The inhalable selector described herein has been redesigned in 2006 to better follow the ISO/CEN/ACGIH curve

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INDUSTRIAL AEROSOL MEASUREMENT ACCORDING TO THE NEW SAMPLING CONVENTIONS

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Member states of the CEN (Comité Européen de Normalisation) voted a new European standard EN481 titled "Specification for Conventions for Measurement of Suspended Matter in Workplace Atmospheres" (CEN, 1993). In the same time the ISO (International Standards Organisation) standard DIS7708 "Particle Size Fraction Definitions for the Health-Related Sampling" has been adopted (ISO, 1993). The American Conference of Governmental Industrial Hygienists (ACGIH) has recently published the same aerosol sampling conventions (ACGIH, 1994). Both standards are equivalent in their definitions of Inhalable, Thoracic and Respirable aerosol fractions. These definitions are slightly different from the previous conventions BMRC (Orenstein, 1960), ACGIH (1985), ISO (1983) and try to unify the requirements on dust exposure measurements in workplace. The new sampling standards were theoretically studied in comparison with former BMRC and ACGIH conventional curves for a wide range of industrial aerosols. Application of these standards to the measurement of health-related aerosol concentrations is discussed and performances of two respirable aerosol samplers, the CIP 10 and the 10 mm cyclone Dorr—Oliver are evaluated on laboratory experimental basis. The results show a complementarity of both instruments when used in various aerosol size distribution conditions. The 10 mm cyclone meets well the new CEN/ISO respirable convention in the case of fine aerosols (e.g., fumes) whereas the CIP 10 satisfies the same convention in the case of slightly coarser aerosols (e.g., mineral dusts).

KEY WORDS: Aerosol, Health-related sampling, Workplace exposure, Particle size fraction, Suspended matter, Measurement convention

INTRODUCTION

Aerosols inhaled by humans are fractionated during inhalation and penetration through the airways. The penetration efficiency is a function of many physical and physiological parameters, but it generally increases with decreasing particle size. Only a part of total ambient aerosol is inhaled and only the very fine particles reach the deep lung region. The particles deposited at different levels of the airways can cause various health effects which depend on their toxicological properties and on their deposition site (Fabriès, 1992). The specific alveolar toxicity (fibrogenicity) of dust containing crys-

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talline silica is well known in occupational hygiene. That was the historical reason to measure the "fine dust", and the so-called "respirable fraction" was the first fraction defined conventionally.

Recently the member countries of the CEN (Comité Européen de Normalisation) voted a new standard EN481 entitled "Specification for Conventions for Measurement of Suspended Matter in Workplace Atmospheres" (CEN, 1993). In the same time the ISO (International Standards Organisation) standard DIS7708 "Particle Size Fraction Definitions for Health-Related Sampling" (ISO, 1993) has been proposed. Both standards are equivalent in their definitions of Inhalable, Thoracic and Respirable aerosol fractions. The ACGIH joined the same conventions (ACGIH, 1994). These definitions are slightly different from the previous conventions BMRC (Orenstein, 1960), ACGIH (1985), etc. and try to unify the requirements on dust-exposure measurements in workplace. The present work discusses the scientific and practical improvements provided by the new sampling conventions to health-related aerosol sampling. The paper examines the main differences between the new and the former definitions and quantifies the bias in the mass concentration measurement between the new and the former respirable aerosol fractions. The CEN Task Committee 137 Working Group 3 is now discussing a prestandard "Sampler Performance Specification" (CEN, 1992), which deals with experimental testing and performance classification of sampling instruments to satisfy the EN481 criteria. However the development of this document still needs some prestandard research. This work is in progress through the European joint research project entitled "Pilot Study of CEN Protocols for the Performance Testing of Workplace Aerosol Sampling Instruments", and many of national research laboratories are involved in this research (Kenny, Lidén, 1989, 1991; Fabriès, 1990; Fabriès *et al.*, 1991; Fabriès, Görner, 1993; Kenny, 1992; Lidén, Kenny, 1992, 1993; Görner, Fabriès 1993; Bartley, Fischbach, 1993; Bartley *et al.*, 1994).

Two types of respirable aerosol samplers were chosen to demonstrate the importance of the particle-size depending performance tests and to show an example about how to take into account the performance data for practical measurements. The statistical data treatment of the tests is abbreviated with a care for clarity and simplicity.

THEORY

The new conventions concerning health-related aerosol sampling specify three aerosol fractions to be measured to assess the exposure of workers to industrial aerosols. The definition of these fractions was made regarding the dichotomous model of aerosol fractionation (Fig. 1):

The Inhalable fraction is defined as the mass fraction of all suspended particulate matter that can be able to penetrate the nose or the mouth of humans with averaged conditions of breathing rates, orientation and external wind speeds. The Thoracic fraction is the mass fraction of inhaled particles penetrating beyond the larynx. The Respirable fraction is the mass fraction of inhaled particles penetrating the unciliated airways. Inhalable, Thoracic and Respirable fractions were retained to build a basis of

air sampling conventions. Extrathoracic and Tracheobronchial conventions may be subsequently derived (CEN, 1993). English, French and German nomenclatures of main aerosol fractions are listed in Table 1.

In order to unify the nomenclature, the previous English term "Inspirable" was replaced by "Inhalable". In the case of the Alveolar fraction the previous English term "Respirable" was maintained because of its widespread utilisation in the field of occupational hygiene. In the German version the previous term "Gesamtstaub", which rather means "Total dust" than "Inhalable dust", was replaced by "Einatembar". Finally, the term "Feinstaub" was replaced by "Alveolengängig".

The choice of the aerosol fraction to be measured depends on regional aerosol toxicity. The Inhalable fraction should be retained in the case of wood dust (nose and sinuses cancer) or in the case of fast soluble toxics. The Thoracic fraction is obviously measured in the case of cotton dust (byssinosis). Recently the measurement of the thoracic fraction was recommended for particles containing some insoluble compounds of beryllium (Raabe, 1988). In fact, there is no specific toxicity for Be in the thoracic region, but the retention time of particles deposited beyond the larynx is long enough to dissolve even very slightly soluble particles (Finch *et al.*, 1988). This fraction might be also interesting for measurement of allergenic substances that can be bronchocon-

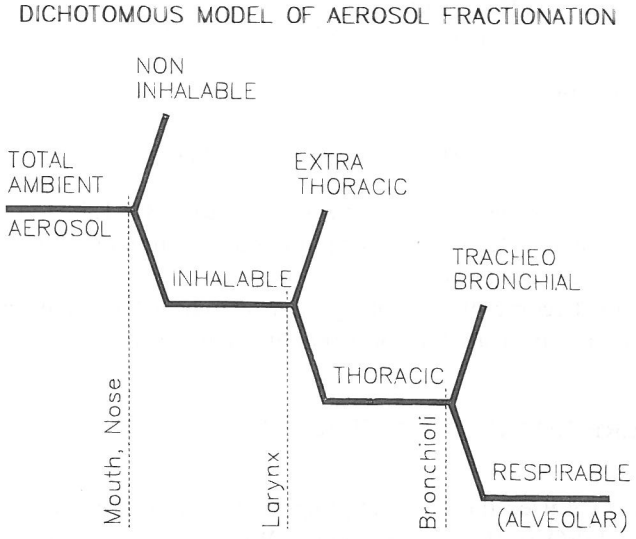


Figure 1 Dichotomous model of aerosol fractionation.

Table 1 Nomenclature of conventional health-related aerosol fractions.

English	*French*	*German*
Inhalable	Inhalable	Einatembar
Thoracic	Thoracique	Thorakal
Respirable	Alvéolaire	Alveolengängig

strictors (occupational asthma) (Alarie, 1973). Recent studies evoke this fraction to be advantageous for sampling asbestos and other mineral fibres (Dement, 1990, WHO, 1994). Finally, the classical respirable fraction is used to assess the workers exposure to fibrogenic dusts like quartz dust, hard metal carbides, etc. (silicosis and pneumoconiosis).

Health-related aerosol fractions defined above are the basis of the new air sampling conventions. The definitions of these conventions take into account recent data (Vincent and Armbruster, 1981, Heyder *et al.*, 1986) and they are expressed like penetration probabilities P as a function of particle aerodynamic diameter Dae (Soderholm, 1989):

Inhalable convention:

$$\begin{aligned} &Pi(Dae) = 0.5[1 + \exp - (0.06\ Dae)] \text{ for } Dae < 100\mu m \\ &[Dae] = \mu m \end{aligned} \quad (1)$$

Thoracic convention:

$$Pt\ (Dae) = Pi\ (Dae) \times [1-F(x)] \quad (2)$$

where F(x) is the cumulative probability function of a standardised normal variable x:

$$x = \frac{\ln Dae\ -\ \ln A}{\ln B} \text{ where } A = 11.64\ \mu m;\ B = 1.5$$

Respirable convention:

$$Pr(Dae) = Pi(Dae) \times [1-F(x)] \quad (3)$$

where x is the same variable as above and $A = 4.25\ \mu m$; $B = 1.5$

Resulting particle-size dependent probability curves are plotted in Fig. 2 and some key probabilities are listed in Table 2.

Each convention becomes the sampling criterion to be achieved by any air sampling instrument in order to measure the corresponding aerosol fraction.

SAMPLER PERFORMANCE SPECIFICATION

After having standardised the new sampling conventions, the working groups CEN TC/137/WG3 and ISO TC/146/SC2&3/ad hoc WG are now working on a text entitled "Assessment of Performance of Instruments Used for the Health-Related Sampling of Particles in the Workplace". According to the draft in discussion (CEN, 1992) the performance of any sampling instrument shall be tested in laboratory conditions, placed in a well-defined test aerosol to establish the particle-size dependent collection efficiency of the instrument with various conditions of external flow. No reference sampling device should be used and the inter-comparison of two samplers as performance test should not be allowed. The results of several test runs will be statistically evaluated and the overall performance of instrument classified according to some specific

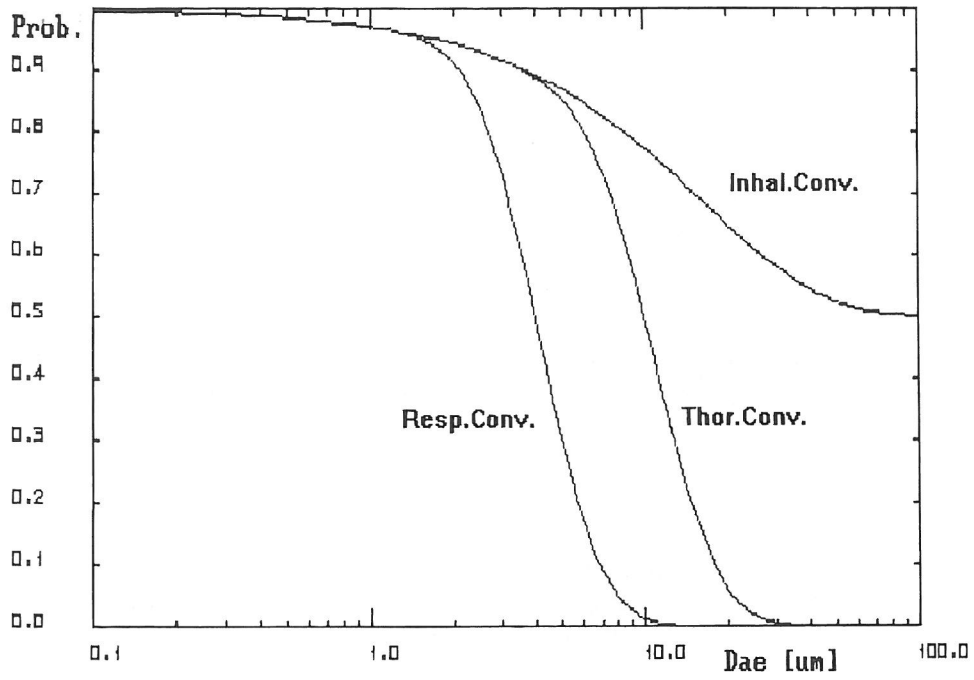


Figure 2 The EN481 Sampling conventions.

Table 2 Particle sizes for 0%, 50% and 100% probability of penetration for each aerosol fraction.

P *[%]*	*Inhalable* *[μm]*	*Thoracic* *[μm]*	*Respirable* *[μm]*
100	0	0	0
50	100	10	4
0	—	50	16

criteria. The classification criteria are not yet definitely stated. A scheme of the sampler performance test is given as follows (CEN, 1992):

Critical review of sampling process

Choice of experimental design

Measurement of sampling efficiency

Interpolation between measured values

Comparison with convent, curves

Computation of bias maps

Computation of precision maps

Classification of sampler according to its performance

Analysis of variance
Calculation of flow related values
Computation of inaccuracy maps

The experimental part of instrument performance test will be carried out in laboratory conditions which have to be fully described in the CEN draft document (CEN, 1992). The experimental run yields instrument sampling efficiency as a function of particle aerodynamic diameter. Mathematical treatment of experimental efficiency data will enable to modelise the sampler's behaviour in various polydisperse aerosols and to assess the statistical meaning of the results. Sampler classification is then estimated on a basis of bias maps, taking into account the precision and inaccuracy of measurement. The statistical approach of the precision and inaccuracy calculation is still in discussion (Kenny, 1995).

Calculation of Bias Maps

Sampler measurement bias is the difference between the mass concentration measured by a sampling instrument "Csamp" and the mass concentration to be measured, following exactly the sampling convention "Cconv".

$$\text{Bias} = \frac{\text{Csamp} - \text{Cconv}}{\text{Cconv}} \tag{4}$$

The measurement bias is strongly dependent on particle-size mass distribution (Fabriès, 1992). For any aerosol distribution it is possible to calculate the Csamp and Cconv as shown in Fig. 3 and described by following equations:

$$Csamp = Co\int_0^\infty E(Dae) \times Fm(Dae) \times d\ln Dae \tag{5}$$

$$Cconv = Co\int_0^\infty P(Dae) \times Fm(Dae) \times d\ln Dae \tag{6}$$

where Fm (Dae) is the aerosol mass distribution function
E (Dae) is the sampling efficiency of instrument under test
P (Dae) is the conventional probability of penetration
Co is the concentration of total ambient aerosol taken here as 1 mg/m^3

The CEN draft document (CEN, 1992) requires calculation of bias for a wide range of log-normally distributed aerosols with following parameters: aerosol MMAD (Mass Median Aerodynamic Diameter) range from 1 to 25 μm in steps of 1 μm and aerosol GSD (Geometric Standard Deviation) range from 1.5 to 3.5 in steps of 0.25. The calculated bias values shall be plotted in the form of bias map with the MMAD and GSD values as abscissa and ordinate.

The maximum allowed bias in sampled concentration for any aerosol distribution is ±10%. The sampler performance can be evaluated by a classification index which is

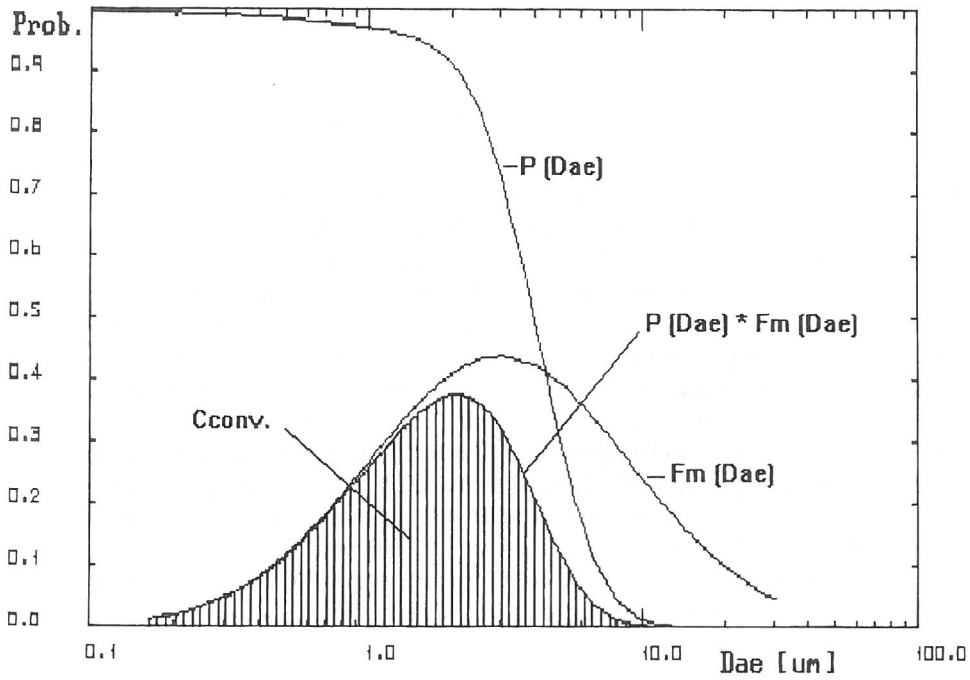


Figure 3 Scheme of Cconv calculation.

the ratio of aerosol distributions for which the bias is less than ±10% among all the aerosols with GSD ≥ 2. (CEN, 1992; Görner and Fabriès, 1993). The classification should be supplemented by accuracy maps that are not discussed here for simplification purposes, because the statistical design of the accuracy data treatment is still in discussion, as it was already pointed out.

COMPARISON OF THE NEW EN481 RESPIRABLE CONVENTION TO THE FORMER CONVENTIONS BMRC AND ACGIH

BMRC (British Medical Research Council) Respirable convention (Orenstein, 1960). The respirable penetration probability Pr as a function of the particle aerodynamic diameter Dae is as follows

$$\Pr(Dae) = 1 - (Dae/7.06)^2 \text{ for } \Pr(Dae < 7.06\ \mu m) = 0 \quad (7)$$
$$[Dae] = \mu m$$

ACGIH (American Conference of Governmental Industrial Hygienists) Respirable convention (ACGIH, 1985).

$$\Pr(Dae) = 1\ F(x) \quad (8)$$

where F(x) is the cumulative probability function of a standardised normal variable x:

$$x = \frac{\ln Dae - \ln A}{\ln B} \text{ where } A = 3.5\mu m;\ B = 1.5$$

The BMRC and ACGIH Respirable conventions represented by equations (7) and (8) are plotted in Fig. 4 along with the new EN481 Respirable convention (CEN, 1993).

It is possible to calculate the bias in mass concentration between the former Respirable conventions and the new EN481 convention as explained in the previous paragraph. The concentration Csamp in equation (4) corresponds to the BMRC or ACGIH "ideal" sampler respectively. Resulting bias maps are plotted in Fig. 5,6. They represent the performance of previous "ideal" samplers that satisfy exactly the former conventions, but used in the context of the present-day standardisation. These three conventions seem to be close to each other (Fig. 4) but the performance of instruments satisfying exactly the BMRC or ACGIH conventions exhibit rather poor performance when compared to the new EN481 standard: the classification index is only 19.4% for the BMRC and 21.1% for the ACGIH (Fig. 5,6). This means that the "ideal" BMRC or ACGIH sampler would measure within the ± 10% bias interval only 19.4% or 21.1% of aerosol distributions in test (Fig. 5,6).

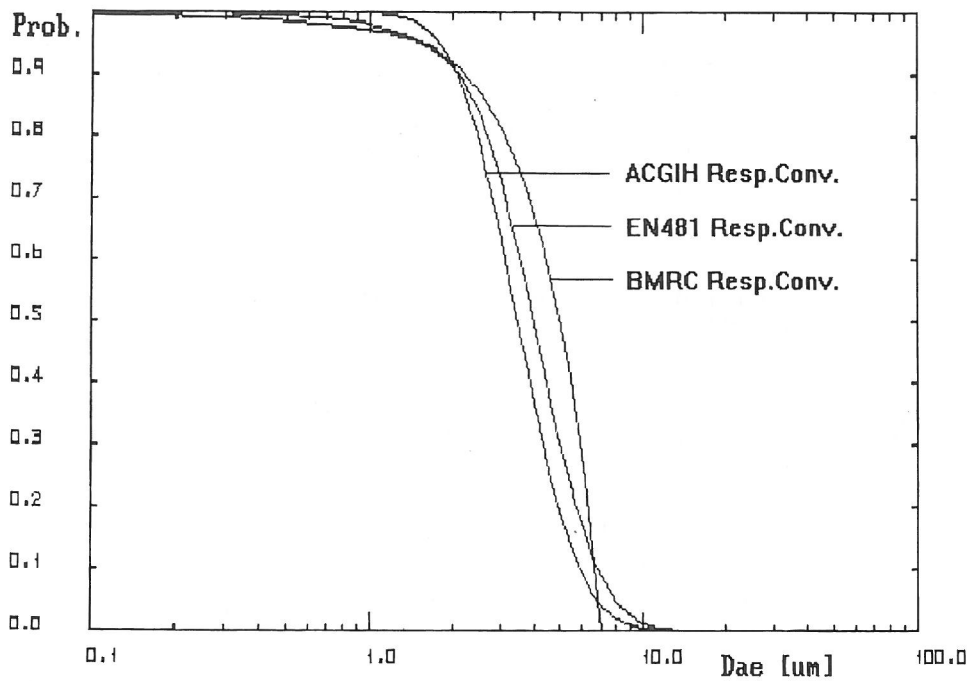


Figure 4 ACGIH, BMRC and EN481 Respirable conventions.

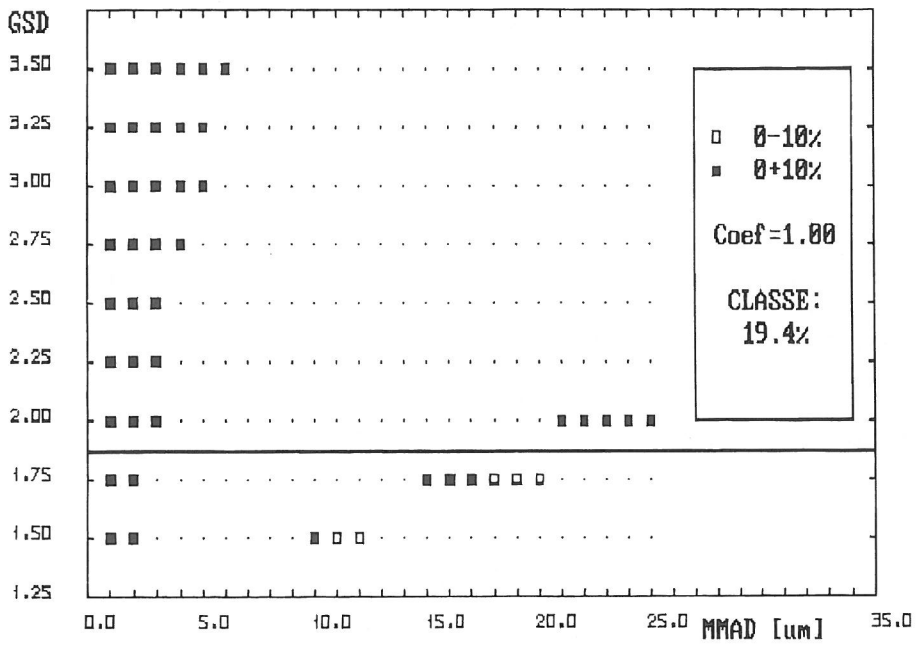


Figure 5 Bias map: BMRC/EN481 Respirable convention.

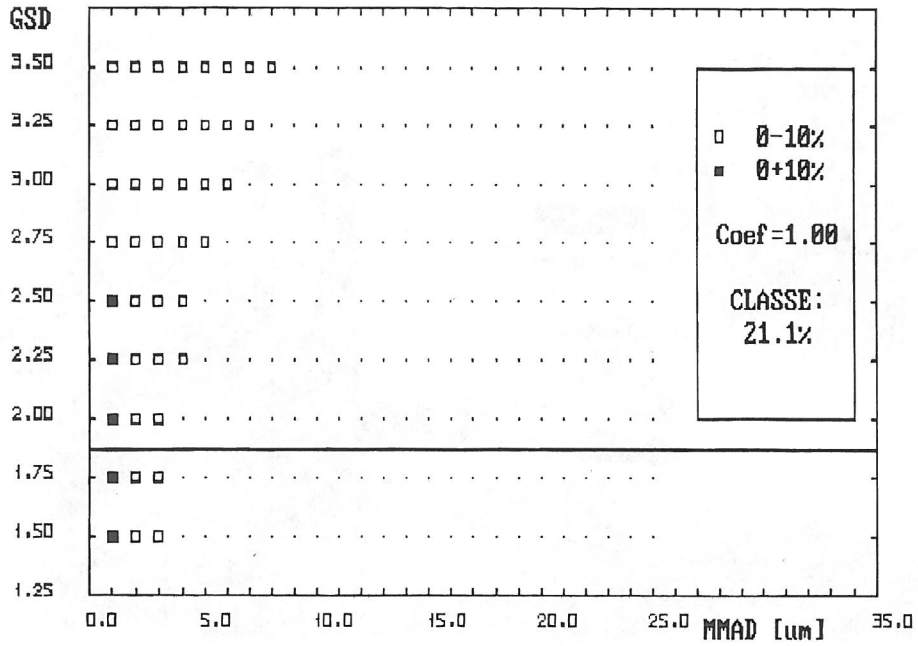


Figure 6 Bias map: ACGIH/EN481 Respirable convention.

PERFORMANCE OF SOME SELECTED PERSONAL RESPIRABLE SAMPLERS

Two personal samplers used in several countries to measure the mass concentrations of aerosol respirable fraction in the workplace were tested as examples. Other instruments could have been considered as well. The first one is the US 10 mm cyclone Dorr—Oliver (Baron, 1981, Fabriès, 1990) with a flow rate of 1.7 l/min obtained from an external pump (Fig. 7). The second one is the French device CIP 10 (Courbon 1987, Courbon *et al.* 1988, Fabriès, 1990), with a flow rate of 10 l/min obtained from an internal air mover (Fig. 8,9). Sampling efficiencies of these devices were experimentally measured in laboratory conditions. The experimental equipment and the method for the measurement of particle size-dependent sampling efficiency were described elsewhere Fabriès *et al.*, 1984, 1991). The least square fitting of the experimental efficiency data E(Dae) by a cumulative log-normally distributed model F (x) yields the following efficiency curves (Fig. 10,11):

Cyclone 10 mm Dorr-Oliver, 1.7 l/min:

$$E(Dae) = 1 - F(x)$$

$$\text{where } x = \frac{\ln Dae - \ln A}{\ln B} \text{ and } A = 3.804\ \mu m;\ B = 1.335 \qquad (9)$$

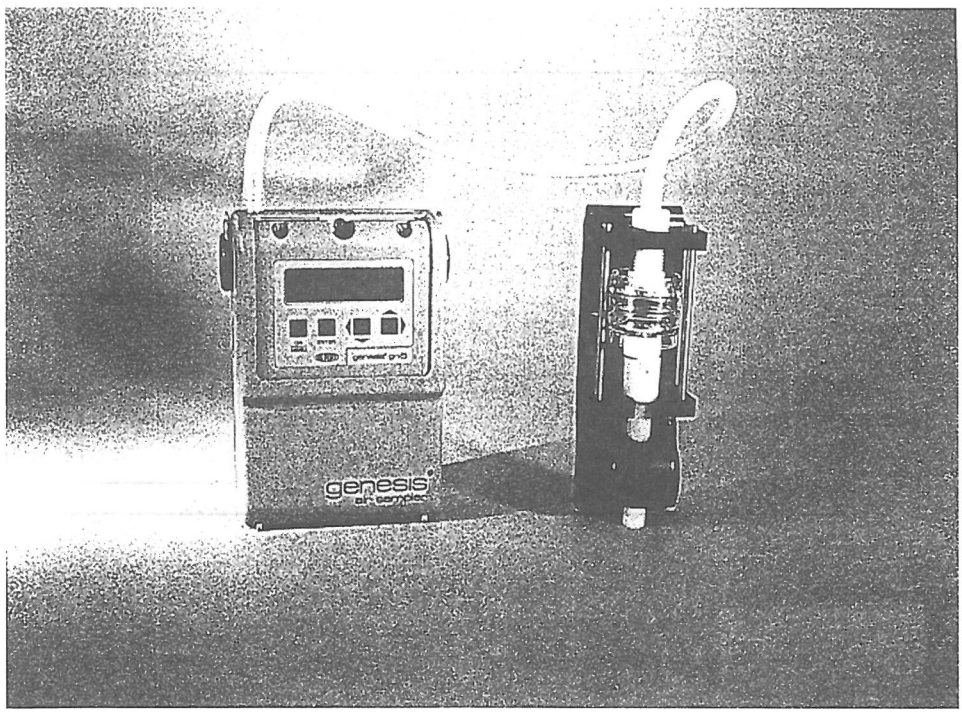
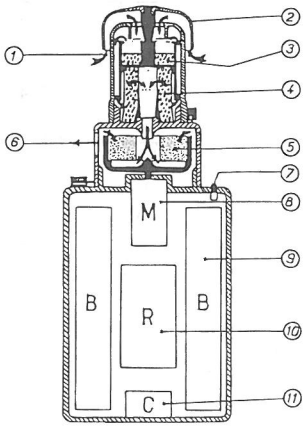


Figure 7 10 mm cyclone Dorr-Oliver respirable dust sampler with a pump.

Figure 8 Respirable aerosol sampler CIP 10.



CIP 10

NOMENCLATURE			
①	Air inlet	⑥	Air outlet
②	Inlet protector	⑦	ON-OFF Diode
③	Impactor	⑧	Motor
④	Selective foam	⑨	Batteries
⑤	Rotating cup	⑩	Regulation
		⑪	Recharging socket

Figure 9 Schematic diagram of the CIP 10.

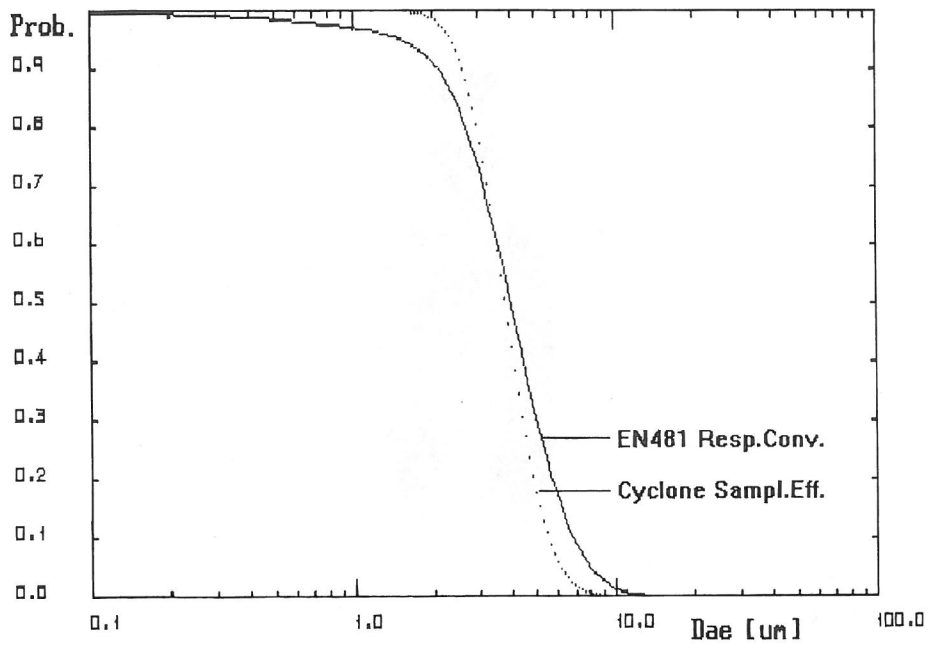


Figure 10 Sampling efficiency of the 10 mm cyclone.

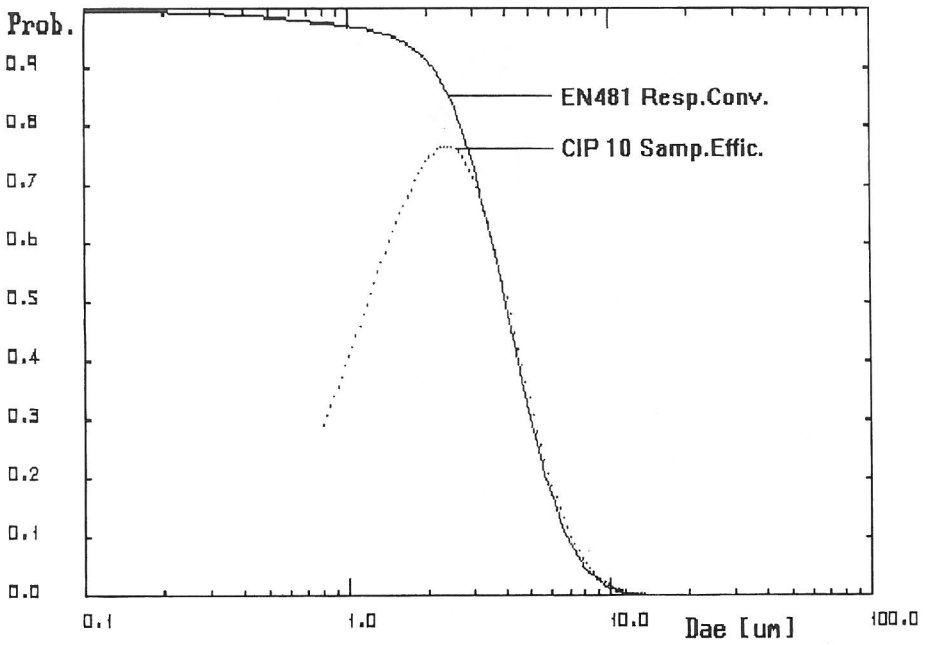


Figure 11 Sampling efficiency of the CIP 10 instrument.

CIP 10 (Capteur Individuel de Poussière), 10 l/min:

$$E(Dae) = E1(Dae) \times E2(Dae) \quad (10)$$

where:

$E1(Dae) = 1 - F1(x)$ with x as above and $A1 = 4.189\ \mu m$; $B1 = 1.505$

$E2(Dae) = F2(x)$ with x as above and $A2 = 1.187\ \mu m$; $B2 = 2.044$

It should be mentioned that the sampling efficiency of the CIP 10 exhibits a maximum for a particle size close to 2 μm and then decreases with decreasing Dae (Fig. 11). This fact is due to the rotating collection filter of the CIP 10 which is made of a cylindrical polyurethane foam with central inlet and radial outlet, placed in a rotating cup. The filter is not only the particle collection stage but also an air mover ensuring the air flow of the instrument. Its filtration efficiency is not total for very fine particles which are partly rejected into the atmosphere (Görner *et al.*, 1990) like particles inhaled by humans (Heyder *et al.*, 1986). The influence of this phenomenon on measured mass concentration strongly depends on aerosol size distribution, and it is quite important only for very fine aerosols like fumes. For the CIP 10 the performance index is 74.9% of test aerosols within the interval ±10% of mass concentration bias (Fig. 13). The cyclone performance index is 44.6% (Fig. 12). Sampling performances of these two instruments are not only different but also complementary: The cyclone is more performant in the case of fine aerosols (e.g., welding fumes), and the CIP 10 covers well the common range of industrial aerosols (e.g., mineral dusts) (Fig. 12,13).

DISCUSSION

The new EN481 standard (CEN, 1993) replaces the former size-selective sampling conventions. It was developed on the basis of recent advances in biophysical research in the field of particle penetration through the human respiratory tract. Most important standardisation organisations, CEN, ISO, and many national industrial hygiene authorities, ACGIH (American Conference of Governmental Industrial Hygienists USA), HSE (Health and Safety Executive UK), BIA (Berufsgenossenschafliches Institut für Arbeitssicherheit D), INRS (Institut National de Recherche et de Sécurité F) and many others, contributed to elaboration of new aerosol sampling conventions. The advantage of this large international agreement will be a single convention per fraction avoiding the development of national conventions as it was the case in the past.

The Respirable EN481 convention seems to be close to the former conventions BMRC and ACGIH for this fraction. However the utilisation of sampling instruments satisfying these old conventions could considerably bias the measurement of the new conventional Respirable fraction (Görner, Fabriès, 1992).

The proposed performance test procedure clearly shows the importance of the choice of the sampling technique with respect to the presumed aerosol size distribution for correct sampling. It would be difficult to satisfy all aerosol situations with a single instrument (except if it is classified with a performance index = 100%). The solution would be to know well the performance of any device and to use it always

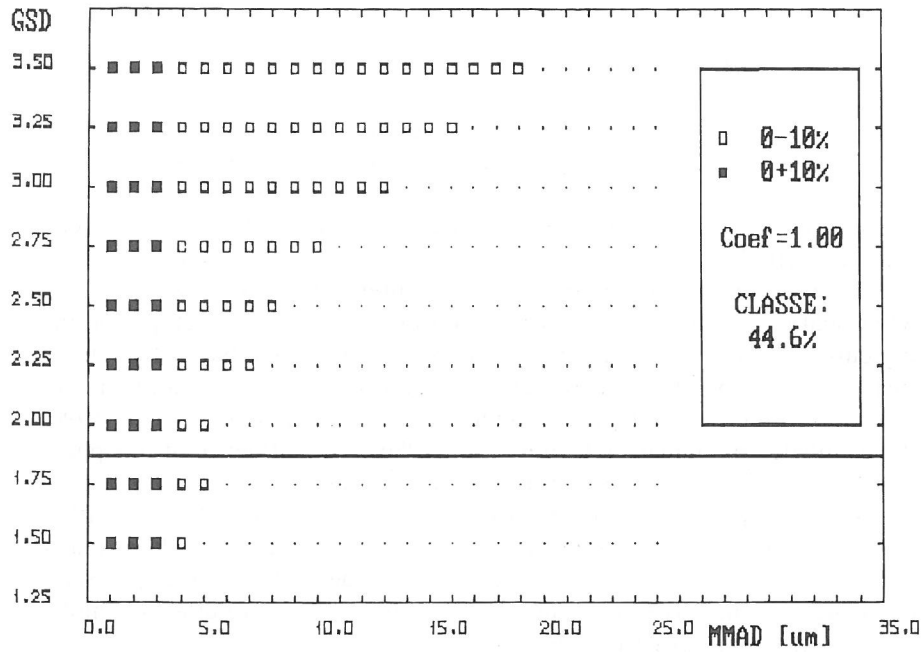


Figure 12 Bias map: Cyclone/EN481.

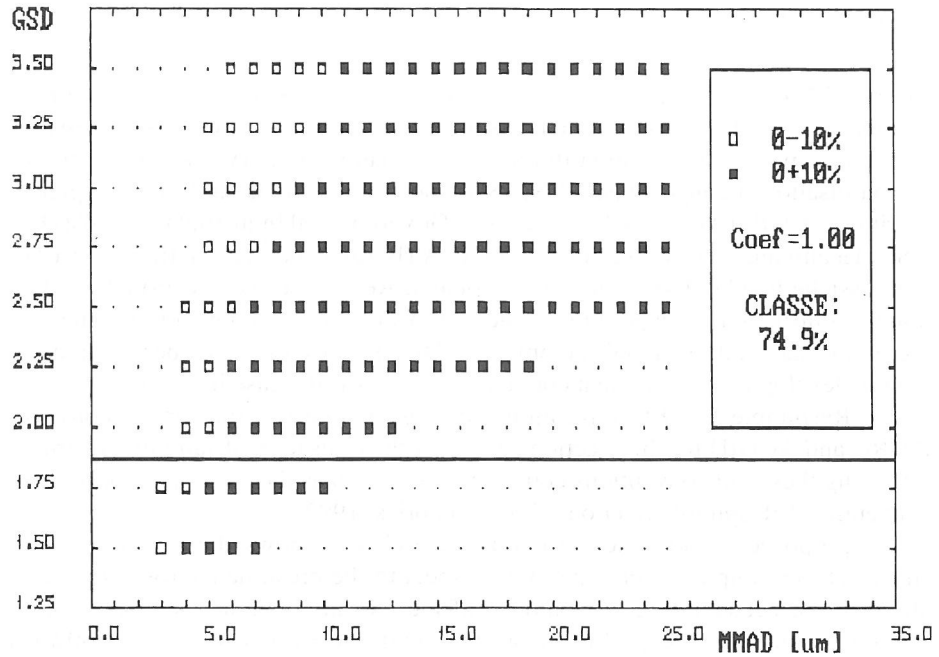


Figure 13 Bias map: CIP10/EN481.

in appropriate situation. There is no more so-called "reference sampler". A sampler inter-comparison in field conditions, largely carried out in the past, is only valid for one specified situation of the field aerosol size-distribution and cannot be extrapolated to other situations. Therefore, such comparisons cannot be considered as performance test.

The statistical treatment of the experimental performance tests is the topic of a pre-standard research and is still in development within the "Pilot Study Steering Committee" (Kenny, 1995). When this work is accomplished, the calculated bias corresponding to the test would be supplemented by their precision and accuracy, and these values should be taken into account in the aerosol sampler performance classification.

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