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BSI Standards Publication

Workplace exposure — Assessment of sampler performance for measurement of airborne particle concentrations

Part 3: Analysis of sampling efficiency data

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National foreword

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Contents

Page

Foreword

This document (CEN/TR 13205-3:2014) has been prepared by Technical Committee CEN/TC 137 "Assessment of workplace exposure to chemical and biological agents", the secretariat of which is held by DIN.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CEN [and/or CENELEC] shall not be held responsible for identifying any or all such patent rights.

This document together with EN 13205-1, EN 13205-2, EN 13205-4, EN 13205-5 and EN 13205-6 supersedes EN 13205:2001.

EN 13205, *Workplace exposure — Assessment of sampler performance for measurement of airborne particle concentrations*, consists of the following parts:

— *Part 1: General requirements;*

— *Part 2: Laboratory performance test based on determination of sampling efficiency;*

— *Part 3: Analysis of sampling efficiency data* [Technical Report] (the present document);

— *Part 4: Laboratory performance test based on comparison of concentrations;*

— *Part 5: Aerosol sampler performance test and sampler comparison carried out at workplaces;*

— *Part 6: Transport and handling tests.*

Introduction

EN 481 defines sampling conventions for the particle size fractions to be collected from workplace atmospheres in order to assess their impact on human health. Conventions are defined for the inhalable, thoracic and respirable aerosol fractions. These conventions represent target specifications for aerosol samplers, giving the ideal sampling efficiency as a function of particle aerodynamic diameter.

In general, the sampling efficiency of real aerosol samplers will deviate from the target specification, and the aerosol mass collected will therefore differ from that which an ideal sampler would collect. In addition, the behaviour of real samplers is influenced by many factors such as external wind speed. In many cases there is an interaction between the influence factors and fraction of the airborne particle size distribution of the environment in which the sampler is used.

This Technical Report presents how data obtained in a type A test (see EN 13205-2) can be analysed in order to calculate the uncertainty components specified in EN 13205-2.

The evaluation method described in this Technical Report shows how to estimate the candidate sampler's sampling efficiency as a function of particle aerodynamic diameter based on the measurement of sampling efficiency values for individual sampler specimen, whether all aspirated particles are part of the sample (as for most inhalable samplers) or if a particle size-dependent penetration occurs between the inlet and the collection substrate (as for thoracic and respirable samplers).

The document shows how various sub-components of sampling errors due non-random and random sources of error can be calculated from measurement data, for example, for individual sampler variability, estimation of sampled concentration and experimental errors.

1 Scope

This Technical Report specifies evaluation methods for analysing the data obtained from a type A test of aerosol samplers under prescribed laboratory conditions as specified in EN 13205-2.

The methods can be applied to all samplers used for the health-related sampling of particles in workplace air.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

EN 1540, *Workplace exposure — Terminology*

EN 13205-1:2014, *Workplace exposure — Assessment of sampler performance for measurement of airborne particle concentrations — Part 1: General requirements*

EN 13205-2:2014, *Workplace exposure — Assessment of sampler performance for measurement of airborne particle concentrations — Part 2: Laboratory performance test based on determination of sampling efficiency*

3 Terms and definitions

For the purpose of this document, the term and definitions given in EN 1540, EN 13205-1 and EN 13205-2 apply.

NOTE With regard to EN 1540, in particular, the following terms are used in this document: total airborne particles, respirable fraction, sampling efficiency, static sampler, thoracic fraction, measuring procedure, non-random uncertainty, random uncertainty, expanded uncertainty, standard uncertainty, combined standard uncertainty, uncertainty (of measurement), coverage factor, precision and analysis.

4 Symbols and abbreviations

4.1 Symbols

4.1.1 Latin

$A\left(D_{\mathrm{A}},\sigma_{\mathrm{A}},D\right)$ relative lognormal aerosol size distribution, with mass median aerodynamic diameter D_{A} and geometric standard deviation σ_{A}, $[1/\mu\mathrm{m}]$

NOTE The word "relative" means that the total amount of particles is unity [-], *i.e.* $\int_0^\infty A\left(D_{\mathrm{A}},\sigma_{\mathrm{A}},D\right)\mathrm{d}D = 1$.

A_p integration of aerosol size distribution A between two particle sizes, [-] – (polygonal approximation method)

$A_{t,p}$ integration of aerosol size distribution A between two particle sizes, calculated using set t of the simulated test particle sizes, [-] – (polygonal approximation method)

$b_{ipr}, b_{ipr}^{\mathrm{left}}, b_{ipr}^{\mathrm{right}}, b_{ipr}^{\mathrm{top}}, b_{ipr}^{\mathrm{front}}$ coefficients in Formula (19) to estimate the test aerosol concentration at a specific sampler position e.g. in a wind tunnel based on nearby concentrations (to the left, right, above and in front of) the sampler measured by thin-walled sharp-

	edged probes, [-]
b_q	regression coefficient q for calibration of particle counter/sizer or similar, [dimension depends on particle counter], (curve-fitting method)
C_{is}	sampled relative aerosol concentration, calculated to be obtained when using the candidate sampler individual s, for aerosol size distribution A at influence variable value ς_i, [-] – (curve-fitting method)
$C_{is,t}$	sampled relative aerosol concentration, calculated to be obtained when using the candidate sampler individual s, for aerosol size distribution A at influence variable value ς_i, using simulated set t of test particle sizes, [-] – (curve-fitting method)
$\bar{C}_{i,t}$	mean sampled relative aerosol concentration, calculated to be obtained when using the candidate sampler, for aerosol size distribution A at influence variable value ς_i, using simulated set t of test particle sizes, [-] – (polygonal approximation method)
$c_{\mathrm{Ref}_{is[r]}}$	correction factor for the measured efficiency values if the total airborne aerosol concentration varies between repeats, [-] – (curve-fitting method)
D	aerodynamic diameter, [µm]
D_{A}	mass median aerodynamic diameter of a lognormal aerosol size distribution A, [µm]
D_{A_a}	mass median aerodynamic diameter a of a lognormal aerosol size distribution A, [µm]
D_c	aerodynamic particle size of calibration particle c (c=1 to N_{C}), [µm] – (curve-fitting method)
D_{max}	diameter of the end of the integration range of the sampled aerosol, [µm] –and H
D_{min}	diameter of the beginning of the integration range of the sampled aerosol, [µm]
D_p	aerodynamic diameter of test particle p (p=1 to N_{P}), [µm]
$D_{t,p}$	simulated test particle size, [µm]
D_u	aerodynamic particle size of small particles u (u=1 to N_{U}) for which the sampling efficiency is known to be e_0, [µm]– (curve-fitting method)
E_{ip}	expectation value of the efficiency for test particle size p at influence variable value ς_i, [-] – (polygonal approximation method)
${}^{\mathrm{est}}E_{is}^{\mathrm{inlet}}$	fitted sampling efficiency curve (of the inlet stage) of the candidate sampler individual s at influence variable value ς_i, [-] – (curve-fitting method)
${}^{\mathrm{est}}E_{is}^{\mathrm{pen}}$	fitted penetration curve (of the separation stage) of the candidate sampler individual s at influence variable value ς_i, [-] – (curve-fitting method)
${}^{\mathrm{est}}E_{is}^{\mathrm{tot}}$	fitted sampling efficiency curve (of the combined inlet and penetration stages) of the candidate sampler individual s at influence variable value ς_i, [-] – (curve-fitting method)
${}^{\mathrm{est}}E_{is,t}$	fitted sampling efficiency curve of the candidate sampler individual s at influence variable value ς_i using simulated set t of N_{P} particle sizes, [-] – (curve-fitting method)

$e_{ipr[s]}$ and $e_{ips[r]}$	experimentally determined efficiency value, with notation for polygonal approximation and curve-fitting methods, respectively. The subscripts are for influence variable value ς_i, particle size p (p=1 to N_P), sampler individual s (s=1 to N_S) and repeat r (r=1 to N_R), [-] – (notation for polygonal approximation and curve-fitting methods, respectively)
e_0	known efficiency value for small particle sizes, [-] – (curve-fitting method)
$F_{\mathrm{LoF}_{is}}$	test variable for "lack of fit" for the regression model $\hat{E}_{is}$ for the sampling efficiency of candidate sampler individual s and influence variable value ς_i, [-] – (curve-fitting method)
$F_{\mathrm{CandSamplVar}_i}$	test variable for the check whether the individual sampler variability exceeds that of the uncertainty of the calculated concentrations, for influence variable value ς_i, [-]
$F_{0.95}(\nu_\mathrm{N}, \nu_\mathrm{D})$	95-percentile of *F* distribution with ν_N and ν_D degrees of freedom, [-]
$f_k(\Xi)$	functions (of Ξ) used to build the regression model of the efficiency curve (index k=1 to N_K), [-] – (curve-fitting method)
$f_k^{\mathrm{inlet}}(\Xi)$	functions (of Ξ) used to build the regression model of the efficiency curve of the inlet stage (index k=1 to N_K), [-] – (curve-fitting method)
$f_k^{\mathrm{pen}}(\Xi)$	functions (of Ξ) used to build the regression model of the penetration curve of the separation stage (index k=1 to N_K), [-] – (curve-fitting method)
$G_{\mathrm{LoF}_{is}}$	uncertainty inflation factor for the "lack of fit" uncertainty of the regression model for candidate sampler individual s and influence variable value ς_i, [-]
$G_{\mathrm{pe}_{is}}$	uncertainty inflation factor for the "pure error" uncertainty of the regression model for candidate sampler individual s and influence variable value ς_i, [-]
$h_{ip}^{\mathrm{left}}, h_{ip}^{\mathrm{right}}, h_{ip}^{\mathrm{top}}, h_{ip}^{\mathrm{front}}$	nearby thin-walled sharp-edged probe concentrations measured in order to be able to estimate the test aerosol concentration at a specific sampler position, e.g. in a wind tunnel (to the left, right, above and in front of) the candidate sampler (see Formula (19)), [mg/m^3] or [1/m^3] depending on the application
${}^{\mathrm{est}}h_{ipr}$	total airborne aerosol concentration estimated from the sharp-edged probe values; the subscripts are for influence variable value i (i=1 to N_IV), particle size p (p=1 to N_P) and repeat r (r=1 to N_R)
N_C	number of sizes for calibration particles – (curve-fitting method)
N_CR	number of regression coefficients for calibration of particle counter/sizer or similar – (curve-fitting method)
N_IV	number of values for the other influence variables at which tests were performed
N_K	number of regression coefficients in the model for the candidate sampler – (curve-fitting method)
$N_\mathrm{K}^{\mathrm{inlet}}$	number of regression coefficients in the model (inlet stage) for the candidate sampler – (curve-fitting method)
$N_\mathrm{K}^{\mathrm{pen}}$	number of regression coefficients in the model of the penetration through the separation stage for the candidate sampler – (curve-fitting method)

N_{P}	number of test particle sizes
N_{R}	number of repeats per tested individual sampler
N_{Ref}	number of reference samplers (thin-walled sharp-edged probes) used per experiment – (polygonal approximation method)
N_{Rep}	number of repeats at particle size p for candidate sampler individual s at influence variable value ς_i – (in the polygonal approximation method N_{Rep} equals the number of repeats, whereas in the curve-fitting method it equals the number of repeats per candidate sampler individual)
$N_{\mathrm{Rep}}{}^{*}$	recalculated number of repeats if the variation among candidate samplers statistically does not exceed that of the uncertainty of the calculated concentration – (curve-fitting method)
N_{S}	number of candidate sampler individuals – (in the polygonal approximation method N_{S} equals the number of sampler individuals tested per repeat, whereas in the curve-fitting method it equals the total number of sampler individuals tested.)
N_{SD}	number of aerosol size distributions A according to EN 13205-2:2014, Table 2
N_{Sim}	number of simulated sets of N_{P} test particle sizes
N_{SR}	number of repeats per sampler individual tested – (polygonal approximation method, see Formula (24))
$N_{\mathrm{S}}{}^{*}$	recalculated number of candidate samplers if the variation among candidate samplers statistically does not exceed that of the uncertainty of the calculated concentration – (curve-fitting method)
N_{TSI}	number of different sampler individuals tested – (polygonal approximation method, see Formula (24))
N_{U}	number of small particle sizes at which the efficiency is known to be e_0 – (curve-fitting method)
Q^0	nominal flow rate of sampler, [l/min]
$RSD_{\mathrm{Est[Ref]}}(\varsigma_i)$	pooled relative standard deviation of the estimate of the thin-walled sharp-edged probe concentration at influence variable ς_i, [-] – (polygonal approximation method)
$RSD_{\mathrm{CandSampl}}(\varsigma_i)$	pooled relative standard deviation of the concentrations sampled by the candidate sampler at influence variable ς_i, [-], (polygonal approximation method)
$RSD_{\mathrm{Ref}}(\varsigma_i)$	pooled relative standard deviation of the thin-walled sharp-edged probe concentrations at influence variable ς_i, [-], (polygonal approximation method)
$s_{\mathrm{CalibrRes}}$	residual standard deviation of the calibration of particle counter/sizer or similar, [dimension depends on particle counter] – (curve-fitting method)
$s_{\mathrm{CandSampl\text{-}Calibr}_{ia}}$	combined non-random and random uncertainty (of measurement) of the calculated sampled concentration, due to the calibration uncertainty of the experiment, for aerosol size distribution A at influence variable value ς_i, [-]
$s_{\mathrm{CandSampl\text{-}Eff}}$	uncertainty of calculated sampled concentration due to uncertainty of efficiency for aerosol size distribution A at influence variable value ς_i, [-] (polygonal approximation method)

$s_{\text{CandSampl-Eff(inlet)}}$	uncertainty of calculated sampled concentration (at the inlet stage) due to uncertainty of efficiency for aerosol size distribution A at influence variable value ς_i, [-] – (polygonal approximation method)
$s_{\text{CandSampl-Eff(pen)}}$	uncertainty of calculated sampled concentration (at the separation stage) due to uncertainty of efficiency for aerosol size distribution A at influence variable value ς_i, [-] – (polygonal approximation method)
$s_{\text{CandSampl-ModelCalc}_{ia}}$	random uncertainty (of measurement) of the calculated sampled concentration, due to the uncertainty of the fitted model, for the a^{th} aerosol size distribution A at influence variable value ς_i, [-]
$s_{\text{CandSampl-PGapprox}}$	uncertainty of calculated sampled concentration due to polygonal approximation for aerosol size distribution A at influence variable value ς_i, [-] – (polygonal approximation method)
$s_{\text{CandSampl-Ref}}$	uncertainty of calculated sampled concentration due to uncertainty of measured total airborne concentrations for aerosol size distribution A at influence variable value ς_i, [-] – (polygonal approximation method)
$s_{\text{CandSampl-Ref(inlet)}}$	uncertainty of calculated sampled concentration (at the inlet stage) due to uncertainty of measured total airborne concentrations for aerosol size distribution A at influence variable value ς_i, [-] – (polygonal approximation method)
$s_{\text{CandSampl-Ref(pen)}}$	uncertainty of calculated sampled concentration (at the separation stage) due to uncertainty of measured total airborne concentrations for aerosol size distribution A at influence variable value ς_i, [-] – (polygonal approximation method)
$s_{\text{CandSampl-Variability}_{ia}}$	random uncertainty (of measurement) of the calculated sampled concentration, due to individual sampler variability, for the a^{th} aerosol size distribution A and influence variable value ς_i, [-]
s_{D}	RMS value of all relative uncertainties of the actual sizes of the monodisperse test aerosols, [-]
$s_{\text{D}c}$	relative uncertainty of the actual size of calibration particle c, [-] – (curve-fitting method) [If the particle size is specified to be within the relative size interval $\pm\beta_c$, then $s_{\text{D}c}$ can be calculated as $s_{\text{D}c} = \beta_c / \sqrt{3}$.]
s_{D_p}	relative uncertainty of the actual size of monodisperse test aerosol *p*, [-] – [If the particle size is specified to be within the relative size interval $\pm\beta_p$, then $s_{\text{D}p}$ can be calculated as $s_{\text{D}_p} = \beta_p / \sqrt{3}$.]
$s_{\text{LoF}_{is}}$	standard deviation pertaining to the possible lack of fit of the regression model for the Ω-transformed sampling efficiency of candidate sampler individual s at influence variable value ς_i, [-] – (curve-fitting method)
$s_{\text{ModelCalc-LoF}_{is}}$	random uncertainty (of measurement) of the calculated sampled concentration, due to the “lack of fit” of the model for candidate sampler individual s, for aerosol size distribution A at influence variable value ς_i, [-]
$s_{\text{ModelCalc-pe}_{is}}$	random uncertainty (of measurement) of the calculated sampled concentration, due to the “pure error” of the experiment for candidate sampler individual s, for aerosol size distribution A at influence variable value ς_i, [-]
$s_{\text{pe}_{is}}$	“pure error” standard deviation of the Ω-transformed experimental data of

	candidate sampler individual s at influence variable value ς_i, [-] – (curve-fitting method)
$s_{\text{RefCorr}_{is}}$	random uncertainty (of measurement) of the calculated sampled concentration, due to the correction of measured sampler efficiency values because of variations in e.g. time, for candidate sampler individual s, at influence variable value ς_i, [-]
$s_{\text{res}_{is}}$	residual standard deviation of the regression model for the Ω-transformed sampling efficiency of candidate sampler individual s at influence variable value ς_i, [-] – (curve-fitting method)
$s_{\text{res(Est[Ref])}_{ip}}$	residual standard deviation of the model for the estimation of the total airborne aerosol concentration for particle size p at influence variable ς_i, [mg/m^3] or [1/m^3] depending on the application – (polygonal approximation method)
$SS_{\text{pe}_{is}}$	"pure error" sum of squares of the Ω-transformed experimental data of candidate sampler individual s at influence variable value ς_i, [-] – (curve-fitting method)
$SS_{\text{res}_{is}}$	residual sum of squares of the regression model for the Ω-transformed sampling efficiency of candidate sampler individual s at influence variable value ς_i, [-] – (curve-fitting method)
$u_{\text{CandSampl-ModelCalc}_i}$	standard uncertainty (of measurement) of the calculated sampled concentration (random errors), due to the uncertainty of the fitted model, calculated as the RMS of the corresponding relative uncertainties over all N_{SD} aerosol size distributions A at influence variable value ς_i, [-]
$u_{\text{CandSampl-Variability}_i}$	standard uncertainty (of measurement) of the sampled concentration (random errors) due to differences among candidate sampler individuals at influence variable value ς_i, [-]
W_p	weighted average of integration of aerosol size distribution A between two particle sizes, [-] – (polygonal approximation)
$W_{t,p}$	weighted average of integration of aerosol size distribution A between two particle sizes, calculated using set t of the simulated test particle sizes, [-] – (polygonal approximation method)
y	instrument response of calibrated particle counter/sizer or similar, [dimension depends on particle counter] – (curve-fitting method)
$z_{t,p}$	random number with a normal distribution, with expectation value equal to zero and standard deviation equal to unity, [-]

4.1.2 Greek

ΔD_p	specified size range within which actual particle size is found with high probability for monodisperse test aerosols with nominal particle size D_p, [µm]
δD_c	relative adjustment of calibration particle size c to obtain a smooth spline, [-] – (curve-fitting method)
$\varepsilon_{ipr[s]}$ and $\varepsilon_{ips[r]}$	random experimental error at particle size p, repeat r and candidate sampler s at influence variable value ς_i, [-] – (notations for polygonal approximation and curve-fitting methods, respectively)
ς	value of other influence variable values, as for example wind speed and mass loading of

sampler, with values for i=1 to N_{IV}, [various dimensions]

ς_i — i^{th} value of another influence variable

NOTE The dimension of each ς_i depends on the influence variable. The dimension selected, however, is not critical, as the values are never part in any calculation.

$^{est}\theta_{isk}$ — regression coefficient number k for candidate sampler individual s at influence variable value ς_i, [dimension depends on selected regression model for the sampling efficiency] – (curve-fitting method)

$^{est}\theta_{isk}^{inlet}$ — regression coefficient number k for model of inlet stage efficiency for candidate sampler individual s at influence variable value ς_i, [dimension depends on selected regression model for the sampling efficiency] – (curve-fitting method)

$^{est}\theta_{isk}^{pen}$ — regression coefficient number k for model of penetration through the separation stage for candidate sampler individual s at influence variable value ς_i, [dimension depends on selected regression model for the sampling efficiency] – (curve-fitting method)

$\nu_{pe_{is}}$ — number of degrees of freedom for the “pure error” standard deviation of the experimental data of candidate sampler individual s at influence variable value ς_i – (curve-fitting method)

$\nu_{res_{is}}$ — number of degrees of freedom for the residual standard deviation of the regression model for the Ω-transformed sampling efficiency of candidate sampler individual s at influence variable value ς_i, (curve-fitting method)

Ξ — transformation of particle size, [dimension depends on transformation] – (curve-fitting method)

Ξ^{inlet} — transformation of particle size for inlet stage, [dimension depends on transformation] – (curve-fitting method)

Ξ^{pen} — transformation of particle size for separation stage, [dimension depends on transformation] – (curve-fitting method)

σ_A — geometric standard deviation of a lognormal aerosol size distribution A from EN 13205-2:2014, Table 2, [-]

σ_{A_a} — Geometric standard deviation a of a lognormal aerosol size distribution A, [µm]

Φ^{-1} — inverse of normal distribution function, [-] – (curve-fitting method)

Ω — transformation of efficiency data, [-] – (curve-fitting method)

Ω^{-1} — inverse Ω-transformation of regression model of the Ω-transformed efficiency curve, [-] – (curve-fitting method)

Ω_{inlet}^{-1} — inverse Ω-transformation of regression model of the Ω-transformed efficiency curve for the inlet stage, [-] – (curve-fitting method)

Ω_{pen}^{-1} — inverse Ω-transformation of regression model of the Ω-transformed efficiency curve for the separation stage, [-] – (curve-fitting method)

4.2 Enumerating subscripts

a — for test aerosols

c — for calibration particle

i — for influence variable values, ς

j for the second estimated regression coefficient in the determination of the covariance $\mathrm{CoVar}\left[{}^{\mathrm{est}}\theta_{isk}, {}^{\mathrm{est}}\theta_{isj}\right]$

k for regression coefficient $\hat{\theta}_{isk}$ and for the first estimated regression coefficient in the determination of the covariance $\mathrm{CoVar}\left[{}^{\mathrm{est}}\theta_{isk}, {}^{\mathrm{est}}\theta_{isj}\right]$

p for test particle size

r for repeats

s for candidate sampler individual

t for simulated set of N_{P} test particle sizes

u for small particle sizes at which the efficiency is known to be e_0

w for repeat within candidate sampler individual z – (polygonal approximation method)

z for candidate sampler individual – (polygonal approximation method)

4.3 Abbreviations

$\mathrm{CoVar}\left[{}^{\mathrm{est}}\theta_{isk}, {}^{\mathrm{est}}\theta_{isj}\right]$	Covariance of the estimated regression coefficients, ${}^{\mathrm{est}}\theta_{isk}$, for the regression model ${}^{\mathrm{est}}E_{is}$ for the sampling efficiency of candidate sampler individual s at influence variable value i, [dimension depends on selected regression model] – (curve-fitting method)
RMS	Root Mean Square

5 Analysis of sampling efficiency data from a performance test according EN 13205-2

5.1 General

This subclause provides illustrations of suitable experimental designs for Type A sampler performance evaluations (see EN 13205-1:2014, Clause 7), and gives two examples of how the experimental data can be statistically analysed. The choice of data analysis method depends primarily on whether the laboratory experiment is carried out using monodisperse or polydisperse aerosols. Two alternative calculation methods, termed the *polygonal approximation* method and the *curve-fitting* method, are described. Alternative methods can be employed provided they are able to calculate the same entities. For monodisperse aerosol tests either method can be used, whereas for polydisperse tests it is better to use the *curve-fitting* method. The small quantity of data typically yielded by monodisperse aerosol experiments can render the curve-fitting method difficult to apply. The curve-fitting method is used when (different) sampling efficiency curves can be determined for the individual candidate samplers.

The simplified treatments of aerosol sampler performance data described allow samplers to be evaluated under specified laboratory conditions, although the results can not necessarily reflect performance under conditions of use.[1)]

1) For worked examples of these and other methods for analysing aerosol sampler performance data, see Bibliography, references [1] to [5].

5.2 Presumption of exactly balanced data

The formulae presented here presume that the number of test particle sizes, N_P, the number of samplers, N_S, the number of repeats, N_Rep, the number of influence variable values, N_IV, and (in the case of the curve-fitting method) the number of regression coefficients, N_K, are identical over the whole experiment, *i.e.* the data are exactly balanced. If this is not so, these numbers will vary across the experimental data, and we will have

$$\begin{cases} N_\text{P} = N_{\text{P}_{isr}} \\ N_\text{S} = N_{\text{S}_{ipr}} \\ N_\text{Rep} = N_{\text{Rep}_{ips}} \\ N_\text{IV} = N_{\text{IV}_{psr}} \\ N_\text{K} = N_{\text{K}_{ipsr}} \end{cases} \qquad (1)$$

Consequently many of the formulae presented below will need to be modified accordingly.

5.3 Examples of balanced experimental designs

Table 1 illustrates an experiment in which six sampler individuals are tested at N_P (=9) diameters (monodisperse test aerosols) in a series of N_Rep (=2) repeats with N_S (=3) sampler individuals tested in each repeat. The N_P diameters will be tested sequentially, and the sampler individuals can be tested either in groups as shown, or sequentially.

Table 1 — Example of a balanced design using monodisperse test aerosols

Test particle size	Repeat 1			Repeat 2		
	Sampler individual 1	Sampler individual 2	Sampler individual 3	Sampler individual 4	Sampler individual 5	Sampler individual 6
1	x	X	x	x	x	x
2	x	X	x	x	x	x
3	x	X	x	x	x	x
4	x	X	x	x	x	x
5	x	X	x	x	x	x
6	x	X	x	x	x	x
7	x	X	x	x	x	x
8	x	X	x	x	x	x
9	x	X	x	x	x	x

Table 2 illustrates an experiment in which N_S (=6) sampler individuals are tested with polydisperse test aerosols with N_Rep (=5) repeats for each sampler (and all test particle sizes).

Table 2 — Example of a balanced design using polydisperse test aerosols

Repeat	Sampler individual 1	Sampler individual 2	Sampler individual 3	Sampler individual 4	Sampler individual 5	Sampler individual 6
1	x	X	x	x	x	x
2	x	X	x	x	x	x
3	x	X	x	x	x	x
4	x	X	x	x	x	x
5	x	X	x	x	x	x

Both designs in Tables 1 and 2 can be part of a larger experiment in which the shown design is repeated for different influential variable conditions, such as wind speeds and sampler loadings. A difference between the two designs is that the subscripts *sampler individual* and *repeat* has different meanings in the two methods. In an experiment with monodisperse test aerosols, the sampler individuals are nested within the repeats, so that (generally) it can be a different set of sampler individuals participating in a different repeat. The number of sampler individuals tested, N_{S}, is therefore equal to the number of sampler individuals *tested per repeat*, not the total number of tested candidate sampler individuals. (At the extreme all N_{S} sampler individuals can be tested together (i.e. N_{Rep} ≥ 1). Where there is a possibility of significant variations between sampler individuals, the number of sampler individuals tested per repeat, N_{S}, should be as large as possible.) In an experiment with polydisperse test aerosols, on the other hand, the repeats are nested within each sampler individual. N_{S} equals the total number of sampler individuals tested, and N_{R} equals the number of repeats per tested individual sampler.

5.4 Analysis of efficiency data based on monodisperse test aerosols using the polygonal approximation method

5.4.1 Statistical model for the efficiency values

The efficiency values $e_{ipr[s]}$ at particle diameter p, influence variable value number i, repeat r, candidate sampler s (within repeat r) are analysed according to the model

$$e_{ipr[s]} = E_{ip} + \varepsilon_{ipr[s]} \tag{2}$$

where

E_{ip} is the expectation value of the efficiency of the sampler type at particle diameter $D = D_p$ for influence variable value number i, [-];

$\varepsilon_{ipr[s]}$ is the random experimental error, including experimental flow deviation and inter-specimen variability where present, [-].

The polygonal approximation to the estimated mean relative concentration [see EN 13205-2:2014, Formula (2)], $E\left[C_i\right]$, can be written as a weighed sum over the sampling efficiencies at diameters D_p [µm], p=1 to N_{p}, (though a similar approach could be used with other integration schemes)

$$\begin{aligned} E\left[C_i\right] &= \int_0^\infty A\left(D_{\mathrm{A}}, \sigma_{\mathrm{A}}, D\right) E_i\left(D\right) \mathrm{d}D \approx \\ &\approx \sum_{p=0}^{N_{\mathrm{P}}} E_i\left(D_p\right) W_p\left(D_{\mathrm{A}}, \sigma_{\mathrm{A}}, D\right) \approx \sum_{p=0}^{N_{\mathrm{P}}} E_{ip} W_p \end{aligned} \tag{3}$$

with

$$\begin{cases} A_p = A_p(D_\mathrm{A},\sigma_\mathrm{A}) = \int_{D_{(p-1)}}^{D_p} A(D)\,\mathrm{d}D = \int_{D_{(p-1)}}^{D_p} A(D_\mathrm{A},\sigma_\mathrm{A},D)\,\mathrm{d}D \\ W_p = W_p(D_\mathrm{A},\sigma_\mathrm{A}) = \dfrac{A_p + A_{(p+1)}}{2}, \qquad 0<p<N_p \\ W_0 = \dfrac{A_1}{2} \\ W_{N_\mathrm{P}} = \dfrac{A_{N_p} + A_{(N_\mathrm{P}+1)}}{2}, \quad \text{respirable or thoracic samplers} \\ W_{N_\mathrm{P}} = \dfrac{A_{N_\mathrm{P}}}{2}, \quad \text{inhalable samplers} \end{cases} \tag{4}$$

where

$A\left(D_\mathrm{A},\sigma_\mathrm{A},D\right)$	is the relative lognormal aerosol size distribution, with mass median aerodynamic diameter D_A and geometric standard deviation σ_A;
A_p	is the integration of aerosol size distribution A between two particle sizes;
$E\left[C_i\right]$	is the polygonal approximation to the estimated mean relative concentration;
$E_i\left(D_p\right) = E_{ip}$	is the sampling efficiency of the candidate sampler for test particle size p at influence variable value ς_i; and
W_p	is the weighted average of integration of aerosol size distribution A between two particle sizes.

This method presumes that sampling efficiency ${}^{\mathrm{est}}E_i\left(D_0\right)$ at $D_0 = 0$ µm can be estimated by linear extra polation or if it is known to be unity, ${}^{\mathrm{est}}E_i\left(D_0\right)$ can be assigned the value of 1,00. For samplers of the respirable and thoracic aerosol fractions, one also needs to estimate the value of an extrapolated particle diameter $D_{(N_\mathrm{P}+1)} = {}^{\mathrm{est}}D_{(N_\mathrm{P}+1)}$, at which ${}^{\mathrm{est}}E_i\left({}^{\mathrm{est}}D_{(N_\mathrm{P}+1)}\right) \approx 0$. This is done by linear extrapolation of the two highest diameter data points. However, for samplers of the inhalable aerosol fraction, the integration is terminated at D_{N_P}, and thus the upper extrapolation is not necessary, and hence W_{N_P} is calculated differently.

NOTE The approach for samplers for the respirable and thoracic fractions presumes that the final term of the summation in Formula (3), $0{,}5\overline{E}_i\left(D_{N_\mathrm{P}}\right)A_{(N_\mathrm{P}+1)}$, is small compared to $\overline{C}_i$.

5.4.2 Estimation of mean sampled concentration

The raw data (efficiency values) are $e_{ipr[s]}$ where subscript i denotes an influence variable value (i = 1 to N_IV), subscript p denotes particle aerodynamic diameter (p = 1 to N_P), subscript r denotes a repeat (r =1 to N_Rep) and subscript s denotes candidate sampler individual (s=1 to N_S) within the repeat r. In the case of static samplers, the repeats can concern either sampler individuals or repeats, i.e. they are not necessarily true replicates. (For personal samplers, however, at least six different sampler individuals should be tested, see EN 13205-2:2014, 6.3.8.) The mean sampling efficiency at each measured diameter D_p for each influence variable value i, $\overline{E}_i\left(D_p\right)$, is estimated as

$$\bar{E}_i\left(D_p\right) = \frac{1}{N_{\mathrm{Rep}}}\frac{1}{N_{\mathrm{S}}}\sum_{r=1}^{N_{\mathrm{Rep}}}\sum_{s=1}^{N_{\mathrm{S}}} e_{ipr[s]} \quad (5)$$

where

$\bar{E}_i\left(D_p\right)$	is the mean is the sampling efficiency of the candidate sampler for test particle size p at influence variable value ς_i ,
$e_{ipr[s]}$	is the experimentally determined efficiency value,
N_{Rep}	is the number of repeats; and
N_{S}	is the number of samplers.

This is a point estimate of the sampling efficiency curve $\bar{E}(D)$ of the sampler at particle aerodynamic diameter $D = D_p$. The polygonal approximation to estimate the mean relative concentration $\bar{C}$ sampled from an arbitrary aerosol $A(D)$ should be calculated using the trapezoidal rule following Formula (3):

$$\bar{C}_i \approx \sum_{p=0}^{N_{\mathrm{P}}} \bar{E}_i\left(D_p\right)W_p \quad (6)$$

where

$\bar{C}_i$	is the mean sampled relative concentration from an arbitrary aerosol $A(D)$;
$\bar{E}_i\left(D_p\right)$	is the mean sampling efficiency of the candidate sampler for test particle size p at influence variable value ς_i ; and
W_p	is the weighted average of integration of aerosol size distribution A between two particle sizes.

The ‘weights’ W_p are calculated according to Formula (4) and the discussion at the latter part of 5.4.1.

For experiments in which the inlet efficiency and the internal penetration are measured in two separate experiments, Formula (6) is modified accordingly

$$\bar{C}_i \approx \sum_{p=1}^{N_{\mathrm{P}}} \bar{E}_i^{\mathrm{inlet}}\left(D_p\right)\bar{E}_i^{\mathrm{pen}}\left(D_p\right)W_p \quad (7)$$

where

$\bar{C}_i$	is the mean sampled relative concentration from an arbitrary aerosol $A(D)$;
$\bar{E}_i^{\mathrm{inlet}}\left(D_p\right)$	is the sampling efficiency of the inlet stage;
$\bar{E}_i^{\mathrm{pen}}\left(D_p\right)$	is the penetration through the separation stage;
W_p	is the weighted average of integration of aerosol size distribution A between two particle sizes.

5.4.3 Estimation of uncertainty (of measurement) components

5.4.3.1 General

Three uncertainty (of measurement) components are estimated: the uncertainty of the calibration of the sampler test system, the uncertainty in the estimate of the sampled concentration, and the individual sampler variability.

5.4.3.2 Calibration of sampler test system

This uncertainty (of measurement) component stems from the uncertainty of the actual size of the monodisperse test aerosols, not the width of their particle size distributions. Each of the particle sizes associated with the N_{P} monodisperse test aerosols has a *relative* uncertainty, s_{D_p} . If the uncertainty of the particle size of a monodisperse test aerosol of size D_p [µm] is specified within a range, $\pm\Delta D_p$ [µm], rather than as a relative standard deviation, s_{D_p} is calculated as

$$s_{\mathrm{D}_p} = \frac{1}{\sqrt{3}} \frac{\Delta D_p}{D_p} \tag{8}$$

where

- D_p is the aerodynamic diameter of test particle p (p=1 to N_{P});
- ΔD_p is the size of the uncertainty range of the particle size of a monodisperse test aerosol; and
- s_{D_p} is the relative uncertainty of the actual size of the monodisperse test aerosol p.

The RMS test particle size uncertainty is calculated, from

$$s_{\mathrm{D}}{}^2 = \frac{1}{N_{\mathrm{P}}} \sum_{p=1}^{N_{\mathrm{P}}} s_{\mathrm{D}_p}{}^2 \tag{9}$$

where

- s_{D} is the RMS value of all relative uncertainties of the actual sizes of the monodisperse test aerosols;
- N_{P} is the number of samplers; and
- s_{D_p} is the relative uncertainty of the actual size of monodisperse test aerosol p.

The uncertainty (of measurement) of the calibration of the sampler test system is calculated by first simulating $N_{\mathrm{Sim}} = 1000$ sets of N_{P} particle sizes, $D_{t,p}$ (subscript t=1 to N_{Sim}), based on the RMS uncertainty of the size of the test aerosols, s_{D} . A random number generator is used to generate a set of $N_{\mathrm{Sim}}\, N_{\mathrm{P}}$ values of $z_{t,p}$, which have a normal distribution with an estimation value of zero and a standard deviation of unity. $D_{t,p}$ is simulated by using the formula

$$D_{t,p} = (1 + z_{t,p} s_{\mathrm{D}})\, D_p \tag{10}$$

where

D_p is the aerodynamic diameter of test particle p (p=1 to N_P);

$D_{t,p}$ is the simulated test particle size;

$z_{t,p}$ is the random number with a normal distribution, with expectation value equal to zero and standard deviation equal to unity; and

s_D is the RMS value of all relative uncertainties of the actual sizes of the monodisperse test aerosols.

For each of the N_Sim simulated sets of particle sizes, the mean sampled relative concentration is calculated according to Formulae (11) and (12), similar to Formulae (6) and (4)

$$\bar{C}_{i,t} \approx \sum_{p=0}^{N_P} \bar{E}_i\left(D_p\right) W_{t,p} \tag{11}$$

with

$$\begin{cases} A_{t,p} = \int\limits_{D_{t,(p-1)}}^{D_{t,p}} A(D)\,dD = \int\limits_{D_{t,(p-1)}}^{D_{t,p}} A(D_\mathrm{A}, \sigma_\mathrm{A}, D)\,dD \\ W_{t,p} = \dfrac{A_{t,p} + A_{t,(p+1)}}{2}, \quad 0<p<N_\mathrm{P} \\ W_{t,0} = \dfrac{A_{t,1}}{2} \\ W_{t,N_\mathrm{P}} = \dfrac{A_{t,N_P} + A_{t,(N_\mathrm{P}+1)}}{2}, \quad \text{respirable or thoracic samplers} \\ W_{N_\mathrm{P}} = \dfrac{A_{N_\mathrm{P}}}{2}, \quad \text{inhalable samplers} \end{cases} \tag{12}$$

where

$A_{t,p}$ is the integration of aerosol size distribution A between two particle sizes, calculated using set t of the simulated test particle sizes;

$\bar{C}_{i,t}$ is the mean sampled relative aerosol concentration, calculated to be obtained when using the candidate sampler, for aerosol size distribution A at influence variable value ς_i , using simulated set t of test particle sizes;

$\bar{E}_i\left(D_p\right)$ is the mean sampling efficiency of the candidate sampler for test particle size p at influence variable value ς_i ; and

$W_{t,p}$ is the weighted average of integration of aerosol size distribution A between two particle sizes, calculated using set t of the simulated test particle sizes.

Similar as with Formula (4) it is presumed both that the efficiency at $D_0 = 0\ \mu$m , ${}^\mathrm{est}E_{i,t}\left(0\right)$, can be estimated, and additionally for samplers of the respirable and thoracic aerosol fractions, that the particle size of zero efficiency, ${}^\mathrm{est}D_{t,(N_\mathrm{P}+1)}$, can be estimated, as discussed in the latter part of 5.4.1.

NOTE In these calculations the efficiency at $D_{t,p}$, ${}^{\text{est}}E_i(D_{t,p})$ for $1 \le p \le N_\text{P}$, is the originally measured efficiency at particle size D_p, $\bar{E}_i(D_p)$, i.e. ${}^{\text{est}}E_i(D_{t,p}) = \bar{E}_i(D_p)$. It is the particle sizes at the measured efficiency that is varied by simulation.

For each of the N_SD aerosol size distributions A and all N_IV influence variable values, calculate the RMS of the mean sampled relative concentration for all N_Sim simulated sets of test particle sizes, from the formula

$$
\begin{aligned}
s_{\text{CandSampl-Calibr}_{ia}}{}^2 &= \frac{1}{N_\text{Sim}} \sum_{t=1}^{N_\text{Sim}} \left(\bar{C}_{i,t} - \bar{C}_i\right)^2 = \\
&= \frac{1}{N_\text{Sim}} \sum_{t=1}^{N_\text{Sim}} \left(\bar{C}_{i,t}\left(D_{\text{A}_a}, \sigma_{\text{A}_a}\right) - \bar{C}_i\left(D_{\text{A}_a}, \sigma_{\text{A}_a}\right)\right)^2
\end{aligned}
\qquad (13)
$$

where

$\bar{C}_i$	is the mean sampled relative aerosol concentration, expressed as a fraction of the total airborne aerosol concentration, calculated to be obtained when using the candidate sampler, for aerosol size distribution A at influence variable value ς_i;
$\bar{C}_{i,t}$	is the mean sampled relative aerosol concentration, calculated to be obtained when using the candidate sampler, for aerosol size distribution A at influence variable value ς_i, using simulated set t of test particle sizes;
D_{A_a}	is the mass median aerodynamic diameter a of lognormal aerosol size distribution A;
N_Sim	is the number of simulated sets of N_P test particle sizes;
$s_{\text{CandSampl-Calibr}_{ia}}$	is the combined non-random and random uncertainty (of measurement) of the calculated sampled concentration, due to the calibration uncertainty of the experiment, for aerosol size distribution A at influence variable value ς_i; and
σ_{A_a}	is the geometric standard deviation a of lognormal aerosol size distribution A.

For each influence variable value calculate the RMS over all the N_SD aerosol size distributions A

$$
\begin{aligned}
u_{\text{CandSampl-Calibr}_i}{}^2 &= \frac{1}{N_\text{SD}} \sum_{a=1}^{N_\text{SD}} \frac{s_{\text{CandSampl-Calibr}_{ia}}{}^2}{C_\text{std}{}^2} = \\
&= \frac{1}{N_\text{SD}} \sum_{a=1}^{N_\text{SD}} \left(\frac{s_\text{CandSampl-Calibr}\left(D_{\text{A}_a}, \sigma_{\text{A}_a}, \zeta_i\right)}{C_\text{std}\left(D_{\text{A}_a}, \sigma_{\text{A}_a}, \zeta_i\right)}\right)^2
\end{aligned}
\qquad (14)
$$

where

C_std	is the target sampled relative aerosol concentration, expressed as a fraction of the total airborne aerosol concentration, that would have been sampled using an ideal sampler with a sampling efficiency identical to the sampling convention for aerosol size distribution A;
D_{A_a}	is the mass median aerodynamic diameter a of lognormal aerosol size distribution A;

N_{SD} is the number of aerosol size distributions A;

$s_{\text{CandSampl-Calibr}_{ia}}$ is the combined non-random and random uncertainty (of measurement) of the calculated sampled concentration, due to the calibration uncertainty of the experiment, for aerosol size distribution A at influence variable value ζ_i;

$u_{\text{CandSampl-Calibr}_i}$ is the standard uncertainty (of measurement) (non-random and random errors) of the calculated sampled concentration, due to the calibration uncertainty of the experiment, calculated as the RMS of the corresponding relative uncertainties over all N_{SD} aerosol size distributions A at influence variable value, ζ_i; and

σ_{A_a} is the geometric standard deviation a of lognormal aerosol size distribution A.

5.4.3.3 Estimation of sampled concentration

This uncertainty (of measurement) component is derived from Formula (3) and it has three sources:

1) the polygonal approximation,

2) the uncertainty of the average sampling efficiencies, and

3) the uncertainty of the total airborne concentrations.

For samplers not deviating too much from the sampling convention, the uncertainty of the polygonal approximation, can be estimated as the difference between the calculated mass concentration using the approximate summation of Formula (3) and the corresponding integral.

$$s_{\text{CandSampl-PGapprox}} = s_{\text{CandSampl-PGapprox}}\left(D_{\text{A}_a}, \sigma_{\text{A}_a}\right) \approx \approx \left| \sum_{p=1}^{N_{\text{P}}} F\left(D_p\right) W_p - \int_{D_{\min}}^{D_{\max}} A\left(D_{\text{A}_a}, \sigma_{\text{A}_a}, D\right) F\left(D\right) dD \right| \quad (15)$$

where

D_{A_a} is the mass median aerodynamic diameter a of lognormal aerosol size distribution A;

$D_{\max}$ in the case of a sampler for the inhalable fraction $D_{\max} = D_{N_{\text{P}}}$, otherwise $D_{\max}$ is determined from the particle size which make integrand $A\left(D_{\text{A}_a}, \sigma_{\text{A}_a}, D\right) F\left(D\right)$ equal to $0{,}5 \times 10^{-3}$;

$D_{\min}$ this diameter is determined from the particle size which make integrand $A\left(D_{\text{A}_a}, \sigma_{\text{A}_a}, D\right) F\left(D\right)$ equal to $0{,}5 \times 10^{-3}$;

$F\left(D\right)$ is the target sampling convention;

N_{P} is the number of test particle sizes;

$s_{\text{CandSampl-PGapprox}}$ is the uncertainty of calculated sampled concentration due to polygonal approximation for aerosol size distribution A at influence variable value ς_i;

W_p is the weighted average of integration of aerosol size distribution A between two particle sizes, calculated according to Formula (4); and

σ_{A_a}	is the geometric standard deviation a of lognormal aerosol size distribution A.

The uncertainty due to the concentration sampled by the candidate sampler is calculated as

$$s_{\text{CandSampl-Eff}}{}^2 = s_{\text{CandSampl-Eff}}{}^2\left(D_{\mathrm{A}_a}, \sigma_{\mathrm{A}_a}, \zeta_i\right) = \frac{RSD_{\text{CandSampl}}{}^2\left(\zeta_i\right)}{N_{\text{Rep}}\, N_{\text{S}}} \sum_{p=1}^{N_{\text{P}}} \left[\bar{E}_i\left(D_p\right) W_p\right]^2 \tag{16}$$

where

D_{A_a}	is the mass median aerodynamic diameter a of lognormal aerosol size distribution A;
$\bar{E}_i\left(D_p\right)$	is the mean sampling efficiency of the candidate sampler for test particle size p at influence variable value ς_i;
N_{P}	is the number of test particle sizes;
N_{Rep}	is the number of repeats;
N_{S}	is the number of samplers;
$RSD_{\text{CandSampl}}\left(\zeta_i\right)$	is the pooled relative standard deviation (over all the N_{P} test particles sizes, N_{Rep} repeats and N_{S} candidate sampler individuals per repeat) of the concentrations sampled by the candidate sampler at influence variable value ς_i;
$s_{CandSampl-Eff}$	is the uncertainty of calculated sampled concentration due to uncertainty of efficiency for aerosol size distribution A at influence variable value ς_i;
W_p	is the weighted average of integration of aerosol size distribution A between two particle sizes, calculated according to Formula (4); and
σ_{A_a}	is the geometric standard deviation a of lognormal aerosol size distribution A.

The uncertainty due to the total airborne concentration is calculated from

$$s_{\text{CandSampl-Ref}}{}^2 = s_{\text{CandSampl-Ref}}{}^2\left(D_{\mathrm{A}_a}, \sigma_{\mathrm{A}_a}, \zeta_i\right) = RSD_{\text{Est[Ref]}}{}^2\left(\zeta_i\right) \sum_{p=1}^{N_{\text{P}}} \left[\bar{E}_i\left(D_p\right) W_p\right]^2 \tag{17}$$

where

D_{A_a}	is the mass median aerodynamic diameter a of lognormal aerosol size distribution A;
$\bar{E}_i\left(D_p\right)$	is the mean sampling efficiency of the candidate sampler for test particle size p at influence variable value ς_i;
N_{P}	is the number of test particle sizes;
$RSD_{\text{Est[Ref]}}\left(\zeta_i\right)$	is the pooled relative standard deviation (over all the N_{P} test particles sizes, N_{Rep} repeats) of the estimate of the total airborne concentrations at influence variable

value ς_i;

$s_{\text{CandSampl-Ref}}$ is the uncertainty of calculated sampled concentration due to uncertainty of measured total airborne concentrations for aerosol size distribution A at influence variable value ς_i;

W_p is the weighted average of integration of aerosol size distribution A between two particle sizes, calculated according to Formula (4); and

σ_{A_a} is the geometric standard deviation a of lognormal aerosol size distribution A.

If the total airborne concentration is estimated as the average of N_{Ref} thin-walled sharp-edged probes, then

$$RSD_{\text{Est[Ref]}}{}^2(\zeta_i) = \frac{RSD_{\text{Ref}}{}^2(\zeta_i)}{N_{\text{Ref}}} \tag{18}$$

where

N_{Ref} is the number of reference samplers used per experiment;

$RSD_{\text{Est[Ref]}}(\zeta_i)$ is the pooled relative standard deviation (over all the N_{P} test particles sizes, N_{Rep} repeats) of the estimate of the total airborne concentrations at influence variable value ς_i;

$RSD_{\text{Ref}}(\zeta_i)$ is the pooled relative standard deviation (over all the N_{P} test particles sizes, N_{Rep} repeats) of the measured total airborne concentrations at influence variable value ς_i, and N_{Ref} is the number of thin-walled sharp-edged probes used per repeat.

In the case where the total airborne concentration is estimated by a formula, ${}^{\text{est}}h_{ipr}$ [mg/m³] or [1/m³] depending on the application, based on for example, the measured total airborne concentrations by thin-walled sharp-edged probes to the left, right, above and in front of a mannequin in a wind tunnel (h_{ipr}^{left}, h_{ipr}^{right}, h_{ipr}^{top} and h_{ipr}^{front}), all [mg/m³] or [1/m³]), $RSD_{\text{Est[Ref]}}(\zeta_i)$ is calculated in a special way.

Here the total airborne concentration is calculated using a formula similar to

$${}^{\text{est}}h_{ipr}(D_{ipr}) = b_{ip} + b_{ip}^{\text{left}} h_{ipr}^{\text{left}} + b_{ip}^{\text{right}} h_{ipr}^{\text{right}} + b_{ip}^{\text{top}} h_{ipr}^{\text{top}} + b_{ip}^{\text{front}} h_{ipr}^{\text{front}} \tag{19}$$

where

${}^{\text{est}}h_{ipr}(D_{ipr})$ is the corresponding total airborne aerosol concentration estimated from the sharp-edged probe values. The subscripts are for influence variable value i (i=1 to N_{IV}), particle size p (p=1 to N_{P}) and repeat r (r=1 to N_{R});

$b_{ip}, b_{ip}^{\text{left}}, b_{ip}^{\text{right}}, b_{ip}^{\text{top}}, b_{ip}^{\text{front}}$ are the coefficients to estimate the test aerosol concentration at a specific sampler position e.g. in a wind tunnel based on nearby concentrations (to the left, right, above and in front of) the sampler measured by thin-walled sharp-edged probes; and

$h_{ip}^{\text{left}}, h_{ip}^{\text{right}}, h_{ip}^{\text{top}}, h_{ip}^{\text{front}}$ are the nearby thin-walled sharp-edged probe concentrations measured in order to be able to estimate the test aerosol concentration at a specific sampler position, e.g. in a wind tunnel (to the left, right, above and in front of) the candidate sampler depending on the application.

The pooled relative standard deviation of the estimate of the total airborne concentrations at influence variable value ς_i, is approximately calculated from the formula

$$RSD_{\text{Est[Ref]}}(\zeta_i)^2 = \frac{1}{N_\text{P}} \sum_{p=1}^{N_\text{P}} \frac{1}{\text{N}_\text{Rep}} \sum_{r=1}^{\text{N}_\text{Rep}} \left[\frac{s_{\text{res(Est[Ref]}_{ip}}}{{}^{\text{est}}h_{ipr}(D_{ipr})} \right] \qquad (20)$$

where

${}^{\text{est}}h_{ipr}(D_{ipr})$	is the corresponding total airborne aerosol concentration estimated from the sharp-edged probe values. The subscripts are for influence variable value i (i=1 to N_IV), particle size p (p=1 to N_P) and repeat r (r=1 to N_R);
N_P	is the number of test particle sizes;
$RSD_{\text{Est[Ref]}}(\zeta_i)$	is the pooled relative standard deviation (over all the N_P test particles sizes, N_Rep repeats) of the estimate of the total airborne concentrations at influence variable value ς_i;
$s_{\text{res(Est[Ref]}_{ip}}$	is the residual standard deviation of the model, [mg/m^3] or [1/m^3] depending on the application, (as exemplified by Formula (19)) to estimate the total airborne concentration for particle size p at influence variable value i.

When the inlet efficiency and the penetration are independently measured by two separate experiments, the variances that are due to each experiment should be calculated separately according to Formulae (16) and (17), and then summed as shown below

$$\begin{cases} s_{\text{CandSampl-Eff}}{}^2 = s_{\text{CandSampl-Eff(inlet)}}{}^2 + s_{\text{CandSampl-Eff(pen)}}{}^2 \\ s_{\text{CandSampl-Ref}}{}^2 = s_{\text{CandSampl-Ref(inlet)}}{}^2 + s_{\text{CandSampl-Ref(pen)}}{}^2 \end{cases} \qquad (21)$$

where the subscripts 'inlet' and 'pen' refer to the quantities calculated for the inlet efficiency and penetration experiments respectively.

where

$s_{\text{CandSampl-Eff}}$	is the uncertainty of calculated sampled concentration due to uncertainty of efficiency for aerosol size distribution A at influence variable value ς_i;
$s_{\text{CandSampl-Eff(inlet)}}$	is the uncertainty of calculated sampled concentration (at the inlet stage) due to uncertainty of efficiency for aerosol size distribution A at influence variable value ς_i;
$s_{\text{CandSampl-Eff(pen)}}$	is the uncertainty of calculated sampled concentration (at the separation stage) due to uncertainty of efficiency for aerosol size distribution A at influence variable value ς_i;
$s_{\text{CandSampl-Ref}}$	is the uncertainty of calculated sampled concentration due to uncertainty of measured total airborne concentrations for aerosol size distribution A at influence variable value ς_i;
$s_{\text{CandSampl-Ref(inlet)}}$	is the uncertainty of calculated sampled concentration (at the inlet stage) due to uncertainty of measured total airborne concentrations for aerosol size distribution A at influence variable value ς_i; and
$s_{\text{CandSampl-Ref(pen)}}$	is the uncertainty of calculated sampled concentration (at the separation stage) due to uncertainty of measured total airborne concentrations for aerosol size distribution A at influence variable value ς_i.

The uncertainty (of measurement) for this source of uncertainty (of measurement) is

$$\begin{aligned} s_{\text{CandSampl-ModelCalc}_{ia}}{}^2 &= s_{\text{CandSampl-PGapprox}}{}^2\left(D_{\text{A}_a},\sigma_{\text{A}_a}\right) + \\ &+ s_{\text{CandSampl-Eff}}{}^2\left(D_{\text{A}_a},\sigma_{\text{A}_a},\zeta_i\right) + \\ &+ s_{\text{CandSampl-Ref}}{}^2\left(D_{\text{A}_a},\sigma_{\text{A}_a},\zeta_i\right) \end{aligned} \tag{22}$$

where

$s_{\text{CandSampl-Eff}}$	is the uncertainty of calculated sampled concentration due to uncertainty of efficiency for aerosol size distribution A at influence variable value ς_i;
$s_{\text{CandSampl-ModelCalc}_{ia}}$	is the random uncertainty (of measurement) of the calculated sampled concentration, due to the uncertainty of the fitted model, for the a[th] aerosol size distribution A at influence variable value ς_i;
$s_{\text{CandSampl-PGapprox}}$	is the uncertainty of calculated sampled concentration due to polygonal approximation for aerosol size distribution A at influence variable value ς_i; and
$s_{\text{CandSampl-Ref}}$	is the uncertainty of calculated sampled concentration due to uncertainty of measured total airborne concentrations for aerosol size distribution A at influence variable value ς_i.

For each influence variable value calculate the RMS over all the N_{SD} aerosol size distributions A

$$\begin{aligned} u_{\text{CandSampl-ModelCalc}_i}{}^2 &= \frac{1}{N_{\text{SD}}}\sum_{a=1}^{N_{\text{SD}}}\frac{s_{\text{CandSampl-ModelCalc}_{ia}}{}^2}{C_{\text{std}}{}^2} = \\ &= \frac{1}{N_{\text{SD}}}\sum_{a=1}^{N_{\text{SD}}}\left(\frac{s_{\text{CandSampl-ModelCalc}}\left(D_{\text{A}_a},\sigma_{\text{A}_a},\zeta_i\right)}{C_{\text{std}}\left(D_{\text{A}_a},\sigma_{\text{A}_a}\right)}\right)^2 \end{aligned} \tag{23}$$

where

C_{std}	is the target sampled relative aerosol concentration, expressed as a fraction of the total airborne aerosol concentration, that would have been sampled using an ideal sampler with a sampling efficiency identical to the sampling convention for aerosol size distribution A;
N_{SD}	is the number of aerosol size distributions A;
$s_{\text{CandSampl-ModelCalc}_{ia}}$	is the random uncertainty (of measurement) of the calculated sampled concentration, due to the uncertainty of the fitted model, for the a^{th} aerosol size distribution A at influence variable value ς_i; and
$u_{\text{CandSampl-ModelCalc}_i}$	is the standard uncertainty (of measurement) of the calculated sampled concentration (random errors), due to the uncertainty of the fitted model, calculated as the RMS of the corresponding relative uncertainties over all N_{SD} aerosol size distributions A at influence variable value ς_i.

This treatment presumes that both the residual variance pooled and the total airborne concentration variances are independent of particle diameter. If this assumption is not justified, more complex data treatments are possible [2]).

5.4.3.4 Individual sampler variability

5.4.3.4.1 General

For samplers for the inhalable sampling convention this uncertainty component is zero, thus $s_{\text{Sampl-Variability}} \equiv 0$. For samplers for the respirable or thoracic sampling conventions this uncertainty (of measurement) component is calculated from the estimated sampled concentration *per tested candidate sampler individual*. For these calculations the individual efficiency values, $e_{ipr[s]}$, are grouped according to with which tested candidate sampler individual it was determined. Thus the notation $e_{ipz[w]}$ will be used for the efficiency values in Formula (24) where subscript z (z=1 to N_{TSI}) describe each tested candidate sampler individual and subscript w (w=1 to N_{SR}) denote repeat values for tested candidate sampler z. If the experiment was conducted with the same set of N_{S} tested candidate sampler individuals used in all repeats, then the total number of sampler individuals tested $N_{\text{TSI}} = N_{\text{S}}$, and correspondingly, the number of repeats per tested candidate sampler individual is $N_{\text{SR}} = N_{\text{R}}$. On the other hand, if the test was conducted with a unique set of tested candidate sampler individuals in each repeat, then $N_{\text{TSI}} = N_{\text{R}} N_{\text{S}}$, and correspondingly, the number of repeats per tested candidate sampler individual is $N_{\text{SR}} = 1$.

The uncertainty due to individual sampler variability is calculated from the formula

$$s_{\text{CandSampl-Variability}_{ia}}{}^2 + s_{\text{CandSampl-ModelCalc}_{ia}}{}^2 = \frac{1}{N_{\text{TSI}} - 1} \sum_{z=1}^{N_{\text{TSI}}} \left[\sum_{p=1}^{N_{\text{P}}} W_p \left(\left(\frac{1}{N_{\text{SR}}} \sum_{w=1}^{N_{\text{SR}}} e_{ipz[w]} \right) - \bar{E}_i \left(D_p \right) \right)^2 \right] \tag{24}$$

where

$\bar{E}_i\left(D_p\right)$	is the mean sampling efficiency of the candidate sampler for test particle size p at influence variable value ς_i;
$e_{ipz[w]}$	is the experimentally determined efficiency value. The subscripts are for influence variable value ς_i, particle size p, sampler individual w (w=1 to N_{TSI}) and repeat z (z=1 to N_{SR});
N_{P}	is the number of test particle sizes;
N_{SR}	is the number of repeats per sampler individual tested;
N_{TSI}	is the number of different sampler individuals tested;
$s_{\text{CandSampl-ModelCalc}_{ia}}$	is the random uncertainty (of measurement) of the calculated sampled concentration, due to the uncertainty of the fitted model, for the a^{th} aerosol size distribution A at influence variable value ς_i;
$s_{\text{CandSampl-Variability}_{ia}}$	is the random uncertainty (of measurement) of the calculated sampled concentration, due to individual sampler variability, for the a^{th} aerosol size distribution A and influence variable value ς_i; and

[2]) See Bibliography, reference [4].

W_p is the weighted average of integration of aerosol size distribution A between two particle sizes.

For each influence variable value calculate the RMS over all the N_{SD} aerosol size distributions A

$$u_{\text{CandSampl-Variability}_i}{}^2 = \frac{1}{N_{\text{SD}}} \sum_{a=1}^{N_{\text{SD}}} \frac{s_{\text{CandSampl-Variability}_{ia}}{}^2}{C_{\text{std}}{}^2} = \\ = \frac{1}{N_{\text{SD}}} \sum_{a=1}^{N_{\text{SD}}} \left(\frac{s_{\text{CandSampl-Variability}_{ia}} \left(D_{\text{A}_a}, \sigma_{\text{A}_a}, \zeta_i \right)}{C_{\text{std}} \left(D_{\text{A}_a}, \sigma_{\text{A}_a} \right)} \right)^2 \tag{25}$$

where

C_{std} is the target sampled relative aerosol concentration, expressed as a fraction of the total airborne aerosol concentration, that would have been sampled using an ideal sampler with a sampling efficiency identical to the sampling convention for aerosol size distribution A;

N_{SD} is the number of size distributions A;

$s_{\text{CandSampl-Variability}_{ia}}$ is the random uncertainty (of measurement) of the calculated sampled concentration, due to individual sampler variability, for the a^{th} aerosol size distribution A and influence variable value ς_i; and

$u_{\text{CandSampl-Variability}_i}$ is the standard uncertainty (of measurement) of the sampled concentration (random errors) due to differences among candidate sampler individuals at influence variable value ς_i.

5.4.3.4.2 Test of whether the individual sampler variability is significant

If the individual sampler variability is not significantly larger than the uncertainty of the estimate of the sampled concentration, then all sampler individuals can be treated as identical. In order to evaluate this, calculate

$$F_{\text{CandSamplVar}_i} = \frac{\frac{1}{N_{\text{SD}}} \sum_{a=1}^{N_{\text{SD}}} s_{\text{CandSampl-Variability}_{\text{ia}}}{}^2 \left(D_{\text{A}_a}, \sigma_{\text{A}_a}, \zeta_i \right)}{\frac{1}{N_{\text{SD}}} \sum_{a=1}^{N_{\text{SD}}} s_{\text{CandSampl-ModelCalc}_{\text{ia}}}{}^2 \left(D_{\text{A}_a}, \sigma_{\text{A}_a}, \zeta_i \right)} \tag{26}$$

where

$F_{\text{CandSamplVar}_i}$ is the test variable to check whether the individual sampler variability exceeds that of the uncertainty of the calculated concentrations, for influence variable value ς_i;

N_{SD} is the number of size distributions A;

$s_{\text{CandSampl-ModelCalc}_{ia}}$ is the random uncertainty (of measurement) of the calculated sampled concentration, due to the uncertainty of the fitted model, for the a^{th} aerosol size distribution A at influence variable value ς_i; and

$s_{\text{CandSampl-Variability}_{ia}}$ is the random uncertainty (of measurement) of the calculated sampled concentration, due to individual sampler variability, for the a^{th} aerosol size distribution A and influence variable value ς_i.

$F_{\text{CandSampVar}_i}$ has an F-distribution with approximately $\left(N_{\text{TSI}} - 1, N_{\text{TSI}} N_{\text{P}} N_{\text{SR}}\right)$ degrees of freedom, and thus the individual sampler variability is significant at the 95 % level if $F_{\text{CandSamplVar}_i} > F_{0.95}\left(N_{\text{TSI}} - 1, N_{\text{TSI}} N_{\text{P}} N_{\text{SR}}\right)$. If $F_{\text{CandSampVar}_i}$ is insignificant, then put $u_{\text{CandSampl-Variability}_i} \equiv 0$.

5.5 Analysis of efficiency data based on monodisperse or polydisperse test aerosols using the curve-fitting method

5.5.1 Statistical model of the sampling efficiency data

If needed a transformation Ω is applied to the measured efficiency values $e_{ips[r]}$ in order to substantially linearize the (transformed) efficiency curve. Suppose that a linear (or non-linear) combination of a small number N_K of functions $f_k\left(\Xi\right)$ can describe the transformed sampling efficiency, $\Omega\left(e_{ips[r]}\right)$, adequately, where Ξ is a transformation of the test particle size, D_p.

NOTE In many cases the simple functions $f_k\left(\Xi\right) = \Xi^{(k-1)}$ have been found to be useful.

Transformations of the efficiency values, $e = e_{ips[r]}$, which have often have been found to be useful are

$$\Omega = \begin{cases} e \\ \ln\left(e\right) \\ \ln\left(\dfrac{1-e}{e}\right) \\ \Phi^{-1}\left(1-e\right) \end{cases} \tag{27}$$

where

e	is the measured efficiency values;
Φ^{-1}	is the inverse of the normal distribution function; and
Ω	is the selected transformation of the efficiency values.

In most cases the particle size, $D = D_p$, is either left untransformed, or a simple logarithmic transformation is used

$$\Xi = \begin{cases} D \\ \ln\left(D\right) \end{cases} \tag{28}$$

where

D	is the measured particle size; and
Ξ	is the selected transformation of the diameters.

The combination of functions $f_k\left(\Xi\right)$ can be obtained, for example, by non-linear least-squares regression. For each candidate sampler individual *s* at influence variable value *i*, regression of that sampler individual's Ω-transformed efficiency values $e_{ips[r]}$ determines the parameter estimates θ_{isk} of regression coefficients in the model

$$\Omega\left(e_{ips[r]}\right) = \begin{cases} \sum_{k=1}^{N_K} \theta_{isk}\, f_k(\Xi_p) + \varepsilon_{ips[r]} & \text{linear combination} \\ \prod_{k=1}^{N_K} \theta_{isk}\, f_k(\Xi_p) + \varepsilon_{ips[r]} & \text{example of non - linear combination} \end{cases} \tag{29}$$

where

$f_k(\Xi_p)$	are the functions (of the transformed diameter, Ξ) used to build the regression model of the efficiency curve;
N_K	is the number of regression coefficients (functions) in the model;
$\varepsilon_{ips[r]}$	is the random experimental error at particle size p, repeat r and candidate sampler s at influence variable value ς_i;
θ_{isk}	is the regression coefficient number k sampler individual s at influence variable value ς_i; and
$\Omega\left(e_{ips[r]}\right)$	is the transformation of measured efficiency data at particle size p, repeat r and candidate sampler s at influence variable value ς_i.

The random experimental errors $\varepsilon_{ips[r]}$ are presumed to be normally distributed with zero mean, and to be the same at all particle diameters. (If they are not, the regression can be carried out by weighted least squares.) The efficiency curve for candidate sampler individual s at influence variable value i is then estimated as the inverse of the Ω function, Ω^{-1}

$${}^{\text{est}}E_{is}(D) = \begin{cases} \Omega^{-1}\left(\sum_{k=1}^{N_K} \theta_{isk}\, f_k\left(\Xi(D)\right)\right) \\ \Omega^{-1}\left(\prod_{k=1}^{N_K} \theta_{isk} f_k\left(\Xi(D)\right)\right) \end{cases} \tag{30}$$

where

${}^{\text{est}}E_{is}(D)$	is the fitted sampling efficiency curve of the candidate sampler individual s at influence variable value ς_i;
$f_k\left(\Xi(D)\right)$	are the functions (of the transformed diameter, Ξ) used to build the regression model of the efficiency curve;
N_K	is the number of regression coefficients (functions) in the model;
θ_{isk}	is the regression coefficient number k sampler individual s at influence variable value ς_i; and
Ω^{-1}	is the inverse of the transformation of estimated efficiency data at particle size p, repeat r and candidate sampler s at influence variable value ς_i.

5.5.2 Estimation of mean sampled concentration

For each candidate sampler individual s at influence variable value i the sampled relative concentration (*i.e.* expressed as a fraction of the total airborne concentration), C_{is}, is calculated as

$$C_{is} = C_{is}\left(D_\mathrm{A}, \sigma_\mathrm{A}\right) = \int_{D_\mathrm{min}}^{D_\mathrm{max}} {}^\mathrm{est}E_{is}(D)\, A(D_\mathrm{A}, \sigma_\mathrm{A}, D)\,\mathrm{d}D = \\ = \begin{cases} \int_{D_\mathrm{min}}^{D_\mathrm{max}} \Omega^{-1}\left(\sum_{k=1}^{N_\mathrm{K}} \theta_{isk}\, f_k\left(\Xi\left(D\right)\right)\right) A(D_\mathrm{A}, \sigma_\mathrm{A}, D)\,\mathrm{d}D \\ \int_{D_\mathrm{min}}^{D_\mathrm{max}} \Omega^{-1}\left(\prod_{k=1}^{N_\mathrm{K}} \theta_{isk} f_k\left(\Xi\left(D\right)\right)\right) A(D_\mathrm{A}, \sigma_\mathrm{A}, D)\,\mathrm{d}D \end{cases} \tag{31}$$

where

$A(D_\mathrm{A}, \sigma_\mathrm{A}, D)$	is the relative lognormal aerosol size distribution, with mass median aerodynamic diameter D_A and geometric standard deviation σ_A;
C_{is}	is the sampled relative aerosol concentration, calculated to be obtained when using the candidate sampler individual s, for aerosol size distribution A at influence variable value ς_i;
D_A	is the mass median aerodynamic diameter a of lognormal aerosol size distribution A;
D_max	in the case of a sampler for the inhalable fraction $D_\mathrm{max} = D_{N_\mathrm{P}}$, otherwise D_max is determined from the particle size which make integrand $A\left(D_\mathrm{A}, \sigma_\mathrm{A}, D\right)\, {}^\mathrm{est}E_{is}(D)$ equal to $0{,}5 \times 10^{-3}$;
D_min	this diameter is determined from the particle size which make integrand $A\left(D_\mathrm{A}, \sigma_\mathrm{A}, D\right) {}^\mathrm{est}E_{is}(D)$ equal to $0{,}5 \times 10^{-3}$;
${}^\mathrm{est}E_{is}(D)$	is the fitted sampling efficiency curve of the candidate sampler individual s at influence variable value ς_i;
$f_k\left(\Xi\left(D\right)\right)$	are the functions (of the transformed diameter $\Xi\left(D\right)$) used to build the regression model of the efficiency curve;
N_K	is the number of regression coefficients (functions) in the model;
θ_{isk}	is the regression coefficient number k sampler individual s at influence variable value ς_i;
σ_A	is the geometric standard deviation a of lognormal aerosol size distribution A; and
Ω^{-1}	is the inverse of the transformation of efficiency data at particle size p, repeat r and candidate sampler s at influence variable value ς_i.

By substitution of C_{is} into Formula (3) in EN 13205-2 the average concentration of the N_S candidate sampler individuals at influence variable value i, $\overline{C}_i$ is calculated.

When the inlet efficiency and penetration are independently measured by two separate experiments, the total sampling efficiency is the product of two functions, the inlet efficiency and the separation efficiency, each of which can have different transformations and different sets of functions, f_k. Formula (32) presents how this will look for the case of a linear combination of functions f_k for both the inlet and the separation stage.

$$
{}^{\text{est}}E_{is}^{\text{tot}}(D) = {}^{\text{est}}E_{is}^{\text{inlet}}(D)\,{}^{\text{est}}E_{is}^{\text{pen}}(D) = \\
= \Omega_{\text{inlet}}^{-1}\left(\sum_{k=1}^{N_{\text{K}}^{\text{inlet}}} \theta_{isk}^{\text{inlet}}\, f_k^{\text{inlet}}\left(\Xi^{\text{inlet}}(D)\right)\right)\Omega_{\text{pen}}^{-1}\left(\sum_{j=1}^{N_{\text{K}}^{\text{pen}}} \theta_{isj}^{\text{pen}}\, f_j^{\text{pen}}\left(\Xi^{\text{pen}}(D)\right)\right) \tag{32}
$$

where

D	is the aerodynamic diameter;
${}^{\text{est}}E_{is}^{\text{inlet}}(D)$	is the fitted sampling efficiency curve (of the inlet stage) of the candidate sampler individual s at influence variable value ς_i;
${}^{\text{est}}E_{is}^{\text{pen}}(D)$	is the fitted sampling efficiency curve (of the penetration stage) of the candidate sampler individual s at influence variable value ς_i;
${}^{\text{est}}E_{is}^{\text{tot}}(D)$	is the fitted sampling efficiency curve (of the combined inlet and penetration stages) of the candidate sampler individual s at influence variable value ς_i;
$f_k^{\text{inlet}}\left(\Xi^{\text{inlet}}(D)\right)$	are the functions (of Ξ) used to build the regression model of the efficiency curve of the inlet stage;
$f_k^{\text{pen}}\left(\Xi^{\text{pen}}(D)\right)$	are the functions (of Ξ) used to build the regression model of the penetration curve of the separation stage;
$N_{\text{K}}^{\text{inlet}}$	is the number of regression coefficients in the model (inlet stage) for the candidate sampler;
$N_{\text{K}}^{\text{pen}}$	is the number of regression coefficients in the model (penetration stage) for the candidate sampler;
$\theta_{isk}^{\text{inlet}}$	is the regression coefficient number k for model of inlet stage efficiency for candidate sampler individual s at influence variable value ς_i;
$\theta_{isj}^{\text{pen}}$	is the regression coefficient number k for model of penetration through the separation stage for candidate sampler individual s at influence variable value ς_i;
$\Omega_{\text{inlet}}^{-1}\left(\sum_{k=1}^{N_{\text{K}}^{\text{inlet}}} \theta_{isk}^{\text{inlet}}\, f_k^{\text{inlet}}\left(\Xi^{\text{inlet}}(D)\right)\right)$	is the inverse Ω-transformation of regression model of the Ω-transformed estimated efficiency curve for the inlet stage; and
$\Omega_{\text{pen}}^{-1}\left(\sum_{j=1}^{N_{\text{K}}^{\text{pen}}} \theta_{isj}^{\text{pen}}\, f_j^{\text{pen}}\left(\Xi^{\text{pen}}(D)\right)\right)$	is the inverse Ω-transformation of regression model of the Ω-transformed estimated efficiency curve for the penetration stage.

5.5.3 Estimation of uncertainty (of measurement) components

5.5.3.1 General

Three uncertainty (of measurement) components are estimated: the uncertainty of the calibration of the sampler test system, the uncertainty in the estimate of the sampled concentration, and the individual sampler variability.

5.5.3.2 Calibration of sampler test system

5.5.3.2.1 General

This uncertainty (of measurement) component has several sources depending on how the sizes of the test particles are determined. It is calculated as the effect of the uncertainty of the test particles on the calculated concentration.

5.5.3.2.2 Monodisperse test aerosols

When the test is based on N_P monodisperse test aerosols, the RMS test particle size *relative* uncertainty, s_D [-], is calculated according to Formula (9).

5.5.3.2.3 Polydisperse test aerosols

5.5.3.2.3.1 General

When the test is based on the calibration of a combined particle counter and sizer, using N_C calibration particles (of size D_c), the uncertainty component due to the calibration has two sources:

1) the (inherent) uncertainty of the calibration particles, relative standard deviation s_{D_c}, and

2) the residual uncertainty of the calibration of the particle counter/sizer.

5.5.3.2.3.2 Spline as calibration function

The use of a spline has the advantage that the curve will pass through the geometric mean of the particle counter size response values corresponding to all calibration particle sizes. However, in order to obtain a curve with the intended shape, (smooth without any humps) one usually has to slightly adjust the nominal particle sizes (with the *relative* amount δ_{D_c}). The RMS test particle size uncertainty, s_D, is calculated as

$$s_\mathrm{D}{}^2 = \frac{1}{N_\mathrm{C}} \sum_{c=1}^{N_\mathrm{C}} \left(s_{\mathrm{D}_c}{}^2 + \delta_{\mathrm{D}_c}{}^2 \right) \quad (33)$$

where

N_C is the number of calibration particle sizes;

s_D is the (relative) RMS test particle size uncertainty;

s_{D_c} is the relative standard deviation of the (inherent) uncertainty of the calibration particles; and

δ_{D_c} is the relative amount with which the nominal particle size was adjusted in order to obtain a curve with the intended shape.

5.5.3.2.3.3 Regression curve as calibration function

A regression curve for the calibration of the geometric mean of the particle counter size response (per calibration particle size, D_c) as a function of the N_C different calibration particle sizes, is presumed,

$$y = \sum_{q=1}^{N_\mathrm{CR}} b_q \, D^{(q-1)} \quad (34)$$

where

D	is the particle aerodynamic diameter;
N_{CR}	is the number regression coefficients for calibration of the particle counter/sizer (or similar);
y	is the particle counter size response [dimension depends on particle counter]; and
b_q	(subscript q=1 to N_{CR}) are the regression coefficients of the model of the calibration function.

The residual standard deviation of the model of the calibration function is termed $s_{\text{CalibrRes}}$ and its dimension depends on particle counter.

NOTE Instead of the variables y and D any transformations of these can be used, and consequently Formula (34) and its derivative in Formula (35) will need to be slightly modified.

A simplified uncertainty for the particle sizes estimated by the particle counter is calculated based only on the residual standard deviation and the slope of the calibration function. The RMS test particle size uncertainty, s_{D}, is then calculated as

$$\begin{cases} s_{\text{D}}^{\ 2} = \dfrac{1}{N_{\text{C}}} \displaystyle\sum_{c=1}^{N_{\text{C}}} \left(s_{D_c}^{\ 2} + \left[\dfrac{1}{D_c} \dfrac{s_{\text{CalibrRes}}}{\left. \dfrac{dy}{dD} \right|_{D_c}} \right]^2 \right) \\ \left. \dfrac{dy}{dD} \right|_{D_c} = \displaystyle\sum_{q=2}^{N_{\text{CR}}} (q-1) b_q D_c^{\ (q-2)} \end{cases} \quad (35)$$

where

D_c	is the calibration particle size c;
N_{C}	is the number of test particle sizes;
N_{CR}	is the number regression coefficients for calibration of the particle counter/sizer (or similar);
s_{D}	is the (relative) RMS test particle size uncertainty;
s_{D_c}	is the relative standard deviation of the (inherent) uncertainty of the calibration particles;
$s_{\text{CalibrRes}}$	is the residual standard deviation of the model of the calibration function;
$\left. \dfrac{dy}{dD} \right\|_{D_c}$	is the derivate of the calibration function at calibration particle size D_c; and
b_q	are the regression coefficients of the model of the calibration function.

5.5.3.2.4 Simulation of particle sizes at which the sampling efficiency could have been determined

Simulate $N_{\text{Sim}} = 1000$ sets of N_{P} test particle sizes, $D_{t,p}$ (subscript t=1 to N_{Sim}), based on the RMS uncertainty of the size of the calibration particles (and for polydisperse test aerosols also the size response of the particle counter), s_{D}, using a random number generator to generate a set of $N_{\mathrm{Sim}}\,N_{\mathrm{P}}$ values of $z_{t,p}$ which have a normal distribution with an estimation value of zero and a standard deviation of unity. $D_{t,p}$ is simulated by using the formula

$$D_{t,p} = (1 + z_{t,p} s_{\mathrm{D}})\, D_p \tag{36}$$

where

D_p	is the aerodynamic diameter of the test particles p (p=1 to N_{P});
$D_{t,p}$	is the simulated test particle size;
$z_{t,p}$	is the random number with a normal distribution, with expectation value equal to zero and standard deviation equal to unity; and
s_{D}	is the RMS value of all relative uncertainties of the actual sizes of the calibration particles (see Formula (33) or (35)).

5.5.3.2.5 Calculation of measured concentrations for simulated test particle sizes

For each of the N_{Sim} simulated sets of particle sizes, determine new (simulated) efficiency curves for all candidate sampler individuals (subscript s) at all influence variable values (subscript i)

$${}^{\mathrm{est}}E_{is,t}(D) = \Omega^{-1}\left(\sum_{k=1}^{N_{\mathrm{K}}} \theta_{isk,t}\, f_k\big(\Xi(D)\big)\right) \tag{37}$$

where

${}^{\mathrm{est}}E_{is,t}(D)$	is the fitted sampling efficiency curve of the candidate sampler individual s at influence variable value ς_i using simulated set t of N_{P} particle sizes;
$f_k\big(\Xi(D)\big)$	are the functions (of the transformed diameter $\Xi(D)$) used to build the regression model of the efficiency curve;
N_{K}	is the number of regression coefficients (functions) in the model;
$\theta_{isk,t}$	is the regression coefficient number k sampler individual s at influence variable value ς_i using simulated set t of N_{P} particle sizes; and
$\Omega^{-1}\left(\sum_{k=1}^{N_{\mathrm{K}}} \theta_{isk,t}\, f_k\big(\Xi(D)\big)\right)$	is the inverse of the transformation of estimated efficiency data at particle size p, repeat r and candidate sampler s at influence variable value ς_i using simulated set t of N_{P} particle sizes.

NOTE In these calculations the efficiency at $D_{t,p}$, ${}^{\mathrm{est}}E_{is,t}(D_{t,p})$, is the originally measured efficiency at particle size D_p, $E_{is}(D_p)$, i.e. ${}^{\mathrm{est}}E_{is,t}(D_{t,p}) = E_{is}(D_p)$. It is the particle sizes at the measured efficiency that is varied by simulation.

For each candidate sampler individual s at influence variable value i, the sampled concentration (expressed as a fraction of the total airborne concentration) is calculated for all simulated sets of particle diameters according to Formula (38) (similar to Formula (31)).

$$C_{is,t} = C_{is,t}\left(D_{\mathrm{A}},\sigma_{\mathrm{A}}\right) = \int_{D_{\min}}^{D_{\max}} {}^{\mathrm{est}}E_{is,t}(D)\, A(D_{\mathrm{A}},\sigma_{\mathrm{A}},D)\,\mathrm{d}D = \\ = \int_{D_{\min}}^{D_{\max}} \Omega^{-1}\left(\sum_{k=1}^{N_{\mathrm{K}}}\theta_{isk,t}\, f_k\left(\Xi\left(D\right)\right)\right) A(D_{\mathrm{A}},\sigma_{\mathrm{A}},D)\,\mathrm{d}D \qquad (38)$$

where

$A(D_{\mathrm{A}},\sigma_{\mathrm{A}},D)$	is the relative lognormal aerosol size distribution, with mass median aerodynamic diameter D_{A} and geometric standard deviation σ_{A};
$C_{is,t}$	is the sampled relative aerosol concentration, calculated to be obtained when using the candidate sampler individual s, for aerosol size distribution A at influence variable value ς_i, using simulated set t of test particle sizes;
D_{A}	is the mass median aerodynamic diameter of a lognormal aerosol size distribution A;
$D_{\max}$	in the case of a sampler for the inhalable fraction $D_{\max} = D_{N_{\mathrm{P}}}$, otherwise $D_{\max}$ is determined from the particle size which make integrand $A\left(D_{\mathrm{A}},\sigma_{\mathrm{A}},D\right){}^{\mathrm{est}}E_{is,t}(D)$ equal to $0{,}5\times10^{-3}$;
$D_{\min}$	this diameter is determined from the particle size which make integrand $A\left(D_{\mathrm{A}},\sigma_{\mathrm{A}},D\right){}^{\mathrm{est}}E_{is,t}(D)$ equal to $0{,}5\times10^{-3}$;
${}^{\mathrm{est}}E_{is,t}(D)$	is the fitted sampling efficiency curve of the candidate sampler individual s at influence variable value ς_i using simulated set t of N_{P} particle sizes;
$f_k\left(\Xi\left(D\right)\right)$	are the functions (of the transformed diameter $\Xi\left(D\right)$) used to build the regression model of the efficiency curve;
N_{K}	is the number of regression coefficients (functions) in the model;
$\theta_{isk,t}$	is the regression coefficient number k sampler individual s at influence variable value ς_i using simulated set t of N_{P} particle sizes;
σ_{A}	is the geometric standard deviation of a lognormal aerosol size distribution A; and
Ω^{-1}	is the inverse of the transformation of efficiency data at particle size p, repeat r and candidate sampler s at influence variable value ς_i using simulated set t of N_{P} particle sizes.

For each of the N_{SD} aerosol size distributions A and all N_{IV} influence variable values, calculate the RMS of the mean sampled concentration for all N_{Sim} simulated sets of test particle sizes, according to the formula

$$s_{\mathrm{CandSampl\text{-}Calibr}_{ia}}{}^{2} = \frac{1}{N_{\mathrm{S}}}\sum_{s=1}^{N_{\mathrm{S}}}\left(\frac{1}{N_{\mathrm{Sim}}}\sum_{t=1}^{N_{\mathrm{Sim}}}\left(C_{is,t}-C_{is}\right)^{2}\right) \\ = \frac{1}{N_{\mathrm{S}}}\sum_{s=1}^{N_{\mathrm{S}}}\left(\frac{1}{N_{\mathrm{Sim}}}\sum_{t=1}^{N_{\mathrm{Sim}}}\left(C_{is,t}\left(D_{\mathrm{A}_a},\sigma_{\mathrm{A}_a}\right)-C_{is}\left(D_{\mathrm{A}_a},\sigma_{\mathrm{A}_a}\right)\right)^{2}\right) \qquad (39)$$

where

C_{is}	is the sampled relative aerosol concentration, calculated to be obtained when using the candidate sampler individual s, for aerosol size distribution A at influence variable value ς_i;
$C_{is,t}$	is the sampled relative aerosol concentration, calculated to be obtained when using the candidate sampler individual s, for aerosol size distribution A at influence variable value ς_i, using simulated set t of test particle sizes;
$D_{\mathrm{A_a}}$	is the mass median aerodynamic diameter a of lognormal aerosol size distribution A;
N_{S}	is the number of candidate sampler individuals;
N_{Sim}	is the number of simulated sets of N_{P} test particle sizes;
$s_{\mathrm{CandSampl\text{-}Calibr}_{ia}}$	is the combined non-random and random uncertainty (of measurement) of the calculated sampled concentration, due to the calibration uncertainty of the experiment, for aerosol size distribution A at influence variable value ς_i; and
$\sigma_{\mathrm{A_a}}$	is the geometric standard deviation *a* of lognormal aerosol size distribution A.

For each influence variable value calculate the RMS over all the N_{SD} aerosol size distributions A

$$u_{\mathrm{CandSampl\text{-}Calibr}_i}{}^2 = \frac{1}{N_{\mathrm{SD}}} \sum_{a=1}^{N_{\mathrm{SD}}} \frac{s_{\mathrm{CandSampl\text{-}Calibr}_{ia}}{}^2}{C_{\mathrm{std}}{}^2} = \frac{1}{N_{\mathrm{SD}}} \sum_{a=1}^{N_{\mathrm{SD}}} \left(\frac{s_{\mathrm{CandSampl\text{-}Calibr}}\left(D_{\mathrm{A}_a}, \sigma_{\mathrm{A}_a}, \zeta_i\right)}{C_{\mathrm{std}}\left(D_{\mathrm{A}_a}, \sigma_{\mathrm{A}_a}\right)} \right)^2 \quad (40)$$

where

C_{std}	is the target sampled relative aerosol concentration, expressed as a fraction of the total airborne aerosol concentration, that would have been sampled using an ideal sampler with a sampling efficiency identical to the sampling convention for aerosol size distribution A;
$D_{\mathrm{A_a}}$	is the mass median aerodynamic diameter a of lognormal aerosol size distribution A;
N_{SD}	is the number of aerosol size distributions A;
$s_{\mathrm{CandSampl\text{-}Calibr}_{ia}}$	is the combined non-random and random uncertainty (of measurement) of the calculated sampled concentration, due to the calibration uncertainty of the experiment, for aerosol size distribution A at influence variable value ς_i;
$u_{\mathrm{CandSampl\text{-}Calibr}_i}$	is the standard uncertainty (of measurement) (non-random and random errors) of the calculated sampled concentration, due to the calibration uncertainty of the experiment, at influence variable value ς_i;
$\sigma_{\mathrm{A_a}}$	is the geometric standard deviation *a* of lognormal aerosol size distribution A.

5.5.3.3 Estimation of sampled concentration

5.5.3.3.1 General

This uncertainty (of measurement) component has three sources:

1) the random “pure error” uncertainty caused by the experiment;

2) a potential non-random “lack of fit” uncertainty which occurs if the regression curve for the sampling efficiency significantly deviates from the average of the (Ω-transformed) measured sampling efficiency at each test particle size; and

3) the uncertainty due to any corrections of the measured sampling efficiencies due to variation of the total airborne aerosol concentration between repeats.

The first two are calculated based on the uncertainty (co-variance matrix) of the N_{K} estimated regression coefficients of the N_{S} models for the candidate sampler individuals. The third is calculated from the uncertainty of the correction factors.

5.5.3.3.2 Effect of possible “lack of fit” of regression models

For each of the N_S regression models for the candidate sampler individuals at influence variable value *i*, check whether the model has “lack of fit” (see Draper and Smith[6]). In the general case the regression model gives a residual standard deviation with $\nu_{reg_{is}}$ degrees of freedom.

$$s_{\mathrm{res}_{is}}{}^{2} = \frac{SS_{r\mathrm{es}_{is}}}{\nu_{\mathrm{res}_{is}}} \qquad (41)$$

where

$SS_{\mathrm{res}_{is}}$ is the residual sum of squares of the Ω-transformed measured efficiency values;

$s_{\mathrm{res}_{is}}$ is the residual standard deviation; and

$\nu_{\mathrm{res}_{is}}$ is the number of degrees of freedom of the regression.

In the case where the number of repeats, N_{Rep}, is identical for all N_{P} particle sizes, the test parameter for “lack of fit”, $F_{\mathrm{LoF}_{is}}$, is calculated according to Formula (42). For other cases the formulae shall be slightly modified accordingly.

$$\begin{cases} F_{\mathrm{LoF}_{is}} = \dfrac{{s_{\mathrm{LoF}_{is}}}^2}{{s_{\mathrm{pe}_{is}}}^2} \\ {s_{\mathrm{pe}_{is}}}^2 = \dfrac{SS_{\mathrm{pe}_{is}}}{\nu_{\mathrm{pe}_{is}}} \\ {s_{\mathrm{LoF}_{is}}}^2 = \dfrac{SS_{\mathrm{res}_{is}} - SS_{\mathrm{pe}_{is}}}{\nu_{\mathrm{res}_{is}} - \nu_{\mathrm{pe}_{is}}} \\ SS_{\mathrm{pe}_{is}} = \sum_{p=1}^{N_\mathrm{P}} \sum_{r=1}^{N_\mathrm{Rep}} \left(\Omega\left(e_{ips[r]}\right) - \dfrac{1}{N_\mathrm{Rep}} \sum_{r=1}^{N_\mathrm{Rep}} \Omega\left(e_{ips[r]}\right) \right)^2 \\ \nu_{\mathrm{pe}_{is}} = N_\mathrm{P} \left(N_\mathrm{Rep} - 1\right) \\ \nu_{reg_{is}} = N_\mathrm{P}\, N_\mathrm{Rep} - N_\mathrm{K} \end{cases} \quad (42)$$

where

$F_{\mathrm{LoF}_{is}}$	is the test variable for “lack of fit” for the regression model ${}^{\mathrm{est}}E_{is}$ for the sampling efficiency of candidate sampler individual s and influence variable value ς_i;
N_K	is the number of regression coefficients in the model for the candidate sampler;
N_P	is the number of test particle sizes;
N_Rep	is the number of repeats at particle size p for candidate sampler individual s at influence variable value ς_i;
$SS_{\mathrm{pe}_{is}}$	is the “pure error” sum of squares of the Ω-transformed experimental data of candidate sampler individual s at influence variable value ς_i;
$SS_{\mathrm{res}_{is}}$	is the residual sum of squares of the regression model for the Ω-transformed sampling efficiency of candidate sampler individual s at influence variable value ς_i;
$s_{\mathrm{LoF}_{is}}$	is the standard deviation pertaining to the possible lack of fit of the regression model for the Ω-transformed sampling efficiency of candidate sampler individual s at influence variable value ς_i;
$s_{\mathrm{pe}_{is}}$	is the “pure error” standard deviation of the Ω-transformed experimental data of candidate sampler individual s at influence variable value ς_i;
$\nu_{\mathrm{pe}_{is}}$	is the number of degrees of freedom for the “pure error” standard deviation of the experimental data of candidate sampler individual s at influence variable value ς_i;
$\nu_{\mathrm{res}_{is}}$	is the number of degrees of freedom for the residual standard deviation of the regression model for the Ω-transformed sampling efficiency of candidate sampler individual s at influence variable value ς_i; and
$\Omega\left(e_{ips[r]}\right)$	is the transformation of the measured efficiency data.

$F_{\text{LoF}_{is}}$ has an F-distribution with $\left(\nu_{\text{res}_{is}} - \nu_{\text{pe}_{is}}, \nu_{\text{pe}_{is}}\right)$ degrees of freedom, and the model has significant "lack of fit" at the 95 % level if $F_{\text{LoF}_{is}} > F_{0.95}\left(\nu_{\text{res}_{is}} - \nu_{\text{pe}_{is}}, \nu_{\text{pe}_{is}}\right)$, where $F_{0.95}\left(\nu_{\text{res}_{is}} - \nu_{\text{pe}_{is}}, \nu_{\text{pe}_{is}}\right)$ is the 95-percentile of the *F* distribution with $\left(\nu_{\text{res}_{is}} - \nu_{\text{pe}_{is}}, \nu_{\text{pe}_{is}}\right)$ degrees of freedom. If so, one usually finds that $s_{\text{LoF}_{is}} > s_{\text{res}_{is}}$.

If "lack of fit" is significant for any of the candidate sampler individuals at any influence variable value ς_i, calculate the "lack of fit" uncertainty inflation factor for all candidate sampler individuals at all influence variable values, $G_{\text{LoF}_{is}}$, and the "pure error" uncertainty inflation factor for all candidate sampler individuals at all influence variable values, $G_{\text{pe}_{is}}$,

$$\begin{cases} G_{\text{LoF}_{is}} \begin{cases} = \dfrac{{s_{\text{LoF}_{is}}}^2}{{s_{\text{res}_{is}}}^2} = \dfrac{1 - SS_{\text{pe}_{is}} \big/ SS_{\text{res}_{is}}}{1 - \nu_{\text{pe}_{is}} \big/ \nu_{\text{res}_{is}}} & F_{\text{LoF}_{is}} \text{ significant} \\ \equiv 0 & F_{\text{LoF}_{is}} \text{ non-significant} \end{cases} \\ G_{\text{pe}_{is}} \begin{cases} = G_{\text{LoF}_{is}} \big/ F_{\text{LoF}_{is}} & F_{\text{LoF}_{is}} \text{ significant} \\ \equiv 1 & F_{\text{LoF}_{is}} \text{ non-significant} \end{cases} \end{cases} \quad (43)$$

where

$F_{\text{LoF}_{is}}$	is the test variable for "lack of fit" for the regression model ${}^{\text{est}}E_{is}$ for the sampling efficiency of candidate sampler individual s and influence variable value ς_i;
$G_{\text{LoF}_{is}}$	is the uncertainty inflation factor for the "lack of fit" uncertainty of the regression model for candidate sampler individual s and influence variable value ς_i;
$G_{\text{pe}_{is}}$	is the uncertainty inflation factor for the "pure error" uncertainty of the regression model for candidate sampler individual s and influence variable value ς_i;
$SS_{\text{pe}_{is}}$	is the "pure error" sum of squares of the Ω-transformed experimental data of candidate sampler individual s at influence variable value ς_i;
$SS_{\text{res}_{is}}$	is the residual sum of squares of the regression model for the Ω-transformed sampling efficiency of candidate sampler individual s at influence variable value ς_i;
$s_{\text{LoF}_{is}}$	is the standard deviation pertaining to the possible lack of fit of the regression model for the Ω-transformed sampling efficiency of candidate sampler individual s at influence variable value ς_i;
$s_{\text{pe}_{is}}$	is the "pure error" standard deviation of the Ω-transformed experimental data of candidate sampler individual s at influence variable value ς_i;
$\nu_{\text{pe}_{is}}$	is the number of degrees of freedom for the "pure error" standard deviation of the experimental data of candidate sampler individual s at influence variable value ς_i; and
$\nu_{\text{res}_{is}}$	is the number of degrees of freedom for the residual standard deviation of the regression model for the Ω-transformed sampling efficiency of candidate sampler

individual s at influence variable value ς_i.

Correct the total uncertainty of the calculated concentration based on the regression model (in 5.5.3.3.2), with $G_{\text{LoF}_{is}}$ for the "lack of fit" of the model and with $G_{\text{pe}_{is}}$ for the "pure error" of the model.

NOTE "Lack of fit" can occur for a model, either if the curvature of the model differs from that of the data, or if the average values for different particle sizes exhibit a very large residual error to whatever curve drawn through them.

5.5.3.3.3 Uncertainty of calculated concentration based upon regression model

For each candidate sampler individual at each influence variable value, the uncertainty of the calculated concentration is calculated by Gauss' formula for the propagation of errors, both for the "pure error" and for any possible "lack of fit". The "pure error" uncertainty and the "lack of fit" uncertainty terms are calculated from

$$\begin{cases} s_{\text{ModelCalc-pe}_{is}}{}^2 = s_{\text{ModelCalc-pe}_{is}}{}^2\left(D_{\text{A}_a}, \sigma_{\text{A}_a}, \zeta_i\right) = \\ \quad = G_{\text{pe}_{is}} \sum_{k=1}^{N_\text{K}} \sum_{j=1}^{N_\text{K}} \left(\frac{\partial C_{is}}{\partial \theta_{isk}}\right)\left(\frac{\partial C_{is}}{\partial \theta_{isj}}\right) \text{CoVar}\left[\theta_{isk}, \theta_{isj}\right] \\ s_{\text{ModelCalc-LoF}_{is}}{}^2 = s_{\text{ModelCalc-LoF}_{is}}{}^2\left(D_{\text{A}_a}, \sigma_{\text{A}_a}, \zeta_i\right) = \\ \quad = G_{LoF_{is}} \sum_{k=1}^{N_\text{K}} \sum_{j=1}^{N_\text{K}} \left(\frac{\partial C_{is}}{\partial \theta_{isk}}\right)\left(\frac{\partial C_{is}}{\partial \theta_{isj}}\right) \text{CoVar}\left[\theta_{isk}, \theta_{isj}\right] \end{cases} \quad (44)$$

where

C_{is}	is the sampled relative aerosol concentration, calculated to be obtained when using the candidate sampler individual s, for aerosol size distribution A at influence variable value ς_i;
$\text{CoVar}\left[\theta_{isk}, \theta_{isj}\right]$	is the covariance of the regression coefficients θ_{isk} and θ_{isj} for candidate sampler individual s, for aerosol size distribution A at influence variable value ς_i;
$G_{\text{LoF}_{is}}$	is the uncertainty inflation factor for the "lack of fit" uncertainty of the regression model for candidate sampler individual s and influence variable value ς_i;
$G_{\text{pe}_{is}}$	is the uncertainty inflation factor for the "pure error" uncertainty of the regression model for candidate sampler individual s and influence variable value ς_i;
N_K	is the number of regression coefficients (functions) in the model;
$s_{\text{ModelCalc-LoF}_{is}}$	is the random uncertainty (of measurement) of the calculated sampled concentration, due to the "lack of fit" of the model for candidate sampler individual s, for aerosol size distribution A at influence variable value ς_i;
$s_{\text{ModelCalc-pe}_{is}}$	is the random uncertainty (of measurement) of the calculated sampled concentration, due to the "pure error" of the model for candidate sampler individual s, for aerosol size distribution A at influence variable value ς_i; and
θ_{isk} and θ_{isj}	are the regression coefficients k and j for candidate sampler individual s, for aerosol size distribution A at influence variable value ς_i.

The derivatives are taken of the integral in Formula (31).

In most cases the derivatives have to be determined numerically.

NOTE For candidate sampler individuals at influence variable value i without significant "lack of fit", $s_{\text{ModelCalc-LoF}_{is}} = 0$ because $F_{\text{LoF}_{is}} \equiv 1$, and hence $G_{\text{LoF}_{is}} \equiv 0$.

When the inlet efficiency and the penetration are independently measured by two separate experiments (as described by Formula (32)) Formula (44) need to be modified. In this case the regression coefficients of the inlet and separation efficiency functions, $\theta_{isk}^{\text{inlet}}$ and $\theta_{isj}^{\text{pen}}$ have zero covariance, $\text{CoVar}\left[\theta_{isk}^{\text{inlet}}, \theta_{isj}^{\text{pen}}\right] \equiv 0$, and Formula (44) will be modified into

$$\begin{cases} {s_{\text{ModelCalc-pe}_{is}}}^2 = G_{\text{pe}_{is}}^{\text{inlet}} \sum_{k=1}^{N_{\text{K}}^{\text{inlet}}} \sum_{j=1}^{N_{\text{K}}^{\text{inlet}}} \left(\frac{\partial C_{is}}{\partial \theta_{isk}^{\text{inlet}}} \right) \left(\frac{\partial C_{is}}{\partial \theta_{isj}^{\text{inlet}}} \right) \text{CoVar}\left[\theta_{isk}^{\text{inlet}}, \theta_{isj}^{\text{inlet}}\right] + \\ \quad + G_{\text{pe}_{is}}^{\text{pen}} \sum_{k=1}^{N_{\text{K}}^{\text{pen}}} \sum_{j=1}^{N_{\text{K}}^{\text{pen}}} \left(\frac{\partial C_{is}}{\partial \theta_{isk}^{\text{pen}}} \right) \left(\frac{\partial C_{is}}{\partial \theta_{isj}^{\text{pen}}} \right) \text{CoVar}\left[\theta_{isk}^{\text{pen}}, \theta_{isj}^{\text{pen}}\right] \\ \\ {s_{\text{ModelCalc-LoF}_{is}}}^2 = G_{\text{LoF}_{is}}^{\text{inlet}} \sum_{k=1}^{N_{\text{K}}^{\text{inlet}}} \sum_{j=1}^{N_{\text{K}}^{\text{inlet}}} \left(\frac{\partial C_{is}}{\partial \theta_{isk}^{\text{inlet}}} \right) \left(\frac{\partial C_{is}}{\partial \theta_{isj}^{\text{inlet}}} \right) \text{CoVar}\left[\theta_{isk}^{\text{inlet}}, \theta_{isj}^{\text{inlet}}\right] + \\ \quad + G_{\text{LoF}_{is}}^{\text{pen}} \sum_{k=1}^{N_{\text{K}}^{\text{pen}}} \sum_{j=1}^{N_{\text{K}}^{\text{pen}}} \left(\frac{\partial C_{is}}{\partial \theta_{isk}^{\text{pen}}} \right) \left(\frac{\partial C_{is}}{\partial \theta_{isj}^{\text{pen}}} \right) \text{CoVar}\left[\theta_{isk}^{\text{pen}}, \theta_{isj}^{\text{pen}}\right] \end{cases} \tag{45}$$

where

C_{is}	is the sampled relative aerosol concentration, calculated to be obtained when using the candidate sampler individual s, for aerosol size distribution A at influence variable value ς_i;
$\text{CoVar}\left[\theta_{isk}^{\text{inlet}}, \theta_{isj}^{\text{inlet}}\right]$	is the covariance of the regression coefficients $\theta_{isk}^{\text{inlet}}$ and $\theta_{isj}^{\text{inlet}}$ describing the sampling efficiency of the inlet stage for candidate sampler individual s, for aerosol size distribution A at influence variable value ς_i;
$\text{CoVar}\left[\theta_{isk}^{\text{pen}}, \theta_{isj}^{\text{pen}}\right]$	is the covariance of the regression coefficients $\theta_{isk}^{\text{pen}}$ and $\theta_{isj}^{\text{pen}}$ describing the sampling efficiency of the inlet stage for candidate sampler individual s, for aerosol size distribution A at influence variable value ς_i;
$G_{\text{LoF}_{is}}^{\text{inlet}}$	is the uncertainty inflation factor for the "lack of fit" uncertainty of the regression model for the inlet stage for candidate sampler individual s and influence variable value ς_i;
$G_{\text{LoF}_{is}}^{\text{pen}}$	is the uncertainty inflation factor for the "lack of fit" uncertainty of the regression model for the penetration stage for candidate sampler individual s and influence variable value ς_i;
$G_{\text{pe}_{is}}^{\text{inlet}}$	is the uncertainty inflation factor for the "pure error" uncertainty of the regression model for the inlet stage for candidate sampler individual s and influence variable value ς_i;

$G_{\text{pe}_{is}}^{\text{pen}}$ is the uncertainty inflation factor for the "pure error" uncertainty of the regression model for the penetration stage for candidate sampler individual s and influence variable value ς_i;

$N_{\text{K}}^{\text{inlet}}$ is the number of regression coefficients (functions) in the model for the inlet stage;

$N_{\text{K}}^{\text{pen}}$ is the number of regression coefficients (functions) in the model for the penetration stage;

$s_{\text{ModelCalc-LoF}_{is}}$ is the random uncertainty (of measurement) of the calculated sampled concentration, due to the "lack of fit" of the model for candidate sampler individual s, for aerosol size distribution A at influence variable value ς_i;

$s_{\text{ModelCalc-pe}_{is}}$ is the random uncertainty (of measurement) of the calculated sampled concentration, due to the "pure error" of the model for candidate sampler individual s, for aerosol size distribution A at influence variable value ς_i;

$\theta_{isk}^{\text{inlet}}$ and $\theta_{isj}^{\text{inlet}}$ are the regression coefficients k and j, respectively, for the model of inlet stage efficiency for candidate sampler individual s at influence variable value ς_i; and

$\theta_{isk}^{\text{pen}}$ and $\theta_{isj}^{\text{pen}}$ are the regression coefficients k and j, respectively, for the model of the penetration through candidate sampler individual s at influence variable value ς_i.

5.5.3.3.4 Uncertainty of calculated concentration due to uncertainty of correction factors for variation in total airborne aerosol concentration

If it is known that the efficiency curve at small particle sizes (smaller than the diameters used for the determination of the sampling efficiency curve) will have the value e_0 (e.g. unity in the case of cyclones and impactors), and it is believed that the obtained difference from e_0 is due to variation in total airborne aerosol concentration the measured efficiency values per run r can be corrected by multiplication of the correction factor, $c_{\text{Ref}_{is[r]}}$. If the measured efficiency values at a small number N_{U} (e.g. 3) of small particle diameters D_u, with corresponding efficiency values $e_{ius[r]}$, then $c_{\text{Ref}_{is[r]}}$ can for example be calculated from

$$c_{\text{Ref}_{is[r]}} = \frac{1}{N_{\text{U}}} \sum_{u=1}^{N_{\text{U}}} \frac{e_0}{e_{ius[r]}} \tag{46}$$

where

$c_{\text{Ref}_{is[r]}}$ is the correction factor for the measured efficiency values for repeat r for candidate sampler individual s, at influence variable value ς_i;

e_0 is the known efficiency value for small particle sizes;

$e_{ius[r]}$ is the experimentally determined efficiency value at small particle size u for repeat r for candidate sampler individual s, at influence variable value ς_i; and

N_{U} is the number of small particle sizes at which the efficiency is known to be e_0.

The corresponding uncertainty of sampling efficiency curve for candidate sampler individual s at influence variable value ς_i, is independent of the size distribution sampled. It is calculated from

$$s_{\text{RefCorr}_{is}}{}^{2} = \frac{1}{N_{\text{Rep}}} \frac{1}{N_{\text{U}}} \sum_{r=1}^{N_{\text{Rep}}} \sum_{u=1}^{N_{\text{U}}} \left[c_{\text{Ref}_{is[r]}} e_{ius[r]} - e_0 \right]^2 \tag{47}$$

where

$c_{\text{Ref}_{is[r]}}$	is the correction factor for the measured efficiency values for repeat r for candidate sampler individual s, at influence variable value ς_i;
e_0	is the known efficiency value for small particle sizes;
$e_{ius[r]}$	is the experimentally determined efficiency value at small particle size u for repeat r for candidate sampler individual s, at influence variable value ς_i; and
N_{Rep}	is the number of repeats at particle size p for candidate sampler individual s at influence variable value ς_i;
N_{U}	is the number of small particle sizes at which the efficiency is known to be e_0; and
$s_{RefCorr_{is}}$	is the random uncertainty (of measurement) of the calculated sampled concentration, due to the correction of measured sampler efficiency values because of variations in e.g. time, for candidate sampler individual s, at influence variable value ς_i.

5.5.3.3.5 Uncertainty (of measurement) of calculated concentration

The uncertainty (of measurement) for this component is calculated as the RMS of the values of the models for the tested individual samplers and the correction factors

$$\begin{aligned} s_{\text{CandSampl-ModelCalc}_{ia}}{}^{2} &= \frac{1}{N_{\text{S}}} \sum_{s=1}^{N_{\text{S}}} \left[s_{\text{ModelCalc-pe}_{is}}{}^{2} + s_{\text{ModelCalc-LoF}_{is}}{}^{2} + s_{\text{RefCorr}_{is}}{}^{2} \right] = \\ &= \frac{1}{N_{\text{S}}} \sum_{s=1}^{N_{\text{S}}} s_{\text{ModelCalc-pe}_{is}}{}^{2} \left(D_{\text{A}_a}, \sigma_{\text{A}_a}, \zeta_i \right) + \\ &+ \frac{1}{N_{\text{S}}} \sum_{s=1}^{N_{\text{S}}} s_{\text{ModelCalc-LoF}_{is}}{}^{2} \left(D_{\text{A}_a}, \sigma_{\text{A}_a}, \zeta_i \right) + \\ &+ \frac{1}{N_{\text{S}}} \sum_{s=1}^{N_{\text{S}}} s_{\text{RefCorr}_{is}}{}^{2} \end{aligned} \tag{48}$$

where

D_{A_a}	is the mass median aerodynamic diameter a of lognormal aerosol size distribution A;
N_{S}	is the number of candidate sampler individuals;
$s_{\text{CandSampl-ModelCalc}_{ia}}$	is the random uncertainty (of measurement) of the calculated sampled concentration, due to the uncertainty of the fitted model, for the a^{th} aerosol size distribution A at influence variable value ς_i;
$s_{\text{ModelCalc-LoF}_{is}}$	is the random uncertainty (of measurement) of the calculated sampled concentration, due to the “lack of fit” of the model for candidate sampler individual s, for aerosol size distribution A at influence variable value ς_i;
$s_{\text{ModelCalc-pe}_{is}}$	is the random uncertainty (of measurement) of the calculated sampled concentration, due to the “pure error” of the model for candidate sampler

	individual s, for aerosol size distribution A at influence variable value ς_i;
$s_{RefCorr_{is}}$	is the random uncertainty (of measurement) of the calculated sampled concentration, due to the correction of measured sampler efficiency values because of variations in e.g. time, for candidate sampler individual s, at influence variable value ς_i; and
$\sigma_{\mathrm{A_a}}$	is the geometric standard deviation a of a lognormal aerosol size distribution A.

For each influence variable value calculate the RMS over all the N_{SD} aerosol size distributions A

$$u_{\mathrm{CandSampl\text{-}ModelCalc}_i}{}^2 = \frac{1}{N_{\mathrm{SD}}}\sum_{a=1}^{N_{\mathrm{SD}}} \frac{s_{\mathrm{CandSampl\text{-}ModelCalc}_{ia}}{}^2}{C_{\mathrm{std}}{}^2} = \frac{1}{N_{\mathrm{SD}}}\sum_{a=1}^{N_{\mathrm{SD}}} \left(\frac{s_{\mathrm{CandSampl\text{-}ModelCalc}_{ia}}\left(D_{\mathrm{A}_a}, \sigma_{\mathrm{A}_a}, \zeta_i\right)}{C_{\mathrm{std}}\left(D_{\mathrm{A}_a}, \sigma_{\mathrm{A}_a}\right)} \right)^2 \quad (49)$$

where

C_{std}	is the target sampled relative aerosol concentration, expressed as a fraction of the total airborne aerosol concentration, that would have been sampled using an ideal sampler with a sampling efficiency identical to the sampling convention for aerosol size distribution A;
$D_{\mathrm{A_a}}$	is the mass median aerodynamic diameter a of lognormal aerosol size distribution A;
N_{SD}	is the number of aerosol size distributions A according to EN 13205-2:2014, Table 2;
$s_{\mathrm{CandSampl\text{-}ModelCalc}_{ia}}$	is the random uncertainty (of measurement) of the calculated sampled concentration, due to the uncertainty of the fitted model, for the a^{th} aerosol size distribution A at influence variable value ς_i;
$u_{\mathrm{CandSampl\text{-}ModelCalc}_i}$	is the standard uncertainty (of measurement) of the calculated sampled concentration (random errors), due to the uncertainty of the fitted model, at influence variable value ς_i; and
$\sigma_{\mathrm{A_a}}$	is the geometric standard deviation a of lognormal aerosol size distribution A.

5.5.3.4 Individual sampler variability

5.5.3.4.1 General

For samplers for the inhalable sampling convention this uncertainty component is zero, thus $s_{\mathrm{Sampl\text{-}Variability}} \equiv 0$. For samplers for the respirable or thoracic sampling conventions this uncertainty (of measurement) component, $s_{\mathrm{Sampl\text{-}Variability}}$, is calculated from the differences in sampled concentrations among the N_{S} candidate sampler individuals using the formula

$$s_{\mathrm{CandSampl\text{-}Variability}_{ia}}{}^2 + s_{\mathrm{CandSampl\text{-}ModelCalc}_{ia}}{}^2 = \frac{1}{N_{\mathrm{S}}-1}\sum_{s=1}^{N_{\mathrm{S}}} \left(C_{is}\left(D_{\mathrm{A}_a}, \sigma_{\mathrm{A}_a}\right) - \bar{C}_i\left(D_{\mathrm{A}_a}, \sigma_{\mathrm{A}_a}\right) \right)^2 \quad (50)$$

where

$\bar{C}_i$ is the mean sampled relative aerosol concentration, expressed as a fraction of the total airborne aerosol concentration, calculated to be obtained when using the candidate sampler, for aerosol size distribution A at influence variable value ς_i (see EN 13205-2:2014, Formula (3));

$D_{\mathrm{A_a}}$ is the mass median aerodynamic diameter a of lognormal aerosol size distribution A;

N_{S} is the number of candidate sampler individuals;

$s_{\mathrm{CandSamplŠModelCalc}_{ia}}$ is the random uncertainty (of measurement) of the calculated sampled concentration, due to the uncertainty of the fitted model, for the a^{th} aerosol size distribution A at influence variable value ς_i (see Formula (48));

$s_{\mathrm{CandSampl\text{-}Variability}_{ia}}$ is the random uncertainty (of measurement) of the calculated sampled concentration, due to individual sampler variability, for the a^{th} aerosol size distribution A and influence variable value ς_i; and

$\sigma_{\mathrm{A_a}}$ is the geometric standard deviation a of lognormal aerosol size distribution A.

For each influence variable value calculate the RMS over all the N_{SD} aerosol size distributions A

$$u_{\mathrm{CandSampl\text{-}Variability}_i}{}^2 = \frac{1}{N_{\mathrm{SD}}}\sum_{a=1}^{N_{\mathrm{SD}}}\frac{s_{\mathrm{CandSampl\text{-}Variability}_{ia}}{}^2}{C_{\mathrm{std}}{}^2} = \frac{1}{N_{\mathrm{SD}}}\sum_{a=1}^{N_{\mathrm{SD}}}\left(\frac{s_{\mathrm{CandSampl\text{-}Variability}_{ia}}\left(D_{\mathrm{A}_a},\sigma_{\mathrm{A}_a},\zeta_i\right)}{C_{\mathrm{std}}\left(D_{\mathrm{A}_a},\sigma_{\mathrm{A}_a}\right)}\right)^2 \quad (51)$$

where

C_{std} is the target sampled relative aerosol concentration, expressed as a fraction of the total airborne aerosol concentration, that would have been sampled using an ideal sampler with a sampling efficiency identical to the sampling convention for aerosol size distribution A;

$D_{\mathrm{A_a}}$ is the mass median aerodynamic diameter a of lognormal aerosol size distribution A;

N_{SD} is the number of aerosol size distributions A according to EN 13205-2:2014, Table 2;

$s_{\mathrm{CandSampl\text{-}Variability}_{ia}}$ is the random uncertainty (of measurement) of the calculated sampled concentration, due to individual sampler variability, for the a^{th} aerosol size distribution A at influence variable value ς_i;

$u_{\mathrm{CandSampl\text{-}Variability}_i}$ is the standard uncertainty (of measurement) of the calculated sampled concentration (random errors), due to individual sampler variability, at influence variable value ς_i; and

$\sigma_{\mathrm{A_a}}$ is the geometric standard deviation a of a lognormal aerosol size distribution A.

5.5.3.4.2 Test of whether the individual sampler variability is significant

If the individual sampler variability is not significantly larger than the uncertainty of the estimate of the sampled concentration, then all sampler individuals can be treated as identical. In order to evaluate this, calculate

$$F_{\text{CandSamplVar}_i} = \frac{\frac{1}{N_{\text{SD}}}\sum_{a=1}^{N_{\text{SD}}} s_{\text{CandSampl-Variability}_{ia}}{}^2\left(D_{\text{A}_a}, \sigma_{\text{A}_a}, \zeta_i\right)}{\frac{1}{N_{\text{SD}}}\sum_{a=1}^{N_{\text{SD}}} s_{\text{CandSampl-ModelCalc}_{ia}}{}^2\left(D_{\text{A}_a}, \sigma_{\text{A}_a}, \zeta_{ii}\right)} \quad (52)$$

where

D_{A_a}	is the mass median aerodynamic diameter a of lognormal aerosol size distribution A;
$F_{\text{CandSamplVar}_i}$	is the test variable for the check whether the individual sampler variability exceeds that of the uncertainty of the calculated concentrations, for influence variable value ς_i;
N_{SD}	is the number of aerosol size distributions A according to EN 13205-2:2014, Table 2;
$s_{\text{CandSampl-ModelCalc}_{ia}}$	is the random uncertainty (of measurement) of the calculated sampled concentration, due to the uncertainty of the fitted model, for the a^{th} aerosol size distribution A at influence variable value ς_i;
$s_{\text{CandSampl-Variability}_{ia}}$	is the random uncertainty (of measurement) of the calculated sampled concentration, due to individual sampler variability, for the a^{th} aerosol size distribution A and influence variable value ς_i.
$\sigma_{\text{A}_\text{a}}$	is the geometric standard deviation a of a lognormal aerosol size distribution A.

$F_{\text{CandSamplVar}_i}$ has an *F*-distribution with approximately $\left(N_\text{S} - 1, N_\text{S}\left[N_\text{P} N_\text{Rep} - N_\text{K}\right]\right)$ degrees of freedom, and thus the individual sampler variability is significant at the 95 % level if $F_{\text{CandSamplVar}_i} > F_{0.95}\left(N_\text{S} - 1, N_\text{S}\left[N_\text{P} N_\text{Rep} - N_\text{K}\right]\right)$. If $F_{\text{CandSamplVar}_i}$ is insignificant, then put $u_{\text{CandSampl-Variability}_i} \equiv 0$, and determine new values for both the number of repeats ($N_\text{Rep}{}^*$) and the number of candidate sampler individuals ($N_\text{S}{}^*$),

$$\begin{cases} N_\text{S}{}^* = 1 \\ N_\text{Rep}{}^* = N_\text{Rep}\, N_\text{S} \end{cases} \quad (53)$$

where

N_Rep	is the number of repeats;
N_S	is the number of candidate sampler individuals:
$N_\text{Rep}{}^*$	is the recalculated number of repeats when the variation among candidate samplers statistically does
$N_\text{S}{}^*$	is the recalculated number of candidate samplers when the variation among candidate samplers

Calculate new values for $s_{\text{CandSampl-Calibr}_i}$ and $s_{\text{CandSampl-ModelCalc}_i}$, and corresponding new $u_{\text{CandSampl-Calibr}_i}$ and $u_{\text{CandSampl-ModelCalc}_i}$.

NOTE For a detailed treatment of the curve-fitting method, see Bibliography, reference [4].

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