



Designation: D8405 – 21

Standard Test Method for Evaluating PM_{2.5} Sensors or Sensor Systems Used in Indoor Air Applications¹

This standard is issued under the fixed designation D8405; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method uses a chamber system to evaluate the performance of stationary PM_{2.5} sensors (sensors) and particle sensor systems (sensor systems) subjected to various test conditions, including temperature, relative humidity, PM_{2.5} concentration, and coarse PM interferent concentration.

1.1.1 This test method covers sensors and sensor systems that can be continuously powered and continuously operated for the duration of any test described in this method through line power or an internal battery of sufficient output. This test method is not meant to evaluate sensors or sensor systems without these capabilities.

1.1.2 This test method evaluates the performance of sensors and sensor systems that allow users to collect data in a systemic manner to assess the capabilities and limitations of these devices.

1.1.3 This test method is not meant to evaluate sensors or sensor systems without data storage and recording capabilities.

1.1.4 This test method is not intended to evaluate indoor air quality sensors and sensor systems for purposes of regulation of outdoor air, homeland security, law enforcement or forensic activity.

1.2 The values stated in SI units are to be regarded as standard. The values given in parentheses after SI units are provided for information only and are not considered standard.

1.3 The text of this standard references notes and footnotes that provide explanatory material. These notes and footnotes (excluding those in tables and figures) shall not be considered as requirements of the standard.

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

1.5 *This international standard was developed in accordance with internationally recognized principles on standard-*

¹ This test method is under the jurisdiction of ASTM Committee D22 on Air Quality and is the direct responsibility of Subcommittee D22.05 on Indoor Air.

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ization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.

2. Referenced Documents

2.1 ASTM Standards:²

D1356 Terminology Relating to Sampling and Analysis of Atmospheres

D3670 Guide for Determination of Precision and Bias of Methods of Committee D22

D6330 Practice for Determination of Volatile Organic Compounds (Excluding Formaldehyde) Emissions from Wood-Based Panels Using Small Environmental Chambers Under Defined Test Conditions

E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method

E3080 Practice for Regression Analysis with a Single Predictor Variable

2.2 International Standards Organization (ISO) Standards:³

ISO 8573-1 Requirements for the purity of compressed air with respect to particles, water, and oil

ISO 12103-1 Road vehicles — Test contaminants for filter evaluation — Part 1: Arizona test dust

ISO 17025 General requirements for the competence of testing and calibration laboratories

2.3 United States (U.S.) Code of Federal Regulations (CFR):⁴

Title 40 Part 53 Requirements for ambient particulate instruments to attain U.S. Environmental Protection Agency (EPA) Federal Equivalent Method (FEM) designations

Title 40 Part 58 Terminology relating to particulate matter fractions

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

³ Available from International Organization for Standardization (ISO), ISO Central Secretariat, Chemin de Blandonnet 8, CP 401, 1214 Vernier, Geneva, Switzerland, <https://www.iso.org>.

⁴ Available from U.S. Government Publishing Office (GPO), 732 N. Capitol St., NW, Washington, DC 20401, <http://www.gpo.gov>.

2.4 U.S. EPA Standards:⁵

Method IP-10A Determination of respirable particulate matter in indoor air

2.5 U.S. Department of Energy (DOE) Standards:⁴

DOE-STD-3020 Specification for HEPA filters used by DOE contractors

3. Terminology

3.1 *Definitions*—For definitions of terms used in this test method, refer to Terminology **D1356**.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *indoor air, n*—air within an enclosed space (structure or vehicle), which is (1) intended for habitation, employment, leisure, retail, transport, or any other forms of occupation by humans and (2) conditioned for temperature or relative humidity (RH), or both, or does not allow for free air change with outdoor air other than through unintentional leakage or filtered mechanical ventilation.

3.2.2 *indoor air quality particle sensors, n*—sensors used to measure and report particle content of indoor air and intended for use in indoor air quality applications.

3.2.3 *intra-model, adj*—within a group of sensor systems of the same make, model, and firmware version. Intra-model results are developed by applying a mathematical operation to a data set developed from testing multiple test sensors or test sensor systems of the same make, model, and firmware version.

3.2.4 *intra-unit, adj*—within an individual unit. Intra-unit results are developed by applying a mathematical operation to a data set developed from testing one test sensor or test sensor system.

3.2.5 *particle-negligible air, n*—purified air for which particles, moisture and other substances that can interfere with a measurement are reduced to meet or exceed purity as specified in ISO 8573-1 for Class 2.4.1 air, that is: solid particulate number concentrations not exceeding (1) 400 000 per m³ for 0.1–0.5 μm diameter particles, (2) 6000 per m³ for 0.5–1 μm diameter particles, and (3) 100 per m³ for 1–5 μm diameter particles; water vapor content not exceeding a vapor pressure dewpoint of 3°C; and total oil content not exceeding 0.01 mg/m³.

3.2.5.1 *Discussion*—For the purposes of this standard, particle-negligible air has particles reduced to concentrations at or below the limit of detection of PM_{2.5} mass concentration reference monitor being used in this test method.

3.2.6 *PM₁₀, n*—particles collectable by a sampler with an upper 50 % cut point of 10 μm in aerodynamic diameter, along with other conditions as defined in the U.S. CFR Title 40, Part 58.

3.2.7 *PM_{2.5}, n*—particles collectable by a sampler with an upper 50 % cut point of 2.5 μm in aerodynamic diameter, along with other conditions as defined in the U.S. CFR Title 40, Part 58.

3.2.8 *PM_{2.5} sensor, n*—a device capable of reporting the concentration of PM_{2.5} in the air without additional manipulation of the data.

3.2.9 *PM_c, n*—particles with an aerodynamic diameter less than or equal to 10 μm and greater than 2.5 μm, often referred to as “coarse” PM; equivalent to the difference between PM₁₀ and PM_{2.5}; equivalent to the definition of PM_{10–2.5} as defined in the U.S. CFR Title 40, Part 58.

3.2.10 *reference monitor, n*—an instrument with a U.S. EPA performance designation of Class III FEM for PM_{2.5}, excluding those using beta attenuation techniques, measuring particle mass concentration or particle mass size distribution, or both, against which test sensors or test sensor systems are compared.

3.2.10.1 *Discussion*—The U.S. EPA FEM designation (1)⁶ is only applicable to, and valid for, stationary ambient monitoring applications. However, FEM designation is required for reference monitors used within this test method to provide a reasonable level of confidence in the acceptability of the reference monitor’s accuracy and precision.

3.2.11 *sensor system, n*—a collection of sensors with integrated power, integrated communication to a user interface, and a user interface.

3.2.12 *test characterization chamber, n*—a chamber into which test sensors or test sensor systems are placed, into which particles are introduced to evaluate the performance of the test sensor or test sensor system, and from which the reference monitor(s) is (are) sampling.

3.2.13 *test sensor, n*—a single sensor evaluated according to this test method.

3.2.14 *test sensor system, n*—a sensor system evaluated according to this test method.

3.2.15 *test system, n*—a system including a test characterization chamber, reference monitor(s), particle systems, and other equipment needed to generate the conditions required for this test method.

4. Summary of Test Method

4.1 This test method uses a test characterization chamber system to evaluate indoor air quality particle sensors and sensor systems on their capabilities to detect and measure particles against reference PM monitors.

4.2 PM_{2.5} is introduced into the test characterization chamber, and test sensors or test sensor systems are tested at prescribed, steady-state concentrations. The test system uses instruments that meet performance criteria demonstrating equivalence with established reference methods, along with ancillary instruments, to evaluate the performance of the test sensors or test sensor systems.

4.3 The test sensor’s or test sensor system’s capabilities are evaluated based on the following parameters: Average; Standard Deviation (SD); Relative Standard Deviation (RSD); Bias; Precision; Intra-Model Variability (IMV); Mean Error; Pearson Linear Coefficient of Determination (*R*²); Climate

⁵ Available from United States Environmental Protection Agency (EPA), William Jefferson Clinton Bldg., 1200 Pennsylvania Ave., NW, Washington, DC 20460, <http://www.epa.gov>.

⁶ The boldface numbers in parentheses refer to the list of references at the end of this standard.

Susceptibility; Response to Interferents; Drift (Span); Data Recovery; and Response to Loss of Power.

5. Significance and Use

5.1 Poor indoor air quality has been implicated in significant adverse acute and chronic impacts on occupant health and performance. The ability to assess the components contributing to poor indoor air quality is critical for determining best practices for improving indoor air quality.

5.2 Measurement of pollutants in indoor environments using sensors and sensor systems provides information needed to improve indoor air quality through pollutant source control, ventilation, filtration or other treatments.

5.3 This method uses a test characterization chamber system equipped with reference monitor(s) to evaluate the response of test sensors or test sensor systems to specific types of particles (for example, salt, polystyrene latex, or dust). To facilitate reproducible results, the test particles used within this method are standardized and have known properties. The user is cautioned that a single particle type is not representative of all particles found indoors. The relative response of test sensors or test sensor systems to a reference monitor can vary by a factor of two for different particle types (for example, primary or secondary, organic or inorganic, outdoor or indoor origin; see 6.11.3 for further discussion). Furthermore, the user is cautioned that the lower limit of particle size detection for optical test sensors and test sensor systems is generally 0.3 μm in diameter; particles below this size are generally undetected and may represent a significant health concern as well.

6. Apparatus

6.1 The test system, used for testing particle sensors and sensor systems, shall include a test characterization chamber. The test characterization chamber is composed of stainless steel or an equivalently non-corrosive and electrically conductive material. The test characterization chamber is constructed to be airtight in accordance with Practice D6330, such that the air leakage rate of the test characterization chamber at +10 Pa gauge pressure shall be less than 1 % of the air change rate under normal operation during sensor tests. Airtightness is measured as follows: (1) seal the outlet(s) of the test characterization chamber; (2) supply air to the test characterization chamber through the inlet and adjust the airflow rate such that the pressure difference between the inside and outside of the test characterization chamber is maintained at 10 ± 1 Pa, measured by pressure transducer with a minimum specified accuracy of ± 1 Pa; and (3) measure the airflow with a device that has a minimum specified accuracy of ± 2 %. This measured airflow is the leakage rate of the test characterization chamber. The minimum test characterization chamber size is such that the cross-sectional area of the arrangement of triplicate test sensors or test sensor systems projected onto any interior face of the test characterization chamber does not exceed 15 % of the area of that interior face.

6.1.1 *Discussion*—Stainless steel is specified as a material for some components in this test standard because it is electrically conductive and non-reactive with the substances used, under the sensor evaluation environmental conditions, in

this test method. According to Baron and Willeke (2), it is important that as many components as possible are electrically conductive to minimize the creation or presence of electric fields in the test characterization chamber that will contribute to particle losses due to static cling to surfaces, biasing the particle concentration in the vicinity of a reference monitor sampling probe or test sensor or test sensor system.

6.2 The test system shall be capable of maintaining air temperature with a minimum range of 20°C to 50°C within the test characterization chamber. All temperature conditions tested in this standard shall be within a tolerance of $\pm 2^\circ\text{C}$. At a minimum, test system temperature probe(s) are calibrated at the vendor-specified frequency using standard reference materials and shall have a minimum specified accuracy of $\pm 1.0^\circ\text{C}$.

6.3 The test system shall be capable of generating a RH range of at least 40 % to 80 % within the test characterization chamber. All RH values listed in this standard shall be within a tolerance of ± 10 %. At a minimum, test system RH probe(s) shall be calibrated at the vendor-specified frequency using standard reference materials and shall have a minimum specified accuracy of ± 2 %.

6.4 The test system includes an instrument serving as a reference monitor possessing U.S. EPA performance designation of Class III FEM for $\text{PM}_{2.5}$. The reference monitor shall be capable of simultaneously providing high-resolution, real-time measurements of both PM_{10} and $\text{PM}_{2.5}$. The reference monitor shall have a time resolution of 1 minute or less. The reference monitor sampling system shall include a particle drying system that can remove moisture from a test characterization chamber air sample at 50°C and 80 % RH, such that the RH of the sample is reduced to no more than 40 % at the temperature of the reference monitor measurement cell. If the reference monitor uses optical scattering, aerodynamic time-of-flight, or electrical mobility techniques, the reference monitor manufacturer shall either provide the particle density used to calculate particle mass, or the reference monitor shall report both particle mass and number size distributions that will allow equivalent spherical particle density to be calculated.

6.5 The test system includes any number of additional instruments to act as supplementary reference monitor(s) capable of providing high-resolution measurements of the particle mass size distribution over the entire particle diameter range from at least 20 nm to 20 μm , if the reference monitor does not already possess this capability. The supplementary reference monitor(s) shall have a time resolution of 5 minutes, or less.

6.6 The test system includes a dynamically controlled fan, or system of fans, and any ancillary components necessary to mix the air within the test characterization chamber to homogeneity. Homogeneity occurs when the average $\text{PM}_{2.5}$ concentration ($n = 20$), for any level specified in this test method, measured with the reference monitor (FEM) does not deviate by more than ± 2 % between the four locations where the three test sensors and one reference monitor sampling probe are located within the test characterization chamber. The test

system shall include dehumidification coils and heating elements or an equivalent system capable of controlling temperature and RH within the specifications described in 6.2 and 6.3, respectively. The fan or system of fans shall be capable of moving air across the dehumidification coils and heating elements. The test system shall be equipped with at least one particle system. An example of a test system is presented in Fig. 1.

6.6.1 *Discussion*—An example of an ancillary component used to mix the air within a test characterization chamber to homogeneity is a mechanized, louvered ceiling that would assist in distributing the air from mixing fans. This test method does not prescribe a mixing airflow rate or an airflow rate through the test characterization chamber; rather, it establishes performance parameters to ensure that the airflow is sufficient to achieve homogeneity under steady state conditions.

6.7 To preclude infiltration of air from outside of the chamber from entering the test characterization chamber, the test characterization chamber shall be maintained at a positive air pressure with respect to the air outside of the chamber. A minimum positive space pressure of 10 Pa shall be continuously maintained throughout the test. This may be accomplished by adjusting the total supply air to the test characterization chamber to exceed the total exhaust air from the chamber. The total exhaust air from the test characterization chamber includes the sum of all air removed from the chamber, including all air sampling devices (for example, reference monitors, gravimetric PM_{2.5} samplers for calibrations, aerosol generators, etc.).

6.8 *Sensor Mounting Devices*—The test characterization chamber shall have stainless steel or equivalently non-corrosive and electrically conductive material mounting de-

vices to hold, hang, or otherwise support test sensors or test sensor systems. The mounting devices shall be capable of supporting at least 3 test sensors or test sensor systems. The mounting devices shall be positioned so that all test sensors or test sensor systems and the reference monitor(s) encounter equivalent exposure as specified in 6.6.

6.9 The reference monitor and its sampling probe shall be connected to the test characterization chamber in a way that limits line losses of PM_{2.5} and PM₁₀ by mass to a maximum of 2 %. Reference monitor sampling probe materials shall consist of stainless steel or conductive silicone tubing, if the instrument does not already include a vendor-supplied sampling probe.

6.10 *Particle Neutralizer*—A bipolar particle neutralizer is installed in the test system downstream of the particle system and upstream of the test characterization chamber. The test characterization chamber interior surfaces and sensor mounting devices shall be electrically grounded or provided with a means to discharge any charged particles present in the test characterization chamber.

6.10.1 *Discussion*—According to Baron and Willeke (2), particles can possess electrostatic charges that influence their movement and losses within an electric field or in the vicinity of conductive and dielectric materials. In ambient air, a very small fraction of particles is electrically charged. However, aerosol nebulization or powder dispersion can generate particles with a significant fraction possessing single or multiple charges. Removing charges from particles is important to reduce particle loss to stray electric fields and adherence to the walls of the test characterization chamber or chamber components, as well as ensuring unbiased measurements if a reference monitor uses particle electrical mobility as the

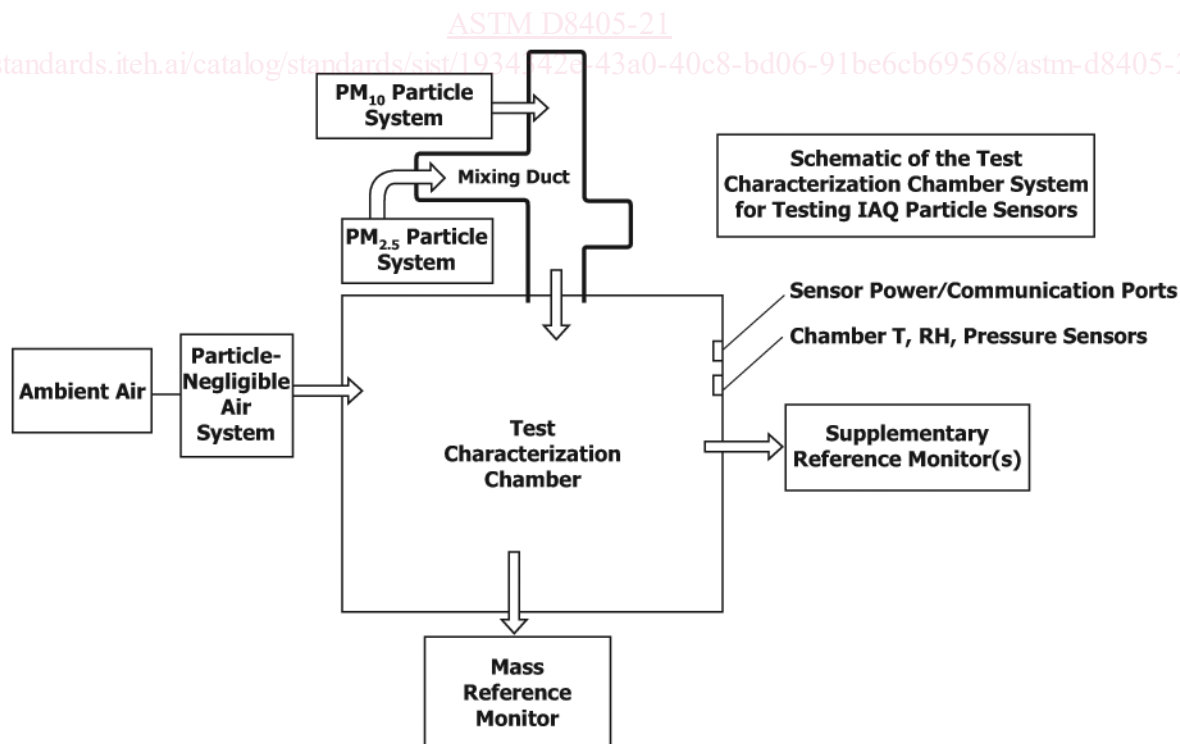


FIG. 1 Example Test System

operation principle. Commercially available particle neutralizers employ radionuclides, soft X-rays, or corona-discharge methods, and can be unipolar (remove only positive or negative charges) or bipolar (remove both types of charges).

6.11 Particle Monitors:

6.11.1 The reference monitor shall have a PM_{2.5} measurement accuracy that meets or exceeds the accuracy requirement of the certification scheme under which it was approved. At a minimum, reference monitors shall be initially calibrated at an ISO 17025 accredited facility following manufacturer guidelines at a frequency no less than the lesser of 12 months or the manufacturer-recommended frequency.

6.11.2 No more than 24 hours prior to Phase 1 of each test, the reference monitor accuracy shall be checked using gravimetric samples from inside the test characterization chamber.

6.11.2.1 The reference monitor accuracy check shall be conducted in accordance with EPA Method IP-10A with the exceptions that a 10 L/min gravimetric sampler with a 2.5 μm size selective inlet and 37 mm polytetrafluoroethylene (PTFE) filters shall be used. The gravimetric sampler shall be located near the center of the test characterization chamber and within 10 cm of the reference monitor inlet. In addition, a mass flow controller shall be utilized to ensure that the gravimetric sampler flow rate is maintained at 10 ± 0.2 L/min.

6.11.2.2 *Zero Concentration*—The inlet of the reference monitor shall be presented a concentration of HEPA-filtered air that does not impact the reference monitor air sampling flow rate. When the standard deviation of at least 20 consecutive measurements from the reference monitor is less than 0.1 μg/m³, the average of those measurements shall be recorded as \bar{R}_{zero} . The gravimetric sampler does not operate during this zero-concentration measurement.

6.11.2.3 *Span Concentration with Inorganic Particles*—The PM_{2.5} inorganic particle source identified in 6.11.2 shall be introduced into the test characterization chamber such that the reference monitor reports a concentration of 300 ± 30 μg/m³ and a relative standard deviation of less than 5 % over 20 consecutive measurements. When this stable condition has been achieved, the gravimetric sampler shall commence operation. Both the reference monitor and gravimetric sampler shall continue to operate during this stable condition for a minimum of 2 hours. The average of the reference monitor concentration during the entire time period the gravimetric sampler was operated shall be recorded as $\bar{R}_{span, inorganic}$. The concentration measured by the gravimetric sampler shall be recorded as $GS_{span, inorganic}$ and shall be calculated using the following equation:

$$GS_{span, inorganic} (\mu\text{g}/\text{m}^3) = \frac{m_{final, inorganic} - m_{initial, inorganic}}{(\bar{Q}_{inorganic} / 1000) \times t_{span, inorganic}} \quad (1)$$

where:

- $m_{final, inorganic}$ = the mass of the filter at the end of the inorganic span concentration sampling period (μg);
- $m_{initial, inorganic}$ = the mass of the filter at the start of the inorganic span concentration sampling period (μg);

- $\bar{Q}_{inorganic}$ = the average gravimetric sampler flow rate during the inorganic span concentrations sampling period (L/min); and
- $t_{span, inorganic}$ = the duration of inorganic span concentration sampling period (min).

If $\bar{R}_{span, inorganic}$ is within ±10 % of $GS_{span, inorganic}$, the reference monitor may proceed to the accuracy check in 6.11.2.4. If $\bar{R}_{span, inorganic}$ is not within ±10 % of $GS_{span, inorganic}$, the reference monitor shall be recalibrated in accordance with 6.10.1.

6.11.2.4 *Span Concentration with Organic Particles*—The PM_{2.5} organic particle source identified in 6.11.2 shall be introduced into the test characterization chamber such that the reference monitor reports a concentration of 300 ± 30 μg/m³ and a relative standard deviation of less than 5 % over 20 consecutive measurements. When this stable condition has been achieved, the gravimetric sampler shall commence operation. Both the reference monitor and gravimetric sampler shall continue to operate during this stable condition for a minimum of 2 hours. The average of the reference monitor concentration during the entire time period the gravimetric sampler was operated shall be recorded as $\bar{R}_{span, organic}$. The concentration measured by the gravimetric sampler shall be recorded as $GS_{span, organic}$ and shall be calculated using the following equation:

$$GS_{span, organic} (\mu\text{g}/\text{m}^3) = \frac{m_{final, organic} - m_{initial, organic}}{(\bar{Q}_{organic} / 1000) \times t_{span, organic}} \quad (2)$$

where:

- $m_{final, organic}$ = the mass of the filter at the end of the organic span concentration sampling period (μg);
- $m_{initial, organic}$ = the mass of the filter at the start of the organic span concentration sampling period (μg);
- $\bar{Q}_{organic}$ = the average gravimetric sampler flow rate during the organic span concentrations sampling period (L/min); and
- $t_{span, organic}$ = the duration of organic span concentration sampling period (min).

If $\bar{R}_{span, organic}$ is within ±10 % of $GS_{span, organic}$, the reference monitor may proceed to the test procedures in Section 10. However, if $\bar{R}_{span, organic}$ is not within ±10 % of $GS_{span, organic}$, an organic calibration function shall be applied to the reference monitor measurements as described in 6.11.2.5.

6.11.2.5 If the reference monitor did not satisfy the criteria in 6.11.2.4, an organic calibration function shall be created to correct the reference monitor measurements specifically when sampling organic particles. The organic calibration shall include a four-point calibration at 0 μg/m³, 50 μg/m³, 150 μg/m³, and 300 μg/m³. The reference monitor value \bar{R}_{zero} from 6.11.2.2 and a zero for the gravimetric value are used for the 0 μg/m³ data point. The reference monitor value $\bar{R}_{span, organic}$ and gravimetric sampler value $GS_{span, organic}$ from 6.11.2.4 are used for the 300 μg/m³ data point. The particle generation and measurement process described in 6.11.2.4 shall be repeated for 50 ± 5 μg/m³ and 150 ± 15 μg/m³ target concentrations. A simple linear regression calibration correction equation shall be

developed to correct all organic particle data from the reference monitor as described in Practice E3080 where:

$$Y = \beta_1 X + \beta_0 \quad (3)$$

where:

X = the set of averaged $PM_{2.5}$ values ($\mu\text{g}/\text{m}^3$) reported by the reference monitor at the 0, 50, 150, and 300 $\mu\text{g}/\text{m}^3$ calibration points;

Y = the set of $PM_{2.5}$ values ($\mu\text{g}/\text{m}^3$) reported by the gravimetric sampler at the 0, 50, 150, and 300 $\mu\text{g}/\text{m}^3$ calibration points;

β_1 = regression slope; and

β_0 = regression intercept.

The organic calibration function shall only be used to correct reference monitor measurements collected during Phase 1 testing using the $PM_{2.5}$ organic particle source identified in 6.11.2, in the following manner:

$$R_{\text{organic}} = \beta_1 R + \beta_0 \quad (4)$$

where:

R_{organic} = the reference monitor organic $PM_{2.5}$ concentration after correction against the gravimetric sampler;

R = the reference monitor organic $PM_{2.5}$ concentration before correction against the gravimetric sampler;

β_1 = regression slope; and

β_0 = regression intercept.

6.11.3 Measurement Corrections:

6.11.3.1 Particle Density:

(1) The particle density values used in this test method shall be 2.65 g/cm^3 for Arizona Test Dust Grade A4 Coarse, 2.17 g/cm^3 for sodium chloride, and 1.05 g/cm^3 for polystyrene latex spheres.

(2) The particle mass concentrations reported by reference monitor(s) using gravimetric filter, or tapered element oscillating microbalance shall not be corrected, for the purposes of evaluation parameter calculations or to account for any differences in particle density values of the particles generated in this test method.

(a) *Discussion*—According to Baron and Willeke (2), the principles of operation for gravimetric filter and tapered element oscillating microbalance particle measurements are directly related to the mass of particles and are therefore not affected by assumed particle density values.

(3) The particle mass concentrations reported by reference monitor(s) using optical scattering, aerodynamic time-of-flight, or electrical mobility techniques shall be corrected, for the purposes of evaluation parameter calculations, to account for any differences in particle density values of the particles generated in this test method and particle density values assumed by the reference monitor manufacturer(s). The particle mass concentrations shall be corrected using the following equation:

$$R = R_0 \times \frac{\rho_{p,\text{actual}}}{\rho_{p,0}} \quad (5)$$

where:

R_0 = the uncorrected particle mass concentration value reported by a reference monitor;

$\rho_{p,\text{actual}}$ = the density of the particles, from 6.11.3.1(1), generated and transported into the test characterization chamber;

$\rho_{p,0}$ = the density of particles assumed by a reference monitor manufacturer; and

R = the corrected particle mass concentration value observed by a reference monitor.

(a) *Discussion*—According to Baron and Willeke (2) and Seinfeld and Pandis (3), the principles of operation for optical scattering, aerodynamic time-of-flight, and electrical mobility measurements are indirectly related to the mass of particles and are therefore affected by assumed particle density values. Manufacturers of optical scattering, aerodynamic time-of-flight, and electrical mobility instruments must assume a particle density value, in some cases to maximize correlation with ambient $PM_{2.5}$ reference measurements. The particle density value assumed by manufacturers of optical scattering, aerodynamic time-of-flight, and electrical mobility instruments often differs greatly from the particle density values of the particles generated in this test method. Therefore, the user shall correct mass concentration values reported by reference monitors using optical scattering, aerodynamic time-of-flight, or electrical mobility techniques to account for either (1) the particle density value explicitly provided by the manufacturer, or (2) the implicit particle density value required to obtain the uncorrected mass concentration reported by the reference monitor given the reported particle mass distribution.

6.11.3.2 Particle Dynamic Shape Factor:

(1) The particle dynamic shape factor values used in this test method shall be 1.5 for Arizona Test Dust Grade A4 Coarse, 1.08 for sodium chloride, and 1.0 for polystyrene latex spheres.

(2) The particle mass concentrations reported by reference monitor(s) using optical scattering techniques shall not be corrected, for the purposes of evaluation parameter calculations, to account for any differences in particle dynamic shape factor values of the particles generated in this test method.

(a) *Discussion*—According to Baron and Willeke (2), analytical functions are lacking to adjust particle mass concentrations reported by optical scattering instruments to account for particle dynamic shape factors. More significantly, diameters of irregularly shaped particles determined through optical scattering techniques have been shown to be nearly identical to those of spherical particles in both limiting cases where particle diameter is much smaller than and much larger than the wavelength of the light source. Given the lack of analytical correction functions and the expected lack of meaningful bias due to differences in dynamic shape factor of particles generated in this test method, correction of measurements to account for particle dynamic shape factor is not justified for optical scattering reference monitor(s).

(3) The sample flow rates of reference monitor(s) using gravimetric filter or tapered element oscillating microbalance that are preceded by a size-selective inlet, such as a cyclone or impactor, shall be adjusted, to account for any differences in particle dynamic shape factor and density values of the particles generated in this test method and particle dynamic

shape factor and density values assumed by the reference monitor manufacturer(s) for proper size-selection by the inlet. The reference monitor manufacturer(s) must be contacted to provide the correct sample flow rates to use such that the size-selective inlet achieves an upper 50 % cut point of 2.5 μm in aerodynamic diameter with the particle densities in 6.11.3.1(1) and the particle dynamic shape factors in 6.11.3.2(1).

(a) *Discussion*—According to Baron and Willeke (2), the principles of operation for gravimetric filter or tapered element oscillating microbalance do not discriminate against particles based on their size. In order to obtain a size-fractionated sample, such instruments are usually preceded by an inlet that uses inertial techniques to allow only particles below a certain diameter to proceed to measurement by the instrument. These inertial inlets, such as cyclones or impactors, are designed with a certain flow rate and assumed particle dynamic shape factor and density values to achieve proper size discrimination. Therefore, if the test particle dynamic shape factor and density values are different from those assumed by the manufacturer, the inlet flow rate must be adjusted to achieve the proper size discrimination. While it may be possible to calculate the maximum particle diameter actually permitted by a size-selective inlet using the particle densities in 6.11.3.1(1) and the particle dynamic shape factors in 6.11.3.2(1), it is usually not possible for a user to correctly determine the flow rate adjustment that must be made for a size-selective inlet to change the maximum particle diameter permitted; this is especially true for cyclones, which lack analytical functions to describe their particle size discrimination behavior. Therefore, the reference monitor manufacturer(s) shall be consulted to obtain correct sample flow rate adjustments to change the maximum particle diameter permitted through the size-selective inlet when using the particles generated in this test method.

(4) The particle diameter bin ranges, as well as any particle mass concentrations that are calculated from particle counts assigned to such bins, reported by reference monitor(s) using aerodynamic time-of-flight techniques, shall be corrected in accordance with reference monitor manufacturer instructions, to account for any differences in particle dynamic shape factor and density values of the particles generated in this test method and particle dynamic shape factor and density values assumed by the reference monitor manufacturer(s). In the absence of manufacturer instructions, the extents of particle diameter bin ranges shall be adjusted using the following iterative equation:

$$D_{p,adj} = D_{p,0} \sqrt{\frac{\chi \rho_{p,0} C_c(D_{p,0})}{\rho_{p,actual} C_c(D_{p,adj})}} \quad (6)$$

$$C_c(D_p) = 1 + \frac{2\lambda}{D_p} \left[1.142 + 0.558 \cdot \exp \left(-0.999 / \left(\frac{2\lambda}{D_p} \right) \right) \right] \quad (7)$$

where:

$D_{p,adj}$ = the adjusted extent of a particle diameter bin range, after accounting for particle dynamic shape factor and density differences;

$D_{p,0}$ = the original extent of a particle diameter bin range assumed by a reference monitor manufacturer;

$\rho_{p,actual}$ = the density of the particles, from 6.11.3.1(1), generated and transported into the test characterization chamber;

$\rho_{p,0}$ = the density of particles assumed by a reference monitor manufacturer;

χ = the dynamic shape factor of the particles, from 6.11.3.2(1), generated and transported into the test characterization chamber;

D_p = the particle diameter;

$C_c(D_{p,adj})$ = the Cunningham slip correction factor for the adjusted extent of a particle diameter bin range;

$C_c(D_{p,0})$ = the Cunningham slip correction factor for the original extent of a particle diameter bin range;

$C_c(D_p)$ = the Cunningham slip correction factor for a given particle diameter D_p ; and

λ = the gas molecular mean free path, which is equal to 0.0665 μm for the purposes of this test standard.

(a) *Discussion*—According to Baron and Willeke (2) and Seinfeld and Pandis (3), the Cunningham slip correction factor accounts for slip flow behavior as particle size decreases and the surrounding gas no longer behaves like a continuum from the perspective of the particle.

(5) The particle diameter bin ranges, as well as any particle mass concentrations that are calculated from particle counts assigned to such bins, reported by reference monitor(s) using electrical mobility techniques, shall be adjusted, to account for any differences in particle dynamic shape factor values of the particles generated in this test method and particle dynamic shape factor values assumed by the reference monitor manufacturer(s). In the absence of manufacturer instructions, the extents of particle diameter bin ranges shall be adjusted using the following iterative equation:

$$D_{p,adj} = \frac{D_{p,0}}{\chi} \cdot \frac{C_c(D_{p,adj})}{C_c(D_{p,0})} \quad (8)$$

$$C_c(D_p) = 1 + \frac{2\lambda}{D_p} \left[1.142 + 0.558 \cdot \exp \left(-0.999 / \left(\frac{2\lambda}{D_p} \right) \right) \right] \quad (9)$$

where:

$D_{p,adj}$ = the adjusted extent of a particle diameter bin range, after accounting for particle dynamic shape factor differences;

$D_{p,0}$ = the original extent of a particle diameter bin range assumed by a reference monitor manufacturer;

χ = the dynamic shape factor of the particles, from 6.11.3.2(1), generated and transported into the test characterization chamber;

D_p = the particle diameter;

$C_c(D_{p,adj})$ = the Cunningham slip correction factor for the adjusted extent of a particle diameter bin range;

$C_c(D_{p,0})$ = the Cunningham slip correction factor for the original extent of a particle diameter bin range;