-products when air is inhaled through the cigarette. In such cases, lower tracer gas concentrations are required.

7.3 Explosive Limits—If the tracer gas is explosive, the tracer gas concentration shall never exceed one tenth the lower explosive limit.

7.4 Compressed Gas Equipment—Observe the supplier's safety information and CGA (2) information on the transportation, use, and storage of compressed gas cylinders, regulators, and related equipment.

8. Procedure for the Concentration Decay Test Method

8.1 Summary—To determine average air change rate, one introduces a small volume of tracer gas uniformly into the zone, ensures a uniform concentration, and then measures tracer gas concentration at known times. One calculates the average air change rate for that period as the difference between the logarithms of the initial and final tracer gas concentrations divided by the time period. When required, one shall obtain additional air samples to test the hypothesis that the air change rate was constant during the test with an optional regression analysis of the logarithms of additional tracer gas concentration measurements. **Fig. 1** gives a simplified overview of this test method.

8.2 Preparation:

8.2.1 Ancillary Measurements—Refer to **11.1**.

8.2.2 Zonal Operation—Prepare the zone according to **11.2**.

8.2.3 Tracer Gas Injection Volume—Determine the volume of the tracer gas to be injected V_{tracer} according to the following steps:

8.2.3.1 Estimate the volume of the zone V_{zone} in the same units as V_{tracer} will be measured (**15.3**),

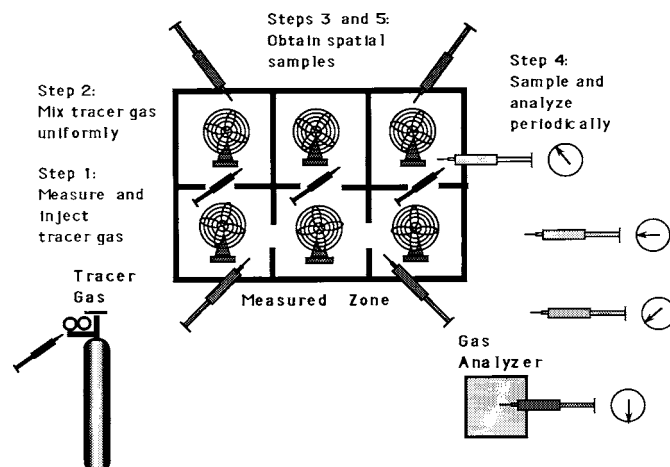


FIG. 1 Simplified Summary of the Apparatus and Procedure for the Concentration Decay Method

⁶ Precision refers to the standard error of the measurement.

⁷ The boldface numbers in parentheses refer to the list of references at the end of this standard.

- 8.2.3.2 Determine the target tracer gas concentration C_{target} at the high end of the detection limits of the gas analyzer, and
- 8.2.3.3 Compute the following:

$$V_{tracer} = C_{target} \times V_{zone} \quad (1)$$

8.2.4 *Sampling*—Emplace the desired apparatus for sampling, according to one of the methods described in Section 13. Note that manual sampling, 13.1, or direct automated sampling, 13.2.2, are the most likely choices.

8.2.4.1 *Sampling Duration*—Table 2 illustrates minimum sampling durations based on a 10 % uncertainty at the 95 % confidence level in the determination of air change rate, a tracer gas concentration measurement precision error (14.1.3), v_{meas} , of 5 % of reading, and various air change rates. Refer to Eq A1.1 for the general case. Note that when using the regression method the minimum test duration is often less than the test duration values shown in Table 2. This decrease in test duration is primarily due to the inclusion of more than two data points in the determination of the best fit line as described in 8.5.3.2.

8.2.4.2 *Sampling Frequency*—For the optional regression method (8.5.3.2), there shall be a minimum of five points, approximately evenly distributed over the measurement period.

8.3 *Tracer Gas Injection*—Note that manual injection, 12.2, is the simplest acceptable technique of those available in Section 12. Record the time and volume of the injection. Distribute the tracer gas uniformly in the zone according to 12.4.2 in order to meet the uniformity of concentration criterion of 12.4.1.

8.4 *Sampling*—First, perform spatial sampling to confirm uniformity of concentration, using 13.3. When the uniformity of concentration criterion 12.4.1 is confirmed, then sample as follows:

8.4.1 *All Conditions*—At a minimum, take a second set of spatial samplings (13.3) at the end of the sampling period, for the period T_{test} . Check for tracer gas sources in adjacent spaces, according to 13.4.3.

8.4.2 *Time Series for the Optional Regression Method*—Take representative samples at intervals, as determined in 8.2.4.2. A minimum of five such samples is required for the regression method (8.5.3.2).

8.5 Analysis:

8.5.1 *Analyze Tracer Gas Concentrations*—Analysis of tracer gas concentration takes place either on site concurrently with the sampling process, or off site, if the samples are stored in sealed, labeled containers. Analyze and record the tracer gas concentration of each sample, together with the sampling time and location, according to the procedures in Section 14. Eliminate any concentration data that are outside the 5 % precision range of the analyzer.

TABLE 2 Examples of Minimum Durations Between the Initial and Final Samples for the Above Assumptions

Air Change Rate (1/h)	Minimum Duration of Test (h)
0.25	4
0.5	2
1	1
2	0.5
4	0.25

8.5.2 *Confirm Uniformity of Concentration*—Assess the concentrations of the spatial samplings for uniformity of concentration, according to 12.4.1. Confirm uniformity of tracer gas concentrations at the beginning and end of the sampling period (8.4.1). Estimate the measurement precision using 14.1.3.

8.5.3 *Calculate Air Change Rate*—Calculate air change rate by the averaged method or the regression method as follows:

8.5.3.1 *Averaged Method*—Calculate C_1 , the average of the concentrations at the time t_1 that confirmed the uniformity of concentration criterion (8.4). Calculate C_2 , the average of the concentrations at the time t_2 that confirmed the uniformity of concentration criterion at the end of the test (8.4.1). Calculate mean air change rate $\bar{A}$ by Eq 2:

$$\bar{A} = [\ln C(t_2) - \ln C(t_1)] / (t_2 - t_1) \quad (2)$$

8.5.3.2 *Optional Regression Method*—Plot the data on axes of $\ln C(t)$ against t , as illustrated in Fig. 2. With the assumption of constant air change, the following relationship holds:

$$\ln C(t) = -At + \ln C(0) \quad (3)$$

Perform a regression of $\ln C(t)$ against t . In a typical regression program on a hand-held calculator or spreadsheet program, one performs a regression on Y against X to find the constants a and b in the relationship:

$$Y = aX + b \quad (4)$$

In this case A corresponds to a , $\ln C(0)$ corresponds to b , $\ln C(t)$ corresponds to Y , and t corresponds to X . Establish confidence intervals for A , according to Appendix X3.1.

8.5.4 *Reporting of Ancillary Measurements*—Refer to 15.4 for reporting of ancillary measurements.

9. Procedure for the Constant Injection Test Method

9.1 *Summary*—To determine the average air change flow, inject tracer gas uniformly into the zone at a known, constant rate, ensure a uniform concentration, and then measure tracer gas concentration at known times. Calculate the average air change flow for the measurement period as the product of the tracer gas flow rate times the average of the inverses of measured concentration less a correction for the beginning and

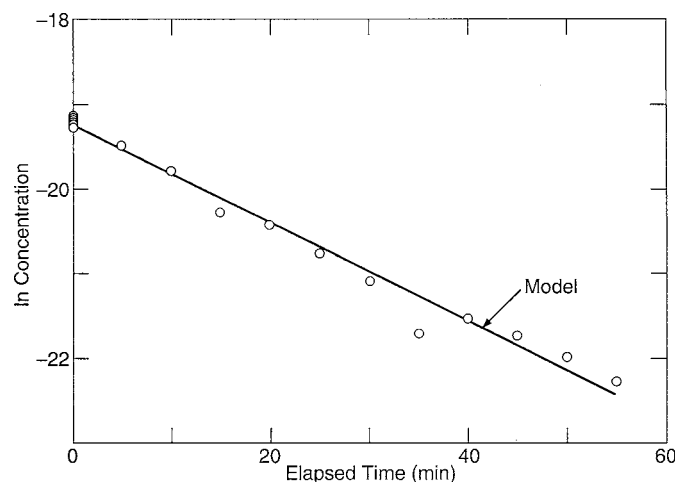


FIG. 2 Concentrations and Estimate of Concentrations Plotted Logarithmically

ending concentrations. It is not necessary to know the volume of the zone if the beginning and ending concentrations used in the calculation are approximately equal. Test the assumption of constant air change for the time period with an optional analysis of confidence intervals of the tracer gas concentrations after equilibrium has occurred. Fig. 3 gives a simplified overview of this test method.

9.2 Preparation:

9.2.1 *Ancillary Measurements*—Refer to 11.1. The constant injection technique requires determination of zone volume (15.3) in the presence of non-steady-state air change flow.

9.2.2 *Zonal Operation*—Prepare the zone according to 11.2.

9.2.3 *Tracer Gas Injection Flow Rate and Initial Volume*—Determine the volume flow rate of the tracer gas to be injected Q_{tracer} according to the following steps:

9.2.3.1 Estimate the volume of the zone being measured V_{zone} in the same volume units as Q_{tracer} .

9.2.3.2 Estimate the air change rate A in the zone and convert it into A_{est} in the time units of Q_{tracer} .

9.2.3.3 Determine the target tracer gas concentration C_{target} that is mid-range in the detection limits of the gas analyzer, and

9.2.3.4 Compute the following:

$$Q_{tracer} = C_{target} \times V_{zone} \times A_{est} \quad (5)$$

Eq 1 presents one method used to calculate an initial dose of tracer gas $C(0) \approx C_{target}$ in order to obtain a more rapid tracer gas concentration equilibrium.

9.2.4 *Sampling*—Emplace the desired apparatus for sampling, according to one of the methods described in Section 13. Automated sampling (13.2) offers a convenient means to obtain a time series. Place the intake of each sampling unit away from tracer gas injection points.

9.3 *Tracer Gas Injection*—Inject tracer gas at a constant, known rate; metered injection (12.3) is one method. Record the starting time, duration, and rate Q_{tracer} of the injection. Also

note any initial measured dose of tracer gas used to achieve an equilibrium. Distribute the tracer gas in the zone according to 12.4.2 in order to meet the uniformity of concentration criterion of 12.4.1. If the equilibrium concentration falls outside of the range for accurate measurement, adjust the flow rate appropriately. Do not use concentration data that are outside the 5 % precision range of the analyzer.

9.3.1 *Tracer Gas Injection Uncertainty and Bias*—The uncertainty of the tracer gas injection rate shall be less than 2 %. The bias of the assumed injection rate shall be no more than 2 % of the true rate.

9.4 *Sampling*—First, perform spatial sampling to confirm adequate uniformity of concentration using 13.3. When the uniformity of concentration criterion 12.4.1 is confirmed, then sample as follows:

9.4.1 *Spatial Sampling*—At a minimum, take a second set of spatial samplings (13.3) at the end of the sampling period, for the period T_{test} . Check for tracer gas sources in adjacent spaces according to 13.4.3.

9.4.2 *Time Series Sampling*—Take a representative sample every 5 min. A minimum of five such samples is required during the measurement period. Compute the average air flow rate with these data.

9.4.3 *Concentration Equilibrium*—If one chooses to test the assumption of constant air change for the time period, then one shall continue to sample (9.4.2) after equilibrium has occurred. The criterion for equilibrium shall have been met if

$$\left| \frac{C_{final} - C_{initial}}{T_{test}} \right| < 0.05 \frac{Q_{tracer}}{V_{zone}} \quad (6)$$

If one starts with a zero tracer gas concentration in the zone and injects at a constant rate, the tracer gas reaches 95 % of the equilibrium concentration within the zone after a period of time, $T_{crit} = 3/A$. So, for $A = 1, 2$, and 3 per hour, $T_{crit} = 3, 1.5$, and 1 hours, respectively.

9.5 Analysis:

9.5.1 *Analyze Tracer Gas Concentrations*—Analysis of tracer gas concentration shall occur either on site concurrently with the sampling process, using network sampling (13.2.1) connected to a gas analyzer, or off site, if the samples are stored in sealed, labeled containers. Note that if off-site analysis reveals that the mixing or equilibrium criterion has been violated, it is too late to remedy the problem with the measurement. Analyze and record the tracer gas concentration of each sample, together with the sampling time and location, according to the procedures in Section 14.

9.5.2 *Confirm Uniformity of Concentration*—Assess the concentrations of the spatial samplings for uniformity of concentration, according to 12.4.1. Confirm uniformity of concentration prior to the time of any grouping of points that is used to calculate air change flows. Estimate measurement precision using 14.1.3.

9.5.3 *Calculate Air Change Flow*—Calculate the average air change flow for the measurement period using time series tracer gas concentration data (9.5.3.1). One may test the assumption of constant air change for the measurement period (9.5.3.2) after an equilibrium tracer gas concentration has occurred.

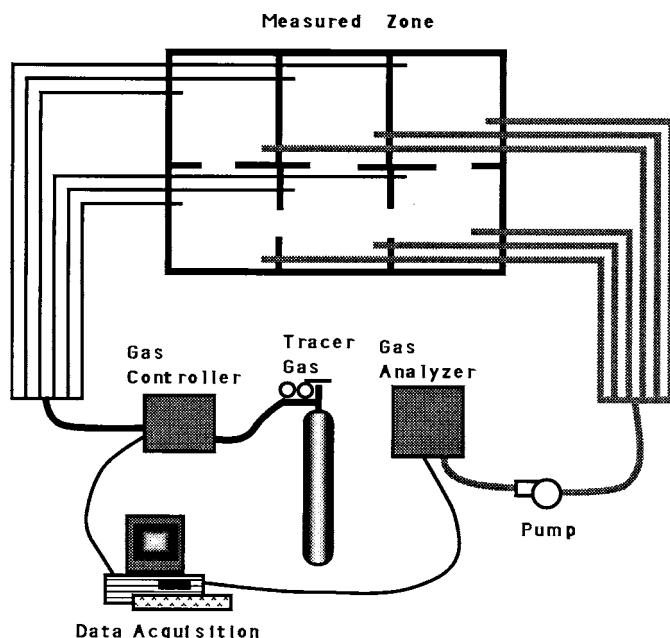


FIG. 3 Schematic Diagram of the Apparatus for the Constant Injection Method

9.5.3.1 *Average Air Change Flow*—Compute average air change flow with Eq 7.

$$Q = Q_{\text{tracer}} \left[\frac{1}{C} \right]_{\text{avg}} - \frac{V_{\text{zone}}}{(t_2 - t_1)} \ln \left[\frac{C_2}{C_1} \right] \quad (7)$$

The uncertainty in the zone volume shall be less than 15 % and the concentration shall never go outside ± 20 % of the average concentration. However, if the zone volume is known to 5 %, then the concentration shall vary by up to ± 40 %. If these conditions are violated, then the user shall do an error analysis (X6.2). Appendix X5 contains one method to measure zone volume. One minimizes the need to know the volume of the zone if the beginning and ending concentrations used in the calculation are close to equal, and Eq 6 is satisfied.

9.5.3.2 *Test for Constant Air Change Flow*—If one has achieved an equilibrium tracer gas concentration (9.4.3), then one may test the assumption of constant air change flow by calculating Q in Eq 7, using individual C data. Application of a confidence interval calculation (Appendix X3.2) to these Q values tests how far the air change flow is from constant.

9.5.4 *Correlation with Ancillary Measurements*—Refer to 15.4 for reporting of ancillary measurements.

10. Procedure for the Constant Concentration Test Method

10.1 *Summary*—To monitor changing air change flow, measure and control tracer gas at a constant concentration with automated equipment. The equipment measures tracer gas concentration and then injects enough tracer gas into the zone to maintain a desired uniform concentration. Calculate the air change flow for each measurement interval from the ratio of the required additional tracer gas to the desired concentration. Fig. 4 gives a simplified overview of this test method. With this technique one is able to achieve a uniform tracer gas concentration in many single zones with complex geometries.

10.2 Preparation:

10.2.1 *Ancillary Measurements*—Refer to 11.1.

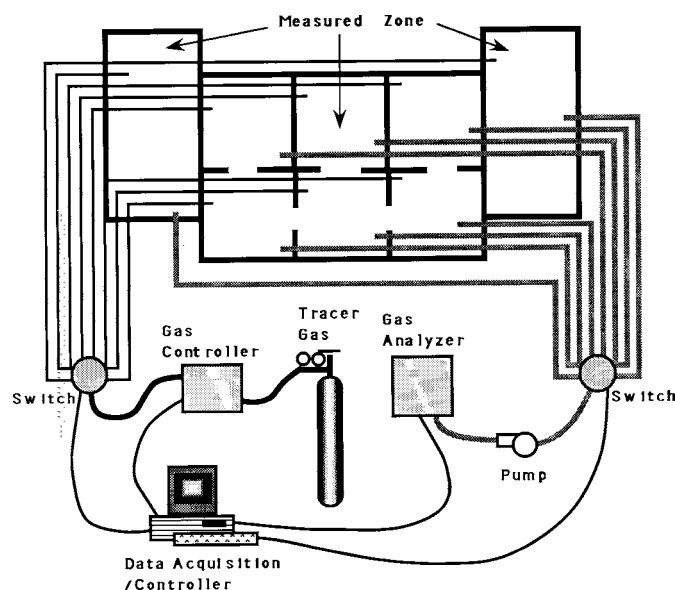


FIG. 4 Schematic Diagram of the Apparatus Used for the Constant Concentration Technique

10.2.2 *Zonal Operation*—Prepare the zone according to 11.2.

10.2.3 *Tracer Gas Injection Flow Rate and Initial Volume*—This technique requires automated, switched, network injection (12.3.2.2). Connect the injection apparatus to the gas metering device and to the computer controlling the process of switching, sampling, and gas injection. Determine the target tracer gas concentration C_{target} that is mid-range in the detection limits of the gas analyzer. Wait for the apparatus to achieve the target concentration. Eq 1 is another method to calculate an initial dose of tracer gas $C(0) \approx C_{\text{target}}$ in order to reach the target concentration more rapidly.

10.2.4 *Sampling*—This technique requires automated, switched, network sampling (13.2.1 and 13.2.1.2). Connect the sampling apparatus to the gas analyzer and to the computer controlling the process of switching, sampling and gas injection. An important limitation on the accuracy of this technique is how frequently a portion of the zone may be measured in order to assure good control of concentration. Given a uniform tracer gas concentration, analysis and injection shall be at a level five times more frequent than the dominant changes in A or every 5 min, whichever is more frequent. A choice of control strategies is available in the literature (1).

10.3 *Tracer Gas Injection*—Metered injection (12.3) is required. After the tracer gas concentration level has reached nominal equilibrium, the rate of tracer gas injection $Q_{\text{tracer}}(t)$ shall be modulated to achieve C_{target} without overshooting by more than 5 % within one sample cycle. A good control algorithm will minimize excessive deviation of C from C_{target} . The record of time and $Q_{\text{tracer}}(t)$ shall be automated and entered in machine-readable form. Accurate determination of $Q_{\text{tracer}}(t)$ is critical to this technique. Distribute the tracer gas in the zone according to 12.4.2 in order to meet the uniformity of concentration criterion of 12.4.1.

10.4 *Sampling*—Allow the tracer gas concentration to reach an approximate equilibrium throughout the zone before determination of Q may begin (10.5.2).

10.4.1 *Minimum Frequency*—As a rule of thumb, take one sample at each sampling location at least every 5 min. When the concentration cannot be maintained within 5 % of C_{target} , then reevaluate the injection control algorithm. Sample a minimum of five times during the test.

10.4.2 *Minimum Duration*—The minimum duration for sampling T_{test} and the resulting analysis depends on the air change rate and the precision of the gas analyzer:

$$T_{\text{test}} > \frac{100}{A_{\text{est}}} v_{\text{GA}} \quad (8)$$

where v_{GA} is calculated in Annex A1.4. The minimum duration for sampling also depends on how much the concentration changes between samples as follows:

$$T_{\text{test}} > \left| \frac{C_{\text{final}} - C_{\text{initial}}}{0.02 A_{\text{est}} C_{\text{target}}} \right| \quad (9)$$

Choose the larger T_{test} from Eq 8 and 9.

10.5 Analysis:

10.5.1 *Analyze Tracer Gas Concentrations*—Analyze and record the tracer gas concentration $C(t)$ of each sample as it is collected together with the time and place it represents,

according to the procedures in Section 14. An accurate measurement of $C(t)$ is critical to this technique. Therefore, assess calibration drift with periodic checks or by before-and-after calibrations and subsequent adjustment of the concentration data, or by some other suitable method. Report the method used.

10.5.2 Concentration Equilibrium—Upon start-up of the injection and sampling system, the injection system is in the full open position and $C(t)$ asymptotically approaches the equilibrium target concentration C_{target} . After $C(t)$ reaches 10 % of C_{target} , perform the uniformity of concentration test (10.5.3).

10.5.3 Uniformity of Concentration Test—If the sampling network does not provide adequate spatial sampling to confirm uniformity of concentration, using 13.3, then perform manual spatial sampling. Begin the determination of Q after nominal tracer gas equilibrium has been achieved (10.5.2) and the uniformity of concentration criterion (12.4.1) has been met. Use the results of spatial sampling to estimate measurement precision (14.1.3).

10.5.4 Measure Tracer Gas Injections—Determine and record the amount of tracer gas injected $Q_{tracer}(t, i)$ for each time t and place i of injection.

10.5.5 Calculate Average Air Change Flow—When the data acquisition and control system is working properly, the sample standard deviation of $C(t)$ shall be less than 10 % of C_{target} and then one calculates:

$$Q_{ave} = \frac{\sum_{t=t_1}^{t_2} \sum_{i=1}^N Q_{tracer}(t, i)}{\sum_{t=t_1}^{t_2} C(t)} \quad (10)$$

where N is the number of branches serving the zone.

10.5.5.1 Calculate Instantaneous Air Change Flow—If the tracer gas concentration is maintained within 2 % of the target tracer gas concentration, then calculate the air change flow over a time interval as:

$$Q(t) = \frac{\sum_{i=1}^N Q_{tracer}(t, i)}{C_{target}} \quad (11)$$

Use the built-in indicators of precision and bias of this calculation to determine confidence intervals, as discussed in Appendix X3.3.

10.5.6 Correlation with Ancillary Measurements—Refer to 15.4 for reporting of ancillary measurements.

11. Procedures for Preparing the Zone

11.1 Ancillary Measurements—One shall determine the status of building systems and envelope features, indoor and outdoor temperatures, and wind speed and direction. When required, one shall determine the volume of the zone or changes in the status of building systems and envelope features.

11.1.1 Temperature and Wind Measurements—Average indoor temperature, outdoor temperature, wind speed, and wind direction are required that pertain to the period of air change measurement. Obtain the outdoor data from a nearby meteorological station or set up a portable meteorology station, according to 15.1.1. To correlate air change with weather, one shall obtain these data at least once an hour from an on-site meteorology station.

11.1.2 Correlation with Building Operation—When required to correlate air change rate with building operation, monitor those elements that change settings during the measurement such as fans, doors, dampers, and so forth.

11.1.3 Volume Measurement—A precise volume measurement (15.3) is required if one converts between air change flow Q and air change rate A , or vice versa.

11.2 Preparation of the Zone—Determine how the zone is to be ventilated during the test, depending on what aspects of operation are of interest. Appendix X4 gives some examples for two cases: (1) when all ventilation systems are in operation and (2) when envelope leakage alone causes air change. Report clearly the status of all mechanical ventilation systems, all passive ventilation systems (windows and other openings), as well as any other envelope features that incorporate leakage sites. When required, report changes in the status of these systems and features.

12. Procedures for Distributing Tracer Gas

12.1 Avoid Contamination—Contamination of the zone occurs from improper handling of the tracer gas, leaks in the tracer gas injection system, tracer gas reentrainment, or the prior presence of the tracer gas in the zone.

12.1.1 Handling Tracer Gases—Tracer gases are often dispensed from pressurized gas bottles. Leakage during gas dispensation changes desired concentrations. Locate the bottle outside the zone or test for leakage (13.4.2). For metered injection, test for tracer gas leaks as follows:

12.1.1.1 Run the network from the room it is in through a sealed exit to the outdoors after it is attached to the metering apparatus and gas supply but before it is distributed in the zone.

12.1.1.2 Sample the air in the vicinity of joints in the distribution network to confirm that it does not leak.

12.1.2 Conservation of Tracer Gas in the Zone—If the sample size is sufficient to affect the tracer gas concentration in that zone, vent the gas analyzer to the zone where each sample originates.

12.1.3 Pre-Existing Tracer Gas—To sample for pre-existing tracer gas or any air constituent that may interfere with the tracer gas analysis, obtain an air sample in the zone prior to injecting the tracer gas. The sample may be drawn from representative areas throughout the zone.

12.2 Manual Injection—Fill the injection container (6.2.1a) with the desired volume of tracer gas. Walk rapidly throughout the zone dispensing the tracer gas. Where the zone comprises interconnected rooms, plan how much gas must be dispensed in each room in proportion to the total zonal volume. In such cases and in large single-volume zones, use multiple containers for simultaneous injection as an alternative to single containers. Another method is to inject tracer gas into the main air supply duct while the fan is running. For techniques that account for the volume of tracer gas, ensure that the duct system has no leaks outside the zone and that the measured amount of tracer gas has been dispensed.

12.2.1 *Record of Injection*—Record the volume of tracer gas and the time and manner of injection.

12.3 *Metered Injection*—Use a critical orifice, critical orifice metering valve, or an electronic mass controller meter tracer gas from a pressurized bottle. The flow shall be either (1) maintained at a constant level, (2) switched on and off at a constant level for controlled periods of time, or (3) the rate of flow varied, depending on the requirements of the test. A computer is one means to control flow rates.

12.3.1 *Direct Injection*—The injection system is placed in the zone or in the air supply system to the zone while the fan is running so that subsequent uniformity of concentration is achieved.

12.3.2 *Network Injection*—The injection system is attached to a network of tubing that distributes tracer gas to regions within the zone. Depending on the technique used, a manifold or a switch shall apportion tracer gas. Note that a network is useful for a collection of rooms that constitute the zone and for long-term tests.

12.3.2.1 *Distribution by Manifold*—When the aim is to apportion a constant flow of tracer gas to different locations, a manifold shall divide the flow equally into each branch of the network. Adjust the flow through each branch with valves or other means to apportion tracer gas according to the amount needed at its destination.

12.3.2.2 *Switched Distribution*—When the aim is to deliver a measured amount of gas to specific branches of the network, use a computer-actuated selection switch. Design each leg to prevent leakage when it is not supposed to be dispensing gas. Each leg shall be fully charged with tracer gas so that there are no delays or uncertainties about the amount that reaches the end of the leg.

12.3.3 *Record of Injection*—Record the flow rate of tracer gas and its schedule for injection into each portion of the zone. Record the location of each network port for dispensing tracer gas.

12.4 *Uniformity of Concentration*—The data analysis in this test method assumes that the space being tested is idealized as a single zone containing uniformly distributed tracer gas. Therefore, confirmation of uniformity of concentration is required.

12.4.1 *Uniformity of Concentration Criterion*—When a precision and bias of 10 % is required, then gas concentrations at representative locations throughout the zone shall differ by less than 10 % of the average concentration for the zone. Perform spatial sampling (13.3) at least at the start and end of the measurement period from which data is to be used to perform air change calculations.

12.4.2 *Aids to Mixing*—When the required uniformity of concentration does not occur within a period of 30 min, use additional devices. Mixing devices include, but are not limited to, portable fans blowing from room to room or air supply fans serving the zone. When required, use a distribution network (13.4.2) to representative locations in the zone in concert with convection or fans.

13. Procedures for Sampling Tracer Gas

NOTE 2—Sections 8-10 require the spatial average concentration in the zone. This section describes appropriate sampling options.

13.1 *Manual Sampling*—Draw air samples using a manual sampler. See 6.3.2 for a description of manual samplers. Move throughout the region to obtain a representative sample. If a uniform concentration has been verified, then the sample shall be a physical average of the entire zone. If not, then sample rooms or other portions of the zone separately.

13.1.1 *Labeling of Containers*—Record the time and location of the sample obtained in a record that is keyed to an identifying label on the container.

13.2 *Automated Sampling*—Use either a sampling network or automated samplers at discrete locations.

13.2.1 *Network Sampling*—One installs network tubing to obtain samples from individual portions of the zone. Confirmation of a uniform concentration or control of concentration requires network sampling. Place the sampling end of each tube at a location that is well away from unmixed sources of tracer gas. Tubing leads back through a manifold or a switch either to a pump that fills containers for later analysis or to a gas analyzer. Avoid placing the sampling openings near sources of air movement, moisture, or temperatures that are different from the rest of the zone. Note that networks are useful for sampling when monitoring for a long period of time.

13.2.1.1 *Sampling Through a Manifold*—The pump continuously draws air samples through a manifold that combines several branches of the network in a manner that draws flow equally from each branch. A manifold network is one method used to test for a uniform concentration if each branch is sampled while the others are shut off.

13.2.1.2 *Switched Sampling*—A computer controls the sampling process. A timer switches between branches of the network and allows the pump to draw and purge the air that was waiting in the line between samples and then to draw a sufficient sample for the gas analyzer. Switching to the next branch and purging can occur while the gas analyzer is measuring and reporting concentration to a printed or machine-readable record, and (for constant concentration) to the device that controls the metering of tracer gas.

13.2.2 *Direct Sampling*—Place automated samplers at one or more locations in the zone. Program the devices to draw air samples at the required intervals. Note that enough samplers, appropriately placed, satisfy the spatial sampling required in 13.3. If the placement of samplers does not satisfy 13.3, then perform additional spatial sampling.

13.2.3 *Record of Automated Sampling*—Record the location of each network sampling port or automated sampler. Record the starting time and frequency of sampling at each location.

13.3 *Spatial Sampling for Uniformity of Concentration*—Spatial sampling is mandatory to determine whether the uniformity of concentration criterion (12.4.1) has been met and to assure that the spatial average is known to 2 %.

13.3.1 *When to Sample*—This is discretionary. However, since no calculations shall be based on data prior to meeting the criterion, the following is advisable. If the gas analyzer is on site, then perform the spatial sampling at 15-min intervals until uniformity of concentration is confirmed. If the gas analyzer is off site, then sampling at least four 15-min intervals shall establish whether and when the criterion was met.

13.3.2 Where to Sample—This depends on foreseeable problems with tracer gas distribution. Sample single-story zones at mid-height between the ceiling and the floor. A high space or a multistory zone requires sampling at the equivalent of mid-height for each story. Sample zones with undifferentiated open space at a minimum of three evenly spaced locations. Separately sample each individual room of zones that have interconnecting rooms.

13.4 Avoid Contamination or Dilution—Manual sample containers shall be sealed to ensure that the tracer gas concentration remains constant. Leaks in sampling networks may dilute or contaminate the air sample stream passing through them. Test networks for leakage.

13.4.1 Test for Contamination or Dilution for Manual Injection—Obtain an air sample outdoors and one in the zone prior to injecting the tracer gas. Also take a sample of the tracer gas calibration standard on site. Subsequent analysis will determine whether the air sample was contaminated in transit, whether the zone had pre-existing tracer gas, and whether the sample of the tracer gas concentration standard was diluted in transit.

13.4.2 Test for Contamination or Dilution for Metered Injection—Run the network through a sealed exit to the outdoors after it is attached to the sampling apparatus and gas analyzer but before it is distributed in the zone. Then inject sufficient tracer gas into the room to establish the maximum foreseeable concentration. A null concentration of tracer gas confirms that the distribution network has no leaks while it is in operation.

13.4.3 Test for Tracer Gas Sources from Outside the Zone—Avoid uncontrolled entry of tracer gas into the zone. Test for concentrations of tracer gas which will bias the measurement unacceptably by sampling areas adjacent to the zone. If an unacceptable concentration exists in an adjacent area, demonstrate the absence of air flow into the zone from that area for the test to be useful.

14. Procedures for Gas Analysis

14.1 Calibration of the Gas Analyzer—The gas analyzer shall be calibrated using tracer gas calibration standards. [Appendix X2](#) illustrates appropriate calibration techniques for certain gas analyzers.

14.1.1 Gas Analyzer Accuracy—Determine the biases of the gas analyzer in order to estimate the accuracy of a given reading of concentration. Calibrate the analyzer with several concentrations of tracer gas calibration standard to estimate bias. Biases for samples near zero concentration and for samples taken over a long period of time, and deviations in detector response from an empirical relationship between concentration and analyzer output, all affect the accuracy of the gas analyzer. A gas analyzer whose bias is less than 1 % of all concentrations encountered in the measurement procedures is assumed to be unbiased for the purposes of this test method. See [Annex A1](#) for details in assessing gas analyzer accuracy.

14.1.2 Gas Analyzer Precision—The precision of the gas analyzer is a measure of reproducibility. Make an estimate of the precision error of a gas analyzer; one method is to use replicate measurements. See [Annex A1](#) for details in assessing gas analyzer precision.

14.1.3 Estimate Measurement Precision—Calculate s_C , the sample standard deviation⁸ of C of the spatial samples obtained when the uniformity of concentration criterion was met and again for the second set of spatial samplings ([8.4.1](#)). Calculate their coefficients of variation ($v_C = s_C/C$). Compare these coefficients of variation with the gas analyzer precision error, v_{GA} , determined in [Annex A1.4](#). The largest becomes the measurement precision error, v_{meas} . Another method is to use $\varepsilon_{meas} = v_{meas} \times C$.

14.2 Tracer Gas Sample Record Keeping—Key all samples to the time and location that they represent and, likewise, to the concentration value obtained from the gas analyzer.

14.3 Tracer Gas Concentrations Measurements—Observe the manufacturer's instructions on use of the gas analyzer. Practice [E260](#) provides guidance for packed-column gas chromatographs. If there is a conflict between two sources of procedure, note which method was used and why.

15. Procedures for Ancillary Measurements

15.1 Outdoor Temperature and Wind—Obtain outdoor temperature and windspeed data from a local meteorological station if no correlation between these data and air change rate are sought. However, if such a correlation is sought, then employ a portable meteorology station to measure and record wind speed and direction at least once an hour.

15.1.1 Nearby Meteorological Station—Obtain outdoor temperature, wind speed, and direction data from the meteorological station to compute their average values during the time of the air change measurement.

15.1.2 Use of a Portable Meteorology Station—If correlation with A or Q is sought, follow Test Method [D4480](#). Place the portable meteorological station at a distance away from the building or enclosure that is five times the height of the enclosure studied and equally clear of other obstructions. Alternatively, place the station on the roof of the enclosure or at the next most unobstructed location. Arrange the wind measurement sensors a minimum of 3 m (10 ft) above the ground. Photograph the station in its environs and note its placement on a site diagram. Record the height of the wind sensors above the ground.

15.2 Indoor Temperature—Measure the temperature near each outside wall at mid-height for each level of the zone. Also, choose one representative site near the lowest floor level and near the highest ceiling level.

15.3 Zone Volume—Zone volume occurs (1) in initial calculations of tracer gas injection volume or rate, (2) in equilibrium and flow rate calculations (Eq [5](#) and [6](#)), and (3) when converting A to Q and vice versa. Report how the determination of volume was made and the precision of that calculation. Use an estimate of volume from measurements or drawings to calculate the initial tracer gas concentration. Other calculations require a higher precision. [Appendix X5](#) offers two methods to estimate zone volume, using tracer gas, with an uncertainty of between 10 and 15 %.

15.4 Correlation with Air Exchange Measurements—Report indoor and outdoor temperatures, wind speed and

⁸ Eq X3.4 is the correct formula for estimate of variance, s^2 , for a sample.

direction, and the state of the envelope and ventilation system to define the context of the air change measurement. Correlation of the concentration data obtained in this procedure with wind, temperature, zonal operation, and occupant behavior is optional but useful. Changes in A or Q indicate that something has changed with the envelope or driving forces. Note that ancillary measurements help explain why.

16. Report

16.1 Report the following information:

16.1.1 Background Information:

16.1.1.1 *Description of Building or Enclosure*—Report the name, address, use, dimensions, construction of walls, windows, doors, roof, foundation, and other important envelope features, including representative photographs.

(1) *Site Plan Sketch*—Show other structures, roads, terrain, major obstructions to wind flow, orientation of the enclosure, and the location of the meteorological station.

16.1.1.2 *Zone Description*—Provide a plan and section sketch of the zone. Report the zone's volume.

(1) *HVAC System*—Report the type, capacity, and mode of ventilation.

(2) *Mechanical Ventilation*—Report the type, number, capacity, and locations of fans.

(3) *Passive Ventilation*—Report the type, the open dimensions, number and locations of doors, windows, vent fan openings, chimney flues, and other passive ventilation openings.

(4) *Leakage Sites*—Report any obvious sites or those that have been determined by such means as infrared thermography.

16.1.2 Design of Test:

16.1.2.1 *Test Method*—Specify concentration decay, constant injection, or constant concentration.

16.1.2.2 *Zonal Operation*—Report whether the zone operated with ventilation systems in operation or off during the air change measurement.

(1) *Active Ventilation*—Report whether the HVAC System was operating or not, with fresh air intake or exhaust open or shut. Report vent fans on or off.

(2) *Passive Ventilation*—Report whether the doors, windows, flue dampers, vent openings, vent fan openings were open, closed, or sealed.

(3) *Occupant Behavior*—Report whether the zone was occupied or unoccupied and any ingress or egress.

16.1.2.3 *Distribution of Tracer Gas*—Report the type of gas, method of injection, volume of initial injection, injection locations, initial concentration, metering or volume measurement system, injection flow rate, target concentration, and method of distribution.

16.1.2.4 *Sampling of Tracer Gas*—Report the location of sampling sites, method of spatial testing, sampling interval, initial sampling time, method of sampling, and method of testing for dilution or contamination in the zone and sampling system.

16.1.2.5 *Gas Analyzer*—Report the type of analyzer and the date, method, and results of its calibration.

16.1.2.6 *Data Acquisition and Control*—Report the format for obtaining and recording data. For the constant concentra-

tion method, report the type of equipment and algorithm used to control the process.

16.1.2.7 *Ancillary Measurements*—Report the method used for obtaining indoor and outdoor temperatures, wind speed and direction, and other meteorological observations. Report the height and location of wind measurements. Report the means used for measuring other phenomena, such as door or damper positions.

16.1.3 Data Analysis:

16.1.3.1 *Record of Tracer Gas Injection*—Report the time, place, and amount.

16.1.3.2 *Record of Tracer Gas Concentration*—Report the time, location, and concentration of samples obtained for the following tests: contamination, uniformity of concentration, equilibrium, and air change.

16.1.3.3 *Calculation of Air Change*—Report the type of calculation. Report the time period for calculation. Report the calculation of A or Q from concentration and injection data. Report the calculation of Q or A from A or Q (optional).

16.1.3.4 *Error Analysis*—If the data meet the applicable criteria for uniformity of concentration, equilibrium, stability, and so forth, state that air change has been determined within 10 %. If not, state that the error and uncertainty of the measurement exceeds 10 %. Alternatively, calculate and report the actual uncertainty and error using a propagation of errors analysis (3) to obtain s for determining concentration or flow rates (Appendix X6). Report the result of any confidence interval calculation on data obtained (optional).

16.1.3.5 *Ancillary Information*—Report wind speed and direction, and indoor and outdoor temperatures. Reporting correlation of wind speed and direction, and zonal operation data with changes in concentrations in the zone during the measurement is optional.

17. Precision and Bias

17.1 If the procedures are followed and the requirements in this test method are met, air change within a zone can be determined within 10 % of its actual value. The precision and bias of this test method is affected by (1) tracer gas injection and distribution procedures, (2) tracer gas sampling and storage, (3) changes in wind, temperature, and zonal operation regimes, and (4) tracer gas concentration determination.

17.2 *Precision*—In general, the degree to which data on tracer gas concentration conform to the expected model line or curve over time offers an indication of precision in each of the three techniques. The models are (1) a tracer gas concentration decay curve, (2) a constant value of concentration achieved by constant injection, or (3) a constant value of concentration met by constant concentration control. The scatter of data about the model relates inversely to precision. A discussion of uncertainty for each technique is presented in Appendix X6.

17.2.1 *Gas Analyzer*—Use a calibration gas in the tracer gas analyzer to determine the precision of tracer gas concentration measurements. Perform a propagation of errors analysis, starting with the precision in determining the concentration of the calibration gas, next with the precision of the gas analyzer, and finally, with the precision of the measurement of tracer gas concentration under field conditions.

17.2.2 Zone Volume—Determination of volume introduces an uncertainty. Depending on the method, one determines either air change rate or air change flow. In order to convert the results into the other air change values, use volume. The constant injection method requires determination of the zone volume. **Appendix X5** offers a technique to calculate the volume of a zone with an uncertainty of 10 to 15 %.

17.2.3 Tracer Gas Concentration Decay—In the presence of a confirmed, uniform concentration, change in the apparent shape of the decay curve or slope of the logarithmic line indicates a change in temperature, wind, zonal operation, or calibration drift. The scatter of points about the decay curve or logarithmic line (**Fig. 2**) relates inversely to precision, as characterized by confidence limits on a regression analysis.

17.2.4 Constant Tracer Gas Injection—In the presence of a confirmed, uniform concentration, a change in the level of concentration from one constant value over time to another indicates a change in temperature, wind, zonal operation, calibration drift, or tracer gas flow variation. The scatter of points about a constant value line relates inversely to precision, as characterized by confidence limits about the mean.

17.2.5 Constant Tracer Gas Concentration—This technique helps assure uniform concentration in the zone as a whole. So, deviation of tracer gas concentration from the target concentration relates inversely to precision and may be characterized by confidence limits.

17.3 Bias—Since no accepted procedure exists to determine air change independently, the statement on bias for the procedure in Test Method E741 is defined theoretically.⁹ However, good distribution as indicated by the uniformity of tracer gas concentration values throughout the zone is an indication of accuracy. The uniformity of concentration criterion of 10 % assures that accurate measurements of gas concentrations will provide air change values within 10 % of the true value for

each of the techniques when their criteria for steady-state conditions, equilibrium tracer gas concentration, or other conditions are met. Drift in the response of the gas analyzer from its calibration is a source of bias.

17.3.1 Tracer Gas Concentration Decay—Sources of bias for this test method include (1) nonuniform tracer gas concentration, (2) dilution or contamination of sample containers before their contents are analyzed for tracer gas concentration, (3) drift in the gas analyzer calibration, (4) detector bias of the gas analyzer, and (5) readings near the lower limit of gas analyzer sensitivity. The average method is unbiased by variations in air change rates over time.

17.3.2 Constant Tracer Gas Injection—Sources of bias for this test method include (1) incorrect determination of how much tracer gas is being released in the zone, or nonuniform tracer gas concentration, (2) dilution or contamination of sample containers before their contents are analyzed for tracer gas concentration, and (3) incorrect determination of zonal volume. In this test method, one can maintain the tracer gas concentration at a level near a well calibrated value for the gas analyzer.

17.3.3 Constant Tracer Gas Concentration—Sources of bias for this test method include (1) incorrect determination of how much tracer gas is being released in the zone, or poor distribution in portions of the zone, (2) dilution or contamination of sampling lines before their contents reach the tracer gas analyzer, and (3) inability of the concentration control system to respond rapidly enough to changes in wind, temperature, and zonal operation regimes. This test method maintains the tracer gas concentration at a level near a well-calibrated value for the gas analyzer.

18. Keywords

18.1 air change; air change flow; air change rate; air changes per hour; air exchange; air leakage; air leakage rate; concentration; tracer gas; concentration decay; constant concentration; constant injection; envelope; building; exfiltration; infiltration; tracer gas; ventilation; ventilation rate; zone

ANNEX

(Mandatory Information)

A1. ANALYZER PRECISION AND BIAS

A1.1 Bias at Zero Concentration—Most analyzers have a threshold at which they cannot distinguish between zero tracer gas concentration and some positive concentration. This constitutes the bias at zero concentration, ε_{zero} . All concentrations used in this test method shall be $C > 20\varepsilon_{zero}$.

A1.2 Drift of Concentration Reading—The response of a gas analyzer to a sample with a known concentration of tracer gas may change over time. Check for this effect during calibration. If it is found to be significant, a similar check and corresponding correction shall be made during field measurements. First, estimate the time that will elapse for readings

from a tracer gas standard or pure air to change by 5 %, and use this as the maximum interval for rechecking response to the tracer gas calibration standard. Then, correct all tracer gas concentration readings between checks. Use no measurement in this test method when the uncorrected drift of a concentration reading exceeds 5 %.

A1.3 Deviate Detector Response—The response of a gas analyzer to different concentrations of tracer gas is usually assumed to follow some empirical relationship, for example, linear or logarithmic, based on a limited number of discrete calibration gas concentrations. The extent to which the gas

⁹ In principle, a chamber with a calibrated source of ventilation could be used to determine the bias of the three techniques. However, no technique has been standardized for this purpose.

analyzer's response differs from the empirical model is the detector bias, ε_{detect} ; this value is a function of C . This test method uses $\varepsilon_{detect} < 0.05 C$ for all C in the range used.

A1.4 Estimate Gas Analyzer Precision Error—Perform the following for at least the maximum and minimum concentrations expected to be analyzed. Determine the standard deviation of at least $n_C = 10$ replicates of the same tracer gas concentration. Calculate s_C , the sample standard deviation⁸ of C of the replicates. Calculate their coefficients of variation ($v_C = s_C/C$). The largest becomes the gas analyzer precision error, v_{GA} .

A1.5 Determine the Number of Replicates Required—Determine the number of replicate samples to obtain a single concentration measurement with the gas analyzer by the following equation:

$$n_{rep} = \frac{t(n_C - 1, 95\%)^2 v_{GA}^2 / 2}{d^2} \quad (A1.1)$$

In this test method, use $d = 0.05$ as a desired precision of the measurement. Round the value of n_{rep} in Eq A1.1 to the next integer.

APPENDIXES

(Nonmandatory Information)

X1. TRACER GASES USED TO DETERMINE AIR CHANGE

TABLE X1.1 Tracer Gases and Safety Issues

Tracer Gas	PEL	Toxicology	Chemical Reactivity	Comments
Hydrogen	Asphyxiant	Non-toxic	Highly reactive in presence of heat, flame, or O ₂	Fire and explosion hazard when exposed to heat, flame, or O ₂
Helium	Asphyxiant	Non-toxic	Inert	
Carbon Monoxide	50 ppm	Combines with hemoglobin to cause anoxia	Highly reactive with O ₂	Fire and explosion hazard when exposed to heat or flame
Carbon Dioxide	5000 ppm	Can be eye irritant	Reacts vigorously with some metals; soluble in water	
Perfluorocarbon tracers (PFTs)	Asphyxiant	Non-toxic	Inert	Thermal decomposition may produce toxic compounds
Nitrous Oxide	25 ppm	Moderately toxic by inhalation	Violent reaction with aluminum; water soluble	Can form explosive mixture with air; ignites at high temperature
Ethane	Asphyxiant	Non-toxic	Flammable	Incompatible with chlorine and oxidizing materials
Methane	Asphyxiant	Non-toxic	Flammable	Incompatible with halogens and oxidizing materials
Octafluorocyclobutane (Halocarbon C-318)	1000 ppm	Low toxicity	Nonflammable	Thermal decomposition yields highly toxic compounds
Bromotrifluoromethane (Halocarbon 13B1)	500 ppm	Moderately toxic by inhalation	Incompatible with aluminum	Dangerous in a fire
Dichlorodifluoromethane (Halocarbon 12)	1000 ppm	Central nervous system and eye irritant; can be narcotic at high levels	Nonflammable; can react violently with aluminum	Thermal decomposition yields highly toxic fumes
Dichlorotetrafluoromethane (Halocarbon 116)	1000 ppm	Can be asphyxiant, mildly irritating, narcotic at high levels	Can react violently with aluminum	Thermal decomposition yields highly toxic fumes

X1.1 Table X1.1 and Table X1.2 list tracer gases that are used to determine air change. They include only those gases that have an established personal exposure limit (PEL, see

Section 7). Table X1.1 describes the safety properties of gases. Table X1.2 highlights the concentration analysis of gases.

TABLE X1.2 Tracer Gas Analysis

Tracer Gas	Ambient Levels	Measurement Techniques	Detection Levels
Hydrogen	0.5 ppm	Katharometer	200 ppm
Helium	5.2 ppm	Katharometer	300 ppm
Carbon Monoxide	0.1–1 ppm	Infrared Absorption	5 ppm
Carbon Dioxide	320 ppm	Infrared Absorption	1 ppm
Sulfur Hexafluoride	1 ppt	Electron Capture Detector	2 ppt
Nitrous Oxide	0.3 ppm	Infrared Absorption	1 ppm
Ethane	1.5 ppb	Flame Ionization Detector	5 ppm
Methane	1.5 ppb	Infrared Absorption	5 ppm
Octafluorocyclobutane (Halocarbon C-318)	^A	Electron Capture Detector	5 ppb
Bromotrifluoromethane (Halocarbon 13B1)	^{A,B}	Electron Capture Detector	0.1 ppb
Dichlorodifluoromethane (Halocarbon 12)	^A	Electron Capture Detector	0.6 ppm
		Flame Ionization Detector	
Dichlorotetrafluoromethane (Halocarbon 116)	^A	Electron Capture Detector	0.3 ppm
		Flame Ionization Detector	

^A Below detection limits.

^B Locally variable.

X2. CALIBRATION OF CERTAIN GAS ANALYZERS

X2.1 Applicability—Certain gas analyzers, including many gas chromatographs, lend themselves to the techniques described in this appendix. Other gas analyzers may lend themselves to analogous techniques.

X2.2 Summary of Calibration Technique—The gas analyzer should be calibrated using at least three, and preferably more, tracer gas concentrations that are in the range anticipated in an actual test. For the concentration decay technique, the measurements need only to be accurate relative to each other. For the constant injection and constant concentration techniques, the measurements must be accurate relative to an absolute standard. Two levels of calibration are recommended here, laboratory and field.

X2.2.1 Frequency of Calibration—A field calibration should be performed every time the analyzer is moved to a new site, before analysis of constant injection samples, and at least before and after a constant concentration experiment. A laboratory calibration should be performed annually, after any servicing that might affect the calibration, or whenever a field calibration indicates a significant change.

X2.2.2 Tracer Gas Concentration Standards—Tracer gas standards should have a 95 % probability of having a concentration that is within 3 % of its stated value.

X2.3 Laboratory Calibration—Use two tracer gas concen-

tration standards, one at the high end and one at the middle of the range of use. Use ultra-high-purity air as a source of dilution of the standard. Test for the background level of the tracer gas in that air. Obtain a minimum of five analyzer readings at each of the three following dilutions of each tracer gas standard: 1 part standard: 0 parts air, 1 part standard: 1 part air, and 1 part standard: 3 parts air. Perform a regression analysis on the data in a manner analogous to that used in 8.5.3.2. Report the estimate of variance from the mean for all samples that were drawn from the undiluted standard. Report also the estimate of variance from the mean for those that were diluted to each level. Report the confidence limits of the calibration.

X2.4 Field Calibration—Use one tracer gas concentration standard at the high end of the range of use. First test for the background level of the tracer gas in the source of air that will be used for diluting the standard. Obtain a minimum of three analyzer readings at each of the three following dilutions of the tracer gas standard: 1 part standard: 0 parts air, 1 part standard: 1 part air, and 1 part standard: 3 parts air. Compare the readings obtained against the calibration curve supplied by the factory. Perform a regression analysis on the data in a manner analogous to that used in 8.5.3.2. If the published regression curve lies outside the 95 % confidence limits for this calibration, perform a laboratory calibration.

X3. CONFIDENCE INTERVALS

X3.1 Concentration Decay Method:

X3.1.1 Test for Constant A—The following procedure statistically establishes one's confidence in *A* as a constant value with the regression method (8.5.3.2). Determine the estimated standard error (4) of *A* by:

$$ESE_A = \frac{s}{[\sum (t_i - \bar{t})^2]^{\frac{1}{2}}} \quad (X3.1)$$

$$s^2 = \frac{\sum (Y_i - \hat{Y}_i)^2}{(n - 2)} \quad (X3.2)$$

where:

Y = $\ln C_i$, and

$\hat{Y}$ = estimate of $\ln C_i$.

The confidence limits on *A* for *n* points in the grouping and a desired probability of 100 (1 – α) % are calculated, using a *t*-distribution table, by:

$$CONF_A(t) = A \pm ESE_A \times t(n-2, 1-\alpha) \quad (X3.3)$$

X3.2 Constant Injection Method:

X3.2.1 *Test for Constant Q*—The following procedure can establish statistically one's confidence in the assumption of a constant Q . Determine the estimate of variance (5)¹⁰ of C by:

$$s^2 = \frac{n \sum C^2 - (\sum C)^2}{n(n-1)} \quad (X3.4)$$

Choose confidence levels at α and $1-\alpha$, for example 0.05 and 0.95. With $t(n-2, 1-\alpha)$ and the mean value of C , calculate upper and lower limits for C :

$$C_{upper} = \bar{C} + t(n-1, 1-\alpha) \times s/\sqrt{n} \quad (X3.5)$$

$$C_{lower} = \bar{C} - t(n-1, 1-\alpha) \times s/\sqrt{n} \quad (X3.6)$$

¹⁰ This analysis assumes that the variances of the gas analyzer and its calibration process are negligible. If not, then an appropriate propagation of errors analysis must be made to allow for analyzer error in the determination of s .

If one assumes equilibrium tracer gas concentration and negligible variance of Q_{tracer} , the corresponding values from using Eq 7 for Q are:

$$Q_{lower} = Q_{tracer}/C_{upper} \quad (X3.7)$$

$$Q_{upper} = Q_{tracer}/C_{lower} \quad (X3.8)$$

X3.3 Constant Concentration Method:

X3.3.1 *Test for Constant C*—This procedure has built-in indicators of bias and precision of the calculation. Because C_{target} is sought, this value may be compared with $\bar{C}$ to characterize bias. The precision of C may be estimated by calculating the estimate of variance¹⁰ of C using Eq X3.4. Choose confidence levels at α and $1-\alpha$, for example, 0.05 and 0.95. With $t(n-2, 1-\alpha)$ and the mean value of C , calculate upper and lower limits for C using Eq X3.5 and X3.6. An analysis of the confidence intervals about Q at any of the branches depends on the algorithm that relates $C(t)$ to Q_{tracer} .

X4. EXAMPLES OF ZONE PREPARATION PROTOCOLS

X4.1 The following protocols may be followed depending on whether the total air change with all ventilation systems in operation is of interest or whether the air change attributable to the envelope is of interest.

X4.2 *Total Air Change with All Ventilation Systems in Operation*—All ventilation systems should be operating in the mode desired by the user. All passive ventilation openings, such as open windows and those for kitchen and bath fans, should be noted. The measured size and location of each passive ventilation opening gives useful ancillary information. The modes of control and operation for each mechanical means of ventilation should be noted. If possible, ensure that ventila-

tion controls remain on one setting during the test, unless change of settings is desired. The labeled air flow capacity of each mechanical ventilating unit provides useful ancillary information.

X4.3 *Air Change Attributable to the Envelope*—All ventilation systems should be turned off and closed. Windows, doors, and fireplace dampers should be closed. Mechanical systems with dampers should have the damper closed but not otherwise sealed. Mechanical systems without dampers should be sealed off with a membrane, PVC plastic, and tape, for instance. Any combustible heating plant should be allowed to operate normally.

X5. ZONE VOLUME MEASUREMENT WITH A TRACER GAS

X5.1 This section offers two methods (direct and indirect) for estimating the effective volume of a zone. They both employ the injection of a pulse of tracer gas into the zone and then a calculation from the volume of the tracer gas and the resulting concentrations to estimate zone volume. The direct method has an uncertainty of 10 %, whereas the indirect method with fewer constraints has an uncertainty of 15 %.

X5.2 *Direct Method*—The direct method requires the ability to inject and mix a pulse of tracer gas quickly, and to make rapid, representative concentration measurements. This method requires that all the tracer gas gets into the zone and that the following time criteria be met.

X5.2.1 *Time Criteria*—The injection time (T_{inj}) shall be short compared to the measurement time (T_{meas}): $T_{inj} < 0.1 T_{meas}$. The mixing time (T_{mix}) shall be short compared to the measurement time: $T_{mix} < 0.2 T_{meas}$. The tracer sampling interval (T_{sample}) shall be short compared to the measurement

time: $T_{sample} < 0.2 T_{meas}$. The measurement time shall be short compared to the decay time: $T_{meas} < \frac{0.1}{A_{est}}$.

X5.2.2 *Uniformity of Concentration Criterion*—Gas concentrations at representative locations throughout the zone shall differ by less than 5 % of the average concentration of the zone. Use spatial sampling (13.3.1 and 13.3.2) to confirm the uniformity of concentration.

X5.2.3 *Tracer Gas Injection*—Observe 14.1, and determine background concentration of the tracer gas, C_0 . Determine the volume of tracer gas required according to 8.2.3. The total volume of tracer gas injected (V_{tracer}) should be known to 2 %. An error of more than 5 % is unacceptable. At $t = 0$, inject the tracer gas according to any of the techniques in Section 12 that will ensure rapid mixing. Adequate mixing usually requires continuous operation of fans or an air distribution system. In this case one can estimate the mixing time by dividing the estimated zone volume by the fan-driven flow.

X5.2.4 Tracer Gas Sampling—Obtain samples at intervals of T_{sample} at representative locations. The initial samples must confirm uniformity of concentration. Thereafter obtain at least 10 samples at intervals of T_{sample} .

X5.2.5 Concentration Measurement—Analyze the samples according to Section 14. Plot the concentration values as a function of time. Determine the length of time for the concentration to reach a plateau. The time to reach this plateau is approximately $3 T_{mix}$. Exclude these data from the following analysis.

X5.2.6 Calculation of Volume—Determine the mean tracer gas concentration of the samples obtained during equilibrium, $\bar{C}$. Calculate the volume of the zone, as follows:

$$V_{zone} = \frac{V_{tracer}}{\bar{C} - C_0} \quad (X5.1)$$

This procedure will estimate V_{zone} with an uncertainty of 10 %, assuming that no significant portion of the tracer gas exits the zone during mixing.

X5.3 Indirect Method—The indirect method may be used when the time, uniformity of concentration, or tracer gas volume accuracy criteria (X5.2.1-X5.2.3) of the direct method cannot be met. It is a combination of the integral pulse and concentration decay techniques.

X5.3.1 Summary—This technique combines a determination of air change flow, using the integral pulse method (6), with a determination of air change rate, using a calculation from the concentration decay method (Section 8), to determine volume. The concentration decay employs points occurring after the peak of the pulse response.

X5.3.2 Determine Air Change Flow—Follow 8.2-8.4.2, except modify the injection and sampling procedures as follows. Rapidly inject a precisely known volume of tracer gas simultaneously at several locations in the zone to achieve rapid uniformity of concentration. Obtain a time series of frequent samplings that start before the gas is released and continue long into the decay process. Calculate Q , as follows:

$$\bar{Q}_{zone} = \sum_{i=1}^n C_i (t_i - t_{i-1})^{-1} V_{tracer} - V_{zone} [C(t_n) - C(t_0)] \quad (X5.2)$$

X5.3.3 Determine Air Change Rate—Plot $\ln C(t)$ versus t . Determine the time t_1 at which the decay of $C(t)$ becomes stable [$\ln C(t)$ becomes a straight line]. Determine air change rate, A , by either the averaged (8.5.3.1) or regression (8.5.3.2) method, using the points in the data set that start with t_1 .

X5.3.4 Calculation of Volume—Calculate the volume of the zone, as follows:

$$V_{zone} = \frac{Q}{A} \quad (X5.3)$$

This procedure estimates V_{zone} with an uncertainty of 15 %.

X6. PROPAGATION OF ERRORS ANALYSIS

X6.1 This appendix contains a summary of propagation of errors equations (7) that pertain to each of the three techniques presented in this test method. One may choose to use other error analyses, such as error bounds (8).

X6.2 Concentration Decay—Two techniques are presented, the averaged method Eq 2 and the regression method Eq 3.

X6.2.1 Averaged Method—For nonsteady-state conditions:

$$s_A^2 = \frac{1}{(t_2 - t_1)^2} \frac{s_{C(t_2)}^2}{C(t_2)^2} + \frac{s_{C(t_1)}^2}{C(t_1)^2} \quad (X6.1)$$

One can develop specialized expressions from Eq X6.1 for gas analyzers that have an error that is a percent of full scale and for those whose error is a percent of the reading.

X6.2.2 Regression Method—Refer to X3.1.

X6.3 Constant Injection—Two techniques are presented, the general case and the constant air change flow case.

X6.3.1 General Case—The error expression is:

$$\frac{s_Q^2}{Q^2} = \frac{s_{Q_{tracer}}^2}{Q_{tracer}^2} + \frac{s_{\bar{C}}^2}{\bar{C}^2} \alpha^2 + \frac{2 V_2}{(t_2 - t_1)^2 Q^2} \quad (X6.2)$$

where:

$$\alpha^2 = \frac{\text{Var}(1/C)}{[s_C (1/C)_{ave}]^2} \approx \frac{\text{Var}(C)}{(s_C)^2} \text{ and}$$

$$\text{Var}(f) = \frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} (f(t) - \bar{f})^2 dt$$

X6.3.2 Constant Air Change Flow—Refer to X3.2.

X6.4 Constant Concentration—In general the error expression is:

$$\frac{s_Q^2}{Q^2} = \frac{s_{Q_{tracer}}^2}{Q_{tracer}^2} + \frac{s_C^2}{\bar{C}^2} \alpha^2 + \frac{2 V_2}{(t_2 - t_1)^2 Q^2} \quad (X6.3)$$

where the subscript *twt* means that the value is weighted, according to the tracer gas flow,

$$\alpha^2 = \frac{\text{Var}_{twt}(1/C)}{[s_C (1/C)_{twt-ave}]^2} \approx \frac{\text{Var}_{twt}(C)}{(s_C)^2}$$

$$\text{Var}_{twt}(f) = \frac{1}{Q_{tracer}(t_2, t_1)} \int_{t_1}^{t_2} (f(t) - \bar{f})^2 Q_{tracer}^{(t)} dt \text{ and}$$

$$Q_{tracer}(t_2, t_1) = \int_{t_1}^{t_2} Q_{tracer}^{(t)} dt$$

X7. SAMPLING DURATION

X7.1 **Table 2** illustrates minimum sampling durations for the concentration decay technique. It is based on a 10 % uncertainty at the 95 % confidence level in the determination of air change rate, a tracer gas concentration measurement uncertainty, v_{meas} , of 5 % of reading, and various air change rates. For

other assumptions, calculate the minimum as:

$$T_{test} > \frac{20}{A_{est}} v_{meas} \quad (X7.1)$$

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