**BSR/ASHRAE Standard 145.4P**

**Public Review Draft**

# Method of Test for Assessing the Gas-Phase Performance of Air Cleaning Devices and Systems in a Duct-Chamber Apparatus

**First Public Review (May 2025)**
**(Draft Shows Complete Proposed Standard)**

This draft has been recommended for public review by the responsible project committee. To submit a comment on this proposed standard, go to the ASHRAE website at www.ashrae.org/standards-research--technology/public-review-drafts and access the online comment database. The draft is subject to modification until it is approved for publication by the Board of Directors and ANSI. Until this time, the current edition of the standard (as modified by any published addenda on the ASHRAE website) remains in effect. The current edition of any standard may be purchased from the ASHRAE Online Store at www.ashrae.org/bookstore or by calling 404-636-8400 or 1-800-727-4723 (for orders in the U.S. or Canada).

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## FOREWORD

*This standard defines a method to compare all types of air cleaning devices under the same standardized conditions to provide gas-phase performance to compare devices and be used to make informed decisions. To date, there is no one standard test method that can compare in-room air cleaners and in-duct air cleaners of any technology under the same test method. It should be noted that this standard does not cover residential in-room air cleaners, which are covered under ANSI/AHAM AC-4. In addition, devices designed to vent into a mechanical system or directly outside the room are not included in this standard.*

*This standard measures the performance of air cleaning devices for gas phase challenges within a closed chamber and duct system. The duct is attached to or inside the chamber where air recirculates from the chamber, through the duct, and then back into the chamber throughout the test. The resulting performance is a measure of the air cleaning impact on the chamber gas concentration (the breathing zone) regardless of where the air cleaning device is located.*

*This standard describes a single gas phase challenge test. Gas mixtures are not used due to the potential interactions between gases. The gas performance is measured as a rate of reduction in the chamber (total decay) compared to a natural decay. In addition, potential byproducts are also monitored and reported when measured including ultrafine particles, NOx, aldehydes, and VOCs.*

*Although real world applications and conditions were taken into consideration when developing this standard, the challenge gas concentrations are generally elevated above what may occur in the real world. This higher concentration is to make sure enough data points can be collected during the draw down for the data analysis.*

*The standard defines the chamber and duct test system to allow for flexibility so existing test chambers can be used and different size devices to be tested. With that said, the given test systems specifications and operating conditions will require most air cleaning technologies to test small and/or scaled air cleaning devices. This standard is not designed to test all sizes of air cleaners, especially very large air cleaning systems.*

*All test systems are standardized to have 5-6 air changes through the system. This was chosen as a method to standardize as it is also something that is similar throughout buildings even if the rooms and ducts are different sizes, air handlers have varying configurations, etc., but there is a minimum number of air changes required.*

*This standard is not intended to replace existing standard 145.2 where a single pass efficiency and capacity with a constant challenge gas concentration provides different performance information compared to the single injection draw down test in this standard.*

## 1. PURPOSE

To provide a laboratory test method for evaluating air cleaning devices for challenge gas removal in a combined duct-chamber system with continuous recirculation.

## 2. SCOPE

**2.1** This standard specifies a duct-chamber test method with continuous recirculation through the duct and chamber for measuring the performance of:
a.in-duct air cleaning devices of any size
b. in-room air cleaning devices used in commercial or industrial spaces
**2.2** The test method measures the performance of air cleaning devices for removing challenge gases.

**2.3** This test method is conducted at elevated challenge gas concentrations (relative to ventilation applications) and therefore should be used to compare devices rather than directly predict performance in real world applications. The challenge gas and likely byproducts will be measured over time.
**2.4** Air cleaner performance is defined as the total impact of the air cleaner on the challenge gas in the chamber air and including any gaseous or particulate byproducts.
**2.5** This standard provides performance specifications for the equipment and measurements required to conduct the test method, defines procedures for calculating and reporting results, and provides a results reporting system.
**2.6** This standard does not address the health and safety effects of operating devices and systems in an occupied room.

## 3. DEFINITIONS AND SYMBOLS

### 3.1 Definitions

Key terms are defined below for the purposes of this standard. For definitions not provided here, refer to ASHRAE Terminology [1]. Otherwise, common usage shall apply.

***air changes per hour (ACH):*** number of times during one hour that the air volume in the chamber is replaced by supply air

***air cleaner:*** device used to remove airborne impurities from air

***air cleaner system***: see device under test

***air filter:*** device for separating solid or liquid particles or gaseous contaminants from an air stream passing through the device

***airflow conditions:*** temperature, pressure, and relative humidity of the air in the test duct

***airflow rate:*** volume of air flowing through the side duct or the air cleaner per unit time

***baseline concentration:*** concentration of contaminant (gases, particles) in the test chamber air before injection of the challenge gas

***burn in:*** conditioning process for devices that utilize UV lamps

***bypass:*** proportion of the challenge air stream that passes around or through an air cleaner without interacting with the air cleaner

***byproduct:*** airborne substance formed in or downstream of an air cleaner as a result of the air cleaning process

Note: the byproducts $CO_2$, $O_2$, and $H_2O$ (the complete oxidation reaction products) will not be measured as it is assumed to be a small potential contribution from reactions compared to the large, expected background levels.

***challenge gas:*** *gaseous* chemical compound that is being used as the contaminant of interest for any given test

***collected air sample:*** sample of airborne contaminant(s) obtained by using a pump to draw air into or through a sorbent tube, cartridge, or other capture device

***concentration:*** quantity of one substance dispersed in a defined amount of another

***device under test (DUT):*** device that is being subjected to performance testing.

Note: The air cleaner may contain multiple stages and/or multiple technologies.

***face velocity:*** velocity of the air at the inlet of the air cleaner

***full-scale test:*** test conducted with a full-size production model of an air cleaner

***in-duct air cleaner (IDAC):*** air cleaner designed to be installed in an HVAC duct

***in-room air cleaner (IRAC):*** device that is placed in a room to clean the air

Note: This may include standalone, portable, and wall- or ceiling-mounted units.

***natural decay rate***: reduction rate of the challenge gas in the test chamber due to natural factors, principally sedimentation, agglomeration, surface deposition, chemical reaction, and air exchange

***operation decay rate***: reduction rate of the challenge gas in the test chamber due to operation of the device under test

***$PM_x$:*** inhalable solid and/or liquid particles that are generally smaller than x micrometers in diameter

**real time measurement:** measurement obtained by direct-reading instrument

Note: typically data from direct-reading instruments takes less than five minutes to record
***recirculated air:*** return air that is circulated through the side duct before re-entering the test chamber as supply air

***resistance to airflow:*** difference in absolute (static) pressure between two points in an airflow system

***return air:*** air moving from the test chamber into the side duct

***supply air:*** air entering the test chamber from the side duct

***test chamber:*** self-contained room with specified characteristics that are used to determine performance of an air cleaner

***total decay rate:*** reduction rate of the challenge gas in the test chamber due to the combined effect of the natural decay rate and the operation decay rate

***ultrafine particle (UFP):*** solid or liquid particle with a maximum size of 0.1 µm (100 nm). (EPA)
Note: the same size range definition applies to nanoparticles (engineered ultrafine particles)

***volatile organic compound (VOC):*** chemical belonging to the medium-volatility subset of the organic compounds that can be present in indoor air under normal indoor atmospheric conditions of temperature and pressure; specifically, an organic compound with a saturation vapor pressure greater than $10^{-2}$ kPa at 25°C ($3x10^{-3}$ inches of mercury at 77°F)

## 3.2 Acronyms and Abbreviations

| | |
|---|---|
| 316SS | stainless steel alloy designation 316 |
| ACH | Air Changes per Hour |
| ASTM | American Society for Testing and Materials |
| BPI | Bi-polar Ionization |
| BPP | Byproduct Production Percentage |
| cfm, $ft^3/min$ | cubic feet per minute |
| cmh, $m^3/h$ | cubic meters per hour |
| DUT | device under test |
| GC | gas chromatograph |
| HEPA | high-efficiency particulate air |
| HVAC | heating, ventilating, and air-conditioning |
| IDAC | In-Duct Air Cleaner |
| IRAC | In-Room Air Cleaner |
| Pa, kPa | pascals, kilopascals |
| PEL | permissible exposure limit |
| ppbv | parts per billion by volume |
| ppmv | parts per million by volume |
| PTFE | polytetrafluoroethylene |
| $Q_{ECA}$ | equivalent clean airflow rate |
| RH | relative humidity, % |
| T | temperature |
| THC | total hydrocarbon analyzer |
| UFP | ultrafine particle |
| VOC | volatile organic compounds |

## 4. ADMINISTRATION

### 4.1 Description of Test

The objective of the standard test is to provide, at a moderate test cost, comparative performance data for full-scale air cleaners in a closed chamber + duct system under recirculation. The data shall be obtained at fixed temperature (T), relative humidity (RH), and air changes and at the air cleaner's design velocity.

**4.1.1** Air Cleaners

The test method covers both In-Room Air Cleaners (IRAC) and In-Duct Air Cleaners (IDAC). Test labs and chamber setups are not required to allow testing of both types to be considered to meet the requirements to run an ASHRAE Standard 145.4 test.

**4.1.2** Challenge gas types

The test method covers single challenge gases, including VOCs and other gases. Gas mixtures are not included.

**4.1.3** Byproducts

The test method measures the potential formation of ultrafine particles, NOx, aldehydes, and some VOCs.

## 5. EQUIPMENT AND TEST CONDITIONS

### 5.1 Test Chamber and Duct System

The test chamber and duct shall meet the following requirements:

**5.1.1** Be constructed of stainless steel, qualified grade, grounded, or bonded. A chamber viewing port of inert material such as glass or other non-reactive suitable material shall be present but should be limited in area. Include a door capable of opening from both the inside and outside and can seal shut during the test.

**5.1.2** Sealed with inert materials. Avoid materials such as silicone which could emit or absorb VOCs. The sealed chamber condition may be verified by aerosol surrogate or gas mixing testing (for example, $CO_2$) (See Section 8).

**5.1.3** The chamber shall be at least 22.7 $m^3$ (800 $ft^3$). The height shall be between 2.4 m and 3.0 m (8 ft and 10 ft). The width shall be at least 85% of the length. Other chamber footprints would require further study on mixing. See mixing Section 8.2.

**5.1.3.1** For duct mounted air cleaners, chamber size shall be large enough to allow the device under test (DUT) to operate at the manufacturer recommended face velocity to achieve the expected operating conditions of the HVAC system and meet the air changes per hour specified in 5.1.4.7.

*Informative Note***:** *For IRAC operating above 1000 $m^3$/h (600 cfm), the draw down may be too rapid and the minimum number of data points may be difficult to collect. Therefore, a chamber larger than the minimum or an alternative analytical test methodology may be required. Chamber size consideration should reflect the measurement instruments, methodology of sample collection, chamber configuration, and the air cleaning effectiveness of the IRAC.*

**5.1.4** The duct shall meet all the following requirements:

**5.1.4.1** Be located inside or outside the chamber.

**5.1.4.2** Accommodate air cleaners intended to be mounted in a duct size 30.5 x 30.5 cm (12 x12 in.) to 61 x 61cm (24 x 24 in.) with up to 30.5 cm (12 inches) of depth (according to the manufacturer's installation instructions) and other sizes outside of this range if proper transitioning can be demonstrated. Any transitions/adapters must be designed for uniform airflow and shall not exceed 7 degrees. See Appendix B for an example of this used with a 24x24 duct.

**5.1.4.3** Accommodate duct wall-mounted DUT.

**5.1.4.4** Allow power lines to connect through the duct wall without air leaks.

**5.1.4.5** Allow visual or other means to check that the DUT is operating.

**5.1.4.6** Be a single duct with one return from the chamber and supply entry point into the chamber.

**5.1.4.7** Include an inline fan that operates at an airflow of 5-6 air changes per hour (ACH) through the system.

ACH Example Calculation with an external duct:

$$ACH = \frac{Q(\frac{ft^3}{min}) * 60\, minutes}{V(ft^3)}$$
$$V = V_{Chamber} + V_{Duct}$$
$$V_{Chamber} = 1000\, ft^3$$
$$V_{Duct} = 125 ft^3$$
$$V = 1000 ft^3 + 125 ft^3$$
$$V = 1125 ft^3$$
$$ACH = 6$$
$$Q = \frac{ACH * V}{60\, minutes}$$
$$Q = \frac{6 * 1125 ft^3}{60\, minutes}$$
$$Q = 112.5 \frac{ft^3}{min}$$

**5.1.4.8** Connecting ducts between chamber and test duct must be designed to allow for proper mixing of the air in the chamber to obtain uniform concentrations throughout the chamber.

**5.1.4.9** Includes a continuous airflow measuring system and a fan at minimum capable of operating at airflows up to 500 cfm and up to 1.0 in $H_2O$ resistance to airflow across a mounted air cleaner. The fan section shall not allow air leakage beyond that allowed for the entire chamber/side duct in the leak test. Note: higher performing systems that are capable of overcoming higher resistance to airflow are acceptable.

**5.1.4.10** May be made of sections that can be interchanged to allow different sizes of air cleaners and/or different airflows. Adapters to allow mounting of various sizes of air cleaners may be necessary. As configured for a test, the side duct shall meet all of the side duct requirements.  Any transitions /adapters must be designed for uniform airflow.

**5.1.5** Include mixing fans as required to achieve good mixing according to Section 8.  They shall be positioned opposite the airflow in the chamber/duct and not pointed at the DUT or at the inlet or outlet.  These fans shall be sufficient to provide well-mixed conditions in the chamber when the fans and duct are operating. The well-mixed conditions may be verified by a gas mixing testing (for example, $CO_2$).

**5.1.6** Mixing fan(s) shall be installed on an upward 45 angle to mix heavier than air gases.  Fans, IRAC exits, duct inlet and outlet shall not all point in the same direction.  The inlet of the duct shall not be in line with the exit to the duct.

**5.1.7** Be equipped with a system to create a starting temperature (T) of 23 +/- 2ºC (73 +/- 4ºF) and relative humidity (RH) of 45-55% and to continuously monitor and record them. This chamber environmental system shall be operated before testing but be turned off during the tests.

**5.1.8** Be equipped to provide 115 V ± 1%; 60 Hz ± 1% to power the DUT(s). Other power levels may be used but must be noted in the test reports.

**5.1.9** The duct and chamber system shall have an air exchange rate with the air outside of the chamber / side duct of <0.03 ACH as determined by ASTM E 741 (Standard Test for Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution)[6] or an equivalent method and allow measurement of pressure difference between inside and outside of duct and chamber system such that pressure change in the system may be measured to within +/- 1% during the natural decay tests. (IEC 63086 Part 1[12].)

**5.1.10** Include sampling ports located in positions representative of the airflow dynamics of the chamber (lacking high turbulence or unidirectional velocity). These probes shall be located at a distance of >0.3 m (1 ft) from each wall and at a distance sufficient from the supply and return openings of the recirculating duct, mixing fan and the air cleaner(s) such that the sample is not influenced. The sampling locations shall be representative of the chamber dynamics and 1.0-1.8 meters above the floor.

**5.1.11** Be capable of mounting and installing the most common DUT: air cleaners, wall-mounted air cleaners, tabletop air cleaners, ceiling-mounted, duct-mounted, and floor air cleaners in a central location in the test system. This includes air-tight ports for power lines and remote controls. DUT shall be installed according to the manufacturer's published installation instructions for proper operation. DUT designed to vent into a mechanical exhaust system or directly outside the room are not included in this standard.

**5.1.12** Be equipped with a contaminant injection port that allows the contaminant to be well mixed within the room. Contaminant injection port shall be located so that it does not interfere with any sampling probes in Section 5.1.9 and 5.1.10.

**5.1.13** Be equipped with a system capable of purging and/or cleaning the air in the chamber pre-and post-testing. For example, air may be pulled from the chamber through a cleanup section before being returned to the chamber. A HEPA filter can provide effective removal of particles; carbon/sorbent beds can be used to remove other species from the air and should be designed to remove all gas challenges and byproducts. This cleanup system shall be designed to be shut completely off from influencing the chamber during the testing.

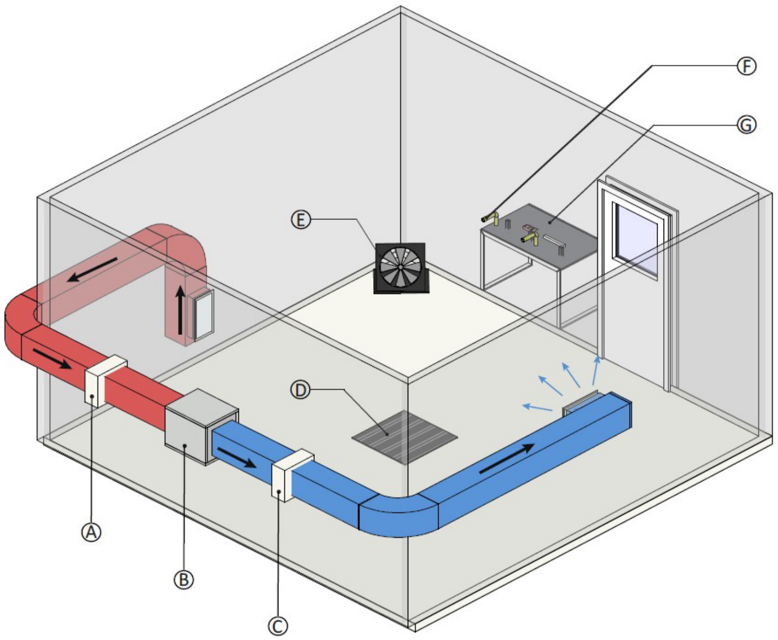
**5.1.14** Be capable of achieving and maintaining all background gas contaminant concentrations, which shall be maintained throughout 60 minutes at a level of concentration below 3% of the starting concentration for the test challenge gas.  Particle, VOC, and aldehyde background levels shall not exceed the levels defined in Table 6.2 and shall be measured using the methods listed in Table 6.2.

**5.1.15** The test chamber shall meet the QA/QC requirements in Section 8 before testing may be performed.

**5.1.16** Example of a chamber+duct system:

A. IDAC, before fan

B. Recirculating Fan



C. IDAC, after fan

D. IRAC position

E. Mixing Fan

F. Sampling port(s)

G. Instrument table
(external of chamber)

**Figure 5-1:** One example of a chamber and external duct test system with mixing fans, recirculating duct, air cleaners location, etc.

### 5.2 Air Cleaners

This standard covers in-duct air cleaners (IDAC) of any size and commercial or industrial in-room air cleaners (IRAC). For residential IRAC, AHAM AC-4 shall be used.

**5.2.1** Air cleaners shall be tested based on their intended use and shall be installed according to the manufacturer's published installation instructions for proper operation. If there are no location instructions, default to the center of the chamber for IRAC while meeting the requirements of 5.2.5. For wall and ceiling mounted IRACs, a stainless steel (SS rack shall be used to mount the IRAC in the center of the chamber.

**5.2.2** For DUTs with multiple operating settings, the DUT should be operated at the maximum operating setting or per the user manual for the challenge gas and may be tested at additional operational settings. The setting used shall be noted clearly on the test report.

**5.2.3** Air cleaners shall have an available means to energize the DUT from outside the chamber. Plug in cords and remotes are acceptable as are externally mounted switches for duct mounted DUTs. This requirement does not apply to DUTs that do not require power.

**5.2.4** IDAC shall be sized for use at the airflow specified for the duct airflow of the test within 20%.

**5.2.5** IRAC shall be installed where it is not in the airflow of the mixing fan. For air cleaners that discharge air in a specific direction, the air discharge shall not be pointed toward the chemical collection port, and the air discharge shall not be directed on the wall or at least 61 cm (2 feet) from the wall.

### 5.3 Gas Sample Ports

**5.3.1** Sampling ports shall be available and sealable with and without sample lines.

**5.3.2** These ports shall be located along the centerline of the room in the lengthwise direction. These ports shall be located at a distance of > 0.3 m (1 ft) from each wall. The ports shall be no closer than 1 ft at the chamber exit into the duct.

**5.3.3** Ports shall not be near the exit of an IRAC or the supply air.

IRAC shall be installed where it is not in the airflow of the mixing fan. For air cleaners that discharge air in a specific direction, the air discharge shall not be pointed toward the chemical collection port, and the air discharge shall not be directed on the wall or at least 61 cm (2 feet) from the wall.

## 6. Challenge Gases and Measured Byproducts

### 6.1 Challenge Gases

This test requires that each gas is tested separately as a single challenge gas. Table 6.1 lists the gases and challenge concentrations, and the first six gases are the recommended gases based on frequency of detection in a building, ability to test, and toxicity. The compounds in Table 6.1 were chosen to represent compounds of interest to commercial buildings and found in ASHRAE Standard 145.2[3], in industry standards, guidelines, and certifications such as ASHRAE Standard 62.1-2022[4], LEED Indoor Air Quality Assessment[15], and WELL Enhanced Air Quality[16].

Initial challenge concentration shall be within +20% of the target concentration listed in Table 6.2. Compounds not included in this table can also be tested using this method as a non-standard test. If a gas is not listed in Table 6.1 then it is recommended to test at 100-200 ppb as a challenge concentration. It is important to have a high enough concentration in the chamber at the start of the test so that there are enough data points collected during the draw down before the test gas cannot be detected (See Section 10.1). Section 5.1.3.1 provides guidance if the minimum data points can't be attained. Gases with boiling points above 200 °C will be difficult to generate at a sufficient concentration and may condense on the surface of the chamber.

### 6.2 Nonstandard Test

**6.2.1** Nonstandard tests are those conducted using the test methodology of this standard with nonstandard test conditions and/or materials for the purposes of the end user or the manufacturer. In addition, an otherwise valid standard test that was conducted (inadvertently or deliberately) at a nonstandard temperature (T) or relative humidity (RH) is permitted to be reported as a valid result of a nonstandard test. The permitted changes allowed include variations in challenge gas concentrations, T, RH, and DUT flow rate.

**6.2.2** The testing organization is required to report the test as a nonstandard test and to record the actual test conditions, end point, and challenge chemicals on all documents and reports related to the test.

**Table 6-1** Challenge Gases

| Compound | CAS Number | MW | Challenge Concentration | |
|---|---|---|---|---|
| | | | ppb | µg/m³ |
| **Recommended** | | | | |
| Ammonia ($NH_3$) | 7664-41-7 | 17.03 | 200 | 139 |
| Formaldehyde | 50-00-0 | 30.03 | 100 | 123 |
| d-Limonene | 5989-27-5 | 136.2 | 150 | 835 |
| Nitrogen Oxides* (NO2+NO) | | | | |
| Nitrogen Dioxide ($NO_2$) | 10102-44-0 | 46.0 | 100 | 188 |
| Nitric Oxide (NO) | 10102-43-9 | 30.0 | Measured Only | |
| Ozone ($O_3$) (generated)** | 10028-15-6 | 48.0 | 100 | 196 |
| Toluene | 108-88-3 | 92.1 | 200 | 753 |
| **Other Challenge Gases** | | | | |
| **Acid** | | | | |
| Sulfur Dioxide ($SO_2$) | 7446-09-5 | 64.1 | 100 | 262 |
| Hydrogen Sulfide ($H_2S$) | 7783-06-4 | 34.1 | 100 | 139 |
| Acetic Acid | 64-19-7 | 60.1 | 150 | 369 |
| **Alcohol** | | | | |
| Ethanol | 64-17-5 | 46.1 | 200 | 377 |
| 2-Propanol (IPA) | 67-63-0 | 60.1 | 200 | 491 |

| | | | | |
|---|---|---|---|---|
| iso-butanol | 78-83-1 | 74.1 | 200 | 606 |
| **Aldehyde** | | | | |
| Acetaldehyde | 75-07-0 | 44.1 | 100 | 180 |
| **Alkane** | | | | |
| n-hexane | 110-54-3 | 86.2 | 200 | 705 |
| n-heptane | 142-82-5 | 100.2 | 200 | 819 |
| **Aromatic** | | | | |
| Xylenes mixed isomers | 1330-20-7 | 106.2 | 150 | 651 |
| Benzene | 71-43-2 | 78.1 | 200 | 639 |
| Phenol | 108-95-2 | 181.8 | 100 | 743 |
| Styrene | 100-42-5 | 104.2 | 150 | 639 |
| **Chlorinated** | | | | |
| P-dichlorobenzene | 106-46-7 | 147 | 100 | 601 |
| Dichloromethane (methylene chloride) | 75-09-2 | 84.9 | 100 | 347 |
| Tetrachloroethylene (TCE/ PERC) | 127-18-4 | 165.8 | 100 | 678 |
| **Inorganic** | | | | |
| Carbon dioxide ($CO_2$) | 124-38-9 | 44.0 | 1100000 | 1978819 |
| **Ketone** | | | | |
| Acetone | 67-64-1 | 58.1 | 200 | 475 |
| 2-Butanone (MEK) | 78-93-3 | 72.1 | 200 | 590 |
| **Miscellaneous** | | | | |
| Acrylonitrile | 107-13-1 | 53.1 | 200 | 434 |
| Vinyl acetate | 108-05-4 | 86.1 | 150 | 528 |

*When $NO_2$ is the challenge gas NO shall not be part of the initial challenge gas but shall be measured with $NO_2$ due to possible generation. See Section 6.4.4 for further information.
**Ozone challenge gas shall be generated. Testing with ozone as the challenge gas may require additional care as ozone can react with the SS chamber and duct surfaces resulting in a rapid decay.

### 6.3 Background measurements

The background concentration for the challenge gas shall not exceed 3% of the starting concentration. This does not apply to $CO_2$. $CO_2$ challenge concentration can use ambient $CO_2$ as part of the total concentration. For ultrafine particles, aldehydes, and VOCs, concentration limits listed in Table 6.2 determine the maximum for background concentrations. For challenge gases that are also listed in Table 6.2 the lowest concentration (either 3% or Table 6.2 limit) shall be met.

### 6.4 Measured Byproducts

**6.4.1** Byproduct sampling shall be performed as described below for all tests. Table 6.2 defines the byproducts to be measured and requirements. Carbon dioxide ($CO_2$) may be a byproduct for certain technologies, but due to the ambient concentrations of $CO_2$, the increase in concentration would be difficult to measure and therefore is not included. When a compound in Table 6.2 is the challenge gas, it shall not be reported as a byproduct.
**6.4.2** Byproducts and background measurements shall use the methods listed in Table 6.2.
**6.4.3** Byproducts listed in Table 6.2 shall be reported when they exceed the concentration limit above the natural decay.
**6.4.4** When testing with a challenge gas containing sulfur, sulfur oxides shall be measured as potential byproducts.

**6.4.5** When Nitrogen dioxide ($NO_2$) is the challenge gas, NO is to be measured. NO shall not be reported as a byproduct when $NO_2$ is the challenge gas. In this instance, the generation of NO will be included in the total decay calculations per the instructions in Appendix B.

**Table 6-2** Background and Byproducts Methods and Limits

| **PM** | **Type of Measurement** | **Method/ Analyzer** | **Concentration Limit** | |
|---|---|---|---|---|
| | | | **Background** | **Byproduct** |
| Ultrafine Particles (UFP, 20-100 nm particles) | Real-time | CPC and SMPS | Report measured background | Report UFP: 5X natural decay |
| | | | | |
| **Compound** | **Type of Measurement** | **Method/ Analyzer** | **Concentration Limit** | |
| | | | **$\mu g/m^{3*}$** | **ppb** |
| Formaldehyde | Real-time or Collected air samples | ISO 16000-3,<br>EPA TO-11A<br>Or Section 7.2.2 | 2 | 1.6 |
| Acetaldehyde | Real-time or Collected air samples | ISO 16000-3,<br>EPA TO-11A<br>Or Section 7.2 | 2 | 3.6 |
| Ozone ($O_3$) | Real-time | Section 7.2.3 | 10 | 5 |
| VOCs (individual) | Collected Air Sample only | ISO 16000-6,<br>EPA TO-15,<br>EPA TO-17 | 5 (for each individual VOC) | Different for each VOC |
| Nitrogen Oxides ($NO_2$+NO) | Real-time | Section 7.2.4 | 19 $NO_2$, 12 NO | 10 (individual) |
| Sulfur Dioxide ($SO_2$)* | Real-time | Section 7.2.5 | 10 | 26.2 |

* Measure only for Sulfur containing challenge gases

## 7. Challenge Gas Generation, Analytical Methods, Sampling, and Measurements

### 7.1 Challenge Gas Generation

**7.1.1** Challenge Gas Overview

Challenge gases and concentrations and byproducts to measure are specified in Section 6, "Challenge Gases and Measured Byproducts". Other than the requirements of the following subsections, the design features of the gaseous generator are left to the discretion of the testing laboratory. Challenge gas generation can be achieved by either liquid or gas standards with an inert carrier gas. Ozone shall be generated by an ozone generator.

**7.1.2** Challenge Gas Consistency

The challenge gas generators shall be designed to ensure that the challenge gas concentration is up to 10% above the target at the start of the test.

**7.1.3** Challenge Gas Purity

The challenge generation method shall not introduce any contaminants other than the intended challenge gas. The challenge gas shall contain less than 1% contaminants other than an inert carrier gas. Formaldehyde shall be methanol free and shall not use paraformaldehyde.

### 7.2 Analytical Methods

The analyzers (or analytical methods) that are selected shall be appropriate for the challenge gas and measured byproducts (gases and particulates). This may require multiple instruments and/or analytical techniques for background, challenge gas, and byproduct measurements. Background analyzers shall have detection limits capable of measuring background concentrations as defined in Section 5.1.13. Challenge gas analyzers shall have a detection limit equal to or lower than 3% of the target challenge gas concentration. Byproduct measurement shall meet the requirements listed in Table 6.2. The analytical method shall have adequate response time, accuracy, and precision, and shall be stable to meet the requirements of the test.

**7.2.1** Formaldehyde analytical methods

Formaldehyde shall be measured using any method described in ASTM D8407[8] that has a detection limit better than 0.5 ppbv (0.6 µg/ $m^3$) for a 1-minute sample.

**7.3.1** Real-time Analyzers

**7.3.1.1** All real-time analyzers, associated equipment, and samplers shall be located outside the chamber.

**7.3.1.2** Real-time analyzers shall be calibrated according to the manufacturer's instructions.

**7.3.1.3** Gas analyzers shall be capable of reporting concentrations for specific compounds.

**7.3.3** Ozone real-time analyzer

Ozone analyzer shall meet the following specifications:

**7.3.3.1** Ranges of 0.02, 0.04, 0.1, 0.2, and 0.4 mg/m3 on the full scale (or have auto ranging capability)

**7.3.3.2** The capability to detect 4 µg/$m^3$ or lower concentration

**7.3.3.3** A precision of ± 2 % from the mean value in the 0 mg/m3 to 0.2 mg/$m^3$ range (i.e. 2 µg/$m^3$ or 1% on the full scale)

**7.3.3.4** A minimum sampling rate of once every 60 seconds

**7.3.3.5** A sampling line that does not exceed 13 feet (4 m) and made of a flexible, inert material, such as PTFE. To prevent impact on the test, the ozone analysis equipment shall be placed outside of the chamber.

**7.3.4** Nitrogen Oxide real-time analyzers

Nitric oxide (NO) and nitrogen dioxide ($NO_2$) are often found together and the concentration of both NO and $NO_2$ shall be measured and reported.

**7.3.4.1** Chemiluminescence is recommended, but other types of analyzers may be used if they provide equivalent data.

**7.3.4.2** A minimum sampling rate of once every 60 seconds shall be used.

**7.3.5** Sulfur dioxide real-time analyzers

The lower detection limit shall be 1 ppb or 0.2% of concentration (whichever is greater). One example is a pulsed UV fluorescent radiation analyzer.

**7.3.6** Collected Air Sampling

**7.3.6.1** Collected air samples shall be analyzed using validated test methods published by nationally or internationally recognized authorities. For byproduct measurements, the methods listed in Table 6.2 shall be used.

**7.3.6.2** The data analysis shall use the mean time of the sample for reference and graphs. For example, a 5-minute sample starting at t=10 min would be considered as data for time t=12.5 min with adjustment for time to get the sample from the chamber to the sampler.

**7.3.6.3** Sequential samples are not allowed to have overlapping time boundaries unless required to achieve the necessary number of data points, given the length of the sample collection compared to the overall length of the test.

### 7.4 Sampling

**7.4.1 Sampling Overview.** PTFE sample lines shall be used when sampling for gas phase and conductive sample lines for particles. Sampling lines length shall be minimized as much as is reasonable to connect the chamber to the analyzer or sampling media. For tests where the chamber concentration changes rapidly, the transport time for the sample lines shall be considered in the data analysis. Tests for transport time with the standard challenge gases can usually be conducted using real-time analyzer(s) if the concentrations are appropriate for the analyzer. Heated sampling lines may be necessary with polar compounds, and care shall be taken to ensure that delay is not observed in real time analysis due to sorption/desorption with sampling line walls. Collected air samples can also be used but require samplers and a pump.

Sampling instruments and sampling volumes shall be chosen in conjunction with analysis techniques to meet acceptable detection limits for each required compound and to limit or eliminate interference. For example, ozone removal cartridges may be needed for some sampling tubes. Samples that are not analyzed in real time shall be stored and analyzed per the sampling techniques requirements.

The real-time analyzer sampling systems shall provide transport of ≥95% of the challenge gas and byproducts from the sample probe inlets within the test chamber to the inlet of the gas analyzers.

**7.4.1.1** Transport time
If possible, the transport time in the total length of the sampling tube should be less than 1 s.
If transport time is greater than 30 s or half of the analyzer sample time for any analyzer, the operator shall account for sampling transport time in the data tabulation, graphs, and analysis.

**7.4.1.2** Sampling pumps
Gas analyzers generally have low sampling rates, therefore auxiliary pumps may be required to move sampled gas more rapidly to the analyzers to minimize transport time. In this case, the capability of the analyzers to sample from below atmospheric pressure shall be considered in the sampling system design. Flow through the sampling system to the vicinity of the analyzers shall be measured with a precision of 5% of the sample rate. The airflow rate of the sampling system shall be as low as possible, consistent with the transport requirements of this section, and not greater than 2% of the test air- flow rate (see Section 5.1 for flow rate specifications).
If an auxiliary pump is required, the pump and associated flow control and flow measurement instruments of the primary sampling lines should be downstream of secondary probes whenever possible. If this is not possible, it shall be demonstrated that they do not contribute contaminants, and they shall be considered in the sample loss evaluation.

**7.4.1.3** Byproduct Sampling
All testing programs are required to measure byproducts and techniques as defined in Section 6. Sampling for byproducts shall be performed during the Natural Decay and Total Decay tests. Byproduct samples can use the same sampling lines as the challenge gas if the flow can be split between the samples. This can be done by using a pump to pull air from the duct to a plenum from which all analyzers pull separate samples. Alternatively, separate sample lines for each analyzer or method may be run.

### 7.5 Sampling Plan

Sampling shall be the same for the natural decay and total decay. Samples are not required to be taken in triplicate.
**7.5.1** For sampling methods not in real-time, the following sampling plan shall be used
**7.5.1.1** A sample shall be taken at time zero (t=0)
**7.5.1.2** Sorbent tube samples shall be taken in equal increments of time to achieve the required minimum of 6 valid samples.
**7.5.1.3** The reported sample time shall be the center time of the total sample collection time.
**7.5.1.4** The test shall run for a minimum of 60 minutes or until ≤50% of the initial challenge gas concentration is measured.
**7.5.1.5** It is recommended that the test run for 1 hour, but the test shall not exceed 4 hours.
**7.5.1.6** Byproducts shall be measured by analytical methods defined in Table 6.2. Methods not measuring in real-time shall collect a minimum of two sequential 15 minute collected air samples.
**7.5.1.7** Tests that meet the 50% initial challenge gas reduction under 30 minutes shall measure byproducts beyond the end of the test to meet the requirements of 7.4.1.6.

## 8. Quality Assurance and Quality Control (QA/QC)

Qualification tests shall verify quantitatively that the chamber + duct system, sampling procedures and equipment are capable of providing reliable challenge gas concentration and air-cleaner draw down measurements.

Qualification tests shall be performed as required by Table 8-1. System qualification shall be done before initial testing, after major changes to the test system, and on the schedule in Table 8-2.

**Table 8-1 Chamber + Duct System and Instrument Qualification Requirements**

| Section Number | Parameter | Specific to Challenge Gas | Requirement |
|---|---|---|---|
| 8.1.1 | Background Level Check | Yes | Meet Requirements in Table 6.2 |
| 8.1.2 | System Purge | No | Meet Requirements in Table 6.2 |
| 8.3 | Air Exchange Rate (Total allowable leakage) | No | ASTM E 741 or ASTM D 6670 (8.2.1) |
| 8.2 | Chamber Mixing and Uniformity | No | ASTM D 6670 (8.4.1) |
| 8.4 | Challenge gas generator | Yes | +10% target concentration |
| 8.5.1 | Analyzer response time | Yes | < 20% sample line transit |
| 8.5.2 | Sample transit time | No | Determine correction factor |
| 8.5.3 | Analyzers and sampling systems zeroes | Yes | Below detection limit |
| 8.5.4 | Gas Sampling pump flow rate check | No | NIST traceable flow instrument |
| 8.5.5 | Gas analyzer calibration | Yes | Use traceable gas standards<br>Must be done for all analyzers<br>Curve fit $R^2 \geq 0.95$ |
| 8.6 | Temperature measuring instrument | No | Factory Calibrated |
| 8.6 | RH measuring instrument | No | Factory Calibrated |

## 8.1 Meeting Background Requirements

**8.1.1** Demonstrate the ability to meet the background levels of ultrafine particles, aldehydes, and VOCs in Table 6.2.

**8.1.2** Purge system shall removal all contaminants (gas and particulates) to levels below the background concentrations limits in Table 6.2.

## 8.2 Chamber Mixing and Uniformity

The chamber shall be evaluated to demonstrate that the challenge gas is well mixed during a test. This can be done by using either the method in ASTM D 6670 (Section 8.4.1)[7] or by using the following procedure using $CO_2$ as a tracer gas:

- Position at least 4 calibrated analyzers (or the inlet ends of the sampling tubes) in the chamber in different locations.
- Turn on side duct to typical airflow (the same airflow used in the leakage test)
- Run purge system for required length of time to meet the background levels, then turn off
- With mixing fans operating as usual, generate challenge gas from standard location, and allow to mix your standard length of time
- Take simultaneous samples with all analyzers or samplers. Repeat this step at least 3 times.
- Using at least 3 data sets, determine the mean for each point and for the whole data set. If all of the sample points' means are within 10% of the overall mean, the chamber/duct is acceptably well-mixed.
- If the chamber is not acceptably well-mixed, examine the data for trends indicating that the mixing improved over time. This may indicate that the lab needs to increase their pretest mixing time. In this case, later samples may be used to determine acceptable mixing. Adjust the required mixing time by adding the time required to meet the acceptance goal.

## 8.3 Air Exchange Rate (total allowable leakage)

The Chamber+ Duct system shall be assembled as it will be used (sample lines in ports, duct, mixing fans, etc.). The air exchange rate of the chamber + duct system also referred to as the total allowable leakage shall be determined by using the methods in ASTM E 741[6] or ASTM D 6670 (Section 8.2.1)[7]. Alternatively, a leak test can be done with the following leak test procedure:

1. Choose a contaminant that can be measured in real-time c. For example, a VOC with PID or 0.5 µm particles would work well.
2. In the duct, place an air cleaner surrogate with a resistance to airflow of ≥1.0 in $H_2O$ (use a value equal to or higher than the highest expected resistance to airflow for actual tests). This can be an orifice plate, a media filter, or similar instrument with airflow resistance.
3. Close the chamber.
4. Turn on the airflow through the duct to a typical value.
5. Run the purge system to clean the chamber.
6. Measure background levels in the space surrounding the chamber + duct system.
7. Measure chamber backgrounds levels.
8. Generate chosen challenge gas (even a small spritz of liquid VOC can suffice).
9. Run mixing fans and duct airflow as you would during a Natural Decay or Total Decay test.
10. Wait until the challenge gas concentration stabilizes (is not fluctuating indicating lack of mixing or contaminant still evaporating). If too high for your test needs, you can run a cleanup system to reduce the level. Then make sure the new value is stabilized.
11. Continue measuring and monitoring concentrations for one hour.
12. Calculate k value or equivalent clean air entering the chamber system.
13. If high, re-gasket, seal openings, make sure the cleanup system is sealed off, etc., and repeat the test.
14. Record the level as usual for the test chamber + duct system so a leak can easily be detected in the future.
15. If an air mixing test is done after this that results in changes to the chamber, repeat the leakage test.

**8.4 Challenge Gas Generation**

For each generator or generation method, a minimum of five generation events shall be run to demonstrate that the system can meet the +10% of target concentration requirement.

*Note: This could be combined with the purge system test in Section 8.1.2*

**8.5 Analyzers and Sampling Systems**

To report the time in the chamber when the sample was removed, it is important to know both the transit times for any sample lines and the analyzer response time for each analyzer. If the airflow through the lines is known (e.g., by calibrated pumps pulling the air), the ID can be used to calculate the transit time.

**8.5.1** Analyzer response

Analyzer response time shall be no more than 20% of the transit time in the sample line.

**8.5.1.1** Determining Analyzer Response Time

With analyzer operating per manufacturer's instruction, expose analyzer to air that meets the clean air requirements in Section 6 long enough to show a steady reading. Then turn on a stable concentration of the appropriate gas. Record the time to a stable and correct reading. Use this time to correct the time for the sample.

**8.5.2** Sample line transit time correction

Setup the sample lines as they will be used and connect to the analyzer. Run clean air through the sample lines and analyzer until a stable reading is obtained. Then turn on a stable concentration of the appropriate gas. Record the time to a stable and correct reading. Subtract the analyzer response time from the combined time. Use this time to correct the time for the sample whenever this sample line is used at the same sample flowrate.

Sample line transit time shall be determined when sample lines are changed in length or diameter.

**8.5.3** Analyzers and sampling systems zeroes

All analyzers and sampling systems shall be zeroed per manufacturers specifications.

**8.5.4** Gas Sampling pump flow rate check

The gas sampling pump flow rate used for collecting air samples shall be checked regularly prior to use in accordance to the laboratory SOP.

**8.5.5** Gas analyzer calibration

Zero, or check zero as appropriate to the analyzer, and calibration at approximately 10%, 50%, and 100% of challenge concentration. Zero air shall have concentration levels below the reporting limit of the analyte. Use traceable gas standards. Calibrations must be done for all analyzers and the curve fit must have $R^2 \geq 0.95$.

**8.5.6** Particle Analyzer Calibration

The particle analyzer shall be calibrated per the manufacturer's instructions.

**8.5.7** Other Calibrations

Measuring instruments used to measure airflow and resistance to airflow shall be calibrated per the manufacturer's recommendations. Any measuring instrument not specified in another section shall be calibrated per the manufacturer's recommendations.

### 8.6 Maintaining temperature and relative humidity levels

Measuring instruments shall determine relative humidity (RH) ±5% at 50% and temperature (T) ±1°C at 23 °C. T and RH instruments shall be calibrated per the manufacturer's instructions.

**Table 8-2 Qualification Maintenance Items and Schedule**

| **Maintenance Item (Subsection Reference)** | **Each Test** | **Each Testing Day** | **Challenge Gas Change** | **Biannually or After Duct Modification** | **Other** |
|---|---|---|---|---|---|
| System Purge (Section 8.1.2) | | | | ■ | |
| Air Exchange Rate (Total allowable leakage) (Section 8.2) | | | | ■ | |
| Chamber Mixing and Uniformity (Section 8.3) | | | | ■ | |
| Analyzer response time (Section 8.5.1) | | | | ■ | |
| Gas analyzers calibration checks at zero, 10%, 50%, and 100% (Section 8.5.5) | | | | | within 2 weeks prior to test and per manufacturers instruction |
| Gas analyzers zero and span (Section 8.5.5) | | ■ | | | |
| Particle analyzer calibration (Section 8.5.6) | ■ | | ■ | | Annually* |
| Challenge Gas Generator (Section 8.4) | | | | ■ | |
| Sample transit time (Section 8.5.2) | | | | ■ | When changing sample lines |
| Analyzer and sampling system zero (Section 8.5.3) | ■ | | | | |
| Gas Sampling pump flow rate check (Section 8.5.4) | ■ | | | | |
| Temperature (Section 8.6) | | | | ■ | |
| Relative humidity (Section 8.6) | | | | | Every 6 months |
| Flow rates, resistance to airflows, etc. (Section 8.5.7) | | | | ■ | |

*or per the manufacturer's recommendations

## 9 Test Procedures

Tests with the air cleaner energized (Total Decay) and without the air cleaner (Natural Decay) shall be performed identically except for the DUT presence and operation. This is critical so that the natural decay test correctly reflects the change in concentrations due to the sampling itself. The order of the tests is not specified. A natural decay test may apply to more than one Total Decay test as long as the tests are run with the same challenge from the same generator, the same recirculation duct airflow, within five days, and with the same sampling time points and changes have not been made to the chamber-duct system.

### 9.1 Air Cleaner Conditioning (burn-in)

**9.1.1** For IRAC with a motor, the air cleaner motor must be properly broken in prior to the test by running the air cleaner per manufacturer instructions up to but not to exceed 48 hours.
If UV-C is included as part of the DUT, the UV-C lamp shall have a burn-in time of 100 hours.
Other DUTs that require burn-in shall follow manufacturer's instructions.
**9.1.2** The burn-in time of the air cleaner shall be conducted in an environment with gas concentrations below the background concentrations as defined in Section 5 and Table 6.2.
**9.1.3** For DUT that influences relative humidity (RH) (for example sorbent based), the DUT shall be conditioned at 50% RH with clean air.

**9.2 Setup**

**9.2.1** Take a picture(s) of the individual DUT(s) to be tested before installing, with identifying markings and labels included.
**9.2.2** Determine the sampling plan, including sample times, lengths of samples, which species/contaminants need to be sampled for, and other relevant details. See Section 7.5.
**9.2.3** For Total Decay tests only, install the DUT per the manufacturer's instructions.

a. Make sure the DUT can be turned on and off once the chamber/duct system is closed without reentering the chamber. The DUT and probes shall be placed so that they do not interfere with each other.
b. Install the IDAC in the duct and/or the IRAC in chamber as appropriate.
c. The IRAC shall follow installation parameters in Section 5.2.
d. Take a picture(s) of the DUT(s) as mounted in duct (IDAC) or in chamber (IRAC).

**9.2.4** Seal chamber and duct.
**9.2.5** Turn on temperature (T) and RH control systems (air conditioning system) until the chamber and duct reach the desired set points.
**9.2.6** Begin recording T and RH and continue throughout the following test. During the test, T shall be 23°+/-5C (73°+/-9F) and RH shall be 40-60%.
**9.2.7** Operate cleanup system as per lab SOP or established procedure to achieve required background levels (as stated in Section 5 and Table 6.2)
**9.2.8** Turn off the cleanup system and T and RH control systems (air conditioning system) before measuring background.

**9.3 Background Contamination Measurement**

This section is a required part of each Natural Decay and Total Decay test.
**9.3.1** Turn on the mixing fan and duct airflow fan. The mixing fan and duct airflow shall remain energized throughout all testing of natural decay and total decay.
**9.3.3** Collect background samples for all species that need separate samples. Record time and sampling rates for the beginning and end of each sample collected.
**9.3.4** Turn on all real-time, direct-read analyzers. Record the start time for each analyzer. Follow analyzer instructions for needed equilibration times before official test data is collected.
**9.3.5** Collect background samples of byproducts to be measured from Table 6.2.
**9.3.6** If the background concentrations exceed the limits specified in Section 5 and Table 6.2, do not continue to the Total Decay test. The cleanup system or cleaning SOP shall be re-executed or diagnostics shall be performed to eliminate sources of contamination. Background concentrations shall be below the limits specified in Table 6.2 before starting a test.
**9.3.6.2** Immediately begin a Natural Decay test or Total Decay test as appropriate.

**9.4 Test Procedure (Natural Decay or Total Decay)**

**9.4.1** Turn off the duct fan
**9.4.2** Begin contaminant generation and inject or operate until the desired concentration is achieved, then stop the generation. Challenge gas specific concentrations are listed in Section 6, Table 6.1, and gas generation methods can be found in Section 7.
**9.4.3** Wait 2 minutes for mixing. Turn on the duct fan and DUT (when applicable). Wait 1 additional minute, then take the initial concentration measurement defined as t=0 minutes.

**9.4.4** For Natural Decay tests, record resistance to airflow for the empty duct, and for Total Decay tests, record the resistance to airflow for IDAC.

**9.4.5** Acquire the concentration data according to the schedule shown referenced by the type of measurement instrument.

**9.4.5.1** For collected air samples (not in real-time sampling), follow the Sampling Plan in Section 7.5.

**9.4.5.2** For other measurement instruments that have real-time measurement characteristics, samples shall be taken over at least 20 minutes until the concentration has reached the minimum limit of instrument measurability.

**9.4.5.3** Sampling schedule for Natural Decay shall be the same as the Total Decay sampling schedule.

**9.4.6** In addition to challenge gas concentration measurements, byproduct sampling is also included according to Table 6.2. If additional measurements are specified by the manufacturer for optimal performance of the DUT(s), then they shall be listed on the test report.

**9.4.7** Turn off the DUT, if conducting a Total Decay test.

**9.4.8** Operate the cleanup system as per lab SOP to remove challenge gas and any byproducts.

**9.4.9** Repeat the procedure from the beginning of the baseline section continuing into the test section for the remaining test(s).

## 10. Calculations and Statistics

### 10.1. Minimum number of data points.

**10.1.1.** The laboratory shall only consider tests with a minimum of 6 remaining data points to be a complete test.

**10.1.2.** Following any removal of data points, the data set shall contain at least 6 remaining data points to be used to calculate the $Q_{ECA}$.

**10.1.3.** A maximum of 20% of data points can be eliminated; otherwise, the test must be rerun.

**10.1.4.** If the minimum number of data points cannot be obtained, a larger chamber, real-time analyzer, or increased sampling frequency may be required.

**10.2. Criteria for Elimination of Data Points.** There are five criteria for eliminating a data point from calculations in a data set.

**10.2.1.** Operator error, such as operating a sampler for the wrong length of time, shall result in the elimination of the data points at the time of the error whether or not the data point is otherwise acceptable or in the anticipated concentration ranges.

**10.2.2.** Equipment error shall result in the elimination of the data point (corresponding to the time the error occurred) whether or not the data point is found within acceptable or anticipated concentration ranges. Typically, this type of error invalidates the entire run.

**10.2.3.** Data points that were below the detection limits of the analytical methods shall be excluded along with all subsequent data points in the run.

**10.2.4.** Any data point found to be outside the 95 % prediction limits of the regression slope line shall result in the elimination of the data point. The laboratory shall investigate the cause of the error. The cause of the outlier data may be due to test chamber instrumentation, air cleaner inconsistency, or other test chamber effects.

**10.2.5.** Any data point collected when the chamber temperature (T) and/or relative humidity (RH) are outside the range specified in 9.2.6 shall be excluded along with all subsequent data points in the run.

### 10.3. Calculating the Decay Constant in Minutes

**10.3.1.** The decay constant, k, for challenge gas is based on the relationship below.

$$C_{t_i} = C_i \, e^{-kt_i} \qquad (10.1)$$

Where:

$C_{t_i}$= concentration at time $t_i$ [μg m$^{-3}$]
$C_i$= concentration at t=0 minute
$k$= decay rate constant (minutes$^{-1}$)

$t_i$= time [minutes]

**10.3.2.** The decay constant, $k$, slope, is obtained using linear regression on the $lnC_{t_i}$ and: $t_i$using the formula:

$$k = \frac{S_{XY}}{S_{XX}} \tag{10.2}$$

Where:

$$S_{XY} = \sum_{i=1}^{n} t_i \ln C_{t_i} - \frac{1}{n}\left(\sum_{i=1}^{n} t_i\right)\left(\sum_{i=1}^{n} \ln C_{t_i}\right) \tag{10.3}$$

$$S_{XX} = \sum_{i=1}^{n} (t_i)^2 - \frac{1}{n}\left(\sum_{i=1}^{n} t_i\right)^2 \tag{10.4}$$

Use the natural decay data to calculate the k value for the natural decay. Use the total decay data to calculate the k value for the total decay.

**10.3.3.** Determine the R-squared ($R^2$) for each fitted line. If the $R^2$ is less than 0.95, either redo the test or consider removing higher CV time periods (for non-continuous sampling) and checking the $R^2$. You must still have five remaining good time period sample sets to consider the test valid (total of six points). If there is a plateau at the end of the data set, the average concentration shall be reported and the data in the plateau shall be eliminated from the calculations.

$$\boldsymbol{R^2} = \left[\frac{\boldsymbol{n}\sum\left(\boldsymbol{t_i ln}\left(\boldsymbol{C_{t_i}}\right)\right) - (\sum \boldsymbol{t_i})\left(\sum \boldsymbol{ln}\left(\boldsymbol{C_{t_i}}\right)\right)}{\sqrt{\boldsymbol{n}\sum \boldsymbol{t_i}^2 - (\sum \boldsymbol{t_i})^2}\sqrt{\boldsymbol{n}\sum\left(\mathbf{ln}\,(\boldsymbol{C_{t_i}})\right)^2 - \left(\sum \mathbf{ln}\,(\boldsymbol{C_{t_i}})\right)^2}}\right]^2 \tag{10.5}$$

See Informative Appendix A for full calculation example and graphs.

### 10.4 Performance Calculations in Minutes

The performance of an air cleaner is represented by an equivalent clean airflow rate ($Q_{ECA}$) for each challenge gas . The method for calculating the equivalent clean airflow rate is:

$$Q_{ECA} = V\,(k_e - k_n) \tag{10.6}$$

Where,

$Q_{ECA}$ = equivalent clean airflow rate [$ft^3\ min^{-1}$ or $m^3\ hr^{-1}$]

$V$ =volume of test chamber+duct [$ft^3$ or $m^3$]

$k_e$ = total decay rate [$\text{min}^{-1}$]

$k_n$ = natural decay rate [$\text{min}^{-1}$]

Note: The chamber+duct includes the total volume of air of the system. For ducts located in the chamber, the total volume of air is nominally equal to the chamber outer dimensions. For IRAC volume above 5% of the chamber volume, the IRAC volume shall be subtracted from the volume used to calculate the $Q_{ECA}$.

## 11. Reporting Results: Minimum required information

An example of a Test Report can be found at the end of this section.
**11.1** Laboratory Information.
**11.1.1** Name and location of the test laboratory.
**11.1.2** Date of the test.
**11.1.3** Laboratory test operator's names.
**11.1.4** Air cleaner manufacturer's name if known. The company submitting the DUT for testing.

**11.2** Description of the DUT, including the following:
**11.2.1** Manufacturer and model number (or description of a prototype).
**11.2.2** If the air cleaner has options, those used in the test must be specified. These may include output settings, fan speed, filters, or shielding.
**11.2.3** Nominal dimensions of the DUT.
**11.2.4** Location of air cleaner(s) in the test chamber/side duct.
**11.2.5** Photos or drawings of the air cleaner as positioned or located during the test.
**11.2.6** Physical description of the air cleaner including technology-specific details

**11.3** Test Description
**11.3.1** DUT conditioning details.
**11.3.2** IDAC resistance to airflow and duct velocity (at DUT section).
**11.3.3** DUT voltage input and wattage draw.
**11.3.4** For IDAC that require sealing, provide description of sealing.
**11.3.5** Deviation from the manufacturer recommended installation.

**11.4** Chamber+Duct System Description (as required in Section 5)
**11.4.1** Actual chamber dimensions and volume in $m^3$ ($ft^3$).
**11.4.2** Duct Description dimensions, airflow rate, air velocity, attachment to chamber locations **.**
**11.4.3** Chamber+Duct system air changes per hour (ACH).
**11.4.4** Mixing fans (airflow, make/model, rotation speed, location).
**11.4.5** Temperature (T)/relative humidity (RH) control system.
**11.4.6** Sampler/ing description and location for challenge gases and byproducts .

**11.5** Challenge Gas and Byproducts
**11.5.1** Challenge Gas name.
**11.5.2** Target Concentration.
**11.5.3** Gas generation method.
**11.5.4** Analysis methods and instruments used for challenge gases and byproducts.

**11.6** Operating conditions and test data
**11.6.1** T in Celsius (Fahrenheit) (average and range).
**11.6.2** RH (average and range).

**11.6.3** Atmospheric pressure.
**11.6.4** Measured challenge concentration (average and range).
**11.6.5** Background requirements are met (Yes/No).
**11.6.6** Length (time) of each test (natural and total decay).
**11.6.7** The calculated $Q_{ECA}$ for the challenge gas and byproduct concentrations when above concentration limit in Table 6.2.

**11.7** Diagrams, Tabulated Data, and Graphs
**11.7.1** Diagram of sampling points, mixing fan location(s), and T/RH control instrument.
**11.7.2** For challenge gas, both tables of concentration and graphs, both with respect to time.
**11.7.3** Tabulate Net % Red for each contaminant at all acceptable time points. Also, tabulate %RED for both Natural Decay and Total Decay tests. Also graphs.
**11.7.4** Byproducts shall be reported as 15 minute averages over the duration of the test per Section 6.4.

**11.8** Required disclaimer to be on the cover or page 1 of the report: The data presented in this report represent conditions existing in this test system consisting of a duct+ chamber with recirculation. Caution must be exercised in drawing conclusions from the data contained in this report as to the efficacy of the air cleaner under different circumstances. If changes are made to any aspect of the air cleaner design that may change or alter the performance, the air cleaner will need to be retested.

**11.9** Example 145.4 Test Report (following page)

## ASHRAE Standard 145.4 Test Report

### Test Laboratory Information (Sections 11.1)

| | | | |
|---|---|---|---|
| Report Number: | | Test Date: | |
| Test Laboratory: | | Operator: | |
| Laboratory Location: | | Test Requested By: | |

### Product Information (Section 11.2)

| | | |
|---|---|---|
| Manufacturer: | | Photo or Drawing of Device During Test: |
| Product Name: | | |
| Model Number: | | |
| Setting(s): | | |
| Nominal Dimensions (cm/in): | | |
| Location of Device: | Chamber/ Duct | |
| Device Description: | | |

### Test Description (Section 11.3)

| | | | |
|---|---|---|---|
| Product Conditioning: | | IDAC Duct Velocity: | |
| DUT Voltage/Wattage: | | | |
| IDAC Sealing Description: | | | |
| Deviation from Manufacturer Installation: | | | |

### Chamber+Duct System Description (Section 11.4)

| | | | |
|---|---|---|---|
| Chamber Dimensions: | | Chamber Volume: | |
| Duct Dimensions: | | Duct Airflow (cfm): | |
| Duct Velocity: | | Duct Attachment locations: | |
| ACH: | | Temp. and RH Control Systems: | |
| Mixing Fans airflow: | | Mixing Fan Description: | |
| Sampler Descriptions: | | Sampler Locations: | |

### Challenge Gas and Byproducts (Section 11.5)

| | | | |
|---|---|---|---|
| Challenge Gas name: | | Target Concentration (ppb): | |
| Gas Generation Method: | | Challenge Analytical Method: | |

### Operating Conditions and Test Data (Section 11.6)

| | | | |
|---|---|---|---|
| Temperature Avg and Range: | | Relative Humidity Avg and Range: | |
| Atmospheric Pressure: | | Background Requirements Met: Yes No | |
| **Natural Decay** Length of Test: | | **Total Decay** Length of Test: | |
| **Natural Decay** Starting & Ending Conc.: | | **Total Decay** Starting & Ending Conc.: | |
| **Natural Decay** Slope: | | **Total Decay** Slope: | |

**Calculated $Q_{ECA}$ (cfm):**

| **Byproducts** | **Conc.** | **Analytical Method** | **Byproducts** | **Conc.** | **Analytical Method** |
|---|---|---|---|---|---|
| UFP | | | $NO_2$+NO | | |
| Formaldehyde | | | $SO_2$ | | |
| Acetaldehyde | | | Individual VOCs | | |
| Ozone | | | | | |

**Attached tabulated data, graphs and diagrams (Section 11.7)**

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# NORMATIVE APPENDIX A
# KINETICS OF $NO_2$ REDUCTION

It is common for NO to be produced when $NO_2$ is the challenge gas and NO is formed at a higher concentration than other byproducts. Due to the $NO_2$ and NO relationship, if the reduction of $NO_2$ was reported exclusively, it would overestimate the performance of the DUT. The following describes the assumptions and kinetics for $NO_2$ and NO and how to calculate the effective $Q_{ECA}$ for $NO_2$+NO rather than just $NO_2$.

Kinetics of $NO_2$ reduction

The basic assumption here is that although there may be many mechanisms involved in the removal of $NO_2$, they can be simplified into processes that remove $NO_2$ from the atmosphere during testing and processes that convert $NO_2$ to NO during the test.

$$NO_2 \overset{K}{\rightarrow} C \cdot NO_2 + NO + C \cdot O$$

$NO_2$ reduction during testing can be considered as the sum of multiple pathways.

$$NO_2 \overset{k_1}{\rightarrow} C \cdot NO_2 \qquad \text{Reaction 1}$$

$$NO_2 \overset{k_2}{\rightarrow} C \cdot O + NO \qquad \text{Reaction 2}$$

Where reaction 1 represents $NO_2$ that has been bound to the carbon $C·NO_2$ or is otherwise removed from the concentration in the atmosphere. Reaction 2 represents $NO_2$ being converted to NO with C·O representing some oxide being formed that results from the conversion, the identity of which is inconsequential for our purposes.

The observed reduction rate constant, *K*, that is being measured by following the reduction of $NO_2$ during testing is the sum of all removal pathways.

$$K = k_1 + k_2 \qquad \text{Equation 1}$$

The rate constant that is of interest for measuring only how much $NO_2$ is removed without being converted to NO is $k_1$.

The equation used for first order kinetics tracks the rate of change of the reactant, in this case, $NO_2$, as follows.

$$-\frac{d[A]}{dt} = K[NO_2] \qquad \text{Equation 2}$$

Integrating this rate law gives

$$[NO_2]_t = [NO_2]_i e^{-Kt} \qquad \text{Equation 3}$$

Where $[NO_2]_i$ is the initial concentration of $NO_2$ and $[NO_2]_t$ is the concentration at time *t*.

However, with multiple pathways each with different rates from reaction 1 and 2, the rate law becomes the sum of each individual rate:

$$-\frac{d[A]}{dt} = k_1[NO_2] + k_2[NO_2] \qquad \text{Equation 4}$$

$$[NO_2] = [NO_2]_i e^{-(k_1+k_2)t}$$ Equation 5

In order to separate $k_1$ and $k_2$ from the effective rate constant, *K,* the concentration of the products can be used with the rate of formation of products defined as:

$$\frac{d[C\cdot NO_2]}{dt} = k_1[NO_2]$$ Equation 6

$$\frac{d[NO]}{dt} = k_2[NO_2]$$ Equation 7

Integrating these rate laws with the boundary condition that at time zero the initial concentration of products is zero results in:

$$[C \cdot NO_2]_t = \frac{k_1[NO_2]_i}{k_1+k_2}\left(1 - e^{-(k_1+k_2)t}\right)$$ Equation 8

$$[NO]_t = \frac{k_2[NO_2]_i}{k_1+k_2}\left(1 - e^{-(k_1+k_2)t}\right)$$ Equation 9

During the testing [NO] and [$NO_2$] are both being measured, through these the amount of bound $NO_2$ denoted as [$C\cdot NO_2$] can be determined since $NO_2$ is either being effectively bound for the duration of test or converted to NO such that the following relationship holds at any time *t*:

$$[NO_2]_i = [NO_2]_t + [C \cdot NO_2]_t + [NO]_t$$ Equation 10

Combining equations 8 and 9 gives:

$$\frac{[NO]_t}{[C\cdot NO_2]_t} = \frac{k_2}{k_1}$$ Equation 11

Substituting in the relationships noted in equations 1 and 10 results in:

$$\frac{[NO]_t}{[NO_2]_i-([NO_2]_t+[NO]_t)} = \frac{K-k_1}{k_1}$$ Equation 12

In equation 12, all values other than $k_1$ are measured during testing, solving for $k_1$ gives:

$$k_1 = \frac{K}{\frac{[NO]_t}{[NO2]_i-([NO_2]_t+[NO]_t)}+1}$$ Equation 13

Using data collected during testing, K can be calculated through the traditional route plotting $\ln\frac{[NO_2]_t}{[NO_2]_i}$ vs. *t* and solving for the slope. The concentrations of NO and $NO_2$ at the end of the test can then be used in equation 13 to calculate k1. The effective $Q_{ECA}$ for $NO_2$ reduction is then:

$$Q_{ECA} = V(k_1 - k_n)$$ Equation 14

Where $k_n$ is the rate constant measured during the natural decay test of $NO_2$ which should be near zero in a well performing chamber.

# INFORMATIVE APPENDIX B
# DUCT TRANSITIONS

The following is taken directly from ASHRAE Standard 52.2-2017[2]:

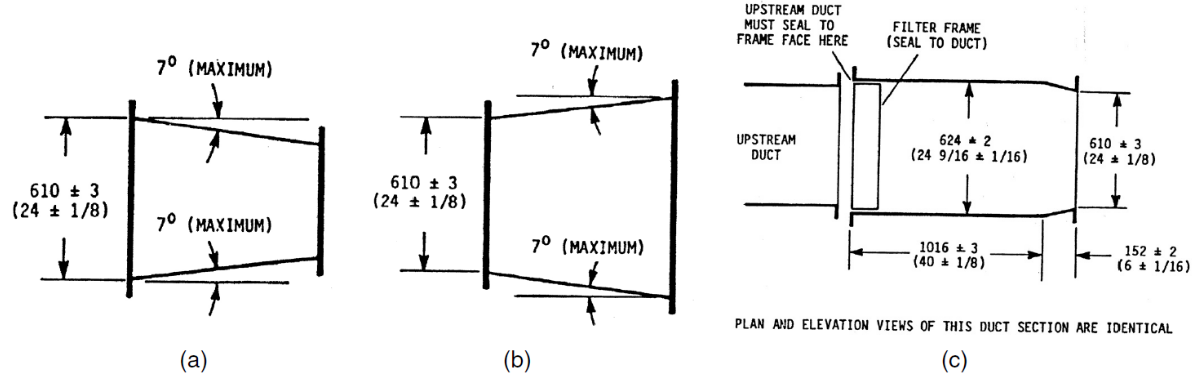


**Figure 4-3 Dimensions are in mm (in.).**
**(a) Transition: test air-cleaner dimensions smaller than test duct (asymmetrical dimensions are allowed).**
**(b) Transition: test air-cleaner dimensions larger than test duct (asymmetrical dimensions are allowed).**
**(c) Allowable special duct section for nonrigid air cleaners (must be symmetrical).**

# INFORMATIVE APPENDIX C
# EXAMPLE CALCULATION

In the example below, a 1000 ft$^3$ chamber with 100 ft$^3$ side duct is used for a test starting at 800 µg/m$^3$. Note that the example works the same if the concentration is in other units. The important units are the time and chamber volume. If you want to use, for example, m$^3$/h, you may convert the answer from cfm to m$^3$/h or use the units of m$^3$ and h to make your data table and do the calculations.

The Natural Decay test concentration goes down slowly while the Total Decay test concentration went down faster. Once the data is tabulated, a simple linear graph is recommended simply to make sure the data is rational, that it makes sense. The curves should be either fairly stable at or near the initial value or decrease over time. It is unlikely that the Total Decay will be higher than the Natural Decay at the end of the test. If this occurs and the initial concentration was close, check your data for errors. Even if the DUT doesn't work at all, less decrease than the Natural Decay may indicate an unnoticed leak in the Natural Decay test that was plugged for the Total Decay test or a similar issue. Zigzags in the data are not usual, some variability is likely.

Preparing a log linear chart should show essentially linear data. For some DUTs, this may not be true. If there is a distinct change in slope and the early portion of the test has enough data points, you may want to report the ECA based on just this data.

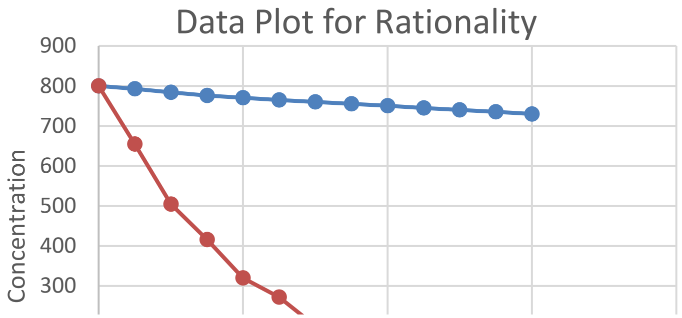
Calculate the natural logarithm (ln) of the concentration, then calculate the slope and R$^2$ of the ln(Conc) vs time relationship. If the R$^2$ is acceptable, the slope will be your k value.

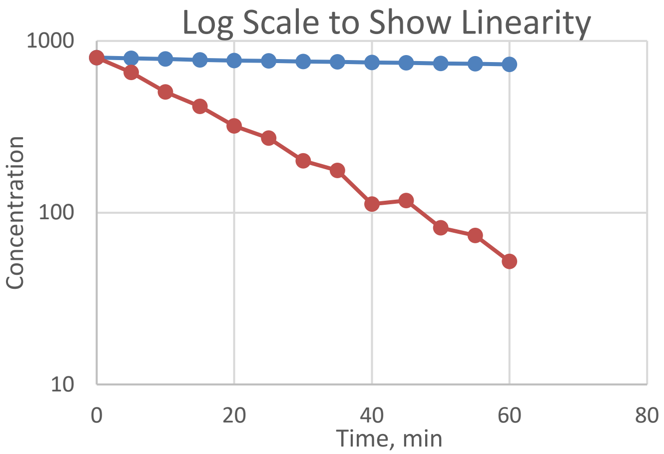
Do these steps for both the Natural Decay and the Total Decay tests. Then calculate the $Q_{ECA}$ from the Total Volume of the chamber and side duct times the difference between the two k-values. Note that if the concentrations went down faster during the Total Decay than the Natural Decay, the $Q_{ECA}$ value will be a positive number.

Chamber Volume ($ft^3$) = 1000
Duct Volume ($ft^3$) = 100
Total Volume ($ft^3$) = 1100

$Q_{ECA}$= 47.9 cfm

| **Natural Decay** | | | |
|---|---|---|---|
| Time (min) | Concentration | ln ( C ) | k value |
| 0 | 800 | 6.68 | 0.0015 |
| 5 | 793 | 6.68 | |
| 10 | 784 | 6.66 | |
| 15 | 776 | 6.65 | $R^2$ |
| 20 | 770 | 6.65 | 0.992 |
| 25 | 765 | 6.64 | |
| 30 | 760 | 6.63 | |
| 35 | 755 | 6.63 | |
| 40 | 750 | 6.62 | |
| 45 | 745 | 6.61 | |
| 50 | 740 | 6.61 | |
| 55 | 735 | 6.60 | |
| 60 | 730 | 6.59 | |





| **Total Decay** | | | |
|---|---|---|---|
| Time (min) | Concentration | ln ( C ) | k value |
| 0 | 800 | 6.68 | 0.0450 |
| 5 | 654 | 6.48 | |
| 10 | 505 | 6.22 | |
| 15 | 416 | 6.03 | $R^2$ |

| | | | |
|---|---|---|---|
| 20 | 320 | 5.77 | 0.994 |
| 25 | 272 | 5.61 | |
| 30 | 200 | 5.30 | |
| 35 | 176 | 5.17 | |
| 40 | 112 | 4.72 | |
| 45 | 118 | 4.77 | |
| 50 | 82 | 4.40 | |
| 55 | 74 | 4.30 | |
| 60 | 52 | 3.95 | |