A COLLABORATIVE EUROPEAN STUDY OF PERSONAL INHALABLE AEROSOL SAMPLER PERFORMANCE


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Abstract—Following the adoption of new international sampling conventions for inhalable, thoracic and respirable aerosol fractions, a working group of Comité Européen de Normalisation (CEN) drafted a standard for the performance of workplace aerosol sampling instruments. The present study was set up to verify the experimental, statistical and mathematical procedures recommended in the draft performance standard and to check that they could be applied to inhalable aerosol samplers. This was achieved by applying the tests to eight types of personal inhalable aerosol sampler commonly used for workplace monitoring throughout Europe. The study led to recommendations for revising the CEN draft standard, in order to simplify the tests and reduce their cost. However, some further work will be needed to develop simpler test facilities and methods. Several of the samplers tested were found to perform adequately with respect to the inhalable sampling convention, at least over a limited range of typical workplace conditions. In general the samplers were found to perform best in low external wind speeds, which are the test conditions thought to be closest to those normally found in indoor workplaces. The practical implementation of the CEN aerosol sampling conventions requires decisions on which sampling instruments to use, estimation of the likely impact that changing sampling methods could have on apparent exposures, and adjustment where necessary of exposure limit values. The sampler performance data obtained in this project were affected by large experimental errors, but are nevertheless a useful input to decisions on how to incorporate the CEN inhalable sampling convention into regulation, guidance and occupational hygiene practice. Crown Copyright © 1997 Published by Elsevier Science Ltd.

INTRODUCTION

The measurement of workplace aerosol concentrations is currently carried out using a wide range of different instruments in the various countries of the European Union. The agreement of common aerosol exposure limits in Europe is rendered difficult by this lack of uniformity in approach, since measurements made in different countries cannot be readily compared.

The European Standards Organisation (Comité Européen de Normalisation, CEN) and the International Organisation for Standardisation (ISO) have agreed standardized conventions for the health-related sampling of aerosols in workplaces [EN 481 (CEN, 1993), ISO 7708 (International Standards Organisation, 1995)]. These conventions provide target specifications for instruments used to assess the possible health effects due to inhalation of aerosols. In order to harmonize the monitoring procedures it is necessary to determine which instruments may be used

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to collect the new aerosol fractions, through the application of standardized test protocols and sampler performance criteria. The development of a performance standard for workplace aerosol samplers has been the task of CEN/TC137/WG3. This CEN working group has so far issued a pre-standard (CEN, 1995), which must be revised into a full standard within 3 years.

The CEN pre-standard was intended to describe a technically feasible and scientifically sound scheme of sampler performance testing. However, given the state of the art at the time it was written, many aspects of the test protocols had only been applied in limited circumstances and thus their general practicability was not proven. A European collaborative study was therefore set up to apply the test protocols laid down in the CEN pre-standard, in order to identify problems with the experimental, statistical and mathematical procedures, and to suggest ways in which they could be improved. This was achieved by carrying out tests on a range of personal inhalable aerosol sampling instruments currently in use throughout Europe. The results of this pilot study will be used by the CEN working group as a basis for revision of the CEN pre-standard.

The project was coordinated by the U.K. Health and Safety Executive and funded in part by the EC BCR 'Measurements and Testing' Programme. The project consortium (the authors of this paper) represented seven European countries, and the majority are also members of CEN/TC137/WG3 and had therefore been actively involved in drafting the CEN pre-standard for aerosol sampler performance. Meetings of the project steering committee were also attended by representatives of the manufacturers of the sampling instruments under test, and by other technical experts from the European and international standards committees.

The main objectives of the project were:
- To examine the test protocols for personal inhalable aerosol samplers described in the CEN pre-standard, and the potential for simplifying them;
- To provide information for CEN/TC137/WG3, to assist them to revise the CEN pre-standard and develop a full European standard for workplace aerosol sampler performance;
- To investigate the performances of eight types of personal inhalable aerosol sampler, either currently in use or proposed for use in various European countries.

The tests followed the protocols recommended in the European pre-standard, which allowed the problems in applying these protocols to be identified and where possible resolved. The data obtained from the experiments were analysed to calculate the performance characteristics of the eight sampler types, to enable comparisons with the inhalable sampling convention, and between sampler types themselves. The project findings and recommendations were discussed within CEN/TC137/WG3.

DESCRIPTION OF THE SAMPLER TYPES TESTED

The sampler types chosen for testing were all commercially available instruments, and the majority are either statutory or recommended methods within the member countries represented in the project consortium, that is, instruments used in workplaces for testing compliance with exposure limits. The
sampling characteristics of some of these instruments had not previously been tested in the laboratory under conditions simulating their use as personal samplers, that is, mounted on a manikin.

The IOM personal inhalable sampler (Manufacturer: SKC). The samplers tested were moulded from plastic and incorporate an internal plastic cassette that is weighed together with the filter it contains. In a limited number of experiments the filter was also weighed separately. Aerosol is aspirated at a flow rate of $21.\text{min}^{-1}$ through a single 15 mm orifice, that faces outwards from the chest of the wearer. All particles that pass the orifice plane are captured in the plastic cassette and are intended to be part of the sample. Most particles entering the cassette are collected on the 25 mm filter and the remainder are deposited on the inner cassette walls. Particles depositing on the outside of the cassette are not intended to be part of the sample and were wiped off before analysis.

The Seven-hole personal sampler is commercially available in three versions, one of which is machined from metal (Manufacturer: Casella) and two injection-moulded from plastic (Manufacturers: SKC, JS Holdings). Aerosol is aspirated at a flow rate of $21.\text{min}^{-1}$ through seven equally-spaced 4 mm orifices that face outwards from the chest of the wearer. The sample is collected on a 25 mm filter held on a supporting metal grid.

The GSP personal sampler (Manufacturer: Ströhlein). The sampler body is constructed from metal with an aluminium conical inlet. Aerosol is aspirated at $3.51.\text{min}^{-1}$ through a single 8 mm orifice that faces outwards from the chest of the wearer. The sample is collected on a 37-mm filter held in a supporting holder which is weighed together with the filter.

The PAS-6 personal sampler (Manufacturer: University of Wageningen). The sampler is of all-metal construction and collects the particles on a 25 mm filter. Aerosol is aspirated at $21.\text{min}^{-1}$ through a single 6 mm orifice of conical shape. The sampler is positioned on the collar bone and the orifice hangs downwards, with its plane at an angle of approximately 45° to the horizontal.

The PERSPEC personal sampler (Manufacturer: Lavoro e Ambiente). The sampler is constructed from metal and collects the particles on a 50 mm filter. The filter may later be subdivided into inhalable, thoracic and respirable fractions by means of shaped cutters. For the purposes of this test, the entire filter deposit was weighed (that is, only the inhalable fraction was analysed). Aerosol is aspirated at $21.\text{min}^{-1}$ through a narrow horseshoe-shaped orifice surrounding a central core of clean air flowing at $21.\text{min}^{-1}$. The orifice plane faces outwards from the chest of the wearer. The aspirated aerosol flows through a narrow annular nozzle, and is then expanded over the filter situated approximately 1 mm below the nozzle outlet. Some particles are lost to the internal walls of the inlet nozzle, from where they may later be brushed down onto the filter using a fine artists brush. This procedure was followed for the majority of the tests conducted.

The CIP10-I personal sampler (Manufacturer: Arelco). The sampler may be used with special attachments for collecting either respirable (CIP 10-R), thoracic (CIP10-T) or inhalable dust (CIP10-I). The inhalable dust version was used in these tests. The sampler is injection moulded from conductive plastic and contains a rotating porous foam plug on which the particles are collected. Aerosol is aspirated at $101.\text{min}^{-1}$ through a narrow annular orifice, the orifice plane being
approximately horizontal when the wearer is upright. The inhalable dust attachment consists of a stainless steel cone that channels the aspirated aerosol vertically down towards the rotating foam collecting cup, which spins on a vertical axis.

The open-face 37-mm polystyrene cassette is a disposable personal sampling head moulded from non-conductive plastic, containing a filter on which the particles are collected. Aerosol is aspirated at 21. min\(^{-1}\) through a large open 35 mm orifice. The sampler is positioned on the collar bone and the orifice hangs downwards, with its plane at an angle of approximately 45° to the horizontal. The cassette exists in many versions supplied by several manufacturers; those tested were supplied by Millipore. For the purposes of these tests, the polystyrene surfaces were painted with conductive paint in an attempt to minimize electrostatic effects, although there was no electrical continuity across the join of the two parts of the cassette.

The closed-face 37-mm polystyrene cassette is the same as the open-face version, except that the upper part of the two-part cassette is in the form of a cover with a single 4 mm orifice. Both parts were painted with conductive paint, with the same limitations as for the open-face version. Sampler flow rate, position and orientation were the same as for the open-face cassette.

For all sampler types except the IOM, only those particles that land on the filter or foam substrate are intentionally included in the sample, although accidental transfer of material between the filter or foam and internal sampler walls is possible during post-handling. The extent of any such accidental transfer of material depends on the sampler design.

WORK PROGRAMME

The experimental part of the programme was carried out initially at the Warren Spring Laboratory, Stevenage, U.K., by personnel and in facilities later transferred to AEA Technology, Harwell, U.K. A separate detailed paper describing the experimental system and protocols is in preparation, and the present paper therefore contains only a brief summary of those aspects to be covered elsewhere.

In the first phase of the project, the experimental system was commissioned. It consisted of a large-section wind tunnel, in which uniform test aerosols could be generated and the wind speed accurately controlled. The personal samplers were mounted on a full-size breathing manikin placed within the working section of the wind tunnel. The samplers were mounted on the upper torso of the manikin, in an area representative of that used in workplace measurements. Both the front and back of the manikin were used so as to maximize the number of samplers that could be tested together in a single experimental run. Initially, the manikin was configured to rotate slowly and continuously in a clockwise direction, in order to expose the samplers uniformly to winds from all directions. The manikin also breathed in through the mouth and out through the nose, at a rate of 20 breaths per minute and 1 l. per breath, allowing the inhaled aerosol to be collected on a filter located behind the mouth. Reference samples of the undisturbed aerosol concentration were taken using an array of sharp-edged probes sampling isokinetically, placed either side of the manikin during the sampler runs and additionally in place of the manikin at the beginning and end of each day of experiments. Near-monodisperse test aerosols were produced from graded narrow-fraction aluminium oxide powders, available
commercially as Aloxite, which has been shown by Mark et al. (1985) to be ideally suited for sampler efficiency experiments where efficiency changes fairly slowly with particle diameter.

An experimental design for testing all eight sampler types at the first wind speed (1 m s\(^{-1}\)), consistent with the requirements of the CEN pre-standard, was drawn up. In this initial design, the test system was set up to generate a chosen particle size and then all eight sampler types (plus two extra replicates of the IOM sampler) were tested in a series of 10 runs over a 2-day period, in random order. In each sampler run, six specimens of the same sampler type were mounted together on the manikin, three on the front and three on the back. The experiments were repeated with nine test aerosols in pseudo-random size order, corresponding to nine particle aerodynamic diameters in the range \(\sim 7 \mu m\) to \(\sim 100 \mu m\).

A Micromeritics Sedigraph was used to measure the particle size distributions of the Aloxite powders. In order to derive the aerodynamic diameter from the sedimentation diameter a correction for the densities of the particles and sedimentation fluid was made, but no correction for particle shape was required. Dust concentrations in the tunnel were typically around 200–300 mg m\(^{-3}\), which is many times greater than any likely to be encountered in an actual workplace. These higher levels were chosen so that test run times of approximately 20 min yielded collected dust masses of the order of 3–5 mg in each sampler. This was sufficient to allow analysis simply by weighing, with only small errors. Sampling efficiencies were calculated by dividing the concentrations measured using each sampler specimen by the reference concentration derived from the isokinetic probe weights.

A statistical analysis of the efficiency values for the first windspeed was carried out in order to examine the main effects, and particularly to look for undesired confounding effects such as manikin position effects. This analysis showed that very small positional differences between the six sampler specimens mounted together on the manikin were present; there was a slight front–back difference in the sampler efficiency, a lateral difference on the front of the manikin and a centre–edge effect on the back. The position effects observed could have been caused by the manikin’s nasal exhalations, coupled with the unidirectional manikin rotation, preferentially flushed clean air across some of the sampler orifices. It was decided that in order to eliminate position effects in subsequent tests, the breathing machine would be turned off while the samplers were being tested, and measurements of inhalability made in a series of separate tests. Also, the unidirectional rotation of the manikin was changed to a reciprocating pattern, in which the manikin stopped momentarily with its back to the wind and reversed direction. Once the position effects had been accounted for it was not possible to detect any remaining differences between the efficiencies of the individual sampler specimens, although there was a large residual random variability at all particle sizes.

A second series of experiments was then carried out at an external wind speed of 0.5 m s\(^{-1}\), again for all eight sampler types and for nine particle sizes. Other than as described above, the experimental design was unchanged from the first windspeed. Instead of carrying out three repeat tests of the IOM sampler, the GSP sampler was tested at three flow rates this time (that is, the design flow rate and the design flow rate \(\pm 5\%\)), to see whether changes in efficiency with flow rate could be detected. The
manikin inhalability was measured for all particle sizes at $0.5 \text{ m s}^{-1}$ in separate experiments.

Statistical analysis of the efficiency values for the second wind speed showed that the torso position effects could no longer be detected, but the residual random variability at each particle size was again very large. This prompted an investigation into the method used to calculate the reference aerosol concentrations in the tunnel from the isokinetic probe data. An improved method for estimating the reference concentration was devised and the efficiency values for the first two wind speeds recalculated. Details of this improved reference concentration method will be presented in a separate paper. The experiment showed sufficient sensitivity to detect the changes in sampling efficiency with flow rate for the GSP sampler, but again no other systematic differences in the efficiencies of individual sampler specimens of a given type could be detected.

The large experimental errors seen in the tests at the first two wind speeds necessitated a re-think of the experimental design in an attempt to identify and eliminate some of the sources of error from the data. Before testing at the final wind speed ($4 \text{ m s}^{-1}$) a new design was drawn up in which specimens of different sampler types were mixed together in each run, so that eight broadly similar mixed-specimen runs would be carried out at each particle size. This allowed an analysis of variances within one run, between runs on one day or between the two days needed to complete tests at each particle size. The tests at $4 \text{ m s}^{-1}$ were then carried out to the new design, at eight particle sizes.

When the data from this high wind speed experiment were analysed, an unexpected finding was the presence of new position effects, with samplers now showing different efficiencies on the front and back of the manikin. These differences were particularly marked at high aerodynamic diameters, and depended also on the type of sampler. The sampler types with outward-facing inlets collected more on the back of the manikin, whereas those with downward-facing inlets collected more on the front. Since the manikin was not exhaling, the only differences between the front and the back were the very minor shape differences of the clothed manikin upper torso, and the fact that due to backlash in the rotation mechanism, the manikin spent marginally more time with its back facing the wind. Assuming the manikin shape differences are too small to be of any significance, the front–back effect could be explained by differences in sampler collection efficiencies whether facing the wind or in the wake of the manikin, with samplers having outward-facing inlets collecting more facing the wind, and samplers having downward-facing inlets collecting more in the wake of the manikin. As regards outward-facing samplers this hypothesis is consistent with existing data (see, for example, Chung et al., 1987; Ogden & Birkett, 1977) but otherwise it cannot be either confirmed or disproved.

After accounting for the position effects it was found that the major source of remaining experimental error was variations within each run rather than between runs or between days. This indicates that the homogeneity and stability of the test aerosol are the major factors dominating the errors in the wind tunnel experiment. In order to reduce the residual errors therefore, improvements may be necessary to the aerosol injection and dispersion systems in order to increase the homogeneity, and more time spent setting up and checking the aerosol distribution for each condition before carrying out sampler efficiency measurements.
Mathematical procedures for analysing the sampler efficiencies in order to extract performance information were developed and applied to the data. The bias in sampled aerosol concentrations, in relation to a hypothetical sampler following the inhalable convention perfectly, was estimated for each sampler type. Since the measured sampling efficiency values are subject to experimental errors, each bias estimate also has an associated uncertainty that was calculated by propagation of errors. The accuracy (which in the absence of inter-specimen variations depends only on the upper confidence limit of the bias) was then calculated for a range of log-normal aerosol size distributions. This analysis allows one to identify the circumstances (that is aerosol size distributions, wind speeds) in which a sampler's aerosol concentration measurements will generally lie within an acceptable range of the true value. For example if the accuracy is 30%, then 90% of measurements taken using the samplers should be within ±30% of the true value (with 90% confidence). Where overall sampler performance could be improved by applying correction factors to the measured concentrations, suitable values for these factors were estimated.

After reviewing the results obtained it was decided to repeat the efficiency measurements for the smallest particle size, using aerosols of monodisperse sodium fluorescein instead of Aloxite. This was because there was some evidence that the aerosols of the smallest Aloxite grade contained agglomerates which could have reduced the sampling efficiency. Sodium fluorescein runs were carried out using a particle aerodynamic diameter of 6 μm, at 0.5 and 4 m s⁻¹ external winds. Finally, a joint meeting of the project steering committee and CEN/TC137/WG3 was held to review the project and to discuss the implications for re-drafting the CEN pre-standard.

RESULTS

Full sampler efficiency results will be presented in a separate paper and are only summarized here. A detailed report containing all the data is also available (Kenny, 1995). Figures 1–8 show the average sampling efficiencies measured for the eight sampler types. Each point in the figures is the average of the six values measured for the individual specimens. Error bars shown for each point are one standard deviation of the estimated mean efficiency (since showing confidence limits, or two standard deviations, would confuse the points for different wind speeds). The standard deviation of the mean efficiency is calculated by combining the uncertainty in the reference concentration—typically 8% at each diameter—and the uncertainty in the mean concentration measured by the samplers, which is typically in the range 2–4%. Each graph shows the inhalable convention for comparison with the data.

Sampler bias and accuracy maps were calculated for each sampler type, at each tested wind speed, for a range of aerosol size distributions with mass median aerodynamic diameters (MMAD) from 1 to 25 μm and geometric standard deviations (GSD) ranging from 1.5 to 3.5. Calculations were limited to this range because extension to higher MMAD values would involve making extrapolations to the measured efficiency beyond 100 μm. Examples of bias and accuracy maps for the IOM and GSP samplers at 0.5 m s⁻¹ external wind are shown in Figs 9 and 10. Note that these maps were calculated using a simple polygonal approach (Kenny &
Fig. 1. IOM sampling efficiency.

Fig. 2. Seven-hole sampling efficiency.
Fig. 3. GSP sampling efficiency.

Fig. 4. PAS-6 sampling efficiency.
Fig. 5. PERSPEC sampling efficiency. Note that 1 m s$^{-1}$ data do not include entry losses.

Fig. 6. CIP10-I sampling efficiency.
Fig. 7. Open-face 37-mm cassette sampling efficiency.

Fig. 8. Closed-face 37-mm cassette sampling efficiency.
Fig. 9. Estimated bias and accuracy of the IOM sampler at 0.5 m\text{\ s}^{-1} external wind.

Fig. 10. Estimated bias and accuracy of the GSP sampler at 0.5 m\text{\ s}^{-1} external wind.
Table 1. Correction factors recommended to obtain satisfactory performance

<table>
<thead>
<tr>
<th>Sampler type</th>
<th>Correction factor 0.5 m s⁻¹</th>
<th>Correction factor 1.0 m s⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>IOM</td>
<td>0.9 (filter + cassette)</td>
<td>1.0 (filter + cassette)</td>
</tr>
<tr>
<td></td>
<td>1.0 (filter only)</td>
<td>1.0 (filter only)</td>
</tr>
<tr>
<td>Seven-hole</td>
<td>1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>GSP</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>PAS-6</td>
<td>1.0</td>
<td>1.25</td>
</tr>
<tr>
<td>PERSPEC</td>
<td>1.0*</td>
<td>†</td>
</tr>
<tr>
<td>CIP10-I</td>
<td>1.15</td>
<td>1.15</td>
</tr>
<tr>
<td>37-mm open face</td>
<td>1.15</td>
<td>1.15</td>
</tr>
<tr>
<td>37-mm closed face</td>
<td>1.0</td>
<td>1.2</td>
</tr>
</tbody>
</table>

*Inlet losses recovered and included in sample; †Inlet losses not recovered.

Table 2. Sampler types ranked in order of precision (residual variance: most precise first)

<table>
<thead>
<tr>
<th></th>
<th>0.5 m s⁻¹</th>
<th>1.0 m s⁻¹</th>
<th>4.0 m s⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSP</td>
<td>GSP</td>
<td>PERSPEC</td>
<td></td>
</tr>
<tr>
<td>PAS-6</td>
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<td>GSP</td>
<td></td>
</tr>
<tr>
<td>PERSPEC</td>
<td>CIP10-I</td>
<td>37-mm closed</td>
<td></td>
</tr>
<tr>
<td>37-mm open</td>
<td>37-mm open</td>
<td>PAS-6</td>
<td></td>
</tr>
<tr>
<td>CIP10-I</td>
<td>37-mm closed</td>
<td>IOM</td>
<td></td>
</tr>
<tr>
<td>IOM</td>
<td>PERSPEC</td>
<td>Seven-hole</td>
<td></td>
</tr>
<tr>
<td>37-mm closed</td>
<td>IOM</td>
<td>CIP10-I</td>
<td></td>
</tr>
<tr>
<td>Seven-hole</td>
<td>Seven-hole</td>
<td>37-mm open</td>
<td></td>
</tr>
</tbody>
</table>

Bartley, 1995) which does not require a smooth curve to be fitted through the efficiency data. All data points have been assumed valid and included in the performance analysis (that is, outliers were not excluded); the data have been extrapolated to an efficiency of 1.0 at aerodynamic diameter zero.

For all sampler types calculations were carried out to see whether correction factors applied to measured concentrations could be used to reduce the bias and hence improve the accuracy. Correction factors for 0.5 and 1 m s⁻¹ are summarized in Table 1; the results at 4 m s⁻¹ were not improved by using correction factors. In Table 2 the samplers are ranked in order of the residual variance of the measured efficiency values at the different test wind speeds.

DISCUSSION

Sampling efficiency values

The general trend was for the sampling efficiency of all sampler types to decrease as wind speed increased. At the lowest wind speed, some samplers types (notably the IOM and PERSPEC) showed a slight positive bias with respect to the inhalable convention. Most sampler types showed a U-shaped response at the highest wind speed, with efficiency first decreasing and then increasing again at large particle sizes. Similar trends are seen in inhalability data obtained using manikins at high external wind speeds (Vincent et al., 1990), although in this case the differences from the inhalable convention are small at 4 m s⁻¹ wind. The CIP10-I and 37-mm open-face
samplers exhibited anomalous behaviour at the highest wind speed, with high collection efficiencies at most particle sizes.

The measured sampling efficiencies for the smallest particle sizes were rather lower than expected; except in the case of the CIP10-I the efficiency would be expected to approach 1.0 as the particle size approaches zero. The suspicion that this may be due to agglomeration of the test aerosol was not confirmed by the separate experiments carried out using monodisperse sodium fluorescein particles. At 0.5 m s\(^{-1}\) the sodium fluorescein data and Aloxite data for small particle sizes are generally in fair agreement (both sets of data are plotted in Figs 1–8).

In the case of the IOM sampler the filter deposits were weighed separately in order to examine the division of collected particles between the filter and the inner walls of the cassette. This is important because some methods for analysing the composition of aerosols such as X-ray fluorescence are typically used directly with particles collected on filters, and extra sample preparation would be required in order to analyse the complete IOM cassette deposit. The percentage of the sample mass on the filter was found to decrease from 100% at small particle sizes to around 75% at 100 μm. At 0.5 m s\(^{-1}\) wind it was found that analysis of the IOM filter deposit alone gave good agreement with the inhalable convention. For the PERSPEC sampler, the procedure for brushing down losses from the inlet onto the filter (which appears to be essential to avoid under-sampling) was not followed at 1 m s\(^{-1}\), only at 0.5 and 4 m s\(^{-1}\). An assessment of losses of material in the CIP10-I inlet cone showed only very small amounts of material deposited in that location.

**Examination of the test system and test protocols**

The wind tunnel used for these experiments was found to have a very uniform velocity profile, and with the exception of the smallest particle sizes where agglomeration was suspected, aerosols with good size distributions were generated. Investigations into the estimation of the reference aerosol concentrations in the tunnel yielded a new method that could find widespread application in other wind tunnel experiments.

On the negative side it proved extremely difficult to generate test aerosols with an acceptable degree of homogeneity and stability in the large-section wind tunnel used. The generation of suitable test aerosols would probably have been easier in a smaller test space, but this is constrained by the need to use a full-size manikin. Previous studies have demonstrated the importance of using a manikin during personal sampler testing, at least in moderate to high wind speeds, and it is not yet known how the manikin effects on sampler performance can be otherwise simulated. There is still an unmet need to develop experimental systems suitable for testing inhalable aerosol samplers at reasonable cost, possibly with tests of reduced scope. Charge neutralization of the generated aerosol cannot be accomplished in the large test space of the wind tunnel, and this factor could affect the behaviour of the samplers, which are not perfect conductors. Also it was not possible to determine the size distribution of the test aerosols directly, only of the bulk material prior to aerosol generation. This could introduce errors into the aerodynamic diameter axes of the sampling efficiency response graphs, and is of particular concern where there is a tendency for the test aerosols to agglomerate. As discussed previously, the breathing and rotation of the manikin used for mounting samplers were shown to have
potential interfering effects on the performances of the samplers under test. It appears likely that exhalations from the nose of the manikin affected the air flow across the upper chest region, particularly in low external winds. The conclusion reached is that a nasally-exhaling manikin should not be used for testing samplers, or it may even be preferable to replace the manikin with a simplified bluff body. Unfortunately the limited scope of this project did not allow us to investigate either a suitable shape or size for such a bluff body, or a limiting wind speed below which it might be unnecessary. The position effects observed at high wind speeds would be difficult to eliminate entirely if they are indeed caused by the reciprocating movement of the manikin, and highlight the care needed to ensure that samplers are exposed equally to winds from all directions.

Revision of the CEN pre-standard

The current pre-standard for workplace aerosol sampler performance draws heavily on experience of testing respirable aerosol samplers. By concentrating in this study on the testing of inhalable aerosol samplers, where least work had been done in the past, useful information was obtained on the design of suitable test protocols and on the treatment and interpretation of the data.

Some factors thought potentially to influence the performance of personal inhalable aerosol samplers were shown to be too small to be detected, given the large random variations inherent in the test system. For example, variations between the individual sampler specimens could not be detected. It was shown to be possible to eliminate unwanted position effects in the experiment at low wind speeds, although it remains important to design the experiment in such a way that position effects can be detected if they are indeed present. Other effects were larger than anticipated: for example since the samplers show large changes in sampling efficiency as the external wind speed is changed, the outcome of the performance tests will depend strongly on the actual wind speed values chosen for testing, which need therefore to be specified in the test protocol.

The CEN pre-standard suggests evaluating the sampler performance in terms of bias and accuracy, that is, 'performance' is based on the concentrations that one would measure with the sampler rather than on excursions from the target sampling convention. The study showed that large experimental errors lead to large uncertainties in the estimated sampler bias, and hence any correction factors used to reduce the sampler bias will also be derived with a large uncertainty. The calculation of the accuracy takes this uncertainty into account and in effect gives a 'worst case' picture of the likely range of results the user would obtain. Where the samplers meet the required accuracy therefore of ±30% on the basis of this experiment, it is very unlikely that future more precise tests would 'reject' those samplers. However, an imprecise experiment has a high false negative rate, that is it may 'reject' samplers whose performance is in fact acceptable.

Both bias and accuracy were shown to be rather sensitive to small systematic changes in the positions of efficiency data points, and strongly dependent on decisions whether to include all points or to exclude outliers. Furthermore, the range of aerosol size distributions over which the bias and accuracy are calculated strongly influences the apparent performance of the sampler; at the limiting MMAD of 25 µm recommended, the experimental data from 1 to 25 µm are given equal weight
with the data from 25 to 100 μm. Thus excursions from the target convention at high aerodynamic diameters are not necessarily important although visual examination of the efficiency data tends to draw attention to them. Extension of the bias and accuracy calculations to larger size distributions would not be justified without both experimental data points and an inhalable convention extending above 100 μm.

The current sampler performance pre-standard suggests classifying sampler types into categories that depend on the range of environmental conditions (that is, wind speeds, aerosol size distributions) over which the accuracy is within the acceptable value of ±30%. The information provided by the pilot study gives the CEN working group the opportunity to examine the validity of the sampler classification scheme. Given the very large uncertainty associated with the experiments, rigid classification of samplers into performance classes is highly problematic. In particular, samplers whose performance falls close to the borders of the classes have a high probability of being wrongly assigned, and thus the classification may be misleading.

The current performance requirements in the pre-standard fail to adequately reflect the fact that some samplers are easier to use than others, and ways to communicate this qualitative information to the end user should be explored as it may be an important factor in the choice of instruments. It may be necessary to incorporate additional tests, for ease of use and stability of samples during handling, into the performance standard. The stability of the collected samples is reflected to an extent in the imprecision of the measured sampling efficiency values, which could perhaps form the basis of a quantitative sampler handling test.

Performance evaluation of personal inhalable aerosol samplers

Many of the sampling instruments included in this study had not previously been systematically tested in the laboratory, under conditions intended to simulate the conditions of use. It is important to consider whether laboratory testing provides valid and useful information on the performance of the samplers.

On the basis of this laboratory test it appears that the tested samplers can be grouped into broadly similar classes that exhibit similar behaviour. According to Table 1, at low external winds five of the eight samplers tested were able to collect the inhalable fraction without any corrections. The IOM sampler oversampled slightly, which means that in practice it could still be used without correction factors, since oversampling is allowed. As wind speed increased only two samplers (IOM and GSP) maintained adequate performance without correction, and the other samplers began to undersample by varying degrees. At high wind speeds none of the samplers performed well. If the results of this laboratory test are used to compare samplers with each other, rather than with the inhalable convention, then it appears that the maximum difference in measured concentration one would expect to see between any pair of sampler types is around 40%, at least for the aerosol size distributions over which we have calculated the bias.

Workplace comparisons of sampler types have been carried out most extensively for the IOM and 37-mm closed face samplers (reviewed by Vincent, 1995), the IOM and 37-mm open-face samplers (Lillienberg & Brisman, 1994) and the IOM and seven-hole samplers (Vaughan et al., 1990). Limited data are also available comparing the CIP10-I and IOM samplers in bakeries and pig farms. The field comparisons of IOM and 37 mm samplers (both closed and open face) generally
show the IOM sampler collecting around 2–3 times as much as the 37-mm sampler (depending on the aerosol size distribution) in contrast to the factor of 1.2–1.4 indicated by our laboratory test results. The comparisons of IOM and seven-hole samplers showed a median IOM/seven-hole ratio of 1.17, and the comparisons of IOM and CIP10-I showed a median IOM/CIP10-I ratio of 1.5. Both of these latter results are reasonably consistent with the laboratory comparisons but are based on a relatively small number of field tests.

In seeking to explain the large discrepancies in the laboratory and field comparisons of the IOM and 37-mm samplers, the differences between the laboratory test conditions and those to be expected in real workplaces should be noted. The laboratory tests were limited in scope to well-mixed aerosols, particle sizes from 6 to 100 μm only and external winds in the range 0.5–4 m s\(^{-1}\). Workplaces can often have much larger particles, localized aerosol sources and very low external winds, much less than 0.5 m s\(^{-1}\). Other possible factors are: that in the laboratory experiment, the 37-mm samplers were given a conductive coating to reduce electrostatic effects whereas the samplers used in the field are non-conductive and known to suffer from large losses of material to the walls (Demange et al., 1990); that in the field there may be extremely large particles present that enter the IOM sampler orifice under their own momentum, but which are less likely to enter the 37-mm orifice (Lidén & Kenny, 1994); that possibly the localized aerosol sources and air movements produce effects that cannot be duplicated in the laboratory setting. Further work to resolve these differences is necessary in order to confirm that laboratory testing provides reliable performance data.

The practical implementation of the inhalable aerosol sampling convention requires decisions on which samplers to use, estimation of the likely impact that changing sampling method will have on measured exposures, and adjustment where necessary of exposure limit values (see for example Vinzents et al., 1995). The results of this study will contribute to this process, but the limited scope of the laboratory tests means that field data will also be needed. Our study indicates that several sampling instruments could potentially be used as inhalable samplers, albeit in limited circumstances. This result should assist in the adoption of the inhalable convention as several countries will not need to change from their current sampling method.

**RECOMMENDATIONS FOR REVISION OF THE CEN PRE-STANDARD**

The project steering committee made the following recommendations for the revision of the aerosol sampler performance pre-standard:

1. Wind tunnel testing of samplers in a range of different wind speeds should no longer be compulsory for samplers intended for use primarily in indoor workplaces.

2. For samplers that are intended for use at higher windspeeds, for example outdoors or in environments with forced ventilation (such as coal mines), wind tunnel tests at specified higher wind speed values should continue to be required.

3. For the purpose of performance evaluation, samplers primarily intended for use indoors should be tested in an environment having low-velocity air
movements, for example not exceeding 0.5 m s\(^{-1}\). Precise recommendations should be made following a review of air movements commonly encountered in indoor workplaces, which on current evidence are generally thought to be below 0.5 m s\(^{-1}\). A check on the response of the samplers at one moderate wind speed should be recommended, but not form part of the performance evaluation.

(4) The protocol used for estimating the reference concentrations in whatever test system is used should be unbiased, and have precision better than a stated limit. Different reference precision limits may be required for respirable, thoracic and inhalable aerosol sampler tests.

(5) Personal samplers should continue to be tested in circumstances that simulate their proximity to the body, however, this should not necessarily be assumed to imply the use of a life-size manikin. Data comparing sampler efficiencies with and without a manikin present should be reviewed, in particular to examine whether there is a wind-speed below which a manikin becomes unnecessary.

(6) The statistical designs recommended in the pre-standard should be either simplified or removed altogether and published in another form. However, the new CEN standard should stress the importance of careful experimental design, giving due attention to randomization and estimation of the main effects.

(7) Consideration should be given to making software for the calculation of performance characteristics available with the standard.

(8) The classification of samplers should be reviewed to decide whether it helps the user. A test for ease of handling the samplers should be included in the standard.

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**REFERENCES**


