INTERNATIONAL STANDARD

ISO 13138

First edition
2012-01-15

Air quality — Sampling conventions for airborne particle deposition in the human respiratory system

Qualité de l'air — Conventions de prélèvement de particules aéroportées en fonction de leur dépôt dans les voies respiratoires humaines

Reference number
ISO 13138:2012(E)

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Published in Switzerland

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Foreword

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International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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ISO 13138 was prepared by Technical Committee ISO/TC 146, *Air quality*, Subcommittee SC 2, *Workplace atmospheres*.

Introduction

Aerosols comprise disperse systems of particles, liquid or solid, inorganic or organic, anthropogenic or natural in origin. They are found in all working and living environments, indoors or outdoors. The range of aerosol types is vast. Many can be hazardous to humans when exposure occurs by inhalation, leading to a wide range of diseases, depending on where inhaled particles are deposited in the respiratory tract. Many specific diseases such as asthma, bronchitis, emphysema, pneumoconiosis (including coal workers' pneumoconiosis, silicosis and asbestosis), and lung cancer are all known to be associated with aerosol exposures by inhalation. Protection of workers and the general public therefore requires meaningful standards by which such exposures may be regulated. The emergence of such standards goes back to the beginning of the 1900s, and has accelerated in the decades running up to the publication of this International Standard with increasing awareness of the associations between exposures and disease, along with better understanding of the nature of aerosols and exposures to them. Even very early on, the particle-size role in the penetration of particles into, and deposition within, the respiratory tract has been acknowledged. Based on a large body of research that has been conducted since 1960 and before, understanding of the role of particle size in the distribution of and deposition of particles in the various regions of the respiratory tract has led to the stipulation of particle size-selective curves that provide guidelines for the performance of sampling instruments, of the type widely used by occupational and environmental hygienists, that may be used to measure exposures in a way that is directly relevant to any of the health effects of interest.

The original conventions, based on experimental data from carefully controlled inhalation studies with human volunteers, were expressed as curves describing *penetration* to the region of interest as a function of particle size, latterly (since the 1960s) in terms of the metric known as *particle aerodynamic diameter* in the size range extending from 0,5 µm to 100 µm. These conventions led to the emergence of samplers for collecting the inhalable, thoracic, and respirable mass fractions of ambient airborne particles, in both working and living environments, although the conventions are not restricted solely to mass sampling. The conventions were deliberately set up conservatively in view of the large inter- and intra-person variation and with full acknowledgement that the actual deposition of particles (and hence true exposure) differs from penetration, e.g. to or within the alveolar region of the lung and other scenarios, especially when there are particularly fine aerosols. From the outset, therefore, it was to be expected that correlations between disease and exposure might be somewhat limited. However, such an approach readily paved the way for aerosol scientists to develop reasonably simple samplers or monitors whose performance could adequately match the conventions of interest.

With the current availability of large amounts of information on aerosol particle deposition in the human respiratory tract, with ongoing development of more advanced and truly representative sampling instruments, and with research into health-effect determinants such as deposited particle surface area (as opposed to mass), the establishment of conventions that allow for more direct estimations of actual deposition is now justified. This International Standard provides conventions for samplers intended to represent fractions of inhaled aerosol particles actually *depositing* in specific areas of the respiratory system. The particle size range is extended below 0,1 µm where deposition is dominated by diffusion (Brownian motion).

Whether these new conventions will in fact lead to significantly improved correlation between exposure and disease is, at the time of publication, still an open question. Nonetheless, deposition is likely to be a more relevant, potentially causative factor than one that includes exhaled particles that do not interact with the body. Whereas the earlier conventions have already been adopted in many legal schemes for determining compliance with exposure levels deemed safe, the newer conventions are expected to be applied initially in forthcoming health effects research. Eventually, however, it is possible that compliance standards themselves will be revised if suitable samplers come into use, and correlation between exposure measurements and health effects are in fact found to be significantly improved.

Air quality — Sampling conventions for airborne particle deposition in the human respiratory system

IMPORTANT — The electronic file of this document contains colours which are considered to be useful for the correct understanding of the document. Users should therefore consider printing this document using a colour printer.

1 Scope

This International Standard specifies sampling conventions to define idealized samplers for estimating the deposition of non-volatile, non-hygroscopic, non-fibrous aerosols in five specific loci of the respiratory tract. The five loci consist of the anterior and posterior areas of the nasal passages, the ciliated and non-ciliated parts of the tracheobronchial area, and the alveolar (gas exchange) region.

The conventions are separated into three independent sampling efficiencies defined in terms of thermodynamic diameter characterizing the diffusive (Brownian) motion of sub-micrometre particles and four efficiencies in terms of aerodynamic diameter >0,1 µm characterizing deposition by impaction, interception or gravitational settling. Each conventional curve has been developed as an average of 12 deposition curves corresponding to 12 breathing conditions ranging from sitting to heavy exercise, male vs female, and breathing mode (mouth vs nasal breathing).

NOTE Deposition is computed according to a model developed by the International Commission on Radiological Protection (ICRP, Reference [3]).

2 Normative references

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

ISO 7708, *Air quality — Particle size fraction definitions for health-related sampling*

ISO/IEC Guide 98-3:2008, *Uncertainty of measurement — Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

EN 481, *Workplace atmospheres — Size fraction definitions for measurement of airborne particles*

EN 13205, *Workplace atmospheres — Assessment of performance of instruments for measurement of airborne particle concentrations*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1
aerodynamic diameter
d_{ae}
diameter of a sphere of density ρ_0 = 10^3 kg m^{-3} = 1 g cm^{-3} with the same terminal velocity due to gravitational force in calm air as the particle, under the prevailing conditions of temperature, pressure and relative humidity within the respiratory tract

NOTE 1 Adapted from ISO 7708:1995, 2.2.

NOTE 2 The aerodynamic diameter is applicable to any particle, but it is dependent on the density, shape and porosity of the particle.

NOTE 3 Under the conditions of interest in this International Standard, the aerodynamic diameter of a spherical particle is generally equal to $d\sqrt{(\rho/\rho_0)}$, where d is the geometric diameter of the sphere. For high-density spheres of diameter of the order of 0,1 µm where the corpuscular aspects of the air can be significant, a "slip"-correction factor is required (see Reference [3]).

NOTE 4 For particles with aerodynamic diameter below approximately 0,4 µm, the thermodynamic diameter becomes more significant in characterizing deposition than aerodynamic diameter.

3.2
thermodynamic diameter
d_{th}
diameter of a sphere with the same diffusion coefficient as the particle under prevailing conditions of temperature and pressure within the respiratory tract

NOTE 1 The weak dependence of the thermodynamic diameter on the relative humidity is neglected (see Reference [3]).

NOTE 2 The thermodynamic diameter is applicable to any particle, regardless of its shape and is independent of the density of the particle.

NOTE 3 The thermodynamic diameter is equal to the geometric diameter for spherical particles of interest in this International Standard.

NOTE 4 For particles of aerodynamic diameter above approximately 0,4 µm, the aerodynamic diameter becomes more significant in characterizing deposition than thermodynamic diameter.

3.3
inhalable fraction
fraction of total airborne particles of given particle size inhaled through the nose and mouth

NOTE 1 Adapted from ISO 7708:1995, 2.3.

NOTE 2 The fractions specified in 3.3 to 3.8, as defined at specific particle size (characterized by thermodynamic and aerodynamic diameters), are independent of the basis of measurement, e.g. mass, area or particle count.

NOTE 3 A significant portion of the inhaled particles may be exhaled, but since these are smaller particles their effect on the mass deposited may be minimal..

3.4
extrathoracic ET_1 deposition efficiency
fraction of inhaled particles of given particle size deposited in the anterior nasal passages (i.e. the entrance to the nose itself)

NOTE 1 Particles can be deposited in the ET_1 region directly following inhalation by the nose or indirectly from interior regions of the respiratory tract upon exhalation. Particles inhaled by mouth are deposited in ET_1 only upon exhalation.

NOTE 2 The nasal/oral division between inhaled particles is reflected in the conventions presented in this International Standard by averaging over breathing habits (6.6) or by individual correction (Annex A).

3.5
extrathoracic ET_2 deposition efficiency
fraction of inhaled particles of given particle size deposited in the posterior nasal passages consisting of the larynx and pharynx

NOTE Particles can be deposited in the ET_2 region directly following inhalation by mouth or indirectly by the nose or upon exhalation.

3.6
tracheobronchial BB deposition efficiency
fraction of inhaled particles of given particle size deposited after the larynx in the trachea and bronchi from which deposited material is cleared by ciliary action

NOTE See Reference [3] for further details.

3.7
tracheobronchial bb deposition efficiency
fraction of inhaled particles of given particle size deposited after the BB region in the bronchioles and terminal bronchioles before the alveolar (gas exchange) region

NOTE See Reference [3] for further details.

3.8
alveolar deposition efficiency
fraction of inhaled airborne particles of given particle size deposited in the alveoli

3.9
tidal volume
V_T
volume of gas entering or leaving the lung during the inspiratory or expiratory phase

NOTE 1 Adapted from ISO 10651-4:2002[1], 3.15.

NOTE 2 The tidal volume is expressed in millilitres.

3.10
breathing rate
f
number of breaths per minute

3.11
inspiratory flow rate
q
sum of the volumes of air inhaled and exhaled from a person's lungs per time

NOTE 1 The inspiratory flow rate is expressed in millilitres per second.

NOTE 2 The inspiratory flow rate is sometimes denoted $\dot{V}$.

NOTE 3 The inspiratory flow rate, q, is given by the equation, $q = 2fV_T$, where f is the breathing rate and V_T is the tidal volume.

3.12
functional residual capacity
FRC
volume of air present in the lungs at the end of expiration when extra effort is not applied

4 Principle

4.1 General

4.1.1 A large body of research has been conducted on deposition of particles within the human respiratory system. Experience has consisted mainly of the study of physical models of the body as exposed to particles of known size under controlled wind conditions or in tracing the fate of radioactively marked particles after inhalation by human subjects. For a review of the various research efforts, see Reference [4]. Reference [3] presents detailed models summarizing the experimental data.

4.1.2 At the time of publication, ISO 7708, EN 481, ASTM D6062[2], and ACGIH[5] provide the only established sampling conventions for classifying mass fractions of ambient particles (as either inhalable, thoracic, or respirable) as to reaching specific parts of the respiratory system. The conventions are the result of a compromise between previous definitions which were designed to approximate the fraction of dust of given size that penetrates to (rather than deposits in) different areas of the body.

4.2 Rationale for the early penetration conventions (EN 481 and ISO 7708)

4.2.1 The conventions have been established conservatively, significantly overstating the actual penetration so as to circumvent large inter- and intra-person variation.

4.2.2 With coarse particles (d_{ae} greater than about 0,5 µm), such as those found in the mining environment, the conventional respirable fraction and aerosol particles deposited in the gas-exchange region correlate well in the mean.

4.2.3 Samplers exist for personal sampling that operate reasonably in accordance with the penetration conventions.

4.3 Need for particle deposition conventions

4.3.1 The penetration conventions (ISO 7708, EN 481) were not set up to account for exhalation of sub-micrometre particles that is needed to achieve correlation with health effects in some situations.

4.3.2 ISO 7708 and EN 481 did not cover increased deposition in the alveolar and extrathoracic regions as particle diameters decrease below 0,5 µm.

4.3.3 ISO 7708 and EN 481 were set up as limits rather than estimates. The deposition conventions, no longer designed around conservative limits (4.2.1), can increase the information obtained in a workplace assessment and also improve the establishment of meaningful occupational exposure limits.

4.4 Intended application

4.4.1 The conventions of this International Standard may find immediate application in health-effects research in providing improved correlation between air quality assessment and observed effects. Specifically, dose received prior to clearance can be estimated. For example, suppose that deposited *mass* is the health-related metric of interest. The estimated dose in region x, $m_{x,D}$, in milligrams, is given by:

$$m_{x,D} = \frac{1}{2} qt \frac{m_x}{q_x t_s} \quad (1)$$

where

q is the inspiratory flow rate, in millilitres per second, of a person;

t is the time, in seconds, of exposure of a person;

m_x is the mass sampled, in milligrams;

q_x is the sampling rate, in millilitres per second;

t_s is the sampling time, in seconds.

4.4.2 The acceptance of definite deposition conventions will stimulate instrument development: either for particle size-distribution measurement (via particle-size classifiers) or for samplers dedicated specifically to the deposition conventions (e.g. see References [6] to [12]).

5 Assumptions and approximations

5.1 Many approximations come into play in establishing sampling conventions intended to mimic deposition of particles within the respiratory system. These may be summarized in 5.2 to 5.6.

5.2 The sampling conventions given here are averages over a representative set of breathing characteristics (see Table 1).

5.3 Particles which reach the alveoli but which are not deposited there can be deposited in the upper respiratory tract as they pass through it during exhalation.

NOTE In the case of a cloud of particles small enough to avoid impaction or gravitational settling in the respiratory tract, deposition can be significant in the extrathoracic region with Brownian motion during exhalation or inhalation.

5.4 The effect of the diameter change of hygroscopic particles due to accumulation of water while within the respiratory system, though significant, for example to the deposition of soluble salts and acid mists, is beyond the scope of this International Standard.

5.5 The effect of particle charge is not considered.

5.6 The ICRP deposition model (see Reference [3]), approximates the net particle capture probability at each locus of the respiratory tract as the root sum of squares (RSS) of thermodynamic and aerodynamic sub-probabilities. RSS is equivalent to a simple sum except in the overlap region from 0,1 µm to 1,0 µm, where impaction, sedimentation, and diffusive deposition are inefficient. The non-linear combination of the deposition probabilities is problematic to apply to a sampler. Therefore, this International Standard adopts a purely linear approximation. Annex A provides a means for reducing inaccuracy in the overlap region by fitting linear combinations of the sampling conventions to the RSS approximation. (See Reference [13] for more details.)

6 Deposition sampling conventions

6.1 As with EN 481 and ISO 7708, a small set of sampling conventions is defined in this International Standard, rather than using raw models (see Reference [3]) involving a great many variable parameters. The aim is to focus on aspects of interest. Furthermore, delimitation of the conventions is expected to concentrate efforts towards developing practical instrumentation.

6.2 This International Standard employs functions $F[d;(d_c,\sigma)]$ and $F'[d;(d_c,\sigma)]$ of (either thermodynamic or aerodynamic) diameter d. The function F is the cumulative lognormal distribution, parameterized in terms of distribution constants, median cut diameter d_c and distribution variance σ^2. The function F', defined as its slope at diameter d, is the lognormal probability distribution function itself:

$$F'[d;(d_c,\sigma)] \equiv \frac{1}{\sqrt{2\pi}\,\sigma\, d}\exp\left[-\frac{\ln^2\left(d/d_c\right)}{2\sigma^2}\right] \qquad (2)$$

Many spreadsheets and all statistical programs have dedicated sub-programs for quickly computing the cumulative distribution function F. Alternatively, an algorithm presented in ISO 7708 may be used.

6.3 The functions F and F' are useful for modelling a variety of curves. Furthermore, integration with particle size distributions is simple. For more information about the use of lognormal functions, see Reference [13].

6.4 Aerosol particle inhalability convention

6.4.1 This International Standard specifies sampling conventions in terms of sampling efficiencies for aerosol particles *following* inhalation. This is possible because the ICRP deposition model (see Reference [3]) itself estimates deposition efficiencies after inhalation. Estimation of dose from an aerosol particle cloud then requires pre-selection accounting for the inhalable fraction (3.3).

6.4.2 For $d_{ae} \leq 1$ µm, the inhalable convention shall be taken as equal to 1,00.

6.4.3 The inhalable convention for $d_{ae} > 1$ µm shall be taken as specified in ISO 7708 or EN 481, covering conditions of moderate wind (see References [14] to [16]). Also, knowledge developing at the time of publication

(see References [17] to [21]) covering inhalability under conditions of the low wind speeds found in indoor workplace environments can be assimilated as available. Acceptance in this aspect shall be in accordance with ISO/IEC Guide 98-3:2008 and EN 13205.

NOTE The ICRP deposition model (see Reference [3]), in addition to specifying deposition following inhalation, presents information on inhalability as known at the time of publication.

6.5 Respiratory tract loci

6.5.1 The ICRP deposition model (see Reference [3]) identifies five regions of aerosol particle deposition within the respiratory tract: extrathoracic ET_1, extrathoracic ET_2, tracheobronchial BB, tracheobronchial bb, and alveolar. For descriptions, see 3.4 to 3.8 and References [3][22][23].

6.6 Breathing conditions

6.6.1 The deposition efficiency in each region varies greatly, depending on breathing characteristics: workload, sex, and breathing mode. Three categories of workload are considered for this International Standard, for an individual either sitting or else performing light or heavy exercise as characterized in Reference [3]. Breathing mode refers to the fact that people can be characterized as either “normal breathers” or “mouth breathers”. Normal breathers inhale air strictly through the nose, except when performing heavy exercise. Mouth breathers, however, always take in a fraction of air through the mouth. This International Standard addresses 12 sets of breathing characteristics which are listed in Table 1.

Table 1 — The 12 specific breathing characteristics addressed: normal vs mouth breathing, male vs female, and workload

Parameter[a]	Male (M)	Female (F)	Oral fraction during normal (n) breathing	Oral fraction during mouth (m) breathing
FRC, ml	3 301	2 681		
Sitting (s):			0,00	0,30
f, min^{-1}	12	14		
V_T, ml	750	464		
q, ml/s	300	217		
Light exercise (l):			0,00	0,60
f, min^{-1}	20	21		
V_T, ml	1 250	992		
q, ml/s	833	694		
Heavy exercise (h):			0,50	0,70
f, min^{-1}	26	33		
V_T, ml	1 920	1 364		
q, ml/s	1 670	1 500		

[a] See definitions 3.9 to 3.12.

6.6.2 The specification of efficiencies for each of the 12 breathing characteristics individually in Table 1 is impractical for the development of dedicated samplers. Instead, averages were taken over the characteristics. Furthermore, the number of independent conventions required to cover the five physiological loci is reduced because of approximate relationships among the deposition functions. For further details, see Reference [13].

6.6.3 It is necessary for the variability associated with the range of possible breathing conditions to be acknowledged in any application of this International Standard with individual samplers performing according to convention. Alternatively, Annex A provides means for approximating deposition under any specific set of

breathing characteristics by combining the information from an array of samplers performing according to the individual conventional efficiencies specified here.

6.7 Conventional deposition efficiencies

6.7.1 Four conventional aerodynamic deposition efficiencies, $D_{a\,ET_1}[d_{ae}]$, $D_{a\ BB}[d_{ae}]$, $D_{a\ bb}[d_{ae}]$, and $D_{a\,Alv}[d_{ae}]$, are specified: for the extrathoracic region, ET_1, the two tracheobronchial regions, BB and bb, and the alveolar, Alv, (gas exchange) region. These functions were established as log–normal representations of the ICRP deposition model (see Reference [3]) efficiencies at each locus averaged over the 12 breathing characteristics of Table 1. The lognormal parameters are presented in Table 2, and the efficiencies are shown graphically in Figure 1.

6.7.2 Three conventional thermodynamic deposition efficiencies, $D_{t\,ET_1}[d_{th}]$, $D_{t\ bb}[d_{th}]$, and $D_{t\,Alv}[d_{th}]$, are specified: for the extrathoracic region, ET_1, the tracheobronchial region, bb, and the alveolar, Alv, region. The lognormal parameters are presented in Table 2, and the efficiencies are shown graphically in Figure 1.

6.7.3 Three dependent thermodynamic deposition efficiencies, for the extrathoracic region ET_2 and the tracheobronchial region BB, and one aerodynamic deposition efficiency for ET_2 are taken as shown in Table 3. The dependent efficiencies are indicated (in grey) in Figure 1.

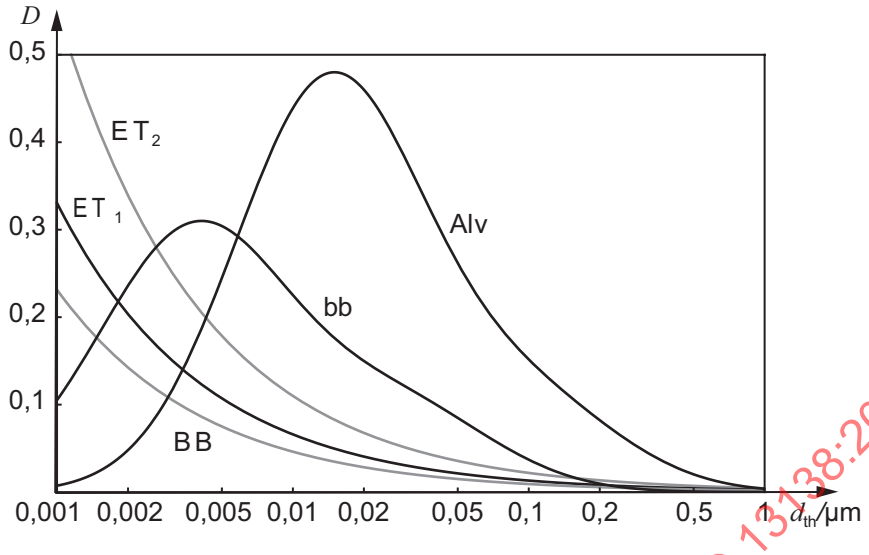
Table 2 — Deposition sampling conventions relative to inhaled aerosol represented in terms of lognormal functions of aerodynamic or thermodynamic diameter

Regime	Deposition conventions	Representation	d_c µm	σ
Thermodynamic	$D_{t\ ET_1}[d_{th}]$	$0{,}002\ 6\ \mu m^{+0,7} d_{th}^{-0,7}$	—[a]	—[a]
	$D_{t\ bb}[d_{th}]$	$\left[0{,}31 + 1\,200\ \mu m^{-2}\left(d_{th} - d_c\right)^2\right]\exp\left[-\frac{1}{2\sigma^2}\ln^2\left(\frac{d_{th}}{d_c}\right)\right]$	0,004 1	ln[2,57]
	$D_{t\ Alv}[d_{th}]$	$\left[0{,}48 + 100\ \mu m^{-2}\left(d_{th} - d_c\right)^2\right]\exp\left[-\frac{1}{2\sigma^2}\ln^2\left(\frac{d_{th}}{d_c}\right)\right]$	0,015	ln[2,54]
Aerodynamic	$D_{a\ ET_1}[d_{ae}]$	$0{,}325F\left[d_{ae},\left(d_c,\sigma\right)\right]$	2,7	ln[2,5]
	$D_{a\ BB}[d_{ae}]$	$0{,}12\exp\left[-\frac{1}{2\sigma^2}\ln^2\left(\frac{d_{ae}}{d_c}\right)\right]$	5,2	ln[2,0]
	$D_{a\ bb}[d_{ae}]$	$0{,}05\exp\left[-\frac{1}{2\sigma^2}\ln^2\left(\frac{d_{ae}}{d_c}\right)\right]$	3,4	ln[2,0]
	$D_{a\ Alv}[d_{ae}]$	$0{,}19\exp\left[-\frac{1}{2\sigma^2}\ln^2\left(\frac{d_{ae}}{d_c}\right)\right]$	2,3	ln[2,0]

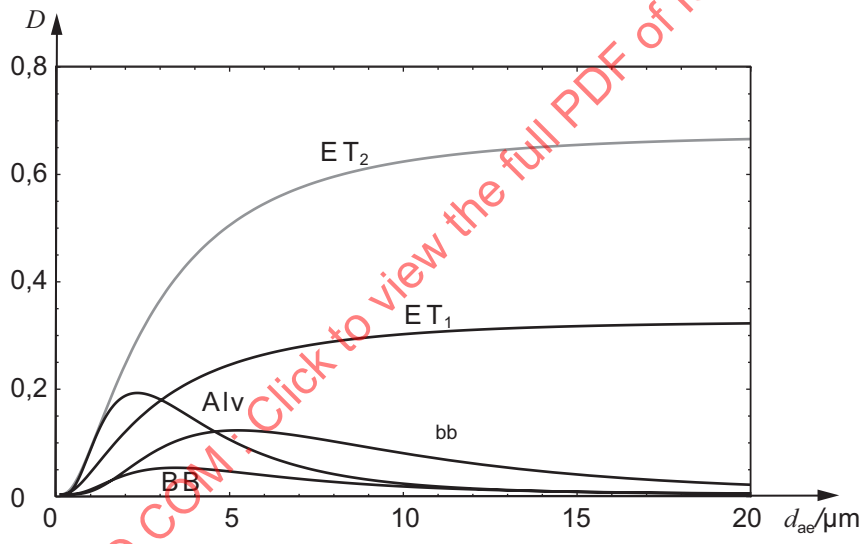
[a] Not applicable.

Table 3 — Dependent conventions

Regime	Deposition conventions	Representation
Thermodynamic	$D_{t\ ET_2}[d]$	$1{,}67 D_{t\ ET_1}[d]$
	$D_{t\ BB}[d]$	$0{,}70 D_{t\ ET_1}[d]$
Aerodynamic	$D_{a\ ET_2}[d_{ae}]$	$2{,}08 D_{a\ ET_1}[d_{ae}]$



a) Thermodynamic plots



b) Aerodynamic plots

Key

D	deposition	BB	tracheobronchial region 1
d_{ae}	aerodynamic diameter	bb	tracheobronchial region 2
d_{th}	thermodynamic diameter	ET_1	extrathoracic region 1
Alv	alveolar region	ET_2	extrathoracic region 2

Figure 1 — Independent aerosol particle deposition conventions (black) parameterized in Table 2; dependent conventions (grey), each proportional to one of the independent conventions

Annex A
(informative)

Deposition variation and its correction

A.1 The variation in aerosol particle deposition, both between and within individuals, is so large that correlation with health effects can be easily obscured. The intent behind this International Standard is to consider the variations relating to workload (heavy exercise vs light exercise vs sitting), breathing mode (normal vs mouth breathing), and sex (see Reference [3]).

A.2 This intention poses more of a problem than in EN 481 or ISO 7708. The earlier penetration conventions skirted the issue of variation by taking a conservative approach. Conservative estimation can be acceptable for compliance applications. However, estimating a dose for a health-research application differs from simply determining whether a limit has been exceeded.

A.3 The extent of variation is shown in Figure A.1 for the five deposition loci in the human respiratory tract. The thicker lines depict the deposition in the extrathoracic (ET_1), extrathoracic (ET_2), tracheobronchial (BB), tracheobronchial (bb), and alveolar (Alv) regions for each influence factor considered. The curves labelled D_{ET_1} , D_{ET_2} , D_{BB}, D_{bb}, and D_{Alv} represent the deposition conventions specified in 6.7.

A.4 One possibility for covering the variations is to measure the full size distribution of aerosol particles of concern and then compute the expected deposition in each region for any condition desired. Perhaps a miniaturized version of the equipment of Reference [12] can be developed for personal sampling. Another possibility is that for some research aims, the variation can be simply ignored or acknowledged. Another suggestion (see Reference [13]) is to use the results from an array of samplers meeting convention to correct the deposition in any particular region under any condition.

NOTE Low-pressure impactors currently available for personal sampling can be used to determine size distributions for very small particle diameters in special cases where the aerosol particles are simple and well characterized, e.g. spherical particles of a single substance with known bulk density. Impaction in this case depends on the physical diameter d through the slip factor and dynamically on $d\sqrt{(\rho/\rho_0)}$ as well. The difficulty is that the thermodynamic diameter is not directly probed.

A.5 Measurements taken by a set of samplers operating in accordance with the conventions of Table 2 can then be used to correct for any specific set of breathing characteristics of Table 1 so as to estimate deposition in any one of the five loci in the respiratory system. This is done through a set of conversion factors which are presented in Table A.1. What is needed is knowledge of the breathing characteristics of any individual whose aerosol dose is to be estimated.

A.6 The conversion factors were determined as follows. Suppose the deposition efficiency provided by the ICRP deposition model (see Reference [3]) for a specific locus and breathing condition is $E[d]$ where d is the (geometric) diameter of a spherical particle of density ρ = 1 g/cm^3. Approximate $E[d]$ as a linear combination of the conventional independent functions $D_j[d]$ of Table 2:

$$E[d] \approx \sum_j C_j D_j[d] \qquad \text{(A.1)}$$

The constants C_j were determined by a least-squares fit of the right-hand side of Equation (A.1) to the function $E[d]$ known from the ICRP deposition model (see Reference [3]). Variations, male to female, were averaged in computing the conversion factors, as differences were generally negligible. (See also Reference [24].) The set of conversion factors so determined is presented in Table A.1. Figure A.1 presents comparisons of the approximations (light lines) to the true ICRP deposition model (see Reference [3]) for all of the loci and the 12 breathing characteristics of Table 1.

A.7 For particle densities ρ differing from 1 g/cm^3 or particles departing from spherical, both sides of Equation (A.1) shift, the right hand side through the dependence of the aerodynamic subset of Table 2 on the aerodynamic diameter d_{ae} and the thermodynamic subset on the thermodynamic diameter d_{th}. The left hand side given by the ICRP deposition model (see Reference [3]) becomes a function of d_{ae} and d_{th} that is not a sum of separate functions of d_{ae} and d_{th}. However, the approximate equality of Equation (A.1) is preserved for any particle size for which only one mechanism (diffusion or impaction) dominates deposition, i.e. where deposition is significant, since overlap occurs where both modes are inefficient.

A.8 A rough estimate of the uncertainty inherent in Equation (A.1) associated with either lack of fit or the shift discrepancy (A.7) in the region of overlap where deposition is inefficient by either mode is presented in Reference [13]. In sampling at random from sets of size distributions, with particle count, surface area, or mass as metric, taken as representative and with random breathing conditions (Table 1), the (relative) uncertainty (one standard deviation) ranged from 9 % to 24 %, depending on the locus in the respiratory tract. For comparison, estimating the deposition efficiency simply from the conventions without correction resulted in uncertainty ranging from 30 % to 122 %.

A.9 Dose is computed as in 4.4.1. The dose at locus x, $m_{x,D}$, in milligrams, for a person is given by:

$$m_{x,D} = \frac{1}{2} qt \sum_j \frac{C_{x\,j} m_j}{q_j t_s} \qquad \text{(A.2)}$$

where

q is the inspiratory flow rate, in millilitres per second;

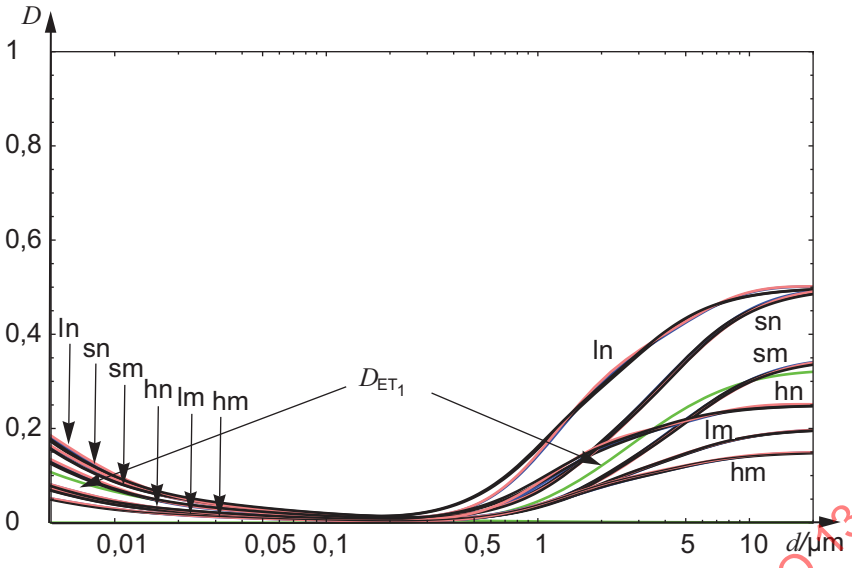
t is the exposure time, in seconds;

$C_{x,j}$ is the coefficient at row x and column j in Table A.1;

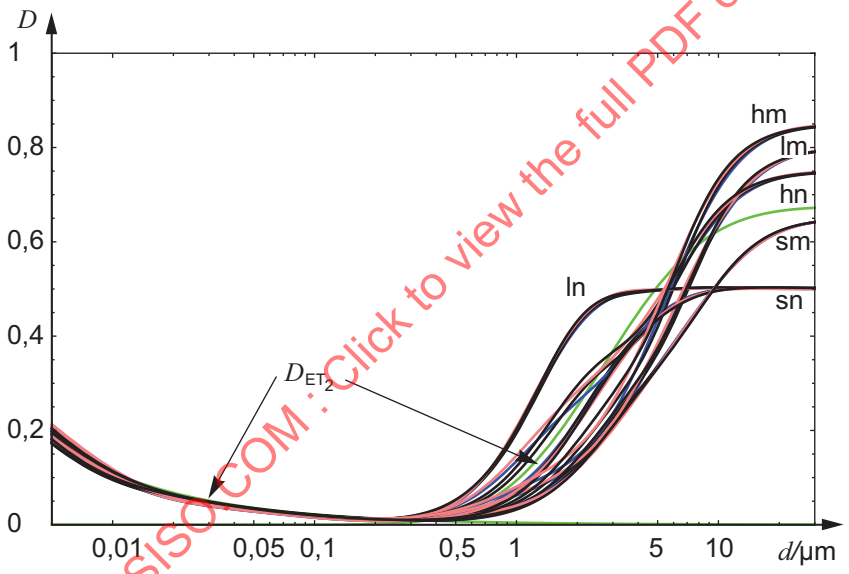
m_j is the mass, in milligrams, collected;

q_j is the sampling rate for sampler j, in millilitres per second;

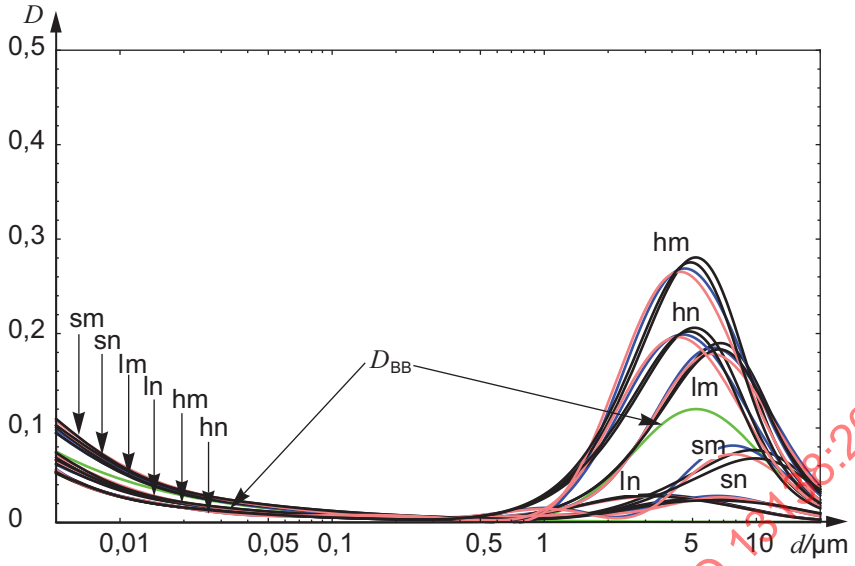
t_s is the sampling time, in seconds.



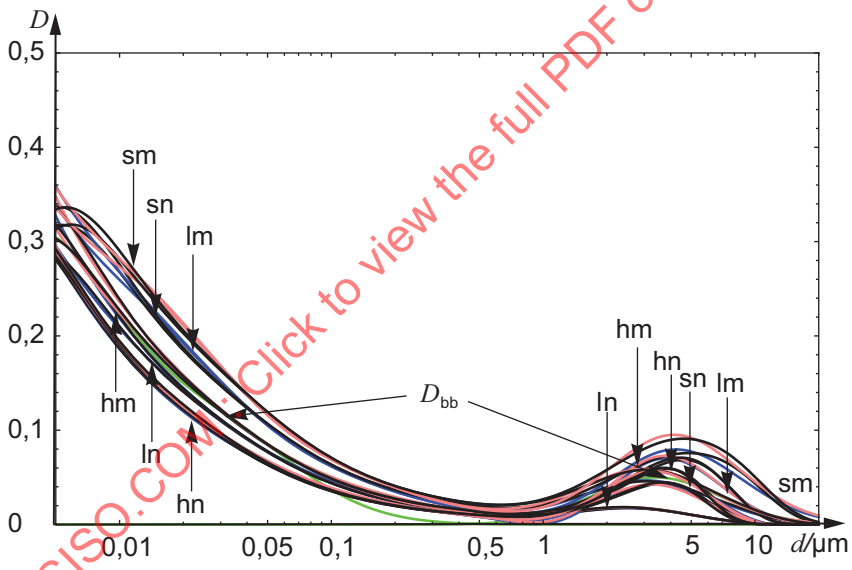
a) Extrathoracic region 1



b) Extrathoracic region 2



c) Tracheobronchial region 1



d) Tracheobronchial region 2