Designation: F1977 − 04 (Reapproved 2017)

An American National Standard

Standard Test Method for Determining Initial, Fractional, Filtration Efficiency of a Vacuum Cleaner System[1]

This standard is issued under the fixed designation F1977; 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 may be used to determine the initial, fractional, filtration efficiency of household and commercial canister (tank-type), stick, hand-held, upright, and utility vacuum cleaner systems.

1.1.1 Water-filtration vacuum cleaners which do not utilize a replaceable dry media filter located between the water-based filter and cleaning air exhaust are not included in this test method. It has been determined that the exhaust of these vacuum cleaners is not compatible with the specified discrete particle counter (DPC) procedure.

1.2 The initial, fractional, filtration efficiencies of the entire vacuum cleaner system, at six discrete particle sizes (0.3, 0.5, 0.7, 1.0, 2.0, and >3 µm), is derived by counting upstream challenge particles and the constituent of downstream particles while the vacuum cleaner system is being operated in a stationary test condition.

1.3 The vacuum cleaner system is tested at the nozzle with the normal airflow rate produced by restricting the inlet to the nozzle adapter with the 1¼-in. orifice.

1.4 The vacuum cleaner system is tested with a new filter(s) installed, and with no preliminary dust loading. The fractional efficiencies determined by this test method shall be considered initial system filtration efficiencies. The filters are not changed between test runs on the same cleaner.

1.5 Neutralized potassium chloride (KCl) is used as the challenge media in this test method.

1.6 One or two particle counters may be used to satisfy the requirements of this test method. If using one counter, flow control is required to switch between sampling the upstream and downstream air sampling probes.

1.7 To efficiently utilize this test method, automated test equipment and computer automation is recommended.

1.8 Different sampling parameters, flow rates, and so forth, for the specific applications of the equipment and test procedure may provide equivalent results. It is beyond the scope of this test method to define those various possibilities.

1.9 This test method is limited to the test apparatus, or its equivalent, as described in this document.

1.10 This test method is not intended or designed to provide any measure of the health effects or medical aspects of vacuum cleaning.

1.11 This test method is not intended or designed to determine the integrity of HEPA filtration assemblies used in vacuum cleaner systems employed in nuclear and defense facilities.

1.12 The inch-pound system of units is used in this test method, except for the common usage of the micrometer, µm, for the description of particle size which is a SI unit.

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

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D1193 Specification for Reagent Water
D1356 Terminology Relating to Sampling and Analysis of Atmospheres
D3154 Test Method for Average Velocity in a Duct (Pitot Tube Method)
F50 Practice for Continuous Sizing and Counting of Airborne Particles in Dust-Controlled Areas and Clean Rooms Using Instruments Capable of Detecting Single Sub-Micrometre and Larger Particles
F395 Terminology Relating to Vacuum Cleaners
F558 Test Method for Measuring Air Performance Characteristics of Vacuum Cleaners

---

[1] This test method is under the jurisdiction of ASTM Committee F11 on Vacuum Cleaners and is the direct responsibility of Subcommittee F11.23 on Filtration.

Current edition approved March 1, 2017. Published March 2017. Originally approved in 1999. Last previous edition approved in 2010 as F1977 – 04 (2010). DOI: 10.1520/F1977-04R17.

[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.

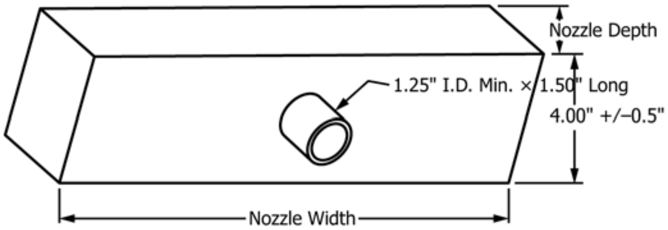

FIG. 1 Nozzle Adapter

2.2 *Other Documents:*

IES Recommended Practice CC021.1 Testing HEPA and ULPA Filter Media[3]

IES Recommended Practice CC001.3 HEPA and ULPA Filters[3]

ISO Guide 25 General Requirements for the Competence of Calibration and Testing Laboratories[4]

EN 1822 High Efficiency Air Filters (HEPA and ULPA)

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *challenge, n*—aerosolized media introduced upstream of the test unit and used to determine the filtration characteristics of the test unit.

3.1.1.1 *Discussion*—Also known as test aerosol. The term "contaminant" shall not be used to describe the media or aerosol used to challenge the filtration system in this test method. The term "contaminant" is defined in Terminology D1356 and does not meet the needs of this test method.

3.1.2 *chamber airflow, n*—the sum of all airflows measured at a point near the downstream probe.

3.1.3 *filter, n*—the entity consisting of the converted filter media and other items required to be employed in a vacuum cleaner for the purpose of arresting and collecting particulate matter from the dirt-laden air stream; sometimes referred to as a filter element, filter assembly, cartridge, or bag.

3.1.4 *normal airflow, n*—that airflow occurring at the system's nozzle due to the 1¼-in. orifice restriction at the inlet to the nozzle adapter.

3.1.5 *nozzle adaptor, n*—a plenum chamber, fabricated to mount to the inlet nozzle of the test unit in a sealable manner and shown in Fig. 1.

3.1.5.1 *Discussion*—Construction specifications are discussed in the Apparatus section.

3.1.6 *particle count, n*—the numeric sum of particles per cubic foot over the specified sample time.

3.1.6.1 *Discussion*—Throughout this test method, the units of measure for this term, generally, do not accompany the term "particle count" and are assumed to be understood by the reader.

3.1.7 *primary motor(s), n*—the motor(s) which drive(s) the blower(s), producing airflow through the vacuum cleaner.

3.1.8 *secondary motor(s), n*—the motor(s) in the vacuum cleaner system not employed for the generation of airflow.

3.1.9 *sheath air, n*—the air flowing over and around the test unit that is mounted in the test chamber.

3.1.10 *stabilization, n*—those conditions of operation which produce results having a total variation of less than 3 % and at least 1000 total count in all size ranges for challenge equal to or less than 15 counts per cubic foot in the 0.3-µm channel for the background count.

3.1.10.1 *Discussion*—Total variation is calculated as the maximum data point minus the minimum data point divided by the maximum data point times 100.

3.1.10.2 *Discussion*—The assurance of statistical control is not a simple matter and needs to be addressed. A process is in a state of statistical control if the variations between the observed test results vary in a predictable manner and show no unassignable trends, cyclical characteristics, abrupt changes, excess scatter, or other unpredictable variations.

3.1.11 *system filtration efficiency, n*—a numerical value based on the ratio of a discrete size, particle count emerging from the vacuum cleaner, relative to the upstream challenge, particle count of the same size.

3.1.12 *test chamber, n*—the enclosed space surrounding the vacuum cleaner being tested, used to maintain the controlled environmental conditions required during the test procedure.

3.1.13 *test run, n*—the definitive procedure that produces a singular measured result.

3.1.13.1 *Discussion*—A test run is the period of time during which one complete set of upstream or downstream air sample data, or both, is acquired.

3.2 *Definitions:*

3.2.1 *aerosol, n*—a suspension of solid or liquid particles in a gas.

3.2.2 *background particles, n*—extraneous particles in the air stream prior to the start of the test.

3.2.2.1 *Discussion*—Under conditions required of this test method, extraneous particles will be found to pass through the test chamber (for example, particles penetrating the test chamber's HEPA filters or being abraded or released from the surfaces of tubing and test equipment). Operating under stabilized conditions, these particles shall be counted in the downstream flow and subsequently subtracted from the test data to determine the initial, fractional, filtration efficiency of the test unit (see Note 3).

3.2.3 *channel, n—in particle analyzers*, a group of particle sizes having a definitive range; the lower end of the range identifies the channel, for example, a range of particle sizes from 0.3 to 0.5 µm is identified as the 0.3-µm channel.

3.2.4 *coincidence error, n—in particle analyzers*, errors occurring at concentration levels near or above the design limits of the instrument being used because two or more particles are simultaneously being sensed.

---

[3] Available from Institute of Environmental Sciences and Technology (IEST), Arlington Place One, 2340 S. Arlington Heights Rd., Suite 100, Arlington Heights, IL 60005-4516, http://www.iest.org.

[4] Available from International Organization for Standardization (ISO), 1, ch. de la Voie-Creuse, Case postale 56, CH-1211, Geneva 20, Switzerland, http://www.iso.ch.

3.2.5 *diffusion dryer, n—in aerosol technology*, a device containing desiccant, surrounding the aerosol flow path, that removes excess moisture by diffusion capture.

3.2.6 *diluter, n—in aerosol technology*, a device used to reduce the concentration of particles in an aerosol.

3.2.7 *downstream, adv*—signifies the position of any object or condition that is physically in or part of the airflow stream occurring after the referenced item.

3.2.8 *DPC, n*—an acronym for discrete particle counter.

3.2.8.1 *Discussion*—The IES Recommended Practice CC001.3 and Practice F50 describe a discrete particle counter as a instrument that utilizes light-scattering or other suitable principle to count and size discrete particles in air, and that displays or records the results. The discrete particle counter is also known as a single-particle counter or simply as a particle counter and it determines geometric rather than aerodynamic particle size.

3.2.9 *fractional efficiency, n*—a numerical value based on the ratio of the number of emergent, downstream particles of a discrete size, relative to the number of incident, upstream particles of the same size.

3.2.9.1 *Discussion*—In practice, a single particle size is reported, having an understood or assumed size range equal to the channel size. This value is also known as the differential size efficiency or particle size efficiency, or both.

3.2.10 *fractional efficiency curve, n*—the fractional efficiency plotted as a function of the particle size.

3.2.11 *HEPA, adj*—an acronym for high-efficiency particulate air.

3.2.11.1 *Discussion*—Additional information pertaining to HEPA may be found in IES 21.1 (99.97 % at 0.3 µ in salt as modified) or EN 1822 (H12 or better at 0.3 µ rather than most penetrating particle size).[5]

3.2.12 *laminar, adj*—in pneumatics, nonturbulent, laminar flow through a pipe is considered laminar when the Reynolds number is less than approximately 2000 and turbulent for a Reynolds number greater than approximately 4000.

3.2.12.1 *Discussion*—Laminar flow in a pipe is characterized by a smooth symmetrical pattern of streamlines. The Reynolds number is a nondimensional unit of measure proportional to the ratio of the inertial force of the gas to the frictional forces acting on each element of the fluid.[6,7]

3.2.13 *neutralizer, n—in aerosol technology*, a device used to minimize losses and coagulation caused by electrostatic charges, and to counteract high charge levels in aerosols generated by nebulization, combustion, or dispersion by neutralizing the particle charge level to the Boltzmann distribution level.

3.2.13.1 *Discussion*—Neutralizers generally use radioactive Krypton gas, Kr-85, sealed in a stainless steel tube shielded by an outer metal housing.

3.2.14 *particle, n*—a small, discrete object.

3.2.15 *particulate, adj*—indicates that the material in question has particle-like properties.

3.2.16 *population, n*—the total of all the units of a particular model vacuum cleaner being tested.

3.2.17 *sample, n*—a small, representative group of vacuum cleaners, taken from a large collection (population) of vacuum cleaners of one particular model, which serve to provide information that may be used as a basis for making a determination concerning the larger collection.

3.2.18 *submicrometer, adj*—describes the range of particles having a mean diameter of less than 1 µm (1×10^{-6} m).

3.2.19 *unit or test unit, n*—a single vacuum cleaner system of the model being tested.

3.2.20 *upstream, adv*—signifies the position of any object or condition that is physically in or part of the airflow stream occurring before the referenced item.

3.2.21 *vacuum cleaner, n*—as defined in Terminology F395.

3.3 *Symbols:*

cfm = cubic feet/minute.
D = diameter, in.
ft = feet.
°F = degrees Fahrenheit.
Hz = frequency, Hertz.
H_2O = water, column.
in. = inch.
psi = pound-force per square inch.
Q = airflow rate, cubic feet/minute.
RH = relative humidity.
RMS = root mean square.
s = second.
$\bar{X}$ = population mean.
X_i = test unit average.
µm = micrometre (10^{-6} m).
% = percent.

4. Summary of Test Method

4.1 This test method provides a procedure to determine the initial, fractional, filtration efficiency of a vacuum cleaner system (system filtration efficiency). The effects of the downstream concentration of particles that may be caused by various factors including the electric motor(s) used in the vacuum cleaner are counted as part of the test method. The report on the results of the testing will indicate if these downstream counts were included or were mathematically removed in the determination of the initial fractional efficiency.

4.2 In determining a vacuum cleaner system's initial, fractional, filtration efficiency, the test unit is placed in a test chamber, and sealed from ambient conditions. In this test chamber, a large, controlled volume of HEPA filtered air (meeting HEPA standards as defined by IES-RC-CC021.1) is passed over and around the test unit. A controlled aerosol challenge is introduced into the vacuum cleaner system. Upstream and downstream, air sampling measurements of the

---

[5] "High Efficiency Particulate Air Filters (HEPA and ULPA)," European Committee for Standardization (CEN), prEN 1822-1:1995, January 1995.

[6] Hinds, William C., *Aerosol Technology—Properties, Behavior, and Measurement of Airborne Particles*, John Wiley & Sons, 1982, ISBN 0-471-08726-2.

[7] Willeke, Klaus, and Baron, Paul A., *Aerosol Measurement—Principles, Techniques, and Applications*, John Wiley & Sons, formerly Van Nostrand Reinhold, 1993, ISBN 0-442-004486-9.

number and sizes of particles, within six particular ranges (channels), are acquired on a near, real time basis. The initial, fractional, filtration efficiency values at six incremental sizes are then calculated.

5. Significance and Use

5.1 It is well known that modern electrical appliances, incorporating electric motors that use carbon brushes for commutation, may emit aerosolized, particles into the surrounding environment. This test method determines the initial, fractional, filtration efficiency of a vacuum cleaner system, taking those emissions into consideration.

5.2 For all vacuum cleaner systems tested, the total emissions of the unit, whatever the source(s), will be counted at each of the six particle size levels identified in the test procedure. This test method determines the initial, fractional filtration efficiency of a vacuum cleaner system, with or without the motor emissions mathematically removed in the calculation of efficiency.

6. Apparatus

6.1 The information provided in this test method is intended to enable a laboratory to design, fabricate, and qualify the various components utilized in this procedure. Detailed and specific information regarding the components, a set of construction drawings, photos, vendor information, assembly, calibration, qualification testing instructions, and so forth, are not provided.

6.2 *Laboratory Filtration Test Room:*

6.2.1 The laboratory shall be maintained at 70 ± 5°F and 35 to 55 % RH.

6.2.2 To maintain the required ambient conditions within the laboratory and the test chamber, the test chamber airflow may be recirculated through the laboratory, in a closed-loop fashion. The air should pass through a HEPA filtration system before exhausting into the laboratory.

6.3 *Main Test Chamber*—The test chamber is mounted in a vertical attitude and shall be capable of enclosing the vacuum cleaner which is to be mounted in a horizontally, centralized position that will allow the test chamber sheath air to flow over and around it. Shown diagrammatically in Fig. 2, the body of the chamber is between approximately 2.5 and 3 ft in diameter (a rectangular chamber may be used) by approximately 4 to 5 ft in height, which is considered adequate for testing household and commercial vacuum cleaners as identified in the scope. The test chamber is fabricated from aluminum or stainless steel and shall be electrically connected to an earth ground. A large access panel or door shall be provided to accommodate the installation of the test unit. This door shall have a peripheral seal to ensure against the loss of aerosolized, challenge particles during testing. A removable wire form grill, capable of supporting the test unit, shall be placed at or near the bottom of the test chamber (opening space 2 in. or greater; 0.2-in. diameter rod or less; open area 80 % or greater).

6.4 *Sheath Air Supply*—The test chamber's sheath airflow shall be produced by a positive pressure blower system. The sheath air is introduced into the top of the test chamber through a manifold and diffuser section in a manner to ensure a velocity profile across a horizontal plane, at the middle of the chamber, that is within 10 % of the maximum velocity measured at any point on that plane, when measured at chamber flow rates of 100 and 1000 cfm; in accordance with the procedure described in Test Method D3154.

6.4.1 The HEPA-rated filtration section and the test chamber's air supply, blower system shall be sized to provide a minimum airflow of 1000 cfm at the load previously described.

6.5 *Challenge Injection System*—Air entering the test chamber at any point or for any purpose, unless specifically stated otherwise, shall initially pass through a HEPA filter. (HEPA filtration specifications are found in IES-RP-CC021.1.)

6.5.1 An atomizing system (challenge feeder) is required to inject the challenge at a constant rate equal to ±5 % of the concentration level required during the data acquisition period. This system is supported with equipment and components to supply the required concentration level of aerosol at a maximum 20 % relative humidity.

6.5.2 The atomizer shall be designed to generate polydisperse aerosols (in particular potassium chloride (KCl)) with the ability to generate sufficient particles in the 0.3 to 3.75-µm ranges as specified in 12.3.2.

6.5.3 A source of high pressure, HEPA-filtered, clean dry air is provided to the challenge feed system. This air supply shall be regulated to ±1 psi and operator controlled between 0 and 80 psi.

6.5.4 Control of the challenge concentration level shall be provided to ensure that the upstream air sampling concentration level does not produce coincidence errors in the upstream DPC. Any control means that does not introduce extraneous contaminants or change the characteristics of the challenge, or the air stream which is transporting it, may be used. A procedure to determine the maximum concentration limit is provided in Annex A4. The amount of challenge for a particular particle size should not exceed 1 million counts upstream.

6.5.5 The challenge passes through a dryer prior to entering the neutralizer. A dryer providing a maximum 20 % relative humidity at its exit is required. The humidity probe is located in the dryer; therefore, the air velocity will not affect the humidity measurement.

6.5.6 After drying, the challenge aerosol shall pass through a krypton-85, gas-charged neutralizer to neutralize or discharge the aerosol to Boltzmann equilibrium.

6.5.7 All air sampling and air handling tubes, positioned downstream of the neutralizer and upstream of the air sampling DPC, shall be metallic or elastomeric tubes with metallic liners. In either case, these tubes shall be earth grounded.

6.5.8 A metallic injector tube with a smooth interior wall is mounted vertically inside the test chamber so that the outlet is positioned above and in close proximity to the inlet point of the test vacuum cleaner. The challenge aerosol is injected into the top of the injector tube, through a dispersion means, to ensure a particle concentration profile, across the diameter of the tube at the position of the probe, that shall be within ±3 % of the measured, maximum particle concentration when the injector tube is operating at steady state conditions of 50 and 100-cfm

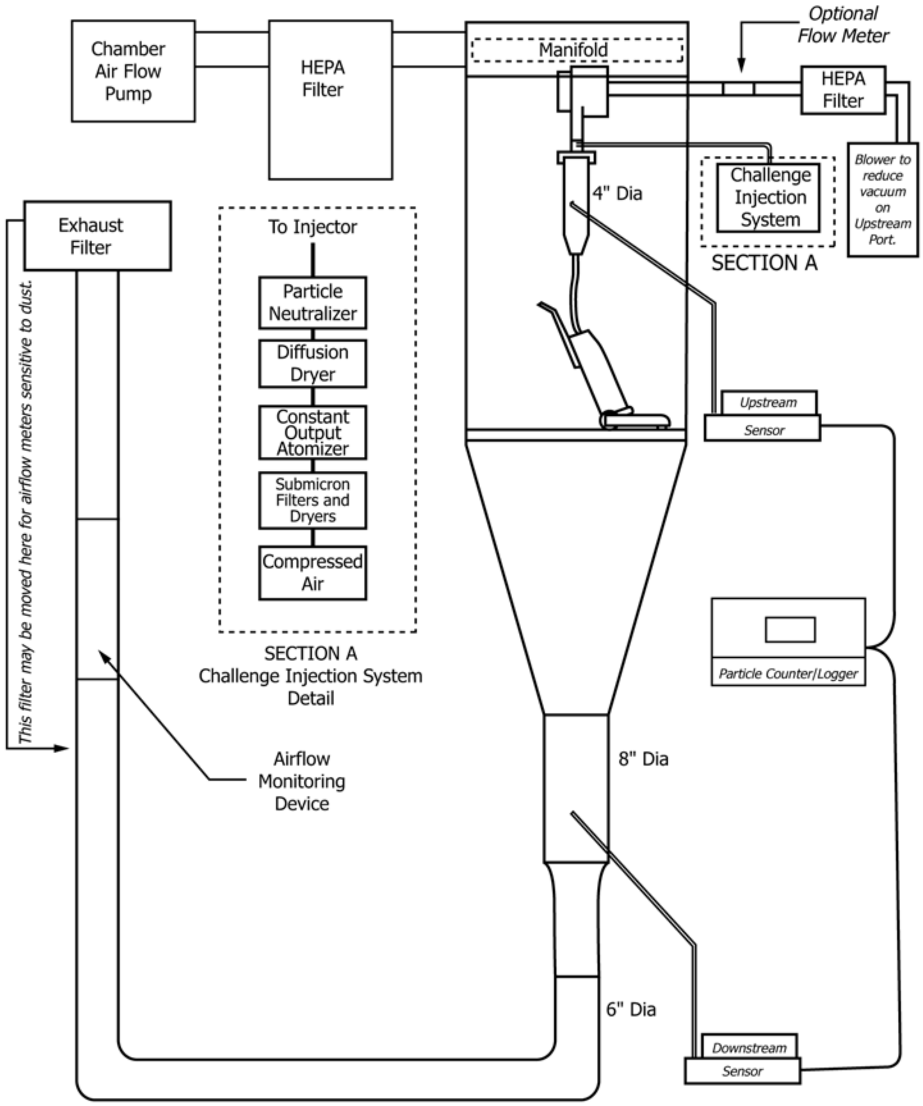

FIG. 2 Filtration Test Chamber and Supporting Equipment

flow rates. This section of pipe will support the thin-walled sampling probe which shall be mounted in a position to ensure its proper function.[6,7]

6.5.8.1 Operating at the specified, normal airflow rate, the injector tube shall be sized to produce turbulent flow. The thin-walled probe and airflow metering device shall be mounted within this tube section in positions to ensure their proper functioning.

(1) The injector tube should be approximately 2-in. diameter and 24 in. long; fabricated from aluminum, stainless steel, or steel with a rust-preventative coating; and shall be earth-grounded.

(2) The airflow metering device shall have an accuracy of ±2 % with a full-scale reading of not more than two times the normal airflow, and readability to 1 cfm.

NOTE 1—This recommended configuration will satisfy the normal airflow requirements for most known vacuum cleaners and is considered a practical size for mounting within the test chamber. However, a laboratory may require several injector tubes, configured differently, to satisfy the entire range of testing conditions it could experience.

6.5.8.2 The HEPA-filtered air enters the top of the injector tube. The airflow can be produced by a DPC vacuum pump, the vacuum cleaner, by an auxiliary air blower, or any combination of those elements. In some cases, such as testing a secondary motor, an auxiliary blower is required.

6.5.8.3 The flexible tube, transporting the challenge aerosol from the outlet of the injector tube to the vacuum cleaner, by means of a nozzle adaptor, shall not be longer than 2 times the distance between the end of the injector tube and the inlet to the nozzle adaptor. An elastomeric tube having an earth-grounded, metallic liner shall be used. The inside diameter of this tubing shall not be less than 1 in.; the wall of the tubing shall not be less than ⅛ in. The tubing shall not be allowed to kink between the end of the injector tube and the inlet to the nozzle adaptor. The interfacing connections of this tube, to the outlet of the injector tube and the inlet of the nozzle adaptor, are to be sealed and constructed to ensure no loss of challenge particles or dilution of the challenge concentration.

NOTE 2—Because the tubing and connections may be operating under negative or positive pressure depending upon the testing conditions, aerosol losses could occur from mechanical means due to improper construction of the joints, and dilution could occur from leaks.

(*1*) The injector tube's blower system shall be sized to minimally provide any additional airflow required to make up for the losses caused by the injector tube, plastic tubing, and the nozzle adaptor (discussed as follows), when the test unit is to be operating at normal airflow. A blower system with the following performance characteristics should be expected to satisfy most test conditions: sealed suction in excess 100 in. H_2O and airflow in excess of 100 cfm at a 2-in. orifice as determined in accordance with Test Method F558.

NOTE 3—During the sequence of determining the background particle counts, normal airflow through the injector tube is not required. Any background particle counts in the injector tube are insignificant and will be counted with the challenge.

6.5.9 The nozzle adaptor (a rectangular-shaped box acting as a plenum chamber; see Fig. 1) is securely attached and sealed to the vacuum cleaner's nozzle. The nozzle adaptor may be fabricated from wood or other suitable construction materials. The seal between the nozzle and the nozzle adaptor shall be leak-free. The nozzle adaptor shall not interfere with the operation of any mechanisms that may be present in the test unit's nozzle, for example, a rotating agitator, bristle brush. The inside, cross-sectional shape and size of the nozzle adaptor is to conform to the inside, perimeter dimensions of the test unit's nozzle. The nozzle adaptor's inside height, in a direction perpendicular from the face of the nozzle, is to be 4 ± ½ in. The flexible tube from the injector tube, is to enter the nozzle adaptor through the center of any one of the three larger surfaces and shall not extend inside the chamber by more than ½ in. (see 12.2 to 12.2.8.5).

6.6 *Lower Chamber:*

6.6.1 The truncated extension at the bottom of the test chamber reduces the test chamber's horizontal cross section, perpendicular to the direction of airflow, resulting in an increase in the air stream velocity through the metallic, lower pipe section placed at the bottom of this truncated section.

6.6.2 The diameter of the lower pipe section should be approximately 6 to 8 in. This will produce a desirable, turbulent flow without greatly restricting the test chamber airflow. This section of pipe will support the downstream, air sampling, thin-walled probe which shall be mounted in a position to ensure its proper function.[6,7] The minimum length for this pipe section shall be no less than 2 ft. Aerosol passing through this pipe at the location of the probe, shall have a concentration profile across the pipe diameter that does not vary by more than 3 % from the maximum measured concentration level when the test chamber is operating under steady-state flow conditions of 100 and 1000 cfm.

6.6.3 The air duct system, downstream from the lower pipe section, may be of any appropriate material and may include air straighteners, filters, and so forth, to accommodate airflow measurement devices placed in this duct section to measure and monitor the test chamber's airflow. A minimum, 6-in. diameter pipe should be used.

6.7 *Discrete Particle Counter(s):*

6.7.1 At least one discrete particle counter (DPC), supported by computer equipment, software, and other peripherals, is required.

6.7.1.1 The three possible test conditions, described in this test method, may utilize either a one- or two-DPC system.

6.7.1.2 The DPC system may acquire air samples through a switching valve system.

NOTE 4—When using either DPC system, the total operational times of the test unit during the test run will be identical to ensure that the unit is subjected to the same operating conditions in both situations. This will result in different test run times; see 12.13.1 and its sub-paragraphs.

(1) In a system using two DPCs, capable of simultaneously switching from sampling one probe to the other, the need to develop a correlation ratio between the two DPCs and apply it when determining the initial, fractional, filtration efficiency is discussed in Annex A5. When a correlation ratio is required, it shall be used in the determination of the fractional efficiency. In most cases, it can be expected that the need will be negated because any difference between the two DPCs and the sampling lines would be canceled out in the switching process.

(2) For the switching process, an electrical mechanical valve system should be used in both DPC systems.

6.7.1.3 The minimal requirements of the DPC system to be used for this procedure are as follows:

Sizing sensitivity	≥0.3 µm
Sample flow rate	≤1.0 cfm nominal; user adjustable within ±20 %
Concentration limit	≥ a minimum 1 000 000 particles ⁄ft^3 with less than 10 % coincidence error at the concentration limit
Operating principle	Laser optics
Sizing information	≥8 channels, user selective

6.8 *Dilution System:*

6.8.1 A dilution system in the downstream sampling line may be required to maintain the DPC concentration level below the limit established in this test method.

6.8.1.1 If the dilution system reduces particle concentration by injecting air into the sampling line, this air shall be filtered through a HEPA filter.

6.8.1.2 An airflow meter that is at least equivalent in accuracy and readability to that used in the DPC shall be used to monitor the dilution airflow.

NOTE 5—Development of a large, upstream particle count is highly desirable so that meaningful downstream counts are established. When testing units which have a high motor emissions count, overconcentrating the downstream DPC may dictate the use of a dilution system. The use of any dilution means will sacrifice precision in the calculation of efficiency. In those cases where high motor emissions are present, the number of test runs required to reach 95 % confidence may become high.

6.9 *Other Equipment:*

6.9.1 *Digital Display Humidity Meter,* used for qualification and verification of the various air supplies. Accuracy: minimum ±3 % at 78°F between 20 and 90 % of range. Display resolution: ±1 % RH. Response time: 15 s for a 60 % step change in moving air.

6.9.2 *Voltmeter,* to measure rated input volts to the vacuum cleaner; capable of providing measurements accurate within ±1 % of the vacuum cleaner's rated input voltage.

6.9.3 *Voltage Regulator System,* to control the input voltage to the vacuum cleaner. The regulator system shall be capable of maintaining the vacuum cleaner's rated voltage ±1 % and rated frequency having a wave form that is essentially sinusoidal with ±3 % maximum harmonic distortion for the duration of the test.

6.9.4 *Thin-Walled Probes* of various sizes may be required to accommodate the flow requirements of the DPC(s). The probes shall be sized to meet the performance requirements of 12.4 and its depending, sub-paragraphs.

6.9.4.1 Probes are to be located and properly mounted in the middle of the airstream of their respective ducts.[6]

6.9.4.2 The output of each probe shall be channeled to the DPC through earth-grounded, smooth bore, metallic tubing. Electrically conductive, plastic tubing with the conductive layer being earth-grounded may also be used. The tubing shall convey the aerosol sample to the DPC through the shortest practical distance. In all cases, the inlet to the DPC shall be physically positioned below the probes outlet and not more than 2 ft from the vertical center line of the test chamber. All bend radii from the probe to the DPC shall be greater than 10 times the inside diameter of the tubing which shall be sized so that high-velocity flow conditions exist (Reynolds number 4000 or larger).

6.9.5 *Time Measuring Device,* accurate to 1 s.

7. Materials

7.1 A solution of KCl and distilled water as required by the aerosol generator.

7.1.1 *KCl* (potassium chloride, pure).

7.1.2 *Reagent Water,* Type IV, grade in accordance with Specification Designation D1193.

7.2 *Latex (Polystyrene) Spherical Particles,* traceable to the National Institute of Standards and Technology, (NIST) used for the calibration or verification, or both, of the DPC.

7.2.1 The proper concentration level of latex spheres shall be used in the aerosol generator as discussed in *Aerosol Measurement-Principles, Techniques, and Applications*, p. 63-64.[7]

8. Hazards

8.1 **Warning—**DPC equipment is extremely sensitive to high concentrations of, and cumulative exposure to, any aerosolized particles.

8.2 **Warning—**DPC equipment is sensitive to high-moisture conditions and water vapor.

8.3 **Warning—**Particle size measurement is a function of both the actual particle dimension or shape factor, or both, as well as the particular physical or chemical properties of the particle being measured. Caution is required when comparing data from instruments operating on different physical or chemical parameters or with different particle size measurement ranges. Sample acquisition, handling, and preparation can also affect the reported particle size results.

9. Sampling

9.1 To determine the best single estimate of the initial, fractional, filtration efficiency for the population of the vacuum cleaner model being tested, the arithmetic mean of the fractional efficiency ratings of the individual units from a sample of the population shall be established by testing the necessary quantity of units from the sample population, to a 90 % confidence level within ±5 % of the mean value of the fractional efficiency, for each particle size required.

9.1.1 A minimum of three units (of the same model vacuum cleaner), selected at random in accordance with good statistical practice, shall constitute the population sample.

9.2 For each particle size required, the mean initial, fractional, filtration efficiency of the individual test unit is established by performing the necessary number of test runs to reach a 95 % confidence level within ±5 % of the mean value of the measurements acquired per particle size from all of the test runs. For each particle size, the mean efficiency of the test unit is then recorded as the best estimate of the initial, fractional, filtration efficiency of that unit and is utilized to calculate the mean initial, fractional, filtration efficiency for the population sample.

9.2.1 For particles sizes having less than 50 counts, the statistics are based upon the Poisson distribution (see Annex A1). For counts greater than 50, use Binomial statistics (see Annex A2).

10. Calibration, Qualification, and Standardization

10.1 Unless otherwise stated in this test method or the annexes, the maximum frequency of calibration or qualification, or both, of the equipment used in this test method is to be based upon the equipment manufacturer's specification. Calibrate or qualify all other equipment based on quality laboratory practices set forth in ISO/DIS 17025.

10.1.1 Calibrate or qualify individual equipment pieces, or both, when abnormal performance of the specific piece is noted or suspected.

10.2 Monitor the high-pressure air supply for the challenge feeder or any dilution system for conformance to humidity and air quality requirements every six months, or immediately if contamination is suspected.

10.3 Calibrate all other equipment, not specifically identified, at least every six months.

11. Conditioning

11.1 Maintain the laboratory in which all conditioning and testing will be performed, at 70 ± 5°F (21 ± 3°C) and 35 to 55 % relative humidity.

11.2 All components involved in this test method are to remain in and be exposed to the controlled environment for a minimum of 16 h prior to the start of the test.

11.3 To stabilize the vacuum cleaner's motor emissions, operate the vacuum cleaner system's motor(s) at nameplate rated voltage (±1 %) and rated frequency (±1 Hz), for a minimum of 3 h or longer if required. For vacuum cleaners with dual nameplate voltage ratings, conduct the run in at the highest voltage.

11.3.1 Determine stabilization by operating the test unit in the test chamber and monitoring the downstream counts. Stabilization requirements are defined in the Terminology section.

12. Fractional Filtration Efficiency Test Procedure

12.1 If the motor emissions are to be excluded from the efficiency calculations used to determine the vacuum cleaner system's initial, fractional, filtration efficiency, do not operate any secondary motor in the vacuum cleaner system during the ingestion of the challenge. However, if the motor emissions are to be included in the efficiency calculations used to determine the vacuum cleaner's initial, fractional, filtration efficiency, any secondary motor in the vacuum cleaner system must be operated during the ingestion of the challenge.

12.1.1 For those units incorporating the secondary motor in a separate attachment (for example, a powered nozzle in a canister vacuum cleaner system), mount this attachment and the connecting hose and wands in the test chamber, as described as follows. Power to the secondary motor may be disconnected during the ingestion of the challenge to aid in reducing the downstream particle count if motor emissions are to be excluded from the efficiency calculations. However, if motor emissions are to be included in the efficiency calculations, all secondary motors must be connected to power and be energized during testing.

MOUNTING OF VACUUM CLEANER

12.2 Mount the entire vacuum cleaning system within the test chamber as follows:

12.2.1 For all test units, securely attach and seal a nozzle adaptor (Fig. 1) to the vacuum cleaner's nozzle as described in the Apparatus section.

12.2.2 Install new filter(s) in the test unit.

12.2.3 Mount the test unit on the support grill as near to the horizontal center of the test chamber as possible.

12.2.4 Mount the injector tube in a vertical position and ensure that the outlet of the injector is above and in close proximity to the inlet of the nozzle adaptor.

12.2.4.1 It is the intent of this procedure that the flexible tube, joining the outlet of the injector tube to the nozzle adaptor, be as short as possible and meet the requirements in 6.5.8.3.

12.2.5 The connection of the flexible tube to the nozzle adaptor and the nozzle adapter to the vacuum cleaner's nozzle is to be sealed so that all of the vacuum cleaner system's airflow passes through this connection. This connection is not to impede the flow or reduce the particle count of the challenge aerosol.

12.2.5.1 It is not the intent of this procedure to seal any positive or negative pressure leaks that the vacuum cleaner may have due to its design or manufacturing. Openings, such as edge cleaning slots, should be sealed during this testing but bleed holes should be left open.

12.2.6 If required, change the injector tube configuration to accommodate positional or flow requirements, or both, (length or diameter, or both).

NOTE 6—Proper dispersion of the challenge and turbulent flow through this tube shall be ensured.

12.2.7 To accommodate test units employing a motorized accessory (for example, a motorized nozzle), this additional component is to be placed within the test chamber in any convenient location.

12.2.7.1 It is required that the accessory be functionally connected to the main unit (for example, the use or mounting of the hose and wand system in a canister-type vacuum cleaner is required).

12.2.8 It is beyond the scope of this test method to provide instructions for mounting all of the various types or styles of vacuum cleaners. It is incumbent upon the laboratory to mount the test units to comply with the intent of the test method and to ensure the mounting of the vacuum cleaner allows the unit to function properly.

12.2.8.1 The exhaust streams of the test unit and any accessory, shall freely enter the sheath air stream.

12.2.8.2 The vacuum cleaner system is not required to be mounted in a position that simulates normal operation. (This does not preclude mounting the unit or accessory in an upside down position.)

12.2.8.3 The normal flow of air through the vacuum cleaner system shall not be restricted.

12.2.8.4 The placement of the unit or the accessories, or both, shall not restrict or interfere with the functionality of one another.

12.2.8.5 Any method of mounting that allows injecting 100 % of the challenge into the test unit and establishing normal exhaust streams is to be used.

EQUIPMENT INITIALIZATION AND SETUP

12.3 Activate the DPC(s) and associated equipment, the computer, and any other electrical or electronic equipment. Allow this equipment to warm up for at least 30 min.

12.3.1 Initialize the DPC(s) channel sizes.

12.3.2 For determining the initial, fractional, filtration efficiency of the test unit, at the required particle sizes, set four particle size channels of the DPC(s) as follows:

Channel 1	0.3 - 0.50 µm
Channel 2	0.5 - 0.70 µm
Channel 3	70 - 1.0 µm
Channel 4	1.0 - 2.0 µm
Channel 5	2.0 - 3.0 µm
Channel 6	>3.0 µm

12.3.2.1 Only the data from these six channels shall be used to determine the respective, fractional, filtration efficiencies at the 0.3, 0.5, 0.7, 1.0, 2.0, and >3.0 µm levels.

12.3.2.2 The cumulative particle count (number of particles that size and greater) data from Channel 1 will be utilized to determine stabilization.

ESTABLISHMENT OF DYNAMIC OPERATING AIRFLOW CONDITIONS

12.4 With the test chamber sealed and the test unit installed in the chamber but not operating, simultaneously flush the test chamber and the test unit with HEPA-filtered air. Flushing may be accomplished more efficiently at high airflows.

12.4.1 Continue flushing until both the upstream and downstream, cumulative particle count in the 0.3-µm channel is stabilized equal to or below 15 counts/ft^3/min at the initial flow conditions of normal airflow through the injector tube and 1000 cfm through the downstream pipe.

NOTE 7—Total airflow through the downstream pipe is the sum of the upstream sources, that is, the injector blower flow and the sheath airflow minus the DPC(s) flow.

12.5 Apply power to the vacuum cleaner's primary motor at nameplate rated voltage (±1 %) and rated frequency (±1 Hz) and readjust the injector tube's flow rate to normal flow rate. If the test unit has a dual voltage nameplate rating, use the higher voltage.

12.5.1 If the motor emissions are to be included in the efficiency calculations, energize the vacuum cleaner's secondary motor(s) at the nameplate rated voltage (±1 %) and rated frequency (±1 Hz). If the test unit has a dual voltage nameplate rating, use the higher voltage.

12.6 The flow restriction caused by the flexible tube connecting the injector tube to the test unit may require using the injector tube's auxiliary air blower to establish normal flow though the injector tube and the test unit.

12.7 With all equipment operating at these initial flow conditions, monitor the downstream air until the cumulative particle count in the 0.3-µm channel has stabilized.

12.8 If the stabilized, downstream particle counts are less than 20 % of the DPC concentration limit, reduce the test chamber airflow rate to arrive at a lower flow rate, Q_{new}, which will simultaneously increase the concentration level to the desired 20 % level.

$$Q_{initial}\left(\frac{0.10}{0.20}\right) = Q_{new} \tag{1}$$

12.8.1 Decrease the test chamber airflow rate by decreasing the sheath airflow rate only. As an example, the desired 20 % concentration level divided into a downstream count of 10 % of the concentration limit, times the initial test chamber flow rate provides the new flow rate.

12.8.2 The test chamber flow rate shall not be reduced to less than 100 cfm.

12.9 If the downstream, cumulative particle count at 0.3 µm is greater than 20 % of the concentration limit of the DPC, then either an increase in the test chamber airflow rate or, the use of a variable controlled, dilution system is required to lower the particle count to 20 % of the concentration limit of the DPC.

12.9.1 If the test chamber is equipped with a blower that will produce higher airflows, increase the sheath airflow rate to arrive at a higher test chamber flow rate, Q_{new}, which will simultaneously decrease the DPC concentration level to 20 %.

12.9.1.1 Increase the test chamber airflow rate by increasing the sheath airflow rate only. As an example, a downstream count at 35 % of concentration limit, divided by the desired 20 % concentration level times the initial test chamber flow rate provides the new flow rate:

$$Q_{initial}\left(\frac{0.35}{0.20}\right) = Q_{new} \tag{2}$$

12.9.2 If higher test chamber airflow rates can not be established, the use of a downstream dilution system is required. Similar calculations based on the 1-cfm flow rate of the DPC can be used to determine the required dilution ratio.

12.10 With all of the equipment operating at the established test conditions, verify that the downstream particle count is 20 % (+0.0 %, –5.0 %) of the DPC concentration limit. Repeat the preceding procedure if required.

12.10.1 Record the established, test condition flow rates (injector tube and test chamber) and any downstream dilution ratio.

DETERMINATION OF THE TEST CHAMBER BACKGROUND PARTICLE COUNTS

12.11 With the test chamber sealed and the test unit not operating, flush the test chamber with HEPA-filtered air. Flushing may be accomplished more efficiently at high airflows.

12.11.1 Monitor the DPC sampling airflow rate and adjust to ±1 % of rated flow.

12.12 Continue flushing until the downstream, cumulative particle count in the 0.3-µm channel is stabilized equal to or below 15 counts/ft^3.

12.13 With all equipment operating within established parameters, with the test unit off, and with the downstream, test chamber counts stabilized, perform three or more test runs to obtain a 95 % confidence level within ±5 % of the mean value of the downstream particle counts and the upstream particle counts for the 0.3, 0.5, 0.7, 1.0, 2.0, and >3.0-µm channels.

12.13.1 Test run time shall be 600 s for a single DPC system and 300 s for a dual DPC system with a 60-s interval between each test run for both systems.

12.13.2 Air sampling of the downstream and upstream probe is to occur in 15-s intervals with a maximum 5-s time delay, between sampling times, incurred for switching.

12.13.3 Record the average value for each of the six channels as the downstream or upstream, background particle counts per channel (see Note 3).

DETERMINATION OF THE VACUUM CLEANERS FILTRATION CHARACTERISTICS

12.14 All individual test runs performed in the following paragraphs shall be conducted to a 95 % confidence level using appropriate statistical methods in accordance with 9.2 and 9.2.1.

12.15 One of two possible conditions for testing exist:

12.15.1 Condition One: The vacuum cleaner system being tested has a single motor.

12.15.2 Condition Two: The vacuum cleaner system being tested has two or more motors.

CONDITION ONE: SINGLE-MOTOR VACUUM SYSTEM

12.16 For Condition One, apply the rated power to the test unit and establish the normal flow rate through the injector tube.

12.16.1 Monitor the DPC sampling airflow rate and adjust to ±1 % of rated flow.

12.16.2 When the downstream cumulative particle count in the 0.3-µm channel stabilizes, perform three or more test runs to obtain a 95 % confidence level, within ±5 % of the mean values, of only the downstream particle counts for the 0.3, 0.5, 0.7, 1.0, 2.0, and >3.0-µm channels.

12.16.2.1 For both the single and dual DPC systems, the test run time shall be 300 s. Between test runs, enough time is allowed to let the background counts become stable.

12.16.2.2 Air sampling of the downstream probe is to occur continuously during the 300 s test run of the motor only.

12.16.3 From the downstream DPC, record the average values from each of the six channels as the downstream, background particle counts, plus primary motor emissions particle counts, per channel.

12.16.4 Following the 300 s downstream count, run the upstream DPC for 300 s and record particle counts.

12.16.5 Activate the challenge feeder and establish a constant feed rate to produce a concentration level of 20 % (+0.0 % -5 %) of the concentration limit of the upstream DPC.

12.16.6 With all equipment operating at these test conditions, perform three or more test runs to obtain a 95 % confidence level within ±5 % of the mean values of both the upstream and downstream particle counts for the 0.3, 0.5, 0.7, 1.0, 2.0, and >3.0-µm channels.

12.16.6.1 The test run time shall be 600 s for the single DPC system and 300 s for the dual DPC system.

12.16.6.2 Enough time is allowed between each test run to let the background counts become stable.

NOTE 8—The different test run and interval times ensure that the unit will be operating for the same length of time when using either DPC system.

12.16.7 From the downstream DPC, record the average values for each of the six channels as the downstream, background particle counts, plus primary motor emissions count, plus challenge penetration particle counts, per channel.

12.16.8 From the upstream DPC, record the average values for each of the six channels as the upstream, background particle counts, plus challenge particle counts, per channel.

CONDITION TWO: MULTIPLE-MOTOR VACUUM SYSTEM, SECONDARY MOTOR(S) INCLUDED

12.17 For Condition Two, apply rated power to the test unit's secondary motor(s) and establish the normal flow rate through the injector tube using the injector tube's auxiliary air blower.

12.17.1 Monitor the DPC sampling airflow rate and adjust to ±1 % of the rated flow.

12.17.2 When the downstream cumulative particle count in the 0.3-µm channel stabilizes, perform three or more test runs to obtain a 95 % confidence level within ±5 % of the mean values of only the downstream particle counts for the 0.3, 0.5, 0.7, 1.0, 2.0, and the >3.0-µm channels.

12.17.2.1 For both the single and dual DPC systems, the test run time shall be 300 s.

12.17.2.2 Air sampling of the downstream probe is to occur continuously during the test run.

12.17.3 From the downstream DPC, record the average values for each of the six channels as the downstream, background particle counts, plus secondary motor(s) emission particle counts, per channel.

12.17.4 Following the 300 s downstream count, run the upstream DPC for 300 s and record particle counts.

12.17.5 With the secondary motor(s) operating, apply rated power to the primary motor, establish the normal airflow rate through the injector tube, and establish the test condition flow rates through the DPC(s) and test chamber.

12.17.6 When the downstream cumulative particle count, in the 0.3-µm channel stabilizes, perform three or more test runs to obtain a 95 % confidence level within ±5 % of the mean values of only the downstream particle counts for the 0.3, 0.5, 0.7, 1.0, 0.2, and the 3.0-µm channels.

12.17.6.1 For both the single and dual DPC systems, the test run time shall be 300 s.

12.17.6.2 Air sampling of the downstream probe is to occur continuously during the test run.

12.17.7 From the downstream DPC, record the average values for each of the six channels as the downstream, background particle counts, plus secondary motor(s) emissions particle counts, plus primary motor emissions particle counts, per channel.

12.17.8 Following the 300 s downstream count, run the upstream DPC for 300 s and record particle counts.

12.17.9 Activate the challenge feeder and establish a constant feed rate to produce a concentration level of 20 % (+0.0 % -5 %) of the concentration limit of the upstream DPC.

12.17.10 With all equipment operating at the established test conditions, perform three or more test runs to obtain a 95 % confidence level within ±5 % of the mean values of both the upstream and downstream particle counts for the 0.3, 0.5, 0.7, 1.0, 2.0, and >3.0-µm channels.

12.17.10.1 The test run time shall be 600 s for the single DPC system and 300 s for the dual DPC system. Enough time is allowed between test runs to let the background counts return to stable.

NOTE 9—The different test run and interval times ensure that the unit will be operating for the same length of time when using either DPC system.

12.17.10.2 Air sampling of the two probes is to be switched from reading one probe to the other in 15-s intervals with a maximum 5-s time delay incurred between sampling times.

12.17.11 From the downstream DPC, record the average values for each of the six channels as the downstream, background particle counts, plus secondary motor(s) emissions particle counts, plus primary motor emissions counts, plus challenge penetration particle counts, per channel.

12.17.12 From the upstream DPC, record the average values for each of the six channels as the upstream, background particle counts, plus challenge particle counts, per channel.

13. Calculation of Initial, Fractional, Filtration Efficiency

13.1 Calculate and record the initial, fractional, filtration efficiency, X_i, of the individual test unit for the 0.3, 0.5, 0.7, 1.0, 2.0, and >3.0-µm channels. See Annex A2 for a detailed procedure and example.[8]

13.2 Repeat the test procedure from Section 11 – 13.1, using other test units from the population sample, until a 90 %

---

[8] Bzik, Thomas, *Statistical Management and Analysis of Particle Count Data in Ultraclean Environments*, Part I, Micro contamination, 1986.

confidence level within ±5 % of the mean initial, fractional, filtration efficiency of all test units has been established for the 0.3, 0.5, 0.7, 1.0, 2.0, and >3.0-µm channels, for the sample population. See Annex A3 for an example.

13.3 Record the best estimate of the efficiency of the population for each of the six channels as the average value, $\bar{X}$, of the individual units, X_i, from the sample.

14. Report

14.1 Report the following information:

14.1.1 Identification of the test samples.

14.1.2 Identification of DPCs.

14.1.3 Efficiency calculations and pertinent backup calculations. The efficiency calculations need to clearly state if all downstream counts were included or if motor emissions were mathematically removed from the downstream counts.

14.1.4 Challenge media.

14.1.5 Sheath airflow rate.

14.1.6 Raw particle count data, which includes:

14.1.6.1 Upstream counts before challenge injection (background). See 12.16.4, 12.17.4, and 12.17.8.

14.1.6.2 Downstream counts with motor on before challenge injection. See 12.16.3, 12.17.3, and 12.17.7.

14.1.6.3 Downstream counts with motor on during injection. See 12.16.6 and 12.17.11.

14.1.6.4 Upstream counts during injection. See 12.16.6 and 12.17.12.

15. Precision and Bias

15.1 *Precision*—No interlaboratory tests have been performed; therefore, no precision statements regarding the repeatability and reproducibility of this test method are available at this time.

15.2 *Bias*—No justifiable statement can be made on the accuracy of this test method, since the true value of the property cannot be established by an acceptable referee method.

16. Keywords

16.1 efficiency; filtration; vacuum cleaner

ANNEXES

(Mandatory Information)

A1. MATHEMATICAL METHOD FOR DETERMINING WITH 95 % CONFIDENCE THE FRACTIONAL, FILTRATION EFFICIENCY OF A SINGLE TEST UNIT WHEN DOWNSTREAM PARTICLE COUNTS ARE LESS THAN 50; BASED ON POISSON STATISTICS

A1.1 *Definitions of Symbols, using Poisson Distribution*:

k = particle counts
v = unit of volume
K = k/v = mean counts/unit of volume
S = k/v^2 = variance
$S_D = (S_x + S_y)^{1/2}$ = difference of variance, where S_x and S_y are the variances of two data groups to be compared.

A1.2 To determine if there is a difference between two data groups, define the following:

A1.2.1 *Test Statistic:*

$$K_D = K_x - K_y \tag{A1.1}$$

where:

K_D = difference in mean counts/unit of volume,
K_x = for Group x, the mean counts/unit of volume, and
K_y = for Group y, the mean counts/unit of volume.

A1.2.2 *Critical Value:*

$$C = Z_B S_D \tag{A1.2}$$

where:

Z_B is determined by the desired level of confidence - for our purposes:

$Z_{0.95}$ = 95 % confidence = 1.645,
$Z_{0.975}$ = 97.5 % confidence = 1.96,
$Z_{0.99}$ = 99 % confidence = 2.33.

A1.3 Using these two values, it can be stated with the appropriate confidence level that if:

$K_D > C$, then the difference is significant

or

$K_D < C$, then the difference is not significant

A2. MATHEMATICAL METHOD FOR DETERMINING WITH 95 % CONFIDENCE THE FRACTIONAL, FILTRATION EFFICIENCY OF A SINGLE TEST UNIT WHEN DOWNSTREAM PARTICLE COUNTS ARE GREATER THAN 50; BASED UPON BINOMIAL STATISTICS

A2.1 *Theory*:

A2.1.1 The most common and ordinarily the best single estimate of the mean fractional, filtration efficiency, $\bar{X}$, at each of six particulate sizes (0.3, 0.5, 0.7, 1.0, 2.0, and >3.0-µm) is simply the arithmetic mean of the measurements. When a reading is taken from a sample, the reading average will seldom be exactly the same as the sample average. It is hoped that it is reasonably close and it would be desirable to state an interval which will confidently bracket the true mean. The following procedure gives an interval that is expected to bracket µ, the true mean, 100(1 – α) % of the time.

A2.1.2 The following procedure provides a confidence interval about the mean which is expected to bracket µ, the true mean, 100(1 – α) % of the time where α is the chance of being wrong. Therefore, 1 – α is the probability or level of confidence of being correct.

A2.1.3 The desired level of confidence is 1 – α = 0.95 or 95 % as stated in Section 15. Therefore, α = 0.05 or 5 %.

A2.1.4 Compute the mean, $\bar{X}$, and the standard deviation, *s*, of the individual efficiency measurements, at each particle size, of the test sample:

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{n} X_i \qquad \text{(A2.1)}$$

$$s = \sqrt{\frac{n\sum_{i=1}^{n} X_i^2 - \left(\sum_{i=1}^{n} X_i\right)^2}{n\,(n-1)}}$$

where:

n = number of test runs, and

X_i = value of the individual efficiency measurement of the *i*th test run. As will be seen in the procedural example to follow, this is the average value of the results from three test runs performed on an individual test unit with the resulting set of data meeting the repeatability requirements of Section 15.

A2.1.5 Determine the value of the *t* statistic for *n* – 1 df, from Table A2.1[9] at a 97.5 % confidence level.

NOTE A2.1—The value of *t* is defined as *t* and is read as "*t* at 97.5 % confidence."

$$t \text{ statistic} = t_{1-\alpha/2} = t_{0.975} \qquad \text{(A2.2)}$$

where:

$1 - \alpha/2 \;=\; 1 - 0.05/2 = 1 - 0.025 = 0.975$ or 97.5 %

A2.1.6 The following equations establish the upper and lower limits of an interval centered about $\bar{X}$ that will provide the level of confidence required to assert that the true population mean lies within this interval:

$$CI_U = \bar{X} + ts/\sqrt{n} \qquad \text{(A2.3)}$$

$$CI_L = \bar{X} - ts/\sqrt{n} \qquad \text{(A2.4)}$$

where:

CI = confidence interval (*U* - upper limit; *L* - lower limit)

= mean score of the sample taken from population,

t = *t* statistic from Table A2.1 at 97.5 % confidence level,

s = standard deviation of the readings taken from the sample, and

n = number of test runs.

A2.1.7 It is desired to assert with 95% confidence that the true efficiency mean, µ, lies within the interval, CI_u to CI_L centered about the calculated mean, $\bar{X}$. Therefore, the quantity $ts/\sqrt{n}$ shall be less than some value, *A*, where $A = \alpha\bar{X}$.

A2.1.8 As $n \rightarrow \infty$, $ts/\sqrt{n} \rightarrow 0$. As this relationship indicates, a numerically smaller confidence interval may be obtained by using a larger number of test runs, *n*, for the sample. Therefore, when the standard deviation, *s*, of the sample is large and the level of confidence is not reached after testing three units, a greater number of test runs, *n*, shall be used.

A2.2 *Procedure*—A graphical representation for the following procedure is shown in Fig. A2.1.

A2.2.1 Conduct three test runs for the sample at each of four particle sizes (0.3, 0.5, 1.0, and 2.5 µm).

A2.2.2 Obtain individual efficiency measurements by averaging the results of the three test runs performed for each of the particle sizes. The data set resulting from the three test runs conducted for each particle size shall meet the respective repeatability requirement found in Section 15.

A2.2.3 Compute $\bar{X}$ and *s* of the measurements.

A2.2.4 $A = 0.05\ \bar{X}$ (for 95 % confidence level).

A2.2.5 Determine the statistic *t* for *n* – 1 df from Table A2.1, where *n* = number of test runs.

TABLE A2.1 Percentiles of the t Distribution[12]

df	$t_{0.95}$	$t_{0.975}$
1.000	6.314	12.706
2.000	2.920	4.303
3.000	2.353	3.182
4.000	2.132	2.776
5.000	2.015	2.571
6.000	1.943	2.447
7.000	1.895	2.365
8.000	1.860	2.306
9.000	1.833	2.262
10.000	1.812	2.228
11.000	1.796	2.201
12.000	1.782	2.179
13.000	1.771	2.160
14.000	1.761	2.145
15.000	1.753	2.131

---

[9] Adapted by permission from *Introduction to Statistical Analysis*, 2nd ed, W.J. Dixon and F.J. Massey, Jr., eds., Copyright, 1957. McGraw-Hill Book Co., Inc. Entries originally from Table III of *Statistical Tables* by R.A. Fisher and F. Yates, 1938, Oliver and Boyd, Ltd., London.

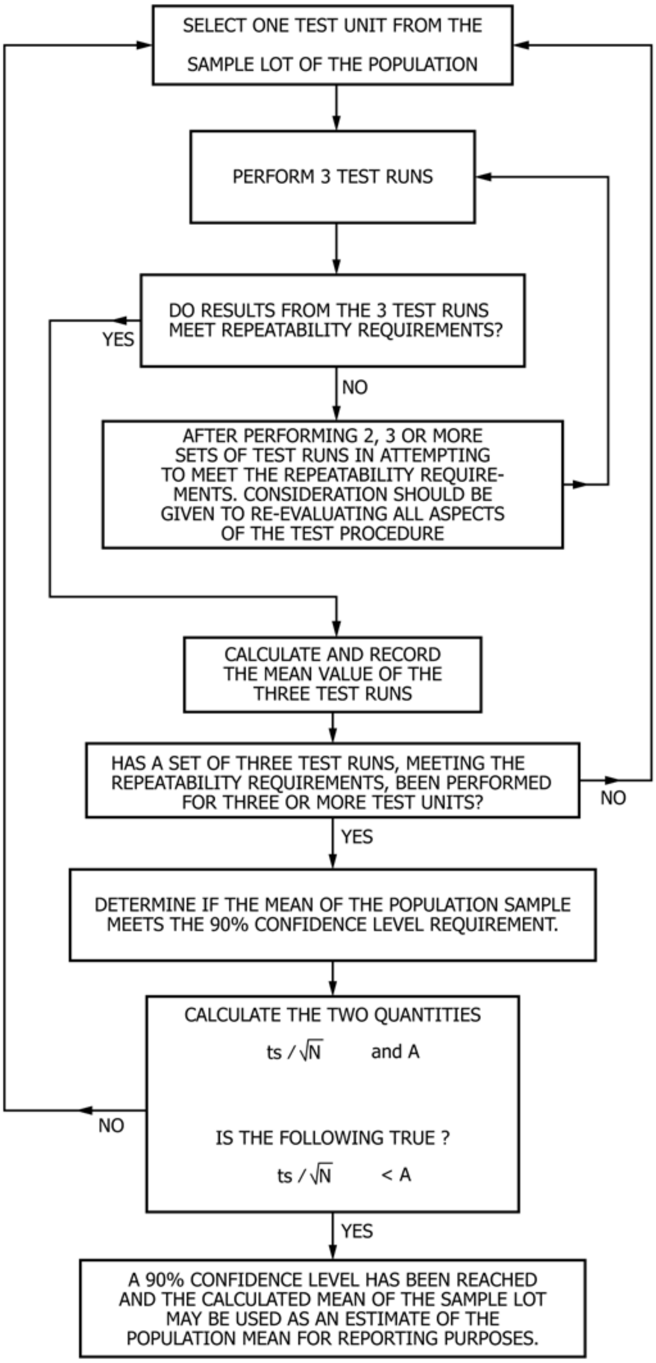

FIG. A2.1 Flow Chart for Procedure in A2.2

A2.2.6 Compute $ts/\sqrt{n}$ for the sample and compare it to the value of *A*.

A2.2.7 If the value of $ts/\sqrt{n}>A$, an additional test run shall be performed, and the computations of A2.2.2 – A2.2.6 are repeated.

A2.2.8 If the value of $ts/\sqrt{n}<A$, the desired 95 % confidence level has been obtained. The value of the final may be used as the best estimate of the mean filtration efficiency at a specific particle size.

A2.3 *Example*—The following data is chosen to illustrate how the mean efficiency value of particle counts, $\bar{X}$, for the sample of a vacuum cleaner model is derived when the motor emissions are excluded.

A2.3.1 Select a vacuum cleaner sample from a population. A minimum of three test runs shall be performed for each particle size.

A2.3.2 Test run measurements at each particle size for Test Run No. 1 are shown in Table A2.2.

A2.3.3 The example shown utilizes two counters, one upstream and one downstream, both used for measuring counts. Because of this, two additional pieces of data are collected. These are described as follows.

A2.3.4 *Upstream Background Counts*—These are the particles counted prior to testing, without the sample running or challenge being introduced in the chamber. If only one counter is used, only one set of background readings are obtained.

A2.3.5 *Downstream Correction Factor*—When two particle counters are used, there could be a difference in their readings. This difference may come from two sources; the test system itself and the counters. The downstream correction factor is the ratio of the readings from the upstream counter to the downstream counter under a constant condition. For example, if the upstream counter is reading a constant 110 particles and the downstream counter reads only 100, the ratio is 1.1:1. Therefore, the downstream correction factor is 1.10.

TABLE A2.2 EXAMPLE OF DATA AND CALCULATIONS

Upstream Particle Counts				Upstream Background Counts			
Particle Size, µm	Test Run 1	Test Run 2	Test Run 3	Particle Size, µm	Test Run 1	Test Run 2	Test Run 3
0.3	390279	391456	391004	0.3	73	74	60
0.5	141906	141875	141866	0.5	12	15	9
1.0	58635	58700	58654	1.0	3	4	2
2.5	5250	5245	5243	2.5	0	2	1
Downstream Particle Counts				**Downstream Background Counts**			
Particle Size, µm	Test Run 1	Test Run 2	Test Run 3	Particle Size, µm	Test Run 1	Test Run 2	Test Run 3
0.3	133529	134256	133789	0.3	15	14	11
0.5	23850	23965	24006	0.5	3	3	4
1.0	6034	6045	6044	1.0	1	1	2
2.5	277	282	276	2.5	0	0	0
Downstream Correction Factor				**Corrected Downstream Counts**			
Particle Size, µm	Test Run 1	Test Run 2	Test Run 3	Particle Size, µm	Test Run 1	Test Run 2	Test Run 3
0.3	1.024448	1.024448	1.024448	0.3	136763	137509	137037
0.5	1.035318	1.035318	1.035318	0.5	24689	24808	24580
1.0	1.045798	1.045798	1.045798	1.0	6309	6321	6319
2.5	1.053653	1.053653	1.053653	2.5	292	297	291
Filtration Efficiency, %				Corrected downstream particle counts are calculated as follows: $C_{D\text{-CORRECTED}} = (C_D)$ (Correction Factor) Efficiency at each particle size is calculated as follows: $EFF = (1 - C_{D\text{-CORRECTED}}/(C_U - C_{U\text{-BACKGROUND}})*100$ where: $C_{D\text{-CORRECTED}}$ = corrected downstream counts, C_U = upstream counts, $C_{U\text{-BACKGROUND}}$ = upstream background counts, and C_D = downstream particle counts.			
Particle Size, µm	Test Run 1	Test Run 2	Test Run 3				
0.3	64.95	64.87	64.95				
0.5	82.60	82.51	82.48				
1.0	89.24	89.23	89.23				
2.5	94.44	94.33	94.45				

A2.3.5.1 Use of the downstream correction factor is optional. Normally, a 1:1 ratio is presumed to exist.

A2.3.6 Table A2.2 assumes the following calculations have been performed:

A2.3.6.1 *For Condition One:*

Downstream counts = (downstream background + primary motor emissions + downstream challenge penetration) – (downstream background + primary motor emissions)
OR
all downstream counts

A2.3.6.2 *For Condition Two:*

Downstream counts = (downstream background + primary motor emissions + secondary motor(s) emissions + downstream challenge penetration) – (downstream background + primary motor emissions + secondary motor(s) emissions)
OR
all downstream counts

A2.3.7 Maximum efficiency spread for each particle size = 0.08 % (0.3 µm), 0.12 % (0.5 µm), 0.01 % (1.0 µm), and 0.12 % (2.5 µm).

A2.3.8 The mean, $\bar{X}$, for a particle size of 0.3 µm is calculated as follows:

$$\bar{X}_{0.3\mu} = \frac{1}{n}\sum_{i=1}^{n} X_i = \frac{1}{3}(64.95+64.87+64.95) = 64.92\,\% \tag{A2.5}$$

In the same manner, the efficiencies at the other particle sizes are as follows: 82.53 % (0.5 µm), 89.23 % (1.0 µm), and 94.41 % (2.5 µm).

A2.3.9 The standard deviation, *s*, for a particle size of 0.3 µm is calculated as follows:

$$s_{0.3\mu m} = \sqrt{\frac{n\sum_{i=1}^{n} X_i^2 - \left(\sum_{i=1}^{n} X_i\right)^2}{n\,(n-1)}} \tag{A2.6}$$

$$= \sqrt{\frac{3(64.95^2 + 64.87^2 + 64.95^2) - (64.95+64.87+64.95)^2}{3(3-1)}}$$

$$= 0.046$$

In the same manner, the standard deviation at the other particle sizes are as follows: 0.062 (0.5 µm), 0.006 (1.0 µm), and 0.067 (2.5 µm).

A2.3.10 The value, *A*, for each particle size = 0.05 $\bar{X}$ = 3.246 (0.3 µm), 4.127 (0.5 µm), 4.462 (1.0 µm), and 4.721 (2.5 µm).

A2.3.11 The quantity, $ts/\sqrt{n}$, for a particle size of 0.3 µm is calculated as follows:

$$ts/\sqrt{n} = (4.303)(0.046)/\sqrt{3} = 0.114 \tag{A2.7}$$

In the same manner, the value, $ts/\sqrt{n}$, at the other particle sizes are as follows: 0.154 (0.5 µm), 0.015 (1.0 µm), and 0.166 (2.5 µm).

For each particle size, the value, $ts/\sqrt{n}$, is less than the value, *A*. Therefore, no further test runs are necessary.

A2.3.12 Thus, the calculated mean values, $\bar{X}$, for filtration efficiency at each of the four particle sizes represents the fractional, filtration efficiency for the sample vacuum cleaner.

A3. MATHEMATICAL METHOD FOR DETERMINING WITH 90 % CONFIDENCE THE FRACTIONAL, FILTRATION EFFICIENCY OF A POPULATION OF VACUUM CLEANERS[10]

A3.1 *Theory*:

A3.1.1 The most common and ordinarily the best estimate of the population mean, µ, is simply the arithmetic mean, $\bar{X}$, of the individual scores (measurements) of the units comprising a sample taken from the population. The average score of these units will seldom be exactly the same as the population mean; however, it is expected to be fairly close so that in using the following procedure it can be stated with 90 % confidence that the true mean of the population, µ, lies within a determined interval of the calculated mean, $\bar{X}$, of the sample taken from the population as stated in Section 15.

A3.1.2 The following procedure provides a confidence interval about the sample mean which is expected to bracket µ, the true population mean, 100(1 – α) % of the time where α is the chance of being wrong. Therefore, 1 – α is the probability or level of confidence of being correct.

A3.1.3 The desired level of confidence is 1 – α = 0.90 or 90 % as stated in Section 15. Therefore, α = 0.10 or 10 %.

A3.1.4 Compute the mean, $\bar{X}$, and the standard deviation, *s*, of the individual scores of the sample taken from the population:

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{n} X_i \tag{A3.1}$$

$$s = \sqrt{\frac{n\sum_{i=1}^{n} X_i^2 - \left(\sum_{i=1}^{n} X_i\right)^2}{n\,(n-1)}} \tag{A3.2}$$

where:

n = number of units tested, and
X_i = value of the individual test unit score of the *i*th test unit. As will be seen in the procedural example to follow, this is the average value of the results from three test runs performed on an individual test unit with the resulting set of data meeting the repeatability requirements of Section 15.

---

[10] Natrella, Mary Gibbons, *Experimental Statistics, National Bureau of Standards Handbook 91*, U.S. Government Printing Office, Washington, DC, 1963, pp. 2-1 to 2-3.

A3.1.5 Determine the value of the t statistic for n – 1 df, from Table A2.1 at a 95 % confidence level.

NOTE A3.1—The value of t is defined as t and is read as "t at 95 % confidence."

$$t\ \text{statistic} = t_{1-\alpha/2} = t_{0.95} \tag{A3.3}$$

where:

$1 - \alpha/2 = 1 - 0.10/2 = 1 - 0.05 = 0.95$, or 95 %.

A3.1.6 The following equations establish the upper and lower limits of an interval centered about $\bar{X}$ that will provide the level of confidence required to assert that the true population mean lies within this interval.

$$CI_U = \bar{X} + ts/\sqrt{n} \tag{A3.4}$$

$$CI_L = \bar{X} - ts/\sqrt{n} \tag{A3.5}$$

where:

CI = confidence interval (U - upper limit; L - lower limit),
$\bar{X}$ = mean score of the sample taken from population,
t = t statistic from Table A2.1 at 95 % confidence level,
s = standard deviation of the sample taken from the population, and
n = number of units tested.

A3.1.7 It is desired to assert with 90 % confidence that the true population mean, μ, lies within the interval, CI_u to CI_L centered about the sample mean, $\bar{X}$. Therefore, the quantity $ts/\sqrt{n}$ shall be less than some value, A.

NOTE A3.2—Generally, the value of A is stated as a percentage of the estimated population mean.

A3.1.8 As $n \rightarrow \infty$, $ts/\sqrt{n} \rightarrow 0$. As this relationship indicates, a numerically smaller confidence interval may be obtained by using a larger number of test units, n, for the sample. Therefore, when the standard deviation, s, of the sample is large and the level of confidence is not reached after testing three units, a larger sample size, n, shall be used.

A3.2 *Procedure*—A graphical flowchart for the following procedure is shown in Fig. A2.1.

A3.2.1 Select three units from the population for testing as the minimum sample size.

A3.2.2 Obtain individual test unit scores by averaging the results of three test runs performed on each of the three individual test units. The data set resulting from the three test runs performed on each individual test unit shall meet the respective repeatability requirement found in Section 15.

A3.2.3 Compute $\bar{X}$ and s of the sample.

A3.2.4 Determine the statistic t for n – 1 df from Table A2.1 where n = number of test units.

A3.2.5 Compute $ts/\sqrt{n}$ for the sample and compare it to the value of A.

A3.2.6 If the value of $ts/\sqrt{n} > A$, an additional unit from the population shall be selected and tested, and the computations of A3.2.2 – A3.2.6 are repeated.

A3.2.7 If the value of $ts/\sqrt{n} < A$, the desired 90 % confidence level has been obtained. The value of the final $\bar{X}$ may be used as the best estimate of the fractional, filtration efficiency for a specific particle size for the population.

A3.3 *Example*—The following data is chosen to illustrate how the mean value of filtration efficiency at a given particle size, $\bar{X}$, for the population of a vacuum cleaner model is derived.

A3.3.1 Select three test units from the vacuum cleaner model population. A minimum of three test runs shall be performed using each test unit.

A3.3.2 Test run scores for Test Unit No. 1 at a particle size of 0.3 µm:

Test Run No. 1 = 85.5 %
Test Run No. 2 = 80.2 %
Test Run No. 3 = 84.6 %

A3.3.3 Maximum spread = 85.5 – 80.2 = 5.3 %; The value of A = 0.05(84.4) = 4.2 This value of the spread is greater than the value of A. The results shall be discarded and three additional test runs performed.

A3.3.4 Test run scores for Test Unit No. 1:

Test Run No. 4 = 84.9 %
Test Run No. 5 = 85.1 %
Test Run No. 6 = 85.8 %

A3.3.5 Maximum spread = 85.8 – 84.9 = 0.9 %; The value of A = 0.05(85.3) = 4.3 This value of the spread is less than the value of A.

A3.3.6 Unit No. 1 score = (84.9 + 85.1 + 85.8)/3 = 85.3 %.

NOTE A3.3—If it is necessary to continue repeated test run sets (7,8,9 - 10,11,12, and so forth) because the spread of data within a data set is not less than the repeatability limit requirement stated in Section 15, there may be a problem with the test equipment, the execution of the test procedure, or any of the other factors involved in the test procedure. Consideration should be given to reevaluating all aspects of the test procedure for the cause(s).

A3.3.7 A minimum of two additional test units must be tested, each meeting the repeatability limit requirement. For this procedural example, assume those units met the repeatability requirements and the individual unit scores are:

Score of Test Unit No. 1 = 85.27 %
Score of Test Unit No. 2 = 87.63 %
Score of Test Unit No. 3 = 86.41 %

A3.3.8 $\bar{X} = \dfrac{85.27 + 87.63 + 86.41}{3} = 86.74\,\%$.

A3.3.9

$$s = \sqrt{\frac{3\left[(85.27)^2 + (87.63)^2 + (86.41)^2\right] - \left[85.27 + 87.63 + 86.41\right]^2}{3(3-1)}}$$ and

s = 1.180 %.

A3.3.10 A = 4.3 %.

A3.3.11 Degrees of freedom, n – 1 = 3 – 1 = 2 and $t_{0.95}$ statistic = 2.920.

A3.3.12 $ts/\sqrt{n} = 2.920\,(1.180)/\sqrt{3} = 1.989\,\%$.

A3.3.13 1.989 < 4.3.
The requirement that has been met because s is smaller than A.

A3.3.14 Thus, the value of $\bar{X}$, 86.74 %, represents the filtration efficiency score for a particle size of 0.3 µm for the vacuum cleaner model tested and may be used as the best estimate of the initial, fractional, filtration efficiency for the population mean. In the same manner, the filtration efficiencies for other particle sizes may be evaluated.

A4. METHOD FOR DETERMINING CONCENTRATION LIMIT OF AUTOMATIC PARTICLE COUNTING SYSTEM

A4.1 The particle concentrations that occur in this method may at times exceed the concentration limit of the particle counting system. An over-concentration of particles will cause both undercounting and skewing of the particle distribution. The procedure to verify that the particle concentration is under the particle counting system's limit is described in this section.

A4.2 *Challenge Injection Rate Method*:

A4.2.1 This method is used during the initial setup of the particle counter to verify that the particle counter's particle concentration limit is not exceeded.

A4.2.1.1 Turn on the main sheath airflow source and the challenge injection system's airflow source without the test unit installed in the main test chamber.

A4.2.1.2 Turn on the challenge injection system and set the injection rate to the intended injection rate for the test.

A4.2.1.3 Measure and record the particle count and size distribution at the upstream probe.

A4.2.1.4 Decrease the challenge injection system's injection rate of 0.5 times the test injection rate.

A4.2.1.5 Measure and record the particle count and size distribution.

A4.2.1.6 Determine the ratio of particle counts per cubic metre at the higher injection rate to the particle counts per cubic metre at the lower injection rate for each bin. This ratio for each bin should not be greater than 10 %.

A4.3 *System Dilution Method:*(This method is used during the test to verify particle counts.)

A4.3.1 Measure and record the particle counts and size distribution at the upstream probe and chosen test sheath airflow rate.

A4.3.2 Increase the sheath airflow rate by at least a factor of 1.5.

A4.3.3 Measure and record the particle counts and size distribution at this higher sheath airflow rate.

A4.3.4 Determine the ratio of particle counts per cubic metre at the lower sheath airflow rate to the particle counts per cubic metre at higher sheath airflow rate.

A4.3.4.1 This ratio should not be greater than 10 %.

A4.3.5 Compare the particle size distribution at the lower sheath airflow rate to the particle size distribution at the higher sheath airflow rate for each bin. The particle size distribution should not change for each bin.

A4.3.5.1 The particle size distribution is considered to have changed if the fractions in each bin at the two sheath airflow rates (concentrations) differ by more than 5 %.

A4.3.5.2 Particle counts in size bins with counts over 1000 can be normalized for direct comparison.

A4.3.6 If either the particle concentration ratio (A4.3.4) or the size distribution (A4.3.5) exceeds the stated allowable difference, then the particle counting system's concentration limit has been exceeded and the test setup must be adjusted to eliminate the overconcentration.

A5. METHOD TO DETERMINE A CORRELATION RATIO BETWEEN TWO, DISCRETE PARTICLE COUNTERS; AND WHEN, WHY, AND HOW TO APPLY THIS RATIO

A5.1 This method verifies the counting correlation between two particle counters. Suspensions of particles are introduced to the test counters at a known rate and concentration, and the particle counter's performance is monitored.

A5.1.1 Test particles, typically salt (KCl), are used. Ambient air can be used if mutually agreed upon.

A5.2 *Determination of Background Particle Counts*:

A5.2.1 Install the two particle counters to be tested.

A5.2.1.1 The particle counters can be simultaneously verified to be count matched or done sequentially at the same sample points.

A5.2.2 Start particle counting systems and sheath airflows with no contaminant injection.

A5.2.3 Measure and record the particle counts in the particle size ranges of interest. This is the apparatus background count since the sheath airflow is filtered by the apparatus inlet HEPA filters.

A5.3 *Count Correlation Between Particle Counters - Using Salt (KCl)*:

A5.3.1 Start the system flow.

A5.3.2 Start the injection of salt (KCl) taking care not to exceed the particle counters concentration limits.

A5.3.3 Measure and record the particle counts and size distribution until at least 1000 particles are recorded in each size range of interest.

A5.4 *Count Correlation Between Particle Counters - Ambient Challenge*:

A5.4.1 Start system flow.

A5.4.2 Start the injection of the ambient challenge by bypassing the test apparatuses inlet HEPA filter at a known airflow rate.

A5.4.3 Measure and record particle counts and size distribution until at least 1000 particles are recorded in each size range of interest.

A5.5 *Acceptance Criteria*:

A5.5.1 The particle count rates in each size range of interest should be within 5 % of each other for the counters, independent of the port.

A5.5.2 The particle count rates in each size range of interest should be within 5 % of each other for the counters tested at separate ports (for example, one at the upstream probe and the other at the downstream probe).

ASTM International takes no position respecting the validity of any patent rights asserted in connection with any item mentioned in this standard. Users of this standard are expressly advised that determination of the validity of any such patent rights, and the risk of infringement of such rights, are entirely their own responsibility.

This standard is subject to revision at any time by the responsible technical committee and must be reviewed every five years and if not revised, either reapproved or withdrawn. Your comments are invited either for revision of this standard or for additional standards and should be addressed to ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee, which you may attend. If you feel that your comments have not received a fair hearing you should make your views known to the ASTM Committee on Standards, at the address shown below.

This standard is copyrighted by ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, United States. Individual reprints (single or multiple copies) of this standard may be obtained by contacting ASTM at the above address or at 610-832-9585 (phone), 610-832-9555 (fax), or service@astm.org (e-mail); or through the ASTM website (www.astm.org). Permission rights to photocopy the standard may also be secured from the Copyright Clearance Center, 222 Rosewood Drive, Danvers, MA 01923, Tel: (978) 646-2600; http://www.copyright.com/