SAMPLING OF AIRBORNE DUSTS IN WORKPLACE ATMOSPHERES

by

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Abstract

Protection of workers from intakes of airborne dusts is receiving increased attention as part of the overall emphasis on minimisation of occupational exposures. So sampling of airborne dusts in workplace atmospheres have been – and continue to be – a major focus of industrial hygiene in both nuclear and non nuclear sectors. This paper provides an overview of aerosol sampling as it relates to different issues, in particular in response to the recent emergence of the health-related particle size-selective criteria. It appears that aerosol sampling continues to require further understanding and development in order to provide arguments about the choice of the sampling strategy in workplaces.

Introduction

Aerosol sampling is carried out by industrial hygienists for a variety of different, but related, reasons. The first is for the assessment of the workplace atmosphere so that aerosol characteristics can be compared against the health-related exposure limits, thus providing a basis for decisions on control action. The second is to provide valid measurements of worker exposure for the epidemiological studies. The third is for the measurement of aerosol characteristics in exhaust ventilation systems to assess the effectiveness of emission control equipment.

Aerosol exposure by inhalation is of great interest in occupational health, representing a major source of hazard in many occupational environments. The nature and magnitude of the hazard in a given situation depend on a combination of many factors, including: (a) particle size distribution (which governs how the aerosol is inhaled, and how it penetrates into and is deposited in the respiratory tract); (b) airborne concentration (which governs how much is deposited); and (c) morphology, chemical composition (which governs the fate and biological responses to the presence of particles).

In the early 1980's, the industrial hygiene and aerosol science communities became aware that sampling for aerosol exposure assessment was not as simple as previously thought. In particular, it was realized that simply drawing air through a filter and measuring the particle matter that is collected is not truly representative of either true total ambiant aerosol or what workers are actually exposed to.

This paper examines different issues, giving the state-of-art based on literature, concerning the sampling of airborne dusts in workplace dealing specifically with: (a) the new standards for health-related aerosol measurement, (b) the assessment of performances of aerosol sampling instruments, (c) the comparison between personal and static (or area) sampling, (d) the sampling instrumentation. Finally, areas for development are proposed that should receive attention by people in charge of assessment of workers exposure by aerosol sampling. Several comprehensive books or guides already exist that deal with aerosol sampling: AIHA (1996), ACGIH (1996), Renoux and Boulaud (1998), Vincent (1989 and 1995), Willeke and Baron (1993). However, some studies recently published on the specific topics are included in this paper.

Particle-size fractions for health-related aerosol measurement

The first part of the overall process of aerosol exposure is the entry by inhalation of particles from ambient air and into the respiratory tract. Once inhaled, aerosols are fractionated during penetration through the airways, and the particles deposited at different levels can cause various health effects which depend on their (radio)toxicological properties and on their deposition site (Fabriès, 1992). In consequence, health-related aerosol sampling criteria should first reflect the aerodynamic process by which particles initially enter the body during the act of breathing (through the nose and/or the mouth) and by which they are subsequently deposited in the various part of the respiratory tract.

Based on results from experimental studies conducted in different laboratories, international agreement between CEN [Comité Européen de Normalisation, CEN (1993)], ISO [International Organization for Standardization, ISO(1995)] and ACGIH [American Conference of Governmental Industrial Hygienists, ACGIH (1996)] has been achieved on a common set of particle size-selective criteria. These specify that health-related sampling should be based on one or more of the three, progressively finer, particle size-selective fractions: inhalable (the aerosol fraction which enters the nose and/or the mouth during breathing), thoracic (the subfraction of inhalable aerosol which penetrates into the respiratory tract below the larynx and respirable (the subfraction of inhalable aerosol that penetrates down to the alveolar region of the lung). These fractions are expressed as curves which relate the probability of inhalation, or of penetration to the thoracic or alveolar regions, as functions of particle aerodynamic diameter. The particle-size dependent curves are plotted in Figure 1. The choice of the aerosol fraction to be measured in a specific workplace depends on regional aerosol (radio)toxicity.

Each curve becomes the sampling criterion to be achieved by any aerosol sampling instrument in order to measure the corresponding aerosol fraction (Görner and Fabriès, 1996).

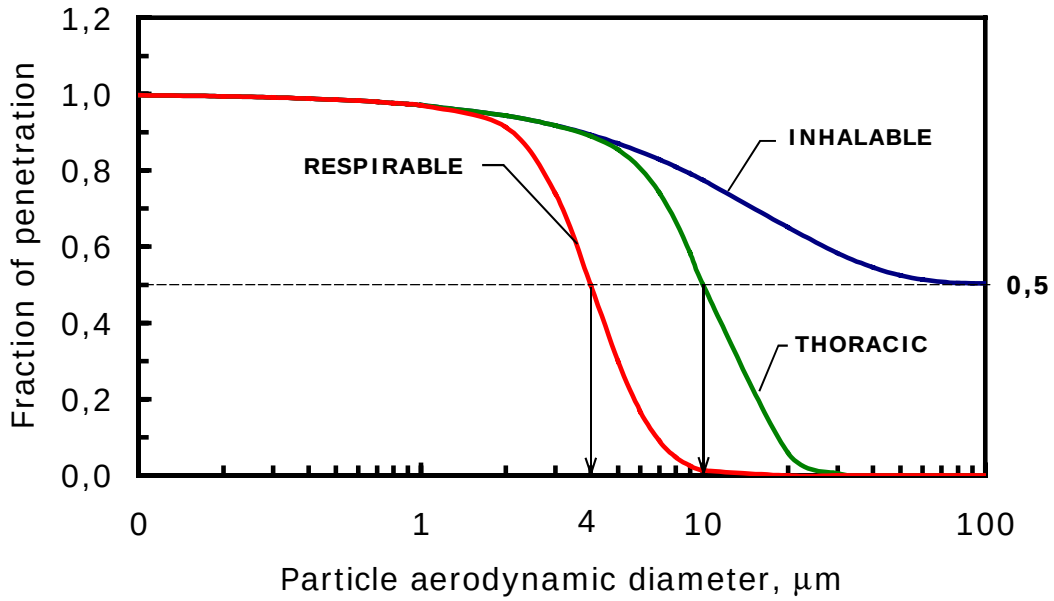

Figure 1 : Particle size fractions (i.e. inhalable, thoracic, respirable) for health-related sampling in workplaces that have been internationally agreed by CEN, ISO and ACGIH.

As an example, Figure 2 shows the particle size distributions for the three fractions and for the "total" ambient aerosol. The three particle size distributions have been calculated from the curves shown in Figure 2 and based on the particle size distribution of the ambient aerosol. The latter was assumed to follow a log-normal distribution, and defined by an activity median aerodynamic diameter (AMAD) of 8 µm and a geometric standard deviation (σ_g) of 2.5, which could be considered to be representative of some workplaces in the nuclear industry (Ansoborlo *et al.,* 1997; Dorrian and Bailey, 1995). In the present example, the results show that the activity concentration contained in the inhalable, thoracic and respirable fractions ($F_{Activity}$) are respectively 79, 55 and 24 % of the total activity of the ambient aerosol. The AMAD moves from 7 µm for the inhalable fraction to 5 µm and 2.9 µm for respectively the thoracic and the respirable fraction.

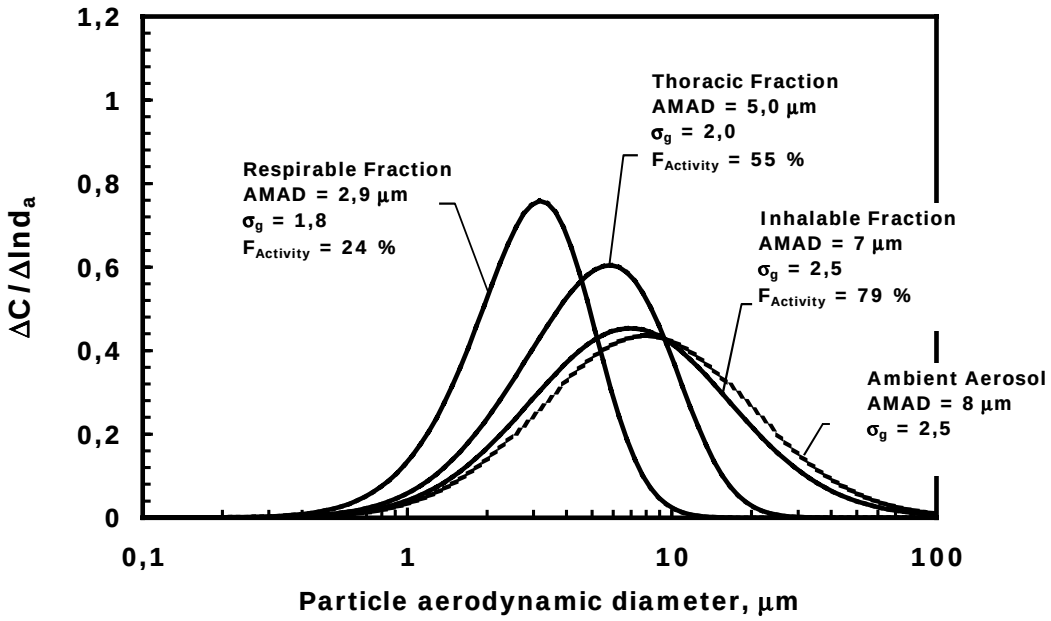

Figure 2 : Particle-size distributions and normalised concentrations for the four fractions (i.e. total, inhalable, thoracic, respirable) assuming a log-normal particle size distribution for the total ambient aerosol.

The importance of well defining the inhalable aerosols is obvious because it provides the basis for describing the fractions of particles depositing in the respiratory tract. The sampling convention for inhalability is derived from measurements made in a large wind tunnel using a life-sized manikin exposed uniformly (by rotating) to all wind directions (windspeeds in the range of approximately 1 to 4 m/s), and to homogenous particle concentration and particle sizes between few micrometers up to close 100 µm. However, in real indoor workplace situations, workers (and inhalable dust samplers) are normally exposed to low air velocities rarely exceeding 0.3 m/s (Baldwin and Maynard, 1998), and may be exposed to particles larger than the upper limit of the sampling inhalable convention. Thus, it is possible that the current definition of the inhalability may be inappropriate under some circumstances. Recently, Aitken *et al.* (1999) and Hsu and Swift (1999) have investigated inhalability of human nose/mouth under calm air conditions and ultralarge aerosols. Results from these two studies show large differences which are not well explained. Even if these studies provides a useful starting point for future discussions of what could be a new convention, further work is clearly desirable.

Assessment of performance of aerosol sampling instruments

The first important aspect of the performance of an aerosol sampler is the efficiency with which particles are transferred by aspiration from the air outside the sampler and into the sampler through its one or more entry orifices. The aspiration efficiency is a strong function of particle size, sampling flow rate, windspeed, sampler orientation, sampler size and shape. After aspiration, the particles are usually transported through some sort of duct to a filter or to a sensing zone (for direct-reading aerosol instruments). During such transport, deposition on the internal walls of the sampler may take place by a variety of mechanisms (sedimentation, inertial impaction, electrostatic attraction). As an example, Figure 3 illustrates the process that may change the aerosol concentration and size distribution during sampling: aspiration to the face of the entry orifice at arbitrary orientation with respect to the incoming moving air flow, bounce from the edge of the orifice, transmission loss in the duct due to gravitational settling, direct wall impaction and turbulence in the vena contracta which is formed when the aspiration velocity exceeds the outside winspeed. A number of experimental and theoretical works have been (and continue to be) devoted for studying the sampling process, leading to the development semi-empirical models or generating large amount of experimental data. However the fact is the scenario is extremely complicated. The study of the basic physical performance characteristics of aerosol samplers is needed because it provide insights to enable the improved development of new instruments to be used by occupational hygienists.

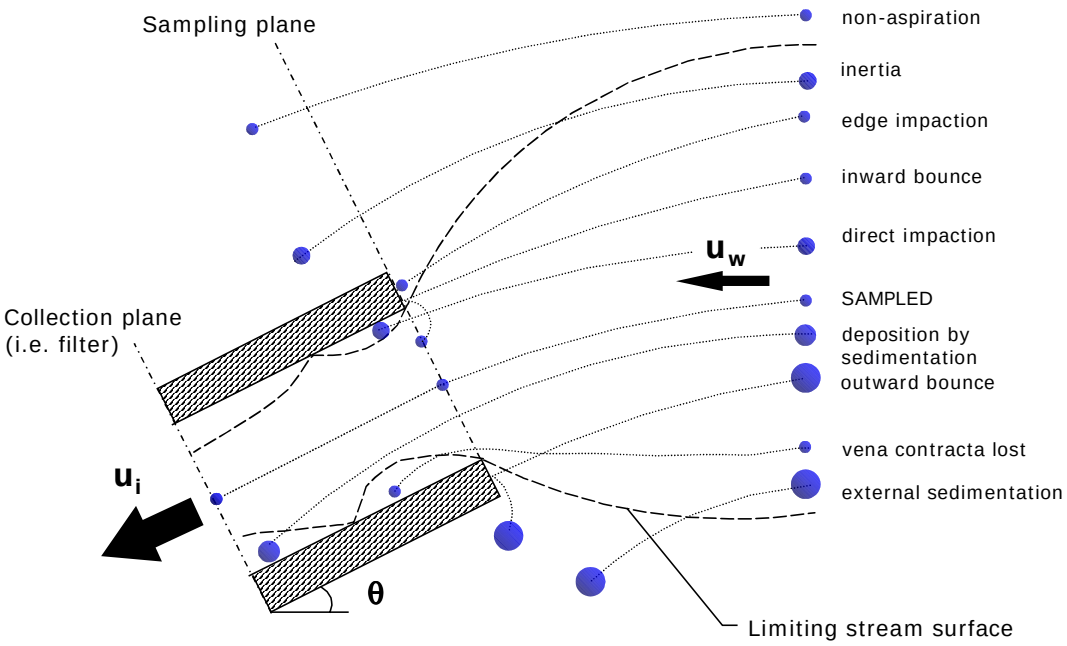

Figure 3 : Schematic representation of the mechanisms that affect the overall efficiency of a sampling inlet.

As seen above in the text, the purpose of particle size-selective criteria such as those described in Figure 1 is to provide "yardsticks" for the performances of aerosol samplers dedicated to single, individual health-related fractions. That is, the sampling efficiency of a given sampler intended for a given aerosol fraction should follow (or come sufficiently close) to the appropiate curve.

Table 1 gives an informative list of the principal factors known to influence the performance of aerosol sampling instruments, and examples of the instruments for which they can cause measurable effects.

Table 1 : Factors influencing the performance of aerosol samplers.

FACTOR	NATURE OF EFFECT	SAMPLER TYPES
Particle size	Size-dependent selection of particles (aspiration, deposition)	All samplers
Wind speed	Affect aspiration of particles (large particles)	Any sampler not having an isokinetic inlet (moving air)
Wind orientation	Affect aspiration of particles (large wind speed)	Any sampler not having an omnidirectional inlet
Nearby human body	Affect flow field near inlet	Many inhalable samplers
Wind turbulence	Variability of the aspiration	All samplers having wind speed and orientation dependance
Aerosol composition	Particle bounce or re-entrainment Breakdown of agglomerates	All samplers having large bluff body

Humidity	Mass variation of filter cartridge	All sampler using a filter cartridge system
Inlet shape	Orientation-dependent and deposition of particles Oversampling of very large particles Passive sampling	Especially inhalable samplers
Inlet-filter geometry	Transmission losses Uniformity of sampled aerosol	Many samplers
Filter sealing	Particle deposition on the periphery of the filter may be lost	All samplers using directly filter
Sampler integrity	Particles my be lost due to leakage especially around filter	Any sampler not airtight
Sampler handling	Variability of the results due to difficulties during diassembing	Any samplers not user-friendly

Specimen variability	Small dimensional differences may cause large aerodynamic effects	e.g. cyclones, impactors
Sampled aerosol mass	Collection efficiency changes for heavily loaded surfaces	e.g. impactors, samplers using porous foam as selector
Electrostatic charge	Attraction to and repulsion from surfaces	Any sampler build with non-conducting material
Flowrate variation	Particle separation mechanism strongly flow-dependent	e.g. cyclones, elutriators, impactors
Surface treatments	Collection efficiency depends collection surface or medium	e.g. impactors, impingers

When using different instruments in workplaces, the data from the different samplers may differ from each other significantly since each sampler has its own design. Thus, it is important to determine the performance characteristics with respect to the sampling curve of interest for each available samplers. To evaluate the sampler performance, the development of an adequate test protocol is essential.

The air flow field around a personal aerosol sampler is different when the sampler is mounted on a person than when it is freestanding. Thus, personal aerosol samplers should be evaluated on a life-sized mannequin simulating the human body. Static (or area) samplers are evaluated as freestanding devices.

A recent study, carried out by Kenny *et al.* (1997) under the auspices of the European Commission to evaluate the performance of eight available personal inhalable samplers, has

clearly shown that experiments of this type (life-size mannikin, large wind tunnel, …) are difficult and expensive, and generally give results with poor precision. Recent works suggest new way of making the wind tunnel evaluation simpler and less expensive. The first approach consists of testing the personal sampler on a simplified smaller well-defined torso (Witschger *et al.,* 1998). The second approach uses scaling relationships to prescribe experimental conditions and small-scale sampler design that can be tested in small wind tunnel (Ramachandran *et al.,* 1998). Although these two approaches acknowledge the need for a new testing protocol, progress still have to be made in order to provide an appropriate and validated protocol to the occupational aerosol community.

Field test are carried out for comparisons of various samplers. Analysis of data from field study allow to obtain a correction function that relates aerosol concentrations measured by a given sampler to those measured by an other sampler taken as reference. It is important to have in mind that the correction function is specific to the workplace activity(ies) included in the field study and cannot be assumed to apply to different circumstances. Because of the typical variability of aerosol concentration in the field, it is difficult to use these situations for accurate assessment of sampler performance. However, field studies are important to verify the overall performance of a sampler, and to indicate specific sampler problems that are usually highlighted only in the field.

Sampling strategy : Static (or area) vs. personal aerosol sampling

There is the question of how best to reflect the true exposures of individual workers (or of groups of workers). The nature of the problem is illustrated in Figure 4. One option is to performed stationary (or area) measurement, where the chosen instrument is located in the workplace atmosphere. The other option is personal measurement, with the chosen instrument mounted on the body, and usually located in the "breathing zone", and moving around with the worker at all times. Although the static sampling is originally dedicated to characterise the aerosol in the whole area, both of them are usually intended for providing a measurement of aerosol concentration and particle size distribution that one hopes is representative of what the worker is exposed to. Ideally, in a perfectly mixed indoor room situation, the aerosol in the breathing zone is the same that in all part of the workplace room.

When choosing one or other of these options, some important considerations need to be taken into account. In workplace, the ventilation, the presence of objects, the worker himself impose constraints on the air movement and so modify the transport of particles. Figure 5

shows the ratios between personal and static sampling measurements reported in the litterature for different environments. The unity ratio represents well-mixed situation with no predominant single source of contamination. It is clear that there is no single ratio, the ratio of personal/static measurement can be very large as well as less than the unity. This strongly suggest that care must be taken when the assumption of well-mixed environment is made to estimate exposure.

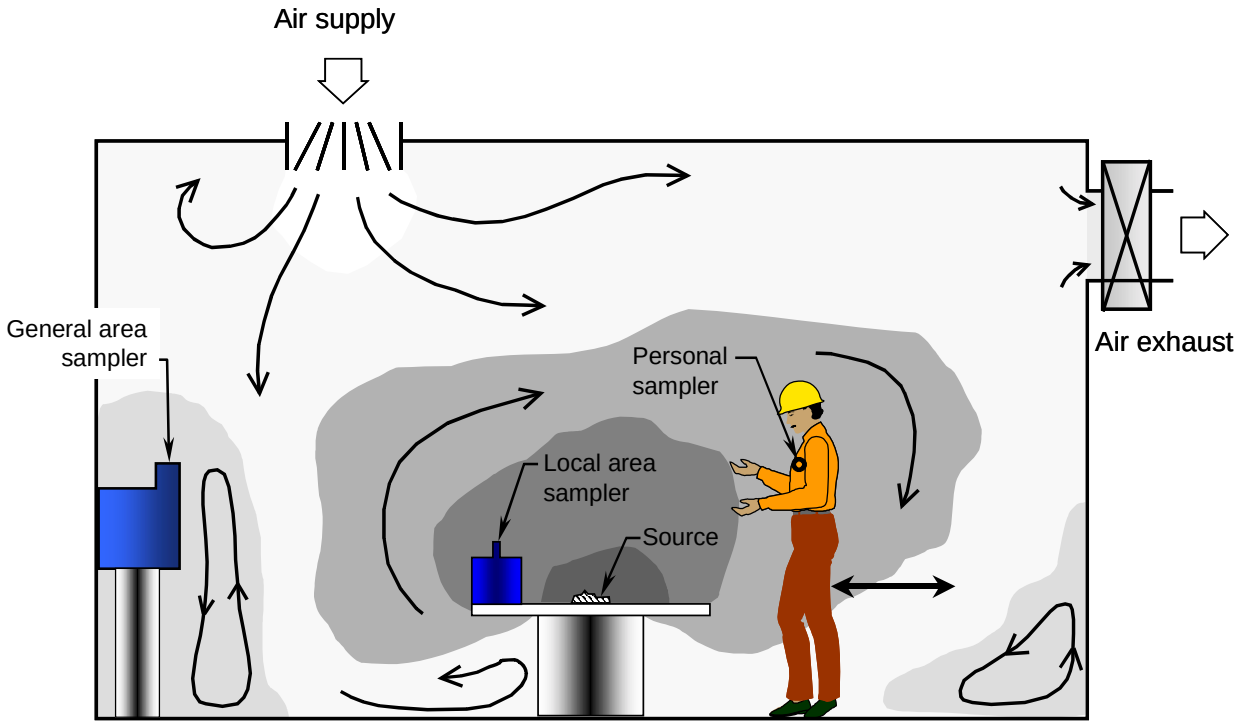

Figure 4 : Illustration of the particulate contaminant dispersion in a ventilated laboratory and the vicinity of a worker. The nature of the aerosol transport and the sampling performances of the samplers account for differences that are usually measured.

Area sampling provide advantages in some situations where concentrations are low and particles are fines, and a high flow rate is required to provide a measurable sample. Furthermore, area sampling is a cost-effective exercise, and has often been employed to attempt to generalise measurements to the workers of a large area. The use of personal samplers is more labour intensive. Futhermore, it involves the cooperation of the workers themselves. However, personal sampling is by far (and widely accepted by industrial hygienists) the most mode of aerosol measurement for aerosol exposure assessment in workplaces.

The representativity of the personal sampling is based on the "breathing zone" concept. The "breathing zone" is somewhat defined as the hemisphere space (generally accepted to be 0.3 m in radius) around the worker's face where he takes his breath. Thus, that is the proximity of the personal sampler which insures the fact that the sampled aerosol (in terms of amount and particle size distribution) corresponds to the inhaled aerosol by the worker. Such guidance can lead to a false sense of security since it does not follow that, just because a sampler is mounted in this manner, it will necessarily collect the same amount of aerosol.
A factor that may not have been recognised in the studies that tried to correlate personal to static sampling is the bias in the aerosol concentration resulting from the poor performances of the static or the personal sampler that have been used. Even though the personal sampling measurement is usually considered the more representative of the aerosol in the breathing zone (hence exposure) than the static (or area) sampling, the personal sampling may be inacurate and imprecise.

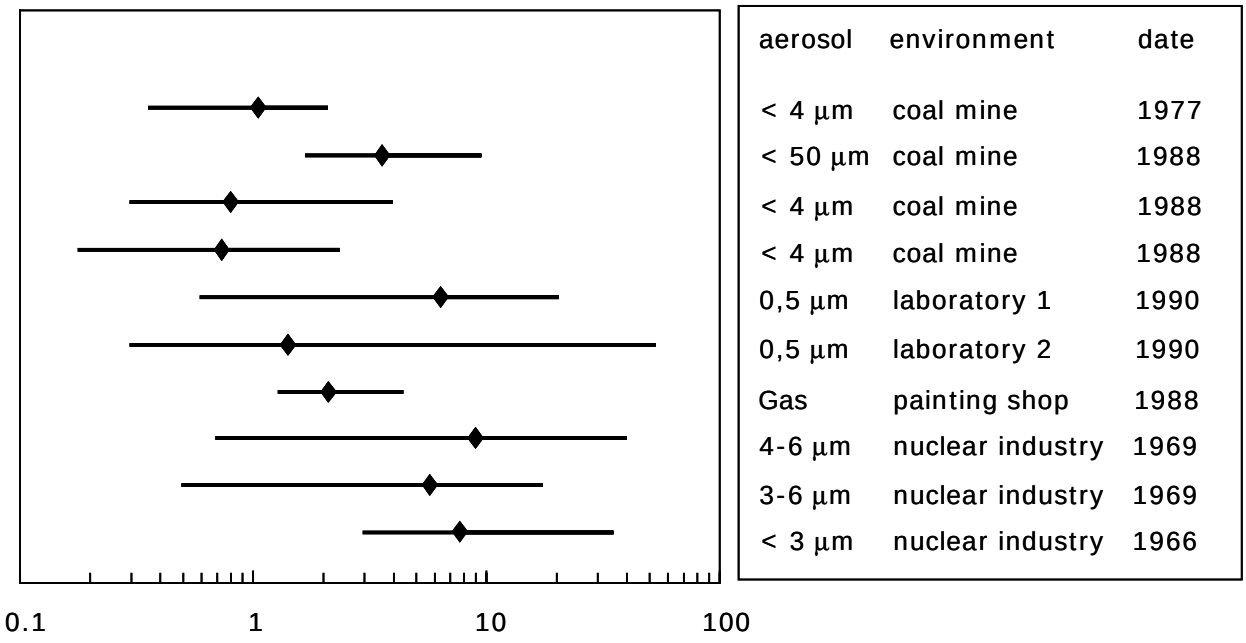

Figure 5 : Ratios between personal and static sampling measurements reported in the litterature.

At present, it is not clear how differences in airflow (ventilation pattern, windspeed, turbulence), proximity of the localised contaminant source location, strength of the source,

worker (location, activity), … would affect the contaminant dispersion and transport in a room, and then the personal/static measurement ratio. There is an area of work for investigating that field. Results from those laboratory studies would help to argue about the choice of the strategy for sampling airborne particles in workplaces. A study is currently carrying out at the IPSN to produce data that could be used as a basis to improve the knowledge of factors affecting the aerosol characteristics in the microenvironment of a worker (including breathing zone) and in the room. The first part of that study was to design and built an experimental room CEPIA (french acronym for: room for studying personal and area samplers). The ventilated chamber (volume 36 m3) is equiped with an air delivery system to insure different ventilation patterns and flowrates. The CEPIA chamber should offer possibilities for performing experiments in situations representing a "typical" workplace environment, with airflows and aerosol parameters well controlled and characterised.

Aerosol sampling instrumentation

A variety of aerosol samplers are commercially available. Several of these samplers have been used and evaluated by researchers. It is not the intention to present an exhaustive list of instruments but, rather, to describe a representative range of types. Table 2 summarizes a description of different classes of instruments that are usually used for aerosol sampling. User should be aware that some of the commercially available samplers were developed decades ago, before the advents of the concepts of the health-related fractions and particle size-selective sampling efficiencies, hence having poor performances. For instance, it is well admit now that the so-called "37-mm closed face filter cassette", the most common personal aerosol sampler, has a sampling efficiency falling short below the inhalable sampling convention.

Table 2 : Description of different aerosol sampling techniques.

Instrument and method	Particle size range	Equivalent diameter	Version
Filter holder	"all" size inhalable fraction thoracic fraction respirable fraction	Physical diameter	Static Personal
Impactor	0.5 – 15 μm 0.03 – 15 μm (low pressure)	Aerodynamic diameter	Static Personal
Cyclone	0.5 – 20 μm thoracic fraction respirable fraction	Aerodynamic diameter	Static Personal
Elutriator	5 – 50 μm	Aerodynamic diameter	Static
Diffusion battery	0.001 – 30 μm	Thermodynamic diameter	Static
Optical detection	0.5 – 20 μm	Optical diameter	Static

Here only two instruments are mentionned. Since they are new developed aerosol samplers, they are of particular value for applications in light of the latest particle size-selective criteria described earlier in the text.

The first is the french CATHIA static sampler (french acronym for: thoracic, inhalable, and respirable aerosol sampler), shown in Figure 6. Originally developed at the Institut National de Recherche et de Sécurité (INRS) in France by Fabriès *et al*. (1998), the sampler is a variant of the CIP-10 french personal sampler (widely used in the past in the mines for respirable fraction measurement). The key feature of the CATHIA sampler is the fact that it can be used for measuring the inhalable, thoracic and respirable fraction by easily changing the particle size selector and the aspiration flowrate, as shown in Figure 6. The sampling inlet is the same for the three different particle size selectors, and consists of an annular slot designed to follow the inhalable convention. Thus, the sampler is based on the concept that

the thoracic aerosol and the respirable fraction are sub-fractions of the inhlable fraction. Sampled particles leaving the selector travel through a tube down to a 25 mm diameter filter. The tubing length was optimised in order to insure a uniform particle deposit on the surface filter.

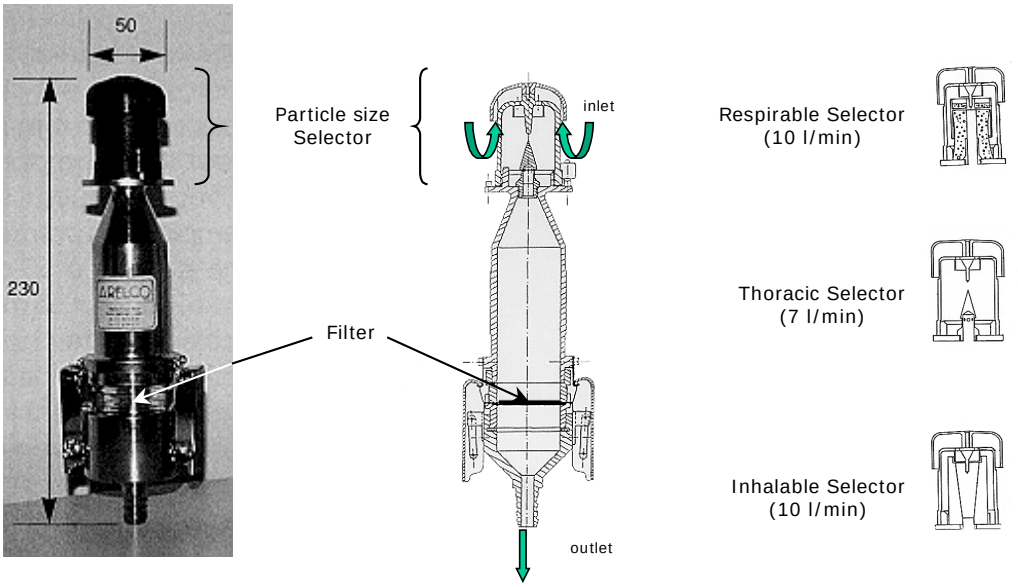

Figure 6 : General view and schematic diagram of the CATHIA static sampler and the differents available particle size selectors for the inhalable, thoracic and respirable fractions. Developed by INRS, France

The second instrument is the so-called "Button Personal" aerosol sampler recently commercially available. This personal sampler is shown in Figure 7. Designed by the Department of Environmental Health of the University of Cincinnati, it is a small sampler with a curved porous inlet surface (Kalatoor *et al.,* 1995). Its inlet is formed by a portion of a spherical shell with numerous, identical, evenly spaced circular orifices. The sampled particles are collected on a 25 mm diameter filter, placed directly behind the inlet, hence reducing the transmission losses. Operated at a flowrate of 4 l/min, the button sampler fits quite well the inhalable sampling convention. Being less sensitive on wind velocity and direction than the other available personal samplers, this sampler is believed to be valuable for aerosol sampling in workplaces where frequent changes in wind direction and velocity are anticipated (Aizenberg *et al.,* 2000).

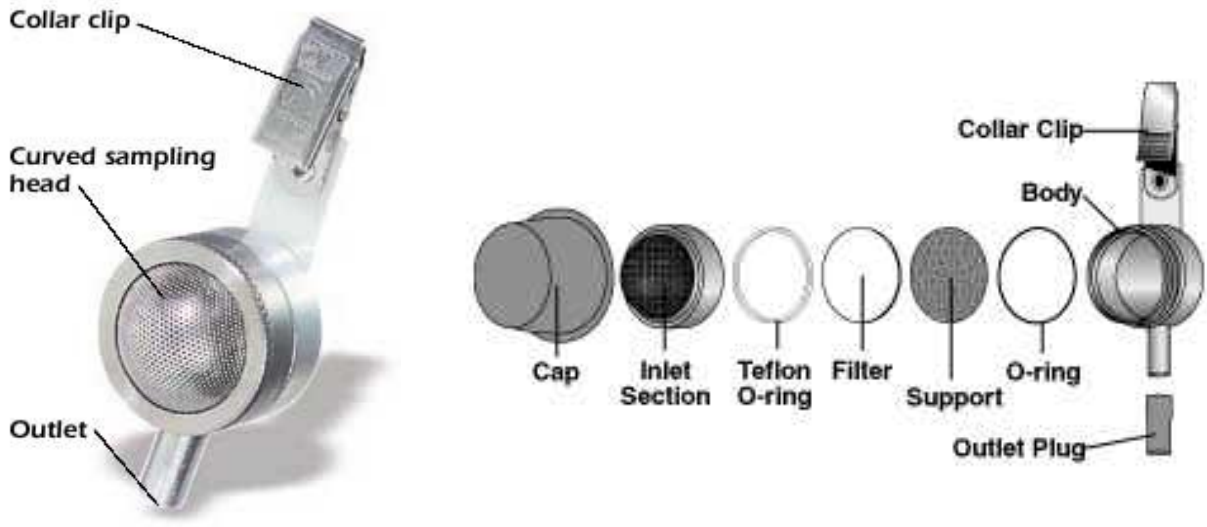

Figure 7 : General and exploded view of the "Button Personal" aerosol sampler for inhalable dust sampling. Designed by the Department of Environmental Health of the University of Cincinnati (Kalatoor *et al.,* 1995).

Conclusion

Protection of workers from intakes of airborne dusts is receiving increased attention as part of the overall emphasis on minimisation of occupational exposures. Sampling for airborne particles plays an important role in the survey of the worker's exposure either in the nuclear and non-nuclear sector. For aerosol sampling in a given situation the questions are: how has the aerosol changed during the act of sampling, and how representative is the collected sample of the aerosol of interest?

There is now a broad international agreement between the CEN, ISO and ACGIH on the qualitative and quantitative definitions of health-related particle size-selective criteria. Health-related sampling should be based on one or more fractions: inhalable, thoracic, and respirable.

At present, further work would be desirable for describing the nature of the inhalable fraction at low winspeeds, more realistic of real workplaces, and where there is little information. The results from those studies would have also important implications in the testing of aerosol samplers.

While aerosol sampling instruments have been available for now many years, today the emphasis is on the development and refinement of personal samplers that are capable of

sampling health-related fractions. Much work about the development of experimental procedures is still necessary, and the test of samplers performance (in laboratory and in the field) appears a big challenge for many research teams.
Finally, studies to improve the knowledge of factors affecting the aerosol characteristics in the microenvironment of a worker (including breathing zone) and in the room are desirable. The results would help in providing a framework within which aerosol sampling instrumentation would be used in practice for assessing the worker's exposure.

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