CRR 1996

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HSE CONTRACT RESEARCH REPORT No. 117/1996

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The work described in this project deals with two issues relating to the usage of personal sampling instruments (IOM personal inhalable sampler and 7-hole) currently recommended (in MDHS 14) for the measurement of inhalable aerosol (i) in relation to the measurement of particles greater than 100 µm and (ii) describing the development of a cassette version of the 7-hole sampler. Measured aspiration efficiency of the samplers and an aspirating rotating manikin indicated the potential for substantial oversampling, with respect to the manikin, at these sizes. The work suggests that the current personal inhalable samplers are unsuitable for the measurement of particle sizes greater than the current maximum size of the inhalable convention to particle aerodynamic diameters of at least 300 µm. The cassette system for the 7-hole sampler proved to be satisfactory.

This report and the work it describes were funded by the Health and Safety Executive. Its contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.

First published 1996

ISBN 0 7176 1270 8

CONTENTS

PRINCIPAL NOMENCLATURE

D	Particle aerodynamic diameter
d	Shield disk diameter
E	Efficiency
F	Flow rate
GSD	Geometric standard deviation
I	Inhalable Fraction
MMAD	Mass median aerodynamic diameter
m	Mass
s	Shield-to-sampler spacing
R	Ratio between concentration measured by scaling isokinetic probes
U	Air velocity
VLP	Very large particle (aerodynamic diameter greater than 100 μm)
W	Fractional wall loss

<u>Subscripts</u>

c	Cassette
b	Manikin
f	Filter
k	Isokinetic
s	Sampler
w	Wall

Subscripts (cont.)

0	System
7	7-hole
7c	7-hole cassette

INSTITUTE OF OCCUPATIONAL MEDICINE

LARGE PARTICLE AND WALL DEPOSITION EFFECTS IN INHALABLE SAMPLERS

by

RJ Aitken and R Donaldson

SUMMARY

For the measurement of exposure to aerosols in the workplace, the use of sampling instruments having aspiration efficiencies which match the definition of the inhalable fraction is now recognised as appropriate. For example, MDHS 14 (Health and Safety Executive 1993) recommends the use of two samplers, the 7-hole head, formerly used as a sampler for 'total' dust, and the IOM personal inhalable sampler (Mark and Vincent 1986).

The work described in this project deals with two issues relating to the practical usage of these instruments, (i) modification of the 7-hole sampler to include a cassette and (ii) determination, and subsequent modification, of the aspiration efficiencies of inhalable samplers for particles having aerodynamic diameter greater than 100 µm (the maximum size for which the inhalable fraction is defined in the current inhalable convention). In relation to this second issue, the nature of the inhalable fraction (based on the aspiration efficiency of a rotating manikin) for particle sizes greater than 100 µm was also investigated.

A cassette system for the 7-hole sampler was developed without modification to the external dimensions. The design allowed complete separation of the aspirated aerosol and that which was externally deposited. Comparative measurements showed that over all size ranges, the net effect of using the cassette version was to increase the efficiency by around 5% when compared to the standard sampler. Direct examination of the fraction deposited on the walls showed that this was dependent on particle size and was at a maximum for particles of 90 µm. At this size, the fraction deposited on the walls was 0.3 of the total sample.

Experiments with the rotating manikin showed that the aspiration efficiency fell for particle sizes greater than 100 µm, reaching a value of 0.12 at a particle aerodynamic diameter of 300 µm. Simultaneous measurements with both the IOM and 7-hole samplers showed mean aspiration efficiencies at 300 µm of 1.5 and 0.6 respectively indicating the potential for substantial oversampling, with respect to the manikin, at these sizes.

The effect of fitting various types of shields to these samplers was investigated. The best of the designs proved to be a basket shaped mesh shield which fitted over the sampler such that the

sampler entry pressed against the mesh. These shields reduced the aspiration efficiency of the sampler-shield unit to close to that of the manikin.

However, this shield design also caused undesirable lowering of the aspiration efficiency for some particle sizes (less than 100 µm) for which the inhalable fraction is currently defined. Further optimisation plus a field investigation is suggested.

The work suggests that the current personal inhalable samplers are unsuitable for the measurement of particle sizes greater than the current maximum size of the inhalable convention. Fitting of shields can improve their performance but the design has not yet been optimised. Based on the results presented here, consideration should be given to extending the inhalable convention to particle aerodynamic diameters of at least 300 µm.

1. INTRODUCTION

For the measurement of exposure to aerosols in the workplace, the use of sampling instruments having aspiration efficiencies which match the definition of the inhalable fraction is now recognised as appropriate.

The inhalable fraction is defined as the fraction of airborne material which can enter the human respiratory tract and so sampling of this fraction is considered to be representative of the total respiratory exposure of an individual. Initial estimates of the inhalable fraction were obtained from the fraction of aerosol, as a function of particle aerodynamic diameter, which entered the mouth orifice of a tailor's manikin aspirating with a sinusoidal breathing pattern at a tidal volume of 20 $l\,min^{-1}$, at various windspeeds, at no preferred orientation to the wind (Vincent and Armbruster (1981)). To achieve this the manikin was sited in a wind tunnel and rotated in a stepwise manner. The aspiration characteristic derived from these experiments was the basis of the definition of the inhalable fraction subsequently adopted by CEN (1993), the American Conference of Industrial Hygienists (ACGIH 1993) and the International Standards Organisation (ISO 1993). The form of the inhalable convention is

$$E_I = 0.5(1 + \exp(-0.06 \times D)) \qquad (1.1)$$

where D is the particle aerodynamic diameter in μm. In the UK, the CEN standard was subsequently adopted by BSI (1993).

For measurement of the inhalable fraction, MDHS 14 (Health and Safety Executive 1993) recommends the use of two samplers, the 7-hole head, formerly used as a sampler for 'total' dust, and the IOM personal inhalable sampler (Mark and Vincent 1986).

However, there are a number of potential problems which have been identified in relation to the practical usage of these instruments.

Firstly, in the 7-hole sampler, dust is known to collect on the internal walls. The ratio of dust on the walls to that on the filter may depend on a number of factors such as particle size, composition, temperature and humidity. The deposit on the walls could conceivably arise during the sampling process or it could occur later, after sampling but before the filter is removed. The problem is then whether or not this mass should be included as part of the inhalable fraction. In most cases it is not.

Secondly, both the IOM and 7-hole samplers are known to collect large particles, having geometric sizes of several hundreds of microns. It is not known whether these should be included or excluded from estimated exposures based on these samples. Inclusion of only a few of these particles can significantly alter the mass of the sample. For example, a single cubic particle of density 10^3 Kg m^{-3} and an edge length of 1000 μm will have a mass of 1 mg. The problem stems from the fact that the current definition of inhalability does not recognise an upper size limit, it merely states that inhalability is only defined for particles up to 100 μm. However, experiments carried out with static samplers (e.g. Aitken et al 1987) suggests that efficiency may in fact increase at larger particle sizes.

The situation is further complicated by the suggestion (Liden and Kenny 1993) that at these higher particle sizes there may be a disparity between the way that the inhalable fraction would be determined (if such an experiment were possible) and what actual human inhalability may be for larger particle sizes.

The original experiments (Vincent and Armbruster 1981) to determine the inhalable fraction were carried out by measuring the ratio of the ambient concentration to that sampled by a rotating (stepwise) aspiration manikin in a series of homogeneous monodisperse test aerosol clouds generated in a large wind tunnel. For such an experiment, repeated with larger particles, it is likely that some would be projected into the mouth of the manikin and therefore appear as a finite measured inhalable fraction.

However, Liden and Kenny's argument, which quotes the work of Rhodes et al (1993), is that a homogeneous aerosol distribution is not a realistic model for larger particles. Instead they suggest that large concentration gradients would be present. Under these circumstances, they argue that while it would be possible for a narrowly defined beam of particles to enter into a sampler, such a beam directed into the face would result in avoiding action being taken by the person exposed. On this basis, collection of particles having aerodynamic diameter greater than 100 μm is inappropriate.

This project is intended to shed light on these issues by (i) constructing a cassette system for the 7-hole sampler, (ii) measuring the inhalable fraction for larger particle sizes and (iii) developing simple shields, for use with the IOM and 7-hole samplers, which can exclude larger particles without undue effect on the selection characteristics for particles less than 100 μm.

2. OBJECTIVES OF THE STUDY

The main aim of the study was to provide practical information in relation to the sampling of inhalable aerosols with particular reference to large particles. Specifically, the following objectives were identified:

1. To solve problems of determining the partition between the filter and wall deposit in the 7-hole sampler by designing and testing a cassette system for the sampler.
2. To quantify the fraction of sampled aerosols depositing on the walls of the 7-hole and IOM personal inhalable samplers.
3. To investigate the nature of inhalability for particles of aerodynamic diameter greater than 100 µm.
4. To investigate the suitability of currently accepted inhalable samplers (the IOM personal inhalable sampler and the 7-hole personal sampler) where such large particles may be present.
5. To develop entry shields for personal inhalable samplers which can exclude large particles.
6. To validate the use of modified IOM and 7-hole samplers for large particles and for particles less than 100 µm.

The design and construction of a cassette system for the 7-hole sampler (Objective 1) is described in Section 3. Initial experiments to demonstrate differing behaviour between the samplers and the inhalable convention, as well as preliminary studies to investigate and develop shields for samplers (Objectives 3, 4 and 5) are described in Sections 4 to 6. A full investigation of the nature of the inhalable fraction for particles greater than 100 µm (Objective 3) is described in Section 7. The testing and validation of shielded samplers (Objective 6) is also described in Section 7.

The fraction of materials deposited on the internal walls of the 7-hole sampler (with and without cassettes) (Objective 2) and for the IOM sampler, is described in Section 8.

3. CASSETTE DESIGN AND CONSTRUCTION

The UKAEA 7-hole personal aerosol sampler is one of only two samplers described in MDHS14 (HSE 1993) as appropriate for measurement of the inhalable fraction of airborne material. In its recommended method of use, the inhalable fraction is obtained from the mass collected on the sample filter. This contrasts with the other recommended sampler, the IOM personal inhalable sampler (Mark and Vincent 1986), in which the inhalable fraction is obtained from the contents of a sampling cassette, which collects everything passing through the entry plane of the sampler.

For the 7-hole sampler, use of the filter mass only can lead to uncertainties in the estimation of the inhalable fraction, since material can deposit on the entry and internal walls of the sampler. This mass may stick to the internal walls or may become dislodged and end up on the filter, either during sampling or in the handling process. Transfer can also occur in the other direction, from the filter to the internal walls. Because of these uncertainties, it is not apparent to the user whether this additional mass should be included in the sample or not.

In order to better identify these problems, and to provide a possible solution to them, a version of the 7-hole sampler was produced which contained a sampling cassette.

As a first step, a number of manufacturers of the 7-hole sampler were approached to determine whether they had produced, or attempted to produce, cassette versions of the device and whether they would be prepared to make any prototypes or ideas available to the study. Although none of the manufacturers had fully commercially developed a system, most had considered the possibility and one had produced some initial prototypes.

With the agreement of the manufacturer a prototype cassette system was produced based on the initial prototype which the manufacturer had produced. This is shown in Figure 3.1.

The cassette was constructed from aluminium and features a thin removable front plate as shown. In use, the cassette is mounted within the sampler assembly as shown. Also, in use, material will deposit on the front face of the cassette as well as within the cassette and on the filter. Removal of the front face plate after sampling allows for complete partitioning of material actually entering the cassette and material depositing on the outside. In this it is analogous to the usage of the IOM personal inhalable sampler.

The objective here was to determine whether the use of the cassette improved the performance of the sampler. It was not and aim to optimise practical features of the cassette such as its weight and weight stability.

4. SHIELD DESIGN AND CONSTRUCTION

An important aspect of the work was concerned with the development of shields which could modify the performance of the IOM and 7- hole samplers. It was required that the shields were of simple design and be capable of retro-fitting to the current samplers so that comparison between the shielded and unshielded samplers could be made.

Making a starting assumption that the aspiration efficiency of current inhalable samplers for very large particles (VLPs) is greater than that of a manikin, the criteria for ideal shield performance were (i) the shields should reduce the aspiration efficiency of samplers for VLPs to that of the manikin (ii) make no change to the aspiration efficiency for particle sizes which are within the current size range of the inhalable fraction (0 to 100 μm). The starting assumption will be tested in Sections 6 and 7. For the moment we define VLPs as any particle having an aerodynamic diameter greater than the maximum currently specified in the Inhalable convention (100 μm).

While the importance of sampling velocity, orifice dimension and location on a bluff body are recognised as important to the sampling efficiency of personal inhalable samplers, the performance of these devices has not yet been fully described by a satisfactory theoretical model. Most of the development of inhalable samplers to date has been based on a largely empirical approach. As such, little in the way of theory was available to guide the design of shields to modify the efficiency of inhalable samplers.

However it is probable that collection of VLPs occurs almost exclusively when the sampler is facing into the wind and arises largely from "projection" of particles into the entry. For a sharp-edged probe facing into the wind in moving air, a sampling efficiency of unity is obtained by matching the sampling velocity (U_s) with that of the air velocity in which the sampler is situated (U_0). This is the condition for isokinetic sampling. When $U_s < U_0$ it is well recognised that the sampling efficiency increases for large particles which, due to their inertia are projected into the sampling entry as the air diverges. For the IOM sampler, U_s is around 0.2 ms^{-1} so for all of the windspeeds relevant to the measurement of the inhalable fraction $U_s < U_0$ indicating possible collection by the projection mechanism. It was expected that placing of shields directly in front of the entry would prevent this to some extent. Other than this however, development of the shields was on an empirical basis.

In all, a total of 33 shield designs were produced. There were four basic designs types, "solid disk", "mesh disk", "mesh basket" and "flush mesh basket". Diagrams of the four types are shown in Figure 4.1.

The "solid disk" shield was constructed from a thin brass disk, held by three narrow legs to a small collar which was located around the body of the sampler. The design variables for this type of shield were the diameter (d) of the disk and the spacing (s) between the disk and the entry (shield-to-sampler spacing). It was considered that this style of disk would decrease collection of VLPs by preventing projection of particles into the entry.

The "mesh disk" was similar but was constructed from a disk of woven wire mesh. In addition to the variables d and s, the mesh type, defined a nominal mesh aperture, given in μm, was also varied.

In the "mesh basket" shields, the mesh disk was extended into a basket shape by removing the support legs and replacing with a cylinder of the same mesh. In this type of shield d was fixed at 35 mm and s fixed at 10 mm.

The flush mesh basket was a truncated version of the mesh basket in which the spacing was reduced to zero and hence the mesh disk top surface pressed flush against the entry of the sampler.

The design specifications of all of the shield types are summarised in Table 4.1. Although the various designs are presented together here, they were not all constructed at the same time. Rather, the various designs evolved in a stepwise process with some being tested before decisions of the parameters for the next design were finalised.

Other shield types were also considered, particularly the use of porous foam plugs. This type of material has been used as a size dependent selection stage in aerosol sampler instruments (e.g. Aitken et at 1993) and has the advantage that models of penetration are available (Vincent et al 1993). However, examination of the performance model showed that the selector having the desired characteristics would be unfeasibly thin (less than 0.5 mm). Therefore this style was not considered further.

5. METHODS FOR MEASUREMENT OF ASPIRATION EFFICIENCY

Measurements of the aspiration efficiency of sampling instruments and manikins have been carried out at the IOM since the early 1980's. The work in this project followed the same approach in the main but with some differences in the detail.

At each particle aerodynamic diameter, a homogeneous test aerosol was generated in our large wind tunnel (having a working cross-section of 3.2 m x 1.8 m). The test dust used was fused alumina (Al_2O_3). This commercially available material (now called Duralum but previously known as Aloxite) is available in a number of sizes (mass median aerodynamic diameters (MMAD) from 6 µm , geometric standard deviations (GSD) typically 1.3) and has been used successfully in the past as a test material for aerosol experiments (Mark et al 1985). The available sizes are listed in Table 5.1. For particle sizes up to 90 µm, the aerodynamic sizes used are those quoted for each grade by Mark et al (1985). At the larger sizes, an estimate of the aerodynamic size was obtained from the size given from a Malvern Diffractometer. This determines a size parameter based on a diffraction pattern obtained by shining a laser through an airborne cloud of test aerosol. By relating the Malvern size parameter to the aerodynamic diameter for dust sizes for which this is already known, a factor was obtained which allowed an estimation of aerodynamic diameter for the other dust sizes.

Test aerosols were generated from this bulk dust using a rotating table dust feed from which dust is lifted by three compressed air-driven aspirators. The three aspirators were located at different vertical positions on a swinging arm arrangement which swept across the working section of the tunnel with a period of approximately twelve seconds.

Measurements of efficiency were carried out in two parts. In the first part, measurements of the spatial distribution of the test aerosol were made. In the second part, measurements of the mass collected by the samplers and (or) the manikin were made.

Considering firstly the distribution measurements, the homogeneity of the aerosol cloud was maintained by varying the vertical spacing of the aspirators and the time for which each of the aspirators was operated. In addition, it was necessary to vary the distance between the aspirators and the samplers or manikin depending on the particle size to take account of differing sedimentation velocities. The spatial distribution of the aerosol cloud was measured using an array of eight isokinetic probes. The normal acceptance criteria was that no probe should collect a mass which differed by more than 10% from the mean of the eight probes, although this was exceeded on some occasions. Two additional isokinetic probes were also used in this (and the subsequent) part of the experiment. These probes were located in the same position (15 cm in front and 17.5 cm to the outside of the main array) in both parts of the experiment and were used to scale the concentration between the two parts. These probes are referred to as, in this part of the experiment, the distribution-scaling probes, and in the second part on the experiment, the manikin-scaling probes. (Although the dust generation conditions were identical in the two parts, some differences in concentration did occur). The total mass collected by the isokinetic probes was measured. This included any mass which was collected on the internal walls of the probes plus the mass collected on the filter. In some cases, for the small particle sizes, it was necessary to wash the walls and filter out the wash-off to ensure complete removal and assessment of any wall deposit.

Provided that a satisfactory distribution had been achieved, the experiment continued with the measurement of the masses collected by the manikin and samplers under test. The isokinetic probe array was removed and replaced by the life size manikin, onto which the samplers under test were mounted. The manikin was positioned such that vertical plane which passed through the mid point of the manikin was aligned with the plane at which the entry of the isokinetic samplers had been located. The manikin rotated with a reciprocal motion during the experiment. The period of one complete rotation was 30 s.

For samplers, the sampling efficiency (E_S) was calculated from

$$E_s = \frac{m_s}{F_s} \times \frac{\overline{F_k}}{\overline{m_k}} \times R \qquad (4.1)$$

where m_S is the mass collected by the sampler, F_S the sampler flow rate, $\overline{m_k}$ the mean mass collected by the isokinetic probes in the distribution, $\overline{F_k}$ the mean isokinetic flow rate and R, the scaling ratio defined as

$$R = \frac{\overline{m_{distribution-scaling}}}{m_{manikin-scaling}} \qquad (4.2)$$

the ratio of the masses on the distribution-scaling and manikin-scaling isokinetic probes.

Simultaneously with these experiments, the aspiration efficiency of the manikin was measured. Air was drawn through the mouth orifice using a "breathing-machine" mounted remotely from the manikin, at a flow rate of 20 $l\,min^{-1}$. The flow followed a sinusoidal pattern with only the inhaled part of the cycle passing through the mouth. A filter holder containing a 47 mm filter was mounted immediately behind the orifice. All of the mass collected in the filter holder (i.e. the filter deposit plus the wall deposit) was regarded as the aspirated mass. As was the case in the distribution part of the experiment, it was sometimes necessary to wash off the internal walls. In later experiments, a cassette system was adopted to ensure complete collection of wall loss mass. Calculation of the aspiration efficiency of the manikin E_b was carried out using an equation similar to Equation 4.1

$$E_b = \frac{m_b}{F_b} \times \frac{\overline{F_k}}{\overline{m_k}} \times R \qquad (4.3)$$

where m_b is the mass sampled by and F_b the flow rate of the breathing manikin.

In previous experiments (e.g. Vincent and Armbruster 1981, Mark et al 1990) it had been common practice to have the exhalation part of the manikin breathing pattern exhaled through the nostrils. However, more recent work (Kenny 1995) has shown that nasal exhalations from manikins are dissimilar to actual human exhalation and can adversely affect the performance of samplers mounted on the chest. Therefore, the exhaled part of the cycle was vented through a point remote from the manikin.

Initial measurements of windspeed were carried out using a hot wire anemometer held close to the sampling position in the wind tunnel. Subsequently however, an improved method was used, based on the measurement of the pressure differential across a grid at the entry of the wind tunnel. This allowed for more accurate setting and continual monitoring of wind speed.

In addition to the windspeed monitoring, the velocity of the aerosol particles was estimated using a timed flash photographic technique. An assessment of the velocity was made by measuring the track lengths generated by the largest aerosol used. At the manikin, for a windspeed of 1 ms^{-1}, the estimated particle velocity was 1.2 ms^{-1}.

6. PRELIMINARY STUDIES

The idea that VLPs or droplets may enter samplers with forward facing entries is based largely on qualitative and anecdotal evidence. For example, Aitken and Maynard (1995) reported that in a study to measure exposure of workers in a bakery, large numbers of cubic sugar crystals having a side length of the order of 1000 μm were found in some samples. Werner et al (1995) reported that in studies in the nickel industry, he found evidence of large droplets on the inside lip of the IOM sampler cassette. Kalil (1995) has reported that in studies in the abrasive blasting industry, large particles can end up on the filter and can even pierce the filter. In other industries, where activities such as grinding are taking place, it is possible to envisage situations where a stream of VLPs are emitted and can be incident on a sampler, allowing for collection, but are unlikely to be incident on a workers face, resulting in little risk of inhalation. No consensus exists about the size of particle at which these effects are significant.

Preliminary studies were carried out to assist definition of the work programme. In particular, the work in these preliminary studies addressed two questions.

1. When sampling VLPs, does the aspiration efficiency of the IOM (and other personal inhalable samplers) differ to that of the manikin to such an extent that it is necessary to introduce modifications to the samplers?

2. If there are substantial differences between the aspiration efficiencies of samplers and the manikin for large particles, which configuration of shield appears to offer the best possibility of reducing these differences whilst at the same time causing minimal modification in performance at particle sizes lying within the conventional definition of the inhalable fraction?

To address these questions a programme of work was carried out to measure the aspiration efficiency of the rotating manikin, IOM personal inhalable samplers and IOM samplers fitted with a variety of shield designs. This work was carried out at one windspeed (1 ms^{-1}) and at two particle aerodynamic diameters. Duralum 90 E having a nominal aerodynamic diameter of 300 μm was chosen to represent an arbitrarily large VLP and Duralum F240 having a nominal aerodynamic diameter of 90 μm was chose to represent a particle lying within the conventional inhalable range.

6.1 Experimental design

Each of the preliminary experiments comprised one measurement of freestream concentration distribution followed by two measurements of sampler and/or manikin aspiration efficiency. The main group of preliminary experiments investigated the aspiration efficiencies of unmodified IOM samplers or IOM samplers mounted with one of the solid or mesh disk shields (Shields 1-28). The samplers were able to be mounted on one of six positions on the manikin (three on the front, three on the back). The position was varied systematically so that there was no preferred position and each sampler-shield configuration was tested in one front and one back position. To investigate the range of sampler-shield options required six experiments at each particle size. The experimental design is summarised in Table 6.1. Simultaneous measurements of aspiration efficiency of the manikin were also carried out during all of the 300 μm experiments and during one of the 90 μm experiments.

A further two experiments were carried out in which the aspiration efficiency of IOM samplers fitted with Shields 29 and 30 (mesh basket shields) was measured.

Some supplementary experiments were also carried out to provide additional data at both particles sizes for the manikin aspiration efficiency and the aspiration efficiency of unmodified samplers and for 7-hole samplers at the large particle size.

6.2 Results and Discussion

A complete set of results is listed in Appendix A1, however, the questions posed at the start of this section may be answered by appropriate summaries of the data which are provided in the main body of this report.

The first question can best be answered by summarising the data for the aspiration efficiencies of the manikin and the unmodified IOM samplers. This has been done in Tables 6.2(A) and 6.2(B).

Table 6.2(A) shows the data for a the nominal 300 μm aerodynamic diameter aerosol and shows the mean aspiration efficiencies for the manikin and unmodified sampler along with the number of results and the calculated standard deviation. For the manikin, the mean aspiration efficiency is 0.12 (12%) and for the samplers 1.55 (155%). This represents a statistically significant oversampling by the samplers when compared with the manikin and indicates clearly that a potential problem exists for particles of this size. Differences of this magnitude indicate that, even for a homogeneous spatial distribution, the unmodified IOM sampler could overestimate the exposure of an individual by a factor of more than 10.

Similar results for the 7-hole sampler (based on only 3 data points) showed a mean sampling efficiency of 0.60, smaller than that for the IOM sampler but still more than a factor of 4 larger than the manikin.

The low value of the manikin aspiration efficiency also offers a strong indication that the shape of the inhalable convention for particle sizes greater than 100 μm should follow a decreasing trend. This will be discussed more fully in Section 7.

Table 6.2(B) show the same data for a nominal aerodynamic diameter of 90 μm. In this case the mean efficiency value for the IOM sampler of 0.56 is consistent with the accepted value of the inhalable convention (0.5). However, the aspiration efficiency the manikin is lower than expected and is significantly lower than the convention and the measured IOM sampler efficiency. This will be discussed in Section 7 where more data will be available.

This evidence clearly shows that there is sufficient difference between the manikin aspiration efficiency and the aspiration efficiency of personal inhalable samplers to warrant the application of some form of shield to reduce the difference.

The second question was concerned with which configuration of shield and sampler offered the best possibility of reducing differences in aspiration efficiency for large particles whilst at the same time causing minimal modification in performance at particle sizes lying within the conventional definition of the inhalable fraction?

Dealing firstly with the performance of the IOM sampler with solid shield designs (Shield numbers 1 to 9 and 28), Figure 6.1(A) summarises the data for particle aerodynamic diameter 90 μm and Figure 6.1(B) summarises the 300 μm data.

In Figure 6.1(A), the general shape of the data shows broadly that for a 90 μm aerosol, the efficiency decreases as the shield diameter (d) increases. The efficiency does not appear to be strongly dependent on the shield-to-sampler spacing (s) although there is a suggestion of a small decrease in efficiency as spacing is reduced, particularly for the 35 mm diameter shield.

Against the target performance of 0.5 (the value of the inhalable convention for this particle size) only the samplers with 25 mm diameter shields appeared to perform reasonably well. At spacings of 5 and 10 mm (Shields 1 and 2) the results were close to 0.5 although at a spacing of 20 mm (Shield 3) the efficiency appeared to increase. All of the samplers with 35 mm diameter shield results were consistently below the target value, regardless of shield to sampler spacing. Similarly, all samplers with the 15 mm diameter shields were higher than the target values regardless of shield-to-sampler spacing.

Figure 6.1(B) shows the results for the same shields with aerosol of aerodynamic diameter 300 μm. The results are almost all below the mean result for an unshielded IOM sampler of 1.55 so in this respect all shield designs have resulted in some improvement in the sampler performance. The results show an apparent decreasing trend as shield-to-sampler spacing increases. Little or no effect with shield diameter is apparent.

None of the shield-sampler configurations are close to the target efficiency of 0.12, the aspiration efficiency of the manikin at this particle size. The lowest efficiency (expressed as a mean of the two data points) was 0.98 for a was for a sampler with a solid shield of diameter 25 mm and an shield-to-sampler spacing of 20 mm.

The results for the samplers with mesh disk shields (Shields 10 to 27) are shown in Figures 6.2 (A and B). Figure 6.2(A) shows the aspiration efficiencies for an aerosol of aerodynamic diameter of 90 μm. For all values of s, as might be expected, there is evidence that the aspiration efficiencies decrease as the mesh size decreases. This is particularly obvious with the zero shield-to-sampler spacing mesh disks. The range of results appears to be much greater for samplers with shields with spacing equal to zero than for those with s equal to 10 and 20 mm.

In relation to the target efficiency of 0.5, almost all designs resulted in efficiencies below this level indicating that all of the shield designs have had the effect of reducing aspiration efficiency by an undesirable amount. The lowest values were for the sampler with a 140 mesh at s equal to zero. Those closest to the target were those with 800 and 1200 meshes having an s value of zero.

The results for samplers with the same shields against a 300 μm aerosol are summarised in Figure 6.2(B). Again almost all designs have resulted in a decrease of aspiration efficiencies when compared with the unmodified IOM sampler. Again the trend is for higher efficiencies to be associated with more open meshes and generally a reduction in efficiency with reducing values of shield-to-sampler spacing. In relation to the target efficiency of 0.12, only samplers with shields of meshes 140 and 225, with s equal to zero approach this value.

The two additional experiments were concerned with the basket style mesh shields (29 and 30). The results for these are shown in Table 6.3. Of the two shields shown, Shield 30 has a very close match to the requirements. At 90 μm, the measured aspiration efficiency is 0.44, close to the target value of 0.50. At 300 μm, the measured aspiration efficiency is 0.14, again very close to the required value of 0.12. The equivalent figures for Shield 29 are, for 90 μm, aspiration efficiency is 0.12 and for 300 μm, 0.03. For both sizes the measured aspiration efficiency is well below the target values.

In summary, on the basis of the experiments carried out, the shield which most closely matches the requirement is Shield 30, a mesh basket shield. None of the solid shield configurations are effective in reducing the aspiration efficiency at 300 μm to the target value. Of the mesh disk shields, only those having s equal to zero (with meshes 140 and 200) were effective in reducing the efficiency at 300 μm to close to the target value; however, in both cases there was more reduction in the efficiency at 90 μm than would be ideal.

Final selection of shields for testing was based on these findings and is described in Section 7.

7. MEASUREMENTS OF SAMPLER AND MANIKIN ASPIRATION EFFICIENCY

The objective for the work described in this section was to validate the performance of the sampler-shield configurations which were considered, on the basis of work carried out in Section 6, to be the most likely to meet the requirements described in Section 4. These requirements were that an ideal shield should (i) reduce the aspiration efficiency of samplers for VLPs (those lying outside the current definition of the inhalable fraction) to (at most) that of the manikin, and (ii) not modify the aspiration efficiency of the samplers for particle sizes within the current definition of the inhalable fraction.

Validation involved (i) the measurement of the aspiration efficiency of each shield-sampler combination and (ii) determination of the fraction of sampled mass which was deposited on the internal walls of the IOM sampler and the modified 7-hole sampler described in section 5.

Simultaneous measurements of the aspiration efficiency of the manikin were also carried out.

7.1 Selection of sampler shields for full testing.

The sampling efficiencies of both the IOM sampler and the 7-hole sampler, fitted with shields and "unshielded" were to be measured. In all, six sampling positions were available on the manikin where testing could be carried out. This allowed six different sampler-shield configurations to be tested simultaneously. Two sampling positions were reserved for the unshielded versions of these samplers.

The preliminary studies described in Section 6 indicated that sampler-shield configuration which most closely matched the requirements was the mesh basket shield (Shield 30). Therefore this shield was selected for further evaluation combined with both the IOM sampler and the 7-hole sampler using two of the remaining sampling positions.

The other shield which showed some promise in the preliminary studies was Shield 25, a 200 mesh shield with zero sampler-to-mesh spacing. However there was a large difference between the two measured values efficiency for this shield. It was thought that this may have been due in part to the design and the difficulty in keeping the mesh disk, from which the shield was constructed, flush with the sampler entry. For this reason the shield was redesigned as a "flush mesh basket" but keeping the same 200 mesh and the same shield-to-sampler spacing (zero). This redesigned shield was given the number 25B. Combined with the IOM sampler, this shield was given the fifth position on the manikin.

The sixth position was used to compare the performance of the standard and cassette versions of the 7-hole sampler and is described in Section 8.

Hence the sampling configurations for testing were;

- IOM sampler unshielded
- IOM sampler with Shield 30
- IOM sampler with Shield 25B
- Standard 7-hole sampler unshielded

- Cassette 7-hole sampler unshielded
- Cassette 7-hole with Shield 30

The experiments in which these configurations were tested are referred to below as the Group 1 and Group 2 experiments.

Subsequently, three new shields were constructed. These were of the flush mesh basket design and had mesh sizes 250, 300 and 335. These were giving the shield numbers 31, 32 and 33 respectively. These were tested in the Group 3 experiments where the configurations tested were;

- IOM sampler unshielded
- IOM sampler with Shield 30
- IOM sampler with Shield 31
- IOM sampler unshielded
- IOM sampler with Shield 32
- IOM sampler with Shield 33

7.2 Experimental methods and design

The experimental methods used were identical to those described in Section 5. The work was carried out at two windspeeds, 1 and 3 ms^{-1}. Ten sizes of test aerosols (listed earlier in Table 5.1) were available for use covering the range of aerodynamic diameters from 6 to 300 μm.

Three groups of experiments were carried out. The six configurations tested in each group are summarised in Table 7.1, along with the test aerosols and the windspeeds used.

The protocol followed was the same as that described in Sections 5 and 6 in that each sampler-shield configuration was tested twice at each condition, once on the back of the manikin and once on the front of the manikin. The sampler position was varied systematically, in a similar way to that described, so that there was no preferred position for any sampler-shield configuration.

For each condition, two measurements of manikin aspiration efficiency were also made.

7.3 Results

The results from the first group (Group 1) of experiments are summarised in Figure 7.1. The results here are presented in the form of aspiration efficiency relative to that of the manikin. The results were presented in this way, rather than the more usual presentation of absolute aspiration efficiency, because an error in the way windspeed was measured (for the Group 1 and 2 experiments) resulted in the experiments being carried out at a velocity 0.3 ms^{-1} higher that planned.

Assessment of windspeed in the Group 1 experiments was carried out using a hot bead anemometer held in the working section of wind tunnel close to the samplers. A re-calibration of the anemometer had been carried out immediately prior to the Group 1 experiments. It subsequently became apparent however, that this calibration had been in error and the true windspeed had been 1.3 ms^{-1}, rather than the target windspeed of 1.0 ms^{-1}. The erroneous windspeed setting had two consequences (i) creating an error in the assessment of the free-stream concentration by isokinetic probes and (ii) changing the aspiration efficiency of the samplers, which together appeared to contribute to an overall reduction in the measured aspiration efficiency. Confirmation of this effect and the a discussion of the consequences in relation to the measurement of inhalability are given in Appendix 2.

Because of this problem, use of these data was restricted to calculation of the "Relative Aspiration Efficiency" (E_R) which we define as the ratio of the measured aspiration efficiency of the sampler (E_s) to that of the manikin (E_b). Ideal performance of a sampler would be an E_R of 1.0 throughout the size range, provided that the assumption that the aspiration efficiency of the manikin matches the current definition of the inhalable convention (up to 100 µm) is valid. This approach, although clearly not ideal, did allow information on the comparative performance of sampler-shield configurations against each other and against the manikin to be obtained.

(The Group 2 experiments were similarly confounded although, in this case, the windspeed error at 0.3 ms^{-1} was less than 10% of the target windspeed. Subsequent measurement and control of windspeed (in the Group 3 experiments) was done using the pressure drop method described in Section 5. This improved method enabled control of windspeed to within 5% allowing sufficient confidence to measure absolute aspiration efficiency.)

For the experiments carried out in Group 1, Figure 7.1 (A) shows the relative aspiration efficiency for an unmodified IOM sampler, an IOM sampler with Shield 25B and an IOM sampler with Shield 30. Figure 7.1 (B) shows the relative aspiration efficiency for a 7-hole sampler, a 7-hole cassette sampler and a 7-hole cassette sampler fitted with Shield 30.

Dealing firstly with the IOM variants, the performance of the unmodified IOM sampler confirms the finding of the preliminary study that, as particle size increases beyond the current maximum size defined in the inhalable conventions, the aspiration efficiencies of the IOM sampler and the manikin become increasingly divergent. At the maximum size for which measurements were made, the relative aspiration efficiency of the sampler was around 15 indicating that the sampler would collect around 15 times that collected by the manikin. At particle sizes less than 100 µm the relative aspiration efficiency is closer to unity but it is also noted that the aspiration efficiency of the sampler is less than unity for sizes 50 and 90 µm.

The two shields have both been successful at reducing (relative) aspiration efficiency to some extent for sizes greater than 90 µm, particularly for the two largest sizes tested. This is in line with what is required. However, the effect on efficiency for particle sizes below this been rather different.

Fitting of Shield 25B has apparently reduced the efficiency of the IOM sampler at all particle sizes. While this is desirable for particle sizes greater than 100 µm, it is not so for sizes less than 100 µm, particularly since, as described above, the relative aspiration efficiency is less that 1.0.

The effect of Shield 30 was different in that, while the reduction in the relative aspiration efficiency for particle sizes greater than 100 µm is similar, for particles in the size range 50 - 100 µm, the efficiency of the IOM sampler appears to have increased as a result of fitting the shield. This surprising result cannot easily be explained but is an indication of the complexity of the processes which determine the aspiration efficiency of samplers. On this occasion, the result is fortuitous in that in this size region, the efficiency of the unshielded IOM sampler is low, so that increasing its efficiency is advantageous. Depending on such a surprising phenomenon, with no clear idea of the mechanisms involved, is rather speculative however, and use of such a shield should only be considered with caution.

Figure 7.1 B show that there are similar trends associated with the 7-hole sampler. Neglecting any differences between the standard and cassette versions of the 7-hole sampler for the moment, the 7-hole aspiration efficiencies show the same rising trend for particle sizes greater than 100 µm (and the same decrease in efficiency, relative to the manikin, at around 50 µm).

Fitting of Shield 30 has, as for the IOM sampler, reduced the efficiency of the 7-hole sampler for particles greater than then 100 µm and <u>increased</u> the efficiency for (in this case) all other sizes greater than 10 µm. This again resulted in a fortuitous effect in that the aspiration efficiency of the arrangement was close to that of the manikin. However, the same caveat applies here.

The results from the second group of experiments (Group 2) for the same sampling arrangements, but at a nominal windspeed of 3 ms^{-1} are shown in Figures 7.2 A (IOM sampler variants) and 7.2 B (7-hole sampler variants). Although fewer particle sizes were tested, the results in all cases are qualitatively similar to those for 1 ms^{-1} (nominal velocity) in Figure 7.1. The same trends are evident (i) both unmodified samplers oversample relative to the manikin for particle sizes greater than 100 µm, (ii), both shield types reduce the aspiration efficiency for particle sizes greater than 100 µm, this time to well below that of the manikin and (iii) Shield 30 increases the sampling efficiencies of both samplers, this time in the size range 10-100 µm. One difference is that in this case Shield 25B does not appear to have caused a substantial reduction in the sampling efficiency of the IOM sampler at particles sizes in the sub-100 µm range.

For the third group of experiments (Group 3), the results of the absolute efficiency are valid. However, it is useful to firstly consider the relative efficiency so that comparisons can be drawn with the Group 1 and 2 results above. Figure 7.3 A shows the relative efficiency results at 1 ms^{-1} for the four shield arrangements tested. The overall impression is that there is little difference between the four arrangements tested but that Shield 25B is better, since only this shield reduces the relative efficiency to approximately 1 for 300 µm test aerosol and also shows a more of a reduction at the other sizes greater than 100 µm. Little difference between the four designs can be seen for particle sizes less than 100 µm.

Comparing these Shield 25B data with results for the unshielded IOM sampler (Figure 7.3(B)) shows similar trends to those in Figure 7.1, confirming the improved performance at particle sizes greater than 100 µm. It is worth noting that for particles less than 100 mm, the differences between the efficiencies of the shielded and unshielded IOM sampler are not as great as had been previously observed.

The significance of all of this can be seen more clearly in Figure 7.4 where the aspiration efficiency of the IOM sampler (E_{IOM}), the IOM sampler with Shield 25B (E_{s25}) and the manikin (E_b) are plotted along with the inhalable convention.

There are several points of interest here:

The divergence between the aspiration efficiencies of the IOM sampler and the manikin for particle sizes greater than 100 µm is clearly evident. Figure 7.4 shows that whilst agreement between E_b and E_{IOM} is reasonable at particle sizes below 80 µm, the divergence between the two increases as particle size increases until, at a particle aerodynamic diameter of 300 µm, E_b is approximately 0.09 whereas E_{IOM} has a value of 1.5. The result is consistent with the aspiration efficiency results obtained in the preliminary studies and with the relative efficiency values (E_R) calculated earlier and confirms the potential for oversampling with the IOM sampler for VLPs.

The difference between the aspiration efficiency of the manikin and the IOM sampler can be reduced for VLPs, by fitting Shield 25B to the IOM sampler. The figure shows that for such an arrangement, aspiration efficiency no longer increases with particle size for particles greater that 100 µm. Rather, aspiration efficiency decreases until at the maximum size tested, the measured value for this combination (E_{s25}) is 0.07, very close to the manikin efficiency (E_b) of 0.09.

Fitting Shield 25B has however, also resulted in a reduced aspiration efficiency for the IOM sampler at particle sizes less than 100 µm. The effect is greater for particle sizes below 45 µm. This may be seen most clearly in Figure 7.4(B). The largest difference appears to be for particles of aerodynamic diameter 12 µm. Examination of the data shows that measured value of E_{IOM} is 0.6 and of E_{s25}, 0.38. Also the values of E_{s25} are substantially less the accepted values of the inhalable fraction for all of the size range for which the fraction is currently defined.

On the evidence of the results presented here, the results of E_{IOM} lie below the values of the inhalable fraction for all particle sizes less than 90 µm. In addition, the values of E_b are low at particle aerodynamic diameters 78 and 90 µm. Although investigations of these features was not a formal objective of the work, it is useful to note that the values of E_{IOM} in particular are consistent with work carried out recently elsewhere (Kenny 1995).

A protocol, currently under development by CEN (CEN 1995) specifies a formal way in which the match between the aspiration efficiency of sampling instruments and conventions may be assessed, in terms if bias and accuracy. Given the relative paucity of data points and the scatter in the data which is a feature of such work, this formal method was not used and comparison was restricted to the qualitative observations given above.

7.4 Discussion

The measured aspiration efficiency of the samplers and the aspirating rotating manikin described in this section strongly indicate the potential for substantial oversampling, with respect to the manikin, for VLPs. This suggests that the current personal inhalable samplers are unsuitable for the measurement of particle sizes greater than the current maximum size of the inhalable convention. Fitting of a shield of the type of Shield 25B, i.e. a flush mesh basket shield, with a 200 mesh and a zero shield-to-sampler spacing, can improve sampler performance against VLPs at least for a windspeed of 1 ms^{-1} (more typical for workplaces than the other windspeed tested, 3 ms^{-1}). However, the design has not yet been optimised and this shield also causes undersampling at particle sizes less than 100 µm.

Shield 30, a mesh basket shield with a 200 mesh and a shield-to-sampler spacing of 20 mm also gave promising results although, a shield of this type should only be used with caution since the way in which it causes an increase in efficiency is not understood.

Further work is require to refine the design of the shield to maintain the improved efficiency characteristics for VLPs while not modifying the sub-100 µm aerosol to the extent to which the current best shield (Shield 25B) does. The best combination should be formally tested according to the protocols for sampler evaluation currently being developed by CEN.

If no improvement to shield performance is possible, a workable strategy for use of Shield 25B may be as follows; (i) if it is suspected that large particles are dominating the sample then the sampler should be fitted with a shield, (ii) in this case, the sampling efficiency of the sampler will be reduced below that of the inhalable convention so that a factor will need to be applied which will "correct" the mass collected and (iii) for the current best shield, the greatest reduction in efficiency relative to the unshielded IOM sampler is at a particle size of 12 µm where the measured IOM efficiency is 0.6 and the shielded IOM efficiency is 0.38 Thus correcting the mass by a factor of 1.6 (0.6/0.38) would prevent any underestimate of exposure.

It is recognised that adoption of such a strategy would not be ideal but may provide improved understanding of the effect of large particles.

8. WALL LOSS AND COMPARISON OF THE PERFORMANCE OF THE STANDARD AND CASSETTE VERSIONS OF THE 7-HOLE SAMPLER

A further aspect of this work was concerned with wall loss inside inhalable samplers. For the IOM sampler, the recommended method of use is to analysis, typically by weighing, the entire contents of the cassette including any wall loss inside the cassette. Hence in this situation, wall loss is part of the sample and is fully accounted for. However, other analytical situations favour analysis of the filter only. In these situations, it is important to know the magnitude of the wall loss so that an assessment of its importance may be made.

For the 7-hole sampler in its standard form, the recommended method of analysis requires only that the filter deposit is assessed. However, for the reasons discussed in Section 4, a cassette version was constructed. Assessment of the wall loss in the cassette version was also carried out. In addition to this, direct comparison of the aspiration efficiencies of the standard and cassette versions of the 7-hole samplers was carried out.

8.1 Experimental methods and design

All of the experiments were carried out as part of the experiments described in Section 7. The fractional wall loss (W) for both the IOM sampler and the cassette version of the 7-hole sampler was evaluated by measuring the mass collected in the sampler cassette (m_c) and the mass deposited on the sampler filter (m_f). Since the mass collected in the cassette is the sum of m_f and the mass collected on the internal walls (m_w), the fractional wall loss is given by

$$W = \frac{m_c - m_f}{m_c} \qquad (8.1)$$

The aspiration efficiencies of the two 7-hole sampler variants was measured directly.

8.2 Results

8.2.1 Fractional wall loss for IOM, shielded IOM and the cassette 7-hole sampler.

Figure 8.1 shows all of the fractional wall loss results for the unmodified IOM sampler. The results exhibit considerable variability, much greater than that previously observed with efficiency measurements. This is consistent with the nature of wall deposits in that they can be very unstable and may, during handling become wholly or partially dislodged and end up on the filter. Although the samples for this exercise where handled with extreme care, this possibility cannot be discounted.

Figure 8.1 shows evidence of a dependence on particle size with a maximum value of about 0.3 at 100 µm and falling to below 0.1 at the limits of sizes tested.

In Figure 8.2, the mean results of the IOM sampler are shown along with the mean results for all of the shielded IOM samplers and the results for the cassette versions of the 7-hole sampler.

The mean results for the unmodified IOM sampler confirm the trend noted from Figure 8.1. For the shielded IOM samplers, the trend is similar. There are also similarities for the 7-hole sampler results. For particle sizes below 100 µm, there is an increasing trend although the magnitude of the results is generally lower then the corresponding results for the IOM and shielded IOM samplers. There is a very large value at around 100 µm and some evidence of a reduction for larger values.

8.2.2 Aspiration efficiencies of the two 7-hole samplers

The results for the aspiration efficiencies of the cassette and standard versions of the 7-hole sampler are shown in Figure 8.3. They are plotted as pairs with the two values having been obtained from a single experimental run. The efficiencies are plotted on a logarithmic scale.

From this figure, there appears to be little difference between the two sets of data. A linear relationship

$$E_{7c} = 1.05 \times E_7 \qquad (8.2)$$

where E_{7c} is the efficiency of the 7-hole cassette and E_7 is the efficiency of the 7-hole standard sampler, appears to fit the data quite well (r^2_{corr} = 0.96) although there is some scatter particularly at the lower efficiency values. Overall, the relationship indicates that the cassette version of the 7-hole sampler would collect around 5% more than the standard version.

8.3 Discussion

From the results described above, it can be seen that the fractional wall loss can form a substantial part of the collected mass for both the IOM and 7-hole cassette samplers. The magnitude varies, depending on the size of the particles an reaches a maximum at around 100 µm.

This probably relates to the adhesion properties of the particle. The test material used in these experiment is a hard mineral material. It is quite probable that the larger particles would come in contact with the sampler walls but would not adhere but "bounce" off and end up on, and be counted as part of the filter deposit. Because of this, it is necessary to interpret these results with caution since particles with different physical properties, for example those having a sticky surface or liquid droplets, may not behave in the same way and may adhere to the walls.

The fraction of wall loss also appears to be highly variable and again this is likely to relate to the nature of material.

These results reaffirm the rationale for using samplers with cassettes. Providing samplers of this type are used correctly, the sample analysis will contain all of the wall deposit and filter deposit.

The direct comparison between the standard and cassette versions of the 7-hole sampler overall has shown that use of the cassette version would increase the amount collected by around 5%. Although this is not particularly large, it is probable that this does depend on size, with the differences being greater at larger particle sizes. The same comments about particle adhesion apply.

Taken together, these results offer a strong argument for the advantages of including a cassette in the 7-hole sampler.

9. CONCLUSIONS AND RECOMMENDATIONS

The main conclusions of the work are given below; they are presented along with the objectives (specified in section 2) to which they relate.

1. ***To solve problems of determining the partition between the filter and wall deposit in the 7-hole sampler by designing and testing a cassette system for the sampler.***

   A cassette version of the 7-hole sampler has been designed and constructed. The cassette incorporates a removable front face which allows complete separation between the particles which enter the cassette and those which are incident on its outer surfaces.

2. ***To quantify the fraction of sampled aerosols depositing on the walls of the 7-hole and IOM personal inhalable samplers.***

   A substantial proportion of the sampled aerosol was found to deposit on the internal walls of the IOM and 7-hole cassette samplers. The fraction was dependent on particle size and appeared to reach a maximum (of about 0.3 for the IOM sampler and 0.5 for the 7-hole cassette) at about 100 μm.

3. ***To investigate the nature of inhalability for particles of aerodynamic diameter greater than 100 μm.***

   The nature of inhalability for particles greater than 100 μm has been investigated by measuring the aspiration efficiency of a breathing rotating manikin using Duralum test aerosol with aerodynamic diameters up to 300 μm. At wind speeds of 1 ms^{-1} the mean aspiration efficiency is 0.1, much lower than the current lowest value of the inhalable fraction (0.5) which applies to particle sizes of 100 μm.

4. ***To investigate the suitability of currently accepted inhalable samplers (the IOM personal inhalable sampler and the 7-hole personal sampler) where such large particles may be present.***

   The suitability of the current inhalable samplers, plus the cassette version of the 7-hole sampler was investigated by measurement of the aspiration efficiency of these instruments while mounted on a rotating manikin simultaneously with the aspiration efficiency of the manikin. The aspiration efficiency of all of these samplers was found to greatly exceed that of the manikin at both 1 and 3 ms^{-1}. Typically, the measured aspiration efficiencies of the samplers lay in the range 1.5 - 2.0 representing a four- to ten-fold increase over that of the manikin. The clear conclusion is that in industrial situations where there are high airborne concentrations of these large particles, the current generation of samplers are not suitable and substantial overestimation of exposure may occur.

5. ***To develop entry shields for personal inhalable samplers which can exclude large particles.***

   Types of entry shields were based either on solid or mesh design. Preliminary studies were carried out to investigate the extent to which parameters such as shield diameter, shield-to-entry spacing, mesh spacing and shield style influenced the aspiration efficiency of IOM samplers mounted with the shields for particles having aerodynamic diameter 100 and 300 μm. The studies demonstrated that none of the solid designs were successful in reducing the aspiration efficiency by the required amount. Several of the mesh designs were also eliminated on this basis.

6. ***Tó validate the use of modified IOM and 7-hole samplers for large particles and for particles less than 100 μm.***

   Several shields, selected on the basis of the preliminary studies as having the greatest probability of success were evaluated. The aspiration efficiencies of IOM samplers mounted with the selected shield was measured for a range of aerodynamic diameters from 6 to 300 μm. All designs were successful to some extent in reducing the very high values of aspiration efficiencies for the largest particle sizes. However, all shields also modified the aspiration efficiency at particle sizes less than 100 μm.

   Based on the work, a best-option shield was selected which was a flush fitting mesh basket with a nominal mesh size of 200 μm (Shield 25B).

The following recommendations have been arrived at based on consideration of the work carried out;

1. Consideration should be given to extending the definition of inhalability up to (and possibly beyond) 300 μm. The manikin aspiration efficiencies included in this report represent the best available basis for this new definition although additional work would be useful.

2. Further work is require to refine the design of the shield to maintain the improved efficiency characteristics for large (greater than 100 μm) aerosols while not modifying the sub-100 μm aerosol to the extent to which the current best shield does. The best combination should be formally tested according to the protocols for sampler evaluation currently being developed by CEN

3. A workable strategy for use of the current shield may be (i) if it is suspected that large particles are dominating the sample then the sampler should be fitted with a shield, (ii) in this case, the sampling efficiency of the sampler will be reduced below that of the inhalable convention so that a factor will need to be applied which will "correct" the mass collected and (iii) for the current best shield, the greatest reduction in efficiency relative to the unshielded IOM sampler is at a particle size of 12 μm where the measured IOM

efficiency is 0.6 and the shielded IOM efficiency is 0.38 Thus correcting the mass by a factor of 1.6 (0.6/0.38) would prevent any underestimate of exposure.

4. Sampler manufacturers should be encouraged to produce 7-hole samplers containing a cassette system which could be based on the one described in this report. Once in production, the use of the cassette version should be preferred.

10. ACKNOWLEDGEMENTS

The authors wish to thank the Health and Safety Executive for their financial support for the work described in this report. In particular we would like to thank Christine Northage (THSD, Bootle), Dr Lee Kenny and Dr Andrew Maynard (HSL, Sheffield) for their support. In addition we are grateful for the helpful comments and suggestions made by colleagues at the IOM, particularly Dr Nigel Crawford and Dr Arthur Johnston.

The authors are also grateful to the sampler manufacturers, in particular to SKC (Blanford Forum, Dorset, UK), for sharing with them information and prototypes relating to the development of a cassette for the 7-hole sampler.

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TABLE 4.1

Specification of the shields

Shield Number	Shield Type	Material solid / nominal mesh aperture	Diameter (mm)	Spacing (mm)
1	solid	solid	15	5
2	solid	solid	15	10
3	solid	solid	15	20
4	solid	solid	25	5
5	solid	solid	25	10
6	solid	solid	25	20
7	solid	solid	35	5
8	solid	solid	35	10
9	solid	solid	35	20
10	mesh disk	335	35	0
11	mesh disk	335	35	10
12	mesh disk	335	35	20
13	mesh disk	450	35	0
14	mesh disk	450	35	10
15	mesh disk	450	35	20
16	mesh disk	800	35	0
17	mesh disk	800	35	10
18	mesh disk	800	35	20
19	mesh disk	1250	35	0
20	mesh disk	1250	35	10
21	mesh disk	1250	35	20
22	mesh disk	140	35	0
23	mesh disk	140	35	10
24	mesh disk	140	35	20
25	mesh disk	200	35	0
26	mesh disk	200	35	10
27	mesh disk	200	35	10
28	solid	solid	25	2.5
29	mesh basket	140	35	10
30	mesh basket	200	35	10
25B	flush mesh basket	200	35	0
31	flush mesh basket	250	35	0
32	flush mesh basket	300	35	0
33	flush mesh basket	335	35	0

TABLE 5.1

Dust types to be used

Dust codes	Estimated aerodynamic diameter (μm)
F1200	6.0*
F800	12.0*
F500	26.0*
F360	46.0*
F280	74.0*
F240	89.5*
220E	120
180E	173
120E	228
90E	302

* Mark et al (1985)

TABLE 6.1

Experimental design allocating shield numbers to be used at each position on the manikin

F240 dust

run no.	expt no.	sampler position on manikin						sampler position on manikin					
		1	2	3	4	5	6	1	2	3	4	5	6
1	004	1	2	3	4	5	6	6	4	5	3	1	2
2	005	8	9	7	14	15	13	13	14	15	7	8	9
3	006	18	16	17	21	19	20	20	21	19	17	18	16
4	007	10	11	12	0	0	0	0	0	0	12	10	11
5	018	22	23	24	25	26	27	27	25	26	24	22	23

E90 Dust

run no.	expt no.	sampler position on manikin						sampler position on manikin					
		1	2	3	4	5	6	1	2	3	4	5	6
1	009	1	2	3	4	5	6	6	4	5	3	1	2
2	010	8	9	7	14	15	13	13	14	15	7	8	9
3	011	18	16	17	21	19	20	20	21	19	17	18	16
4	012	10	11	12	0	0	0	0	0	0	12	10	11
5	014	22	23	24	25	26	27	27	25	26	24	22	23
6	020	22	25	28	0	0	0	0	0	0	-	-	28

Notes 1. Shield number "0" refers to an unmodified IOM sampler

TABLE 6.2(A)

Aspiration efficiencies (E) of the manikin and the IOM sampler shown along with the standard deviation (sd) and the number of measurements (n) for nominal particle aerodynamic diameter 300 µm

	E	sd	n
manikin	0.12	0.03	12
IOM sampler	1.55	0.23	27
inhalable definition	nd	nd	nd

nd not defined

TABLE 6.2(B)

Aspiration efficiencies (E) of the manikin and the IOM sampler shown along with the standard deviation (sd) and the number of measurements (n) for nominal particle aerodynamic diameter 90 µm

	E	sd	n
manikin	0.28	0.06	6
IOM sampler	0.56	0.10	9
inhalable definition	0.50	nd	nd

nd not defined

TABLE 6.3

Aspiration efficiencies (E) of the IOM sampler with shields 29 and 30 shown along with the standard deviation (sd) and the number of measurements (n)

shield	D nominal (µm)	E	sd	n
29	90	0.12	0.03	6
29	300	0.03	0.02	6
30	90	0.44	0.07	6
30	300	0.14	0.03	6

TABLE 7.1

Sampling configurations tested

Experimental Group	U_0 (ms^{-1})	Configurations
1	1	IOM sampler unmodified
		IOM sampler with shield 25B
		IOM sampler with shield 30
		Standard 7-hole sampler
		Cassette 7-hole sampler
		Cassette 7-hole sampler with shield 30
2	3	IOM sampler unmodified
		IOM sampler with shield 25B
		IOM sampler with shield 30
		Standard 7-hole sampler
		Cassette 7-hole sampler
		Cassette 7-hole sampler with shield 30
3	1	IOM sampler unmodified
		IOM sampler with shield 25B
		IOM sampler with shield 31
		IOM sampler with shield 32
		IOM sampler with shield 33
		IOM sampler unmodified

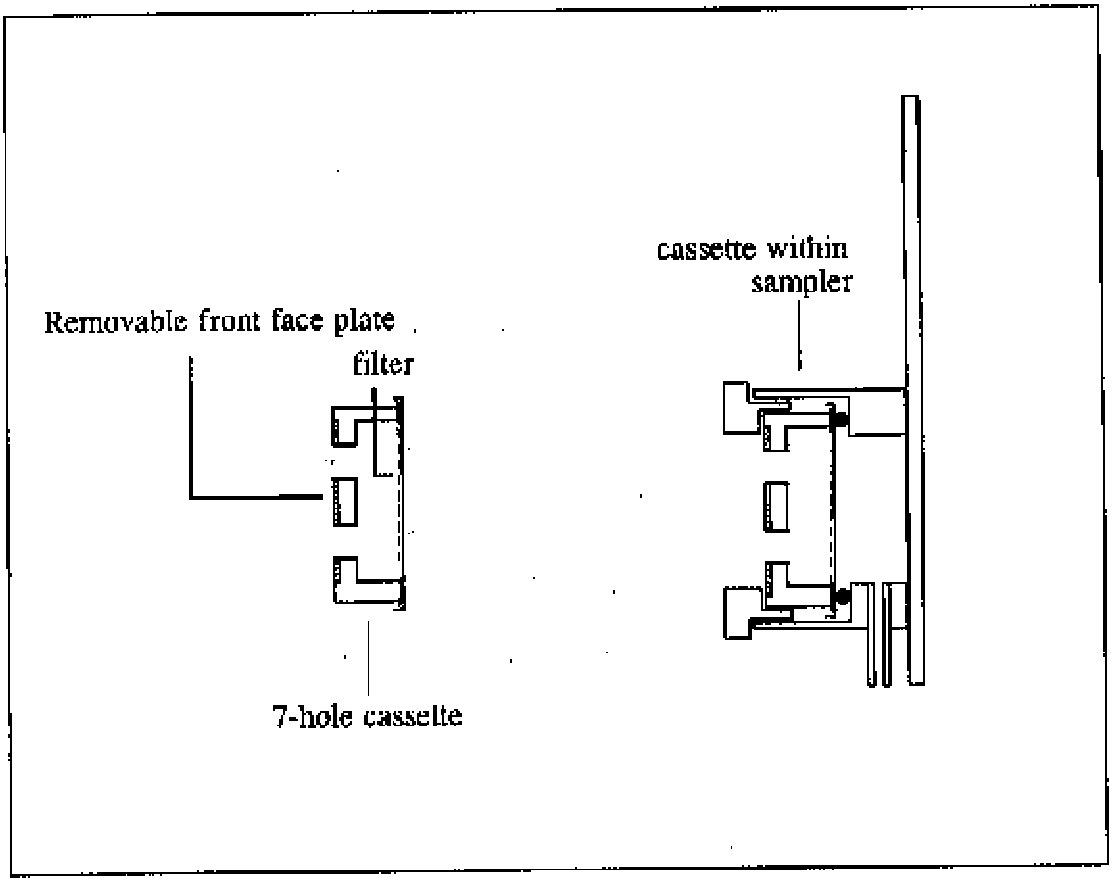

Figure 3.1. **Cassette system for the 7-hole sampler**

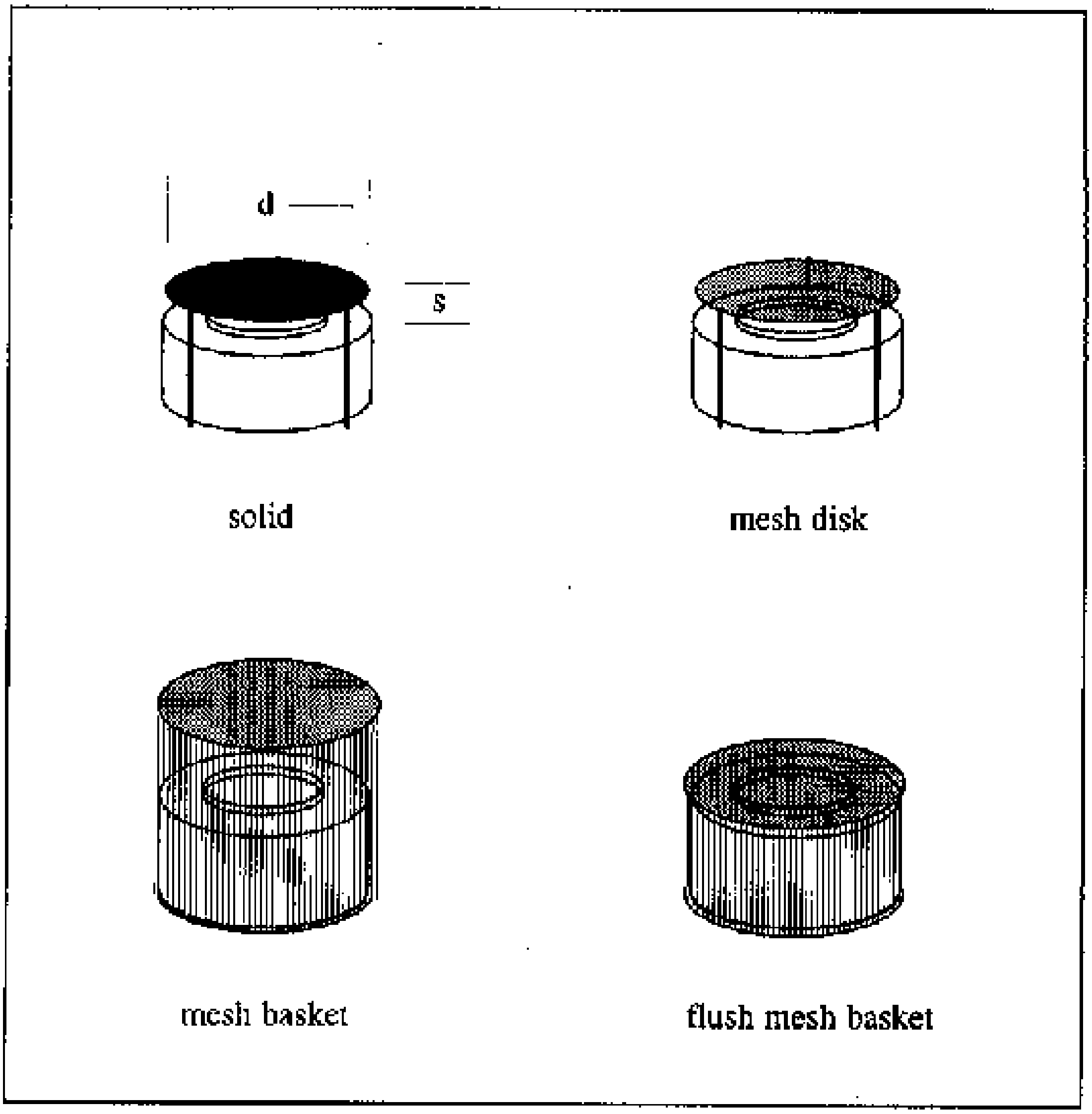

Figure 4.1 **The four basic shield designs shown along with and IOM sampler and indicating shield diameter (d) and shield-to-sampler spacing (s)**

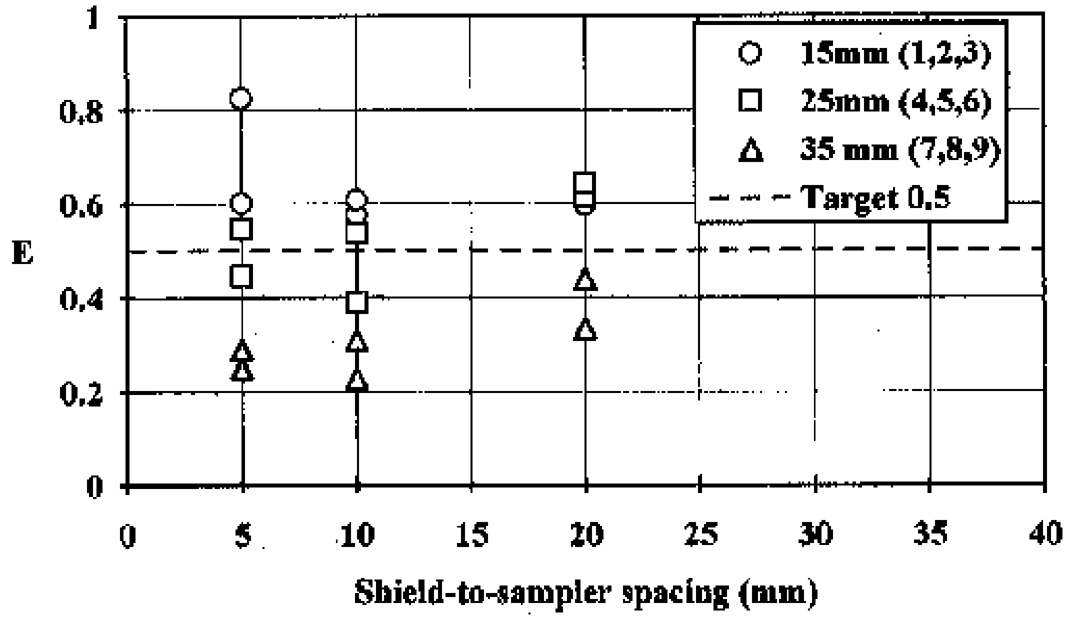

Figure 6.1 (A) Sampling efficiency of all solid shield configurations, showing the shield diameter in mm and the shield number in parenthesis, as a function of spacing, for 90 μm aerosol.

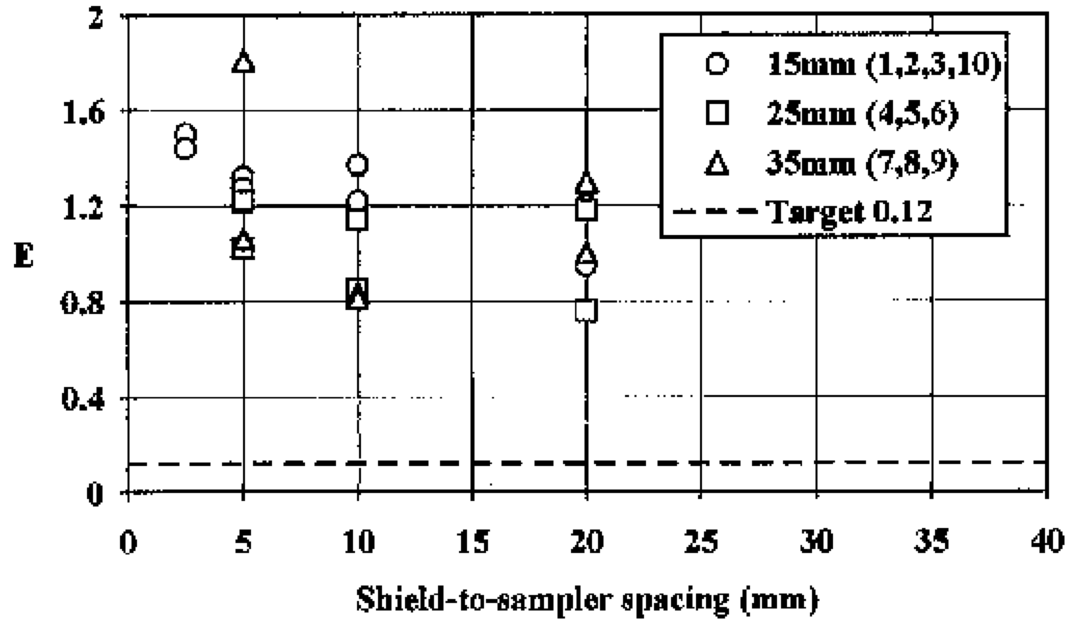

Figure 6.1 (B) Sampling efficiency of all solid shield configuration, showing the shield diameter in mm and the shield number in parenthesis, as a function of spacing, for 300 μm aerosol.

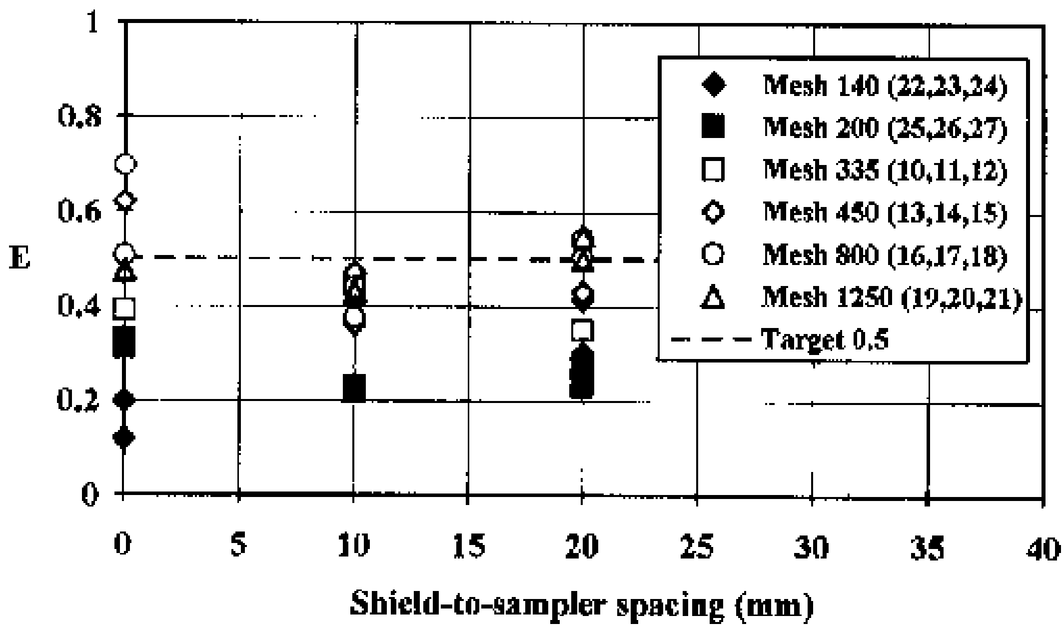

Figure 6.2 (A) Sampling efficiency of 35 mm diameter mesh shields, showing the mesh size and the shield number in parenthesis, as a function of spacing, for 90 μm aerosol.

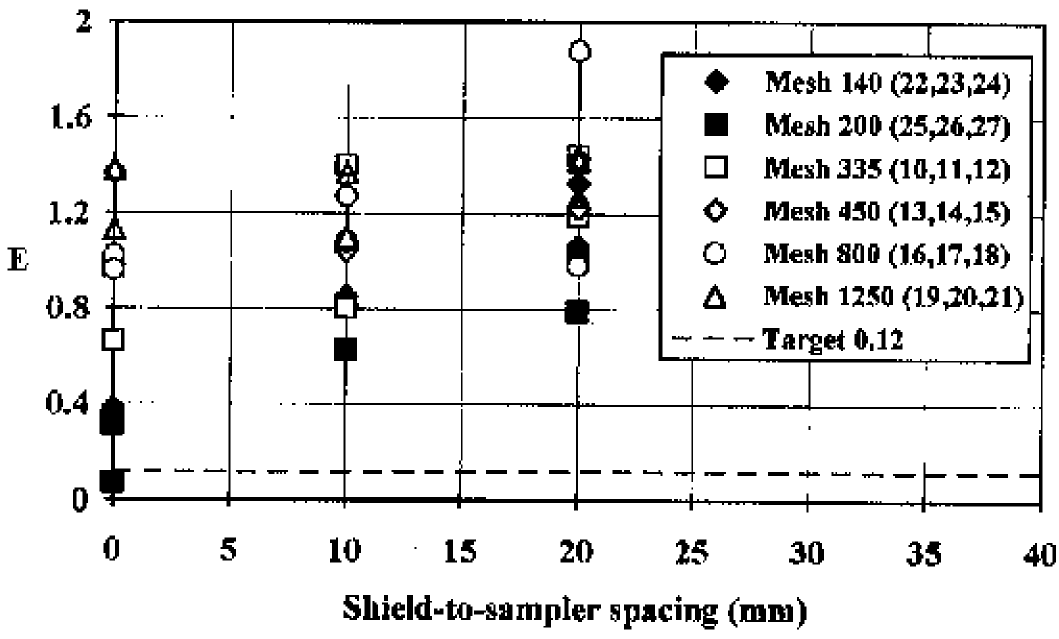

Figure 6.2 (B) Sampling efficiency of 35 mm diameter mesh shields, showing the mesh size and the shield number in parenthesis, as a function of spacing, for 300 μm aerosol.

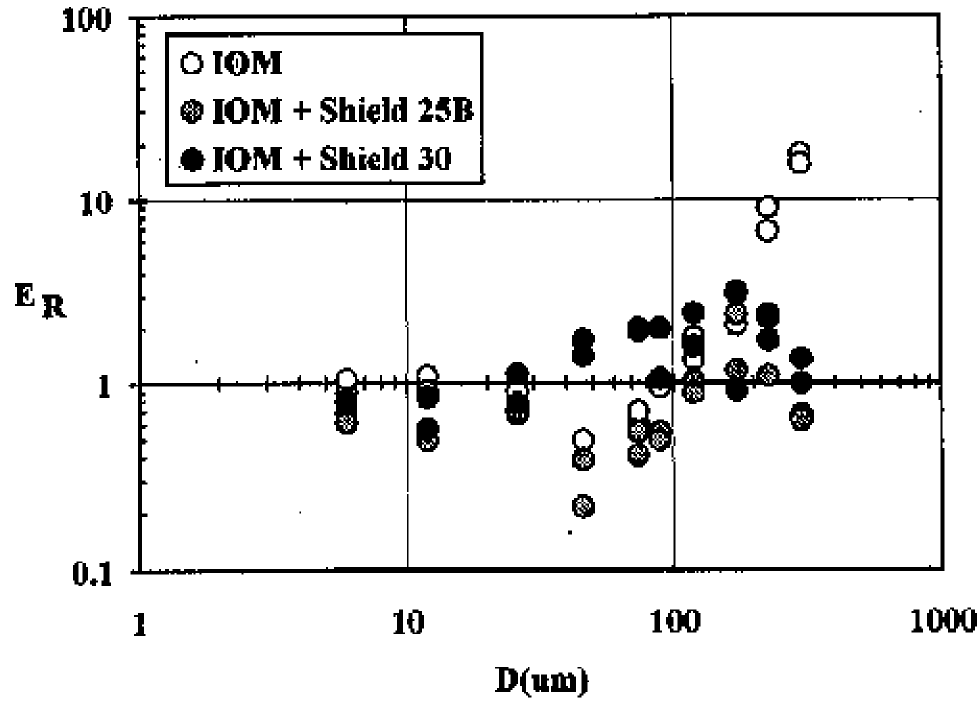

Figure 7.1 A Relative aspiration efficiency at $1ms^{-1}$ (as a fraction of the manikin aspiration efficiency) for the unmodified IOM sampler and the IOM sampler with two shield designs

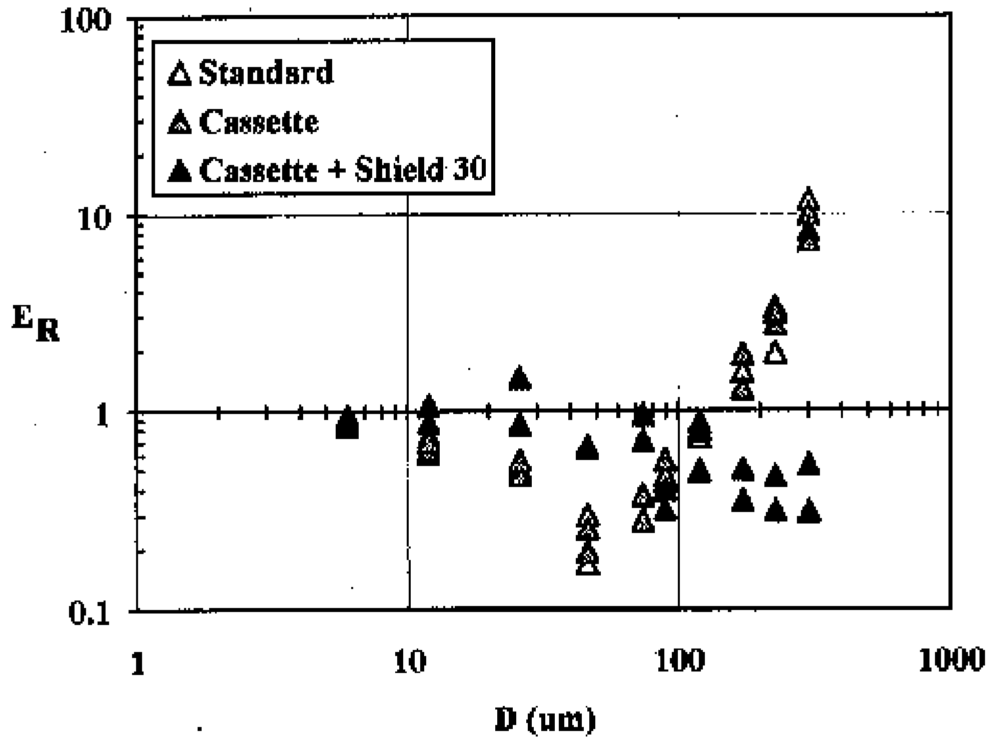

Figure 7.1 B Relative aspiration efficiency at 1ms-1 (as a fraction of the manikin aspiration efficiency) for the unmodified 7-hole sampler, a 7 hole sampler with a cassette and a 7-hole sampler with a cassette and a shield.

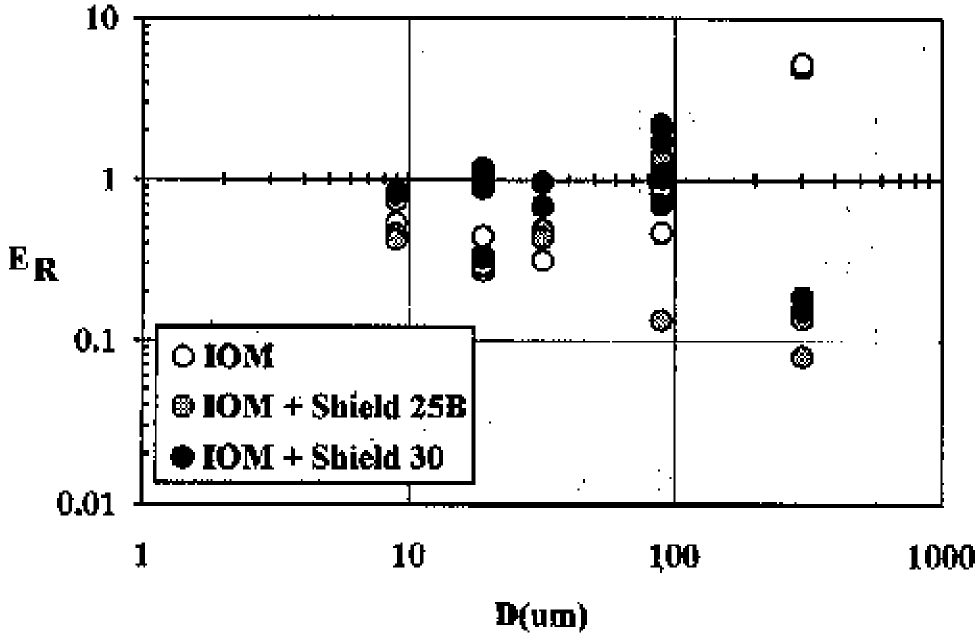

Figure 7.2 A Relative aspiration efficiency (E_R) at $3ms^{-1}$ (as a fraction of manikin aspiration efficiency) for the IOM sampler and the IOM sampler with two shield designs

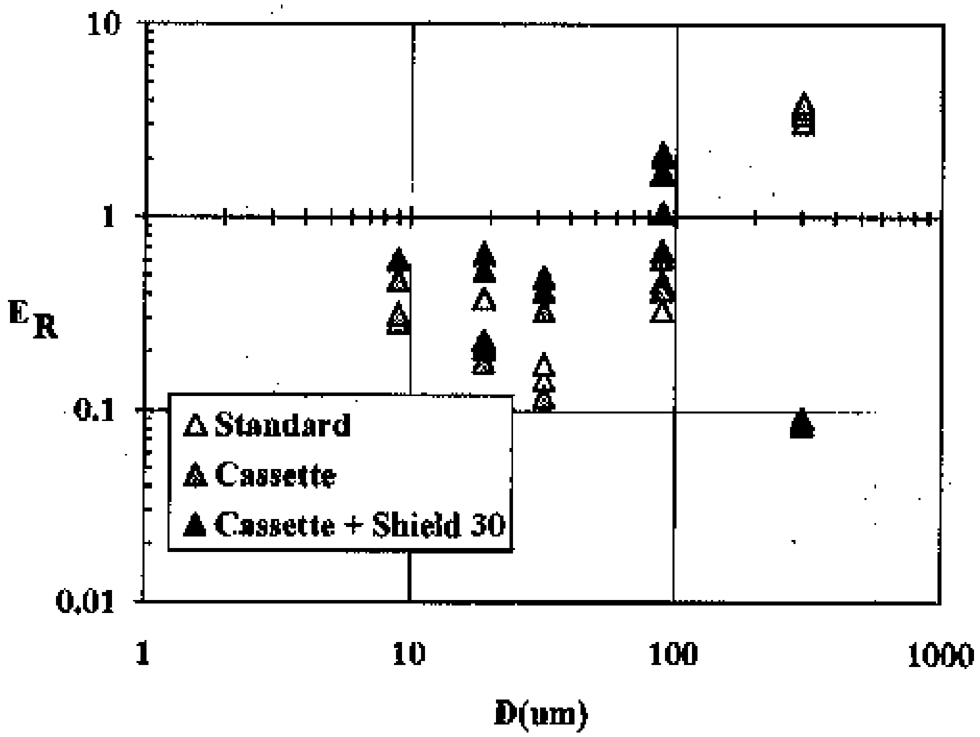

Figure 7.2 B Relative aspiration efficiency (E_R) at $3ms^{-1}$ (as a fraction of the manikin aspiration efficiency) for the unmodified 7-hole sampler, a 7 hole sampler with a cassette and a 7-hole sampler with a cassette and a shield.

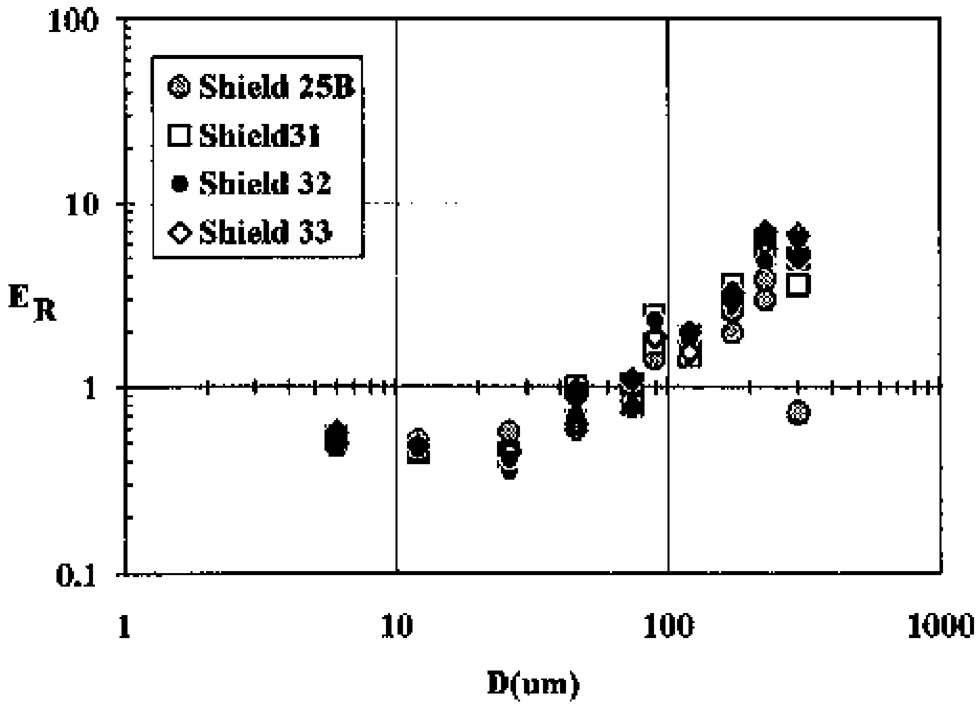

Figure 7.3 A Relative aspiration efficiency (E_R) at $1ms^{-1}$ (as a fraction of manikin aspiration efficiency) for the IOM sampler with four shield designs

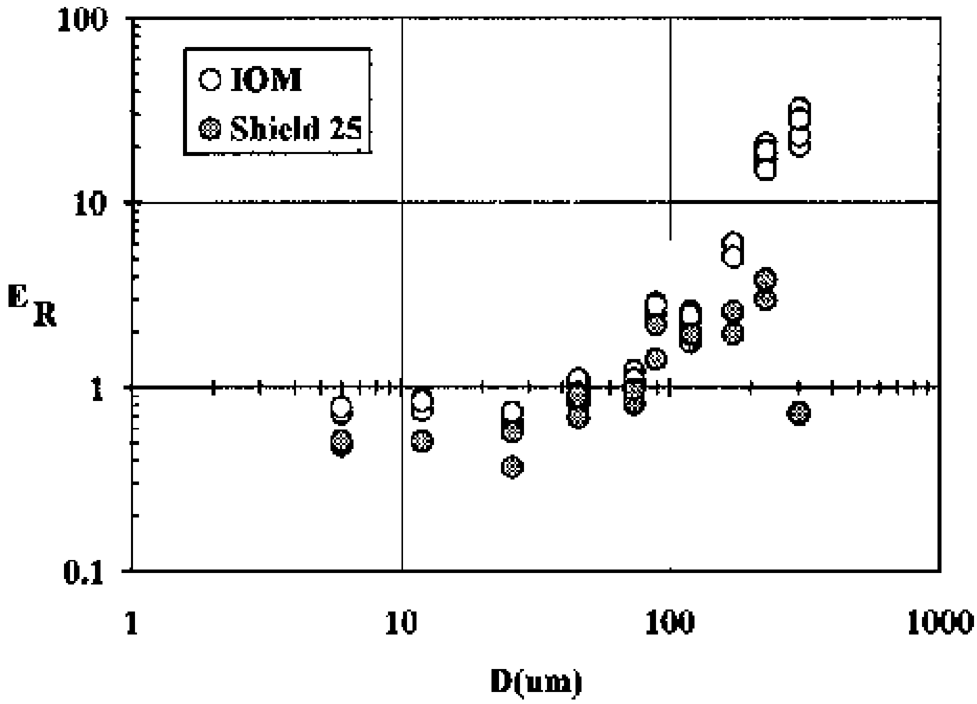

Figure 7.3 B Relative aspiration efficiency (E_R) at $1ms^{-1}$ (as a fraction of manikin aspiration efficiency) for the IOM sampler and the IOM sampler with shield 25B

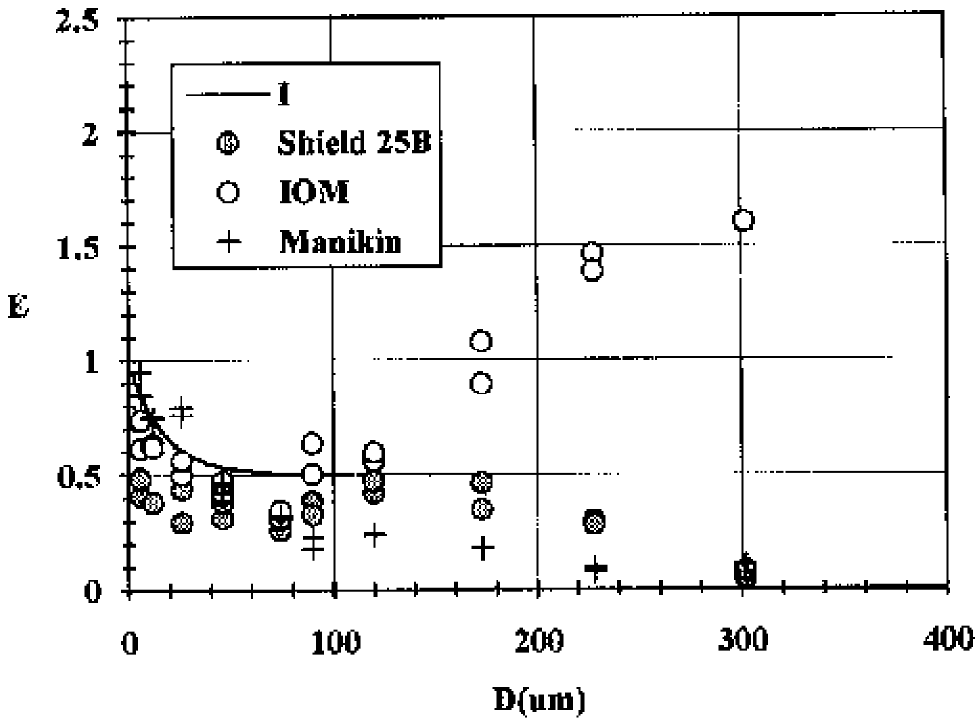

Figure 7.4(A) Aspiration efficiencies of the manikin, IOM sampler and IOM sampler with shield 25B as a function of particle aerodynamic diameter.

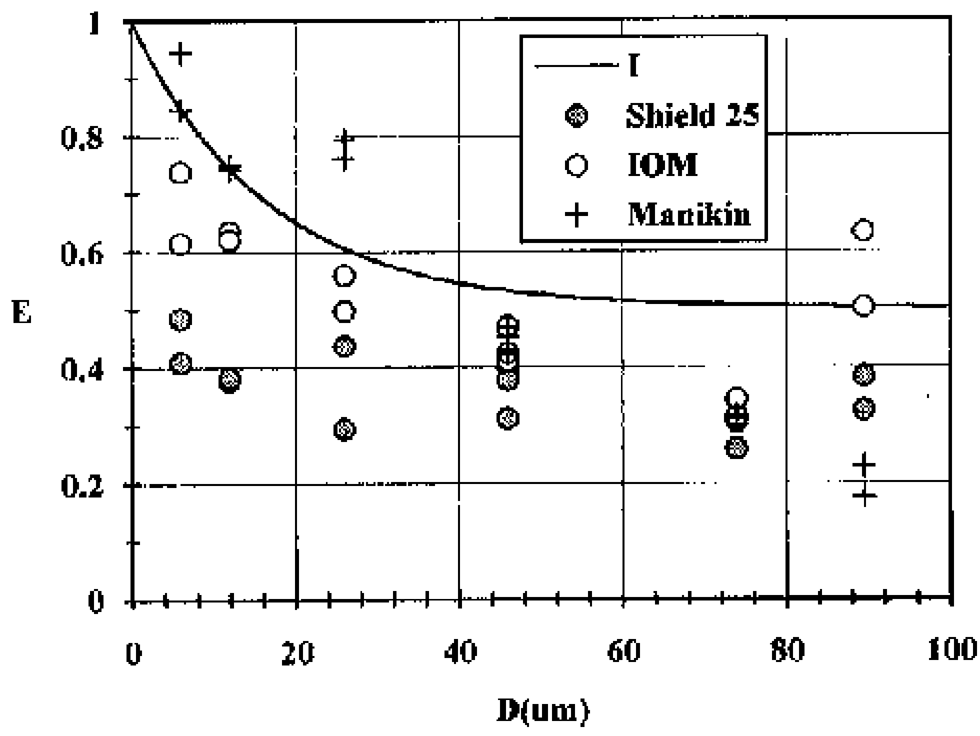

Figure 7.4(B) Aspiration efficiencies of the manikin, IOM sampler and IOM sampler with shield 25B as a function of particle aerodynamic diameter.

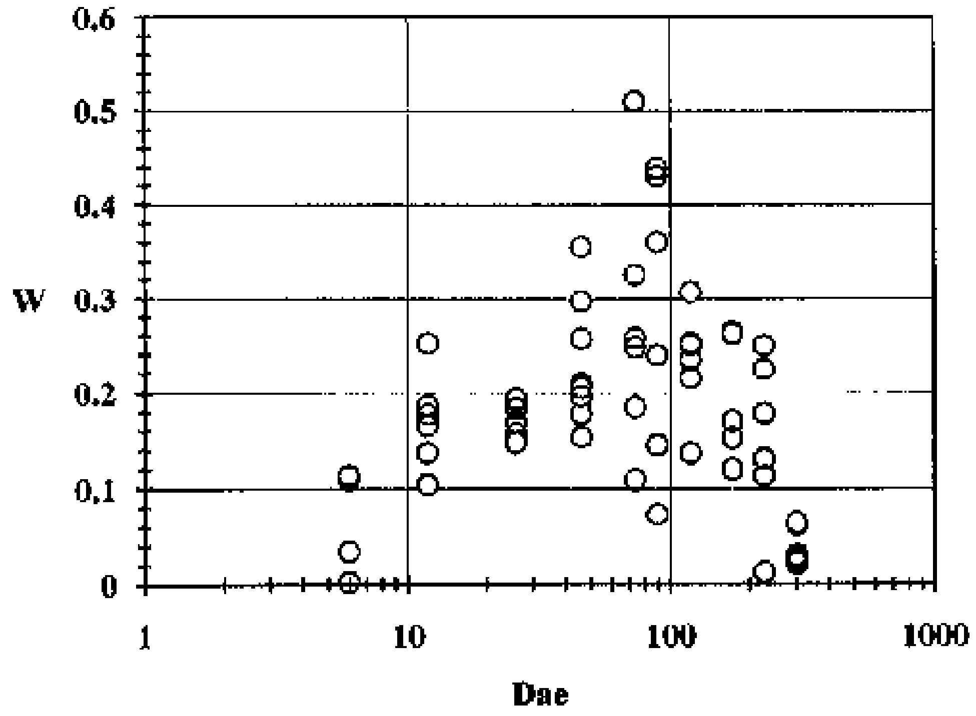

Figure 8.1 Fractional wall loss for all IOM type samplers

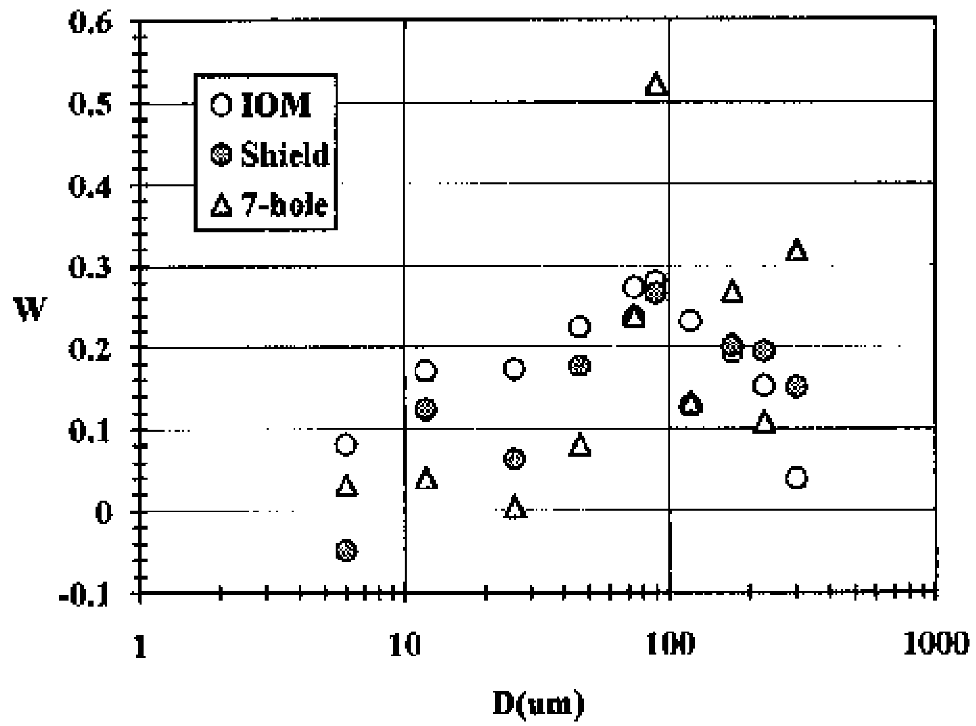

Figure 8.2 Fractional wall loss (W) for IOM, shielded IOM and 7-hole samplers

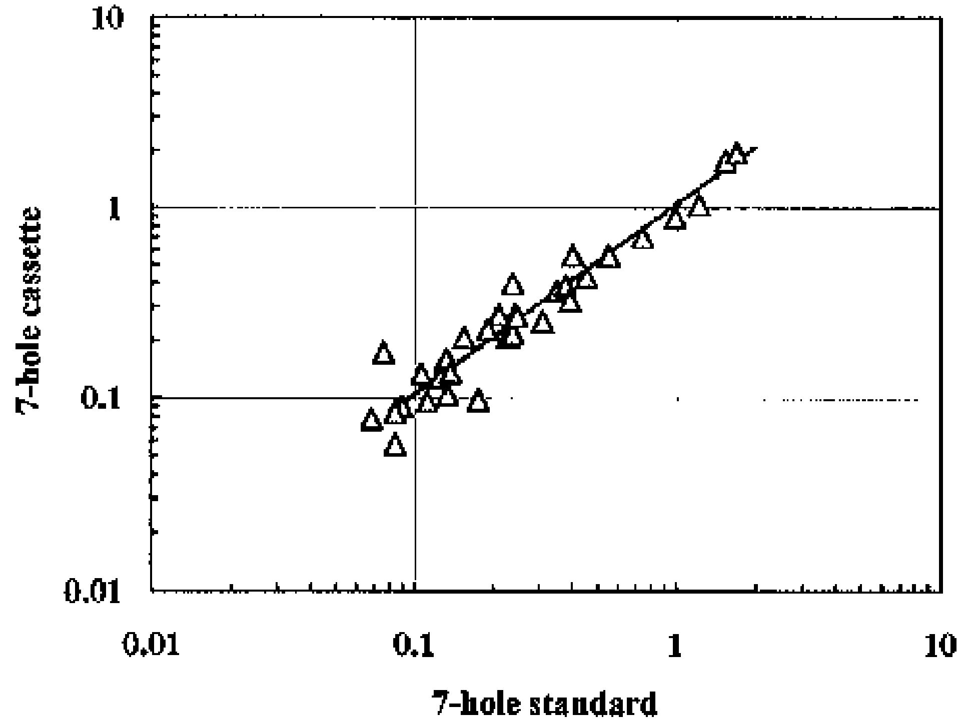

Figure 8.3 Aspiration efficiencies of the 7-hole standard and 7-hole cassette samplers showing best-fit line

APPENDIX 1

FULL RESULTS

TABLE A1.1

Efficiency results, multishield trials, nominal 100μm (Section 6, Preliminary Studies)

Shield Number	Material solid / mesh size	Diameter (mm)	Spacing (mm)	Position	E
1	solid	15	5	1	0.824
1	solid	15	5	5	0.600
2	solid	15	10	2	0.573
2	solid	15	10	6	0.607
3	solid	15	20	3	0.597
3	solid	15	20	4	0.619
4	solid	25	5	4	0.543
4	solid	25	5	2	0.444
5	solid	25	10	5	0.390
5	solid	25	10	3	0.536
6	solid	25	20	6	0.614
6	solid	25	20	1	0.641
7	solid	35	5	3	0.248
7	solid	35	5	4	0.289
8	solid	35	10	1	0.227
8	solid	35	10	5	0.309
9	solid	35	20	2	0.335
9	solid	35	20	6	0.439
10	335	35	0	1	0.390
10	335	35	0	-	-
11	335	35	10	2	0.443
11	335	35	10	-	-
12	335	35	20	3	0.348
12	335	35	20	-	-
13	450	35	0	6	0.621
13	450	35	0	1	0.506
14	450	35	10	4	0.472
14	450	35	10	2	0.362
15	450	35	20	5	0.415
15	450	35	20	3	0.430
16	800	35	0	2	0.697
16	800	35	0	6	0.507
17	800	35	10	3	0.377
17	800	35	10	4	0.441
18	800	35	20	1	0.504
18	800	35	20	5	0.543

TABLE A1.1 (cont.)

Efficiency results, multishield trials, nominal 100µm (Section 6, Preliminary Studies)

Shield Number	Material solid / mesh size	Diameter (mm)	Spacing (mm)	Position	E
19	1250	35	0	5	0.472
19	1250	35	0	3	0.476
20	1250	35	10	6	0.434
20	1250	35	10	1	0.428
21	1250	35	20	4	0.549
21	1250	35	20	2	0.493
22	140	35	0	1	0.20
22	140	35	0	4	0.12
23	140	35	10	2	0.22
23	140	35	10	5	0.22
24	140	35	20	3	0.35
24	140	35	20	6	0.30
25	200	35	0	4	0.33
25	200	35	0	1	0.31
26	200	35	10	5	0.23
26	200	35	10	2	0.22
27	200	35	20	6	0.23
27	200	35	20	3	0.27
29	140	35	0	1	0.14
29	140	35	0	2	0.14
29	140	35	0	3	0.17
29	140	35	0	4	0.10
29	140	35	0	5	0.07
29	140	35	0	6	0.08
30	200	35	0	4	0.48
30	200	35	0	5	0.45
30	200	35	0	6	0.36
30	200	35	0	1	0.44
30	200	35	0	2	0.38
30	200	35	0	3	0.55

TABLE A1.2

Efficiency results, multishield trials, nominal 300μm
(Section 6, Preliminary Studies)

Shield Number	Material solid / mesh size	Diameter (mm)	Spacing (mm)	Position	E
1	solid	15	5	1	1.32
1	solid	15	5	5	1.27
2	solid	15	10	2	1.37
2	solid	15	10	6	1.22
3	solid	15	20	3	1.20
3	solid	15	20	4	0.95
4	solid	25	5	4	1.02
4	solid	25	5	2	1.22
5	solid	25	10	5	0.85
5	solid	25	10	3	1.14
6	solid	25	20	6	0.76
6	solid	25	20	1	1.18
7	solid	35	5	3	1.81
7	solid	35	5	4	1.06
8	solid	35	10	1	0.83
8	solid	35	10	5	0.81
9	solid	35	20	2	1.30
9	solid	35	20	6	1.00
10	335	35	0	1	0.97
10	335	35	0	5	0.66
11	335	35	10	2	1.40
11	335	35	10	6	0.80
12	335	35	20	3	1.44
12	335	35	20	4	1.19
13	450	35	0	6	1.37
13	450	35	0	1	0.98
14	450	35	10	4	1.04
14	450	35	10	2	1.28
15	450	35	20	5	1.43
15	450	35	20	3	1.22
16	800	35	0	2	1.02
16	800	35	0	6	0.96
17	800	35	10	3	1.27
17	800	35	10	4	1.08
18	800	35	20	1	1.88
18	800	35	20	5	0.98

TABLE A1.2 (cont.)

Efficiency results, multishield trials, nominal 300µm (Section 6, Preliminary Studies)

Shield Number	Material solid / mesh size	Diameter (mm)	Spacing (mm)	Position	E
19	1250	35	0	5	1.13
19	1250	35	0	3	1.38
20	1250	35	10	6	1.10
20	1250	35	10	1	1.37
21	1250	35	20	4	1.42
21	1250	35	20	2	1.27
22	140	35	0	2	0.38
22	140	35	0	1	0.37
23	140	35	10	5	0.85
23	140	35	10	3	0.81
24	140	35	20	3	1.33
24	140	35	20	4	1.06
25	200	35	0	1	0.31
25	200	35	0	5	0.07
26	200	35	10	4	0.80
26	200	35	10	6	0.62
27	200	35	20	6	1.00
27	200	35	20	4	0.79
22	140	35	0	4	-
22	140	35	0	1	0.04
25	200	35	0	5	-
25	200	35	0	2	0.10
28	solid	25	2.5	6	1.5
28	solid	25	2.5	3	1.44
29	140	35	0	1	0.02
29	140	35	0	2	0.05
29	140	35	0	3	0.04
29	140	35	0	4	0.01
29	140	35	0	5	0.02
29	140	35	0	6	0.01
30	200	35	0	4	0.17
30	200	35	0	5	0.19
30	200	35	0	6	0.11
30	200	35	0	1	0.15
30	200	35	0	2	0.14
30	200	35	0	3	0.13

TABLE A1.3

Efficiency results for IOM samplers
(Section 6, Preliminary Studies)

Position	d nominal µm	flow-rate $lmin^{-1}$	E_s
1	100	2	0.63
2	100	2	0.63
3	100	2	0.47
4	100	2	0.69
5	100	2	0.49
6	100	2	0.46
4	100	2	0.58
5	100	2	0.65
6	100	2	0.42
1	300	2	1.61
2	300	2	1.63
3	300	2	1.51
4	300	2	1.65
5	300	2	1.50
6	300	2	1.72
4	300	2	1.41
5	300	2	1.46
6	300	2	1.48
1	300	2	2.09
2	300	2	2.03
3	300	2	1.53
1	300	2	1.32
2	300	2	2.10
3	300	2	1.80
4	300	2	1.65
5	300	2	1.49
6	300	2	1.50
1	300	0	1.50
2	300	0	1.45
3	300	0	1.40
1	300	2	1.16
2	300	2	1.40
3	300	2	1.45
4	300	2	1.55
5	300	2	1.38
6	300	2	1.20

TABLE A1.4

Sampling Efficiency for IOM manikin
(Section 6, Preliminary Studies)

D nominal µm	E
300	0.10
300	0.11
300	0.12
300	0.18
300	0.12
300	0.09
100	0.31
100	0.19
100	0.31
100	0.30
100	0.33
100	0.23
300	0.09
300	0.13

TABLE A1.5

Sampling Efficiency for 7-hole
(Section 6, Preliminary Studies)

Position	D nominal µm	flow-rate $l min^{-1}$	E_7
1	300	2	0.78
2	300	2	0.52
3	300	2	0.48

TABLE A1.6

Aspiration efficiencies for IOM, shielded IOM (E_{25} and E_{30}), standard 7-hole (E_7), cassette 7 hole (E_{7c}) and shielded cassette 7-hole (E_{7c30}) samplers and the manikin (E_b) at nominal 1 ms^{-1}

(Section 7, Group 1 Results)

D	Run	E_{IOM}	E_{25} IOM	E_{30} IOM	E_7	E_{7c}	E_{7c30}	R_1	R_2	E_b
6	30a	0.539	0.420	0.487	0.548	0.558	0.579	0.077	0.018	0.608
6	32b	0.699	0.409	0.522	0.555	0.558	0.556	0.077	0.024	0.666
12	34a	0.628	0.326	0.480	0.351	0.363	0.495	0.324	0.034	0.572
12	34b	0.563	0.303	0.348	0.454	0.430	0.658	0.282	0.031	0.615
26	33a	0.297	0.335	0.490	0.226	0.208	0.640	0.582	0.213	0.437
26	33b	0.439	0.344	0.380	0.242	0.270	0.409	0.471	0.141	0.483
46	30a	0.186	0.082	0.643	0.112	0.096	0.246	0.544	0.360	0.376
46	30b	0.199	0.156	0.563	0.068	0.078	0.266	0.590	0.484	0.402
74	35a	0.202	0.137	0.659	0.125	0.127	0.236	0.479	0.663	0.334
74	35b	0.224	0.175	0.615	0.089	0.090	0.306	0.496	0.761	0.320
89.5	28a	0.250	0.130	0.470	0.106	0.133	0.076	0.522	0.669	0.238
89.5	28b	0.267	0.139	0.295	0.132	0.160	0.114	0.726	1.030	0.281
120	36a	0.484	0.279	0.655	0.238	0.216	0.136	0.558	0.852	0.272
120	36b	0.346	0.229	0.412	0.191	0.227	0.210	0.538	0.946	0.260
173	31a	0.410	0.234	0.627	0.379	0.388	0.101	0.567	1.085	0.199
173	31b	0.598	0.461	0.178	0.309	0.252	0.069	0.746	0.604	0.195
228	37a	1.850	0.459	0.482	0.401	0.560	0.095	0.538	0.216	0.204
228	37b	1.493	0.243	0.380	0.744	0.700	0.070	0.706	1.985	0.223
302	29a	2.165	0.082	0.122	0.991	0.887	0.065	0.283	0.383	0.122
302	29b	1.614	0.065	0.140	1.218	1.033	0.032	0.312	0.846	0.103

TABLE A1.7

Aspiration efficiencies for IOM, shielded IOM (E_{25} and E_{30}), standard 7-hole (E_7), cassette 7 hole (E_{7c}) and shielded cassette 7-hole (E_{7c30}) samplers and the manikin (E_b) at nominal 3 ms^{-1}

(Section 7, Group 2 Results)

D	Run	E_{IOM}	E_{25} IOM	E_{30} IOM	E_7	E_{7c}	E_{7c30}	R_1	R_2	E_b
9	44a	0.450	0.384	0.683	0.238	0.397	0.511	0.194	0.056	0.838
9	44b	0.626	0.360	0.717	0.246	0.269	0.511	0.131	0.069	0.851
19	45a	0.157	0.195	0.188	0.134	0.104	0.122	0.366	0.312	0.582
19	45b	0.205	0.461	0.542	0.175	0.098	0.301	0.346	0.181	0.461
19	45c	0.171	0.520	0.544	0.137	0.135	0.313	0.272	0.139	0.590
32	39a	0.257	0.257	0.502	0.076	0.172	0.259	0.272	0.369	0.525
32	39b	0.153	0.210	0.332	0.084	0.057	0.203	0.673	0.541	0.486
89.5	43a	0.155	0.242	0.392	0.393	0.325	0.403	0.296	0.485	0.188
89.5	43b	0.438	0.278	0.343	0.084	0.084	0.335	0.575	0.461	0.200
89.5	43c	0.298	0.085	0.440	0.210	0.272	0.426	0.311	0.517	0.635
89.5	43d	0.299	0.338	0.362	0.155	0.207	0.352	0.281	0.622	0.333
302	42a	2.414	0.067	0.092	1.541	1.778	0.045	0.119	0.354	0.490
302	42b	2.616	0.040	0.078	1.698	1.951	0.042	0.017	0.317	0.498

TABLE A1.8

Aspiration efficiencies for IOM, shielded IOM (E_{25} $E_{31}E_{32}$and E_{33}) samplers and the manikin (E_b) at indicated windspeed U ms^{-1}

(Section 7, Group 3 Results)

D µm	Run	E_{IOM}	E_{25} IOM	E_{31} IOM	E_{32} IOM	E_{IOM}	E_{33} IOM	E_b	U ms^{-1}
6	52a	0.622	0.407	0.440	0.422	0.613	0.420	0.845	1.011
6	52b	0.722	0.483	0.512	0.557	0.737	0.545	0.945	***
12	53a	0.559	0.377	0.330	0.352	0.634	0.363	0.749	0.944
12	53b	0.641	0.381	0.342	0.365	0.619	0.359	0.742	0.906
26	54a	0.514	0.292	0.347	0.282	0.496	0.357	0.793	1.011
26	54b	0.476	0.436	0.307	0.311	0.558	0.346	0.759	1.004
46	47a	0.374	0.404	0.361	0.372	0.421	0.418	0.468	***
46	47b	0.369	0.402	0.333	0.368	0.410	0.415	0.428	***
46	49a	0.378	0.311	0.363	0.317	0.424	0.288	0.451	1.009
46	49b	0.423	0.378	0.424	0.298	0.469	0.246	0.422	1.038
74	55a	0.347	0.258	0.253	0.337	0.314	0.345	0.316	1.053
74	55b	0.384	0.305	0.325	0.243	0.344	0.243	0.311	1.031
89.5	50a	0.492	0.383	0.424	0.380	0.501	0.324	0.175	1.021
89.5	50b	0.568	0.325	0.391	0.525	0.632	0.428	0.228	1.021
120	56a	0.481	0.421	0.350	0.442	0.557	0.475	0.239	1.106
120	56b	0.623	0.470	0.465	0.494	0.591	0.377	0.243	1.096
173	57a	***	0.463	0.644	0.594	1.075	0.529	0.180	1.107
173	57b	0.887	0.346	0.534	0.511	0.892	0.578	0.177	1.052
228	58a	1.594	0.295	0.484	0.540	1.461	0.471	0.077	1.019
228	58b	1.550	0.280	0.492	0.455	1.387	0.659	0.094	1.066
302	51a	2.237	0.050	0.346	0.444	1.600	0.473	0.07	1.002
302	51b	2.138	0.078	0.379	0.523	2.986	0.537	0.106	1.014

APPENDIX 2

INHALABILITY AND INHALABLE SAMPLING, FURTHER EXPERIMENTS

In addition to the main focus of the work described, two further issues arose in relation to inhalability and inhalable sampling. Specifically these were; (i) the effect which variations in windspeed can have on experiments to measure the aspiration efficiency of samplers and manikins, and (ii) differences arising from continuous or stepped rotation in such experiments. Since these topics were outside the scope of the project, neither was investigated by rigorous experiment, however, sufficient information was gained in each case to illustrate possible effects. A description of the work carried out and the results obtained is now given.

A2.1 The importance of windspeed

A2.1.1 Introduction

As part of the work programme in this project, a series of measurements were carried out of the aspiration efficiencies of both the manikin and of IOM samplers. This was done in conjunction with a series of measurements of the aspiration efficiencies of modified IOM samplers fitted with shields to exclude large particles. Examination of the data obtained for the unmodified samplers showed that aspiration efficiency was consistently lower than that expected on the basis of historical results. Although more recent work carried out elsewhere also showed low efficiency values at most sizes when compared with the inhalable convention, the effect in the current data was much more marked.

Closer inspection of the data for this project and that gained in earlier work (Aitken et al 1996) showed that for particle sizes F240 and F360 (the sizes for which there was the most data) there were further inconsistencies between older and more recent data. These are summarised in Table 2.1.1. Taken together, the results appear to show a decrease in the measured aspiration efficiencies for both the manikin and the samplers between 1994 and 1995.

The test system was modified substantially in early 1994, in particular with the introduction of a swinging arm dust dispersion system and a reciprocating manikin. However, these changes were prior to all of the above experiments and could not account for the differences observed.

A number of possible reasons for this difference were suggested including that small differences in the relative position of the manikin and scale probes were causing the problem. However, this was investigated in a set of runs in which the manikin was moved and was subsequently discounted. Other suggestions which were considered and discounted included (i) that the manikin was not rotating through a full 360° (observation showed that it was) and (ii) that the dust size was changed because of agglomeration (data obtained by laser diffraction showed that it wasn't).

A2.1.2. Measurement of windspeed

The method used previously to measure windspeed was to use a hot bead anemometer and to scan by hand around the general vicinity of the sampling area in the wind tunnel and to read the mean windspeed of the gauge. This was consistent with practice in the 1980s and was considered sufficient since it was not felt that windspeed would have great influence on the result.

On checking the details of the various experimental logs it was noted that the procedure for measuring the windspeed in the wind tunnel had modified to bring the methods in line with the quality system operating internally, immediately prior to the onset of the low results.

The "improvement" made at this time was to calibrate the anemometer using an appropriate method detailed in the quality system. Using the calibration curve derived, the windspeed was set with the anemometer (but still by hand held scanning in the sampling area).

Following the concerns about the magnitude of the results obtained, the calibration of the hot bead anemometer was redone and this time yielded a markedly different calibration curve. The second set of calibration data was reproducible, whereas the first was not, indicating the possibility that the first had been in error. If this was the case, the error was such that the windspeed previously reported as 1 ms^{-1} was in fact 1.3 ms^{-1}.

A2.1.3 The effect of windspeed variations on aspiration efficiency

A small set of experiments was carried out to determine whether windspeed differences of this magnitude could account for differences in the measured aspiration efficiencies of the manikin and of the IOM samplers. The set comprises three experiments in which the isokinetic samplers were set up for flows appropriate to a windspeed of 1 ms^{-1} but in which the actual windspeed was set (using the hot bead anemometer and current calibration) to 0.8, 1.0 and 1.3 ms^{-1} respectively. The dust size used was F360 (nominal aerodynamic diameter 46 µm). The results are given in Table A2.1.2 below.

The results show a very clear relationship between the actual velocity and the magnitude of the aspiration efficiencies with aspiration efficiency decreasing as the windspeed increased. This result is entirely consistent, qualitatively and quantitatively with a scenario in which, for the 1995 data the actual windspeed was 1.3 ms^{-1}, resulting in relatively low values of aspiration efficiency and for the 1994 data, the actual windspeed was 1.0 ms^{-1} resulting in aspiration efficiencies which were consistent with historical data.

If this is the case, are there mechanisms which would explain why windspeed variations of the sort described cause such large differences in aspiration efficiency?

In our test system the efficiency of a sampler Es may be calculated from the relationship

$$E_s = \frac{m_s}{F_s} \times \frac{\overline{F_k}}{m_k} \times R \qquad \text{(A2.1.1)}$$

where F_s is the sampler flow rate and m_s, the mass collected by the sampler. F_k and m_k are the flow rate and mass collected by the isokinetic probes used to measure concentration and R is the ratio of the scale isokinetics in the two parts of the experiment. A number of models are available which may be used to estimate the anisokinetic performance of sharp edged probes. The most commonly accepted is that of Belyaev and Levin (1972). Using this model it is estimated that the mass collected by a sharp edged probe of the dimensions used where the ambient velocity is 1.3 ms^{-1} and the sampling velocity 1.0 ms^{-1}, (mk'), is given by

$$m_k' = 1.21 \times m_k \qquad \text{(A2.1.2)}$$

at a particle size of 50 μm.

Secondly, although there is not satisfactory model to quantify the effect, there is evidence that the aspiration efficiencies of personal samplers decreases as windspeed increases. This would have the effect of decreasing m_s in Equation A2.1.1 above.

Both of these factors would have the effect of decreasing the apparent value of Es in the scenario described and taken with the experimental evidence support the view that the variation in the measured efficiency was caused by a wrong windspeed.

A2.1.4 Discussion

There are a number of features of this work which have consequences both for the project and for the wider issue about measuring inhalability and aspiration efficiency.

Dealing firstly with the consequences for the project:

1. For the measurements which have already been carried out at a windspeed of 1.3 ms^{-1}, rather than the correct value of 1 ms^{-1}, it is highly probable that the magnitude of the results is in error in that they underestimate the aspiration efficiency. However, the results can still be used by considering the relative performance of the various shield configurations with respect to the unshielded samplers. This applies to both the IOM and 7-hole sampler. It is clear at this stage that all of the shield configurations tested thus far have significantly modified the behaviour of the samplers.

2. The results could be adjusted for anisokinetic sampling using a correction factor derived from the model of Belyaev and Levin. However, in the absence of a model, we could not make any sensible correction on the second component, the actual reduction in efficiency of the samplers. The usefulness of this correction could be tested by comparing the corrected results with new data obtained in the final set of experiments now underway. A further refinement would be to test the appropriateness of the Belyaev model by performing a series of side-by-side measurements with sharp edged probes however, there is insufficient time to carry this out in the current project.

3. The windspeed is much more critical to the experiment than had been previously realised and needs to be carefully controlled and monitored. It is not sufficient to monitor only prior to the test run and near to the sampler position with an anemometer which is difficult to read. Therefore a new measurement protocol has been developed based on measurements of the pressure drop across a grid at the entry to the wind tunnel.

In the wider context, it would be useful to investigate this effect more fully in a larger study which would be an extension of experiments 046-048. There was insufficient time within the current project to carry this out however.

This very high dependence on windspeed may explain much of the variability, observed both in IOM data and elsewhere, associated with experiments of this type. Better control of windspeed and the improved data which will be produced should lead to a better understanding of a range of issues which are at present unresolved including differences in the performance of different sampler types and positional effects on the manikin body.

A2.2 Differences arising from continuous or stepped rotation of the manikin

The current definition of the inhalable convention (CEN 1993) refers the aspiration efficiency "averaged over all directions". The original measurements of the aspiration efficiency of a manikin achieved this by locating the manikin in four orientations with respect to the wind, front-on, left side-on, back-on and right side-on. Current practice at the IOM and elsewhere is to use a manikin which is continually rotating.

As part of this study, a limited direct comparison between these two approaches was carried out. This involved the measurement of the aspiration efficiency of samplers mounted on the manikin (and of the manikin) while the manikin was "rotated" using the four step approach immediately followed by an identical sampling configuration while the manikin was rotated continuously. Data was obtained for the manikin and for shielded and unshielded inhalable samplers.

The data are plotted in Figure A.2.2.1. Each point plotted is the pair of efficiencies obtained in the stepped and continuous modes.

Observation of the figure and formal analysis, where linear regression resulted in the relationship

$$E_{continuous} = 0.984 \times E_{4-pt} \qquad \text{(A2.2.1)}$$

with an r^2_{corr} value of 0.942 does not suggest a significant difference between the two methods at these sizes. Further work at other sizes would be desirable however.

A.2.3 Additional References

Aitken RJ, Donaldson R, Stevenson B (1995). Dust monitoring in welding and allied processes. HSE Contract Research Report (in press). London: Health and Safety Executive.

Belyaev SP, Levin LM (1972). Investigation of aerosol aspiration by photographing particle tracks under flash illumination. Journal of Aerosol Science, 5: 325-38

TABLE A2.1.1

Details of the variability in measurements of the aspiration efficiency of the IOM samplers (E_{iom}) and manikin (E_b) also showing standard deviations(sd) and number of data points [n]

Dust	Dates	Experiment numbers	mean E_{iom} (±sd) [n]	mean E_b (±sd) [n]
F360	14/11/94-18/11/94	023,024,025.653	0.36 (0.03) [10]	-
	23/3/95-15/5/95	030,038.658	0.20 (0.01) [4]	0.40 (0.01) [4]
	1/6/95	040.658	0.34 (0.02) [6] 0.42 (0.02) [6]	0.53 (0.01) [3]
	27/7/95-31/7/95	046.658	0.21 (0.03) [12]	0.37 (0.00) [2]
F240	9/9/94-15/9/94	033,077.658	0.56 (0.10) [9]	-
	23/1/95	036.653	0.37 (0.04) [8]	-
	2/3/95-15/3/95	025,026,028.658	0.26 (0.01) [2]	0.28 (0.04) [6]

TABLE A2.1.2

Results of experiments to measure the effect of windspeed variations on aspiration efficiency of the IOM samplers (E_{iom}) and manikin (E_b), dust F360.

Experiment number	Actual windspeed ms^{-1}	mean E_{iom} (±sd) n = 12	mean E_b (±sd) n = 2
046	1.3	0.21 (0.03)	0.37 (0.00)
047	1.0	0.39 (0.03)	0.45 (0.03)
048	0.8	0.62 (0.09)	0.56 (0.04)

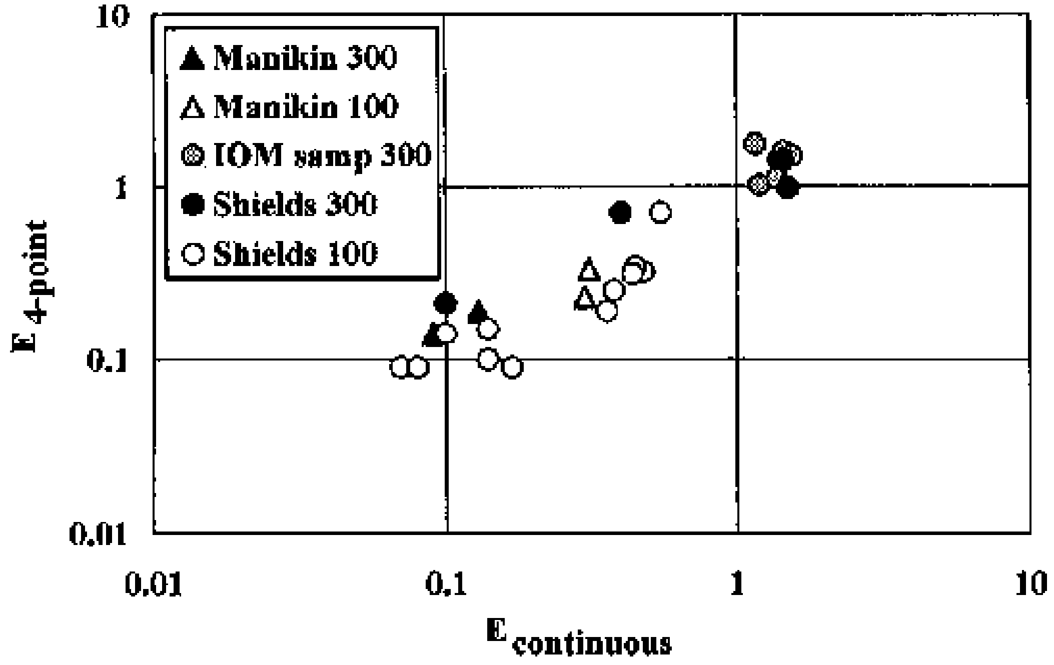

Figure A.2.2.1 Comparison between the aspiration efficiencies obtained for continuous and 4-point rotation, for the manikin (at particle aerodynamic diameter 300 and 100 μm), the IOM sampler (at 300 μm) and various shielded IOM samplers (300 and 100 μm).

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ISBN 0-7176-1270-8

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