Testing personal inhalable aerosol samplers: a suggested improved protocol based on new scientific knowledge†

James H. Vincent*

Received 30th June 2005, Accepted 8th November 2005
First published as an Advance Article on the web 5th December 2005
DOI: 10.1039/b509222a

In 2002 the Comité Européen Normalisation (CEN) published its document *Workplace atmospheres—assessment of performance of instruments for measurement of airborne particle concentrations* (EN 13205) that describes a standard protocol by which to carry out the testing and validation of personal aerosol samplers of the type widely used for occupational aerosol exposure assessment. It emerged from more than a decade of discussion and a large body of research experience involving several laboratories. The protocol that is described, however, still poses significant technical and economic challenges, not least because it involves laborious—and hence costly—procedures in large, specialized wind tunnel facilities. More recent research has identified a number of areas by which the protocol may be improved and made more accessible to testing laboratories, including a set of validated aerosol sampler scaling laws, a better understanding of the reduced role of the bluff body of the wearer on sampler performance, and the availability of new options for rapid sampler testing methods. Taking these into account, a dummy new protocol is offered for discussion.

1. Introduction

Human inhalation exposure to airborne particles is associated with a wide range of possible health effects. So the assessment of exposure by aerosol sampling continues to be a priority for air monitoring, for both working and ambient living environments. For occupational exposures in particular, it has become an almost universal practice during the past two or more decades that sampling should be carried out using small personal samplers that can be worn on the body, usually the lapel, with aspiration powered by means of small pumps of the type that can be worn on the worker's belt. Such pumps are now very widely available.

James H. Vincent, PhD, DSc, FRSC is Professor and former Chair of Environmental Health Sciences in the School of Public Health at the University of Michigan. He has published many articles on many aspects of aerosol science as it relates to occupational and environmental health, as well as two books, with a new book on aerosol sampling due in 2006.

Department of Environmental Health Sciences, School of Public Health, University of Michigan, Ann Arbor, MI 48109, USA. E-mail: jhv@umich.edu

† Presented at the Fifth International Symposium on Modern Principles of Air Monitoring & Biomonitoring, June 12–16 2005, Norway.

In 1989, Soderholm[1] proposed that particle size-selective criteria for defining health-relevant fractions, based on knowledge of how particles enter the body through the nose and/or mouth during breathing and subsequently penetrate into the human respiratory tract, should be harmonized between the premier international standards setting bodies. Subsequently, harmonized criteria for aerosol sampling appeared in the Standard EN 481 of the Comité Européen Normalisation (CEN, 1993),[2] the ISO Standard 7708 of the International Standards Organisation (ISO, 1995)[3] and the recommendations of the American Conference of Governmental Industrial Hygienists (ACGIH, 1999).[4] These prevail to this day, and have since been adopted by a number of national standards setting bodies. The coarse *inhalable* fraction represents the aerosol that enters the body during breathing, the intermediate *thoracic* fraction represents the aerosol that penetrates into the lung beyond the larnyx, and the finer *respirable* fraction represents the aerosol that penetrates further into the alveolar region. These fractions are all expressed as curves expressing probability (*e.g.*, of inhalation) as functions of particle aerodynamic diameter, d_{ae}. Here, d_{ae} is defined as the equivalent diameter of a particle of density 10^3 kg m^{-3} that has the same falling speed in air as the particle in question. The conventions that have been promulgated are based on studies either with inert mannequins (for the inhalable fraction) or with actual human volunteer subjects (for the thoracic and respirable fractions). One or more of these curves may be identified as appropriate criteria for exposure assessment in a given situation with respect to a given class of health effect. In practice, such curves are applied as 'yardsticks' against which the performance of individual technical sampling devices must be assessed.

Laboratory-based experimental studies of aerosol sampler performance have been reported ever since the 1950s, and the level of such activity has been driven by the perceived need at

various points in time over the years.[5] Initial interest was driven by the needs of stack emission sampling, and later by the needs to sample for the finer respirable fraction when occupational exposure limits (OELs) began to emerge for pneumoniosis-forming dusts. More recently, the need to define and accurately sample the coarser inhalable fraction has been quite prominent as new OELs are sought that better reflect the nature of human exposure to particles in this size category. For these, experimental methods have been perceived by aerosol scientists as being quite difficult because they are subject to physical processes outside the sampler that are not always well-defined. For this reason, there has been interest in both the United States and Europe in the development of standardized protocols by which to achieve consistent validation and characterization of the performances of samplers considered to be candidates for practical application in the real world of occupational aerosol exposure assessment. To this end, research projects have been funded during the past decade by both the United States National Institute for Occupational Safety and Health (NIOSH) and the European Commission.

CEN was the first organization to set out to develop standard methods for aerosol exposure assessment along the lines described. Its Technical Committee 137 identified a number of working areas. In addition to the area of sampling conventions already mentioned above, these included sampling strategy, general performance requirements, and performance requirements for gas and vapor sampling instruments, aerosol samplers and sampling pumps. At the Airmon 1993 Symposium in Geilo, Norway, Lidén[6] presented the ingredients of an early draft of a standard method for evaluating the performances of aerosol samplers. The CEN document that was eventually published in 2002, *Workplace atmospheres—assessment of performance of instruments for measurement of airborne particle concentrations* (EN 13205), grew out of such earlier deliberations.[7] The present paper describes how knowledge gained from even more recent research paves the way for an improved standardized protocol for aerosol sampler evaluation.

2. EN 13205

The CEN standard protocol is a good model for further development. It requires that, 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*. It 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 with directly respect to sampling conventions; (b) the laboratory comparison of instruments; and (c) the field comparison of instruments. The second and third of these involves the identification and use of an existing aerosol sampler that is known and agreed to be capable of accurately sampling the appropriate health-based aerosol fraction as a reference sampler. For the inhalable fraction, for example, the IOM sampler—first described in 1986 by Mark and Vincent,[8] and commercially available from SKC Ltd. (Blandford Forum, Hants, England, UK)—has, perhaps, been most consistently shown to be the best candidate currently available for this role.[9] The candidate test sampler of interest is then operated alongside the reference sampler, and the mass of aerosol collected in the test sampler is compared to that in the reference. In the laboratory, these experiments should be performed for the range of relevant simulated environmental conditions identified in the critical review. In the field, the comparisons should be carried out for as wide a range of conditions as possible pertaining to the field site(s) in question. For the latter, it is clear that the results can only be considered useful for future application at the same—or demonstrably similar—sites. So this approach may be of limited general value. The first test method identified by CEN, in Annex A to the main EN 13205 document, is the one that is directly relevant to the present paper.

Annex A provides a useful framework for the application of the new knowledge gained from recent research. Its structure is outlined in Table 1. The main philosophy of the process is summarized in Fig. 1. It shows how the sampler performance must be fully characterized for a representative range of particle sizes, windspeeds and sampler orientations (where sampling is usually orientation-averaged, as has been the case in the most of the research described in this report). The resultant data are used to construct a representative performance curve (aspiration efficiency or sampling efficiency, depending on the recommended mode of operation of the sampler, see below) as a function of particle aerodynamic particle diameter. Then the sampling performance curve is assessed by first calculating the measured sampled mass

Table 1 Contents of Annex A of EN 13205

Principle	
Test method	Test conditions, Test variables (particle size, windspeed, wind direction, aerosol composition, sampled mass, aerosol charge, specimen variability, flowrate variations, surface treatments), Experimental requirements (environmental conditions—temperature and humidity, choice of monodisperse or polydisperse test aerosol, method for measuring particle aerodynamic diameter, characteristics of monodisperse and polydisperse test aerosols, test aerosol homogeneity and stability, methods for taking reference samples and obtaining sampler efficiency, windspeed variability and homogeneity, wind tunnel blockage, turbulence, number of samplers to be tested simultaneously, position on body, methods of data processing and analyses, sampling pumps)
Calculation methods	Nomenclature, Calculation of the actual sampled concentration, Calculation of ideal sampled concentration, Calculation of sampler bias, Application of a sampler correction factor, Calculation of uncertainty in the estimated sampler bias, Calculation of sampler accuracy
Test report	

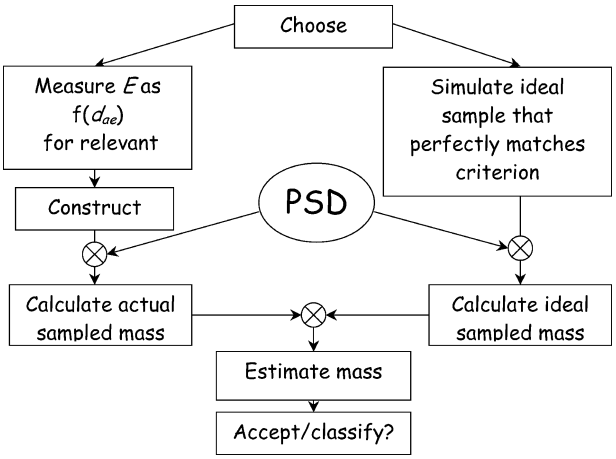

Fig. 1 Summary of the approach described taken in Annex A of EN 13025. Here, 'PSD' refers to the particle size distribution: in the approach shown many such distributions are applied in order to build up a map of the bias between the actual and ideal sampler performance over a wide range of particle size distribution parameters as indicated in Annex A.

fraction for a representative set of log-normal particle size distributions. For each particle size distribution, this calculated mass is then compared with the equivalent results for a hypothetical ideal sampler that perfectly matches the convention of interest (*e.g.*, the inhalable fraction). The two sets of calculated results for the full range of particle size distributions are then used to construct a 'map' of the collected mass biases that would be found when the sampler is used over relevant ranges of conditions. Any given sampler can then be classified according to its ability to sample more or less closely to the desired criterion. This classification then provides the basis of the choice of sampling instrument that an occupational hygienist might make in a given exposure scenario.

3. Earlier knowledge

Aerosol sampler performance indices

The simple schematic diagram in Fig. 2 provides the basis for discussing aerosol sampler performance. The first index is the *aspiration efficiency* (A) that defines how efficiently particles are extracted from the external environment and enter the sampler. For given sampling conditions and particle size, it is given by $A = c_s/c_0$, where c_s is the concentration of the aerosol passing through the plane of the inlet and c_0 is the concentration in the undisturbed environment outside the sampler. For samplers where performance is determined entirely by everything that is collected inside the sampler, A is an appropriate performance index. On the other hand, for many samplers performance is defined by the aerosol that is collected on a filter (or other collecting substrate) inside the sampler. For these, again by reference to Fig. 2, *sampling efficiency* is given by $E = c_F/c_0$, where c_F is the concentration of aerosol arriving at the filter. c_F may differ from c_s if particles are lost by collection on internal walls of the sampler before they can reach the filter; in which case, $E < A$.

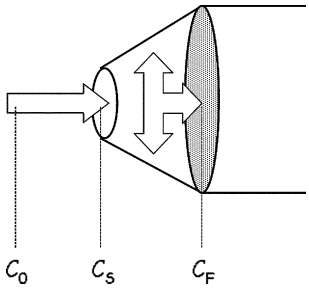

Fig. 2 Schematic on which to base the indices of performance for a hypothetical aerosol sampler.

Earlier studies of personal sampler performance

Earlier studies of the performances of personal samplers were carried out under simulated laboratory conditions, usually in wind tunnels, that were considered at the time to be most relevant to actual workplace environments. These involved large wind tunnels in which life-sized model human torsos (*i.e.*, mannequins) could be installed without excessive blockage and on which personal samplers of the types of interest could be mounted. Most of these studies were aimed at the sampling of coarse particles falling within the inhalable fraction. With careful choice of well-characterized, relatively-monodisperse test aerosols generated from narrowly graded powders (*e.g.*, fused alumina) and careful experimental procedures, an excellent body of data was obtained for samplers worn on torsos for which the orientation with respect to the wind was averaged over time, by either slowly or incrementally rotating the torso.[8,10] Windspeeds in such experiments were generally upwards of 0.5 ms^{-1} and the results were considered to be applicable to many occupational exposure situations. Although there has more recently been considerable discussion about the importance of windspeeds in the range below this, and the fact that many workplaces are likely to come into this category, experiments like the ones for moving air cited above form the basis of most current recommendations for how to choose aerosol sampler for given applications. In turn, they underpin much of what is now published in EN 13205. However, the methodology for moving air is generally applicable to both moving and nearly-calm air situations. So the latter is implicitly included in EN 13205.

The general method that has thus evolved from the earlier wind tunnel work has been shown to be effective and allowed researchers from different laboratories, using different facilities, to arrive at consistent results. However, it is widely acknowledged that the method is laborious, time-consuming and—therefore—costly. In addition, there are relatively few institutions around the world that can devote the space and personnel to the facilities and resources that are need to carry out such testing on a routine basis. Fortunately, new knowledge is emerging from recent and current research that goes towards alleviating some of these difficulties.

4. New knowledge

Since EN 13205 was drafted, new scientific progress has been made in three key areas: aerosol sampler scaling laws, the role of the body of the wearer, and rapid testing methods.

Sampler scaling laws

Aerosol sampling science is essentially a branch of engineering science, for which the engineering principles of dimensional analysis applies. It is first appropriate to discuss aerosol sampler performance in terms of aspiration efficiency (A) since this embodies the primary overarching physical influences for all aerosol sampling. Full details of the expected functional behaviour of A were given in our paper to Airmon 2002 in Lillehammer (Brixey *et al.*, 2002).[11] It was argued that Reynolds' number and gravity effects may be neglected so that

$$A = f\{S, R, r, \theta\} \quad (1)$$

where

$$\text{Stokes' number, } S = d_{ae}^2 \rho^* U/18 \eta \delta \quad (2)$$

$$\text{Velocity ratio, } R = U/U_s \quad (3)$$

$$\text{Dimension ratio, } r = \delta/D \quad (4)$$

in which d_{ae} is particle aerodynamic diameter, U the external windspeed, U_s the mean velocity of air passing through the plane of the sampler orifice, δ the sampler orifice diameter, D the characteristic sampler body dimension and θ the sampler orientation with respect to the external air movement, and where ρ^* is the density of water and η the viscosity of air. The dependency on θ disappears when A is orientation-averaged. The relationship embodied in eqn. (1) is acknowledged to be simplistic in relation to all possible situations, but it is applicable to most practical scenarios. However, caution is recommended whenever it is used in order to avoid its inappropriate application outside the range where experiments have shown it to be valid (*e.g.*, as observed for low testing windspeed conditions by Brixey *et al.*, 2005).[12]

For E, the same functional dependencies are expected to apply. Additional ones may come into play only if the internal geometry or other physical conditions (*e.g.*, state of electric charge) are such that additional aerosol mechanical processes are introduced. Otherwise, however, for samplers with the same overall geometry, eqn. (1) for A will apply also for E.

For the purpose of scaling, eqn. (1) informs us that, for a given sampler geometry A (and E) will be the same for constant combinations of S, R and r. So, as already described:[10] to achieve constant R, both U and U_s should be scaled by the factor k_U; to achieve constant r, both δ and D should be scaled by the factor k_δ; to achieve constant S, particle size should be scaled by the factor k_{dae} where $k_{dae}^2 = k_U/k_\delta$.

Role of the body of the wearer

Physically, a personal aerosol sampler may be thought of as a small sampling inlet on a large bluff body, mostly comprising the body of the worker. This suggests an important role for the size and shape of the body that is to be simulated in the testing set-up and the dimension ratio, r. Indeed, until recently this was assumed to be the case, and is reflected in the current Annex A of EN 13205. But some new research has illuminated matters. In the first instance, Aizenburg *et al.* (2001)[13] showed that a somewhat smaller, highly simplified bluff body may be used on which to mount the test sampler. In addition to the simplifications that came out of this work, it was shown that a wind tunnel could be used that was significantly smaller than the ones that had featured in the earlier work cited above.

Recent research in our own laboratory for blunt samplers of simple shape facing the wind, and using conventional gravimetric methods, suggested that the sensitivity of aspiration efficiency to r is considerably less than had previously been thought.[14] Subsequent experiments were reported for the aspiration efficiency of a full-size IOM sampler mounted on a small rectangular, slowly-rotating bluff body that could be accommodated in our small 30 cm × 30 cm wind tunnel working section.[12] These experiments were scaled to correspond to equivalent full-scale conditions, as shown in Table 2, and aspiration efficiency was measured by the gravimetric assessment of samples collected by the test and reference isokinetic samplers, respectively. In Table 2, and by reference to eqn (2) to (4), it is seen that both R and S were held constant between the laboratory-scale and the equivalent full-scale system. However, in order to allow testing of the full-sized IOM sampler in the small wind tunnel system, and in light of the suggestion about the weakness of the dependence of A on r, scaling of D was allowed to relax. The experimental results are shown in the form of A *versus* d_{ae} alongside the curve for the inhalable fraction in Fig. 3. The plotted points (shown as open circles) are very consistent with results that have been reported many times from experiments for the IOM sampler with everything at full-scale, and also compare favorably with the inhalability curve. They also add further support to the suggested weak dependence of A on r.

From the three experimental studies cited above, it is reasonable to conclude that the aspiration efficiency A (and in turn, where appropriate, sampling efficiency E) of blunt aerosol samplers is only weakly dependent on the size of the sampler body. So, for the testing of personal aerosol samplers, strict scaling with respect to r is not necessary. It follows that the size of the bluff body on which the sampler will be mounted for the purpose of testing may therefore be significantly smaller than the actual size of a the body of a human subject who might be asked to wear the sampler in a real-world situation. The implications to future testing protocols are considerable. This knowledge, along with the confirmation of the validity of the aerosol sampler scaling laws with respect to the other dimensionless parameters identified, paves the way towards aerosol sampler test procedures using much smaller wind tunnels than previously.

Table 2 Summary of experimental conditions for scaled IOM sampler experiments, where scaling factors are here expressed as full-scale/small-scale. Here, Q is the sampling volumetric flowrate

	Full scale	Laboratory scale
δ/mm	15	15
D/mm	300	120
U/m s^{-1}	1.0	2.5
Q/L min^{-1}	2.0	5.0
U_s/m s^{-1}	0.024	0.059
k_{dae}	1	1.58
k_δ	1	1
k_U	1	0.40

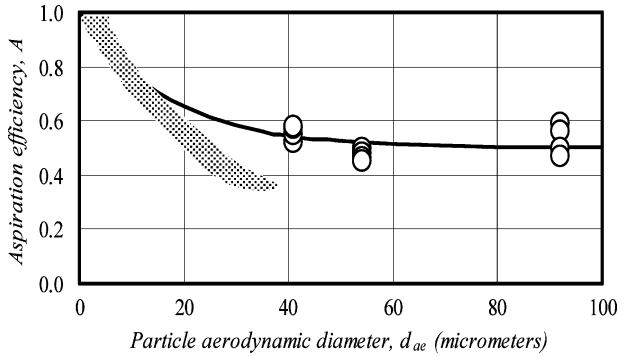

Fig. 3 Aspiration efficiency for IOM-like personal inhalable aerosol samplers as measured in scaled experiments conducted in a small wind tunnel. The circles represent results obtained using the traditional gravimetric method. The shaded area represents results obtained using the new rapid testing method described by Brixey *et al.* (2002).[11] Also shown (continuous curve) is the curve for the inhalable fraction.

Rapid testing methods

In their 2002 paper, Brixey *et al.*[11] reported a new rapid testing method, using polydisperse aerosols and a direct-reading, time-of-flight-based aerodynamic particle sizer (APS) (TSI Inc., St. Paul, MN, USA) by which measurements of sampler aspiration efficiency across a whole range of particle sizes were achieved in a single experimental run. In summary, the method involved experiments in which sampled particles—in both the sampler under test and an accompanying reference sampler—were counted and sized by means of the APS (and hence according to particle aerodynamic diameter), thus providing information that permitted in one sampling run for a given set of external conditions a complete set of data for c_s and c_0 (as defined earlier), and in turn for sampling efficiency, as a function of particle aerodynamic diameter (d_{ae}). Similar procedures have been reported extensively by others in relation to the testing of samplers for finer aerosol fractions.[15] Brixey *et al.* described experiments for a range of actual windspeeds from 0.7 to 4.6 m s^{-1}, all corresponding—by scaling—to the same full-scale scenario identified in Table 1 for the gravimetric experiments. The results are summarized by the shaded area in Fig. 3.

The trend of the results from the rapid testing method is seen to generally follow that expected for the IOM sampler from all the previous work. However, at the larger end of the particle size range, A falls somewhat below corresponding results obtained by other methods, including the ones shown by the open circles. This suggests that the particular rapid testing method described by Brixey *et al.* is not yet quite sufficient alone to be recommended as the 'ultimate' test method. In any case, because of the particle size range limitations of the APS, its scope is already somewhat limited. At this point, therefore, it is recommended that a combined approach, like the one reflected in Fig. 3, can provide the most useful range of information about sampler performance.

5. An improved testing protocol

The new knowledge that has been described above provides important insights that can allow significant improvements to the existing EN 13205 sampler testing protocol. These may be supplemented by some further improvements derived from other, earlier research. With this in mind, the Appendix shows a dummy new protocol that incorporates the new knowledge. It is structured broadly in a manner similar to the Annex A in the original EN 13205. The primary benefits from application of the new knowledge are as follows:

(1) Testing may be carried out at dimensional and velocity scales other that those corresponding directly to full-scale scenarios. This may be achieved by appropriate application of the full set of scaling laws that have been identified. In addition, the need to scale the bluff body size may be relaxed. Taken together, these mean that significantly smaller wind tunnels may be used, providing easier achievement of uniform spatial aerosol distribution, more consistently representative measurement of reference aerosol concentrations (c_0), easier access to test systems, and generally faster and more efficient test runs. The net effect is a reduction in the cost of testing and the prospect of more consistent results. The first part of the dummy new protocol is written to reflect such changes and their benefits.

(2) Rapid testing methods are quite promising, and can allow still further savings in time and convenience. Here, however, as seen in the above, there are some outstanding scientific issues that still need to be addressed. Even so, systems like the one that has been described are already useful in conjunction with the more traditional measurement methods. A new section is added to the dummy new protocol that opens the door to the use of such methods, provided that current scientific uncertainties can be resolved. For the present, however, the dummy protocol is written in a way that permits important progress to be made in the improvement and speeding up of aerosol testing procedures even while the search for that further new knowledge is taking place.

6. Concluding remarks

It is clear that aerosols in both working and living environments will continue to be a concern in relation to occupational and environmental health. So the monitoring of aerosol exposures will continue to be of interest, including the search for new instruments that better reflect the actual nature of human exposure. This paper has drawn together the results from a large body of research from several laboratories over two decades that now points the way towards realistic applications in the prescription of improved standard methods for the testing of aerosol standards. More specifically the new knowledge that has emerged in recent years has come from experimental research at the University of Cincinnati and the University of Michigan in the United States, and the Institute of Occupational Medicine and the Health and Safety Laboratory in the United Kingdom, involving widely differing research facilities and methods. The dummy new protocol that is contained in the Appendix to this paper is respectfully offered for discussion by appropriate committees within the CEN (since these are the origins of the current EN 13205), as well as for consideration by other standards organizations throughout the world.

Finally, it is important to reiterate that many workplaces are characterized by very low windspeeds, lower than those in most of the research that underpinned the original EN 13205. It is emerging to aerosol scientists that a different approach to aerosol sampling beyond 'conventional' wind tunnel testing will eventually be required in order to achieve further progress. New research is under way to explore aerosol sampling under such conditions, including in our own laboratory, and it is expected that this will lead to further improvements to the testing protocol.

Appendix

Dummy protocol for testing personal inhalable aerosol samplers (presented in the manner of the original Annex A in EN 13025).

1. Principle

Laboratory experiments are conducted to characterize the sampling efficiency of a given candidate sampler as a function of particle aerodynamic diameter over the relevant range, and for relevant external conditions. The results are compared to the relevant target sampling convention.‡ Mathematical modeling is used to estimate the concentrations that would be sampled from a range of ideal log-normally distributed aerosols, both for the actual sampler that is being tested and for a hypothetical ideal sampler that perfectly matches the target sampling convention. From these data, the sampler bias and precision are estimated with respect to the desired aerosol fraction. The experimental design for the protocol will be preceded by a critical review of the sampling process for the sampler to be tested. The review will address all the variables that may be influential in the performance of the sampler with respect to the target sampling convention. The review, the experimental design for the test, the test results, the mathematical and statistical methods and the conclusions will all be described in a test report.

2. Test method using monodisperse test aerosols

The sampling efficiency value for a given set of conditions is determined by comparing the aerosol concentration measured using the sampler under test with a reference sample of the ambient aerosol concentration. An experimental design shall be devised that takes account of appropriate aerosol sampler physical scaling relationships§ and also gives due attention to randomisation of the data and to estimation of the main effects. The design, and its associated statistical model, shall be explained in a test report.

2.1 Test conditions. Experiments to test candidate samplers for the inhalable fraction shall be carried out in a wind tunnel or aerosol chamber. Personal inhalable samplers intended for use outdoors or in environments with forced ventilation (*i.e.*, wind speeds in excess of 0.5 m s^{-1}) shall be tested while mounted on a life-size mannequin, or under circumstances shown to give equivalent results, unless it can be demonstrated—or argued from appropriate peer-reviewed literature—that the size or shape of the mannequin has negligible influence on the performance of the sampler being tested. For the latter, for example, it might be deemed from the initial critical review that it is appropriate for the sampler to be mounted on a bluff body whose size may be smaller and its shape simpler.¶ If used, the mannequin set-up shall reproduce the effects of the presence of a life-size, human-shaped head and torso, wearing a clean cotton boiler suit or similar clothing, unless—again—it can be scientifically argued that these have little bearing on the results, after appropriate scaling. If a sampler is tested as a personal sampler, the results may not apply to its use as a static sampler (and *vice versa*), unless the above have been demonstrated.‖

2.2 Test variables. The laboratory tests of sampling efficiency shall be designed to quantify the effects of all variables that may be important to the performance of the sampler under test. Table 3 lists the most important influencing variables and identifies those for which testing is compulsory (C), compulsory for some sampler types or uses only (C′), or optional (O). Excluded variables shall be clearly identified in the section of the test report that describes the scope of the test. Table 3 also summarizes the ranges of values for which the selected variables should be tested, and the number of values within these ranges. In general, the values chosen need not include the extremes of the range, although specific requirements may be stated in some cases. Where the experimental design requires a choice to be made, for example the physical nature or chemical composition of the aerosol used for the tests, or the type of collecting substrate used, the effect of the choices made on the applicability of the test results to routine sampling shall be considered and noted in the test report.

2.2.1 Particle size. For inhalable aerosol samplers, the largest equivalent full-scale particle aerodynamic diameter tested shall be no smaller than 90 μm, but may be smaller in reality if scaling of physical variables is appropriately carried out.**

2.2.2 Windspeed. The 'outdoor workplace' range of windspeeds shall also apply to samplers intended for use in forced ventilation (equivalent full-scale >1 m s^{-1}). The highest equivalent full-scale windspeed value recommended here may be altered if the initial critical review identifies a more suitable upper limit, depending on the intended use of the

‡ The original Annex A of EN 13205 is general and is aimed at the testing of samplers for any aerosol fraction inhalable, thoracic, respirable or any other. In principle, this proposed new protocol also applies generally. However the emphasis here, as it is drawn from the new knowledge summarized in the main body of this paper, is aimed specifically at the testing of samplers for the inhalable fraction.

§ Scaling of sampler performance with respect to the appropriate variables has been demonstrated during the research cited.

¶ As has been suggested by some of the recent research cited in the main body of the paper.

‖ Again, the validity of scaling of sampler performance with respect to appropriate variables, so that small-scale test conditions can be set up to be equivalent to full-scale conditions, has been demonstrated. Also, it has been shown (see main text) that the effect of the size of the bluff body carrying the sampler is weak.

** Note that the scaling laws that have been developed describe the roles not only of the main macroscopic variables (sampler size, windspeed, *etc.*) but also particle size.

Table 3 Variables to be tested

Variable	Status	Range	Number of values
d_{ae}	C	Inhalable: 1 to 100 μm	≥ 9, spaced to cover important features of the efficiency curve
U	C	Indoor workplace with 0 to 1 m s^{-1}	2: ≤ 1 m s^{-1}
	C	Indoor or outdoor with 0 to 4 m s^{-1}	3: 0.5, 1 and 4 m s^{-1}
θ	C	Omnidirectional average	Continuous revolution or ≥ 4 values stepwise
Composition	O	Phase: solid and/or liquid; particles of known shape	Choose suitable materials
Agglomeration	O	Unagglomerated dust	Choose and document
Sampled mass	O	Up to mass corresponding to: maximum concentration × design flowrate × sampling time	≥ 3
Electric charge	O	Charged or neutralised aerosol, conducting or insulating sampler	Choose and document
Sampler variability	C′	Inhalable: one or more specimens	
Flowrate variation	C′	Design flowrate ±10% for inhalable samplers, at one windspeed	
Collection surface	O	Choice of materials (*e.g.* filters, foams) and details of any surface treatments to be stated	≥ 3

sampler. Again, testing may be carried out at different windspeeds by the application of appropriate scaling laws.††

2.2.3 Wind direction. In accordance with the definition of the inhalable convention, the effects of wind direction shall be averaged out by rotating the sampling system (including the sampler itself and the mannequin or any bluff body on which it is mounted) during the course of each test run, either slowly and continuously, or stepwise with four or more steps.

2.2.4 Aerosol physical and chemical properties. Particles used for tests to classify samplers should be spherical (solid or liquid), or approximately isometric. The degree of agglomeration of the test aerosol itself may be verified by the visual microscopic inspection of particles collected by elutriation onto slides placed in the working section of the wind tunnel or test chamber used. In general it is assumed that the chemical composition of the test aerosol is not influential. But in cases where the critical review suggests a possible composition-related effect (*e.g.*, on particle retention on sampler surfaces), this may influence the choice, and this should be noted in the test report.

2.2.5 Sampled mass. For given test conditions of test aerosol concentration, a minimum sampling time should be chosen to ensure a collected sample that exceeds the limit of quantitation for the collecting substrate and the gravimetric measurement system used. In addition, a maximum sampling time should be chosen to minimize effects associated with overload or blow-off.

2.2.6 Aerosol charge. If the sampler is non-conducting it should be tested with a neutralised aerosol, unless it can be demonstrated—or argued from the peer-reviewed scientific literature—that the results for aerosols charged during mechanical generation and dispersal into the test system are not significantly different. Electrostatic influences should be reduced where possible, by choosing samplers made from conducting materials, cleaning them thoroughly, and grounding them during all tests.

2.2.7 Specimen variability. This is optional for inhalable aerosol samplers.

†† Again, by the use of scaling laws.

2.2.8 Flowrate variations. For inhalable samplers, the sampling flowrate should be within ±10% of the recommended value, or of the value used in the tests after appropriate scaling.‡‡ The flow dependence should be tested at the windspeed most representative of the conditions of use. Tests to obtain this information need not be carried out where reliable data are available in the published literature.

2.2.9 Surface treatments. Examples of surface treatments are the greasing and cleaning of collection substrates, the neutralising of filters and foams, and the method of sampler cleaning. Differences between the surface treatments actually tested and those recommended in the sampler's instruction manual shall be clearly stated and explained in the test report.

2.3 Experimental requirements. The experimental system shall have the following characteristics:

2.3.1 Environment. The experiments shall be carried out in an environment with temperature between 15 °C to 25 °C, atmospheric pressure between 960 hPa and 1050 hPa and relative humidity between 20% and 70%, unless the sampler is to be used in more extreme environments, in which case the conditions of use should be reproduced as closely as possible. A full description of the test environment shall be given in the test report, and the actual conditions existing at the time of testing documented.

2.3.2 Test aerosols. Tests should be carried out using monodisperse or nearly-monodisperse aerosols. When nearly-monodisperse test aerosols are used, a single experiment gives rise to a single measurement of sampling efficiency at a single nominal particle aerodynamic diameter covering the range of interest. Therefore nine different test aerosols should be used in order to obtain sampling efficiency values corresponding to nine particle sizes covering the desired range (as recommended in Table 3). Correction factors for particle shape and particle density, where used, shall be determined for each aerosol or obtained from appropriate reliable literature.§§

‡‡ Again using the scaling laws.

§§ This section of the protocol refers only to methods where nearly-monodisperse test aerosols are used for the testing of inhalable aerosol samplers. A new section is added (see below) that deals specifically with the application of polydisperse aerosols coupled with direct reading particle sizing and counting instrumentation.

2.3.3 Particle aerodynamic diameter. The choice of test aerosol depends on the availability of a suitable method for the measurement of mass median particle aerodynamic diameter for the individual aerosols generated and used for testing or of appropriate valid pre-existing data. Such properties should be measured independently unless data are available in the peer-reviewed literature to provide the necessary information for aerosol generated from a particular substance in a particular way. If it is decided to conduct experimental calibration of the test aerosols, this may be done by any method having a unique, monotonic calibration curve over the appropriate particle size range. Full details of the calibration method shall be given in the test report, including the use of correction factors (*e.g.*, for particle density, particle shape, *etc.*). The particle aerodynamic diameter values measured shall be those pertaining to the Stokes regime, and their precision (including uncertainty in any correction factors used) shall be determined and stated in the test report.

2.3.4 Particle size distribution and monodispersity. For tests on inhalable aerosol samplers, the nearly-monodisperse test aerosols shall have geometric standard deviation less than 1.50.

2.3.5 Spatial and temporal distribution of test aerosol. The test aerosols should be spatially homogeneous to within ±20% with respect to both particle size distribution and concentration over the region of the test system occupied (or projected) by the test sampler system. Mass concentration should not vary or change over time by more than ±25%. The aerosol concentration and particle size distribution during the tests should be carefully chosen for compatibility with the limitations of the particle aerodynamic diameter measurement method, and shall be documented. The aerosol particle size distribution and concentration shall be sufficient to ensure that analytical errors in the measurement of the sampled aerosol are less than 2% for analysis by weighing or chemical methods, and less than 1% for analysis by particle counting.

2.3.6 Reference samplers. Reference samples shall be collected with thin-walled sharp-edged probes operating isokinetically in the case of a wind tunnel, or in the case of an aerosol chamber by any method for which it can be demonstrated that the sampling efficiency is unity for all particle sizes of interest. Alternatively, anisokinetic operation of reference samplers may be applied provided that an appropriate validated aspiration efficiency model is identified and used for the correction of reference aerosol concentrations. Reference probes shall be situated at representative positions within the area in which the test samplers are placed, so that spatial variations in the test aerosol can be identified. The method used to calculate the sampler efficiency shall be clearly stated, and should take into account, where possible, temporal and spatial variations in concentration. The method used to estimate the reference concentration shall have relative standard deviation lower than 10%.

2.3.7 Windspeed. The actual values of wind speed (or any other environmental variable) during the test runs, scaled or otherwise, shall not differ by more than 10% from the target value over the spatial area in which test specimens are situated. Where a wind tunnel is used the blockage by the mannequin or samplers shall be less than 20%. The turbulence length scale and intensity in the wind tunnel shall be estimated if possible and documented in the test report.¶¶ The values should be kept constant for each of the test windspeeds.

2.3.8 Multiple samplers and positional effects. Several sampler specimens may be tested together provided they are not so close that they interfere with one another. The experimental design shall be capable of isolating and eliminating any positional effects from the experiment. Samplers shall be tested together with their appropriate holders; the plane of the inlet with respect to vertical shall be orientated as recommended during actual field sampling. The positions and orientations used shall be documented. The positions at which personal samplers are placed on a mannequin or other bluff body during testing shall be representative of where they are designed to be used, unless it can be shown—or argued from the peer-reviewed literature—that such positional effects are not significant.

2.3.9 Data processing and analyses. The test report shall contain full details of the methods used to process and analyse the samples taken during the tests, and of the procedures used to clean samplers between experimental runs.

2.3.10 Pumps and flowrate. Samplers should be tested together with suitable, properly maintained pumps. For test purposes the sampler volumetric flowrates shall be carefully adjusted and measured, using a bubble flowmeter or gasmeter, and recorded. The pumps used shall meet general requirements (*e.g.*, EN 1232), and any more stringent requirements specified in the instruction manual for the sampler. Samplers with an integral pump or air mover shall be tested under flow conditions having the same characteristics as the integral pump or air mover.

3. Test method using polydisperse test aerosols‖‖

The sampling efficiency for a given set of conditions is determined by comparing the aerosol concentration measured using the sampler under test with a reference sample of the ambient aerosol concentration. An experimental design shall be devised that permits the application of polydisperse aerosols and appropriate direct reading instrumentation such that rapid acquisition of sampler efficiency data can be achieved within a single experiment, as opposed to the multiple experiments that would be needed using the approach described in Section 2. Also as for the approach described in Section 2, this

¶¶ Turbulence intensity and length scale are difficult to measure, and require sophisticated equipment. For good estimates for grid-generated turbulence, see Baines and Peterson (1951).[16]

‖‖ This method provides means to carry out performance tests of aerosol samplers that are less time-consuming and hence less costly. Research in this area has shown great promise for this type of approach, especially for the finer thoracic and respirable aerosol fractions. For the inhalable fraction, while research here too has shown considerable promise, there remain some outstanding questions before such methods can be fully implemented. The method described here is introduced by way of illustration of what is being sought and the state of current knowledge, and to provide guidelines for future consideration.

method should also take account of appropriate aerosol sampler scaling relationships. If, for the specific method chosen, scaling does not permit simulation of the full desired range of equivalent full-scale particle size, then the results may be supplemented at larger particle sizes by data points obtained using the method described above in Section 2. The experimental design, and its associated statistical model, shall be explained in the test report.

3.1 Test conditions. Same as in Section 2.

3.2 Test variables. See also Table 3.

3.2.1 Particle size. For inhalable aerosol samplers, the equivalent full-scale particle size tested shall range from 0 to 90 μm. But appropriate scaling laws can be used to narrow this range for the purpose of testing. Such application of scaling laws may enable the application of specific direct-reading instrumentation for the accurate rapid-detection, sizing and counting of particles in the test system.***

3.2.2 Windspeed. Same as in Section 2.

3.2.3 Wind direction. Same as in Section 2.

3.2.4 Aerosol physical and chemical properties. Same as in Section 2.

3.2.5 Sampled concentration. The sampled aerosol concentration must be in the range that is (a) large enough to provide sufficient individual particle counts across the whole range of particle size of interest, in order that particle concentration may be defined with sufficient statistical accuracy, but (b) not so large that particle counting artifacts may occur due to counting coincidences or other apparent 'phantom' particles.†††

3.2.6 Aerosol charge. Same as in Section 2.

3.2.7 Specimen variability. Same as in Section 2.

3.2.8 Flowrate variations. Same as in Section 2.

3.2.9 Surface treatments. Same as in Section 2.

3.3 Experimental requirements. The experimental system shall have the following characteristics.

3.3.1 Environment. Same as in Section 2.

3.3.2 Test aerosols. Tests should be carried out using polydisperse, preferably non-agglomerated test aerosols with continuous particle size distribution.

3.3.3 Particle aerodynamic diameter. The direct-reading instrumentation used should be capable of providing particle size information specifically in terms of particle aerodynamic diameter. Alternatively, however, an instrument that provides particle size in terms of some other metric would be acceptable provided that it can either be calibrated in terms of particle aerodynamic diameter or the particle size it provides can be converted to particle aerodynamic diameter by the application of other information (*e.g.*, particle density or shape) according to established aerosol science principles. If the latter approach is adopted, full details of the conversion method shall be stated in the test report.

3.3.4 Particle size distribution and concentration. The particle size distribution and concentration should be such that ample particles are available throughout the range of the direct-reading particle measuring instrument that has been demonstrated as effective for the accurate counting and sizing of particles, bearing in mind the possibility of counting errors at high or low particle number concentrations. Details of the particle number statistics should be noted in the test report.

3.3.5 Spatial distribution of test aerosol. Same as in Section 2.

3.3.6 Reference samplers. Same as in Section 2.

3.3.7 Windspeed. Same as in Section 2.

3.3.8 Multiple samplers and positional effects. The experimental design shall be capable of isolating and eliminating any positional effects from the experiment. In this method, only one sampler can be tested in any given test. Its position and orientation used shall be documented. That position may be changed in different experimental runs. In general, the position at which a personal sampler is placed on a mannequin or other bluff body during testing shall be broadly representative of where they are designed to be used.

3.3.9 Experimental procedure. Any test method involving the use of a direct-reading instrument to determine sampling efficiency must require consideration of the flow interface between the air movement outside the sampler inlet to that inside the sampler inlet. It will also be necessary to account for the particle losses that will occur after passing through the inlet but before arrival at the sensing zone of the direct-reading instrument. This must apply to both the sampler being tested and the reference sampler. The method must therefore either take quantitative account of such particle losses, or it must be designed so that such losses cancel out between the test and reference sampler respectively. In addition, sampler flowrates appropriate to the sampler being tested (after appropriate scaling) and the reference sampler may need to take account of the flowrate specified for the direct-reading instrument used, such that appropriate flow matching may be required (*e.g.*, by the addition or subtraction of air from the sampler air flow).‡‡‡ The overall method that is used should be shown to provide results that are equivalent, after appropriate scaling, to those that would be obtained using the method described in Section 2. The test report shall provide details of all procedures used to clean and prepare samplers during experimental runs.

3.3.10 Data processing and analysis. The test report shall contain full details of the methods used to process and analyse

*** Currently-available direct-reading particle counters operate efficiently only for particles with aerodynamic diameter up to no greater than about 20 μm.

††† The particle coincidence or 'phantom' artifacts referred to are a function of the specific direct reading instrument used.

‡‡‡ This may be addressed by the use of a suitable flow adaptor.

the particle number and size information obtained during the tests.

3.3.11 Test report. Same as in Section 2.

4. Calculation, analysis, evaluation and reporting§§§

Acknowledgements

The author wishes to thank the US National Institute for Occupational Safety and Health for its support of this research through grant number RO1-OH02984-06; also the many scientists with whom he has discussed these matters over the years, especially at the five successive Airmon conferences.

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§§§ The original Annex A in EN 13205 protocol contains detailed information on calculation methods, analysis of results, sampler evaluation and reporting of the results (as outlined in the main body of this report). These will apply to the modified protocol suggested here, and so the details are not repeated.

