
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*

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Foreword

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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.

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

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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 $>0,1 \mu\text{m}$ 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

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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 $\rho_0 = 10^3 \text{ kg m}^{-3} = 1 \text{ g cm}^{-3}$ 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 ET₁ 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 ET₁ 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 ET₁ 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 ET₂ 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 ET₂ 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, $q = 2f V_T$, 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:

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

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:

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

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 $d_{ae} \leq 1 \mu\text{m}$, the inhalable convention shall be taken as equal to 1,00.

6.4.3 The inhalable convention for $d_{ae} > 1 \mu\text{m}$ 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