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Road Vehicles — Aerosol separator performance test for internal combustion engines —

Part 4:
Laboratory fractional efficiency test method

Véhicules Routiers — Essai de performance du séparateur d'aérosols pour les moteurs à combustion interne —

Partie 4: Méthode d'essai de l'efficacité fractionnelle en laboratoire

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 22, *Road vehicles*, Subcommittee SC 34, *Propulsion, powertrain and powertrain fluids*.

A list of all parts in the ISO 17536 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user’s national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Engine crankcase blowby is composed of combustion exhaust gases, which have escaped to the crankcase via piston ring seals, and lube oil aerosols generated by thermal and mechanical action within the engine. These gases are vented from the crankcase to prevent a build-up of high pressure. The constituents of vented engine blowby gases are recognized as an undesirable contaminant and technology for their containment is therefore evolving.

The device used to separate oil aerosols from the blowby typically releases cleaned gases to atmosphere or into the air inlet prior to the engine or turbo compressor (if present). The latter has led to the requirement for a pressure control device to isolate the engine from turbo inlet suction.

It is the purpose of this document to define standardized and repeatable test procedures for the evaluation of blowby oil aerosol separators and filtering devices using this laboratory fractional efficiency test method.

Road Vehicles — Aerosol separator performance test for internal combustion engines —

Part 4:
Laboratory fractional efficiency test method

1 Scope

This document defines standardized and repeatable test procedures for the evaluation of blowby oil aerosol separators and filtering devices and specifies laboratory fractional separation efficiency in both open and closed crankcase ventilation systems.

Filter life is not evaluated in this document.

The conditioned portion of this test only applies to filters that can meet the Dp stability requirements referenced in ISO/TS 17536-2.

Conformance of a device to legislation is outside of the scope of this document.

Due to limited precision using current equipment, this document is not suitable for filters above an efficiency of 99 %.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 17536-1:2015, *Road vehicles — Aerosol separator performance test for internal combustion engines — Part 1: General*

ISO/TS 17536-2, *Road vehicles — Aerosol separator performance test for internal combustion engines — Part 2: Laboratory test method*

3 Terms, definitions, and abbreviated terms

For the purposes of this document, the terms and definitions given in ISO 17536-1 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1 Terms and definitions

3.1.1
fractional separation efficiency
ability of the separator to remove particles of a specified size expressed as a percentage

3.1.2
particle instrument
instrument for sizing and/or counting aerosol particles

Note 1 to entry: Recommended particle instruments are LSAS's, or other instruments demonstrating they can measure results to within 5 % of an LSAS.

3.2 Abbreviated terms

PSD particle size distribution

PSE particle size removal efficiency

PSL polystyrene latex, referring to commercially available particles of various specific sizes

LSAS light scattering aerosol spectrometer

4 Measurement accuracy

The measurement accuracy of this document shall be in accordance with ISO 17536-1:2015, Clause 3.

5 Test materials and conditions

5.1 Absolute filter, wall flow trap and leakage

The provisions related to the absolute filter (if present), the downstream wall flow trap (if present) and leakage shall be in accordance with ISO 17536-1.

5.2 Test temperature

The volume directly outside of the unit under test (UUT) and internal temperature of the efficiency test shall be either:

— Condition A: 80 °C ± 3 °C

— Condition B: 23 °C ± 5 °C

The condition that is run shall be documented in the test report (see Annex B).

5.3 Test conditions

All test measurements shall be performed under the following stable conditions:

a) Flow rate: Air flow rate and mass oil flow are specified by the customer or by the test requestor.

b) Clean condition: The user should run a clean pressure loss test as specified in ISO/TS 17536-2. The clean pressure loss test is conducted before any oil aerosol is allowed to enter the unit under test (UUT).

c) If gravimetric efficiency (per ISO/TS 17536-2) and fractional efficiency tests are being performed simultaneously, once the oil flow has been started for a test the air flow and oil flow shall not be interrupted until the completion of the fractional efficiency test.

d) The conditioned fractional efficiency is measured after reaching the condition specified in ISO/TS 17536-2.

NOTE Aerosol size distribution is not specified in this document, however two possible distributions are as follows. D50: 0,85 µm to 0,9 µm (same as ISO/TS 17536-2) or to the customer's specification.

6 Test procedure

6.1 General

Performance tests shall be performed on a complete aerosol separator assembly. The tests shall consist of a fractional efficiency test and a conditioned fractional efficiency test (when applicable). If a gravimetric efficiency test, conditioned gravimetric efficiency test, pressure loss, crankcase pressure control test (when pressure regulator is present), or a drain interval test (when applicable) will be performed, it shall be done in accordance with ISO/TS 17536-2.

6.2 Test equipment

NOTE The definitions of the following terms related to the test equipment are defined in ISO 17536-1; upstream particle instrument, particle instrument calibration, maximum particle concentration and particle instrument flow.

6.2.1 The duct material shall be electrically conductive and electrically grounded (metal duct), have a smooth interior finish, and be sufficiently rigid to maintain its shape at the operating pressures. The background air shall be tested with a particle instrument.

6.2.2 The test bench used to determine fractional efficiency shall be the same as one of the benches that are shown in Annex C.

6.2.3 Use an aerosol generator which is capable of dosing oil mist over the range of sizes required as per customer specification.

6.2.4 An upstream wall flow trap should be used between the oil mist generator and the inlet duct to eliminate any oil wall flow to the inlet duct. Use a wall flow trap conforming to ISO 17536-1.

6.2.5 Use an inlet piezometer tube conforming to ISO 17536-1. The cross-section shall be the same as the aerosol separator inlet. In the case of non-uniform flow conditions caused by special inlet ducts, special precautions may be required.

6.2.6 Use a manometer or other differential pressure measuring device with the specified accuracy described in ISO 17536-1.

6.2.7 A downstream wall flow trap should be used between the unit under test and the outlet piezometer tube described in 6.2.5 (if present) to eliminate any oil wall flow. Use a wall flow trap conforming to ISO 17536-1.

6.2.8 Use an outlet duct conforming to ISO 17536-1. The cross-section shall be the same as the aerosol separator outlet. In the case of non-uniform flow conditions caused by special inlet ducts, special precautions may be required.

6.2.9 Use an air flow rate measuring system having the accuracy described in ISO 17536-1. The device needs to be calibrated to the environmental conditions inside the inlet duct at the test conditions used.

6.2.10 Use an air flow rate control system with a refresh rate greater than or equal to 2 Hz capable of maintaining the indicated flow rate to within 5 % of the selected value.

6.2.11 Use compressed air/blower/exhauster for controlling air flow through the system, which has adequate flow rate and pressure characteristics for the oil separators to be tested.

6.2.12 If the unit under test has a pressure regulator or bypass, the use of a blower/exhauster on the downstream of the system can be used to regulate the pressure on the outlet of the unit under test. Devices with pressure regulators shall have air pushed through the inlet, because the pressure regulator device regulates the amount of vacuum allowed on the system.

6.3 Aerosol generator

6.3.1 Aerosol concentration shall be measured by particle counting. The concentration shall be documented in the test report.

6.3.2 The test oil shall be documented for surface tension, density and viscosity. The temperature of the aerosol flow shall be measured at the filtration system inlet. Run test at conditions specified in 5.3. Periodically check these parameters.

6.4 Aerosol sampling system

6.4.1 The design criterion for the sampling system should be to provide a particle transport of >95 % for 3 µm diameter particles from the sample probe inlet within the test duct to the inlet of the particle instrument.

This shall be verified by experimental measurement or by numerical calculation of particle transport based upon the geometry of the sampling system, the sampling flow rate, and particle deposition associated with diffusion, sedimentation, turbulent flow, and inertial forces, as described in Reference [1].

6.4.2 The use of a sampling system is allowed to optimize particle transport from the inlet probe to the particle instrument. The sampling system shall meet the following criteria:

6.4.2.1 The portion of the sampling line in the duct shall block less than 25 % of the duct cross-sectional area.

6.4.2.2 Isokinetic sampling (to within +0 % to -10 %) shall be maintained on both upstream and downstream probes for the requestors specified flow rate of the UUT.

6.4.2.3 Flow through the sampling system shall be measured to within 5 % with volumetric devices (e.g. orifice plates and variable area flowmeters).

Sampling air flow should be considered in total flow rate (e.g. 3 l/min sampling at 30 l/min rated flow).

6.4.2.4 Combined particle losses in the system should be <5 % for 3 µm diameter particles, based on particle transport modelling.

6.4.2.5 The upstream and downstream sampling systems shall be of equal length and equivalent geometry.

6.4.2.6 Where the upstream sampling system flow rate is greater or equal to 20 % of the system air flow rate, compensation of the downstream particle count system flow rate shall account for the flow through the particle sizer to maintain UUT constant flow rate.

6.4.2.7 Where the downstream sampling system flow rate is greater than or equal to 20 % of the system air flow rate, compensation of the downstream particle count system flow rate shall account for the flow through the particle sizer to maintain UUT constant flow rate.

6.4.2.8 Position of auxiliary components (i.e. wall flow trap) shall not change PSD, will need to verify by measurement.

6.4.2.9 User shall verify the dilution ratio and ensure that the dilution does not change the particle distribution.

6.4.2.10 Ground all metal tubing and/or use grounded plastic tubing (carbon or embedded wire). The upstream and downstream sample lines should be nominally identical in geometry and shall use the minimal length of tubing possible.

6.4.2.11 The inlet nozzles of upstream and downstream sample probes shall be sharp edged (<15° included angle) and of appropriate entrance diameter to maintain isokinetic sampling within +0 to -10 % at the test airflow rate.

6.5 Particle sizing and counting monitor(s)

Permissible instruments used to measure the size and concentration of the aerosol shall meet the following criteria:

6.5.1 Shall measure particle diameters between 0,3 um and 5 um particles and group them into at least 8 channels per decade.

6.5.2 At least 90 % of all observed counts shall register between 0,7 µm to 1,3 µm when the particle instrument is challenged with monodisperse 1,0 µm diameter PSL particles.

6.5.3 Shall have at least 50 % counting efficiency at 0,3 um.

6.5.4 Shall have less than 10 % coincidence loss during the measurement.

6.5.5 Shall measure no more than 10 counts per min over the 0,30 µm to 5 µm range with a HEPA filter mounted at the inlet of the counter.

6.5.6 The particle instrument shall be periodically calibrated according to manufacturer specifications.

6.5.7 The particle instrument shall be calibrated to measure oil particles.

NOTE Particle counters often are calibrated for dust, which can give erroneous results when used for this test.

7 Apparatus qualification testing

7.1 Test stand verification

7.1.1 Apparatus qualification tests shall verify quantitatively that the test rig and sampling procedures are capable of providing reliable particle size efficiency measurements. The tests shall be performed in accordance with Table 1.

Table 1 — System qualification measurement requirements

Parameter	Requirement
100 % efficiency test: based on HEPA filter test	>99 %
Correlation ratio test	See Clause 9, Table 7

Table 1 *(continued)*

Parameter	Requirement
Duct leakage: ratio of leak rate to test airflow rate	<1,0 %
Particle instrument zero count check: based on HEPA filter attached to the instrument's inlet	<10 counts per min over the 0,30 µm to 10 µm range
Particle instrument sizing accuracy check: based on sampling of aerosolized monodisperse PSL spheres of known size	Relative maximum shall appear in the appropriate sizing channel

7.2 Concentration limit of the particle instrument

7.2.1 A series of initial efficiency tests shall be performed over oil aerosol concentrations to determine a total concentration level for the PSE tests that does not overload the particle instrument(s). The lowest total concentration level shall be less than 1 % of the instrument's stated total concentration limit. The tests shall be performed following the procedures of 8.1 through 8.5 on a device using a range of upstream aerosol concentrations. The tests shall be performed at 10 %, 50 %, 100 % and 200 % of rated flow.

7.2.2 The aerosol for these tests shall be generated using the same system and procedures as described in Clause 8 for fractional efficiency tests.

7.2.3 The tests shall be performed over a sufficient range of total challenge concentrations to demonstrate that the particle instrument(s) is not overloaded at the intended test concentration.

7.3 100 % efficiency test and development of purge time

7.3.1 An initial efficiency test shall be performed using a HEPA filter as the test device to ensure that the test duct and sampling system are capable of providing a >99 % efficiency measurement. The test procedures for determination of PSE given in Clause 9 shall be followed, and the test shall be performed at 10 %, 50 %, and 100 % of test systems flow rate range.

7.3.2 The computed PSE values shall be greater than 99 % for all particle sizes.

7.3.3 One parameter affecting the efficiency during the 100 % efficiency test is the purge time. The purge time is too short if, after switching from the upstream to the downstream line, residual particles from the upstream sample are counted during the downstream sampling and yield an efficiency of <99 %. In this case, the purge time shall be increased and the 100 % efficiency test repeated.

7.4 Correlation test

7.4.1 A test shall be performed without a test device in place to check the adequacy of the overall duct, sampling, measurement, and aerosol generator.

7.4.2 The test procedures, given in 9.6, for determination of the correlation ratio shall be followed.

7.4.3 The correlation ratio for each particle size shall meet the requirements specified in Table 7.

7.5 Test duct air leakage test

7.5.1 Air leakage from the test duct shall not exceed 1 % of the airflow rate of test filter.

7.5.2 The leak rate of the test duct shall be evaluated by a method similar to that delineated in ANSI/ASME N510. The test duct shall be sealed immediately upstream of the aerosol injection location.

Carefully meter air into the test duct until the lowest test pressure of 1,2 × loaded filter (OCV/CCV) is achieved. The airflow rate required to maintain the pressure constant shall be measured and recorded as the leak rate, and the test shall then be repeated for the other two test pressures. The measured leak rates shall not exceed 1 % of the corresponding test airflow rate.

7.6 Apparatus maintenance

7.6.1 Maintenance items and schedules shall conform to the following:

a) Calibration performed at least annually or in accordance with manufacturer specifications.

b) Monthly visual inspection for proper installation and operation.

c) Cleaning intervals of the test duct, aerosol generator system, aerosol sampling lines, and other test components is discretionary.

8 Fractional efficiency test

8.1 General

The purpose of this test is to determine the particle collection capabilities of the filter in two conditions.

8.1.1 New state (if possible)

High efficiency separators shall not exceed 3 h for 8.1.1 testing, as new state is no longer maintained. For such separators 8.1.2 shall be performed to complete a final efficiency evaluation on the product.

8.1.2 Conditioned state as per ISO/TS 17536-2

The fractional efficiency test is conducted with constant air flow rate using the aerosol generator described in 6.3.

8.2 Method

The filter efficiency test procedure can be performed with a pair of particle instruments used to sample the upstream and downstream flow nearly simultaneously, or with one particle instrument alternatively sampling the air flow upstream and downstream. In the case of the single counter system, it shall be of a single sampling or dual sampling arrangement. In the case of a single particle instrument, the upstream counts that occurred during the time the downstream sample is taken are estimated from upstream counts taken before and after the downstream count. The upstream counts shall be taken as soon before and after the downstream count as possible while allowing for appropriate purge time between upstream and downstream sample periods. Use of a single particle sizer and counter downstream and/or estimating the upstream counts from measurements that are not taken during the test is not allowed. Estimating the upstream counts from measurements with a different sizing method is not allowed.

8.3 Calculations

The calculations shown in Clause 9 are for single counter, single (sequential) or dual sampling systems. Calculations for dual counter systems are the same except that the observed upstream counts are used rather than estimated upstream counts. The data quality requirements for single and dual particle instrument systems are identical.

8.4 Correlation and tare

For tests as shown in Figure C.1 or C.2, correlations and pressure loss tare measurements are conducted with a "blank duct" replacing the aerosol separator to be tested. The blank duct should be smooth, conductive metal tubing that includes the minimum bends and area changes required to replace the filter housing and connect the inlet and outlet piezometers in the same positions as when the device to be tested is installed.

8.5 Fractional efficiency test

8.5.1 Temperature, relative humidity and barometric pressure are recorded at the beginning and end of each test. The temperature and relative humidity are monitored continuously throughout the test to ensure that the stability requirements according to 5.3 are met.

8.5.2 Install the blank duct or element housing in the test system in place of the test device. Set the specified volume flow rate and measure and record the tare pressure loss, background counts and correlation ratios. See items 1, 2, and 3 in Table 2. See Clause 9 for sampling sequence, number of samples required, calculations, and for criteria for accepting background count and correlation ratio data.

8.5.3 Mount the filter assembly or filter element in the respective test housing (if applicable). Test filter assemblies shall be mounted in the same orientation as when installed in the vehicle.

8.5.4 Set the specified volume air flow rate. The volume flow rate shall be maintained at the specified value ±2 % throughout the test.

8.5.5 Condition the aerosol separator and filtering device as per ISO/TS 17536-2.

8.5.6 Measure the background counts as per item 4, Table 2. See Clause 9 for acceptance criteria.

8.5.7 Measure and record the pressure loss (Δp_1).

8.5.8 Start to feed the oil aerosol at the determined flow rate.

8.5.9 Allow the upstream and downstream aerosol concentration to stabilize, then measure fractional efficiency of the UUT. See Clause 9 for sampling sequence, number of samples required, calculations, and for criteria for accepting data. Efficiency curves shall be drawn for any or all of the particle size ranges of the test protocol. Efficiency measurements should be made at 50 %, and 100 % of customer or requestor specified flow rate or at agreed flow rate points with customer.

8.5.10 Turn off the aerosol and measure the background counts as per Clause 9.

8.5.11 Feed the oil aerosol at the determined flow rate until the filter reaches it second test condition as described in ISO/TS 17536-2.

8.5.12 Measure and record the pressure loss (Δp_1).

8.5.13 Stop the test aerosol generator. Measure background counts according to 9.6.

8.5.14 Start the aerosol. Allow the upstream and downstream aerosol concentration to stabilize then measure fractional efficiency of the UUT. See Clause 9 for sampling sequence, number of samples required, calculations, and for criteria for accepting data. Efficiency curves shall be drawn for any or all of the particle size ranges of the test protocol. Efficiency measurements should be made at 10 %, 50 %, 100 % and 200 % of customer or requestor specified flow rate.

8.5.15 Stop the aerosol.

8.5.16 Measure background counts according to 9.6.

8.5.17 Measure and record temperature, relative humidity and barometric pressure.

9 Calculations and data acceptance criteria

9.1 Symbols used in following formulae

9.2 Symbols

U = upstream counts of each size range (or channel)

D = downstream counts of each size range (or channel)

R = correlation ratio

P = penetration

P' = penetration calculated using Poisson statistics

E = efficiency

T = sampling time

δ= standard deviation of a sample

n = number of sample sets

t = t distribution variable

9.3 Subscripts used in the following formulae

i = run number

o = observed

c = correlation

b = background

t = testing an aerosol separator

u = upstream

d = downstream

e = estimated

lcl = lower confidence limit

ucl = upper confidence limit

n = number of sample sets

9.4 Average used in the following formulae

Over bar is used to denote averages, for example $\overline{P}$.

9.5 Test sampling

9.5.1 Table 2 is an illustration of the test sequence, Table 3 is the sampling sequence for single counter single sampling systems, Table 4 is the sampling sequence for single counter dual sampling system and

Table 5 is the sampling sequence for each efficiency measurement for dual counter dual sampling systems. The sampling pattern in Tables 3, 4, and 5 illustrate one iteration of a sequential upstream-downstream sampling sequence. Sample counts in each size range shall be handled the same way, and this pattern shall be followed for all fractional efficiency tests. An initial upstream sample shall be followed by an upstream to downstream purge. The first downstream sampling shall be followed by a downstream to upstream purge and then shall be followed by another upstream sample. The last four time periods shall be repeated for as many sample sets as are required.

NOTE Dual counter dual sampling systems are often referred to as dual counter systems without referring to the number of sampling inputs.

Table 2 — Test sequence for either the new or conditioned state efficiency

#	Procedure #	Test type	Device in test position	Fractional efficiency aerosol generator	Counters sampling, or protected
1	8.5.2	Background 1	Blank duct or empty housing.	Off	On
2	8.5.2	Correlation	Blank duct or empty housing.	On	On
3	8.5.2	Background 2	Blank duct or empty housing.	Off	On
4	8.5.6	Background 3	Housing with filter element	Off	On
5	8.5.9	Efficiency/ Penetration	Housing with filter element	On	On
6	8.5.10	Background 4	Housing with filter element	Off	On

Table 3 — Sampling sequence for a single counter, single sampling system

Sampling step	Particle counting	Purging
0	No	For first upstream sample
1	Upstream	No
2	No	Upstream to downstream purge
3	Downstream	No
4	No	Downstream to upstream purge
5	Upstream	No
Repeat steps 2 through 5 until a minimum of 4 upstream samples and 3 downstream samples have been taken. More repetitions may be required to meet the data quality requirements. Final upstream count is not required when measuring background counts.		

Table 4 — Sampling sequence for a single counter, dual sampling system

Sampling step	Particle counting	Purging
0	No	For first upstream sample
1	Upstream	No
2	No	For first downstream sample
3	Downstream	No
4	Upstream	No
5	Downstream	No
Repeat steps 4 through 5 until a minimum of 4 upstream samples and 3 downstream samples have been taken. More repetitions may be required to meet the data quality requirements. Final upstream count is not required when measuring background.		

Table 5 — Sampling sequence for dual counter, dual sampling systems

Sampling step	Particle counting	Purging
0	No	For first sample
1	Upstream and downstream	No
2	Upstream and downstream	No
3	Upstream and downstream	No
Take additional samples as needed to meet data quality requirements.		

The calculations and data quality requirements according to 9.6 through 9.9 are performed separately for each of the particle sizing ranges.

9.5.2 These formulae are set up to calculate values by channel. At no time should the user be combining data for multiple channels.

9.6 Correlation ratio

9.6.1 The correlation ratio, R, shall be used to correct for any bias between the upstream and downstream sampling systems and counters. The correlation ratio shall be established from the ratio of downstream to upstream particle counts with a blank duct for filter tests or with an empty housing for element tests installed in the test system and before testing a crank case ventilation filter. The correlation ratio measurement shall be performed at the airflow rate of the test device fractional efficiency test. Formula (1) describes the correlation ratio as used in this standard:

$$R = \frac{downstream\ particle\ concentration}{upstream\ particle\ \ concentration} \quad (1)$$

with the fractional aerosol generator in operation and with a blank test device in place.

Changing the bin widths could lead to a different correlation ratio for similarly sized particles. The correlation ratio should be performed with the same number of channels that are to be used for the efficiency and background tests.

9.6.2 Background counts shall be measured before generating test aerosols. Upstream and downstream sampling shall be performed sequentially, starting with an upstream sample $U_{1,o,b}$, followed by a downstream sample $D_{1,o,b}$, alternating back and forth. The total number of samples and sampling times shall be determined by the data quality requirements in 9.9.2, except when the final upstream sample is not needed for background sampling. Sampling times upstream and downstream shall be the same for this test.

NOTE Some particle counters have a total count limit. Make sure the total sample time is not so long as to go over this total count limit or the correlation ratio will be incorrect.

9.6.3 Start generating aerosol when background counts are complete. Begin sampling after stabilization of the test aerosol, starting with an upstream sample $U_{1,o,c}$, followed by a downstream sample $D_{1,o,c}$. An additional upstream sample $U_{(n+1),o,c}$ shall be made following the last downstream sample $D_{n,o,c}$. The total number of samples and sampling times shall be determined by the data quality requirements in 9.9.2. Sampling times upstream and downstream shall be the same for this test. Total background counts from 9.6.2 shall be less than 1 % of total counts measured when the aerosol generator is on, as specified in Reference [2].

9.6.4 Aerosol generation shall be turned off and background sampling shall be repeated after completion of the required correlation sampling sets.

9.6.5 The correlation ratio shall then be calculated in accordance with 9.9.1.

9.7 Penetration / Fractional efficiency

9.7.1 For the purposes of this standard, penetration P shall be the fraction of particles that pass through the filter, follow Formula (2) for penetration:

$$P = \frac{downstream\ particle\ concentration}{upstream\ particle\ \ concentration} \quad (2)$$

with the fractional aerosol generator on and the test device in place.

9.7.2 Background counts shall be made before generating test aerosols. Upstream and downstream sampling shall be done sequentially, starting with an upstream sample $U_{1,o,b}$, followed by a downstream sample $D_{1,o,b}$, alternating back and forth. The total number of samples and sample times shall be determined by the data quality requirements according to 9.9.4, except that the final upstream sample is not needed for background sampling. A difference between upstream sampling time T_u and downstream sampling time T_d is allowable.

9.7.3 Start generating aerosol when background counts are complete. Start sampling with an upstream sample $U_{1,o,t}$, followed by a downstream sample $D_{1,o,t}$, after stabilization of the test aerosol. Take an additional upstream sample $U_{(n+1),o,t}$, following the last downstream sample $D_{n,o,t}$. Sampling times T_u and T_d shall be the same as those used for background sampling.

9.7.4 Aerosol generation shall be turned off and background sampling shall be repeated after completion of the required penetration sampling sets.

9.7.5 Test device penetration shall then be calculated in accordance with 9.9.3.

9.8 Efficiency

9.8.1 In this document, the general formula for fractional efficiency shall be Formula (3):

$$E = \left(1 - \frac{downstream\ particle\ concentration}{upstream\ particle\ concentration}\right) = (1 - P) \quad (3)$$

9.8.2 Filter efficiency shall be calculated in accordance with 9.9.7.

9.9 Data reduction

9.9.1 Correlation ratio data reduction

9.9.1.1 The upstream counts from two samples shall be averaged to obtain an estimate of the upstream counts that would have occurred at the same time as the downstream counts were taken, see Formula (4):

$$U_{i,e,c} = \frac{U_{i,o,c} + U_{(i+1),o,c}}{2} \quad (4)$$

9.9.1.2 The background counts before (Table 2 – Sequence 1) and after (Table 2 – Sequence 3) the correlation aerosol test generation shall be averaged. For Formulae (5) and (6) the total runs between background 3 and 4 are used.

$$\bar{U}_b = \frac{\sum_{i=1 \to n} U_{i,o,b}}{n} \quad (5)$$

$$\bar{D}_b = \frac{\sum_{i=1 \to n} D_{i,o,b}}{n} \tag{6}$$

9.9.1.3 The correlation ratio shall be calculated for each upstream and downstream sample set using the observed downstream count, the estimated upstream count, the average downstream background count, and the average upstream background count, see Formula (7):

$$R_i = \frac{D_{i,o,c} - \bar{D}_b}{U_{i,e,c} - \bar{U}_b} \tag{7}$$

9.9.1.4 These correlation ratios shall be averaged to determine a final correlation ratio value, see Formula (8):

$$\bar{R} = \frac{\sum_{i=1 \to n} R_i}{n} \tag{8}$$

9.9.1.5 The standard deviation of the correlation ratio shall be determined by Formula (9):

$$\delta_c = \sqrt{\frac{\sum_{i=1 \to n} (R_i - \bar{R})^2}{n-1}} \tag{9}$$

9.9.1.6 The standard deviation of the background counts shall be determined by Formulae (10) and (11):

$$\delta_{u,b} = \sqrt{\frac{\sum_{i=1 \to n} (U_{i,o,b} - \bar{U}_b)^2}{n-1}} \tag{10}$$

$$\delta_{d,b} = \sqrt{\frac{\sum_{i=1 \to n} (D_{i,o,b} - \bar{D}_b)^2}{n-1}} \tag{11}$$

9.9.1.7 The 95 % confidence limits of the correlation value shall be determined by Formulae (12) and (13):

$$\bar{R}_{lcl} = \bar{R} - \delta_c \cdot \frac{t}{\sqrt{n}} \tag{12}$$

$$\bar{R}_{ucl} = \bar{R} + \delta_c \cdot \frac{t}{\sqrt{n}} \tag{13}$$

using the t distribution variable from Table 6 for a given n.

Table 6 — *t* distribution variable

Number of samples n	Degrees of freedom $v = n - 1$	t
3	2	4,303
4	3	3,182
5	4	2,776

Table 6 *(continued)*

Number of samples *n*	Degrees of freedom ν = *n* − 1	***t***
6	5	2,571
7	6	2,447
8	7	2,365
9	8	2,306
10	9	2,262
11	10	2,228
12	11	2,201
13	12	2,179
14	13	2,160
15	14	2,145
16	15	2,131
17	16	2,120
18	17	2,110
19	18	2,101
20	19	2,093
21	20	2,086
22	21	2,080
23	22	2,074
24	23	2,069
25	24	2,064
26	25	2,060
27	26	2,056
28	27	2,052
29	28	2,048
30	29	2,045
inf.	inf.	1,960

9.9.1.8 The 95 % upper confidence limits of the background counts shall be determined by Formulae (14) and (15):

$$\bar{U}_{\text{b,ucl}} = \bar{U}_{\text{b}} + \delta_{\text{u,b}} \cdot \frac{t}{\sqrt{n}} \tag{14}$$

$$\bar{D}_{\text{b,ucl}} = \bar{D}_{\text{b}} + \delta_{\text{d,b}} \cdot \frac{t}{\sqrt{n}} \tag{15}$$

using the *t* distribution variable from Table 6 for a given *n*.

9.9.2 Correlation ratio data acceptance criteria

9.9.2.1 Correlation ratio error limit. The number of correlation sample runs, *n*, shall be at least three and sufficient to satisfy the following conditions, see Formula (16):

$$\delta_c \cdot \frac{t}{\sqrt{n}} \leq 0{,}2 \tag{16}$$

This requirement shall be satisfied by calculating this expression after each sample set and halting the testing sequence when the requirement is reached for each size range, or by an acceptance criterion for a predetermined number of sample sets.

NOTE Increasing upstream and downstream sampling time during correlation testing has been proven to help meet the error limit requirement.

9.9.2.2 Limits on magnitude of correlation ratio. The correlation ratio shall meet the requirements specified in Table 7.

Table 7 — Limits on magnitude of correlation ratio

Size range µm	Limits on correlation ratio
0,30 to 1,0	0,90 to 1,10
1,0 to 3,0	0,80 to 1,20
3,0 to 5	0,70 to 1,30

9.9.2.3 Correlation ratio maximum background counts. The 95 % upper confidence limit of the upstream and downstream background counts shall be less than 5 % of the average estimated upstream count when the particle generation is on, see Formula (17):

$$\bar{D}_{\text{b,ucl}}, \bar{U}_{\text{b,ucl}} < \frac{\sum_{i=1 \to n} U_{i,\text{e,c}}}{n \cdot 20} \tag{17}$$

9.9.2.4 Correlation ratio minimum average upstream counts. The sum of the estimated upstream counts shall be greater than or equal to 500, see Formula (18). If a sufficient number of counts is not obtained, the sample time or aerosol concentration shall be increased. The aerosol concentration shall not exceed the concentration limit of the particle instrument(s), as determined by 7.2.

$$\sum_{i=1 \to n} U_{i,\text{e,c}} \geq 500 \tag{18}$$

9.9.3 Penetration data reduction

9.9.3.1 The upstream counts from the first two samples shall be averaged to obtain an estimate of the upstream counts that would have occurred at the same time as the downstream counts where taken, see Formula (19):

$$U_{i,\text{e,t}} = \frac{U_{i,\text{o,t}} + U_{(i+1),\text{o,t}}}{2} \tag{19}$$

9.9.3.2 The background counts before (Table 2 – Sequence 4) and after (Table 2 – Sequence 6) the penetration test shall be averaged. For Formulae (20) and (21) the total runs between background 1and background 2 are used.

$$\bar{U}_{\mathrm{b}} = \frac{\sum\limits_{i=1 \to n} U_{i,\mathrm{o,b}}}{n} \tag{20}$$

$$D_{\mathrm{b}} = \frac{\sum\limits_{i=1 \to n} D_{i,\mathrm{o,b}}}{n} \tag{21}$$

9.9.3.3 The observed penetration shall be calculated for each upstream and downstream set using the observed downstream count, the upstream count, the average downstream background count, the average upstream background count, the upstream sampling time, and the downstream sampling time. See Formulae (22) and (23).

$$P_{i,\mathrm{o}} = \frac{D_{i,\mathrm{o,t}}}{U_{i,\mathrm{e,t}}} \cdot \frac{T_{\mathrm{u}}}{T_{\mathrm{d}}} \text{ if } \bar{D}_{\mathrm{b,ucl}} \le 0{,}05 \cdot \frac{\sum_{i=1 \to n} U_{i,\mathrm{o,u}}}{n} \cdot \left(\frac{T_{\mathrm{d}}}{T_{\mathrm{u}}} \right) \tag{22}$$

$$P_{i,\mathrm{o}} = \frac{D_{i,\mathrm{o,t}} - D_{\mathrm{b}}}{U_{i,\mathrm{e,t}} - U_{\mathrm{b}}} \cdot \frac{T_{\mathrm{u}}}{T_{\mathrm{d}}} \text{ if } \bar{D}_{\mathrm{b,ucl}} > 0{,}05 \cdot \frac{\sum_{i=1 \to n} U_{i,\mathrm{o,u}}}{n} \cdot \left(\frac{T_{\mathrm{d}}}{T_{\mathrm{u}}} \right) \tag{23}$$

9.9.3.4 These observed penetrations shall be averaged to determine an average observed penetration value, follow Formula (24):

$$\bar{P}_{\mathrm{o}} = \frac{\sum\limits_{i=1 \to n} P_{i,\mathrm{o}}}{n} \tag{24}$$

9.9.3.5 The standard deviation of the observed penetration shall be determined by Formula (25):

$$\delta_{\mathrm{t}} = \sqrt{\frac{\sum\limits_{i=1 \to n} (P_{i,\mathrm{o}} - \bar{P})^2}{n-1}} \tag{25}$$

9.9.3.6 The observed penetration shall be corrected by the correlation ratio to yield the final penetration, see Formula (26):

$$\bar{P} = \frac{\bar{P}_{\mathrm{o}}}{\bar{R}} \tag{26}$$

9.9.3.7 The standard deviation of the correlation ratio shall be combined with the standard deviation of the observed penetration to determine the total error, see Formula (27):

$$\delta = \bar{P} \cdot \sqrt{\left(\frac{\delta_{\mathrm{c}}}{\bar{R}} \right)^2 + \left(\frac{\delta_{\mathrm{t}}}{\bar{P}_{\mathrm{o}}} \right)^2} \tag{27}$$

9.9.3.8 The 95 % confidence limits of the penetration shall be determined by Formulae (28) and (29):

$$\bar{P}_{\mathrm{lcl}} = \bar{P} - \delta \cdot \frac{t}{\sqrt{n}} \tag{28}$$

$$\bar{P}_{\text{ucl}} = \bar{P} + \delta \cdot \frac{t}{\sqrt{n}} \quad (29)$$

using the *t* distribution variable from Table 6 for a given *n*.

9.9.3.9 The standard deviation and 95 % upper confidence limits for the background counts shall be determined using Formulae (10), (14), and (15).

9.9.4 Penetration Data Acceptance Criteria

9.9.4.1 Penetration error limit. The number of sample runs, *n*, shall be at least three and sufficient to satisfy the following condition, see Formulae (30) and (31):

$$\delta \cdot \frac{t}{\sqrt{n}} < 0{,}07 \cdot \bar{P} \text{ or } \le 0{,}05\text{, whichever is greater,} \quad (30)$$

for particle size ranges 0,3 µm to 1,5 µm

$$\delta \cdot \frac{t}{\sqrt{n}} < 0{,}15 \cdot \bar{P} \text{ or } \le 0{,}05\text{, whichever is greater,} \quad (31)$$

for particle size ranges 1,5 µm to 10 µm.

The requirement shall be satisfied by calculating this expression after each sample set and halting the testing sequence when the requirement is reached for each size range, or by acceptance criteria for a predetermined number of sample sets. If these conditions are met, $\bar{P}$ is used to calculate the efficiency.

9.9.4.2 Penetration calculation if penetration error limit is not met. If the above condition cannot be met, the sum of the upstream counts and the sum of the downstream counts shall be calculated using Formulae (32) and (33):

$$U'_{\text{t}} = \sum_{n=1 \to n} U_{i,\text{e,t}} \text{ (sequential) or } U'_{\text{t}} = \sum_{n=1 \to n} U_{i,\text{o,t}} \text{ (simultaneous)} \quad (32)$$

$$D'_{\text{t}} = \sum_{n=1 \to n} D_{i,\text{o,t}} \quad (33)$$

The sums of the upstream and downstream counts are used to calculate an alternate upper confidence limit for observed penetration, P'_{ucl}, using Poisson statistics. See Formula (34)

$$P'_{\text{ucl,o}} = \frac{D'_{\text{ucl,t}}}{U'_{\text{lcl,t}}} \quad (34)$$

For values ≤ 50, $D'_{\text{ucl,t}}$ and $U'_{\text{lcl,t}}$ shall be calculated according to Annex A, Table A.1. For values > 50, $D'_{\text{ucl,t}}$ and $U'_{\text{lcl,t}}$ are found following Formulae (35) and (36):

$$D'_{\text{ucl,t}} = D'_{\text{t}} + 2 \cdot \sqrt{D'_{\text{t}}} \quad (35)$$

$$U'_{\text{lcl,t}} = U'_{\text{t}} - 2 \cdot \sqrt{U'_{\text{t}}} \qquad (36)$$

The observed upper confidence level penetration using Poisson statistics shall be corrected by the correlation ratio to yield the final upper confidence level penetration using Poisson statistics, see Formula (37):

$$P'_{\text{ucl}} = \frac{P'_{\text{ucl,o}}}{\overline{R}} \qquad (37)$$

The greater of the two upper confidence limits for penetration, $\overline{P}_{\text{ucl}}$ or P'_{ucl} shall be used to calculate efficiency for that size range. These criteria shall be used even if the penetration error limit is met but it has channels one or two sizes higher and lower that do not meet the penetration error limit.

9.9.5 Penetration maximum background counts

For correlation tests and tests before dust loading, the 95 % upper confidence limits of the upstream and downstream background counts shall be less than 5 % of the average estimated upstream count when the particle generation is on, see Formula (38):

$$\overline{D}_{\text{b,ucl}}, \overline{U}_{\text{b,ucl}} < \frac{\sum_{i=1 \to n} U_{i,\text{e,t}}}{n \cdot 20} \qquad (38)$$

9.9.6 Penetration minimum upstream counts

The sum of the estimated upstream counts shall be greater than or equal to 500, see Formula (39):

$$\sum_{i=1 \to n} U_{i,\text{e,t}} \geq 500 \qquad (39)$$

9.9.7 Efficiency

Fractional efficiency is determined by Formula (40)

$$E = (1 - P) \qquad (40)$$

where P is replace by $\overline{P}$ or $\overline{P}_{\text{ucl}}$ or P'_{ucl} as determined in 9.9.4.1 and 9.9.4.2.

Annex A
(normative)

Poisson statistics

When using particle instruments to evaluate fractional filtration efficiency, it is necessary to consider limitations imposed by this method. The efficiency is determined by comparing the particles detected and counted upstream of the aerosol separator and filtering device to the particles detected and counted downstream of the aerosol separator and filtering device. Inevitably, there are differences between the upstream and downstream sampling and detection equipment. 9.6 presents a method to calculate correlation ratios to minimize the errors due to the difference between the upstream and downstream equipment.

In the efficiency tests described in this document, at least three upstream and three downstream samples are counted. For sequential sampling systems, the average of the upstream counts before and after a downstream count is used to estimate the upstream count during the downstream sampling time. Then 3 or more penetration values are calculated and analysed for data quality using a t-test. However, when the number of particles counted in a size class is low, potential uncertainty may occur as a result of counting a few randomly occurring events. In that case, it may be difficult or impossible to meet the penetration error limits in 9.9.4.1. For that case, an alternative method to quantify the size of the potential error from counting a few particles is presented in 9.9.4.2. Because the error due to counting random events is a function of the total number of particles counted, it is important to work with the actual counts not concentrations or averages. For the calculations in 9.9.1.4, the sum of the estimated upstream counts is used along with the sum of the actual downstream counts.

When a well-mixed, stable aerosol penetrates a filter, penetrating particles will appear downstream of the filter (or in a small downstream air sample) randomly, but at some average rate. The relationship between the results of a single sample or a finite set of samples and the true mean result is of importance to efficiency testing. This relationship between an observed result and the confidence limits on the true mean result is described by Poisson statistics.

Table A.1 gives the 95 % confidence limits on a single observed particle count N when $N \leq 50$. For a single observed particle count N, there is a 95 % confidence that the true mean count is between the upper and lower limits given by Table A.1. For particle counts >50 Formula (36) is used to estimate the confidence limits.