Good discussion of total, Inhalable and ACGIH Vs ISO Curves. NO mention of CIP-10

Measurement of Coarse Aerosols in Workplaces* A Review

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Coarse aerosol fractions in workplaces are sampled if it is felt that particles of all sizes may pose a risk to health. Although the so-called 'total' aerosol has been widely used to refer to the relevant coarse fraction, practical measurement has been very dependent on the actual sampling instrument used. This in turn has led to great uncertainty about what was being measured. In the 1980s, the concept of inhalability was proposed, based on the aerosol particle size fraction that enters the human head through the nose and/or mouth during breathing. Now there is substantial agreement by most of the world's major criteria-setting bodies on a quantitative definition taking the form of a single curve describing the probability of inhalation as a function of particle aerodynamic diameter. This definition now forms a truly health-related 'yardstick' against which to assess the performances of practical sampling devices. In turn, more and more countries are beginning to adopt the new criterion for health-related aerosol measurement in their standards, replacing the old 'total' aerosol concept. Experiments in wind tunnels to investigate the performances of previous samplers for 'total' aerosol show that most of them do not satisfactorily match the new inhalability criterion. A small number of samplers designed specifically for the inhalable fraction have been proposed and are available commercially. They include samplers for both static (or area) and personal sampling.

Keywords: *Coarse aerosols; workplace monitoring*

Introduction

The routes of aerosol exposure may involve skin deposition, the food chain (after deposition on plants, *etc.*) and inhalation. Of these, the inhalation route is of great interest in occupational health, representing a major potential source of hazard for workers in many occupational environments. The nature and magnitude of the hazard in a given situation depend on a complex combination of many factors, including particle size distribution (which governs how the aerosol enters the body by inhalation, and how it penetrates into and is subsequently deposited in the respiratory tract), airborne concentration (which governs how much is deposited), and particle morphology, mineralogy and chemical composition (which govern the subsequent fate and biological responses to the presence of the particles in contact with vulnerable tissue).

Ideally a *standard* should contain the following main components:

(1) *Criteria* relating to the scientific basis upon which, for a given contaminant, a measurement or assessment procedure is chosen. For aerosols, a fraction may be identified based on chemical composition and on particle size.

(2) *Measurement instrumentation*, the technical means by which the relevant airborne contaminant, as identified in the specific criteria, can be quantified. This includes particle size-selective sampling instrumentation backed up by appropriate analytical methodology.

(3) *Sampling strategy*, describing how such instrumentation is used in practice to assess the exposures of individuals (or groups of individuals). This involves considerations of where to sample, duration, frequency, *etc.*, and should take account of the inter- and intra-individual variabilities in exposure.

(4) *A limit value*, defining the upper end of the range of intensity or magnitude of permissible exposure to the fraction identified in the criterion for the substance in question. For airborne contaminants, it is usually described in terms of an airborne concentration (*e.g.*, mass or number per unit volume of air), derived from a measurement made by sampling over an appropriate period of time. The usual underlying rationale is that this represents the 'threshold' level of exposure at, and below, which, according to current knowledge, there is no evidence of injury to workers if the substance is inhaled day after day. For many substances, a 'full-shift' 8 h time-weighted average (TWA) is appropriate; for others, a shorter reference period might be defined.

In principle, a limit value should not be assigned until the other three components have been established.

Some biologically active particles (*e.g.*, bacteria, fungi, allergens) may, if they deposit in the extrathoracic airways of the head, lead to inflammation of sensitive membranes in that region, such as symptoms of 'hay-fever' (*e.g.*, rhinitis). Other types of particle (*e.g.*, nickel, radioactive material, wood dust) depositing in some parts of the same region may lead to more serious local conditions, such as ulceration or nasal cancer. Other types of particle may not produce such serious clinical effects, but may result in significant irritation and so constitute a 'nuisance'. For all these, and for aerosol substances that are soluble and are known to be associated with systemic effects (where toxic material can enter the blood after deposition in any part of the respiratory tract and be transported to other organs), criteria for standards should be specified in terms of all that is *inhaled*. It is therefore clear that *inhalable* aerosol is a fraction which is an objective for measurement in itself in many occupational situations. This is the subject of this paper.

Criteria for the Sampling of Coarse Aerosols

In the past and, indeed, in most countries, the previous recommendations for the health-related sampling of coarse particles have been based on the concept of so-called 'total' aerosol. This concept is intended to relate to all particulate matter which might be considered airborne. However, most

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practical sampling instruments for 'total' aerosol have been developed without particular regard to specific quantitative criteria or indices, and their performance characteristics have varied greatly from one to the other. Hence it follows that switching from one instrument to another in a given practical situation might well produce different measurements of exposure, even though the actual level of exposure itself might not actually have changed. With this in mind, the idea first emerged in the 1970s of the human head as an aerosol sampler and, hence, of inhalability as a quantitative definition of what had previously been known as 'total' aerosol.

A number of important experimental studies were subsequently conducted in laboratories in the UK and Germany to determine the efficiency with which particles enter the human head during breathing through the nose and/or mouth. These experiments, involving life-sized human mannequins in wind tunnels, provided data for a range of wind speeds relevant to workplace exposures and for particles with aerodynamic diameter up to 100 μm.[1–4] All the sampling efficiency results were reported for head orientations with respect to the wind averaged uniformly over 360° about a vertical axis. It was found that this orientation-averaged efficiency of inhalation of a particle can, for most practical workplace purposes, be described in terms of a single function of particle aerodynamic diameter (d_{ae}), starting off at 100% for very small particles and falling to about 50% for particles with d_{ae} around 30 μm and above.

Data from experiments such as these have formed the basis of recommendations for replacing the old 'total' aerosol concept with a quantitative sampling convention based on human inhalability. The first, and historically important, was by the International Standards Organization (ISO),[5] which proposed a curve described by the empirical expression

$$I = 1 - 0.15\,[\log(1 + d_{ae})] - 0.10\log(1 + d_{ae}) \quad (1)$$

based on available data which, at the time (the late 1970s), included d_{ae} values only as high as 30 μm. In this expression d_{ae} is in micrometres and the aspiration efficiency for the human head is represented by inhalability (I). The curve is shown in Fig. 1.

The subsequent availability of a more comprehensive data set provided the basis for the proposal of a revised curve.[6] In the recommendations of the American Conference of Governmental Industrial Hygienists (ACGIH),[7] this new curve was adopted as a convention for defining the inhalable fraction and described by the empirical expression

$$I = 0.5\,[1 + \exp(-0.06\,d_{ae})] \quad (2)$$

for d_{ae} (again expressed in micrometres) up to and including 100 μm, beyond which it is explicitly acknowledged that there is no information on which to base a firm recommendation. This curve is shown also in Fig. 1.

In these ISO and ACGIH proposals, attention has been focused primarily on particle size-selective criteria for sampling in indoor workplaces where wind speeds even as high as 4 m s^{-1} are uncommon. However, there are some outdoors workplaces where conditions might sometimes lie outside this wind-speed range. Further, at least as far as the ISO is concerned, sampling in the ambient atmosphere for the purpose of evaluating the risk to the community at large is an important part of its general remit. From the more recent experimental evidence,[4] it is clear that the existing ISO and ACGIH conventions do not properly represent what happens at those higher wind speeds. In particular, the experimental data suggest that using samplers with performance based on either of these curves could lead to a significant underestimation of the exposure of humans to large particles. This could be important in situations where there are large particles containing potentially hazardous substances (*e.g.*, radioactive nuclides, heavy metals, polycyclic aromatic hydrocarbons). It is therefore appropriate to consider how the definition of inhalability might be extended. With this in mind, a new convention has been proposed, based on a simple modification of the old ACGIH curve, along the lines

$$I = 0.5\,[1 + \exp(-0.06\,d_{ae})] + B \quad (3)$$

where the wind-speed-dependent term B is given by

$$B = 10^{-5}\,U^{2.75}\exp(0.55\,d_{ae}) \quad (4)$$

where U (m s^{-1}) is the wind speed. This modified curve is being incorporated into a revised set of ISO proposals.

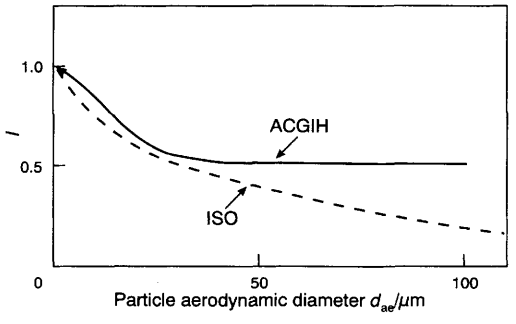

Fig. 1 Conventional particle size selection curve for the inhalable fraction (I)

At the time of writing, considerable progress has been achieved on harmonization of the ISO and ACGIH proposals, in particular agreement that the ACGIH curve should be universally adopted for workplaces. Now discussion is focusing increasingly on the practicalities by which the curve described (and also the equivalent curves for health-related finer fractions) might be used as a 'yardstick' for the performances of sampling instruments. In general, the definition of a curve for defining a particular aerosol fraction raises the difficult question of how we decide whether or not the performance of a given instrument in relation to the convention is acceptable. At first glance, 'acceptability' might be defined simply by requiring that an instrument's performance curve falls within the specified tolerance band. However, herein lies a potential problem. As may be demonstrated numerically for aerosol samplers with performance characteristics apparently matching fairly closely a given convention, and for ranges of typical workplace aerosol particle size distributions, the collected mass of that particular aerosol fraction can vary enormously. This therefore alerts us to the general need, when testing aerosol samplers in relation to specific particle size-selective criteria, to take account not only of the proximity of data points to the 'target' curve but also the implications for errors in mass measurement dependent on particle size distribution. Some progress has been achieved in understanding the nature and magnitude of the problem.[8] However, further work is needed to achieve a practical solution. In the meantime, the best that can be recommended is that we should continue to judge sampler performance on the basis of its proximity to the specified curve, but that we should be vigilant to the errors that can arise and the conditions under which they can become significant.

Strategies for the Sampling of Coarse Aerosols

Health-related aerosol measurement in general, whether it be for coarse or for finer aerosol fractions, needs to be carried out with regard not only to such particle size-selective criteria but also to (a) the kinetics of the processes by which the particles can cause harm after inhalation and (b) the variability of exposure. Rappaport[9] has recently addressed these factors in relation to occupational exposure. From such considerations,

it is clear that, for aerosols, we should be concerned not only with choices about the particle size selectivity of measuring instruments but also with the duration and frequency of sampling. For some workplace aerosols, the biological effects of exposure for short periods at high concentration may be severe and rapid. For these, sampling should be of appropriately short duration and at relatively frequent intervals. On the other hand, for most aerosols encountered in workplaces, such biological processes are relatively long-term so that the effects of short-term high exposures are strongly damped out by the body's defence mechanisms. For such aerosols, the sampling strategy may be based on longer duration (typically full-shift 8 h TWA) and less frequent measurements.

In any given sampling exercise, there remains the further question about how best to reflect the true exposures of individual workers (or of groups of workers), either static (or area) measurement, where the chosen instrument is located in the workplace atmosphere and provides a measurement of the ambient aerosol concentration, or personal measurement, with the chosen instrument mounted on the body of the exposed subject and moving around with him or her at all times.

When choosing one or other of these alternatives, some important considerations need to be taken into account. For a few workplaces (*e.g.*, some working groups in longwall mining), it has been shown that reasonably good comparison may be obtained between suitably placed static instruments and personal samplers. More generally, however, static samplers have been found to perform less well, tending to give aerosol concentrations that are consistently low compared with those obtained using personal samplers. One advantage with static samplers is that a relatively small number of instruments may be used to survey a whole workforce. If this can be shown to provide valid and representative results, it is a simple and cost-effective exercise. Further, the high flow rates that are acceptable for static samplers mean that, even at very low aerosol concentrations, a relatively large sample mass can be collected in a short sampling period.

In contrast, the use of personal samples is more labour intensive, requiring more instruments and hence greater effort in setting them up and in recovering and analysing the samples afterwards. Further, it involves the direct co-operation of the workers themselves. Also, for such samplers, it is inevitable that the capacities of the pumps used will be limited by their portability. Hence flow rates will usually be low (usually less than 4 l min^{-1}). However, personal aerosol sampling is widely accepted as the only reliable means of assessing the true aerosol exposures of individual workers. This is therefore by far the most common mode of aerosol measurement adopted by industrial hygienists.

Implications of New Sampling Criteria for Limit Values

As already stated, a limit value is prescribed in terms of an appropriately time-weighted average (TWA) airborne concentration of a given fraction of a given aerosol above which 'unacceptable' health risks may occur if exposure occurs at that level 'day-after-day'. In addition, however, for some substances where exposure can lead to acute health effects, maximum exposure (or ceiling) limits (MELs) are assigned, indicating levels of exposure which should not be exceeded under any circumstances.

The American (ACGIH) list of threshold limit values (TLVs) is highly influential, not only in the USA but also in many other countries. In that list, limits are suggested for a wide range of substances that can appear as aerosols. Regarding coarse aerosols, the TLV list currently recommends limits for 'total' aerosol only, although progress is being made in many countries towards a change to inhalability-based limit values. In the UK, the Health and Safety Executive (HSE) has already taken that step. There, in the occupational exposure standards (OESs, generally equivalent to the American TLVs), the old 'total' aerosol concept has been replaced by the inhalability criterion and options for suitable sampling instrumentation have been clearly identified.

It is noted that limit values for many types of coarse aerosol are the same for both 'total' and inhalable aerosol in the American and British lists, respectively. This poses an interesting problem since, although such numbers were usually derived from the same source, they are now subject to different measurement criteria. This was highlighted during a recent Swedish study,[10] which compared individual dust exposures of flour mill workers using two different personal sampling instruments, one of the type widely used in the USA for 'total' aerosol and the other a new sampler with performance conforming to the inhalability criterion. The results showed that, on average, the inhalable aerosol sampler collected about twice as much mass as the 'total' aerosol sampler. Such a difference is strongly dependent on the particle size distributions of the aerosol studied, and so will vary substantially from one workplace situation to another. Hence the actual result in the flour mills should not be generalized directly to other industries. However, it is likely that the broad trend will be the same elsewhere; indeed, results just beginning to emerge from studies in other industries appear to be consistent with this expectation. This new knowledge carries the implication that it is inappropriate, for a given substance, to assign the same numerical limit value in lists of limit values where the underlying criteria are different (*e.g.*, the American and British lists).

Practical Sampling for Coarse Aerosols in Workplaces

Static (or Area) Samplers for 'Total' or Inhalable Aerosol

Static (or area) samplers have been used for many years in the sampling of coarse aerosol in workplace atmospheres. The simplest are open-filter arrangements mounted on the box which contains the pump (see Fig. 2) or systems in which the open-filter holder is mounted independently. The sampler shown is widely used in the UK, sampling at flow rates up to 100 l min^{-1}. Similar devices have been used elsewhere, both in workplace and in ambient air sampling. So too have many other forms of static device, including the widely used (and aptly named) 'Hi-Vol' sampler. The performances of such

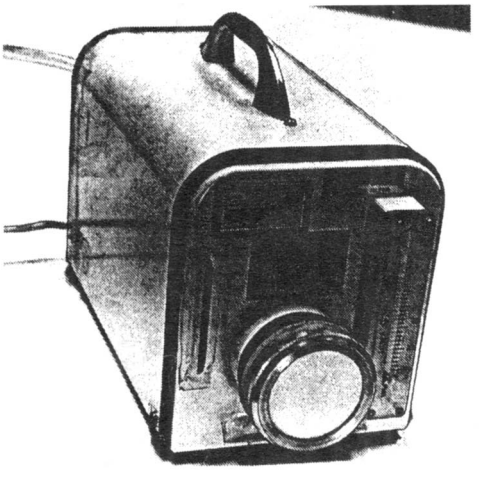

Fig. 2 Typical open-filter arrangement of the type widely used for the static sampling of coarse aerosol in the UK (shown in the pump-mounted version with a recommended flow rate of 60 l min^{-1})[11]

instruments, originally intended as samplers for 'total' aerosol, should now be assessed in the light of the latest health-related particle size-selective criteria described earlier. The available data suggest that none of them adequately matches the inhalability criterion.[11]

Ideally, the design of sampling instruments for sampling the inhalable fraction should be based on a detailed knowledge of the physical processes by which particles are aspirated from the air into the instrument itself. Despite the fact that we have a fairly good appreciation of what happens for thin-walled sampling probes (such as those used for so-called isokinetic sampling in stacks and ducts) and other very simple sampler configurations, theory has not yet reached the stage where it can be applied to the types of device which might typically find application in aerosol sampling in the industrial hygiene context. This is an area where further work is clearly needed. In the meantime, the design of new practical sampling instruments matching the latest particle size-selective criteria has been, and continues to be, largely empirical and based on trial-and-modification.

Nevertheless, new generations of aerosol sampler are beginning to appear, designed from the outset to match the inhalability criterion. One intended for use in workplaces is the 3 l min^{-1} Institute of Occupational Medicine (IOM) static inhalable aerosol sampler (shown in Fig. 3).[12] It incorporates a number of novel features. First, the sampler contains a single sampling orifice located in a head which, mounted on top of the housing containing the pump, drive and battery pack, rotates slowly about a vertical axis. In this way sampling is carried out whilst the orientation of the entry with respect to the wind is uniformly averaged. Hence it is analogous to the manner in which the inhalability curve had been defined for the human head. The entry orifice forms an integral part of an aerosol-collecting capsule which is located mainly inside the head. This capsule also houses the filter. In the use of the instrument, the whole capsule assembly (tare weight of the order of a few grams) is weighed before and after sampling to provide the full mass of aspirated aerosol. This system eliminates the possibility of errors associated with internal wall losses of the type described earlier. When the capsule is mounted in the sampling head, the entry itself projects about 2 mm out from the surface of the head, creating a 'lip' around the orifice itself. This has the effect of preventing the secondary aspiration of any aerosol particles which strike the outside surface of the head and fail to be retained. The performance of this sampler, shown in Fig. 4, is in fairly good agreement with the inhalability curve for particles with d_{ae} up to about 100 μm for wind speeds up to 3 m s^{-1}. At present this is the only static sampler specifically for the inhalable fraction which is commercially available (from Negretti Automation, Aylesbury, UK), although prototype higher flow rate versions were built at the Institute of Occupational Medicine in Edinburgh during the late 1980s, and have subsequently been tested at Warren Spring Laboratory (Stevenage, UK) as possible candidate samplers for atmospheric suspended particulate matter.

Fig. 3 The IOM 3 l min^{-1} static sampler for inhalable aerosol[12]

Personal Samplers for 'Total' or Inhalable Aerosol

For reasons outlined above, personal sampling is generally the preferred approach for workplace aerosols. Here, for coarse aerosol, a large number of different devices have been used, again originating, historically, for the purpose of sampling for 'total' aerosol. Again, the simplest is the open filter arrangement, that shown in Fig. 5 being the 25 mm open filter used in the UK by occupational hygienists in some applications. Other personal samplers for 'total' aerosol currently in use in the UK are the single (4 mm) hole sampler recommended by the HSE for lead aerosol and the modified seven-hole version recommended for general coarse aerosol sampling. These are also shown in Fig. 5. Both of these closed-face samplers also employ 25 mm filters. All three samplers are intended for use at a sampling flow rate of 2 l min^{-1}.

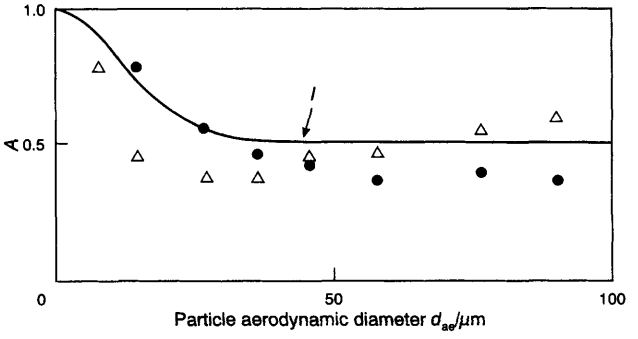

Fig. 4 Sampling efficiency (shown here as A) of the IOM static inhalable aerosol sampler as a function of particle aerodynamic diameter for a range of relevant wind speeds.[12] (Also shown for the purpose of comparison is the ACGIH inhalability curve.) U: ●, 1 and △, 3 m s^{-1}

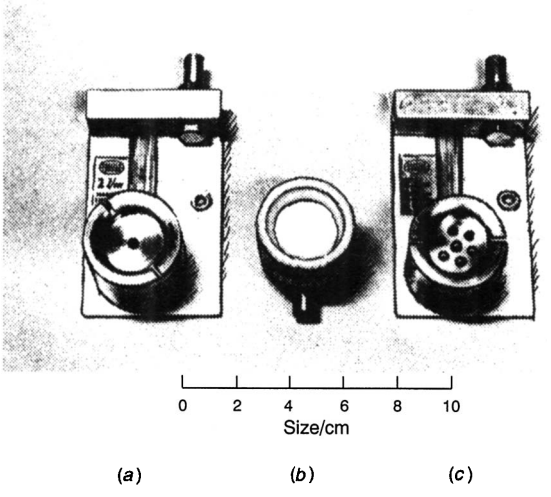

Fig. 5 Three personal samplers of the type widely used for sampling coarse aerosol in the UK:[13] (*a*) open filter holder; (*b*) single-hole sampler; and (*c*) seven-hole sampler. Recommended sampling flow rate for each is 2 l min^{-1}

Experiments have been conducted to compare their performances with the inhalability curve.[13] It is particularly important to note here, and for all the other personal samplers discussed below, that only data obtained with each sampler tested whilst mounted on a life-size torso (*e.g.*, of a mannequin) are considered useful in this context. It should not be assumed that, if such samplers were to be tested whilst located independently, they would necessarily provide the same results. It follows as a general principle that devices designed as personal samplers should not be used in the static mode.

The results reported by Mark and Vincent[13] for the three samplers in Fig. 5 indicate that all match the inhalability criterion fairly well for particles with d_{ae} up to about 15 μm and for wind speeds of 1 m s^{-1} and below. However, for conditions outside these ranges, yet typical of those found in many workplaces, the performances are less satisfactory, with a strong wind-speed dependence (especially for the single-hole and seven-hole samplers) and with a tendency towards undersampling. Interestingly, it was found that the performances of these, and indeed other personal samplers, are not strongly dependent on where the device is mounted on the torso.

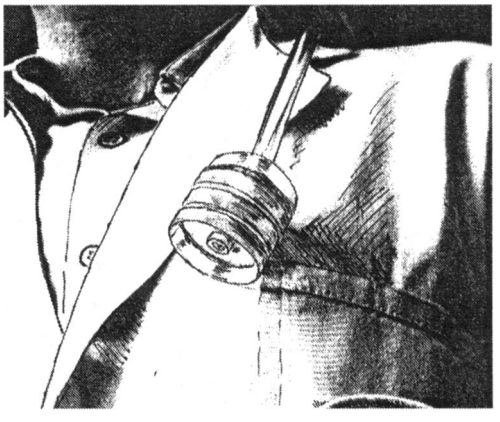

Fig. 6 The 37 mm cassette of the type widely used in the US for the personal sampling of coarse aerosol. Recommended sampling flow rate is 2 l min^{-1}

Fig. 7 The IOM 2 l min^{-1} personal sampler for inhalable aerosol.[13] (Photograph supplied by courtesy of SKC)

The physical and design features of these three samplers are, in one way or another, representative of those exhibited by most of the many others which have been designed and used over the years in many countries. One is the 37 mm plastic cassette which is employed widely, either open-faced or closed-faced, by occupational hygienists in the USA (see Fig. 6). Test results for this sampler are limited in number and range of d_{ae} covered,[14] but they are sufficient to suggest similar trends as for the samplers shown in Fig. 5, in particular that this sampler also provides a fair measure of the inhalable fraction for particles with d_{ae} less than about 15 μm, but again tends to undersample for the large particles.

In the light of the generally poor performances of many existing 'total' aerosol samplers with respect to the inhalability criterion, a new personal sampler has been proposed.[13] This is the 2 l min^{-1} IOM personal inhalable aerosol sampler (see Fig. 7). It features a 15 mm diameter circular entry which faces directly outwards when the sampler is worn on the torso. Like the IOM static inhalable aerosol sampler in Fig. 4, the entry is incorporated into an aerosol-collecting capsule which, during sampling, is located behind the face-plate. Use of this capsule ensures that the over-all aspirated aerosol is always assessed. Also, as for the static sampler, the lips of the entry protrude outwards slightly from the face-plate in order to prevent oversampling associated with particle blow-off from the external sampler surfaces. Experimental data for this instrument are shown in Fig. 8, and they show a good match with the inhalability curve for particles with d_{ae} up to 80 μm and for wind speeds up to 2.6 m s^{-1}. Again, as for the IOM static inhalable aerosol sampler, this instrument is the only one currently available commercially (from SKC, Blandford Forum, Dorset, UK) that is known to match adequately the inhalability criterion.

Conclusion

During the past decade or so, great progress has been made towards placing the health-related sampling of coarse workplace aerosols on a more rational footing. In particular, recognition of the inconsistencies of the old 'total' aerosol approach and the emergence of a new criterion based on human inhalability have been great steps forward. The wide degree of international agreement has been most reassuring, and some regulatory bodies have begun to adopt the new approach. However, its wider acceptance as the basis of standards is tempered in some quarters by fears of the possible implications for limit values (as suggested earlier). Meanwhile, the current commercial availability of appropriate instrumentation should expedite full implementation of the inhalability criterion and hasten the development of new and

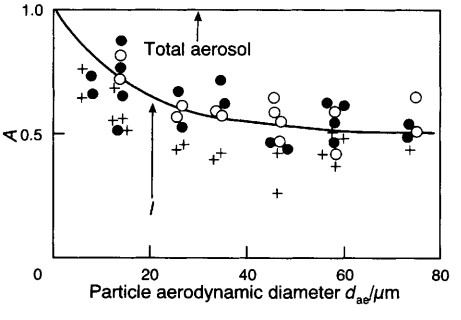

Fig. 8 Sampling efficiency (shown here as A) of the IOM personal inhalable aerosol sampler as a function of particle aerodynamic diameter for a range of relevant wind speeds.[13] Also shown for the purpose of comparison is the ACGIH inhalability curve. U: ○, 0.5; ●, 1.0; and +, 2.6 m s^{-1}

improved standards. Indeed, there appears to be no justification for further delay. At the same time, the adoption of the proposed new framework for standards would stimulate the development of further new, and improved, instruments.

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