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Applications of Low-Cost, Dual-Fraction Dust Samplers

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Porous polyurethane foams provide a low-cost method for separating dust into health-related fractions in accordance with recognized sampling conventions. A number of dust sampling instruments that make use of foam selectors have been described in recent literature, but practical experiences of using these instruments in real workplaces have not been widely reported. An IOM inhalable dust sampler incorporating a respirable-fraction selector foam was evaluated in a range of industries, for general occupational dust monitoring. The key issues addressed were those that determine the practicability of the instrument, such as limitations on particulate loading, losses or movements of particles during transportation of samples, and equivalence with conventional respirable dust sampling methods. The new sampler was found to be satisfactory in all these respects. The minor problems experienced have been addressed during the design of the production version of the foam cassette, which is available as an accessory for the existing IOM inhalable dust sampler. The key advantage of the new dust sampler is that it measures both inhalable and respirable dust concentrations in a single sample (hence the name: dual-fraction dust sampler). Therefore, it saves both time and money in industries where both inhalable and respirable dust are routinely monitored.

Keywords: inhalable dust; respirable dust; porous foam sampler; dust sampling

INTRODUCTION

Porous polyurethane foam is increasingly being used as a particle size-selective medium for dust sampling applications (Aitken *et al*., 1993; Chung *et al*., 1997; Görner and Fabriès, 1997; Chen *et al*., 1998). The Health and Safety Laboratory (HSL) have used polyurethane foam to develop a range of low-cost samplers for monitoring inhalable, thoracic and respirable dust concentrations simultaneously. Foam inserts are placed within standard IOM personal inhalable dust samplers, where they separate the inhalable dust into thoracic and/or respirable sub-fractions. HSL's interest in these foam inserts was originally directed towards the monitoring of bioaerosols, since the foam provides a good medium for retaining micro-organisms in a viable state (Kenny *et al*., 1998). The foam-based bioaerosol samplers were tested in both laboratory and field situations (Kenny *et al*., 1999), with promising results.

The study reported here was set up to assess the potential for utilizing the adapted IOM dust samplers, with size-selective foam inserts, for general occupational dust monitoring. This was achieved by evaluating the samplers in a range of industries, by experienced occupational hygienists working in those industries. The study sought to identify and solve practical problems experienced with use of the samplers, to investigate limitations on particulate loading, and to evaluate losses or movements of particles during transportation of samples. The results obtained with the adapted IOM samplers were compared with those obtained using conventional methods. Finally, recommended procedures were agreed for use of the new samplers.

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DESCRIPTION OF THE DUAL-FRACTION FOAM SAMPLERS

The foam samplers utilized in this study are based on the IOM personal inhalable dust sampler, and are illustrated schematically in Fig. 1. The IOM multi-fraction dust sampler contains a slightly extended cassette that has been engineered to contain either one or two size-selective foams, inserted in front of the normal filter. The foam inserts have been designed so that the inhalable dust, aspirated by the sampler inlet, is then fractionated according to both the respirable and thoracic sampling conventions (multi-fraction version), or the respirable sampling convention alone (dual-fraction version). A dual-fraction inhalable/thoracic sampler is also available. Note that similar foam inserts have also been developed for the conical inhalable sampler (CIS), which is an alternative method for inhalable dust sampling (MDHS 14/2, 1997), although only the IOM-based samplers were used in this study. Full details of the optimization of the foam inserts, determination of their size-selection characteristics and respirable fraction sampling bias, are given by Kenny *et al*. (1998).

For ease of use the dual-fraction respirable IOM sampler was used exclusively in this study, whereas the previous bioaerosol field trials tested the multi-fraction version. The dual-fraction inhalable/respirable IOM dust sampler enables the user to measure both inhalable and respirable dust concentrations in a single sample, by weighing (or otherwise analysing) the foam and filter substrates separately. The advantage of the dual-fraction version is that the user is not required to handle the foam insert during analysis by weighing. The cassette is separated into two halves, with the foam weighed in the front portion and the filter weighed in the back portion. The current multi-fraction prototypes are more difficult to use as one of the two foams must be taken out of the cassette and weighed or analysed separately.

With the dual-fraction inhalable/respirable sampler, the inhalable dust concentration is calculated from the weight of dust collected in the entire cassette (that is on both the filter and foam), and the respirable dust concentration is calculated from the dust weight on the filter alone. The respirable foam plugs are 12 mm thick, 16.5 mm in diameter, and are made with polyurethane foam having a cell diameter of 420–460 μm (that is a nominal porosity of 85–90 pores per inch).

EXPERIMENTAL METHODS

Procedures for using the foam samplers

Each industrial partner was supplied with two batches of six prototype IOM foam cassettes, at intervals over the period of the trial. In each set of six pre-loaded cassettes sent out, at least two cassettes were retained as blanks. A total of 140 cassettes were prepared in all, 110 of which were returned after use, and the remainder returned without use (or retained as controls by HSL). Partners used the foam cassettes within their own IOM inhalable dust samplers, and with their own pumps. Sampling times were usually several hours although in some cases short-term samples were taken.

Dust samples were taken at a wide range of industrial premises, mainly in the chemicals and material processing sectors and covering processes such as metal refining, casting, mineral production, tyre production, foods and pharmaceuticals. As far as possible, the prototype samplers were included in the routine hygiene monitoring activity of each plant. However, in order to provide a significant challenge

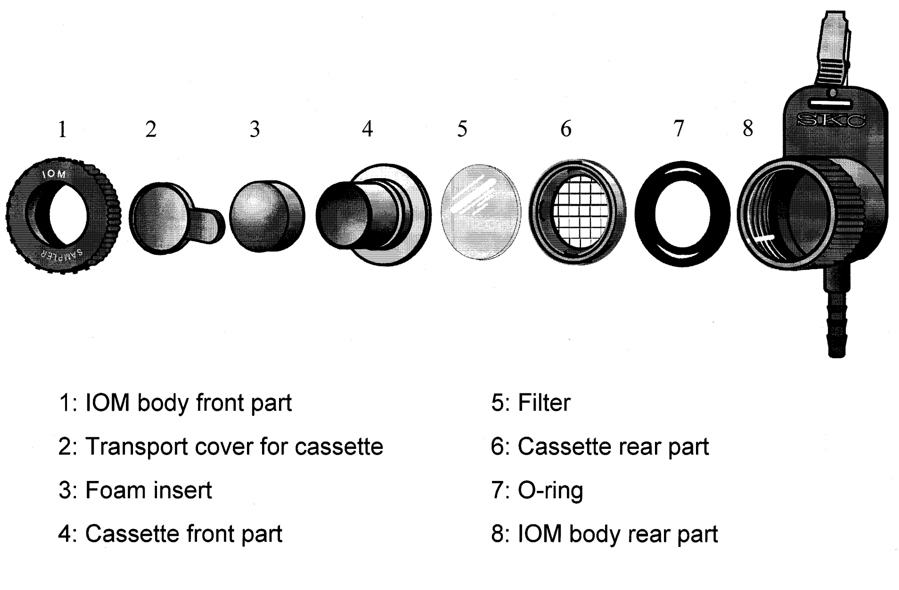

Fig. 1. Schematic diagram of the IOM dual-fraction dust sampler, showing the components of the new foam cassette.

to the instruments, sampling was concentrated on activities likely to lead to high concentrations of dust. This often involved placing the IOM samplers on people wearing respirators for part of their working day, and for this reason the concentrations measured do not necessarily represent typical personal exposures.

The first batches of cassettes sent out contained membrane filters (Millipore AA) whereas the second batches contained glass fibre filters (Whatman GF/A). Both types were included since glass fibre filters are more commonly used for gravimetric analysis, and membrane filters are more common for chemical analysis. Prior to beginning the field evaluation a briefing session was held and a Standard Procedure for use of the samplers was prepared and sent out with the batches of cassettes. Further opportunities for feedback and on-site discussions arose during the course of the fieldwork.

Post was used as the primary method for dispatching cassettes between the industrial partners and HSL. The first batches of cassettes were ‘sealed’ using the standard IOM cassette clip and sent out and returned in re-sealable plastic bags. However, for heavily loaded samples, there was concern that material could be lost from the cassettes. The standard IOM cassette clip was not a good fit to the longer modified foam cassette, with the result that dust could potentially leak from the cassette into the bag. Later batches of cassettes were sent out with a conductive plastic lid fitted to the cassette, and the lidded cassette fully enclosed in a small plastic container. This effectively eliminated losses from the cassette, although internal transfers of dust between foam and filter could still occur.

Preparation of the foams and insertion into cassettes was carried out at HSL. The foams were rinsed in de-ionized water containing a drop of detergent, drained, and then dried at 50°C for 1 h. Washed foams were stored under controlled conditions in the dark. The foams were inserted into the cassettes using laboratory gloves, and the cassettes conditioned for 48 h and weighed in an environmentally controlled weighing room. The cassettes were packed in plastic bags or containers and sent to the partners in the post.

After delivery the cassettes were again conditioned and pre-weighed by the industrial partners prior to use. All the cassettes were removed from the weighing room and taken to the sampling site, so that the blanks were treated as far as possible in an identical manner to the cassettes that were used (except for exposing them to dust). After use the conditioning and post-weighing procedure was again followed before sending the cassettes back to HSL, for final conditioning and weighing. The balances used in each participating laboratory were calibrated according to in-house procedures and no special checks were made for inter-laboratory consistency in weighing. Therefore, the results reflect normal levels of inter-laboratory variation.

The use of blanks is of particular importance for weighing porous foam substrates since the foam matrix is very susceptible to moisture uptake. By treating the blanks and real samples in the same manner, both are subjected to similar temperature and humidity changes and hence the reliability of the blank weight corrections is greatly improved. The weighing procedures used followed the general guidance given in MDHS 14/2, with the exception that a longer conditioning time was recommended for the foams. This precaution is to allow the foams more time to reach equilibrium with their surroundings prior to weighing. Also, MDHS 14/2 recommends one blank per batch of 10 samples, with a minimum of three blanks altogether. As our batch sizes were small (six per batch) the minimum number of blanks per batch was reduced to two.

Determination of loading effects

It is known that the aerosol size-selection characteristics of polyurethane foams change in response to particle loading (Brown and Wake, 1999). In the case of the prototype dual-fraction samplers, it was not known whether the loading effects would be large enough in practise to degrade the sampler performance. Tests were therefore carried out to determine whether the respirable selection characteristics of the respirable selector foam remained unchanged, after typical loadings obtained during full-shift workplace sampling, and for typical particle types.

Loading effects were assessed by measuring the size-selective aerosol penetration through used foams, and comparing the results with those for clean foams. The loading effect is manifested as a decrease in the D_{50} value (that is the particle aerodynamic diameter for which 50% of the particles penetrate the foam onto the filter). For optimum agreement with the CEN respirable convention EN481 (1993) the foam should have a D_{50} value close to 4.5 μm, which is the cut-point leading to minimum bias in sampling the respirable fraction. If a significant downward shift in D_{50} occurs during an extended sampling period, the foam would retain too many particles and hence the filter weight would be too low. The net effect would be to underestimate the respirable dust concentration, although the measurement of the inhalable dust concentration would still be correct, as this is calculated from the sum of dust weights deposited on both the filter and the foam.

The experimental methods used to test the foam aerosol penetration were similar to those described in detail by Maynard and Kenny (1995). The tests were carried out using an aerodynamic particle sizer (APS), and a test aerosol of glass microspheres. The test procedure involved placing a used foam cassette inside one IOM inhalable dust sampler, and an empty identical cassette, with no foam, inside another (reference) sampler. Both IOM samplers were connected to the APS via metal tubing with a ball-valve switching arrangement. Samples of the test aerosol were taken alternately through the IOM/foam and IOM/no-foam lines and the average number of particles in each size range was calculated for each line. The ratio of the two particle number distributions gives the size-selection characteristics of the foam alone, since all other factors are identical in both lines. The flow rate was checked and adjusted if necessary before each test using a bubble flow meter.

Penetration tests were carried out for a total of 30 used and three blank foams. Twenty of the used foams had been loaded with dust in workplaces and 10 had been loaded with dust in the laboratory. The workplace foams were from a range of industries and were selected to cover different particle types and dust loadings (on the foam) of up to 20 mg. The laboratory-loaded foams were made by sampling from an exceptionally high concentration of Aloxite F800 dust, over short time periods (5–10 min), and covered dust loadings up to 50 mg. Both types of loaded foams were included to test whether the dust loading effect depended on the rate of loading.

Handling and dispatch of the samplers

Since the foam cassettes were pre- and post-weighed by both HSL and the industrial partners, this allowed the weight changes during postal dispatch of both clean and used cassettes to be examined. In addition, six loaded workplace cassettes, taken from the samples supplied to HSL by the industrial partners, were weighed, packaged in containers as described earlier, and posted to one of HSL's regional offices. There the package was re-directed without opening back to HSL. The cassettes were unpacked and conditioned for re-weighing of both foams and filters, and the changes in weight after postal dispatch were calculated. The cycle of packing, posting, unpacking and re-weighing was repeated three times on the same batch of six samples.

Comparison with standard respirable sampling methods

Side-by-side paired samples were taken with the IOM dual-fraction samplers and with personal cyclones, in order to assess whether the two methods measured equivalent respirable dust concentrations. Static or fixed-point sampling was used so that a large number of paired results could be gathered over a short period. The results from static sampling are not necessarily indicative of personal exposures in the industries visited. Sampling sites were chosen to give a wide range of respirable dust concentrations.

A total of 80 paired samples was taken in a number of industrial environments where the samplers were exposed to a range of substances (man-made mineral fibre, silica dust, metal dust and metal fume) over sampling periods of 2–7 h. Personal sampling pumps were used to draw air through the IOM dual-fraction samplers at 2 l. min^{-1} and through the cyclones at 2.2 l. min^{-1} (as advised in MDHS 14/2). Flow rates were checked at the beginning and end of sampling, and at periodic intervals throughout, with a bubble flow meter. Gravimetric analysis of the samples was performed in accordance with the procedures described earlier. Dust concentrations were calculated in accordance with the procedures recommended in MDHS 14/2 (1997).

RESULTS

The weights of both respirable and inhalable dust collected in the IOM dual-fraction samples sent back to HSL spanned two orders of magnitude. To illustrate the range of the data, Fig. 2 shows the inhalable mass (that is mass collected in the entire cassette) plotted against the respirable mass (that is mass collected on the filter alone). The samples collected cover a wide range of substances, including very fine and very coarse materials, compact particles, ultrafine agglomerates and fibres. The inhalable dust weights span the range expected when sampling at the inhalable dust limit of the 10 mg m^{-3} exposure limit, assuming that in most cases around 1 m^3 of air will be sampled. The respirable dust weights are almost all well below the weight expected when sampling at the respirable dust limit of 4 mg m^{-3}.

Usability

Some practical problems were experienced during use, dispatch and weighing of the new dual-fraction samplers. For example, it was observed that the foam insert was vulnerable to being prodded by a curious wearer, and could be pushed into contact with the filter. There were the concerns mentioned earlier over the potential for losses and movements of the particles during posting. During weighing, the main problems were filter damage and excessive weight. The majority of partners weighed the cassettes using a five-figure balance (that is to 0.01 mg), as the tare weight was too large for most six-figure balances. Problems were reported with the procedure for weighing the filter part and foam part of the cassette separately, since with the stainless steel prototype cassettes, the two parts were not always easy to join and separate without damaging the filter (particularly when glass fibre filters were used).

Loading effects

Figure 3 shows the D_{50} values measured for the used respirable selector foams, plotted as a function of foam loading. The D_{50} value for the clean foams was intended to be 4.5 µm. The scatter in the measured D_{50} values is due in part to experimental errors in the measurement system, and in part to real variability in the foam plugs. Non-uniformity can be

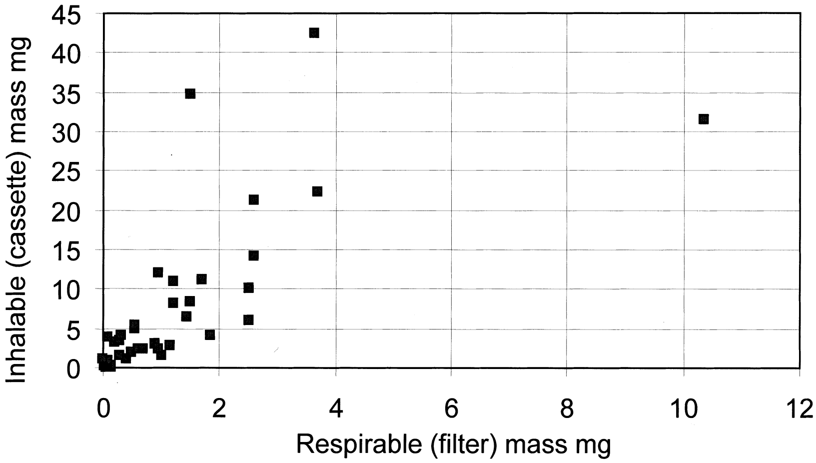

Fig. 2. Weights of dust collected in workplaces in the entire cassette (inhalable dust) and on the filter only (respirable dust).

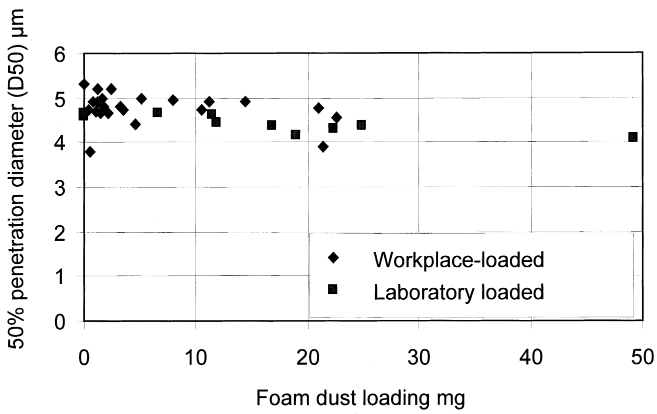

Fig. 3. Loading effects in the respirable selector foam, for samples loaded gradually in the workplace, and loaded rapidly in the laboratory.

present in the foam material itself, and further variation arises during insertion of the foams into the cassettes, and in setting the flow rate through the foam.

A slight trend for D_{50} to decrease with increasing loading is evident, but the effect is generally small, even with exceptionally high loadings well above the range likely to be encountered during normal use. The laboratory-loaded samples, which were subjected to a sudden high concentration, do not appear to be any more affected than the gradually loaded workplace samples. Within the limitations of the experiment there is no evidence that the loading effects are dependent on the nature of the particles sampled. The systematic loading effect is small when compared with the inherent variability of the foams.

It should be noted that more serious loading effects were observed when similar samplers were used to collect welding fume (Stancliffe and Chung, 1997). In that case, a linear decrease in D_{50} was observed with increasing loading of fume. The shape of the penetration curve did not change apart from the systematic downward shift. The magnitude of the shift was a decrease in the D_{50} value by 1 µm for each 1 mg of fume loaded; this is enough to significantly bias the respirable selection. Therefore, the potential for loading to degrade the performance of the foam inserts, particularly when very fine particles or long chain agglomerates are collected, should not be ignored.

Losses during handling and dispatch

If HSL's pre-weights are compared with the industrial partners' pre-weights, the average weight change of the entire cassette during dispatch was a loss of 0.33 mg. For used cassettes, comparing the industrial partners' post-weights to HSL's post-weights, the average weight change was a gain of 0.5 mg. Hence the weight changes in both directions largely cancelled each other out, and can be explained by differences in moisture content during weighing at HSL and the partner laboratories. It appears there was no net loss of dust from the cassettes during dispatch of the used cassettes, despite the concerns provoked by the ill-fitting clips used for the first cassette batches.

If the data for the filter part of the cassette only are analysed, the filters lost an average of 0.11 mg after dispatch from HSL to the partners. A further average loss of 0.10 mg occurred during the return of used cassettes. Hence, a net average loss of 0.21 mg occurred from the filters during the dispatch cycle. When only the blank (unused) cassettes are considered, the average filter weight changes during dispatch are −0.14 mg (outward) and + 0.03 mg (return), which being in opposite senses, can again be attributed to moisture changes. Hence it is the *used* filters that have suffered a net weight loss.

The weight loss of each used filter during return to HSL is plotted against its weight before posting, as measured in the partner laboratory, in Fig. 4. A slight downward trend associating weight loss with filter loading is evident in the data, with isolated instances of serious weight loss. The three largest losses all occurred for samples of titanium dioxide. Examination of these cassettes at HSL revealed that dust had been dislodged from the filter and had migrated onto the bottom surface of the foam.

Analysing the weight history of the six samples sent repeatedly through the post (which did not include any titanium dioxide samples), no significant transfer of material was evident throughout the experiment. After the third postal round the net weight change in the entire cassette was −0.086 mg (mean), standard deviation 0.58 mg. The net weight change in the filter part only was −0.136 mg, standard deviation 0.28 mg.

Comparison with standard respirable sampling methods

The respirable dust loadings in the static paired samples were higher than the workplace samples taken by the industrial partners. The maximum concentration measured using the cyclone was 14.8 mg m^{-3}. Figure 5 shows the results of the comparison exercise plotted on linear axes, and Fig. 6 shows the same data on logarithmic axes. At low concentrations the scatter in the data is due to imprecision in weighing the filters from both sampler types. The data are well described by a simple line, passing through zero, with slope of 0.93 (r^2 = 0.8). Analysis of the confidence limits on this relationship shows that the slope is not significantly different from unity, and hence one can regard the two sets of respirable dust concentrations as equivalent.

DISCUSSION

The dual-fraction inhalable/respirable sampler was found to be useful for workplaces in which both inhalable and respirable dust are routinely measured. The new sampler cuts both the cost of equipment and the expense of workplace sampling exercises, since both measurements are made from a single sample. The results provide useful insights into the relative importance of the two dust fractions, and help the occupational hygienist to assess dust exposure and control strategies. The foam inserts were thought generally easy to use, and the IOM dual-fraction sampler as a whole compared favourably with the usability of a respirable cyclone.

The prototype cassettes used in this study were made from stainless steel, which offers exceptionally good weight stability and chemical durability. The disadvantage of stainless steel is that it is expensive and has a high tare weight (a loaded cassette weighs 4–5 g). The manufacturer of the IOM sampler (SKC Ltd) now makes the elongated foam cassette by plastic injection moulding. The plastic cassettes are nickel-plated to reduce the problems of moisture uptake that have been observed with older uncoated plastic IOM cassettes (Li and Lundgren, 1999). The tare weight of a loaded plastic cassette is less than 2 g. Foams, tweezers and gloves for insertion of the foams and handling the cassettes are available as an upgrade kit for existing users of the standard IOM inhalable dust sampler.

The practical problems experienced during use of the prototype dual-fraction samplers have been addressed during the design of these new plastic cassettes. The foam-dislodgement problem has been

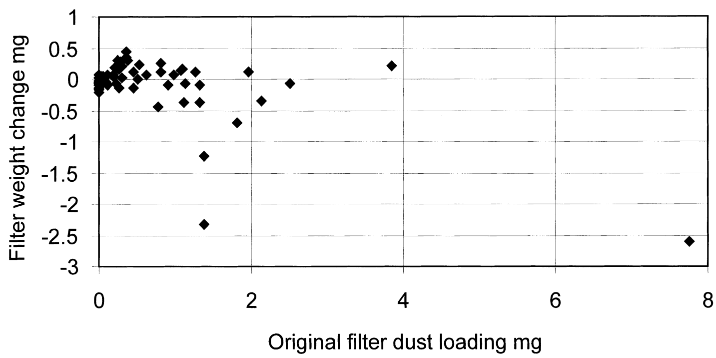

Fig. 4. Filter weight changes during postal dispatch of used cassettes.

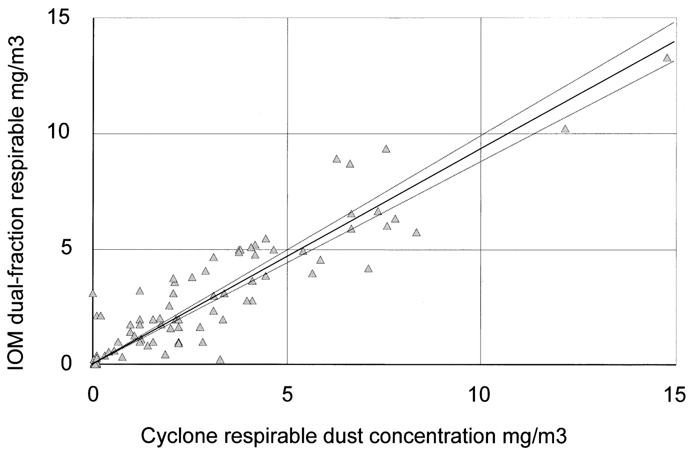

Fig. 5. Comparison of results from new dual-fraction samplers and conventional cyclones in workplaces, plotted on linear axes.

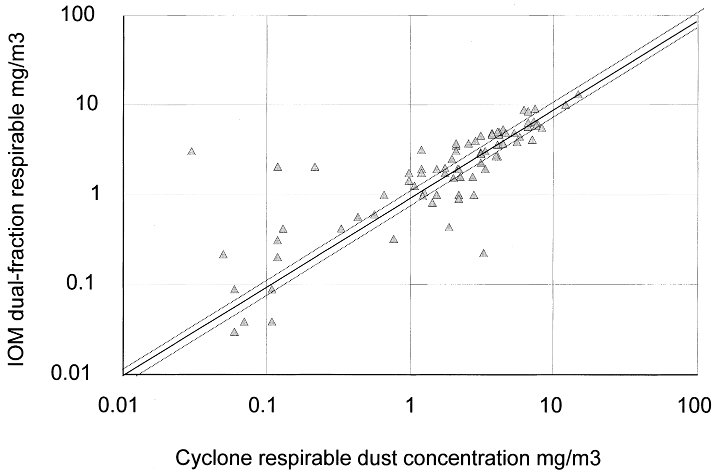

Fig. 6. Comparison of results from new dual-fraction samplers and conventional cyclones in workplaces, plotted on logarithmic axes.

reduced by introducing a small lip in the cassette, at the lower edge of the foam, in order to provide more resistance if the foam is prodded. The plastic cassette has a weighable lid and a well-fitting clip to prevent potential losses during dispatch. The two parts of the plastic cassette allow it to snap together and unsnap without twisting, thereby minimizing filter damage and making handling easier. Simple instructions for use have been prepared, based on the experience gained during this work.

The problem of internal movements of particles during postal dispatch is not so easy to solve. Particle movement could be avoided by packing the filter and foam separately, however, this adds expense to the method, and would cause problems since a clean place to handle samples is not always available at industrial sites. Likewise, changing from postal dispatch to another method would seriously compromise the utility of the sampler. This problem, though possibly infrequent in practice, may require further work in order to develop an acceptable solution.

CONCLUSIONS

This study has successfully highlighted the advantages and limitations of low-cost, dual-fraction dust samplers that use porous foam selectors. The new dual-fraction samplers were found to be particularly useful in industries where both inhalable and respirable dust are routinely measured, and for investigative work to examine the relative importance of respirable and inhalable dust. For typical particle types and dust loadings, the respirable selection by the foam was not adversely affected by particle loading. However, it is known that loading effects can occur with very fine fume particles, and that particles can move from heavily loaded filters onto the foam insert during posting.

With these limitations borne in mind, the IOM dual-fraction inhalable/respirable sampler provides a valid alternative method to the respirable cyclone, for measuring personal exposures to respirable dust. However, since the method is novel, checks are advisable in order to verify that the new sampler gives equivalent results in the industry being assessed.

This work is part of HSL's input to a collaborative European project to develop a range of porous foam aerosol samplers (SMT4-CT96-2137). The EC-funded project is concerned not only with sampler design, but also with the development of analytical procedures for organic and inorganic substances collected on foam substrates. The EC project will greatly expand the future scope for using foam-based samplers in occupational hygiene.

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