ANSI/ASHRAE Standard 129-1997 (RA 2002)
(with minor editorial changes)

ASHRAE STANDARD

Measuring Air-Change Effectiveness

Approved by the ASHRAE Standards Committee on June 26, 2002; by the ASHRAE Board of Directors on June 27, 2002; and by the American National Standards Institute on March 12, 2003.

ASHRAE Standards are updated on a five-year cycle; the date following the standard number is the year of ASHRAE Board of Directors approval. The latest copies may be purchased from ASHRAE Customer Service, 1791 Tullie Circle, NE, Atlanta, GA 30329-2305. E-mail: *orders@ashrae.org.* Fax: 404-321-5478. Telephone: 404-636-8400 (worldwide) or toll free 1-800-527-4723 (for orders in U.S. and Canada).

ISSN 1041-2336

When addenda or interpretations to this standard have been approved, they can be downloaded free of charge from the ASHRAE web site at http://xp20.ashrae.org/standards/addenda.htm or http://xp20.ashrae.org/standards/intpstd.htm.

Approved American National Standard
ANSI

AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS, INC.
1791 Tullie Circle, NE • Atlanta, GA 30329

ASHRAE Standard Project Committee 129-1997
Cognizant TC: TC 5.3, Room Air Distribution
SPLS Liaison: Frederick H. Kohloss

SPECIAL NOTE

This American National Standard (ANS) is a national voluntary consensus standard developed under the auspices of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). Consensus is defined by the American National Standards Institute (ANSI), of which ASHRAE is a member and which has approved this standard as an ANS, as “substantial agreement reached by directly and materially affected interest categories. This signifies the concurrence of more than a simple majority, but not necessarily unanimity. Consensus requires that all views and objections be considered, and that an effort be made toward their resolution.” Compliance with this standard is voluntary until and unless a legal jurisdiction makes compliance mandatory through legislation.

ASHRAE obtains consensus through participation of its national and international members, associated societies, and public review.

ASHRAE Standards are prepared by a Project Committee appointed specifically for the purpose of writing the Standard. The Project Committee Chair and Vice-Chair must be members of ASHRAE; while other committee members may or may not be ASHRAE members, all must be technically qualified in the subject area of the Standard. Every effort is made to balance the concerned interests on all Project Committees.

The Manager of Standards of ASHRAE should be contacted for:

a. interpretation of the contents of this Standard,
b. participation in the next review of the Standard,
c. offering constructive criticism for improving the Standard,
d. permission to reprint portions of the Standard.

CONTENTS

ANSI/ASHRAE Standard 129-1997 (RA 2002)
Measuring Air-Change Effectiveness

1791 Tullie Circle NE
Atlanta, GA 30329
www.ashrae.org

(This foreword is not part of this standard but is provided for information only.)

FOREWORD

This standard defines a method of measuring air-change effectiveness in mechanically ventilated buildings or spaces. The method involves an age-of-air approach to air-change effectiveness and employs tracer gas procedures to measure the age of air. The age of the air at a given location is the average amount of time that has elapsed since the air molecules at that location entered the building. The definition of air-change effectiveness is based on a comparison of the age of air in the occupied portions of the building to the age of air that would exist under conditions of perfect mixing of the ventilation air.

The need for a test method for air-change effectiveness arose from discussions concerning ANSI/ASHRAE Standard 62-1989, Ventilation for Acceptable Indoor Air Quality *with regard to the uniformity of air distribution within buildings and mixing within ventilated spaces. Short-circuiting airflow patterns, in which a significant portion of supply air flows directly to the exhaust, bypassing the occupied portion of the ventilated space, have been a source of concern. Short circuiting could adversely impact indoor air quality and thermal comfort in the occupied space and increase energy use. Additionally, there is an increased interest in innovative ventilation, such as displacement ventilation, that may be more effective in maintaining acceptable indoor air quality than ventilation that causes indoor air to be thoroughly mixed.*

The effective rate at which outside air is provided to the occupied portion of the ventilated space is determined by both the pattern of air flow within the ventilated space and by the extent of the mechanical recirculation of air by the ventilation system. Increased mechanical recirculation decreases both the adverse effect of short circuiting and the benefits of displacement flow. The air-change effectiveness parameter defined in this standard reflects the combined influence of the indoor airflow pattern and mechanical recirculation on the age of air at locations where people breathe. Appendix B describes how measured values of air-change effectiveness can be used to adjust the outdoor air requirements for ventilation determined in accordance with ANSI/ASHRAE Standard 62-2001.

The test method has been used successfully in laboratory test rooms to study the performance of different ventilation systems, but there is considerably less experience in the field where many factors can complicate the measurement process and increase measurement uncertainty. Therefore, the standard places strict limitations on the characteristics of the spaces that can be tested with the method. While the test method will not be usable in all field situations, it is generally applicable in laboratory test rooms. Future versions of the standard will benefit from additional experience with the test method in the field, perhaps making the test method more widely applicable.

1. PURPOSE

This standard prescribes a method for measuring air-change effectiveness in mechanically ventilated spaces and buildings that meet specified criteria. The air-change effectiveness is a measure of the effectiveness of outdoor air distribution to the breathing level within the ventilated space.

2. SCOPE

2.1 The method of measuring air-change effectiveness compares the age of air where occupants breathe to the age of air that would occur throughout the space if the indoor air were perfectly mixed.

2.2 The standard includes measurement procedures and criteria for assessing the suitability of the test space for measurements of air-change effectiveness.

3. DEFINITIONS

adjoining spaces: any ventilated or unventilated indoor space that adjoins, or is surrounded by, the test space.

age of air: the average time elapsed since molecules of air in a given volume of air entered the building from outside.

building air infiltration: uncontrolled inward leakage of air (that may contain enriched water vapor) through cracks and interstices in any building element and around windows and doors of a building, caused by the pressure effects of wind or the effect of differences in the indoor and outdoor air density.

calibration gas: a mixture of air and tracer gas with a tracer gas concentration that is known within specified tolerances, used to calibrate tracer gas instruments.

concentration: the quantity of one constituent dispersed in a defined amount of another.

concentration, tracer gas: the volume or mass of tracer gas divided by the volume or mass of air plus tracer gas.

exfiltration: converse of building air infiltration.

exhaust air: air discharged from a space to the outdoors as differentiated from air transferred from one space to an adjacent space.

indoor air volume: the entire air volume of a space or building in which the ventilation air is distributed, including ductwork and plenums. The volume of indoor furnishings, equipment, and occupants must be subtracted from the gross indoor volume that is based on interior dimensions of the space or building.

nominal time constant: the indoor air volume of a space or building divided by the rate of outdoor air supply; the nominal time constant also equals the average age of air exiting from the space or building. The reciprocal of the nominal time constant is called the nominal air-change rate.

outdoor air: air outside a building or taken from outdoors and not previously circulated through the system.

perfect mixing: a theoretical airflow distribution pattern within a ventilated space where the supply air is instantaneously and uniformly mixed with the air in the space such that the concentration of all constituents in the air, and the age of air, are spatially uniform.

real-time measurement: In the context of this standard, a real-time measurement of a tracer gas concentration is a measurement that includes sample analysis by a tracer gas analyzer during the tracer gas decay or step-up. The output from the tracer gas analyzer is available within approximately a ten-minute period after the air is sampled.

return air: air extracted from a space and totally or partially returned to an air conditioner, furnace, or other heat source.

supply air: air entering a space from an air-conditioning, heating, or ventilating apparatus.

test space: a building or portion of a building that is the subject of the air-change effectiveness measurement.

tracer gas: a gas that can be mixed in trace amounts with air for the purpose of studying airflow patterns and measuring ages of air and air-change rates.

4. CRITERIA FOR ACCEPTABLE TEST SPACE

To help ensure repeatable and accurate measurements, the space or building in which air-change effectiveness is measured, hereinafter called the "test space," must meet the following criteria.

4.1 This standard applies to single-room or multi-room test spaces, which may be a research laboratory, an entire building, or a section of a building. Test spaces may be partly or entirely surrounded by other indoor spaces. In all cases, the test space shall be representative of a space designed for human occupancy.

4.2 This standard applies to spaces that are mechanically ventilated. During the measurement of air-change effectiveness, all airstreams of the HVAC system serving the test space, including the supply air, return air, outdoor air, and the airstreams exiting each supply outlet and entering each return inlet, shall have a constant flow rate to the degree practical, e.g., the difference between the maximum and minimum should be within 10%. Fan and damper controls shall be overridden if necessary so that damper positions and fan speeds are constant during the test. HVAC systems that supply air to or remove air from the test space shall not supply air to or remove air from any other space. Mechanical recirculation of air is permitted but not required.

4.3 The standard applies to test spaces that have limited temporal variation in heat loads and limited variation in the operation of air-moving equipment according to the following criteria:

(a) The difference between maximum and minimum internal heat generation by equipment (e.g., lights, space heaters, computers) shall not be larger than 10% during a test.

(b) The difference between maximum and minimum number of occupants within the test space shall not be larger than 10% or the test space shall be unoccupied. No restrictions are placed on occupant movement within the test space.

(c) The range of the temperature difference between all return airstreams and the supply airstream shall not be larger than 2°F (1.1°C) during the test. The difference between the maximum and minimum temperature of each return airstream shall not be larger than 6°F (3.3°C).

(d) The difference between maximum and minimum rate of airflow through fans operating within the test space, e.g., desktop fans, shall not be larger than 10% during a test.

4.4 This standard applies to test spaces with limited air infiltration, exfiltration, and air exchange with surrounding indoor spaces. This standard includes test procedures to assess the extent of infiltration, exfiltration, and air exchange with surrounding spaces, as well as criteria for acceptability.

5. INSTRUMENTS AND APPARATUS

5.1 Tracer Gas. A tracer gas is used to label the indoor air at the start of a tracer decay measurement procedure or to label the outdoor air during a tracer gas step-up. The tracer gas must be nontoxic at the concentration used (if used in an occupied space). The tracer gas should not be removed from the indoor air by adsorption or absorption on indoor surfaces or by chemical reaction at a rate that is significant compared to the rate of tracer gas removal by ventilation. Ease and accuracy of measuring the concentration of the tracer gas are additional considerations. The tracer gas shall not be a compound that is prohibited to be released to the atmosphere in the Federal Clean Air Act Amendments of 1990. ASTM Standard E741-95[1] discusses tracer gas properties and tracer gas selection.

5.2 Tracer Gas Analyzer

5.2.1 Selection. The selection of a tracer gas analyzer depends on the tracer gas utilized and the tracer gas concentration employed. The tracer gas analyzer shall be capable of measuring tracer gas concentration over a range of a factor of 50 with a precision in the upper 95% of this range as defined in Section 5.2.2. Normal constituents or pollutants of air should not interfere with tracer gas measurements using the analyzer.

5.2.2 Precision and Stability. Acceptable measurement precision and minimal drift in analyzer response shall be demonstrated as follows:

(a) At the maximum and at 5% of maximum tracer gas concentration measured during tests, the arithmetic standard deviation of ten sequential measurements of tracer gas concentration in a calibration gas must be less than 4% of the average of the ten measurements.

(b) Repeating the ten measurements of the calibration gas after a period of six hours has elapsed (six hours is a typical period for measurements of air-change effectiveness) must yield the same average concentration within ±3%.

(c) This demonstration must be conducted and documented within the three-month period prior to the measurement of air-change effectiveness.

5.2.3 Calibration. Tracer gas analyzers shall be calibrated with at least six calibration gases during the three-month period preceding the measurement of air-change effectiveness. The calibration gases shall include a zero gas containing no tracer, a span gas at the maximum anticipated concentration, and at least four other calibration gases with intermediate and approximately equally spaced concentrations. The concentration of tracer gas in each calibration gas shall be known within ±5%. During the one-hour period that precedes the measurement of air-change effectiveness, the analyzer's calibration shall be checked with at least two calibration gases—one each in the top and bottom 30% of the calibrated range. If the instrument response has changed by more than ±5% from the preceding calibration, a recalibration with six or more tracer gases shall be completed before the measurement of air-change effectiveness.

If the tracer gas analyzer is not designed to accept an internal six-point calibration, the analyzer may be calibrated according to the manufacturer's instructions and then the instrument accuracy checked using six calibration gases. If necessary, the six-point calibration check may then be applied by correcting the tracer gas concentration data via a spread sheet or other computer program.

5.3 Tracer Gas Injection Equipment

Equipment and methods to inject tracer gas must meet the following criteria.

5.3.1 In tracer gas step-ups, the tracer gas injection rate must be stable; however, an accurate measurement of the absolute value of the tracer injection rate is not required. To confirm that the injection rate is sufficiently stable, the injection rate shall be measured and recorded at least every thirty minutes during the measurement of air-change effectiveness using an instrument with a resolution less than or equal to 2% of the average injection rate. During the measurement of air-change effectiveness, the standard deviation of the measured injection rates divided by the average must be less than 0.05.

5.3.2 Leakage of tracer gas from the injection system when the outlet of the system is capped at the actual point of injection must be nondetectable based on measurements of tracer gas in all rooms containing the tracer injection apparatus. There must be no leakage of air into the injection system at any point between the source of tracer gas and the location of the instrument used to measure injection rate. The leakage test shall be performed whenever components of the injection system are changed or any components of the system are disconnected and reconnected.

5.4 Tracer Gas Sampling Equipment

5.4.1 Sample System. Samples of air containing tracer gas may be drawn to a tracer gas analyzer or pumped into a sample storage bag through a sampling system that may include sample tubing, tube fittings, valves, and pumps. The sampling system shall be checked for leakage, and negligible leakage shall be demonstrated. A recommended procedure for this leakage test is provided in Appendix H.

5.4.1.1 Tracer Losses in Tubing. Negligible loss of tracer gas from the sample stream as it passes through the tubing shall be demonstrated using the following procedure:

(a) Samples of a calibration gas shall be directed into the tracer gas analyzer through metal tubing of the minimum practical length. Ten sequential measurements of tracer gas concentration shall be completed.

(b) The same calibration gas shall be directed into tracer gas analyzer through the type of tubing that will be used in the measurement of air-change effectiveness with a tubing length greater than or equal to the maximum anticipated length of sample tubing. Ten sequential measurements of tracer gas concentration shall be completed.

(c) The average of the ten measurements of tracer gas concentration determined in steps (a) and (b) must be equal within ±5%.

5.4.1.2 Sample Tube Purging and Tracer Gains in Tubing. Sample tubes shall be adequately purged of the prior sample. Also, negligible gain of tracer gas as samples pass through sample tubing must be demonstrated. This gain can occur due to desorption of tracer gas from tubing previously exposed to a higher tracer gas concentration. The procedure for demonstrating adequate sample tube purging and negligible gain of tracer gas is as follows:

(a) A calibration gas with the maximum tracer gas concentration shall be drawn through the type of tubing that will be used in the measurement of air-change effectiveness with a tubing length greater than or equal to the maximum anticipated length of sample tubing. The rate of flow shall be representative of the rate of sample flow in measurements of air-change effectiveness and shall be maintained for a period of 10 minutes or more.

(b) Immediately after stopping the flow described in (a), tracer-free air shall be drawn through the tubing at the same airflow rate. The flow of tracer-free air shall be continued for a time equal to the minimum time between sample analyses, then a sample from the outlet of the tube shall be directed into the tracer gas analyzer and the sample shall be analyzed. The concentration of tracer gas in this sample must be less than 3% of the concentration in the calibration gas. If this criterion is not met, the investigators shall change the sample flow rate, time interval between sample analyses, or the type and length of tubing such that the criterion is satisfied.

5.4.1.3 Test Frequency. The tests described in Sections 5.4.1.1 and 5.4.1.2 are required before the first measurement of air-change effectiveness is taken and thereafter only when the types of materials in the sampling system are changed, the sample flow rate is decreased by more than 10%, or the length of sample tubing is increased by more than 10%.

5.4.2 Grab Sampling. A grab sample is a sample collected from a single location during a period of 30 seconds or less. Grab samples of air containing tracer gas may be collected in containers and analyzed after some period of storage. For example, a sample may be manually drawn into a disposable or reusable syringe that is sealed with an airtight cap immediately after collecting the sample.

5.4.2.1 Negligible loss of tracer gas during storage in the grab-sample containers and acceptable measurement precision must be demonstrated and documented using the following procedures.

(a) Ten grab samples shall be withdrawn from a stream of calibration gas.

(b) The containers shall be capped and stored for at least six hours or the maximum anticipated storage period, whichever is greater.

(c) The samples shall be introduced into the tracer gas analyzer using the same method employed in measurements of air-change effectiveness.

(d) The same calibration gas shall be directed into the tracer gas analyzer through the minimum practical length of metal tubing.

(e) The response of the analyzer to the calibration gas stream must equal the average response to the ten grab samples within ±5%.

(f) The standard deviation of the analyzer's response to the ten grab samples divided by the average response must be less than 5%.

(g) This procedure shall be repeated whenever the type of tracer gas, grab-sampling equipment, grab-sampling procedure, or method of introducing samples into the tracer gas analyzer is changed.

(h) If grab samples will be transported via airplane, where leakage is possible due to the reduced pressure, the sample storage test described in this subsection shall include a period of transportation of samples in an airplane.

5.4.2.2 If grab-sample containers are to be reused, negligible transfer of tracer gas from prior samples to new samples must be demonstrated using the following procedure:

(a) Ten grab samples of a calibration gas shall be collected and stored for at least six hours.

(b) The samples shall be ejected from the grab-sample container and the containers purged with tracer-free air (e.g., outdoor air) five times.

(c) Samples of tracer-free air shall be stored in the containers for at least six hours.

(d) The concentration of tracer gas in each container shall be analyzed and must be less than 2% of the concentration of calibration gas used for this test.

(e) This procedure shall be repeated whenever the type of tracer gas, type of container, or method of introducing samples into the tracer gas analyzer is changed.

5.4.3 Time-Integrated Sampling with Sample Bags. Samples can be drawn at a constant rate for the duration of a tracer decay or step-up and stored in sample bags. Subsequent analyses of these samples yields the time-averaged tracer gas concentration during the period of sampling. For accurate time-integrated sampling in bags, the sample flow rate must be constant, losses of tracer gas due to sorption on bags or leakage must be negligible, and the transfer of tracer gas from prior samples to new samples must be negligible. The following tests are required to verify the performance of bag sampling apparatus and procedures.

5.4.3.1 Before the first measurement and at least once in every ten measurements of air-change effectiveness, the flow rate through each equipment system used for time-integrated bag sampling shall be monitored every 30 minutes during a continuous period of six hours. The standard deviation of the measured flow rates divided by the average must be less than 5%.

5.4.3.2 Before each measurement of air-change effectiveness, bags shall be checked for leakage by filling the bag with air, immersing the bag in water, and inspecting for air bubbles that indicate leakage. A bag that leaks during this test must not be used for subsequent measurements of air-change effectiveness.

5.4.3.3 The test procedures described in Sections 5.4.2.1 and 5.4.2.2 for grab sampling shall be performed for time-integrated sampling in sample bags. For this test, the introduction of calibration gas into the sample bags may be completed at any rate.

5.4.4 Representative Sampling from Airstreams

5.4.4.1 General Requirements. Air samples withdrawn from airstreams must have a tracer gas concentration representative of the average concentration at the same cross section of the airstream. An exact determination of the average concentration would require measurements of concentration and air velocity at every point in the cross section, which is not possible. To demonstrate that the samples withdrawn from each airstream are reasonably representative, the following test must be performed using the airstreams that supply air to, or remove air from, the test space. The representativeness of samples withdrawn from each location shall be confirmed through performance of this test. To the degree practical, airflow rates and temperatures shall be identical to those during the measurement of air-change effectiveness.

5.4.4.2 Procedure and Criteria. The following procedure shall be used to ensure that samples withdrawn from airstreams are sufficiently representative.

(a) The concentration of tracer gas in the samples withdrawn from each airstream using the same equipment and methods employed during measurements of air-change effectiveness shall be determined.

(b) At least six grab samples shall be withdrawn within one minute of the sample collection in step (a) from a cross section of the same airstream. Each of the six or more locations in the cross section shall be at the center of an approximately equal but different area of the cross section.

(c) The average concentration of tracer gas in the six or more grab samples must be within ±5% of the concentration of tracer gas in the sample described in step (a).

5.4.5 Sample Pumps. Sample pumps used to direct samples into gas sample bags or located upstream of a tracer gas analyzer shall be gas tight so that air at the location of the pump does not leak into the sample.

5.5 Temperature Measurements

Instrumentation used for temperature measurements shall have a resolution of 1°F (0.6°C) or better and must be calibrated by comparison to an instrument with a resolution of 0.5°F (0.3°C) or better that is traceable to the National Institute of Standards and Technology (NIST).

5.6 Measurement of Airflow Rates

5.6.1 The measurements of airflow rate required in Section 5.7 shall be made using one of the following options:

(a) Instruments and procedures described in ANSI/ ASHRAE Standard 41.7-1984 (RA 2000).[2] However, the specifications in ASHRAE Standard 41.7 for differential pressure measurement (i.e., a minimum pressure difference of 5 in. water (1250 Pa) measured with a mercury manometer) are relaxed. The differential pressure must be measured with sufficient accuracy to determine airflow rate with an accuracy of ±4% or better.

(b) A dry test meter with a rated accuracy of ±4% or better.

(c) A bubble flow meter with a rated accuracy of ±4% or better.

5.6.2 Except as required in Section 5.6.1, airflow rates can be measured using any instrumentation and procedure that result in a maximum uncertainty of ±10%. ANSI/ASHRAE Standard 111-1988[3] provides guidance on procedures for measuring airflow rates in ducts and contains information on measurement accuracy.

5.7 Verification of the Accuracy of the Tracer Gas Measurement via Tests in a Well-Mixed Chamber

The precision and accuracy of the measurement system and procedures shall be evaluated by a tracer gas measurement in a well-mixed test chamber under controlled conditions at the following times:

(a) prior to conducting measurements for the first time,

(b) before using a new tracer gas analyzer or equipment or method of obtaining samples for analysis, and

(c) at least once in every two-year period.

The test chamber shall be of a size and configuration (e.g., small and with a single compartment) to aid mixing of the indoor air. Very small chambers, e.g., a few cubic meters in volume, are acceptable. The rate at which air samples are withdrawn from the chamber must not exceed 0.01 chamber volumes per hour. The chamber shall be ventilated with tracer-free air at a stable rate between 0.75 and 1.25 chamber volumes per hour. The air within the chamber shall be mixed with fans as needed to ensure uniformity of mixing of the indoor air.

The same measurement method, tracer gas decay or tracer gas step-up, that will be used to measure air-change effectiveness shall be selected and implemented using the test chamber. The measurement shall be performed according to the procedures outlined in Section 6 except tracer gas concentration shall be measured within the chamber at eight locations, each at the approximate center of an equal volume of air. Each air volume shall be distinct from other volumes and contain approximately one eighth of the indoor air. Tracer concentration shall also be measured in the exhaust airstream. All ages of air within the chamber must be equal to the age of air in the exhaust airstream, within ±10%.

6. PROCEDURES FOR MEASURING AIR-CHANGE EFFECTIVENESS

6.1 Selection of Either a Tracer Gas Decay or a Tracer Gas Step-Up

Based on a review of the requirements for a tracer gas decay and a tracer gas step-up and consideration of available measurement equipment and the nature of the test space and associated HVAC systems, either a tracer gas decay or a tracer gas step-up is selected as the procedure for measuring air-change effectiveness (see Appendix F).

6.2 Measurement of Supply and Return Airflow Rates

With operating conditions identical, to the degree practical, to those during the air-change effectiveness measurement, the rates of air supply to the test space and return and exhaust from the test space shall be measured. To the degree possible, the measurement locations shall be selected to reflect the airflow into and out of the test space and not the rates of flow to or from the outdoors, which may be different due to leakage in ducts. The ratio of total supply flow rate to the total return plus exhaust flow rate must be within 0.10 of unity. If this criterion is not met, the rate of air leakage into or out of the test space is considered excessive and the test space does not meet the criteria of this standard.

6.3 Measurement of Exhaust Airflow Rates

If the test space has multiple exhaust airstreams, the flow rate of each exhaust airstream shall be measured.

6.4 Test of Infiltration and Air Exchange with Adjoining Spaces

This section describes measurements that must be completed to determine if the test space has limited air infiltration and limited air exchange with adjoining indoor spaces. If the requirements listed in this section are not met, the test space is not acceptable according to the criteria of this standard.

If a tracer gas decay is selected for measurement of air-change effectiveness, a special tracer step-up test called the

"Test of Infiltration and Air Exchange with Adjoining Spaces" is required based on the procedures in Sections 6.4.1 through 6.4.8. If a tracer gas step-up is selected for measurement of air-change effectiveness, the measurements required in Sections 6.4.1 through 6.4.8 may be completed in a special tracer step-up test or during the measurement of air-change effectiveness. The tests of infiltration and air exchange with adjoining spaces shall be performed

(a) before the first measurement of air-change effectiveness,

(b) whenever the size of any openings in the envelope of the test space are increased, or

(c) whenever, in the judgment of the personnel performing the measurement, the indoor pressure in the test space or pressure in surrounding rooms or weather changes sufficiently to significantly affect air infiltration and interzonal air exchange.

6.4.1 The internal loads, furnishings, ventilation equipment, and operating conditions during this test must be identical, to the degree practical, to the conditions during the tracer decay measurement of air-change effectiveness. Identical set points must be used for the fans and dampers that control rates of airflow supplied to the test space and removed from the test space. The set point for the supply air temperature must also be identical to the conditions during the tracer decay measurement of air-change effectiveness. Small differences in loads, e.g., due to changes in weather or to normal changes in occupants use of equipment in a space with many occupants, are unavoidable and considered acceptable. Minor differences in furnishings (e.g., the position of chairs or the location of one out of many desks or partitions) are also permissible.

6.4.2 Tracer gas measurements are required in each exhaust airstream of the test space with a flow rate exceeding 10% of the total exhaust airflow rate. Sufficient measurements are required to characterize the tracer gas concentration in at least 85% of the air exhausted from the test space. Measurements are also required in the supply airstreams of the test space and from one breathing-level location within each adjoining space with a volume greater than 2% of the volume of the test space. If an adjoining space has no supply and exhaust airstreams, tracer gas measurements are required from one centrally located point in the space. Measurements in the exhaust airstream of the test space must be in real time with an approximately constant interval and a frequency of at least five measurements during each nominal time constant. At other measurement locations, only the final tracer gas concentration must be measured.

6.4.3 The equipment for tracer gas measurements shall be installed as required.

6.4.4 Real-time measurement of tracer gas concentration in the exhaust airstreams shall be initiated. After one or more measurements are complete in each exhaust airstream, start the injection of tracer gas into the outdoor air supply airstream at a constant rate. Appendix G provides guidance on selection of tracer gas injection rates.

6.4.5 Tracer gas injection shall be continued until tracer gas concentrations in all exhaust airstreams have increased by less than 8% during the previous hour. Samples shall then be collected or measurements completed at other required measurement locations.

6.4.6 If samples were collected for subsequent analyses of tracer gas concentrations, analyze all samples using the tracer gas analyzer.

6.4.7 Calculate the ratio of each final exhaust-air tracer gas concentration to the final supply-air tracer gas concentration. These ratios must be within 0.10 of unity. Ratios less than unity indicate air infiltration, airflow into the test space from adjoining spaces, or measurement errors.

6.4.8 Calculate the ratio of each final tracer gas concentration in adjoining rooms to the final supply-air tracer gas concentration. These ratios must be less than 0.10.

6.5 Determination of the Tracer Gas Measurement Locations for the Measurement of Air-Change Effectiveness

6.5.1 Measurements are required at a typical breathing level of occupants in the test space at 25% of workstations but not at less than ten workstations nor at less than the total number of workstations if the test space contains fewer than ten. If the space is predominantly occupied by seated adults, a height of 42 in. (1.1 m) above the floor shall be used as the breathing level. If the space is predominantly occupied by standing adults, a height of 66 in. (1.7 m) above the floor shall be used as the breathing level. If the space is occupied by children, the appropriate breathing level shall be selected by the person measuring air-change effectiveness. To the degree practical, these measurement locations shall be spaced evenly per unit floor area throughout the test space. Because a selection of measurement locations that are predominantly near either supply outlets or return grilles may cause a measurement bias, the breathing-level measurement locations shall be selected without consideration of the positions of supply outlets and return grilles.

6.5.2 Measurements are required in all exhaust airstreams with a flow rate exceeding 10% of the total exhaust airflow rate, and sufficient measurements are required to characterize the tracer gas concentration in at least 85% of the air exhausted from the test space. Any location in the exhaust airstream may be selected subject to the requirements of Section 5.4.4.

6.5.3 If air from a single outdoor airstream is supplied to the test space, a measurement of tracer gas concentration in the outdoor airstream is not required even when the tracer gas step-up method is used. If air from multiple outdoor airstreams is supplied to the test space, the concentration of tracer gas in each outdoor airstream must be measured in order to confirm that each airstream has the same tracer gas concentration within 15% (i.e., the maximum difference between any two concentrations is 15%). Consequently, with multiple outdoor airstreams, the HVAC systems must have outdoor air ducts or apparatus such that the tracer gas and outdoor air mix thoroughly before the outdoor airstreams mix with recirculated air or divide into more than one airstream.

6.6 Selection of the Tracer Gas Sampling and Measurement Methods and Frequencies

6.6.1 In each exhaust airstream, tracer gas concentration shall be measured in real time (i.e., during the test) at a fixed time interval of no more than one-fifth the nominal time constant.

6.6.2 In the occupied zone, tracer gas concentration shall be measured in one or more of the following ways. At breathing-level locations, tracer gas concentration may be measured in real time at the same minimum frequency required for exhaust airstreams, or grab samples may be collected at the same locations and times and analyzed subsequently, or a time-integrated sample (e.g., bag sample) may be collected continuously and at a constant rate during the test for subsequent analysis and determination of the time-averaged tracer gas concentration at the measurement location. Where time-integrated samples are collected and a tracer gas decay is employed, the tracer gas concentration at the start of the decay must also be measured. (The same measurement can be used to verify the initial mixing of tracer gas within the test space.) Where time-integrated samples are collected and a tracer gas step-up is employed, the tracer gas concentration at the end of the step-up, as defined in Section 6.11.4, must also be measured.

6.6.3 When measurements of tracer gas concentration in outdoor airstreams are required, tracer gas concentration may be measured in real time at the same frequency required for exhaust airstreams or grab samples may be collected at the same locations and times and analyzed subsequently.

6.7 Air Temperature Measurements

To determine compliance with Section 4.3, air temperature must be measured during the measurement of air-change effectiveness in the center of a cross section of the supply airstream(s) and in the center of a cross section of all exhaust airstreams at a fixed interval at least five times per each nominal time constant.

6.8 Maintaining Constant Internal Heat Generation

The operation of internal sources of heat and air motion and the number of occupants in the test space shall be documented during the test to determine if the requirements in Section 4.3 are met. As an alternative to documenting the use of heat-producing equipment and fans, prior to the test the occupants can be instructed not to turn heat-producing equipment or fans on or off during the test.

6.9 Overriding HVAC Controls

During the measurement of air-change effectiveness, fan and damper controls must be overridden so that damper positions and fan speeds are constant during the test.

6.10 Tracer Gas Decay Procedure

6.10.1 Install the instrumentation for sampling and measurement of tracer gas concentration and air temperatures at the required locations. Install tracer gas injection equipment.

6.10.2 Use any method to label the indoor air uniformly with tracer gas. Two common methods are

(a) to rapidly inject a volume of tracer into the supply or return air or indoor air while the outdoor air supply is temporarily stopped, and

(b) to inject tracer gas at a constant rate into a supply airstream without stopping the supply of outdoor air.

Unless a continuous injection process as described in (b) is used, the supply of outdoor air must be temporarily stopped; otherwise tracer concentrations will never stabilize and the initial tracer gas concentration cannot be determined. Fans may be operated within the test space to facilitate the initial mixing of tracer gas. When the process described in (a) is used, unstable air temperatures at the time the supply of outdoor air is started may lead to an invalid test based on the criteria in Section 4.3. Collect and analyze samples from the required measurement locations at breathing level and in exhaust airstreams. The standard deviation divided by the mean of the measured concentrations must be less than 10%, and the ratio of the maximum to minimum concentration must be less than 1.2.

6.10.3 Initiate the real-time measurement of tracer gas concentration in exhaust airstreams. After one measurement is complete in each exhaust airstream, start the supply of outdoor air if it has been stopped or terminate the injection of tracer gas and record the time. Turn off any fans used to facilitate initial mixing of tracer gas and indoor air. Simultaneously, initiate the required sampling of tracer gas concentration at breathing-level locations.

6.10.4 Continue sampling of tracer gas until the tracer gas concentrations in all exhaust airstreams have decreased by 95%, which will have occurred when approximately three nominal time constants have elapsed. Record the time. This time is referred to as the end of the tracer gas decay.

Continuing the tracer gas decay until concentrations in all exhaust airstreams have decreased by 95% is generally sufficient to prevent significant errors in measurement of air-change effectiveness but can result in significant errors (e.g., 15%) in the ages of air computed using Equation 1. When more accurate measurements of age of air are desired, measurements should be continued until tracer concentrations have decreased by 97% or the calculation procedure described in Appendix C should be used.

6.10.5 If samples were collected for subsequent analyses of tracer gas concentrations, analyze all samples using the tracer gas analyzer.

6.11 Tracer Gas Step-Up Procedure

6.11.1 Install instrumentation for sampling and measurement of tracer gas concentration and air temperatures at the required locations.

6.11.2 Install tracer gas injection equipment. Tracer gas must be injected into each stream of outdoor air that is supplied to the test space. With multiple outdoor airstreams, tracer gas injection rates must be adjusted so that each outdoor airstream has the same tracer gas concentration within 15%. In a tracer gas step-up, the air and tracer gas must mix thoroughly between the location of tracer gas injection in the outdoor air and the downstream location in the outdoor air or supply air where the concentration of tracer gas in the airstream is measured or at a downstream location where the airstream divides into two or more airstreams. To check for tracer mixing, air samples shall be withdrawn from at least six locations in the appropriate cross section of the airstream. If this airstream contains recirculated indoor air, the samples shall be collected within ten minutes of the start of tracer gas injection. Collection of samples during the minimum practical time period is recommended. Each location shall be at approximately the center of an equal area of the cross section. The subsequent analyses of these air samples must confirm that each sample has a tracer gas concentration within ±15% of the average concentration. This check of tracer gas mixing can be completed at any time; however, the tracer injection location, rate, and equipment and the airstream flow rate and temperature must be identical, within practical limit, to those during the measurement of air-change effectiveness.

6.11.3 Initiate the real-time measurement of tracer gas concentration in exhaust airstreams. After at least one measurement is complete in each exhaust airstream, start the injection of tracer gas into the outdoor airstream and record the time. Simultaneously, initiate the required sampling of tracer gas concentration at breathing-level locations. The concentration of tracer gas measured in the exhaust airstream prior to the start of tracer gas injection must be less than 10% of the tracer gas concentration at the end of the tracer gas step-up as described in Section 6.11.4.

6.11.4 Continue sampling of tracer gas until the tracer gas concentrations in all exhaust airstreams have increased no more than 8% during the previous hour, which will have occurred when approximately three nominal time constants have elapsed. Then, at each location where a time-integrated sample is collected, collect a grab sample or measure the final concentration and record the time.

Continuing the measurements until tracer gas concentrations in all exhaust airstreams have increased by less than 8% during the previous hour is generally sufficient to prevent significant errors in measurement of air-change effectiveness but can result in significant (e.g., 15%) errors in the ages of air computed using Equation 2. When more accurate measurements of age of air are desired, measurements should be continued until tracer concentrations have stabilized within the precision of the measurement system or the calculation procedure described in Appendix C should be used.

6.11.5 Stop the injection of tracer gas.

7. CALCULATIONS

7.1 Age of Air From a Tracer Gas Decay

The age of air from a tracer gas decay is calculated from Equation 1:

$$A_i = (t_{stop} - t_{start}) C_{i,avg} / C_i(t_{start}) \qquad (1)$$

where

A_i = the age of air at location i

t_{stop} = the time of the final tracer gas measurement at location i during the tracer gas decay or, with time-integrated sampling at location i, the time when sampling is terminated

t_{start} = the time when outdoor airflow is started or tracer injection is stopped at the beginning of a tracer gas decay

$C_{i,avg}$ = the time-averaged tracer gas concentration at location i between time t_{start} and t_{stop}

$C_i\,(t_{start})$ = the tracer gas concentration at location i at time t_{start}

The parameter $C_{i,avg}$ is the concentration in the sample bag when time-integrated bag sampling is employed. This parameter, $C_{i,avg}$ equals the arithmetic average of the measured tracer gas concentrations at location i when concentration is measured at approximately equally spaced intervals of time. Appendix D provides a recommended equation for computing $C_{i,avg}$ from a series of concentration measurements with uneven time intervals.

7.2 Age of Air from a Tracer Gas Step-Up

The age of air at location i from a tracer gas step-up measurement is calculated from Equation 2:

$$A_i = (t_{end} - t_{start})\{1 - [C_{i,avg} / C_i(t_{end})]\} \qquad (2)$$

where

t_{end} = the time when the final tracer gas concentration is measured at location i during the tracer gas step-up or, with time-integrated sampling at location i, the time when sampling is terminated

t_{start} = the time when tracer gas injection starts at the beginning of the tracer gas step-up

$C_i(t_{end})$ = the tracer concentration at location i and time t_{end}

7.3 Nominal Time Constant

The nominal time constant is calculated using Equation 3:

$$\tau_n = \frac{\sum_m (Q_{ex,m} A_{ex,m})}{\sum_m Q_{ex,m}} \qquad (3)$$

where

τ_n = the nominal time constant

m = an identification number unique for each exhaust airstream

$Q_{ex,m}$ = the rate of airflow in exhaust airstream m

$A_{ex,m}$ = the age of air in exhaust airstream m

The symbol $\sum_m$ indicates a summation for all m exhaust airstreams.

7.4 Air-Change Effectiveness

The air-change effectiveness is calculated from Equation 4:

$$E = \tau_n / A_{avg} \qquad (4)$$

where

E = the air-change effectiveness

A_{avg} = the arithmetic average of the ages of air measured at breathing level within the test space

8. REPORTING OF INFORMATION ON TEST SPACE AND HVAC SYSTEM

Features of the test space, HVAC system, and operating conditions influence the air-change effectiveness and should be included with reports of measurements of air-change effectiveness.

8.1 Inclusion of the following information with reports of the measurement of air-change effectiveness is required:

(a) the nominal time constant or its reciprocal—the nominal air-change rate,

(b) the total supply airflow rate,

(c) the flow rate of each exhaust airstream,

(d) the flow rate through each supply diffuser,

(e) the flow rate through each return grille,

(f) the percentage of outdoor air in the supply air,

(g) the history of supply and return air temperatures during the measurement, and

(h) the height above the floor of the breathing-level measurements of age of air.

8.2 Inclusion of the following information with reports of the measurement of air-change effectiveness is recommended:

(a) a floor plan with dimensions and measurement locations indicated on the plan,

(b) a diagram of the HVAC system with measurement locations indicated on the diagram,

(c) a description of internal loads,

(d) a description of supply diffuser types and locations,

(e) a description of return outlet types and locations,

(f) a record of the position of doors (open or closed) within the test space during the measurement of air-change effectiveness, and

(g) the rate of airflow through fans operating within the test space, e.g., desktop fans.

It is beyond the scope of this standard to describe the methods for determining each of these parameters. Substantial guidance is provided in the documents listed in Section 9 and Appendix A.

9. REFERENCES

1. ASTM Standard E741-95*, Standard Test Methods for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution*, American Society for Testing and Materials, Philadelphia, PA.
2. ANSI/ASHRAE Standard 41.7-1984 (RA 2000)*, Method of Test for Measurement of Flow of Gas*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.
3. ANSI/ASHRAE Standard 111-1988*, Practices for Measurement, Testing, Adjusting and Balancing of Building Heating, Ventilation, Air-Conditioning and Refrigeration Systems*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

(This appendix is not part of this standard but is provided for information only.)

Appendix A—Bibliography

Bauman, F.S., D. Faulkner, E.A. Arens, W.J. Fisk, L.P. Johnston, P.J. McNeel, D. Pih, and H. Zhang. 1991. Air movement, comfort, and ventilation in workstations. Lawrence Berkeley Laboratory Report, LBL-30574, Berkeley, CA.

Fisk, W.J., J. Binenboym, H. Kaboli, D. Grimsrud, A.W. Robb, and B. Weber. 1985. A multi-tracer system for measuring ventilation rates and ventilation efficiencies in large mechanically ventilated buildings. Supplement to the *Proceedings of the 6th AIVC Conference, Ventilation Strategies and Measurement Techniques*, pp. 69-92. Air Infiltration and Ventilation Centre, Coventry, Great Britain.

Fisk, W.J., D. Faulkner, and R.J. Prill. 1991. Air exchange effectiveness of conventional and task ventilation for offices. In *IAQ '91, Healthy Buildings*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA.

Fisk, W.J., R.J. Prill, and O. Seppanen. 1988. Commercial building ventilation measurements using multiple tracer gases. *Proceedings of the 9th AIVC Conference, Effective Ventilation*, vol. 1, pp. 161-182. Air Infiltration and Ventilation Centre, Coventry, Great Britain.

Fisk, W.J., R.J. Prill, and O. Seppanen. 1989. A multi-tracer technique for studying rates of ventilation, air distribution patterns, and air exchange efficiencies. *Building Systems: Room Air and Air Contaminant Distribution*, pp. 237-240. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

Offermann, F.J. 1988. Ventilation effectiveness and ADPI measurements of a forced-air heating system. *ASHRAE Transactions*, Vol. 94, Part 1, pp. 694-704. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

Persily, A.K., and R.A. Grot. 1985. Ventilation measurements in large office buildings. *ASHRAE Transactions*, Vol. 91, Part 2a., pp. 488-502. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

Persily, A.K. 1986. Ventilation effectiveness measurements in an office building. *IAQ '86, Managing Indoor Air for Health and Energy Conservation*, pp. 548-567. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

Persily, A.K., and W.S. Dols. 1989. Field measurements of ventilation and ventilation effectiveness in an office/library building. *Indoor Air* 1, pp. 229-246.

Persily, A.K., W.S. Dols, and S.J. Nabinger. 1994. Air change effectiveness measurements in two office buildings. *Indoor Air* 4, pp. 40-55.

Sandberg, M., C. Blomquist, and M. Sjoberg. 1982. Warm air systems, part 2: Tracer gas measurements and ventilation efficiencies. Bulletin M82:23. Swedish Institute for Building Research, Gavle, Sweden.

Sandberg, M., and M. Sjoberg. 1983. The use of moments for assessing air quality in ventilated rooms. *Building and Environment*, Vol. 18, pp. 181-197.

Seppanen, O. 1986. Ventilation efficiency in practice. *IAQ '86, Managing Indoor Air for Health and Energy Conservation*, pp. 559-567. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

(This appendix is not part of this standard but is provided for information only.)

Appendix B—Relationship of Air-Change Effectiveness to Design Ventilation Rates in ANSI/ASHRAE Standard 62-2001

This appendix discusses how the values of air-change effectiveness determined with this test method can be used with the Design Ventilation Rates from *ANSI/ASHRAE Standard 62-2001, Ventilation for Acceptable Indoor Air Quality.*

Standard 62-2001 describes the determination of the Design Ventilation Rate (DVR62) for a ventilated space based on the space type and occupancy and an analysis of contaminant sources. The DVR62 is the minimum recommended amount of outdoor air that must be delivered to the occupied portion of a space in order to comply with the ventilation requirements of Standard 62-2001. The calculation of DVR62 is based on the assumption that the indoor air is well mixed. Indoor airflow patterns that are distinct from perfect mixing within the ventilated space may result in a difference between the effective outdoor air delivery rate to the occupied space and the DVR62 of the space. If such a difference exists, then the value of DVR62 for a space should be corrected to account for other mixing conditions. The corrected value, referred to as CDVR, is the outdoor airflow rate that should be supplied to the space and used in the ventilation system design.

The air-change effectiveness, E, determined with this standard can be used to relate CDVR and DVR62 according to

$$\text{CDVR} = \text{DVR62}/\text{E}$$

In other words, if a design ventilation rate of DVR62 has been determined for a space using the procedures in Standard 62-2001, the actual outdoor airflow rate CDVR provided to the space by the ventilation system should be equal to DVR62 divided by the air-change effectiveness, E.

If the ventilation air within a space is perfectly mixed, i.e., E = 1, then the outdoor airflow rate to the ventilated space should be identical to the required rate of outdoor airflow DVR62. While perfect mixing is an idealized airflow pattern, it is the objective of induction air diffusers commonly used in mechanically ventilated commercial buildings. If these diffusers are performing properly, then a measurement of E using this standard will yield a value essentially equal to one, and the outdoor airflow rate to the space CDVR should be equal to DVR62.

If for some reason a significant amount of the supply airflow from the diffusers flows directly into the return vents without mixing with the room air, then the effective rate of outdoor airflow to the occupied portion of the space will be less than the total outdoor airflow rate into the space. An air-change effectiveness measurement using this standard will yield a value of E that is significantly less than 1. Under these circumstances, the ventilation process will be less effective in delivering outdoor air to the occupied portion of the space than it would be under conditions of perfect mixing. The outdoor airflow rate provided to the space CDVR should be increased above DVR62 to account for this short-circuiting.

Some ventilation systems are designed so that the ventilation air is delivered within the occupied portion of the space and sweeps through the space to the return vents with little mixing of the ventilation air with the room air. Such systems are more effective in delivering outdoor air to the occupied portion of the space than systems that offer perfect mixing with the same outdoor airflow rate to the space. An air-change effectiveness measurement conducted in accordance with Standard 129 will yield a value of E that is greater than 1. The outdoor airflow rate to the space CDVR can therefore be decreased below the value of DVR62 based on the above equation.

At present, only limited measurements of E are available for mechanical ventilation systems. Ideally, a series of values for air-change effectiveness would be available for different ventilation system types at different supply air and room air temperatures and airflow rates. These would then be used at the system design stage to adjust the DVR62 values for each space to determine the outdoor air delivery rates required for each space. However, values of E for different circumstances will not be available until more experimental work is performed in the laboratory and the field. Given the current lack of values for E, one can adjust the DVR62 for a space by measuring the value of E in a mock-up of the space.

The air-change effectiveness varies with HVAC system operating conditions. The extent of mechanical recirculation (e.g., percent outside air in the supply airstream) and the supply air temperature, when it exceeds the room air temperature, have a particularly strong influence on air-change effectiveness. Additionally, the configuration of the ventilated space and the sources of heat generation and air motion in the ventilated space will influence the air-change effectiveness. Therefore, corrections to the design ventilation rate for a particular HVAC operating condition and ventilated space condition must be based on measured values of air-change effectiveness made in a similar space under the same or very similar operating conditions.

(This appendix is not part of this standard but is provided for information only.)

Appendix C—Exact Equations for Calculating Age of Air from Tracer Gas Concentrations

The test method uses approximate equations to determine the age of air A_i from tracer gas concentrations. These equations result in sufficiently accurate determinations of air-change effectiveness given the restrictions in the test method.

Significant (e.g., 15%) errors in age of air can result from use of these equations. This appendix presents the theoretical equations relating tracer gas concentrations to the age of air for both decay and step-up tests.

Decay

In a decay test, the space being tested is assumed to be at a uniform tracer gas concentration, C_0, at time $t = 0$. The tracer gas concentration in the space then decreases toward the outdoor concentration, assumed to equal zero, at a rate that depends on the air-change rate of the space and the location within the space. The age of air at a point $_i$ in the space is given by Equation C1:

$$A_i = \frac{1}{C_0}\int_0^{\infty} C_i(t)dt \tag{C1}$$

Equation C2 is presented in the standard to calculate A_i for a decay test:

$$A_i = (t_{stop} - t_{start})C_{i,avg}/C_i(t_{start}) \tag{C2}$$

This equation is essentially the same as Equation C1, except that the integral is terminated at t_{stop} instead of being evaluated through to infinity. The errors associated with a finite period of integration are lessened by determining $C_{i,avg}$ over a period of about three nominal time constants. Equation C2 can be corrected to account for the early termination of the integral by adding the following term:

$$C_i(t_{stop})/LC_i(t_{start}) \tag{C3}$$

where L is the negative of the slope of the natural logarithm of the concentration as a function of time calculated at the end of the concentration decay. In practice, this slope can be determined based on the concentration data over the last time constant prior to t_{stop}. The equation for the corrected age of air, $A_{i,corr}$, is, therefore,

$$\begin{aligned} A_{i,corr} = {} & (t_{stop} - t_{start})C_{i,avg}/C_i(t_{start}) + \\ & C_i(t_{stop})/LC_i(t_{start}) \end{aligned} \tag{C4}$$

Step-Up

In a step-up measurement, the tracer gas concentration throughout the space being tested is assumed to equal zero at time $t = 0$. At that time, tracer gas is injected into the outdoor air being delivered to the space at a constant rate. The tracer gas concentration in the space increases to an equilibrium value C at a rate that depends on the air-change rate of the space and the location within the space. The local age of air at a point $_i$ in the space is given by Equation C5:

$$A_i = \int_0^{\infty} \left(1 - \frac{C_i(t)}{C_\infty(t)}\right)dt \tag{C5}$$

Equation C6 is presented in the standard to calculate A_i for a step-up test:

$$A_i = (t_{end} - t_{start})\ \{1 - [C_{i,avg}/C_i(t_{end})]\} \tag{C6}$$

As discussed for the decay test, this equation is essentially the same as Equation C5, except that the integral is terminated at t_{stop} instead of being evaluated through to infinity. The errors associated with a finite period of integration are lessened by determining $C_{i,avg}$ over a period of about three nominal time constants. If the concentration of tracer gas in the incoming outside air, C_{eq}, is known, Equation C6 can be corrected to account for the early termination of the integral by adding the following term:

$$[C_{eq} - C_i(t_{end})]/L'C_{eq} \tag{C7}$$

where L' is the negative of the slope of the natural logarithm of the concentration difference ($C_{eq} - C_i(t)$) as a function of time calculated at the end of the concentration step-up. In practice, this slope can be determined based on the concentration data over the last time constant prior to t_{end}. C_{eq} is identical to the tracer gas concentration in the outdoor air (C_{oa}) downstream of the tracer gas injection location. The equation for the corrected age of air $A_{i,corr}$ is, therefore,

$$\begin{aligned} A_{i,corr} = {} & (t_{end} - t_{inj})\{1 - [C_{i,avg}/C_i(t_{end})]\} + \\ & [C_{eq} - C_i(t_{end})]/L'C_{eq}. \end{aligned} \tag{C8}$$

(This appendix is not part of this standard but is provided for information only.)

Appendix D—Determination of Average Tracer Gas Concentration from a Series of Concentration Measurements with Uneven Time Intervals Between Measurements

An accurate value of the time-average tracer gas concentration, $C_{i,avg}$, is required to calculate the age of air with Equations 1 and 2. When $C_{i,avg}$ is determined from a series of concentration measurements with uneven time intervals, Equation D1 is recommended:

$$C_{i,avg} = \frac{\sum_{n=first}^{n=last-1}\left[\frac{C_{i,n} + C_{i,n+1}}{2}(t_{n+1} - t_n)\right]}{(t_{last} - t_{first})} \tag{D1}$$

where C is a tracer gas concentration, t is a time, subscript $_i$ refers to a specific location, subscript n refers to an individual measurement in the time series of measurements, last refers to the final measurement in the time series, and first refers to the first measurement in the time series.

(This appendix is not part of this standard but is provided for information only.)

Appendix E—Measurement Uncertainty

A large number of factors can cause errors in measurements of air-change effectiveness. Assuming that the measurement procedures and quality-control checks described in this standard are followed, an estimate of measurement uncertainty has been developed. This appendix describes the method of estimating uncertainty and reports the uncertainty estimates.

A list of the factors considered most likely to cause significant measurement errors was developed, and either standard propagation of error techniques or example calculations were used to estimate the uncertainty in measured air-change effectiveness associated with each factor. The inputs for these calculations are based on the specifications within the standard and also on professional judgment (e.g., a judgment of the precision of tracer gas analyzers) of those experienced with measurements of air-change effectiveness. The total estimated uncertainty was then computed as the square root of the sum of the squares of the individual uncertainties.

Table E1 lists the factors considered, some of the assumed inputs for the uncertainty estimates, and the estimated uncertainties associated with each factor. Some factors caused unexpectedly small errors in the measurement of air-change effectiveness because the resultant error in the numerator and denominator of the air-change effectiveness parameter largely canceled out. Based on these calculations, the estimated total uncertainty in the measured values of air-change effectiveness is approximately ±16% for both the tracer gas decay measurement procedure and the step-up measurement procedure. This estimate of uncertainty does not account for temporal variations in airflow rates or in internal loads during tests. Temporal variations in flow rates and loads may increase the imprecision of air-change effectiveness measurements, not because of increased measurement errors but due to instabilities in the system subject to the measurements.

The estimated measurement uncertainty of ±16% may be an overestimate of actual measurement uncertainty for many situations. The calculations are based on the maximum allowable tolerances in the measurement standard. In addition, some near-worst-case assumptions were made to simplify the calculations. In general, measurement uncertainty will decrease as the air-change effectiveness becomes closer to unity.

Measurement uncertainties may be reduced by eliminating or decreasing some sources of error. For example, an average error of ±3% (maximum error of 7%) was obtained from 11 measurements of the air-change effectiveness in a research facility containing fans that vigorously mixed the indoor air.[1-5]

REFERENCES FOR APPENDIX E

1. Bauman, F.S., D. Faulkner, E.A. Arens, W.J. Fisk, L.P. Johnston, P.J. McNeel, D. Pih, and H. Zhang. 1991. Air movement, comfort and ventilation in workstations. *ASHRAE Transactions* 98 (1), pp. 756 - 780. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.
2. Faulkner, D., W.J. Fisk, and D.P. Sullivan. 1993. Indoor air flow and pollutant removal in a room with desk-top task ventilation. *ASHRAE Transactions* 99 (2), pp. 750-758. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.
3. Faulkner, D., W.J. Fisk, and D.P. Sullivan. 1995. Indoor airflow and pollutant removal in a room with floor-based task ventilation: Results of additional experiments. *Building and Environment* 30(3): 323-332.
4. Fisk, W.J., D. Faulkner, D. Pih, P.J. McNeel, F.S. Bauman, and E.A. Arens. 1991. Indoor air flow and pollutant removal in a room with task ventilation. *Indoor Air* 1 (3), pp. 247-262.
5. Faulkner, D., and W.J. Fisk. 1994. Unpublished data, Lawrence Berkeley Laboratory, Berkeley, CA.

(This appendix is not part of this standard but is provided for information only.)

Appendix F—Selecting the Tracer Decay or Tracer Step-Up Methods

The selection of either the decay or step-up method should be based on the ability to achieve the conditions required by the respective method. The decay method should be used if it is easier to achieve an initial uniform tracer gas concentration throughout the test space, and the step-up method should be used if it is easier to achieve a uniform and identical tracer gas concentration in the outdoor airstream(s).

In a large test space with many air handlers, it may be difficult to use the step-up method, which requires that the concentration of tracer in each outside airstream be uniform and identical within specified limits. For this type of test space, a uniform initial concentration in the test space may be achieved through controlled tracer gas injections into selected air handlers with the air handlers adjusted for maximum recirculation.

For test spaces that are physically divided into many zones with little recirculation, it may be difficult to use the decay method, which requires a uniform initial tracer gas concentration throughout the entire test space. For this type of test space, the requirements of a tracer gas step-up may be achieved by adjustment of the tracer gas injection rates into each outside airstream as required to obtain identical tracer gas concentration. Multipoint injection of tracer into each outside airstream may be necessary to ensure a uniform concentration in the outside airstream. Passage of the airstream through a fan also facilitates mixing of the tracer in the airstream.

(This appendix is not part of this standard but is provided for information only.)

Appendix G—Estimation of Tracer Gas Injection Rates

This appendix provides guidance on estimating tracer gas injection rates for performing measurements of air-change effectiveness.

When performing a decay test to determine air-change effectiveness, it is required that the space start with a uniform tracer gas concentration at time $t = 0$. Any method that achieves these conditions is acceptable. Two common methods are described in this appendix. The first method is to inject tracer at a constant rate and wait until the concentration is uniform throughout the space. The second method is to release a quantity of tracer gas over a short period of time (relative to the nominal time constant) and wait for this gas to mix throughout the interior of the space. As discussed in the standard, mixing fans can be used in the space in either case to facilitate achieving a uniform concentration.

When performing a step-up measurement of air-change effectiveness, the constant injection method must be used.

Constant-Injection Method

If the constant-injection method is used, one can estimate the required tracer injection rate based on the outdoor air

TABLE E-1
Estimates of Uncertainty Due to a Variety of Factors

Source of Measurement Error	Assumed Condition	Method of Estimating Error	Estimated Error in Measured Air-Change Effectiveness	
			Decay	Step-Up
Uncertain calibration gas concentrations	Random 4% error in calibration gas concentrations	Propagation of error analysis	5.7%	5.7%
Imprecision and bias of analyzer	5% error in tracer gas concentration	Propagation of error analysis	8.5%	8.5%
Exhaust airstream sample doesn't have average exhaust concentration	5% error in exhaust tracer gas concentration	Propagation of error analysis	6%	6%
Loses or gains of tracer in sampling system(s)	5% error in tracer gas concentration	Propagation of error analysis	8.5%	8.5%
Uneven tracer concentration at start of decay	10% difference between initial concentration in two adjacent zones	Example calculations with two-zone model	2.6%	not applicable
Exhaust air age based on a portion of all exhaust air	Concentration not measured in 10% of exhaust flow, age in uncharacterized exhaust is 75% of measured exhaust age	Example calculations	2.5%	2.5%
In step-up, different outside airstreams have different tracer concentration	Two outside airstreams have 15% different tracer concentration	Example calculations with two-zone model	not applicable	1.5%
Air leaks into test space or exhaust air duct from outside	Air leakage rate is 10% of mechanical delivery of outside air	Example calculations with two-zone model	0%	4.4%
Air leaks into test space or exhaust air duct from surrounding indoor space(s)	Air leakage rate is 10% of mechanical delivery of outside air, age identical in test space and leakage air	Example calculations	0 to 9%, Avg. 4.5%	0 to 9%, Avg. 4.5%
Test stopped before time of infinity	Stop after 3 nominal time constants, no estimate of remainder	Example calculations	< 1%	< 1%
Uncertain time at start of decay or step-up	1 minute uncertainty in start time, nominal time constant is 0.25 h, air-change effectiveness ~0.75	Example calculations	1.6%	1.6%
Unstable tracer concentration in outside air	Step change in concentration by 5%, after 2 h in a 4-h step-up, nominal time constant = 1 h, air-change effectiveness ~ 0.75	Example calculations with two-zone mass balance model	not applicable	2.4%
		Estimated Total Uncertainty	**16%**	

ventilation rate of the space being tested and the concentration range of the measurement device. Ideally, the outdoor air ventilation rate of space Q will have been measured previously under the test conditions. If not, then the user must estimate its value. Based on the concentration range of the tracer gas analyzer, the user should select a concentration near the middle of the measurement range, C_{mid}. The tracer injection rate, q, to the space is then given by Equation G1:

$$q = Q \times C_{mid}. \tag{G1}$$

When using these equations, the user must be careful in dealing with the units. The ventilation rate, Q, is generally expressed as a volumetric airflow rate in L/s or cfm. Tracer gas concentrations are usually expressed in parts per million or billion (ppm or ppb) and in some cases in percentage. Tracer gas injection rates are expressed in a variety of units, such as L/min., mL/min., cfm, or scfh (standard cubic feet per hour). Depending on the units employed, the user may have to employ various unit conversions to determine q.

For example, if the outdoor air ventilation rate of the space is 5000 L/s and the target tracer gas concentration is 25 ppb, then the tracer injection rate, q, is calculated as shown below:

$$q = 5000\mathrm{L/s}(25 \times 10^{-9})\frac{6 \times 10^4\mathrm{mL/min}}{1\mathrm{L/s}} = 7.5\mathrm{mL/min} \tag{G2}$$

If the ventilation rate is 10,000 cfm, then the tracer gas concentration is calculated as follows:

$$q = 10000\frac{\mathrm{ft}^3}{\mathrm{min}}(25 \times 10^{-9})\frac{2.832 \times 10^4\mathrm{mL}}{1\mathrm{ft}^3} = 7.08\frac{\mathrm{mL}}{\mathrm{min}} \tag{G3}$$

Inject and Mix Method

In this method, a short-term tracer gas injection is followed by a mixing period. One estimates the injection volume based on the volume of the space being tested and the concentration range of the measurement device. The tracer gas injection volume, v, into a space of volume, V, is then given by Equation G4:

$$v = V \times C_{mid} \tag{G4}$$

When using these equations, the user must again be careful in dealing with the units. The space volume V is generally expressed m^3 or ft^3, and the tracer gas volume is usually expressed in L, mL, or ft^3. Depending on the units employed, the user may have to employ various unit conversions to determine v.

For example, if the space volume is 5000 m^3 and the target tracer gas concentration is 25 ppb, then the tracer injection volume, v, is calculated as shown below.

$$v = 5000\text{m}^3(25 \times 10^{-9})\frac{10^6\text{mL}}{1\text{m}^3} = 125\text{mL} \tag{G5}$$

If the space volume is 100,000 ft^3, then the tracer gas concentration is calculated as shown below.

$$v = 100,000\text{ft}^3(25 \times 10^{-9})\frac{2.832 \times 10^4\text{mL}}{1\text{ft}^3} = 70.8\text{mL} \tag{G6}$$

Given the tracer gas injection volume, one can measure out the volume and inject it all at once. Alternatively, one can inject the tracer gas through a flow meter over some short period of time at a constant rate. In this case, the injection rate will equal the injection volume divided by the length of the injection period. The injection period should be short relative to the nominal time constant of the space and is typically on the order of a few minutes.

(This appendix is not part of this standard but is provided for information only.)

Appendix H—Recommended Procedure for Ensuring Negligible Leakage in Sampling Systems

Leakage of air into sampling systems may lead to significant errors in measurements of tracer gas concentration. The recommended procedure for checking for leakage in sampling systems follows:

Step a) Fill a gas sample bag with a calibration gas. Draw a sample from the sample bag into the calibrated tracer gas analyzer through metal tubing with the minimum practical length and with the minimum practical amount of fittings and valves in the sample path. Analyze the sample ten times to determine the average measured tracer gas concentration. This concentration should equal the known concentration of the calibration gas, within the limits of the analyzer's accuracy.

Step b) After the sampling system is fully assembled, select a time period when the tracer gas concentration in the air surrounding the sampling system is less than 5% of the tracer gas concentration in the sample bag. Connect the sample bag filled with calibration gas to the inlet end of a sample tube. Draw a sample from the bag into the tracer gas analyzer, allowing for sufficient purging of the sampling system. Using the tracer gas analyzer, determine the tracer gas concentration. Repeat the measurement ten times and compute the average measured tracer gas concentration. Within the limits of the analyzer's accuracy, the average concentration should match that measured in step a.

Step c) Repeat Step b for each sample tube.

POLICY STATEMENT DEFINING ASHRAE'S CONCERN FOR THE ENVIRONMENTAL IMPACT OF ITS ACTIVITIES

ASHRAE is concerned with the impact of its members' activities on both the indoor and outdoor environment. ASHRAE's members will strive to minimize any possible deleterious effect on the indoor and outdoor environment of the systems and components in their responsibility while maximizing the beneficial effects these systems provide, consistent with accepted standards and the practical state of the art.

ASHRAE's short-range goal is to ensure that the systems and components within its scope do not impact the indoor and outdoor environment to a greater extent than specified by the standards and guidelines as established by itself and other responsible bodies.

As an ongoing goal, ASHRAE will, through its Standards Committee and extensive technical committee structure, continue to generate up-to-date standards and guidelines where appropriate and adopt, recommend, and promote those new and revised standards developed by other responsible organizations.

Through its *Handbook*, appropriate chapters will contain up-to-date standards and design considerations as the material is systematically revised.

ASHRAE will take the lead with respect to dissemination of environmental information of its primary interest and will seek out and disseminate information from other responsible organizations that is pertinent, as guides to updating standards and guidelines.

The effects of the design and selection of equipment and systems will be considered within the scope of the system's intended use and expected misuse. The disposal of hazardous materials, if any, will also be considered.

ASHRAE's primary concern for environmental impact will be at the site where equipment within ASHRAE's scope operates. However, energy source selection and the possible environmental impact due to the energy source and energy transportation will be considered where possible. Recommendations concerning energy source selection should be made by its members.