



Designation: **D 6061 – 9601**

Standard Practice for Evaluating the Performance of Respirable Aerosol Samplers¹

This standard is issued under the fixed designation D 6061; 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 practice covers the evaluation of the performance of personal samplers of non-fibrous respirable aerosol. The samplers are assessed relative to a specific respirable sampling convention. The convention is one of several that identify specific particle size fractions for assessing health effects of airborne particles. When a health effects assessment has been based on a specific convention it is appropriate to use that same convention for compliance with setting permissible exposure limits in the workplace and ambient environment and for monitoring compliance. The conventions, which define inhalable, thoracic, and respirable aerosol sampler ideals, have now been adopted by the International Standards Organization (Technical Report ISO TR 7708), the Comité Européen de Normalisation (CEN Standard EN 481), and the American Conference of Governmental Industrial

¹ This practice is under the jurisdiction of ASTM Committee D-22 on Sampling and Analysis of Atmospheres and is the direct responsibility of Subcommittee D22.04 on Analysis of Workplace Atmospheres.

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Hygienists (ACGIH, Ref (1)),² developed (2) in part from health-effects studies reviewed in Ref (3) and in part as a compromise between definitions proposed in Refs (3,4). This practice is specific to respirable aerosol sampler evaluation because of simplifying characteristics particular to this fraction.

1.2 This practice is complimentary to Test Method D 4532, which specifies a particular instrument, the 10-mm cyclone.³ The sampler evaluation procedures presented in this practice have been applied in the testing of the 10-mm cyclone as well as the Higgins-Dewell cyclone.^{3,4} The sampler evaluation procedures presented in this practice have been applied in the testing of the 10-mm cyclone as well as the Higgins-Dewell cyclone.^{4,5} Details on the evaluation have been recently published (5-7) and can be incorporated into revisions of Test Method D 4532.

1.3 Units

1.3 A central aim of this practice is to provide information required for characterizing the uncertainty of concentration estimates from samples taken by candidate samplers. For this purpose, sampling accuracy data from the performance tests given here can be combined with information as to analytical and sampling pump uncertainty obtained externally. The practice applies principles of ISO GUM, expanded to cover situations common in occupational hygiene measurement, where the measurand varies markedly in both time and space. A general approach (8) for dealing with this situation relates to the theory of tolerance intervals and may be summarized as follows: Sampling/analytical methods undergo extensive evaluations and are subsequently applied without re-evaluation at each measurement, while taking precautions (for example, through a quality assurance program) that the method remains stable. Measurement uncertainty is then characterized by specifying the evaluation confidence (for example, 95 %) that confidence intervals determined by measurements bracket measurand values at better than a given rate (for example, 95 %). Moreover, the systematic difference between candidate and idealized aerosol samplers can be expressed as a relative bias, which has proven to be a useful concept and is included in the specification of accuracy (3.2.9-3.2.10).

1.4 Units of the International System of Units (SI) are used throughout this practice and should be regarded as standard.

1.4.5 *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:

D 1356 Terminology Relating to Atmospheric Sampling and Analysis⁵

² The boldface numbers in parentheses refer to a list of references at the end of this practice.

³ The sole source

³ If you are aware of supply of the 10-mm cyclone known alternative suppliers, please provide this information to ASTM Headquarters. Your comments will receive careful consideration at this time is Mine Safety Appliances Co., Instrument Div., P.O. Box 427, Pittsburgh, PA 15230; a meeting of the responsible technical committee,¹ which you may attend.

⁴ If you are aware

⁴ The sole source of alternative suppliers, please provide this information to ASTM Headquarters. Your comments will receive careful consideration at a meeting supply of the responsible technical committee,¹ which you may attend. Higgins-Dewell cyclone known to the committee at this time is BGI Inc., 58 Guinan Street, Waltham, MA 02154.

⁵ The sole source

⁵ Annual Book of supply of the Higgins-Dewell cyclone known to the committee at this time is BGI Inc., 58 Guinan Street, Waltham, MA 02154; ASTM Standards, Vol 11.03.

- D 4532 Test Method for Respirable Dust in Workplace Atmospheres⁵
- D 6062M Performance Specifications for Samplers of Health-Related Aerosol Fractions⁵
- D 6552 Practice for Controlling and Characterizing Errors in Weighing Collected Aerosols⁵

2.2 *International Standards:*

- ISO TR 7708 Technical Report on Air Quality—Particle Size Fraction Definitions for Health-Related Sampling, Brussels, 1993⁶
- ISO GUM Guide to the Expression of Uncertainty in Measurement, Brussels, 1993⁶
- CEN EN 481 Standard on Workplace Atmospheres. Size Fraction Definitions for the Measurement of Airborne Particles in the Workplace, Brussels, 1993⁷
- CEN prEN 1232 Pre-Standard on Workplace Atmospheres. Requirements and Test Methods for Pumps used for Personal Sampling of Chemical Agents in the Workplace, Brussels, 1993⁷
- CEN EN 13205 Workplace Atmospheres- Assessment of Performance of Instruments for Measurement of Airborne Particle Concentrations, 2001⁷

2.3 *NIOSH Standards:*

- NIOSH Manual of Analytical Methods, 4th ed., Eller, P. M., ed.: Dept. of Health and Human Services, 1994⁸
- Criteria for a Recommended Standard, Occupational Exposure to Respirable Coal Mine Dust, NIOSH, 1995⁹⁻¹⁰

3. Terminology

3.1 *Definitions:*

- 3.1.1 For definitions of terms used in this practice, refer to Terminology D 1356 and ISO GUM.
- 3.1.2 Aerosol fraction sampling conventions have been presented in Performance Specifications D 6062M. The relevant definitions are repeated here for convenience.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *aerodynamic diameter, D* (μm)—the diameter of a sphere of density, 10³ kg/m, with the same stopping time as a particle of interest.

3.2.2 *respirable sampling convention, E_R*—defined explicitly at aerodynamic diameter D , defined explicitly D (μm) as a fraction of total airborne aerosol in terms of the cumulative normal function Φ as follows:

$$E_R = 0.50 (1 + \exp[-0.06 D]) \Phi [\ln[D_R/D]/\sigma_R] \tag{1}$$

where the indicated constants are $D_R = 4.25 \mu\text{m}$ and $\sigma_R = \ln[1.5]$. The function Φ may be approximated using the algorithm presented in Appendix X1. = $\ln[1.5]$.

3.2.2.1 *Discussion*—The respirable sampling convention, together with earlier definitions, is shown in Fig. 1. This convention

Annual Book of ASTM Standards, Vol 11.03.

⁶ Available from International Organization for Standardization, Caisse Postale 56, CH-1211, Geneva 20, Switzerland.
⁷ Available from International Organization for Standardization, Caisse Postale 56, CH-1211, Geneva 20, Switzerland; CEN Central Secretariat: rue de Stassart 36, B-1050 Brussels, Belgium.
⁸ Available from CEN Central Secretariat: rue de Stassart 36, B-1050 Brussels, Belgium; Superintendent of Documents, U.S. Government Printing Office, Stock No. 917-011-00000-1, Washington DC 20402.
⁹ Available from NIOSH Publications, 4676 Columbia Parkway, Cincinnati, OH 45226; TSI, Inc., P.O. Box 64394, St. Paul, MN 55164 is the sole aerodynamic particle sizer presently available suitable for this purpose.
¹⁰ Available from Superintendent of Documents, U.S. Government Printing Office, Stock No. 917-011-00000-1, Washington DC 20402; NIOSH Publications, 4676 Columbia Parkway, Cincinnati, OH 45226.

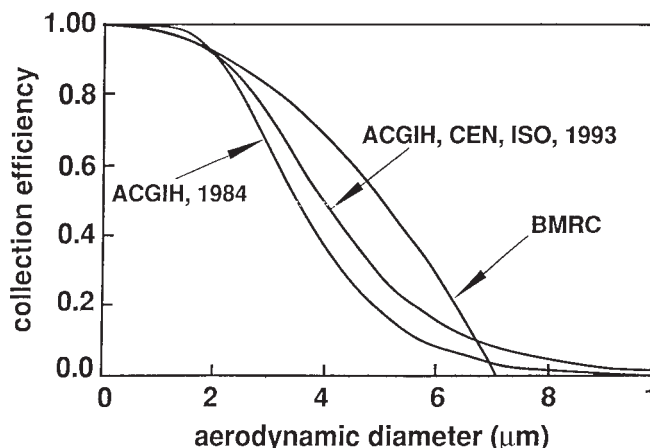


FIG. 1 Respirable Aerosol Collection Efficiencies

has been adopted by the International Standards Organization (Technical Report ISO TR 7708), the Comité Européen de Normalisation (CEN Standard EN 481), and the American Conference of Governmental and Industrial Hygienists (ACGIH, Ref (1)). The definition of respirable aerosol is the basis for the recommended exposure level (REL) of respirable coal mine dust as promulgated by NIOSH (*Criteria for a Recommended Standard, Occupational Exposure to Respirable Coal Mine Dust*) and also forms the basis of the NIOSH sampling method for particulates not otherwise regulated, respirable (*NIOSH Manual of Analytical Methods*).

3.2.3 size-distribution $C^{-1} dC/dD$ ($\text{mg}/\text{m}^3/\mu\text{m}$)—of (μm^{-1})—of a given airborne aerosol, the mass concentration of aerosol per unit aerodynamic diameter range per total concentration C .

3.2.3.1 log-normal size distribution dC_{ln}/dD —an idealized distribution characterized by two parameters: the *geometric standard deviation (GSD)* and *mass median diameter (MMD)*. dC_{ln}/dD is The distribution is given explicitly as follows:

$$dC_{ln}/dD = \frac{1}{\sqrt{2\pi}} \frac{C}{D \ln[GSD]} \exp\left[-\frac{1}{2} \ln[D/MMD]^2 / \ln[GSD]^2\right] \quad (2)$$

$$C^{-1} dC/dD = \frac{1}{\sqrt{2\pi} D \ln[GSD]} \exp\left[-\frac{1}{2} \ln[D/MMD]^2 / \ln[GSD]^2\right] \quad (2)$$

where C is the total mass concentration.

3.2.4 true conventional respirable concentration c_R (mg/m^3)—the concentration measured by a conventional (that is, ideal) respirable sampler and given in terms of the size distribution dC/dD as follows:

$$c_R = \int_0^\infty dD E_R dC / dD \quad (3)$$

3.2.4.1 Discussion—Note that samples are often taken over an extended time period (for example, 8 h), so that dC/dD of Eq. 3 represents a time-averaged, rather than instantaneous, size-distribution.

3.2.5 sampler number $s = 1, \dots, S$ —a number identifying a particular sampler under evaluation.

3.2.6 sampling efficiency $E_{s_s}(D, Q)$ —the modeled sampling efficiency of sampler s as a function of aerodynamic diameter D and flow rate Q (9.1).

3.2.6.1 model parameters θ_{j_p} where $j_p = 1, \dots, J_P$ (for example, 4)—parameters that specify the function $E_{s_s}(D, Q)$.

3.2.7 mean sampled concentration c_s —the concentration that sampler s would give, averaged over sampling pump and analytical fluctuations, in sampling aerosol of size-distribution $C^{-1} dC/dD$ and is given as follows:

$$c_s = \int_0^\infty dD E_s dC / dD \quad (4)$$

3.2.8 mean concentration \bar{c} —the average population mean of c_s over the samplers tested.

3.2.9 mean bias Δ —relative to a conventional sampler, defined as follows:

$$\Delta = (c - c_R) / c_R \quad (5)$$

3.2.10 The imprecision or relative standard deviation RSD is defined here in terms of independent analytical, intra-sampler, and inter-sampler components:

3.2.10.1 uncertainty components:

3.2.9.1 analytical relative standard deviation $RSD_{\text{analytical}}$ —the precision standard deviation relative to the true respirable concentration c_R associated with mass analysis, for example, the weighing of filters, analysis of α -quartz, and so forth.

3.2.10.2 pump-induced relative standard deviation RSD_{pump} —the intra-sampler imprecision standard deviation relative to the true respirable concentration c_R associated with both drift and variability in the setting of the sampling pump.

3.2.10.3 inter-sampler relative standard deviation RSD_{inter} —the inter-sampler imprecision standard deviation (varying sampler s) relative to the true respirable concentration c_R and taken as primarily associated with physical variations in sampler dimensions.

3.2.10.4 The

3.2.10 mean relative bias Δ total imprecision RSD—of measurement c is then given relative to the conventional respirable concentration c_R , defined as follows:

$$RSD = \sqrt{RSD_{\text{analytical}}^2 + RSD_{\text{pump}}^2 + RSD_{\text{inter}}^2} \quad (6)$$

$$\Delta = (c - c_R) / c_R \quad (5)$$

3.2.11 flow rate Q (L/min) symmetric-range accuracy A —the flow rate sampled by a given sampler. fractional range, symmetric about the conventional concentration c_R , within which 95 % of sampler measurements are to be found (8,10-13 and the NIOSH Manual of Analytical Methods).

3.2.12 flow rate Q (L/min)—the average flow rate of air sampled by a given sampler over the duration of the sampling period.

3.2.13 flow number F —the number (for example, 4) of sampler flow rates Q tested.

3.2.13.4 replication number n (for example, 4)—the number of replicate measurements for evaluating a given sampler at specific flow rate and aerodynamic diameter.

3.2.14 parameter number $p = 1, \dots, P$ (for example, 4)—a number identifying parameters θ_p in modeled sampling efficiency data as in Section 9.

3.2.15 *Accuracy A, Busch probabilistic*—the fractional range, symmetric about the true concentration c_R , within which 95 % of sampler measurements are to be found (9-12 and the NIOSH Manual of Analytical Methods):

3.2.15.1 *Discussion*—The function A depends only on the bias Δ and total imprecision RSD in the event that these quantities are independent of c_R . A is defined implicitly as follows:

$$\Phi[(\Delta + A)/RSD] - \Phi[(\Delta - A)/RSD] = 95 \% \quad (7)$$

where Φ is the cumulative normal function. The function $A(\Delta, RSD)$ may be computed numerically and is depicted in Fig. 2. Alternatively, Eq 7 has an approximate solution (13) for $A[\Delta, RSD]$ given as follows:

$$A[\Delta, RSD] = \frac{\Phi^{-1}(0.95) \times RSD + \text{Sqrt}[(\Phi^{-1}(1.95/2) - \Phi^{-1}(0.95))^2 RSD^2 + \Delta^2]}{2} \quad (8)$$

This expression is easily evaluated using a calculator, noting that $\Phi^{-1}(0.95) = 1.645$, and $\Phi^{-1}(1.95/2) = 1.960$.

3.3 Symbols and Abbreviations:

A —(Busch probabilistic)—symmetric-range accuracy as defined in terms of bias and precision (see 3.2.151).

\hat{A} —estimated accuracy A .

NOTE 1—Hats as in A refer to estimates, both in sampler application and sampler evaluation.

$95 \% A$ —95 % confidence-level limit on the (Busch probabilistic) symmetric-range accuracy A .

\bar{c} (mg/m^3)—expected value of the sampler-averaged concentration estimates c_s .

c_s (mg/m^3)—expected value (averaged over sampling pump and analytical variations) of the concentration estimate from sampler s .

c_{ovij} —covariance matrix for sampler s and efficiency parameters θ_i and θ_j .

c_R (mg/m^3)—concentration measured by a conventional (that is, ideal) respirable sampler.

\hat{c} —sampler-averaged concentration estimate.

\hat{c}_s —concentration estimate from sampler s .

D (μm)—aerosol aerodynamic diameter.

D_0 —sampling efficiency model parameter.

D_R (μm)—respirable sampling convention parameter equal to 4.25 μm in the case of healthy adults, or 2.5 μm for the sick or infirm or children.

E —sampling convention in general.

E_R —respirable sampling convention.

E_s —sampling efficiency of sampler s .

F —number of flow rates evaluated.

GSD —geometric standard deviation of a representative log-normal lognormal aerosol size distribution.

MMD —mass median diameter of a representative log-normal lognormal aerosol size distribution.

MSE_c —mean square element for sampler in application (see 10.4).

MSE —mean square element for evaluation data (see A1.5).

n —number of replicate measurements.

P —number of sampling efficiency parameters.

Q (L/min)—sampler flow rate.

RSD —relative standard deviation (relative to true concentration c_R as estimated by an ideal sampler following the respirable sampling convention).

$RSD_{\text{analytical}}$ —analytical imprecision component—relative standard deviation component characterizing analytical random variation.

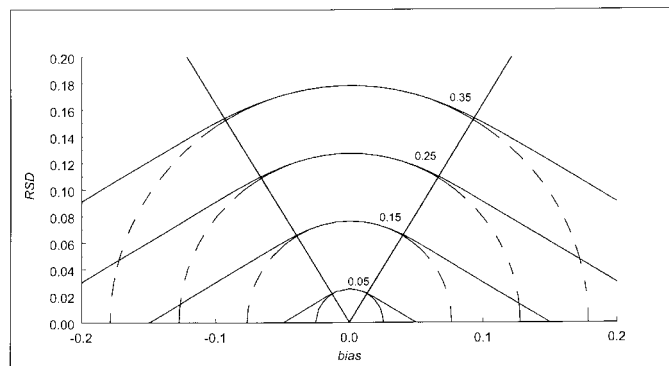


FIG. 2 Symmetric-Range Accuracy. Plotted are (solid) curves of constant accuracy = 5 %, 15 %, 25 %, and 35 %. The dashed curves identify circles in the approximation of Eqs. 14 and 15.

$RSD_{floweval}$ —relative standard deviation component characterizing uncertainty in from the pump flow rate. evaluation experiment itself (Annex Annex A1).

RSD_{inter} —relative standard deviation component characterizing random inter-sampler imprecision.

RSD_{pump} —imprecision induced by imprecision in relative standard deviation component characterizing the effect of random sampling pump variation.

\hat{RSD}_{inter} —estimated inter-sampler imprecision \hat{RSD}_{inter} .

\hat{RSD}_{pump} —estimated pump-induced imprecision \hat{RSD}_{pump} .

s —sampler number.

S —number of samplers evaluated.

t —sampling time (for example, 8h).

U —expanded uncertainty.

u_c —combined uncertainty.

v (m/s)—wind speed.

Δ —bias relative to an ideal sampler following the respirable sampling convention.

$\hat{\Delta}$ —estimated bias $\hat{\Delta}$.

$\epsilon_{eval,s}$ —random variable contribution to evaluation experimental error in a concentration estimate.

ϵ_s —random variable contribution to inter-sampler error in a concentration estimate.

θ —sampling efficiency model parameter.

σ_0 —sampling efficiency model parameter.

σ_{eval} —evaluation experimental standard deviation in a concentration estimate.

σ_{inter} —inter-sampler standard deviation in a concentration estimate.

$\hat{\sigma}_{eval}$ —estimate for σ_{eval} .

$\hat{\sigma}_{inter}$ —estimate for σ_{inter} .

σ_R —respirable sampling convention parameter equal to $\ln[1.5]$.

$\sigma_{weightmass}$ —weighing imprecision in mass collected on a filter.

$\Phi[x]$ —cumulative normal function defined; given for argument x .

4. Summary of Practice

4.1 Calm-air Evaluation—The

4.1 The sampling efficiency from $D = 0$ to $10 \mu\text{m}$ and its variability are measured in calm air ($<0.5 \text{ m/s}$) for several candidate samplers operated at a variety of flow rates. This information is then used to compute concentration estimates expected in sampling representative log-normal aerosol size distributions. Precision and bias (4.1.1 and 4.1.2) Random variations (10.2) as well as systematic deviation (10.1) are therefrom determined specified relative to a conventional sampler. Overall performance in calm air can then be assessed by computing a confidence limit $_{95\%}A$ on the Busch probabilistic accuracy, symmetric-range accuracy (3.2.11), accounting for uncertainty in the evaluation experiment, given measured estimated bias and imprecision at each log-normal aerosol size distribution of interest. This test has evolved from work described in Refs The symmetric-range accuracy confidence limit (14-21).

4.1.1 Precision— $_{95\%}A$ provides conservative confidence intervals bracketing the sampling of aerosol, several components of precision have been found (5) significant. These include inter-sampler variability, caused by physical variations conventional concentration at given confidence in the samplers; intra-sampler variability, from inaccuracy in method evaluation, analogous to the setting and maintenance use of required airflow; and analytical error, for example, in the weighing of filters, or, as another example, expanded uncertainty U in the measurement of α -quartz.

4.1.2 Bias—As no real sampler follows the aerosol fraction conventions exactly, bias always exists between true and conventional (ideal) samplers. ISO GUM (See Eq. 16). This bias depends on the particle size-distribution of the aerosol sampled. The worst-case situation is performance evaluation has evolved from work described in the sampling of monodisperse aerosol. However, in most workplaces, aerosol is present in a broad distribution of sizes. The cancellation of positive and negative components of bias at different particle sizes reduces the overall bias in this case. Refs (8, 14-21).

5. Significance and Use

5.1 This practice is significant in providing the experimental means for replacing instrument or sampler specification by determining performance criteria based on accuracy relative to ideal sampling conventions. The advantages purposes are multifold:

5.1.1 The conventions have a recognized tie to health effects and can easily be adjusted to accommodate new findings.

5.1.2 Performance criteria permit instrument designers to seek practical sampler improvements.

5.1.3 Performance criteria promote continued experimental testing of the samplers in use with the result that the significant variables (such as wind speed, particle charge, etc.) affecting sampler operation become understood.

5.2 One specific use of the performance tests is in determining the efficacy of a given candidate sampler for application in regulatory sampling. The accuracy of the candidate sampler is measured according to in accordance with the evaluation tests given here. The A sampler is may then certified as acceptable be adopted for a specific application if the accuracy is better than a specific value.

5.2.1 *Discussion*—In some instances, a sampler so selected for use in compliance determinations is specified within an exposure standard. This is done so as to eliminate differences among similar samplers. Sampler specification then replaces the respirable sampling convention, eliminating bias (3.2.10), which then does not appear in the uncertainty budget.

5.3 Although the criteria are presented in terms of accepted sampling conventions geared mainly to compliance sampling, other applications exist as well. For example, suppose that a specific aerosol diameter-dependent health effect is under investigation. Then for the purpose of an epidemiological study an aerosol sampler that reflects the diameter dependence of interest is required. Sampler accuracy is may then be determined relative to a modified sampling convention.

6. Apparatus

6.1 *Small Single-pass Wind Tunnel* (or, equivalently, a static exposure chamber). The following dimensions are nominal:

6.1.1 Cross section: 500 by 500 mm; Length: 6 m.

6.1.2 Air speed: <0.5 m/s.

6.1.3 Air speed uniformity: $\pm 3\%$ over 250 by 250-mm central cross-sectional area.

6.1.4 Turbulence <3 %.

6.1.5 *Test Aerosol Generation System* :

6.1.5.1 Generation system: ultrasonic nebulizer.

6.1.5.2 Static discharging nozzle.

6.1.5.3 Mixing with tunnel air by turbulence created by 100 by 100-mm rectangular plate 10 cm downstream of the nebulizer and perpendicular to the tunnel's airflow.

6.1.5.4 Concentration: 5000 aerosol particles/L.

6.1.5.5 Size distribution: count median diameter = 4 μm and geometric standard deviation = 2.2.

6.2 *Aerodynamic Particle Sizer (APS)*.^{3,9}

6.3 *Tube-Mounted Hot-Wire Anemometer Probe*, or equivalent, ac voltmeter or oscilloscope.

7. Reagents and Materials

7.1 *Reagents*:

7.1.1 *Potassium Sodium Tartrate*, A.C.S.-certified reagent grade, for generating solid spherical aerosol particles.

7.1.2 *Standard Polystyrene Latex Spheres* for calibrating APS (6.2).

7.2 *Materials*:

7.2.1 *Five-micrometre PVC Membrane Filters and Conductive Filter Cassettes*.^{3,11}

8. Data Representation through Sampling Efficiency Model

8.1 Determine a sampling efficiency curve for each of the S (for example, eight) samplers by least squares fit to the data taken in four replicates at the four flow rates. Thus eight functions of aerodynamic diameter D and flow rate Q are determined. Use the following model (5) or equivalent for characterizing the candidate cyclones:

$$E_s(D; Q) = \Phi \left[\frac{1}{\sigma_0} \ln \left(\frac{D_0}{D} \right) \right] \quad (6)$$

where Φ is the cumulative normal function (8) (9), which may be approximated using the algorithm presented in Appendix X1, easily computed within most statistical software packages. The indicated constants are defined in terms of model parameters θ_{jP} , determined by the least squares fit to the data using a standard nonlinear regression routine:

$$D_0 = \theta_1 (Q/2.0 \text{ L/min})^{-\theta_2} \quad (10)$$

$$D_0 = \theta_1 \times (Q/2.0 \text{ L/min})^{-\theta_2} \quad (7)$$

$$\sigma_0 = \theta_3 (Q/2.0 \text{ L/min})^{-\theta_4}$$

$$\exp[\sigma_0] = \theta_3 \times (Q/2.0 \text{ L/min})^{-\theta_4}$$

In this case the curve fitting would determine eight sets (one for each sampler) of four parameters each.

9. Procedure

9.1 General procedures for evaluating respirable aerosol samplers are presented in this practice. For other details on the experimental procedures, see Refs (5,6,22-24).

9.2 Set up the APS (6.2) for operation in the small wind tunnel (6.1). Check the APS calibration using (nominally) 3 and 7- μm standard polystyrene latex spheres (7.1.2) by comparing measured and known particle sizes. Set up the potassium sodium tartrate (7.1.1) aerosol generator (6.1.5.1) with charge neutralizer (6.1.5.2) and adjust to achieve about 5000 aerosol particles/L in the test region of the wind tunnel. Adjust the nebulizer aperture and aerosol solution concentration to achieve a test size distribution with

¹¹ The TSI Aerodynamic Particle Sizer 3300 from TSI, Inc., P.O. Box 64394, St. Paul, MN 55164 is the sole aerodynamic particle sizer presently available suitable for source of supply of conductive cassettes known to the committee at this time is Omega Specialty Instrument Co., 4 Kidder Road, Chelmsford, MA 01824.

count median diameter $\approx 4 \mu\text{m}$ and geometric standard deviation ≈ 2.2 , covering the aerodynamic diameter region of interest. Test the aerosol concentration for stability in time by taking a series of size distribution measurements. Variation should be $<1\%$ over 2-min periods.

9.3 Determine the sampler sampling efficiency from $D = 0$ to $10 \mu\text{m}$ by measuring the aerosol size distribution before and after the samplers with 1-min exposures in accordance with an experimental design similar to the following experimental design: following:

- $F = 4$ sampler flow rates: distributed between 50 and 200 % of the presumed optimal sampler flow rate,
- $S = 8$ samplers, numbered $s = 1, \dots, S$, and
- $n = 4$ replicates, numbered $r = 1, \dots, n$.

10. Performance Classification Measurement Uncertainty

10.1 ~~Bias~~ Systematic Deviation Relative to Convention:

10.1.1 ~~Background~~—~~FAs no real sampler follows the aerosol fraction conventions exactly, bias always exists between candidate real and conventional (3.1.2) respirable (ideal) samplers with sampling of monodisperse aerosol can be determined directly efficiency given by comparing Eq. 1. With minimal loading effects, this bias depends only on the mean fitted sampling efficiency curve (from particle size-distribution of the results aerosol sampled, and is therefore a constant when expressed as a fraction of Section 8) to the conventional efficiency. However, a comparison concentration c_R . The largest values of candidate to ideal samplers bias occur in the measurement sampling of aerosol particles distributed monodisperse aerosol. However, in-size most workplaces, aerosol is more relevant to workplace atmospheres, as mentioned present in Section 4. To a broad distribution of sizes. The cancellation of positive and negative components of bias at different particle sizes reduces the overall bias in this end, it has case.~~

~~It has, therefore, become conventional to compare samplers as applied in sampling aerosol distributed in size. Particularly, bias is estimated in the sampling of specific log-normal size distributions (3.1.3.1):~~

~~10.1.1.1 This (3.2.3.1). Such a comparison is then also applicable to those more realistic size distributions which can be approximated as a superposition of several lognormal distributions.~~

~~As with EN 13205, this practice requires a comparison over all log-normal particle size distributions with geometric standard deviations between 1.75 and 3.5 and mass median diameter $<25 \mu\text{m}$. Furthermore, respirable samplers would only be evaluated at aerosol size distributions with the fraction of respirable to total aerosol greater than 5 %. This omits sizes beyond the line defined by: (mass median diameter, geometric standard deviation) = $(10 \mu\text{m}, 1.5)$ to $(25 \mu\text{m}, 2.75)$. The narrowest distributions of largest-size aerosols performance tests are therefore omitted from consideration. The rationale is that size not applicable to the sampling of rarely occurring narrow distributions with small of large-size aerosols.~~

~~Note that the variety of environments in which respirable fraction generally either have aerosol measurements are taken precludes a small respirable mass concentration (that is, accuracy simple elimination of this bias in aerosol measurement is not needed except in special cases), or actually consist the mean through calibration, with associated imprecision from variation of small-diameter respirable influence parameters (ISO GUM). For example, assuming a lognormal size-distribution, the aerosol mixed with extremely large aerosols, size distribution parameters, MMD and so would GSD may be regarded as influence parameters. It is simplest to explicitly account for the bias in the development of confidence intervals about the measurand values (the conventional concentrations c_R).~~

10.1.2 ~~Bias Estimate~~—Compute the estimated concentration \hat{c}_s numerically for each sampler s at each log-normal size distribution (MMD, GSD) of interest, as indicated in (3.2.7). Estimate the constant c by the sampler average as follows: average:

$$\hat{c} = \frac{1}{S} \sum_s \hat{c}_s \tag{8}$$

$$\hat{c} = \frac{1}{S} \sum_s \hat{c}_s, \tag{8}$$

~~Then compute the bias estimate Δ by means of 3.2.9.~~

~~10.1.3 Bias Estimate Uncertainty~~—This sampler performance assessment accounts for uncertainty $\hat{\Delta}$ as in Eq. 5.

10.2 ~~Random Variations~~—In the sampler evaluation by computing an accuracy confidence limit as well as an estimate sampling of the sampler accuracy itself. For this purpose an estimate aerosol, several sources of the bias uncertainty is necessary. This is accomplished by analyzing the concentration estimates \hat{c}_s from sampler s random variation have been found (5) significant. These include inter-sampler variability (RSD according to the following model:

$$\hat{c}_s = c + \epsilon_{\text{eval } s} + \epsilon_s \tag{12}$$

The errors, $\epsilon_{\text{eval } s} = N[0, \sigma_{\text{eval}}^2]$ and $\epsilon_s = N[0, \sigma_{\text{inter}}^2]$, are represented (3.2.9.3)), caused by their respective standard deviations, σ_{eval} and σ_{inter} . The quantity σ_{eval} contains, for example, evaluation concentration fluctuations and aerosol counting errors. The quantity σ_{inter} characterizes the inter-sampler variability.

10.1.3.1 The variance $\sigma_{\text{eval}}^2 + \sigma_{\text{eval}}^2$ of \hat{c}_s is estimated with $S-1$ df as follows:

$$\sigma_{\text{inter}}^2 + \sigma_{\text{eval}}^2 = \frac{1}{s-1} \sum (\hat{c}_s - \bar{c})^2 \quad (13)$$

With $\text{var}(\hat{c})$ given as follows:

$$\text{var}(\hat{c}) = \frac{1}{s} [\sigma_{\text{inter}}^2 + \sigma_{\text{eval}}^2] \quad (14)$$

the quantity $\text{var}(\Delta)$ is then given as follows:

$$\sigma_{\Delta}^2 \equiv \text{var}(\Delta) = \frac{1}{s} [\sigma_{\text{inter}}^2 + \sigma_{\text{eval}}^2] / c_R^2 \quad (15)$$

and is estimated physical variations in accordance with Eq 13.

10.2 Imprecision:

10.2.1 As mentioned in 3.2.10, the sampler imprecision is represented samplers; intra-sampler variability, from inaccuracy in terms the setting and maintenance of three dominant components:-

required airflow ($RSD_{\text{analytical}}$, RSD_{pump} , and RSD_{inter}). The total imprecision RSD is then given in 3.2.10.4:

10.2.2 $RSD_{\text{analytical}}$ is not estimated within the sampler evaluation described here as it depends on specific filter measurement procedures. For example, an early assessment (25) of mass weighing by the Mine Safety(3.2.9.2)), and Health Administration (MSHA) indicated an imprecision σ_{weight} equal to 81 μg . From such an estimate analytical error ($RSD_{\text{analytical}}$ can be computed as follows, given(3.2.9.1)), for example, from variations in the flow rate Q (L/min), sampling time, and true respirable concentration c_R weighing of interest:

$$RSD_{\text{analytical}} = \frac{\sigma_{\text{weight}} \times 1000 \text{ L/m}^3}{Q \times 8 \times 60 \text{ min}} / c_R \quad (16)$$

assuming a sampling time = 8 h.

10.2.3 RSD_{pump} expresses filters, or, as another example, in the effect measurement of pump uncertainty and requires results at neighboring values of flow rate Q . The mass m sampled at collected α -quartz mass. Like the filter over time t depends on relative bias, the flow rate Q as follows:

$$m = Q \times t \times c(Q) \quad (17)$$

where the dependence of the concentration c on Q is indicated. Let relative standard deviations, $RSD_{\text{flowinter}}$ represent the uncertainty in the pump flow rate. Then the effect on the sampled mass m is expressed by and RSD_{pump} given approximately as follows:

$$RSD_{\text{pump}} = RSD_{\text{flow}} \left| 1 + \frac{Q}{c} \frac{\partial c}{\partial Q} \right| \quad (18)$$

The quantity $\partial c / \partial Q$ is computed through the Q -dependence determined in the fitted sampling efficiency model (9.1). As suggested in the *NIOSH Manual of Analytical Methods*, the relative standard deviation of the pump flow rate are roughly constant, whereas $RSD_{\text{flowanalytical}}$ may depend on the conventional concentration c_R . For example, a recent assessment (25) by the Mine Safety and Health Administration (MSHA) indicated an uncertainty σ_{mass} in measuring filter mass changes equal to 9.1 μg . From such an estimate $RSD_{\text{flow}} = 5\%$ with a high degree of confidence (>95%).

10.2.4 Obtain analytical can be computed, given the flow rate Q (L/min), sampling time $RSDt$ (for example, 8 · 60 min), and conventional respirable concentration c_R from Eq 13 by estimating σ_{eval} from of interest:

$$RSD_{\text{analytical}} = \sigma_{\text{mass}} \cdot 1000 \text{ L/m}^3 / (c_R \cdot Q \cdot t), \quad (9)$$

which depends inversely on the conventional concentration c_R .

10.3 Measurement Model—The various aspects of concentration measurement accuracy covered in 10.1 and 10.2 lead to the fitted parameters at fixed sampler following approximation for modeling the measurement:

$$\hat{c}_s = \hat{m}_s / (\hat{Q} \cdot t) \quad (10)$$

$$= [(1 + \Delta) + \epsilon_s + \epsilon_{\text{pump}} + \epsilon_{\text{analytical}}] \cdot c_R$$

where ϵ signifies random variables approximated as normally distributed about zero:

$$\epsilon_s \approx N[0, RSD_{\text{sampler}}] \quad (11)$$

$$\epsilon_{\text{pump}} \approx N[0, RSD_{\text{pump}}]$$

$$\epsilon_{\text{analytical}} \approx N[0, RSD_{\text{analytical}}]$$

remembering that $RSD_{\text{analytical}}$ depends specifically on the analytical method and is not necessarily constant.

The measurement model specified in Eq. 10 indicates that all the total relative standard deviation RSD (the combined relative uncertainty is from experimental error and no part from lack of fit to u_c/c_R (ISO GUM)) in the model. Then estimate $\text{var}(\hat{c}_s)$ at fixed s from is given through the nonlinear regression's asymptotic variance-covariance matrix ${}_s \text{cov}_{ij}$ as follows: lowest order approximation to the law of propagation of uncertainty (ISO GUM) by:

$$\text{var}(\hat{c}_s) \Big|_s \approx \sum_{ij} \frac{\partial \hat{c}_s}{\partial \theta_{ij}} c \hat{v}_{ij} \frac{\partial \hat{c}_s}{\partial \theta_j} \quad (\text{fixed } s)$$

$$RSD = \sqrt{RSD_{inter}^2 + RSD_{pump}^2 + RSD_{analytical}^2} \quad (12)$$

This quantity

10.4 *Symmetric-range Accuracy A*—The definition in (3.2.11) is proportional equivalent to $(nF - P)^{-1}$, where the following implicit definition of the function nA is the number in terms of replicates, relative bias Δ and $FRSD$, the number assuming approximately normal distributions of flow rates, in the evaluation, and P concentration estimates:

$$\Phi\left[\frac{\Delta + A}{RSD}\right] - \Phi\left[\frac{\Delta - A}{RSD}\right] = 95\%, \quad (13)$$

where Φ is the number of model parameters, cumulative normal function. The derivatives, accuracy $\partial \hat{c}_s / \partial \theta_i$, are computed numerically. Averaging over $A[\Delta, s]$, an estimate of $\sigma_{eval} RSD$ may be computed numerically and is depicted in Fig. 2. Alternatively, Eq. 13 has an approximate solution (8) for $A[\Delta, RSD]$ given as follows by:

$$\sigma_{eval}^2 \approx \frac{1}{S} \sum_s \sum_{ij} \frac{\partial \hat{c}_s}{\partial \theta_{ij}} c \hat{v}_{ij} \frac{\partial \hat{c}_s}{\partial \theta_j}$$

$$A[\Delta, RSD] = 1.960 \times MSE_c^{\frac{1}{2}} \quad (14)$$

with approximately $S(nF - P)$ degrees of freedom, since $P - S$ degrees of freedom determine where the fitted parameters:

10.2.4.1 The simultaneous Eq 13 and Eq 20 permit estimation of σ_{inter} and σ_{eval} individually (neglecting lack combined mean square element MSE_c , is defined as:

$$MSE_c = \Delta^2 + RSD^2 \quad (15)$$

The approximation of-fit) Eq. 14 is extremely accurate for small bias magnitude $|\Delta|$ (that is, for $|\Delta| < RSD / 1.645$), A being overestimated fractionally by up to 1 %, only in Eq 14 and Eq A1.4. As applied a narrow region close to $|\Delta| = RSD / 1.645$. In fact, over the data presented in Ref (5) region $|\Delta| < RSD$, Eq. 14 overestimates the experimental design adopted (9.2) results in small evaluation errors accuracy fractionally by less than 5 %. Therefore, Eq. 14 may be regarded as follows:

$$\sigma_{eval}^2 \ll \sigma_{inter}^2 / S \quad (21)$$

10.2.5 Compute a minimally conservative estimate of the variability symmetric range accuracy over ranges of bias and RSD of general interest. Ref (8) indicates how to handle yet larger bias magnitudes.

10.5 *Estimating Components of the estimate σ Combined Mean Square Element MSE_c*

10.5.1 The components (Δ^2 , RSD_{inter}^2 through, RSD_{pump}^2 , and $RSD_{analytical}^2$) of the combined mean square element MSE_c (Eqs. 12 and 15) can be estimated as follows. The components, Δ^2 and RSD_{inter}^2 , may be categorized as *Type A standard uncertainties* (ISO GUM), meaning that their estimates are obtained by statistical means from the data obtained during sampler evaluation. RSD_{pump}^2 can be, and has, also been estimated by statistical means in specific applications. However, for illustration, RSD_{pump}^2 is estimated here as a *Type B standard uncertainty*, meaning, determined on the basis of Eq 13 “experience with, or general knowledge of, the behavior and Eq 20 property of relevant materials and instruments” (ISO GUM). $RSD_{analytical}^2$ may be obtained from experiment separate from this practice as a *Type A standard uncertainty*, as in Practice D 6552.

10.5.2 Compute estimates of Δ^2 and RSD_{inter}^2 at each size distribution (*MMD, GSD*) of interest. The statistical details required for these estimates are presented in Annex A.

10.5.3 Assume, as suggested in the NIOSH Manual of Analytical Methods, that $RSD_{pump}^2 = 5\%$, with infinite degrees of freedom. As described in ISO GUM, this assumption corresponds to stating that variation from pump fluctuation follows an approximately rectangular distribution with estimates ranging within $\pm \sqrt{3} \times 5\%$ of the mean.

10.5.4 $RSD_{analytical}^2$ depends on the specific analysis required and therefore is not estimated within the sampler evaluation described in this practice.

10.6 *Confidence Limit on the Combined Mean Square Element MSE_c*

10.6.1 Statistical details of this calculation may be found in Annex A. However, the basic idea is as follows: The variances of each component of MSE_c are estimated. Then the part of the estimate of MSE_c which varies (that is, excluding the constant RSD_{pump}^2) is approximated as proportional to a chi-square variable with an effective number of degrees of freedom determined so that the variance is consistent (Satterthwaite approximation (ISO GUM)). The result is a 95 % confidence level for MSE_c , and therefore, through Eq. 14, the symmetric-range accuracy confidence limit $_{95\%}A$.

10.6.2 The confidence limit $_{95\%}A$ (accounting for evaluation uncertainty) is a counterpart to what is denoted the sampler’s Busch probabilistic accuracy as *expanded uncertainty U* in Ref (ISO GUM). Aside from differences in application, both quantities are used for bracketing the measurand by confidence intervals. The expanded uncertainty (5) U , used for constructing symmetric intervals about measured values in the case that bias is negligible, is equal to the combined uncertainty $u_{repeated}$, multiplied by a coverage factor given in Annex A1 terms of a Student-t quantile, indicating continual re-evaluation of a method at each application. In contrast, $_{95\%}A$ leads, with 95 % confidence in a single (extensive) initial method evaluation

to intervals that enclose the conventional concentration at least 95 % of the time. For example, suppose $_{95\%}A$ is approximately independent of the measurand value c_R and that the likelihood that $_{95\%}A > 1$ is negligible. Then 3.2.11 implies the following inequality:

$$\frac{\hat{c}}{1 + _{95\%}A} < c_R < \frac{\hat{c}}{1 - _{95\%}A} \quad (16)$$

for $> 95\%$ of estimates \hat{c} , at 95 % confidence in the evaluation experiment. Note that the interval of Eq. 16 is not exactly symmetrical about the estimate \hat{c} , unlike intervals using the expanded uncertainty U (ISO GUM), with bounds $\hat{c} \pm U$.

10.6.3 An example of the difference between $_{95\%}A$ and \hat{A} can be given: At $MMD = 10\mu\text{m}$ and $GSD = 3$, the Higgins-Dewell cyclone has (5) $\hat{A} = 7\%$, $RSD_{inter} = 5\%$, $RSD_{pump} < 1\%$. Now suppose that $c_R = 2\text{ mg/m}^3$ and that (25) $\sigma_{mass} = 9.1\mu\text{g}$; then Eq. 9 gives $RSD_{analytical} = 0.4\%$. Thus, the total random variation is $RSD = 5.1\%$, and so $\hat{A} = 15\%$. Following Annex A, it is found that $_{95\%}A$ is about 40 % larger than \hat{A} . This value is expected to be typical of the evaluation uncertainty (at 95 % confidence) over a wide range of size distributions at $c_R = 2\text{ mg/m}^3$ and analytical error $\sigma_{weight} = 9.1\mu\text{g}$. For other specific applications, the corresponding figure can be calculated.

11. Non-Performance Items—

Because of the complexity of aerosol sampling, several respirable aerosol sampler characteristics remain unevaluated. These may be controlled as suggested in this section through sampler specification, rather than performance criteria. Any of the suggested features not presently available are to be considered recommendations for future sampling equipment.

~~10.4.1—~~

11.1 Recommendation of the Use of Only Conductive Samplers—This practice presents a recommendation that only conductive samplers be used in aerosol sampling.

~~10.4.1.1—~~

11.1.1 Justification for Recommendation— Various authors have reported sampling problems specifically posed by the nonconductive 10-mm cyclone. The basic problem is that charges on a nonconducting sampler are immobile and therefore provide a localized source of electric field. This can strongly affect the trajectories of charged aerosol particles in the air flowing into the sampler. Quantitatively, a 10 % variability has been reported to be associated with charge effects (26). Furthermore, evidence exists that a charged sampler may undersample moderately charged aerosol by as much as 40 % (27). Finally, the conductivity of the filter holder itself following the 10-mm cyclone may be significant. A 25 % increase in the aerosol collected upon increasing the holder's conductivity has been reported (28). Electrical charging typical on aerosol to be found in many workplaces has also been documented (29).

~~10.4.1.2—~~

11.1.2 Availability of Samplers—The presently used 10-mm cyclones⁴ are fashioned out of a poorly conductive plastic relative to metals. At one time, however, a conductive graphite-filled plastic was used in the construction of the sampler. Therefore, with a minor shift in the manufacturing process, a 10-mm conductive cyclone could again be available. The Higgins-Dewell cyclone,^{4,5} now available in the United States, is made of metal and is therefore conductive. The 37-mm filter cassette^{4,11} which is used with the cyclone should be made of a conductive material, for example, graphite-filled plastic.

~~10.4.2—~~

11.2 Recommendation of Controlled Pump Fluctuations —Pulsation amplitude must be less than 20 % of the mean flow. ~~Measure this~~ This amplitude may be measured with an in-line hot-wire anemometer placed close to the sampler, ~~and analyzing~~ the output using an oscilloscope or ac voltmeter.

~~10.4.2.1—~~

11.2.1 Justification—Bias has been shown (30,31) to be caused in a cyclone by pulsation of the personal sampling pump. Cyclone samplers with pulsating flow can have negative bias as large as -22% relative to samplers with steady flow. The magnitude of the bias depends on the amplitude of the pulsation at the cyclone aperture and the aerosol size distribution. For pumps with instantaneous flow within 20 % of the mean, the pulsation bias is estimated at less than -2% for most size distributions encountered in the workplace.

~~10.4.3—~~

11.3 Recommendation of Controlled Pump Accuracy—In accordance with 10.25.3, control the relative standard deviation of the pump flow rate RSD_{pump} through the use of a self-regulating network to $RSD_{pump} \leq 5\%$ (NIOSH Manual of Analytical Methods) at confidence $>95\%$.

11. Methods).

12. Report

12.1 Several alternatives exist for using the results of the experimental evaluations described in this practice. For example, it is possible to classify the samplers ~~according to~~ in accordance with specific accuracy criteria. Alternatively, the NIOSH accuracy criterion (9-1210-13 and the NIOSH Manual of Analytical Methods) presents a pass/fail requirement that acceptable sampling methods have better than 25 % symmetric-range accuracy at the 95 % (evaluation) confidence level. ~~The What~~

is denoted as *sampler accuracy* itself may, in fact, be defined in alternative manners. Here it is suggested simply that sufficient information is presented that a large number of such most performance criteria suited selected for specific applications can be easily implemented. Therefore, as a minimum, the following should appear in the report of the sampler evaluation.

142.2 Describe the sampling efficiency model used. Present a short table giving the fitted sampling efficiency parameters θ_p , $p = 1, \dots, P$ (for example, 4). Obtain these parameters through fitting the composite data from the different flow rates, sampler specimens, and replications. Plot sampling efficiency data, averaged over sampler and replicate, together with the model curves at the four sampler flow rates of the evaluation.

142.3 Present maps giving iso-curves over $MMD = 1$ to $25 \mu\text{m}$ and $GSD = 1.5$ to 3.5 for estimates of the following: sampler imprecision RSD_{inter} , pump-effect imprecision RSD_{pump} (assuming $RSD_{\text{flow}} = 5\%$), and bias Δ .

142.4 Prepare tables of the information estimates of (11.3) is application-specific because of the assumed values of RSD_{flow} , Δ , $RSD_{\text{analytical}}$, RSD_{inter} , and c_R . Therefore, prepare tables of RSD_{eval} and MSE (A1.5) in digital form. Relevant estimates of the combined mean square element MSE_c (Eq. 15) and confidence limit (equivalent to $95\%A$) can then be constructed, given external knowledge of RSD_{inter} , RSD_{pump} (assuming $RSD_{\text{flow}} = 5\%$), and Δ in digital form. Relevant estimates of the accuracy or its confidence limit can therefore be constructed: analytical. The tables should be at $MMD = 1 \mu\text{m}$, $2 \mu\text{m}$, ..., $25 \mu\text{m}$ and $GSD = 1.5, 1.6, \dots, 3.5$.

12. Accuracy

12.1 This practice provides an estimate

12.5 Present maps of the Busch probabilistic accuracy estimates of a candidate sampler under evaluation, accounting for precision and bias relative to a conventional sampler. Because the evaluation is not perfect, the estimate itself may be biased or imprecise. The uncertainty in the estimate is characterized by means of Annex A1 by computing a 95 % confidence level, thereby accounting for both precision and bias in the accuracy measurement.

12.1.1 The Busch probabilistic accuracy estimate \hat{A} and its 95 % confidence level $95\%A$ both depend on quantities estimated by the evaluation presented in this practice as well as on both the respirable concentration c_R of interest and the analytical error setting $RSD_{\text{analytical}}$ which depends on details as equal to zero. A note should be included stating that $RSD_{\text{analytical}}$ of a particular analytical application would generally increase the respirable sampler is applied. Therefore, values of the uncertainty in estimates of A depends on factors external to the evaluation results.

12.1.2 Nevertheless, an example of the difference between and $95\%A$ and \hat{A} can.

12.6 It may also be given: At $MMD = 10 \mu\text{m}$ and $GSD = 3$, useful to give a brief statement as to the Higgins-Dewell cyclone has purpose behind estimating (5) $\Delta = 7\%$, $RSD_{\text{inter}} = 5\%$, and $RSD_{\text{pump}} < 1\%$, and $\hat{A} = 20\%$. Now suppose that $c_{R_{95\%}} = 2 \text{ mg/m}^3$ and that (25) $\sigma_{\text{weight}} = 81 \mu\text{g}$; A . An example would be:

“With 95 % confidence in the Eq 16 gives method evaluation, the symmetric-range accuracy confidence limit $RSD_{95\%A_{\text{analytical}}} = 4\%$. Thus, results in confidence intervals enclosing measurands $>95\%$ of the total imprecision is time. $RSD = 6.4\%$. These figures, as input to the algorithm in Annex A1, $95\%A$ then give plays the fractional difference as follows:

$$\frac{(95\%A - \hat{A})}{\hat{A}} = 25\% \quad (22)$$

This value is expected to be typical role of the evaluation expanded uncertainty (at 95 % confidence) over a wide range of size distributions at $c_R = 2 \text{ mg/m}^3$ and analytical error $\sigma_{\text{weight}} = 81 \mu\text{g}$. For other specific applications, the corresponding figure can be calculated. *U* (ISO GUM).”

13. Keywords

13.1 accuracy;

13.1 aerosol; air monitoring; bias; confidence; conventions; deposition; evaluation; fractions; particle; particulates; penetration; performance; precision; random variation; respirable; sampling and analysis; sampling efficiency; size-selective; tolerance; uncertainty; workplace atmospheres

ANNEX

(Mandatory Information)

A1. ACCURACY CONFIDENCE LIMIT

A1. STATISTICAL DETAILS

A1.1 The confidence limit on the Busch probabilistic accuracy A , accounting sampler performance assessment of this practice accounts for uncertainty in the sampler evaluation experiment, is computed by computing a confidence limit on the combined mean square element **(5) MSE_c (Eq. 15) as well as an estimate of MSE_c itself. This is accomplished by approximating analyzing the surface, A concentration estimates $\hat{c}_{s+\Delta}$, from sampler RSD s in accordance with the following model characterizing the sampler evaluation:**

$$\hat{c}_s = c + \epsilon_{eval_s} + \epsilon_s, \quad (A1.1)$$

where random variables, $\epsilon_{eval_s} = N[0, \sigma_{eval}^2]$ and $\epsilon_s = N[0, \sigma_{inter}^2]$, as a plane tangent to the surface at the estimated values (Δ, RSD) , are represented by their respective standard deviations, σ_{eval} and σ_{inter} . This linearization procedure leaves an error dependent on. The quantity σ_{eval} contains, for example, evaluation concentration fluctuations and aerosol counting errors. The quantity σ_{inter} characterizes the curvature of the accuracy surface; that is, an $O(S \text{ inter-sampler variability})^{-1} \partial^2 A / \partial RSD^2$

A1.2 The variance $\sigma_{inter}^2 + \sigma_{eval}^2$ of \hat{c}_s is estimated with $S - 1$ df by:

$$\hat{\sigma}_{inter}^2 + \hat{\sigma}_{eval}^2 = \frac{1}{S-1} \sum_s (\hat{c}_s - \hat{c})^2 \quad (A1.2)$$

A1.3 σ_{eval} is itself estimated from the uncertainty in the derived confidence limit. Limiting cases fitted parameters at fixed sampler s from the assumption that all the uncertainty is from experimental error and no part from lack of this approach reduce fit to classical tolerance interval theory the model. In other words, $\text{var}(\hat{c}_s)$ is estimated at fixed **(32,33) s applied from the nonlinear regression's asymptotic variance-covariance matrix (23) cov_{ij} as:**

$$\hat{var}(\hat{c}_s)_s \approx \sum_{i,j} \frac{\partial \hat{c}_s}{\partial \theta_i} cov_{ij} \frac{\partial \hat{c}_s}{\partial \theta_j} \quad (\text{fixed } s) \quad (A1.3)$$

This quantity is proportional to sampler evaluation. Details are as follows:

A1.1.1 The function $(n \cdot F - P A)^{-1}$, where n (Δ , is the number of replicates, RSD , F , the number of flow rates in the evaluation, and P is the number of model parameters. The derivatives, $\partial \hat{c}_s / \partial \theta_j$ are computed numerically. Averaging over the samplers tested, an estimate of σ_{eval} is therefore given by:

$$\hat{\sigma}_{eval}^2 \approx \frac{1}{S} \sum_s \sum_{i,j} \frac{\partial \hat{c}_s}{\partial \theta_i} cov_{ij} \frac{\partial \hat{c}_s}{\partial \theta_j} \quad (A1.4)$$

with approximately $S \cdot (n \cdot F - P)$ degrees of freedom, since $P \cdot S$ degrees of freedom determine the fitted parameters.

A1.4 The estimate for σ_{inter} (at fixed α (for example, 95%)) is linearized by means then found from Eqs. A1.2 and A1.4.

A1.5 Estimation of Taylor's series expansion as follows:

$$A(\Delta, RSD_{inter}) \approx \beta_0 + \beta_1 \Delta + \beta_2 RSD_{inter} \quad (A1.1)$$

where the coefficients β_j combined mean square element MSE_c may be computed as follows:

$$\frac{\partial A}{\partial RSD} = \frac{\Phi_+ \frac{\Delta + A}{RSD} - \Phi_- \frac{\Delta - A}{RSD}}{\Phi_+ + \Phi_-} \quad (A1.2)$$

(A1.2) $\partial A \partial RSD = \Phi_+ \Delta + ARSD - \Phi_- \Delta - ARSD$ $\Phi_+ + \Phi_-$ is simplified through computing an estimated mean square element MSE **(32) defined by:**

$$\frac{\partial A}{\partial \Delta} = \frac{\Phi_- - \Phi_+}{\Phi_+ + \Phi_-}$$

$$MSE \equiv \frac{1}{S} \sum_s (\hat{c}_s - c_R)^2 / c_R^2 \quad (A1.5)$$

$$\Phi_{\pm} \equiv \exp \left[-\frac{1}{2} (\Delta \pm A)^2 / RSD^2 \right]$$

$$= \hat{\Delta}^2 + RSD^2_{inter} + RSD^2_{eval}$$

Given knowledge of R

A1.1.2 In Ref $\hat{SD}^2_{analytical}$ and **(5) RSD^2_{pump} , the estimate of MSE_c may then be directly obtained (Eqs. 12 and 15) by using MSE (Eq. A1.5), eliminating RSD^2_{eval} (that is, σ_{eval}^2 / c_R^2) through Eq. A1.4.**

A1.6 Finally, a confidence limit on MSE_{ν} , and therefore (from Eq. 14) the symmetric-range accuracy $_{95\%}A$, may be calculated in accordance with the sketch given by Eq A1.1 in 10.6.1. To this end, the estimation of the various variance components is approximated as normally distributed. Here, a more accurate and yet simpler approach is taken simplified by using the noncentral t -distribution. If u following:

A1.6.1 u is a standard normal variable $\hat{S}E$ and independent x^2 is χ^2 -distributed with ν df, then t , defined as

$$t \equiv \frac{u + \delta}{\sqrt{x^2/\nu}} \quad (A1.3)$$

for any constant δ , follows a noncentral t -distribution (34), whose computations are easily effected using standard statistical routines. Let u and X^2 take on the following values:

$$u = \frac{\Delta - \Delta}{\sqrt{RSD_{inter}^2/S + RSD_{eval}^2}} \quad (A1.4)$$

$$\nu \left[\frac{R\hat{S}D_{inter}}{RSD_{inter}} \right]^2 = x^2 \quad (A1.5)$$

The variable u and x^2 are uncorrelated.

A1.6.2 R is standard normal following Eq 15. Then if the RSD_{eval}^2 in Eq A1.4 can be neglected by means approximated in terms of a chi-square variable.

A1.6.3 $S \times M\hat{S}E/(R\hat{S}D_{inter}^2 + R\hat{S}D_{eval}^2)$ is a noncentral chi-square random variable (33). In terms of the number of degrees of freedom S and noncentrality parameter λ , the expected value and variance of the noncentral χ^2 are $S + \lambda$ and $2S + 4\lambda$, respectively. The parameter λ is given by:

$$t = \frac{\Delta - \Delta + \delta \times RSD_{inter}/\sqrt{S}}{R\hat{S}D_{inter}/\sqrt{S}} \quad (A1.6)$$

$$= \frac{\Delta - (A - \beta_0)/\beta_1 + \frac{\beta_2}{\beta_1} \times RSD_{inter} + \delta \times RSD_{inter}/\sqrt{S}}{R\hat{S}D_{inter}/\sqrt{S}}$$

A1.1.3 Now δ is chosen to make the right two terms in the numerator of Eq A1.6 vanish as follows:

$$\delta = -\frac{\beta_2}{\beta_1} \sqrt{S} \quad (A1.7)$$

A number $t(1 - \gamma, \nu; \delta)$ is now computed, using a standard statistics subroutine, as the value for which the probability that noncentral $t > t(1 - \gamma, \nu; \delta)$ is equal to γ (for example, 95%). Thus, a 95%-confidence interval on A is obtained in the following form:

APPENDIX

(Nonmandatory Information)

X1. ALGORITHM FOR CUMULATIVE NORMAL FUNCTION

X1.1 The cumulative normal function $\Phi[x]$ is easily approximated on a calculator or small computer using the following algorithm (8):

$$\Phi[x] = 1 - Z[x](a_1 t + a_2 t^2 + a_3 t^3) \quad (X1.1)$$

$$\Phi[x] = 1 - Z[x](a_1 t + a_2 t \lambda = S \times \Delta^2 / (RSD_{inter}^2 + RSD_{eval}^2)) \quad (X1.1)$$

where t is given in terms of x by:

$$t = 1/(1 + px) \quad (X1.2)$$

and where the function $Z[x]$ is defined as follows:

$$Z[x] \equiv \frac{1}{\sqrt{2\pi}} \exp[-x^2/2] \quad (X1.3)$$

and where the constants p , a_1 , a_2 , and a_3 are given as follows:

$$(a_1, a_2, a_3) = (0.4361836, -0.1201676, 0.937298) \quad (X1.4)$$

$$p = 0.33267 \quad (X1.5)$$

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