O. FACTORS AFFECTING AEROSOL SAMPLING

by Paul A. Baron, Ph.D., NIOSH/DART

This chapter adapted from Baron [1].

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1. INTRODUCTION

The American Conference of Governmental Industrial Hygienists (ACGIH) [2], the International Organization for Standardization (ISO) [3], and the European Standardization Organization (Comité Europeén de Normalisation, CEN) [2,3] have adopted identical particle size-selective sampling conventions for inhalable, thoracic, and respirable aerosols (Figure 1). The purpose of these conventions is to provide a scientific basis for a new generation of particle size-selective occupational exposure limits (OELs) for aerosols. Such OELs can therefore be matched to the relevant sites of aerosol deposition after inhalation into the respiratory tract, and in turn to the health effects of interest in a given exposure assessment. These sampling conventions are used throughout this manual unless otherwise specified. The criteria presented in this manual are used to determine the most appropriate aerosol sampling equipment. The type of sampling to be performed determines which criteria are important for estimating the adequacy of the sampler and determining aerosol concentration levels. For example, “total dust” samplers generally do not have a size selective particle classifier preceding the filter media and fall under the inhalable sampling convention. Alternatively, sampling for regulatory or voluntary compliance with aerosol exposure standards usually requires greater accuracy, increased efficiency, size-specific selectivity, and good analytical precision. Furthermore, regulations may require the use of a specific sampler and sampling conditions to standardize sampling results (eliminate bias) and reduce uncertainty among laboratory reports. See Chapter P, Measurement Uncertainty and NIOSH Method Accuracy for further discussion on standardization and aerosol measurement error.

Over the past two decades, researchers have pointed out strengths and weaknesses with several types of aerosol samplers (Figures 2a-j). Some of these samplers were adapted from existing devices used for other purposes, e.g., the 10-mm nylon cyclone and the 37-mm cassette, without the benefit of current testing technology and understanding of particle behavior. More recently developed aerosol samplers were designed to either maximize the information gained regarding aerosol concentration levels or to minimize any inherent losses associated with the sampler design. Thus, each sampler design may have been based on some of the following criteria: inlet efficiency, classifier accuracy, cassette assembly (bypass leakage), electrostatic losses, particle deposition uniformity, collection media stability, sampler surface losses, and sampler field comparisons. These criteria are discussed in the following sections of this chapter.

2. INLET EFFICIENCY OF THE SAMPLER

An important review of sampling theory and practice was compiled in a book by Vincent [4]. The inlet efficiency of several samplers has been evaluated including thin-walled tubular inlets [5], a cyclone [6], an asbestos sampler [7], total aerosol sampling cassettes [8], and inhalable aerosol samplers [9,10]. All samplers have an inlet efficiency that varies as a function of particle aerodynamic diameter, inlet velocity, inlet shape and dimensions, dimensions of the body it is attached to, external wind velocity, and external wind direction. The *aspiration efficiency* of an aerosol sampler can be defined as

$$A = c_s / c_0$$

where c_s is the concentration of particles passing directly through the plane of the sampling orifice and c_0 is the ambient concentration. This is true for aerosol samplers for which the entire amount of aerosol that enters the plane of the sampling orifice is quantified, as is the case for the IOM sampler (SKC, Inc., Eighty Four, PA). However, it is important to note that many commercially available aerosol samplers use only the aerosol collected on the filter that is housed in the sampler, while any particles deposited on the inner surfaces upstream of the filter are disregarded. Performance of this type of sampler is therefore best characterized by its *sampling efficiency*, in which the aspiration efficiency is modified by the particle size-selective losses prior to the filter. The aspiration or sampling efficiency of a particular aerosol sampler, whichever is the most relevant, expressed as a function of particle aerodynamic diameter, is the primary index of sampler performance and should match the appropriate health-based criterion (e.g., the inhalability criterion) so that it may be said to provide a valid health-based assessment of personal aerosol exposure.

As an aerosol is being sampled, the large-particle trajectories are more affected by external flow fields than those of small particles. Thus, the shape, orientation, and inlet flow field will be most critical for inhalable aerosol sampler inlets; they will be less important for thoracic samplers and unlikely to be important for respirable samplers, except at very high wind velocities. The flow field near the inlet of a sampler is different when the sampler is mounted on a person (or in laboratory simulations using a mannequin) than when it is freestanding. Therefore, it has been recommended that measurement of inhalability be determined from mannequins in wind tunnels [11-14]. Flow field studies using mannequins in wind tunnels indicate that the air is slowed down by the body, resulting in an enrichment of large particles in the upstream side of the body [15]. When intended for use at low wind speeds (less than about 1 m/s [200 ft/min], representing most indoor workplaces), it may be possible to test the samplers as freestanding devices if it can be shown there is no effect from the mannequin body [16]. However, if the sampler is to be used at higher windspeeds, which frequently occur outdoors, personal aerosol samplers should be evaluated on a mannequin in a wind tunnel [16].

Respirable aerosol samplers generally do not have problems with inlet effects because the particles being sampled have low enough inertia and settling velocity. However, Cecala et al. [6] found that the 10-mm nylon cyclone operated free-standing in a wind tunnel oversampled at external air velocities greater than 4 m/s when the inlet faced the wind and undersampled at 90° and 180° to the wind at velocities greater than 1 m/s. The maximum sampling error of about 40% was observed at 10 m/s. It is expected that these errors would be reduced if the sampler were located on a person, because the air velocity decreases near the body surface. It should be noted that the Cecala *et al*. work was conducted in the context of aerosol sampling in underground mining environments. Here, windspeeds of the magnitude quoted are not uncommon. However, in industrial workplaces more generally, windspeeds are much lower. Two surveys of a wide range of workplaces [17,18] revealed that actual indoor windspeeds rarely exceeded 0.2 to 0.3 m/s and more typically were less than 0.1 m/s.

The EPA PM-10 standard for environmental sampling specifies a sampler that has a 50% cutpoint at 10.6 µm, approximately the same as that for the thoracic sampler [19]. Although the requirements for environmental PM-10 samplers stipulate wind tunnel testing, similar work on personal PM-10 and thoracic samplers has yet to be performed. It is expected that these samplers will be more susceptible to wind effects than respirable samplers because larger particles are more susceptible to inertial and gravitational effects.

The most extensive comparison of available inhalable aerosol samplers was that carried out under the auspices of the European Commission (EC) [9]. Eight samplers were tested: CIP-10 (foam-based, French); 37-mm closed-face cassette (Spain and US) (Figure 2a); 37-mm open-face cassette (Sweden) (Figure 2a); PAS-6 (Netherlands); PERSPEC (Italy); GSP (Germany, sold as CIS sampler in US; BGI, Inc. Waltham MA); IOM (United Kingdom; (Figure 2b); and the Seven-Hole Sampler (United Kingdom; Casella CEL, Inc., UK) (Figure 2c). Conditions of the experiment included measurement of sampler collection efficiencies on a mannequin for aerosol particles with diameters as large as 100 µm at a wind speed of 0.5 m/s, 1.0 m/s, and 4 m/s. Samplers were positioned on a mannequin rotating within a wind tunnel. The samplers were all conductive; the 37-mm cassette samplers were painted with an external conductive coating. The aerosol was, however, not neutralized. The results of this experiment indicated high inter-sampler variability, but permitted estimates of bias relative to the inhalable convention. The EC study also indicated that most samplers work reasonably well at low wind speeds (<1 m/s) for particle median diameters below 25 µm [20]. The study indicated that experiments of this type were difficult, expensive, and generally had poor precision. Perhaps better understanding of the flow field near the body may lead the way to improved and simplified sampler testing. Recent work suggests ways of making the wind tunnel testing of inhalable samplers simpler and less expensive, e.g., by using a compact body to simulate the chest of a mannequin [21] and by using miniaturized mannequins and samplers that are calculated to be aerodynamically equivalent [22].

The orientation and diameter of an inhalable sampler inlet may affect the collection of very large particles (generally >100 µm), since these may be thrown into the inlet as projectiles. The current definition of inhalable aerosol only covers particles up to 100-µm aerodynamic diameter.

In situations where large particles can be generated (e.g., abrasive blasting, wood working, and grinding operations) excessive collection of particles up to the millimeter range is likely to occur. There have been some attempts to modify inlets with shields to provide a barrier against the collection of large particles, but these modified inlets have not been demonstrated to provide the same agreement with the inhalable convention as the unmodified ones.

Another potential problem with inhalable samplers is the collection of passively sampled particles. Measurements when the sampler airflow is turned off indicate that IOM samplers, which pointed outward from the body and had a large inlet diameter (15-mm), can collect quite significant amounts of dust, with median values of 9 to 32 percent of the mass collected during active sampling [23]. Open-faced cassettes had only 2 to 11 percent of the mass passively collected. These samplers have a larger inlet (37-mm), but point downward, reducing the likelihood of particle settling onto the collection surface. The mechanism of collection is unclear, but the dust may be transported into the inlet by turbulence and deposited by settling or turbulent diffusion. How this passively collected dust modifies the amount collected during active sampling remains under investigation.

A comparison of measurements obtained with the 37-mm closed face cassette (4-mm inlet diameter) to the IOM sampler (15-mm inlet diameter) in several workplaces gave similar results when the material on the interior walls of the 37-mm cassette were added to the analyte deposited on the filter [24]. This suggests that the two samplers can have similar inlet efficiencies in spite of differences in inlet size and orientation if the median particle size sampled is not too large. Other studies did not include wall deposits in evaluation of the 37-mm cassette.

3. CLASSIFIER ACCURACY

The theory of classifier separation is based on particle aerodynamic diameter, which is defined as the diameter of a 1 g/cm^3 density sphere having the same settling velocity as the particle in question. If the particle is markedly non-spherical, the aerodynamic diameter may not be well defined, possibly resulting in sizing errors. For example, fibers and plate-like particles settle slightly differently depending on orientation. Thus, the sampling conventions, based on aerodynamic diameter of particles reaching specified parts of the respiratory system, become somewhat ambiguous for these types of particles. For such non-ideal particles, further testing of classifiers to simulate particle behavior in the respiratory tract may be necessary. For instance, Maynard [25] found that plate-like particles may orient differently in elutriators, impactors, and cyclones. This preferred orientation in a cyclone produced a collection efficiency 15% below that estimated to occur in the respiratory system. Improved understanding of fiber [26] and plate-like particle [25] behavior in the respiratory tract is needed to aid in development of more accurate samplers for these types of particles.

Various types of classifiers have been constructed to meet the ACGIH/ISO conventions. For example, respirable samplers have used cyclones [27], impactors [28-30], elutriators [31], and porous foam [32,33] to remove non-respirable particles from the aerosol prior to filter collection. The technology for testing these samplers has improved in recent years through use of a real-time aerodynamic sizing instrument and resulted in quicker and more precise measurements [34,35]; this technique has allowed the accuracy of these samplers to be investigated more carefully [36]. However, a round-robin comparison of 50% cut-point measurements from six laboratories using an aerodynamic sizing instrument to test the same cyclone agreed within a range of 11% [37]. Further work on the testing protocol is needed to improve interlaboratory agreement. Many current classifiers do not match the shape of the respirable convention exactly and produce biases that depend on size distribution. Two comparisons of several respirable samplers have been performed using the aerodynamic sizing technique [38,39].

The introduction of the thoracic fraction in the ACGIH/ISO conventions has spurred interest in thoracic classifiers for certain types of aerosols, e.g., cotton dust, asbestos and sulfuric acid [19]. The performance characteristics of the vertical elutriator (operated at 7.4 L/min) used for cotton dust approximately meets the thoracic definition [40]. Laboratories in many countries perform asbestos fiber measurement using the technique of counting only fibers with diameters of 3 µm or less; this size selection was shown to be approximately equivalent to thoracic sampling [41]. Further tests indicate that several thoracic samplers may be appropriate for asbestos sampling [42,43]. Thoracic sampling is also recommended for sulfuric acid [44] and metal working fluids [45].

Several samplers based on inertial, cyclone and foam separators have been specifically developed to meet the thoracic definition [46-49]. The CIP-10 sampler has been used for thoracic sampling in Europe [50], but is not applicable to aerosols with a significant submicrometer fraction [46]. Several of these samplers have been tested to compare with the thoracic convention [42,43]. The GK2.69 cyclone (Figure 2i) has been used for metal working fluids [45]. The other samplers referenced are in the development stage and need further testing. The PM-10 standard for environmental sampling is very similar to the thoracic convention and impactors with a 10 µm cutoff size have been used for personal PM-10 sampling [51]. A cascade impactor, e.g., the Andersen personal cascade impactor (Figure 2j), can be used to calculate the thoracic fraction of an aerosol. Although a thoracic sampler is commercially available (Figure 2i), further work is needed to determine its applicability for specific types of aerosol. For example, a thoracic sampler for fibers must result in a uniform deposit of the particles on the filter for accurate analysis results.

The overall accuracy of a classifier with respect to sampling in accordance with the one of the sampling conventions can be estimated using a bias map (Figure 3). The bias map displays the percent difference between the predicted mass collected by the sampler and the mass expected according to the convention as a function of the parameters of a lognormal particle diameter distribution for a range of likely workplace distributions. Such a bias map can be used for selecting a sampler for a workplace having a certain range of particle sizes or for developing samplers that agree more closely with the sampling conventions.

The bias map in Figure 3 was created by: (a) fitting the penetration curve for the 10-mm nylon cyclone (Figure 2g [35]) at 1.7 L/min with a lognormal curve (a logistic curve also can be used), (b) calculating the bias between the respirable convention and the curve from the previous step for a range of lognormal size distributions, and (c) plotting the bias contour lines as a function of the size distribution mass median aerodynamic diameter (MMAD) and geometric standard deviation (GSD). The 10-mm nylon cyclone shows significant negative biases, especially at large MMADs and small GSDs because the cyclone penetration curve drops off more rapidly with size than the curve for the respirable convention. The “best” flow rate to use in a workplace when sampling according to one of the conventions becomes a matter of judgment, depending on the size distribution typically encountered in that workplace. A cyclone that fits the convention more exactly will exhibit smaller biases throughout the entire size distribution range. Bias maps are available for several respirable samplers [38, 39]. It should be mentioned that in some cases, e.g., coal mine dust sampling, a single sampler is specified by regulation. This sampler specification eliminates the question of bias for that type of measurement.

Investigation of the effect of changing the physical dimensions of a commercial cyclone resulted in modifications that improved the match to the respirable sampling convention [52]. Chen and coworkers developed a virtual cyclone that appeared to give excellent compliance with the respirable curve [53]. It is possible to make samplers that have predicted biases less than 10% over the entire range of likely workplace size distributions. While the behavior of certain samplers, such as impactors, can be predicted theoretically, it is still important to measure penetration curves experimentally to ensure correct application of the theory. Bias maps based on these data then allow estimation of accuracy for a specific workplace application. As improved samplers are tested and become commercially available, more accurate thoracic and respirable aerosol measurement on a routine basis will be possible.

As mentioned above, several inhalable samplers were investigated in a wind tunnel to evaluate their sampling efficiency compared to the inhalable convention [9]. Based on these data, sampler performance (maximum bias confidence limit) was ranked [Bartley 1998] and the IOM, GSP, and CIP-10 samplers were rated the best.

As interest in the new particle size-selective conventions by standards setting bodies has grown, efforts have been made to define protocols to guide the testing and validation process for available samplers. One approach was developed by the CEN [54, 55]. In the CEN model, for any given sampler to be tested, the first step is a critical review of the sampling process for the instrument in question. This is intended to identify factors that may influence the performance of the sampler, including particle size, windspeed, aerosol composition, filter material, etc. This is essential in the process of sampler evaluation, determining under what conditions the sampler will need to be tested. Three options are then presented for the testing of samplers: (a) the laboratory testing of samplers to compare performance with the sampling conventions, (b) the laboratory comparison of instruments, and (c) the field of comparison of instruments. Research projects have been conducted in recent years to define testing protocols (option a), funded both by the European Community and by NIOSH, to consolidate the scientific basis for such protocols and to identify improved and more cost-effective methods.

4. SAMPLER ASSEMBLY

Some samplers are designed such that improper assembly can result in internal leakage, i.e., aerosol particles bypassing the filter. This bypass leakage has been noted in the 37-mm closed-face cassette [56,57]. Although at least one study found no problem with hand assembly of these cassettes [58], NIOSH and others [59] have occasionally observed, after sampling black or colored dusts, streaks of dust on the filter's compression seal region or an incomplete compression mark, indicating aerosol leakage bypassing the filter. An airtight seal in these cassettes is achieved by compression of two plastic parts that must be parallel and joined with the proper force. If this seal is not compressed with sufficient force, the vacuum behind the filter may pull the filter from the seal, especially at high flow rates. Too high a compression force results in cracking the cassette or cutting the filter, also producing leakage.

Prudence dictates that a check of cassette integrity and the seal area on each filter should be made after sampling to ensure that the cassette was properly assembled; otherwise, the sample may underestimate the actual exposure.

At least two approaches to eliminating the sealing problem with press-fitted cassettes have been taken. One was to assemble the cassette using a press. Pressing the cassette together by hand often produces misalignment of the cassette parts, resulting in bypass leakage. Frazee and Tironi designed a mechanical press that held the two cassette pieces in proper alignment, while applying just enough pressure to effect a seal, but not so much as to cause cracking of the plastic [56]. This press was designed to allow motion of the cassette pieces to compress to a certain distance. A commercial pneumatic press (Accu-Press, Omega Specialty, Chelmsford MA) used a selected pressure to compress the cassette components. For additional information on bypass leakage and bypass leak test procedures see Chapter N: Aerosol Sampling: Minimizing Particle Loss from Bypass Leakage. The second approach was to redesign the cassette to provide a more positive filter seal [57]. In a well-designed sampler, opening the seal should not cause tearing and loss of the filter or collection medium during removal from the sampler.

The 37-mm closed-face cassette is usually sealed with tape or shrink bands around the outside. There is a common misconception that this seal prevents bypass leakage in the cassette. These external seals primarily cover the joint between the cassette components to prevent deposited particles on the external surface of the cassette from contaminating the sample during filter removal. The tape or shrink band also aids in holding the cassette together and preventing external air leakage. However, Puskar, et al. [58] found that even by using this precaution, a significant amount of dust was found downstream of the filter. The authors hypothesized that this dust was deposited during filter removal.

Three other commercial samplers, the IOM (figure 2b), the CIS, and the coal mine dust sampler (MSA, Inc, Pittsburgh) use a cartridge to hold the filter. For the first two samplers, an external threaded cover applies pressure to the cartridge to ensure a good seal around the filter. This prevents twisting at the filter surface while creating positive, even contact around the filter edge.

5. ELECTROSTATIC LOSSES

Most aerosol particles generated in workplaces have electrostatic charge levels considerably higher than the minimum level [60]. Minimum charge (Bolzmann equilibrium) levels are usually achieved after particles are suspended in the atmosphere for an hour or so because of the presence of naturally occurring ions. When freshly generated particles are sampled in an electric field, as when a sampler is highly charged [61], the particle trajectories may be modified to such an extent that the particles are inefficiently sampled. No electrostatically induced particle motion occurs when either the particle charge or electric field during sampling is zero; when both the sampler and particle are highly charged, particle acceleration is much greater than that caused by gravity, inertia, diffusion or other mechanisms.

Samplers can achieve a high charge level when they are electrically insulated from ground and are triboelectrically charged (i.e., by contacting or rubbing against other surfaces); this sampler charging, as well as particle charging, tends to occur more frequently at low (<20% RH) humidity levels. Certain plastic materials, such as polycarbonate, polytetrafluoroethylene, polyvinyl chloride (PVC), and polystyrene readily retain high charge levels; others, such as Tygon®, retain relatively little charge [62]. The PVC/polystyrene copolymer used in the 37 mm closed-face cassette is an excellent electrical insulator and can retain high charge levels on its surface. These charges can be incorporated in the bulk plastic during manufacture or accumulated on the surface by handling or contact with other objects; the charge levels and polarity are highly localized and variable. Such samplers can exhibit particle losses to the internal walls of the cassette and negative sampling biases [63]. Non-conductive plastic asbestos samplers were shown to produce large negative biases and variable results [61, 63, 64].

Conductive samplers have demonstrably lower losses when sampling charged particles. Metal samplers obviously have high conductivity. Samples collected using nylon cyclones were shown to exhibit higher variability [65, 66] and negative biases [66] when sampling charged dusts. However, the degree of conductivity required is not high; as long as charges can move over the sampler surface and reach equilibrium in seconds, the effect of charges transferred to the sampler is likely to be minimized. Materials with this low level conductivity (surface resistivity < 10^8 ohms/square) are often termed "static-dissipative." Graphite-loaded plastics were developed that have adequate conductivity to distribute charges over the surface of the cassette (e.g., the 25-mm asbestos sampler). A simple test to ensure adequate conductivity of these samplers can be performed by attaching a good quality multimeter at any two points on the sampler surface. Resistance readings in the range of tens of megohms or less indicate sufficient conductivity for sampling purposes.

Some metals are coated with a thin, non-conductive layer, e.g., anodized aluminum. These coatings may retain a surface charge, but this charge will induce an opposite charge in the conductive layer beneath the surface, effectively canceling out the field produced by the surface charge. Recent measurements at NIOSH using a non-contacting electrostatic voltmeter (Model 300, Trek Inc. Medina NY) indicated that no significant external field (< 50 volts) could be produced near an anodized surface by rubbing the surface with various plastics or other materials. Plastic or cellulose-based materials rubbed in a similar manner produced electrostatic potentials measured in the hundreds to thousands of volts. Thus, metals with a thin, insulating surface layer are not likely to produce significant external fields that would affect aerosol sampling.

A further electrostatic problem not specifically associated with the cassette is the use of filters made of highly nonconductive materials, such as PVC, polytetrafluoroethylene, or polycarbonate. In addition to having desirable chemical properties, these filters have the advantage of not absorbing water from atmosphere, leading to improved weight stability [67-69]. However, these filters can retain a high electrostatic charge level, resulting in non-uniform particle deposition and even repulsion of particles from the filter surface. Such filters are also more difficult to handle during weighing because of charge effects. Even filters that are normally more conductive, such as cellulose-based filters, can become non-conductive and exhibit non-uniform particle deposition and particle losses at very low humidity levels (< 10% RH) [70]. A treatment was developed to make filters more conductive without significantly affecting weighing accuracy or moisture absorption [71]. In one study, it was found that applying this treatment to the filter decreased particle losses from 14% to 2% [72]. Anti-static sprays are available that leave a temporary static-dissipative coating on surfaces.

6. SAMPLE DEPOSITION UNIFORMITY

Some analytical methods require that sampled particles be deposited uniformly on the filter surface. For instance, asbestos fiber analysis by microscopy requires uniform deposition of fibers on the filter for accurate results. Direct silica analysis of collected filter samples also is improved with uniform particle deposition. Classifiers using inertial or gravitational forces tend to stratify the aerosol stream. A small, high velocity inlet in a sampler, such as the 4-mm opening in the 37-mm closed-face cassette, can also result in the larger particles being deposited in a small central area on the filter. Even sampling at high flow rates through more open inlets can cause a non-uniform deposit [73]. This results in particle deposits that vary in uniformity as a function of particle size. Such deposition patterns are visible when sampling colored particles [74]. Open-pore foam classifiers may improve the uniformity of particle deposits on the filter, but have not been thoroughly evaluated [75, 76]. Careful design of classifiers to ensure mixing of the aerosol prior to deposit on the filter may result in adequate uniformity [47]. Even inhalable samplers or samplers that have no classifier may be prone to non-uniform deposits under certain conditions of sampler orientation relative to gravitational settling, orientation relative to external winds, or when sampling charged particles [61, 62, 64, 70]. Flaring the inlet of such a sampler, as in the commercial “bell-mouth cowl,” (Figure 2f, Envirometrics, Charleston SC), is one approach to improving sample uniformity under anisokinetic conditions [73]. In another study, a sampler having an inlet screen (button sampler, Figure 2d, SKC, Inc. Eighty Four PA) exhibited improved filter deposit uniformity when compared to a closed-face cassette [77].

The filters in some samplers require support to prevent tearing or distortion of the filter. The support device may cause occlusion of parts of the filter surface, resulting in non-uniform particle deposits [78].

On occasion, it was observed that poorly-sized tubing connectors protruded into the 37-mm cassette and touched the filter surface. This caused all the airflow to pass through the filter adjacent to the small area of the connector opening. When undetected, this caused low sampling efficiency and pump failure because of the high pressure drop.

7. SAMPLER WALL LOSSES

Particle deposits on internal surfaces (i.e., wall losses) of the 37-mm closed-face cassette for several hundred field measurements were found to be large and highly variable (2 - 100% of dust collected in the cassette) [79]. Another study found only 22% of the dust on the filter, 65% on the upstream portion of the cassette, and 22% downstream of the filter [58]. In a study of an in-line cassette of similar shape, it was found that the internal wall deposition of particles could be largely eliminated by: (a) making the cassette conductive, (b) creating an aerodynamically smooth surface having no corners for eddies to form, and (c) decreasing the diameter of the filtration area so that dust does not deposit on the filter adjacent to the upstream walls of the cassette [72]. By incorporating these three corrective measures, the wall losses in the latter cassette were reduced from 25-30% to 5%. These losses appear to be caused by a combination of electrostatic, inertial, gravitational and diffusion mechanisms.

Another solution to the problem of not capturing 100% of the sampled particles on the filter is to use an internal cartridge sealed to the filter. All the particles collected in the combined filter/cartridge are analyzed. The air stream entering the cassette is surrounded by the cartridge and any deposition on the walls of the cartridge is retained for analysis. The IOM sampler for inhalable dust uses this approach by having the cartridge form the inlet of the sampler (Figure 2b). This approach also has been used in the in-line cassette of the coal mine dust personal sampling unit (MSA, Pittsburgh PA) where an aluminum foil cover is crimped onto the filter. A similar cartridge was designed for the 37 mm closed-face cassette in measurements of pharmaceutical dust [80]. Another cartridge made of “static dissipative” plastic is commercially available (Accu-Cap, Omega Specialty Instruments, Chelmsford MA). However, it is important that cartridge material be compatible with the analytical method. For instance, the plastic material used in the first version of the IOM sampler cartridge (Figure 2b, SKC, Eighty Four PA) was found to absorb milligrams of water over periods of days, making the accuracy of gravimetric measurements problematic [81-83]. Demange et al. more recently demonstrated significantly improved agreement between inhalable sampling using the IOM sampler and the 37-mm cassette by including all deposits inside the cassette [23]. This suggests that the accuracy and precision of the 37-mm cassette can be improved by including internal sampler deposits by wiping or washing, or by using an internal cartridge such as the Accu-Cap.

8. COLLECTION MEDIA AND ANALYTICAL ISSUES

The sampling medium should be compatible with the analytical method. Some analytical methods require specific filter properties. For instance, atomic absorption and inductively coupled plasma analyses typically require complete ashing of the filter material; organic compound analyses require that no reaction or adsorption of the compounds occur at the filter surface. Several studies have dealt with gravimetric stability of filters and recommended specific procedures [67-69, 84, 85]. Generally, plastic materials that do not absorb water (polycarbonate, polyvinyl chloride, polytetrafluoroethylene) are more weight stable than natural cellulose-based materials; uncoated glass fiber filters also may absorb water [67-69, 84, 85]. Note, however, that the more weight stable materials also tend to be more highly charged, resulting in more charged particle repulsion and deposit non-uniformity. When a plastic (Tyvek®) backup pad is crimped into a cartridge together with a filter, the weight stability of the cartridge may suffer [86]. To improve the weight stability of coal mine dust sampler cartridges, stainless steel backup pads have been used by MSHA. The IOM sampler can be purchased with either a plastic or a stainless steel cartridge. The plastic cartridge has been shown to exhibit poor weight stability and should not be used for gravimetric analysis [81, 83].

Lawless and Rodes investigated the use of modern electronic balances to determine factors affecting the accuracy of gravimetric measurements and found that balance stability, balance leveling, vibration and thermal drafts, electrostatic charge reduction, positioning of the filter in the balance so that the filter did not hang over the edge of the pan, and temperature and humidity control were all important in achieving accurate results [87].

Although not strictly a problem with the collection medium, the sampler construction material should not outgas vapors that can condense on the collection medium and affect the analysis. Early (circa 1970) versions of the closed-face cassette were made of a plastic called “tenite,” which resulted in weight gain of the filter over time. This currently does not appear to be a problem.

Impactors have been used as samplers and, especially with cascade impactors, the deposits on the impaction stages are measured. Particle bounce from the collection substrates on the impaction plates can be severe, especially for solid particles impacting onto a smooth metal plate. Several modifications to the collection substrate are available to improve collection efficiency of each stage. These modifications should be compatible with the analytical method. Oil can be placed on the collection substrate that wicks up over collected particles and continually provides an oiled surface. A filter or sintered metal can be used to provide a reservoir for this oil. For gravimetric analysis, this oil must have a low vapor pressure and not migrate off the collection substrate. Alternatively, grease can be used, but after the surface is coated with collected particles, additional particles are more likely to bounce. Filters have also been used as substrates and provide a convenient substrate that is somewhat better than a smooth metal surface. Selection and use of an impactor is a complex issue and has been described in reviews [88, 89]. Accurate analysis of cascade impactor data can also be difficult and simple regression analysis of the data may not provide the best answer [89-91].

9. SAMPLER FIELD COMPARISONS

Direct field comparisons of various samplers are frequently reported in the literature. Because of the typical high variability of aerosol concentrations and size distributions in workplaces, 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 issues. The problems with samplers as discussed above can be highlighted with some examples observed in field studies.

a. Sampler Bias Affected By Internal Deposits

A study of wood dust sampling comparing collocated free-standing samplers indicated that an MSA cassette (having an aluminum cartridge crimped onto the filter) used as a sampler gave two times better precision and collected 2.6 to 3.5 times more dust than the standard 37-mm closed-face cassette [92]. Both these samplers have the same size and shape of inlet. The same study showed that the IOM sampler collected 1.3 times more dust than the MSA cassette, indicating that the particle size, inlet shape and inlet orientation are important factors in inhalable sampling. Among a number of inhalable samplers in current use around the world, the IOM sampler appears to agree the best with the inhalable dust sampling convention [9, 93]. Several studies have shown that the IOM sampler collects anywhere from slightly more to 3.5 times more dust than the closed-face cassette [94-98]. However, Demange et al. showed that for several work sites with relatively small MMAD particles (about 15 µm), the 37-mm cassette results agreed well with the IOM results if the deposits on the internal surfaces of the cassette were added to the filter analyte [23]. Measurements with the 37-mm cassette are not expected to agree as well with the IOM when the particle sizes are much larger because of differences in aspiration efficiency. However, by including all aspirated material, i.e., all material entering the 37-mm cassette inlet, in the analysis, it appears that agreement with the inhalable convention is improved.

b. Sampler Precision Affected By Internal Deposits

Internal wall deposition in a sampler can also contribute to variability of results. In a field study of lead dust, it was found that the results from a closed-face 37-mm cassette gave a coefficient of variation (CV) of 1.0 and 0.33 when sampling at 2 L/min and 10 L/min, respectively, while the button sampler gave a CV of 0.10 under the same conditions [77]. The button sampler has few internal surfaces for wall deposition, suggesting that elimination of this type of loss would improve the precision of the 37-mm cassette. Demange et al. found improved precision for the 37-mm cassette data when the wall deposits were added to the analyte [23].

In spite of some of its drawbacks, the 37-mm cassette is likely to be used for some time. It appears that from the standpoint of improving agreement with the inhalable convention and improving precision, the inhalable sampler wall losses should be minimized through sampler design (use of a cartridge such as the AccuCap or in the MSA coal mine cassette) or the wall deposits should be added to the analyte.

10. CONCLUSIONS

Clearly, when proper features are incorporated in the sampler design, significant improvements in bias and precision can be achieved for some currently used aerosol samplers. Several recommendations regarding the application of these samplers are listed:

a. Classifiers used to select respirable, thoracic, or other fractions should be evaluated based on bias maps obtained from experimental data and combined with size distributions from workplace measurements to evaluate their applicability.

b. Further research and development is needed to improve sampler design to better match ACGIH/ISO conventions and reduce inter-laboratory variability in conducting aerosol sampling. It is important to report the sampler and flow rate used to allow evaluation of potential biases due to sampling.

c. The filter cassette and fittings should be air-tight and have no by-pass leakage. A pneumatic or mechanical press should be used to assemble the cassette and a leak test should be used to establish appropriate pressure and proper assembly procedures. See chapter entitled: Aerosol Sampling Cassette Assembly: Leak Testing

d. The sampler should be made of conductive or static-dissipative materials.

e. Internal deposits in sampling cassettes should be included in the analysis. One approach to improving the closed-face cassette is to use an internal cartridge that collects all the sampled dust entering the cassette. The cartridge must be compatible with the analytical method. Another approach is to wipe or wash the internal surfaces of the cassette and add this material to the filter analyte.

11. DISCLAIMER

Mention of company names or products does not constitute endorsement by the Centers for Disease Control and Prevention.

12. FIGURES

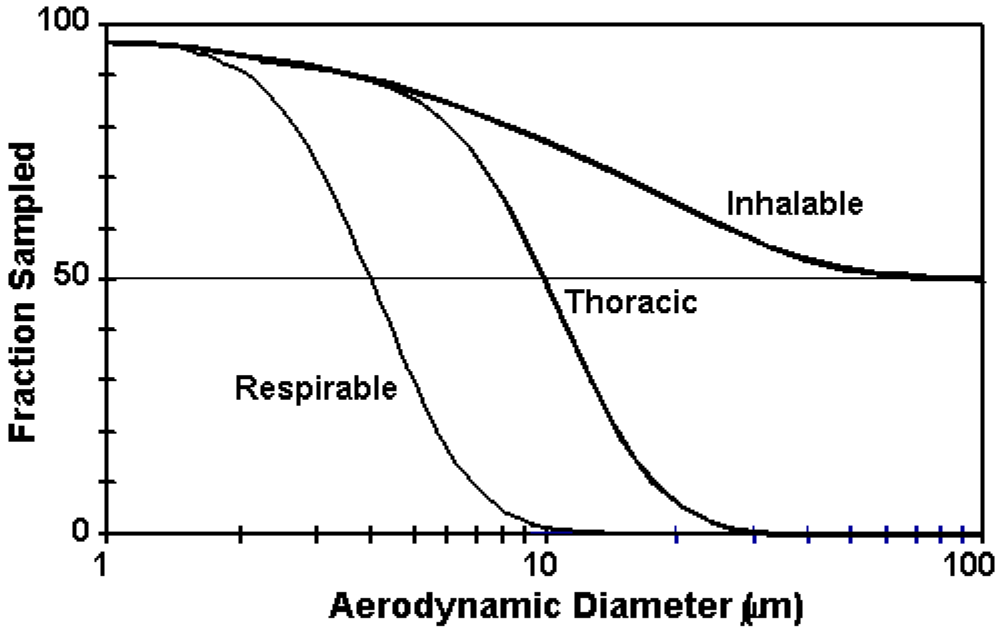

Figure 1. ISO/ACGIH/CEN sampling conventions. An ideal sampler should have a sampling efficiency curve that matches one of these curves as closely as possible under all wind directions and velocities. The 50% cutpoints for the respirable and thoracic conventions are 4 and 10 µm respectively.

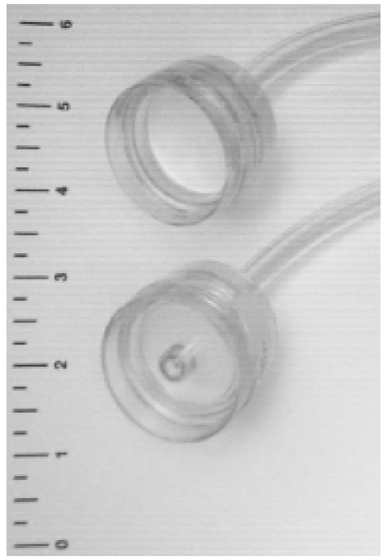

Figure 2a. Examples of personal aerosol samplers. a. Open faced (top) and closed face (bottom) 37 mm cassette samplers. These are shown in acrylic copolymer (clear, non-conducting) material and are more prone to electrostatic losses. Other construction materials are available, including conducting plastic. Sampling flow rates range from 0.5 to 10 L/min.

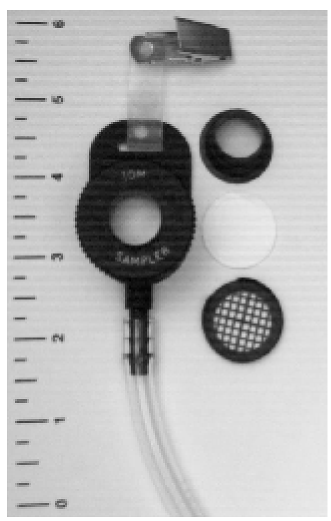

Figure 2b. IOM inhalable sampler. This is the first sampler designed specifically to match the inhalable sampling convention. The sampling cartridge is shown on the right with the inlet, filter, and support grid from top to bottom. All dust entering the cartridge is collected and analyzed. Sampler is made of conductive plastic and operates at 2 L/min.

Figure 2c. Seven hole sampler used for inhalable dust sampling in the UK. Sampler is made of conductive plastic and operates at 2 L/min.

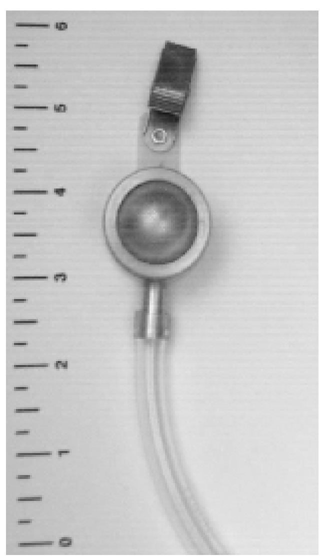

Figure 2d. Button sampler. So-named because the inlet, a hemispherical screen with ~380 µm diameter holes, resembles a large button. Developed as an inhalable sampler with reduced wind direction response and improved filter deposit uniformity. Uses metal construction and operates a 4 L/min.

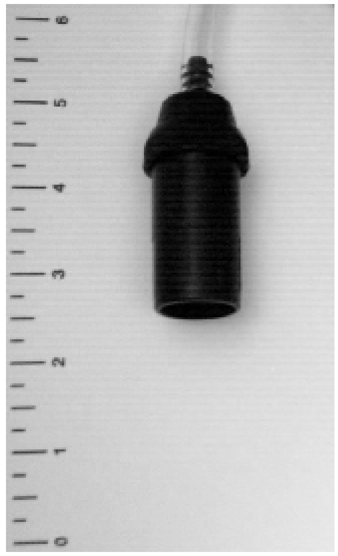

Figure 2e. Asbestos sampling cassette. The long (50 mm) inlet was designed to prevent incidental contact with the filter surface and, when facing downward, acts to a certain extent as an elutriator, preventing larger particles from reaching the filter surface. Made of conductive plastic and is operated at a flow rate between 0.5 L/min to 16 L/min.

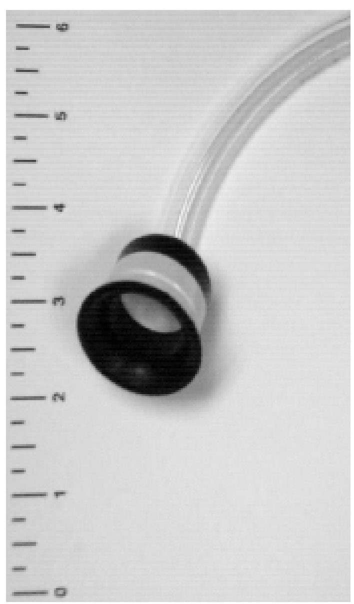

Figure 2f. Bell mouth cowl sampler. An alternative to the standard asbestos sampling cassette. The inlet is flared to reduce the effect of external air motion on sample uniformity. Made of conductive plastic and is operated at a flow rate between 0.5 L/min to 16 L/min.

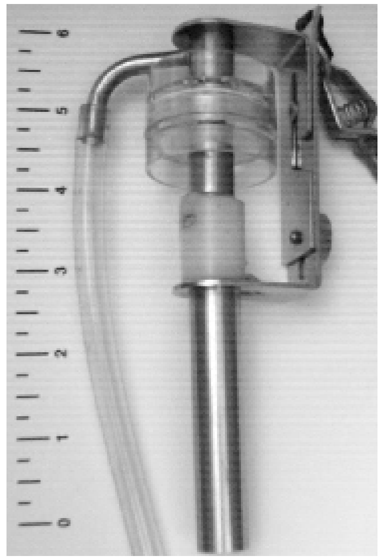

Figure 2g. Dorr-Oliver 10-mm nylon cyclone. Used as a respirable sampler most often at 1.7 L/min. A version of this sampler is used at 2 L/min in coal mines with a 1.38 correction factor applied to the resultant mass. The holder encases body of the cyclone so that only the inlet section is visible just below the connection to the 37 mm cassette. The coal mine dust sampler version uses a cassette with an aluminum cartridge encasing the collection filter.

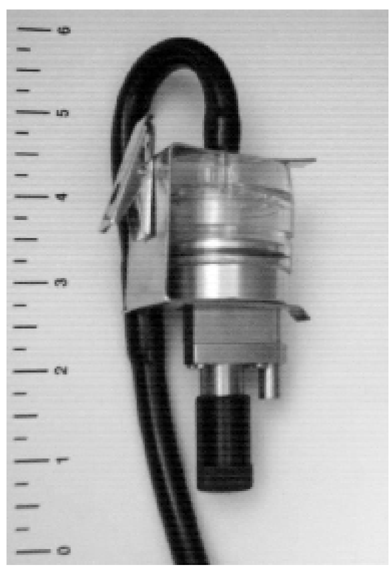

Figure 2h. Higgins-Dewell cyclone. Developed and used primarily as a respirable sampler in the UK. This version provides an interface directly to a 37-mm cassette. Cyclone construction is steel and operates at 2.2 L/min.

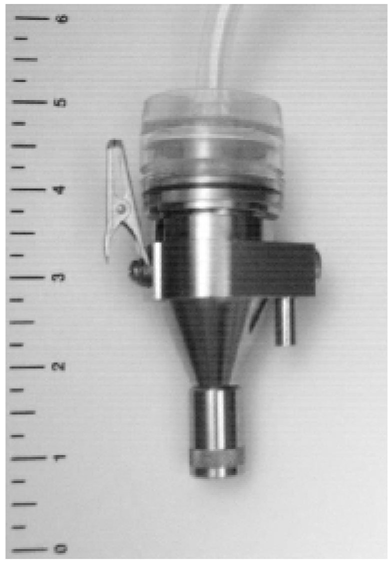

Figure 2i. GK2.69 cyclone. This cyclone was designed to match the slope of the thoracic and respirable conventions more closely than other sampling cyclones. Cyclone construction is stainless steel and operates at 4.2 L/min as a respirable sampler and 1.6 L/min as a thoracic sampler.

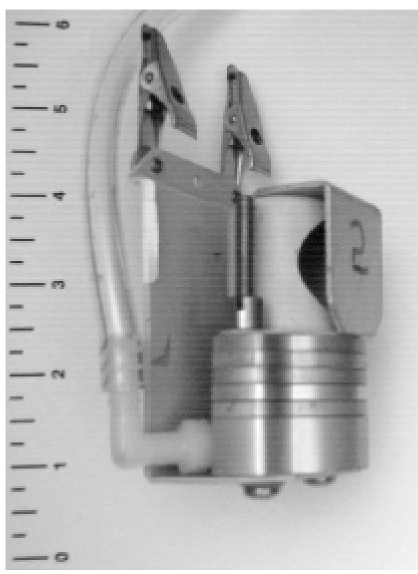

Figure 2j. Personal cascade impactor sampler (model Marple 290, Thermo Andersen, Atlanta). The sampler has five stages in the version shown and an additional three stages are available to provide cutpoints from 0.4 µm to 21µm. The flap over the inlet reduces direct projection of large particles into the inlet. This sampler allows measurement of aerosol size distribution and calculation of respirable and thoracic fractions. Aluminum construction and operates at 1.7 L/min.

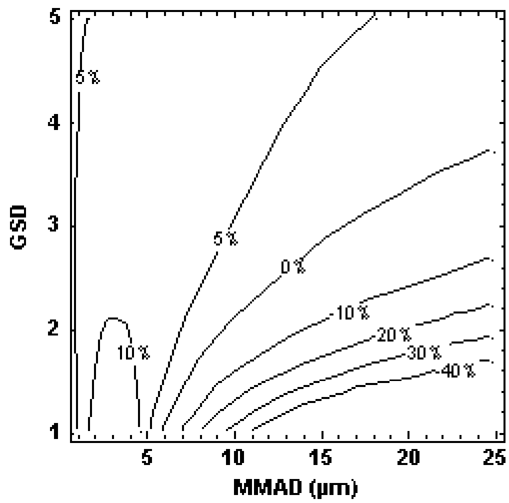

Figure 3. Bias map for the 10-mm nylon cyclone (operated at 1.7 L/min) compared with the respirable convention [33]. The contour lines represent percent bias for specific lognormal size distributions. The calculation of this map is based on laboratory measurement of cyclone penetration and can be used with measured field size distributions to estimate sampling bias.

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