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RECENT DEVELOPMENTS IN AIRBORNE DUST MONITORING

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ABSTRACT

Many ambient pollutants are in particulate form and there is a need to sample them for a variety of reasons. A wide range of samplers is available for different purposes but, unfortunately, there does not seem to be a very good understanding of the reasons governing the choice of samplers for different tasks. The present paper attempts to address some of these problems by reviewing briefly the types of sampler used for collecting airborne dust in the ambient atmosphere and the reasons for their choice. Special attention is given to sampler performance and to wind effects on performance, since this is one of the main features of the atmosphere affecting sampler behaviour. Some recent developments in sampler design are discussed. A shorter version of this paper was originally presented as a lecture by the first author to the Investigation of Air Pollution Standing Conference in June 1992, following which it was extended and adapted by the second author for use as lecture notes to an MSc course on Integrated Pollution Control. In view of the great interest that has been shown in this subject, it was felt that the work merited a wider audience and it has been extended again to form the present paper.

1. BACKGROUND

The sampling of particles in the ambient atmosphere (not including measurements in chimney stacks and exhaust ducts) is carried out for two main reasons:

a) to determine levels of airborne dust for correlation with respiratory health effects and to ensure that they are below health-derived limits,

b) to determine levels of deposited dust to the ground or to other surfaces. This may be for health reasons, deposited material such as heavy metals or dioxins may be ingested through secondary pathways, or for correlation with perceived nuisance and loss of amenity. Deposited dust is one of the two major causes of complaint about air pollution (alongside odours), since its effects can be directly perceived.

A great variety of samplers have been developed and used for both reasons in the UK and elsewhere. The reasons for their development, their effectiveness and manner of use are not always clear. This paper provides a brief explanation, paying special attention to sampler performance. One of the main parameters affecting ambient sampler performance is windspeed and there is no practical control over this. Thus it is important that ambient samplers should have a largely windspeed-independent performance, at least within the size range of particles they are intended to sample. Often they do not.

References to particle sizes in this paper are to the particle aerodynamic diameters. Besides the present paper, a recent review of monitoring of radioactive particles by Nicholson and Garland(1991) may be useful, and Vincent's(1989) recent book on aerosol sampling covers many related areas of interest.

2. PREVIOUS STUDIES OF AIRBORNE DUST

Though measurements of deposited dust were amongst the first studies of air pollution, around the beginning of the century (Brimblecombe(1987)), airborne dust measurements generally have been of limited extent compared with those of other pollutants. The major dust monitoring activities of recent years are outlined below.

As a result of the large number of deaths in the early 1950's from bronchitis caused by inhalation of smoke and sulphur dioxide during the smog episodes, a countrywide network of simple samplers was set up in the 1960's to measure the levels of black smoke in the atmosphere. The sampler used, shown in Figure 1, comprised a downward-facing funnel into which air was drawn, with the sampled airborne particles collected on a paper filter at some distance (typically 2m) from the inlet. The quantity of dust was assessed by means of light obscuration, with the black particles prevalent in smoke from fossil fuels contributing most to the measurement. This was adopted by the British Standards Institute as the standard method for measuring black smoke (BSI(1969a)). It is still in operation and its use is now additionally covered by an EC directive (800/779/EEC). Its performance, also shown in Figure 1, was measured by McFarland (1982) (in the USA, after 20 years of use in the UK), when it was found to collect particles below about 4μm very well, but for larger particles its collection performance was poor. For the measurement of black smoke this was satisfactory. The initial size distribution of smoke particles is very fine and, though these can agglomerate in the atmosphere into quite large particles at times, their aerodynamic diameter remains small. However, for other, larger particles or for particles of different colour, it is not a very satisfactory method.

In the early 1970's, the government instigated two national surveys of ambient dust levels to investigate the health effects of ambient particles. In the main survey, levels of sulphate particles were determined, whilst in the other a limited survey of metal particles was carried out in order to identify regions of high concentration of these pollutants. The samplers used in both surveys were very similar, as can be seen in Figure 2. They each comprised a downwards-facing cylindrical hood covering either eight inverted 25mm open-faced filter holders in the sulphate sampler (called the S-type sampler) or a single 37mm open-face filter holder in the metal sampler (called the M-type sampler). The design, incorporating a cylindrical hood and downwards-facing filter holders, was influenced by the need to protect the collected sample from rain, wind and birds. However, this hood affected the sampling characteristics. In very light winds large particles were not sampled due to elutriation in the vertical flow into the sampler. Also, the sampler showed a strong sensitivity to wind effects generally. Upton and Barrett(1985) investigated its sensitivity to wind effects in a wind tunnel and their main results are given in Figure 3, which shows its particle collection efficiency as a function of windspeed and particle size. It is an effective sampler for small particles, below about 10-15μm diameter, but above these sizes its performance is erratic and falls off markedly with increasing windspeed. The 'M' type sampler, with a single filter holder, was also adopted for sampling for the EC Lead Directive (82/884/EEC) along with a number of other particle samplers used in different European countries. Whilst bearing some resemblance to health-related dust fractions such as the thoracic and the respirable (which are discussed below), this sort of performance does not agree very well with either, so these samplers cannot be considered suitable for measuring health-related dust fractions in the ambient atmosphere. Also, unless the particle size range of interest is in the smaller fractions, where it will all be collected, this sort of wind-dependent sampling behaviour is generally unsatisfactory. In the cases of sulphate, lead and the heavy metals, for which the 'M' and 'S' type samplers were originally designed, it was presumed that the bulk of the sample was in the fine particulate fraction, which was all collected. However, this is not entirely certain as, though the sources of these materials are mostly fine particulate, the proportion attached to larger particles (that of lead onto road dust, for example) is generally less certain. The performance of most of the other samplers used for the lead directive was investigated at the same time (Barrett et al(1985)); they all showed a variable, wind-affected performance.

The measurement of deposited dust was also the subject of a countrywide national survey from the 1960's to 1980. This was instigated to provide information on average levels at different locations so that cases of nuisance caused by dust have a framework for assessment. The instrument used was the British Standard Dust Deposit Gauge (BS 1747 Pt 1). It is a passive device (shown in Figure 4), little changed since its first use nearly a hundred years ago (Brimblecombe(1983)). It is essentially a large bowl with its opening facing upwards, with a bird guard and a collecting bottle, fixed to a stand so that the horizontal gauge opening is about 1.5 m from the ground. This gauge remains the current British Standard. Again, it was only after considerable use had been made of the BS gauge that investigations of the sampling performance were carried out, at Warren Spring Laboratory, by Ralph and Barrett(1984). Some of these results are presented in Figure 5, showing that collection efficiency was very dependent upon windspeed and particle size. The collection efficiency was especially poor for the particle sizes likely to travel any distance in the wind (below 200μm) and windspeeds above 2 - 3ms^{-1}. This performance is doubly poor when it is remembered that the levels of wind blown dust increase markedly with increasing windspeed.

A later device for monitoring windborne dust - the British Standard Directional Gauge (BSI, 1972) - uses four flux gauges set at orientations of 90° in order to determine the source direction of the dust as well as the flux. The flux of dust is the passage of dust horizontally past the sampling station. A diagram of the Directional Gauge is shown in Figure 6. Each flux gauge is a cylindrical tube with a vertical opening intending to collect the horizontal flux of particles past a measuring station. This gauge may be used to assess the source strength of windblown dust and its depletion rate with distance away from the source. Despite this being a relatively recent development (Lucas and Moore, 1964) investigations of its performance were not reported until the 1980's (Ralph and Hall, 1989). The results, given in Figure 7, show a low collection efficiency that is strongly dependent upon both windspeed and particle size. Though it does not give a very reliable measure of flux, the gauge does have quite good directional properties so it can be used effectively to determine dust sources.

This very brief summary of the equipment commercially available and presently used in the UK for monitoring dust in the ambient atmosphere, does not fill one with confidence as to the validity and reliability of many of the measurements made. However, considerable progress has been made in recent years, both in the criteria for sampling and in actual sampler developments to enable us to look ahead with more confidence. The remainder of this paper will present some of the more recent developments in sampling technology for dust in the ambient atmosphere. Unfortunately not all of the developments are currently commercially available.

3. HEALTH-RELATED DUST SAMPLING

3.1 New health-related sampling conventions for airborne dusts

For health effects that are suspected to have arisen from particles that have entered the body through the nose and mouth during breathing, one must have a sampler whose performance mimics the efficiency with which particles enter the nose and mouth and which may then penetrate to the region in the body for which harmful effects occur. Workers in the occupational hygiene field have realised this for some years and have defined the different fractions of those particles that penetrate to the different regions.

Since the early 1980's an ad-hoc working group of the International Standards Organisation has been formulating health-related sampling conventions for airborne dusts both in the ambient atmosphere and in the workplace. The final agreed conventions have passed through most stages of the approval procedure and should soon become international standards (ISO CD7708). They are defined in Figure 8 and comprise three main fractions:

a) the INHALABLE fraction, defined as the mass fraction of total airborne particles which is inhaled through the nose and mouth,

b) the THORACIC fraction, defined as the mass fraction of inhaled particles penetrating beyond the larynx,

c) the RESPIRABLE fraction, defined as the mass fraction of inhaled particles which penetrates to the unciliated airways (the alveolar region).

These conventions provide target specifications for the design of health-related sampling instruments, and give a scientific framework for the measurement of airborne dust for correlation with health effects. For example, the inhalable fraction applies to toxic pollutants which are only required to enter the body and dissolve, while the respirable fraction which penetrates to the alveolar region of the lung can cause diseases such as pneumoconiosis, silicosis, asbestosis, etc. This philosophy has not until quite recently been taken on board by the environmental community.

3.2 Ambient samplers designed to meet health-related sampling conventions

3.2.1 PM10 Samplers

During the early 1980's, the US Environmental Protection Agency stated that for ambient airborne dust levels, a thoracic dust fraction known as the PM10 should be used as the sampling convention. This convention, shown in Figure 9, is close to the ISO thoracic convention with 50% collection at 10 μm, although there are differences (the thoracic convention requires a greater collection of larger particles up to 25μm). High standards of collection performance are required of these samplers, including independence of windspeed, and there is a demanding test protocol for determining this (EPA(1987)). Following this decree a number of researchers in the US developed 'PM10' samplers, two of which are shown in Figure 10. They both comprise an omni-directional, rain-protected entry followed by a size-selective stage with the PM10 dust collected on a filter. The Andersen 321A is a self-contained device based on the earlier hi-volume sampler with a flow rate of 1200l min^{-1}, whilst the EPA Dichotomous Sampler is used both in a self-contained sampler and as the inlet to other designs using instantaneous mass monitors. The performances of the two samplers, measured by Hall et al (1988), are given in Figure 11. It can be seen that they both agree very closely with the PM10 sampling convention. These and other similar samplers are now used routinely in the USA for measuring ambient dust levels. A recent Development has been the use of a Tapered Element Oscillating Microbalance (TEOM) following the size-selective inlet instead of a dust collecting filter. This is capable of measuring the small variations in the collected mass of dust with time.

3.2.2 Developments in Europe

Researchers in Germany and the Netherlands, following closely the developments in the USA, obtained CEC funding to make measurements of ambient dust levels with the PM10 samplers in European conditions. At the same time DG X1 of the CEC provided a small amount of funding to the Institute of Occupational Medicine to develop a European Reference Sampler that first sampled the inhalable fraction and then further selected the thoracic fraction of the inhaled particles. The final prototype version (Mark et al, 1990) is shown in Figure 12. It was found that reliable measurements of both inhalable and thoracic particles could not be obtained with one sampling head, rather it was necessary to use two heads - one for the inhalable dust and one which uses a combination of inhalable entry and thoracic size selector for thoracic dust. The performances of the two sampling heads obtained during the development are given in Figure 13, from which it can be seen that they agreed reasonably well with the inhalable and thoracic conventions. However, in subsequent wind tunnel tests at Warren Spring Laboratory (Hall et al, 1990), both sampling heads showed excessive internal wall losses when using relatively soft solid test aerosols and liquids. These losses were not observed in the original work which used gritty alumina test particles which bounced well. In addition, field experiments carried out in the Netherlands showed good performance for the inhalable sampler, and over-sampling for the thoracic sampling head.

As a consequence of this work, the CEC decided in 1991 that the IOM sampler was not sufficiently well-developed to become the European Reference Sampler and so chose the PM10 convention as the reference for the thoracic fraction in its revision of the European Directive (80/779/EEC) for SO_2 and Suspended Particles. The other main reason for this decision was that fully-tested samplers for PM10 dust are available from the USA. The CEC is currently devising a test protocol based on field-only comparisons for testing the performance of new PM10 samplers.

Further development at Warren Spring Laboratory of the inhalable sampling head described above has largely cured its original problems (Upton et al(1992). The problems of avoiding wall losses when sampling large particles are fundamental to any sampler of this sort and difficult to avoid. However, by fitting the sampler with an internal cassette, in which the whole sample is retained, wall losses became irrelevant and it now satisfies the inhalable criterion very well. It is currently the only ambient sampler design which does this. Unfortunately it is not yet available commercially.

4. DEPOSITED DUST MEASUREMENTS

4.1 Background

Deposition of particles to the ground is found in one of two ways, depending upon whether the particles are large or small. The boundary between 'large' and 'small' is around 10-20μm.

Large particles are presumed to fall to the ground like other forms of precipitation and the rate of deposition, D, is given by the product of the airborne concentration, χ, and the particle gravitational falling speed, v_s. That is,

$$D = \chi v_s.$$

The deposition of large particles is usually measured by passive dust deposition gauges, like the British Standard Dust Deposit Gauge described earlier.

Small particles are deposited on the ground by a variety of processes, by falling under gravity, by trapping or impaction on to surface roughness (grass, for example) and by diffusion to the surface. The deposition rate is defined in the same way as for large particles, but the falling speed is replaced by an effective deposition velocity which takes account of these other processes. The effective deposition velocity of small particles is always higher than their gravitational falling speeds. Typical value of deposition velocity in many practical cases are around 1cm s^{-1}. The deposition of small particles is estimated by measuring their airborne concentration and assuming an effective deposition velocity derived from experimental measurements.

The flux of particles, F, blown by the wind past a point, needs brief consideration as it is not directly related to deposition. It is defined as the product of the airborne particle concentration, χ, and the windspeed, V. That is,

$$F = \chi V.$$

Flux can be related to deposition only if the relationship between particle size (and therefore falling speed), windspeed and airborne concentration is known. This is never known. Thus measurements of particle flux using a flux gauge of the sort described earlier serve a special purpose and usually need to be made in combination with measurements of deposition.

4.2 Ambient Dust Concentration Measurements for Small Particle Deposition

There are no samplers designed especially for this purpose. If a certain size range of particles is of interest then a sampler can be selected from the sort that have previously described for health related or other sampling. Thus, for example, a PM10 sampler would provide measurements of the particle size range (below 20μm) to which the small particle deposition criteria apply. If a sample is required of the whole of the ambient particle size distribution for deposition estimates, then larger particles must be collected as well. There is no formal definition of this particle size range. There is an EC limit concentration for 'Total Suspended Particulate', but it is not defined effectively. Nor is there is a sampler specifically designed to collect this size fraction other than the WRAC (the Wide Range Aerosol Classifier), a large, expensive and specialised device of which there are three known examples and whose collection performance is uncertain. The samplers closest to obtaining the total atmospheric particulate mass are the US Hi-Volume sampler (Wedding (1977), which has variable collection characteristics and an upper size cut-off around 50μm, or the sampler for the inhalable criterion (the only present example of which is described above), which has a defined collection characteristic and will sample particles beyond 100μm in a controlled way.

4.3 Dust Deposit Gauges For Direct Measurement of Particle Deposition

The poor performance of the British Standard Gauge and its relatively high cost led researchers at Warren Spring Laboratory to look for a better, cheaper design. They identified two main reasons for the poor performance of the BS and other similar gauges. Firstly, aerodynamic blockage caused by the substantial bulk of the collecting bowl caused a rising and accelerating airstream over the gauge. Particles descending under gravity in the wind, which would be expected to enter the gauge, tend to be displaced away from the opening, thus reducing the catch. Secondly, a circulating flow was driven inside the gauge by the wind which can remove particles already collected.

In their search for a collector with low aerodynamic blockage, the performance of an inverted frisbee was investigated by Hall and Waters(1986) and by Hall and Upton(1988). They found that, provided that the collection surface was made sticky, a considerable improvement over the BS gauge was achieved, as shown in Figure 14. Whilst the performance of the plastic frisbee showed promise and it was very cheap, it was not suitable (due to warping and splitting) for sampling trials lasting longer than a few days. A new metal gauge was therefore produced which retained the low aerodynamic blockage of the frisbee, whilst incorporating a shallow curvature to improve drainage of rainwater. It is shown in Figure 15, both the collecting bowl and a complete version of the gauge are commercially available.

Field experiments showed variable differences in the collected mass between the frisbee gauges and the BS gauges. This seemed to be due to different causes of particle loss between the two types of gauge. It was thought that the BS gauge had poor collection but better retention than the frisbee type, where loss of collected particles, probably due to the splashing of raindrops removing particles from the surface, seemed to be higher. Using a sticky gauge surface greatly reduced losses, but there were practical problems in recovering the sample. Further investigations (Hall et al, (1992), Vallack(1993)) and subsequent investigations) showed that the use of a disc of porous polyester foam in the bowl of the gauge to be almost as effective for retention as a sticky surface, to eliminate splashing entirely and to be easier to use in practice. In a more recent development (Hall et al(1993)), a slightly deeper shape has been designed so that a foam liner can be better accommodated, this also has a turned-in lip and a flow deflecting ring fitted around the gauge to provide better control over the airflow. A cross section of this design is shown in Figure 16. It has a flat, unaccelerated flow over the gauge opening and it proved impossible to blow out collected dust up to windspeeds of $10ms^{-1}$. It is intended that this should be the basis of a new standard gauge design.

4.4 Flux Gauge Developments

Flux gauges are used to provide a measurement of the horizontal flux of particles passing a given point, and when arranged in four orthogonal directions, as in the BS directional gauge, give an indication of the source of the wind-blown particles. However, as an individual flux gauge the collection efficiency of each of the four tubes in the BS Directional Gauge has been shown to be poor. Two main problems were identified with its performance. Firstly, there is no flow into the closed container of the gauge and so the flow stagnates at the entry and particles enter only by virtue of their inertia. This makes the performance both windspeed and particle size dependent. Secondly, there is a wind-driven circulation inside the gauge which tends to remove collected particles.

Two approaches for developing an improved flux gauge were investigated by Hall et al (1992). In the first approach the effect on performance of various parameters of a closed container type of gauge were investigated. There seemed to be no way of controlling the internal circulation in a gauge with a vertical slot opening. Even a simple forward facing tube with a blanked-off end proved a better collector. A tentative design for a gauge of this sort comprised a number of small cylindrical tubes arranged horizontally together and feeding into a central collection tube. A sketch of this design is given in Figure 17, together with the performance of a single tube at two windspeeds and for two particle sizes. The performance of the BS gauge is also given (the cross-hatched results) and it can be seen that a considerable improvement has been made. A better approach has involved the development of a flux gauge with an airflow through it past some sort of particle trap. A number of different designs were investigated, both to generate the necessary airflow through the gauge and to capture and retain the collected particles. The final design is shown in Figure 18 and full details of it can be found in Hall et al(1993). It uses a wedge shape to provide airflow through the gauge and a piece of porous polyester foam to trap the particles. Its performance in relation to the BS Directional Gauge is also given in Figure 19. It is intended that this also should be the basis of a new standard flux gauge design. It is available commercially.

5. DIRECTIONAL SAMPLING

An important practical problem that arises with many industrially-generated dust sources is the apportionment of the contribution of different sources to dust levels at a site. This can be done by directional sampling, that is, by sampling with multiple samplers which operate only over fixed arcs of wind direction. This can be done quite simply using two samplers and a wind velocity and direction meter. When the wind velocity is above a given threshold value and from a direction contained within a given arc, then one of the samplers is operational, and when the wind is from all other directions the other sampler is operational. The contribution made by the source under investigation to the dust measured at the sampling station can then be calculated. This can be a very powerful and effective technique for apportioning dust nuisance.

A directional sampling systems has been set up for monitoring ambient airborne dust levels using two sampling heads within the hood of the M-type sampler (Barnett et al, 1987), which is available commercially. There is also a design for monitoring deposited dust levels with two frisbee gauges (Clayton et al, 1992) where the gauge not in use is automatically covered. In principle, any sort of sampler can be used in this fashion as long as it can be stopped and started in some way as the wind speed and direction varies.

6. CONCLUDING REMARKS

This paper has outlined very briefly the methods used in the UK for monitoring dust in the ambient atmosphere, both in the past and the more recent developments. Past and many present procedures have used instrumentation of doubtful validity and reliability and have not covered very well the types of sampling needed. However, developments have taken place, both in the measurement of health-related dust and in the measurement of "nuisance" dust such that improved, validated equipment should become available within the next few years.

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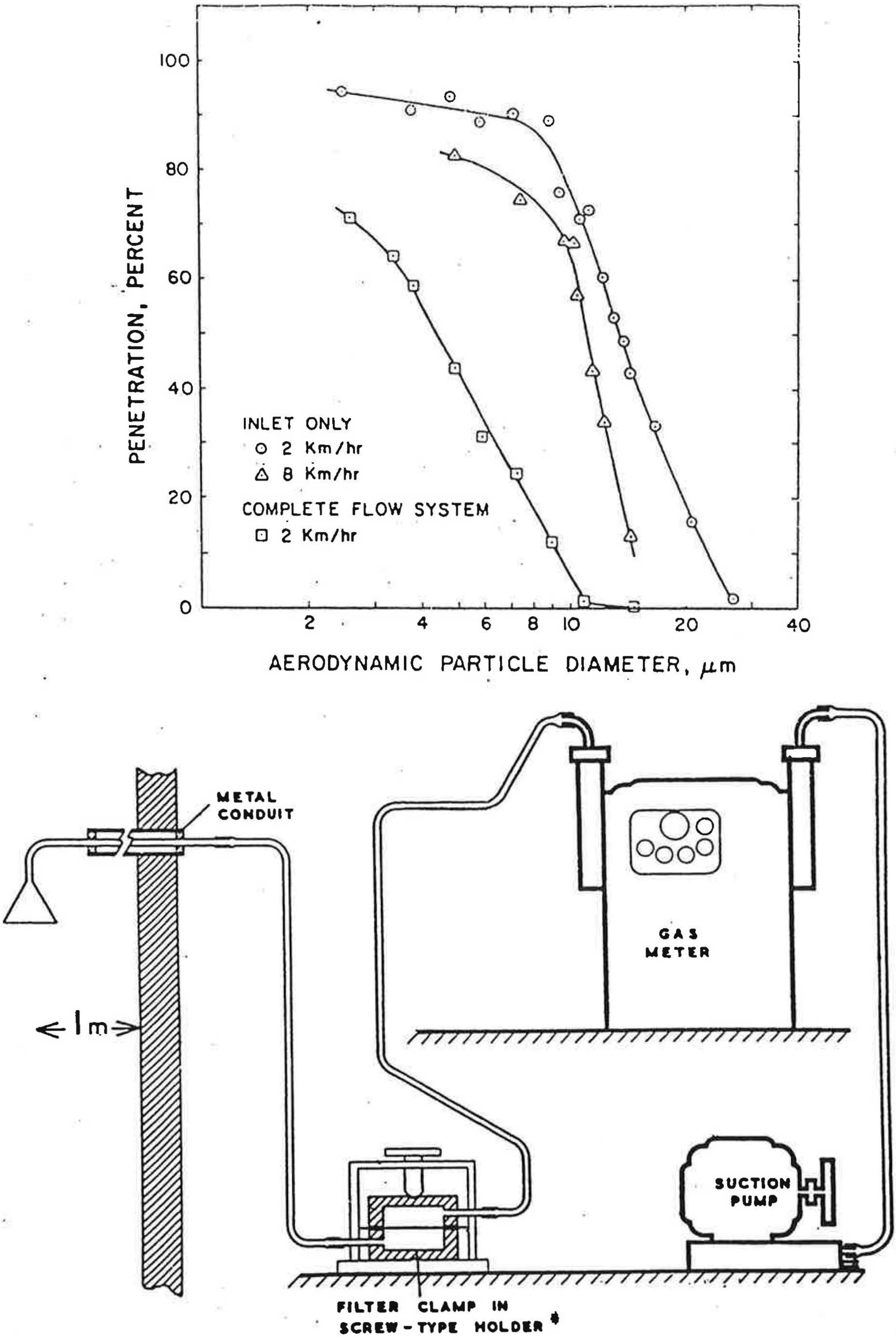
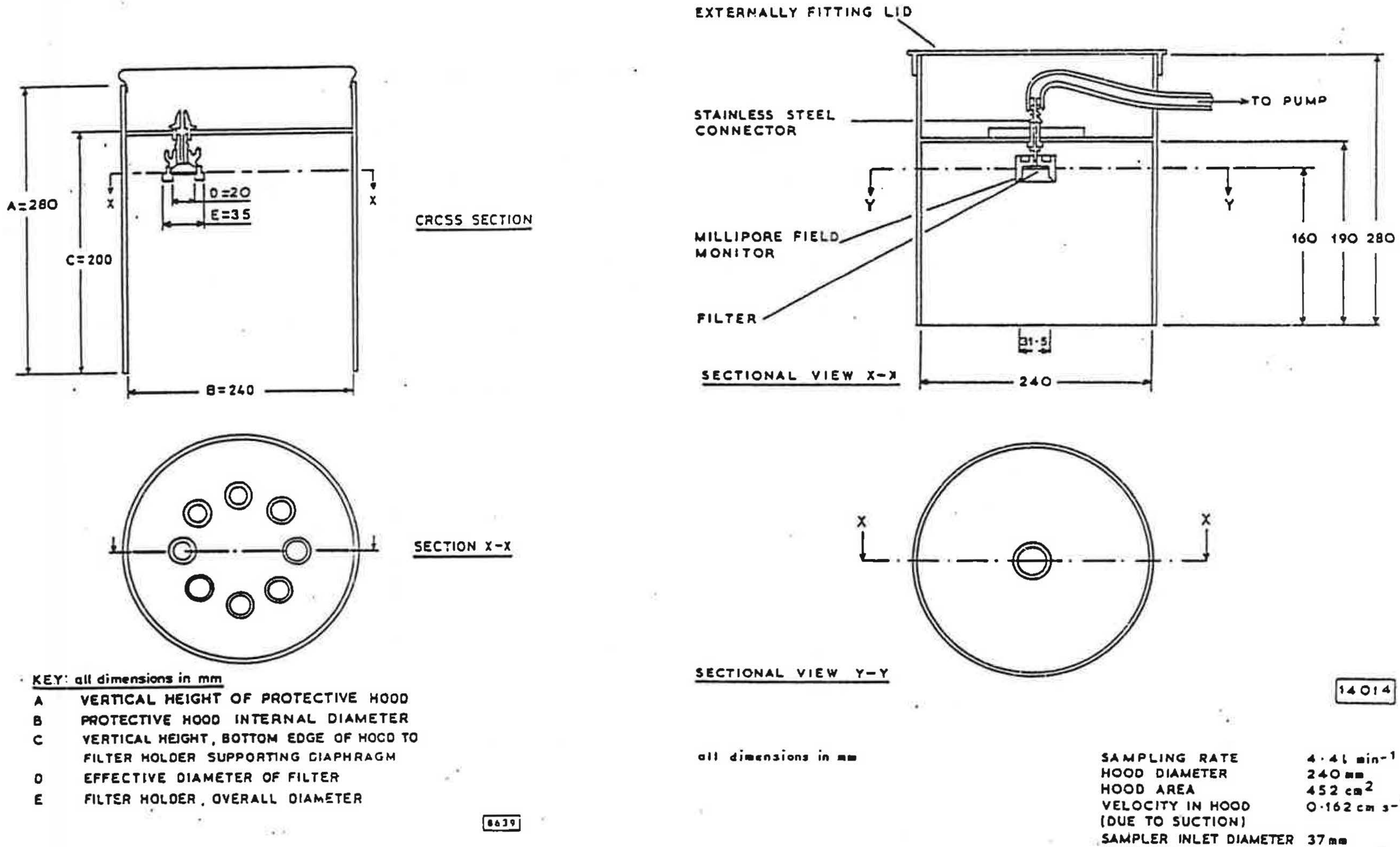


*STAINLESS STEEL STANDARD 47mm AEROSOL FILTER HOLDER ALSO USED

Fig. 1. Basic Components of British Standard Black Smoke Sampler, Together with its Sampling Characteristics.

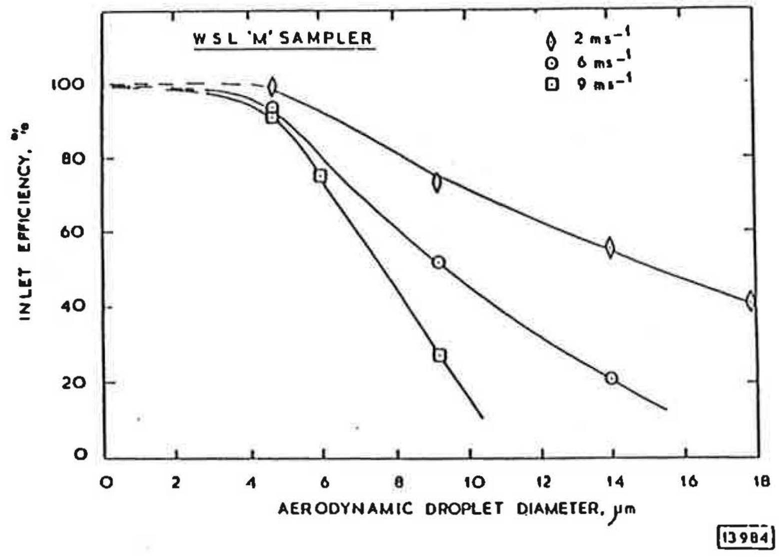


KEY: all dimensions in mm

A	VERTICAL HEIGHT OF PROTECTIVE HOOD
B	PROTECTIVE HOOD INTERNAL DIAMETER
C	VERTICAL HEIGHT, BOTTOM EDGE OF HOOD TO FILTER HOLDER SUPPORTING DIAPHRAGM
D	EFFECTIVE DIAMETER OF FILTER
E	FILTER HOLDER, OVERALL DIAMETER

SAMPLING RATE	4·4 l min^{-1}
HOOD DIAMETER	240 mm
HOOD AREA	452 cm^2
VELOCITY IN HOOD (DUE TO SUCTION)	0·162 cm s^{-1}
SAMPLER INLET DIAMETER	37 mm
VELOCITY AT SAMPLER INLET	6·8 cm s^{-1}
EFFECTIVE FILTER DIAMETER	31·5 mm
EFFECTIVE FILTER AREA	7·8 cm^2
FILTER FACE VELOCITY	9·4 cm s^{-1}

Figure 2. Samplers used for national survey of ambient dust levels a) sulphate sampler S-type b) metals sampler M-type.



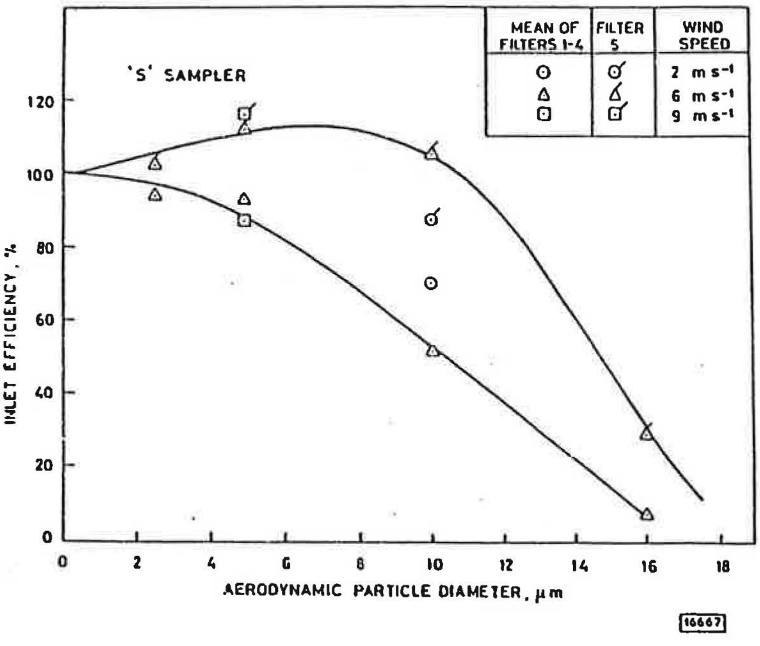


Figure 3. Performance of M-type and S-type ambient dust samplers

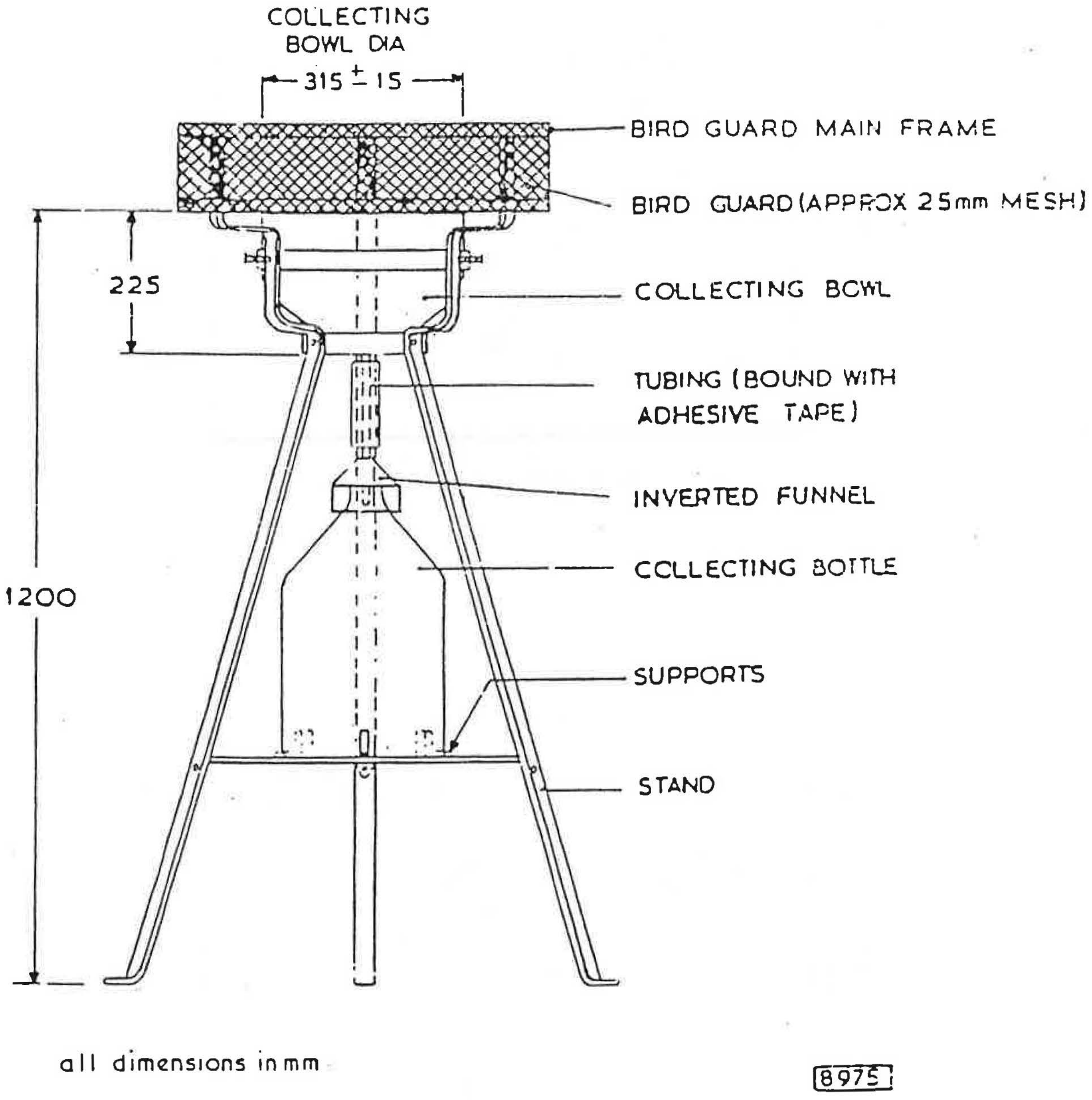


Figure 4. British Standard horizontal dust deposit gauge

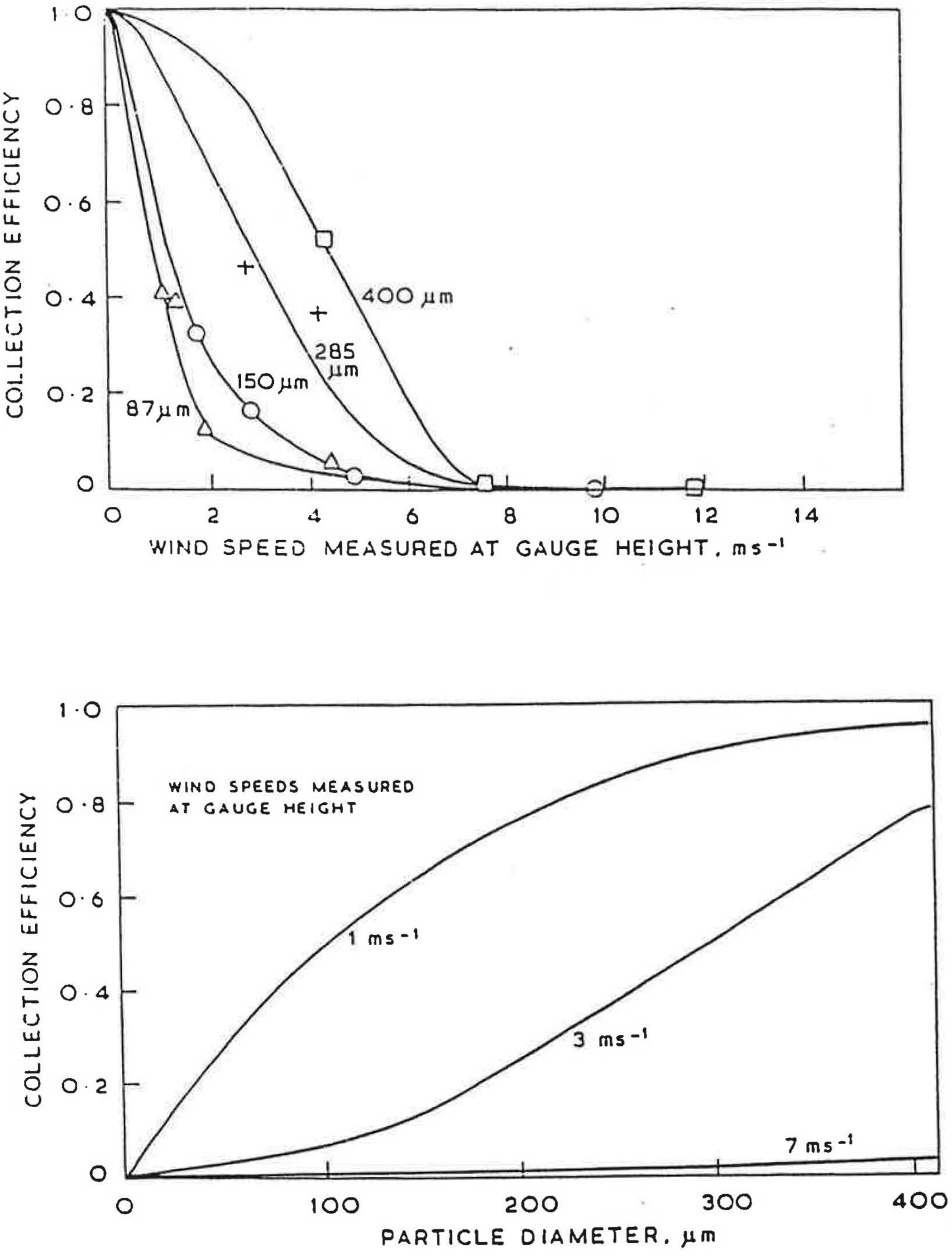


Figure 5. Performance of BS horizontal dust deposit gauge

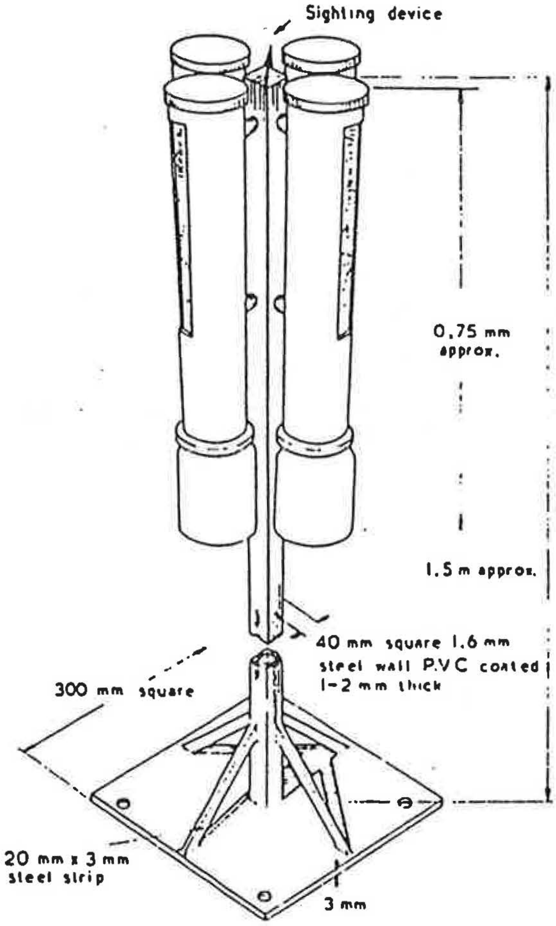


Figure 6. British Standard directional dust gauge

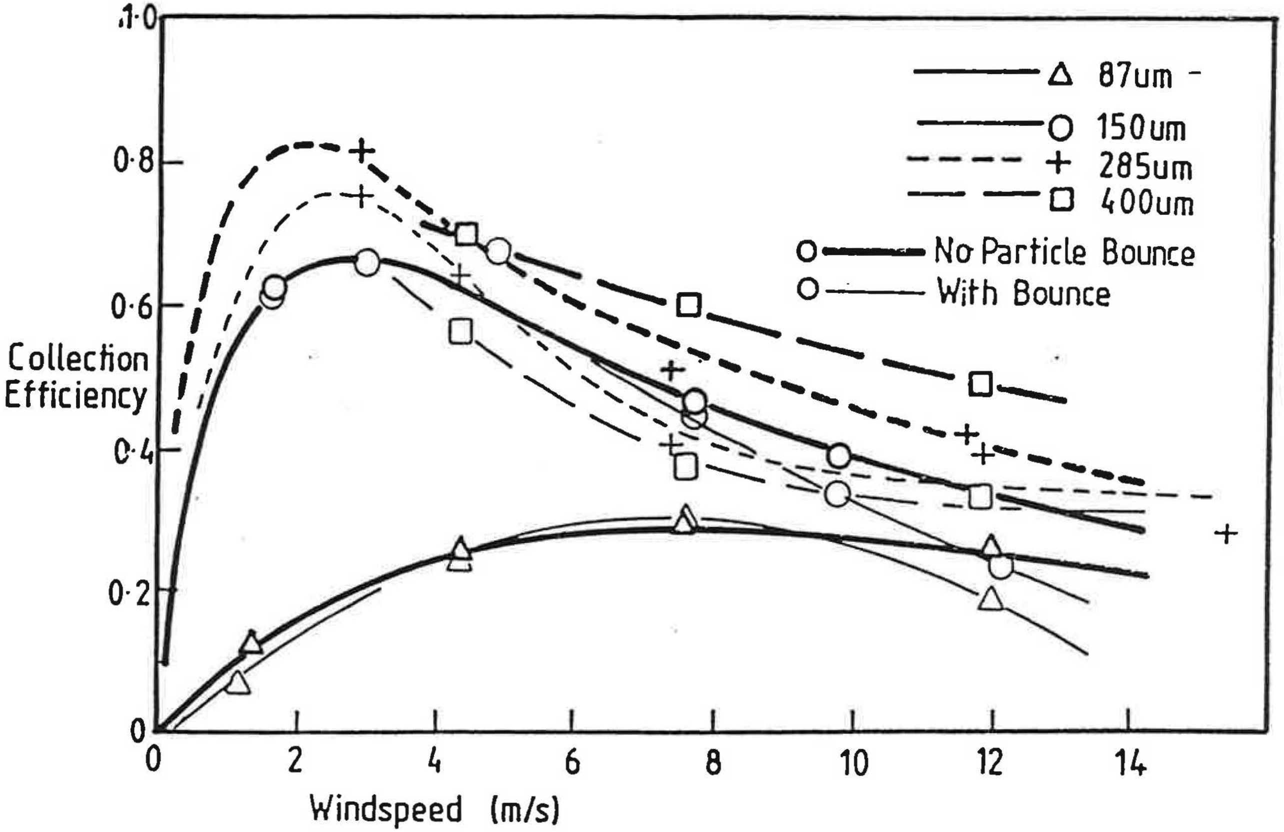


Figure 7. Performance of BS directional dust gauge

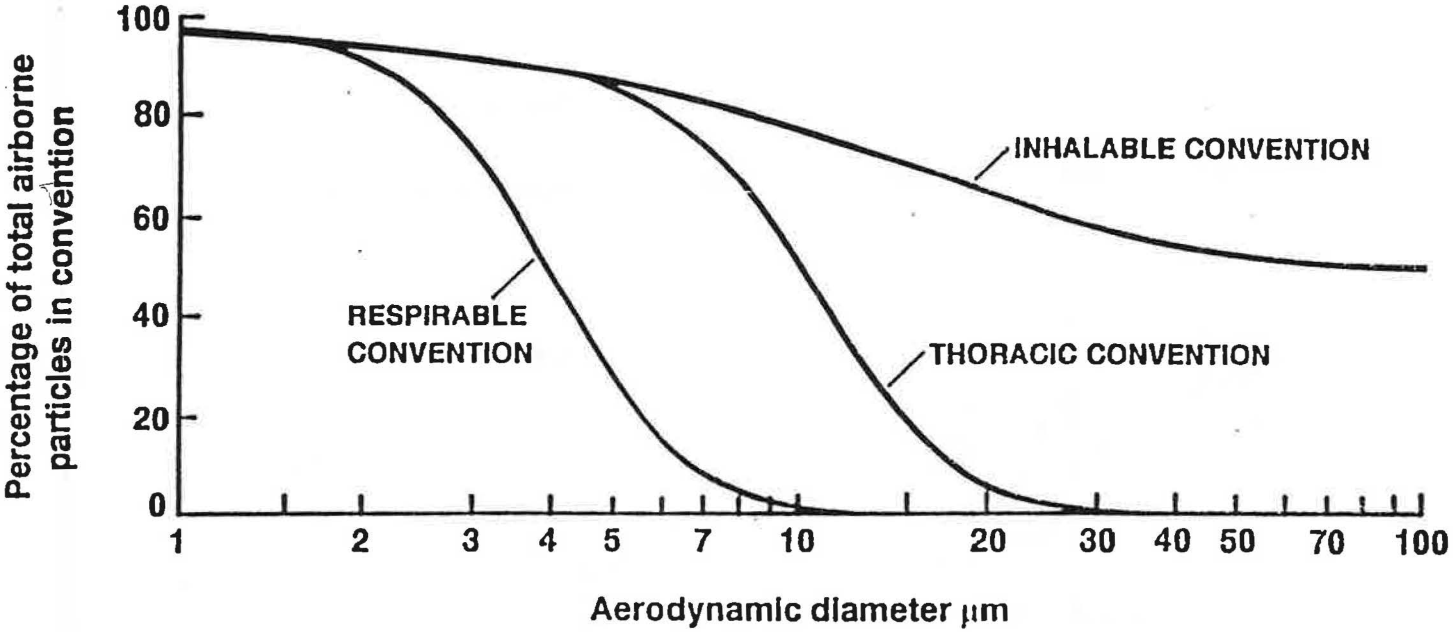


Figure 8. ISO health-related sampling conventions

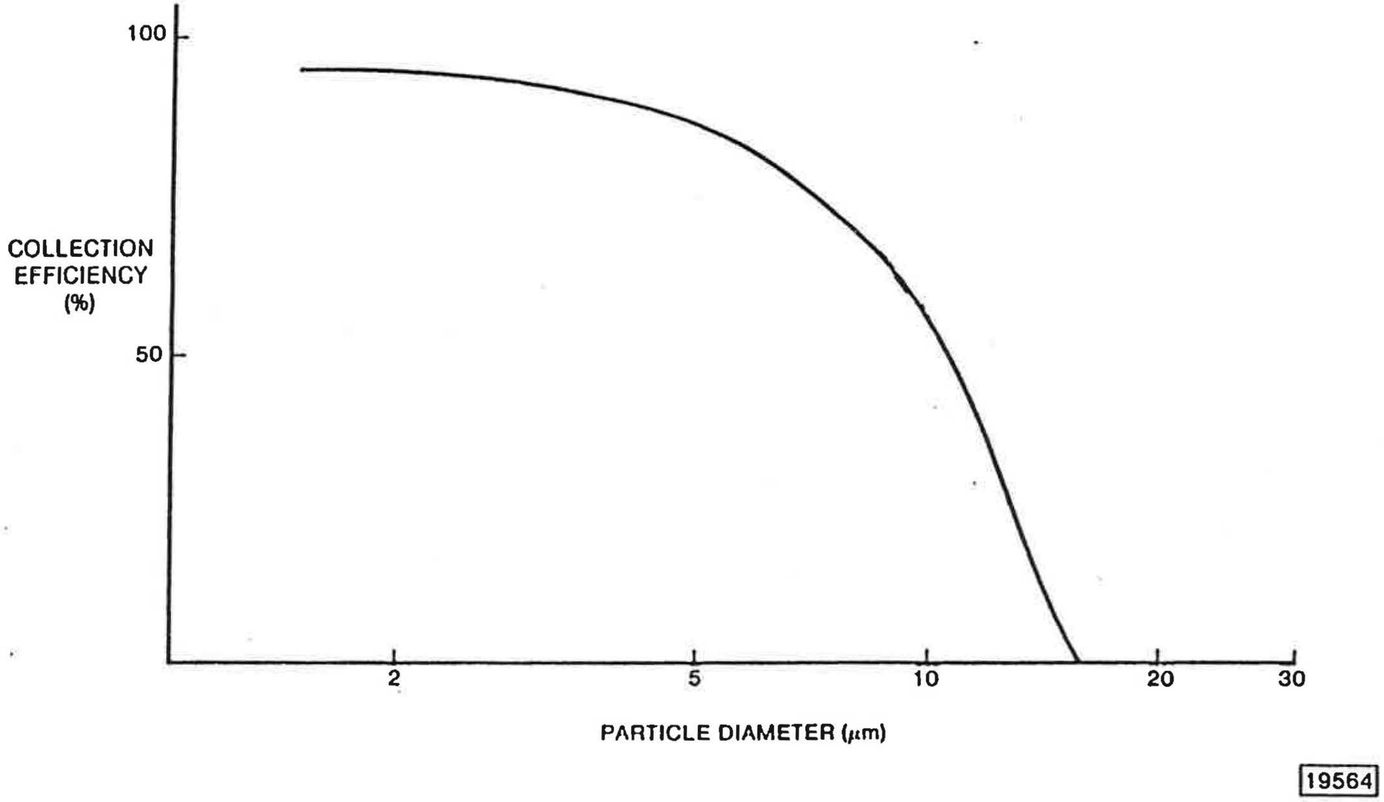


Figure 9. US Environmental Protection Agency PM10 sampling convention

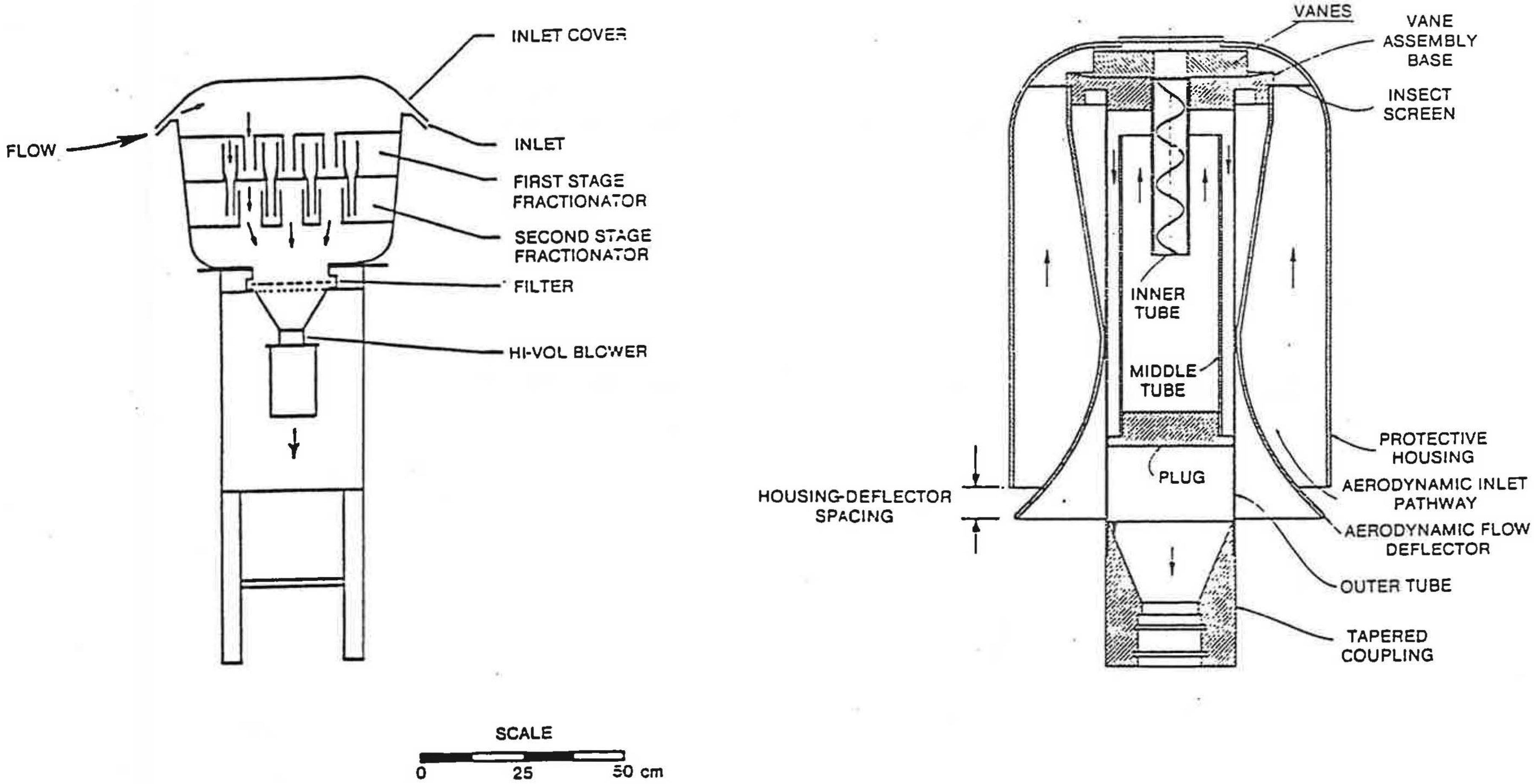


Figure 10. Samplers for PM10; a) Sierra-Andersen 321A, b) inlet for EPA dichotomous sampler

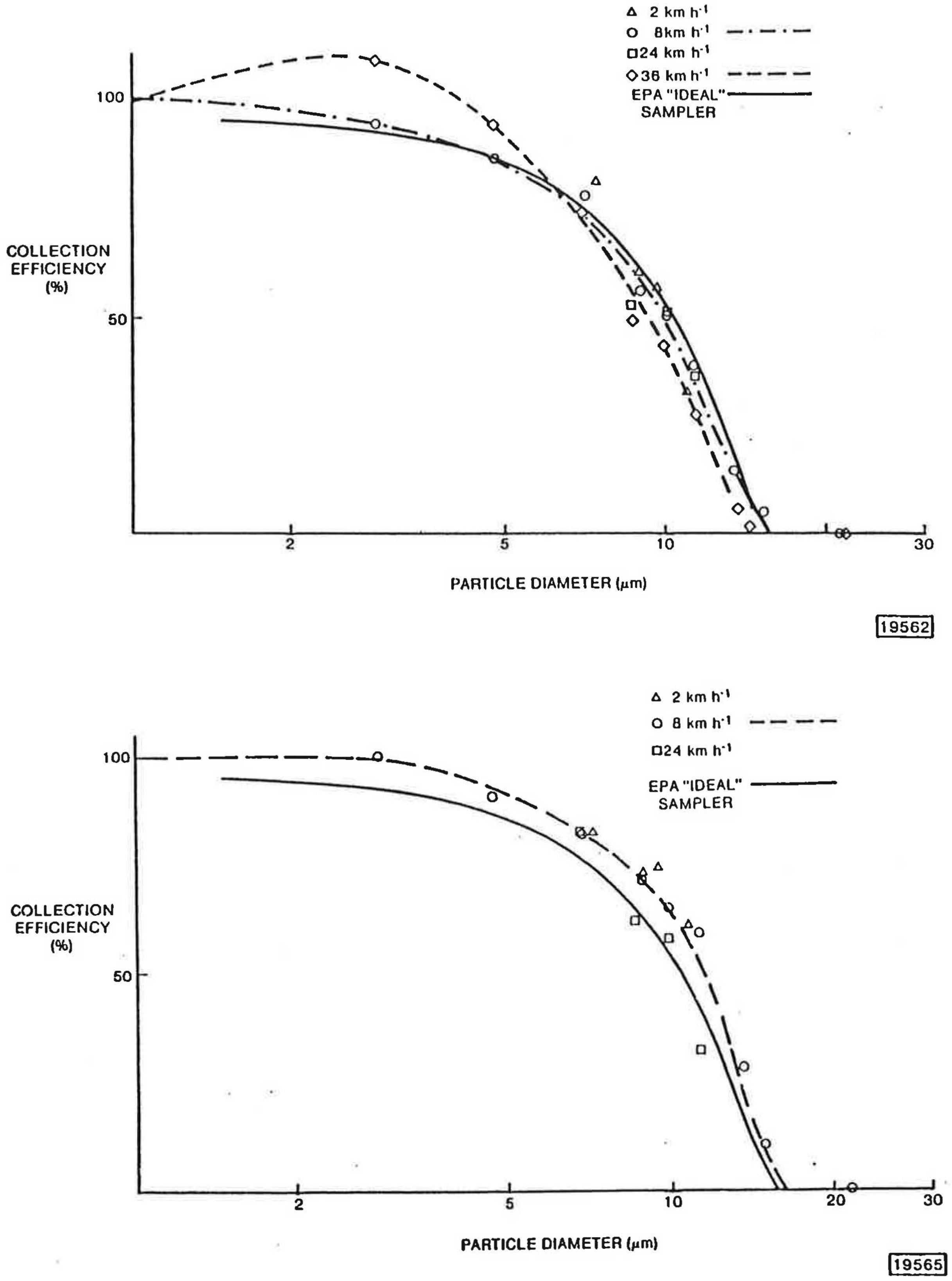
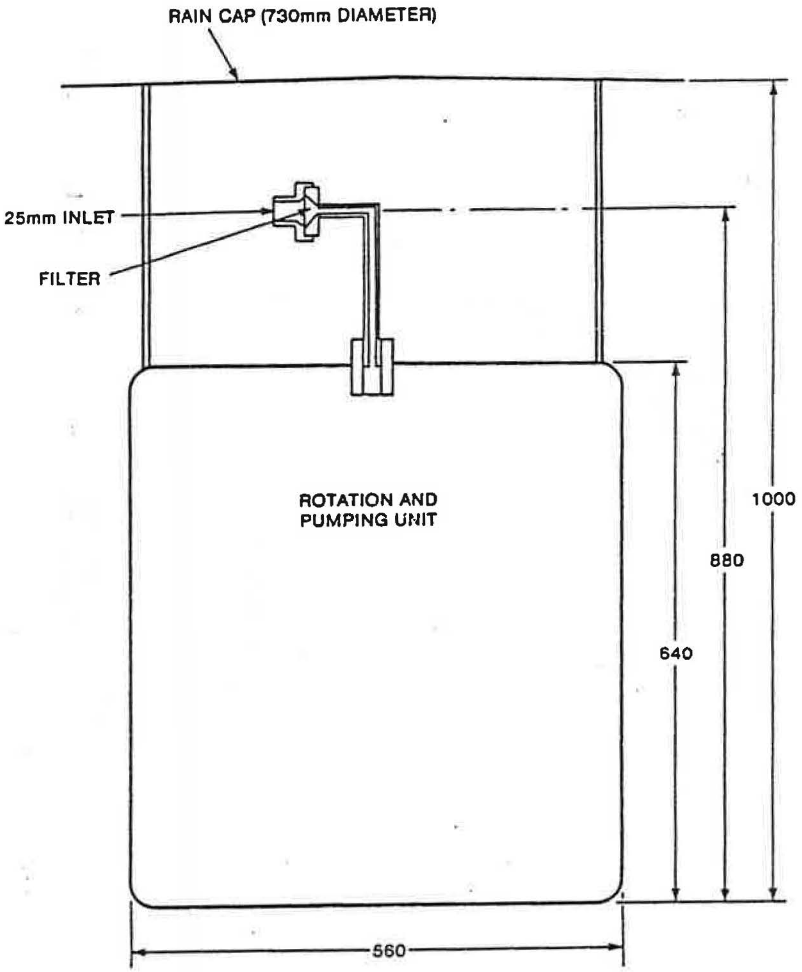


Figure 11. Performance of PM10 samplers; a) Sierra-Andersen 321A, b) inlet for EPA dichotomous sampler



ALL DIMENSIONS IN mm

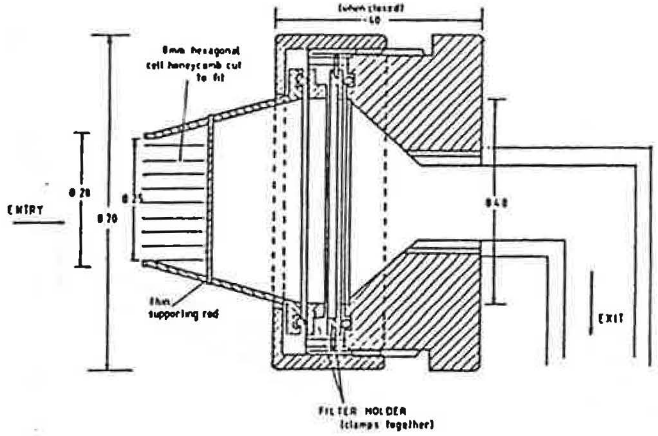


Figure 2. Diagram of Inhalable Inlet.

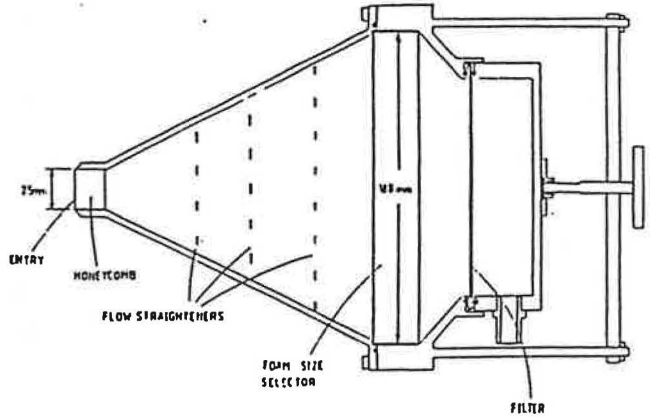


Figure 3. Diagram of Thoracic Inlet

Figure 12. Prototype IOM sampler for inhalable and thoracic dust in the ambient atmosphere

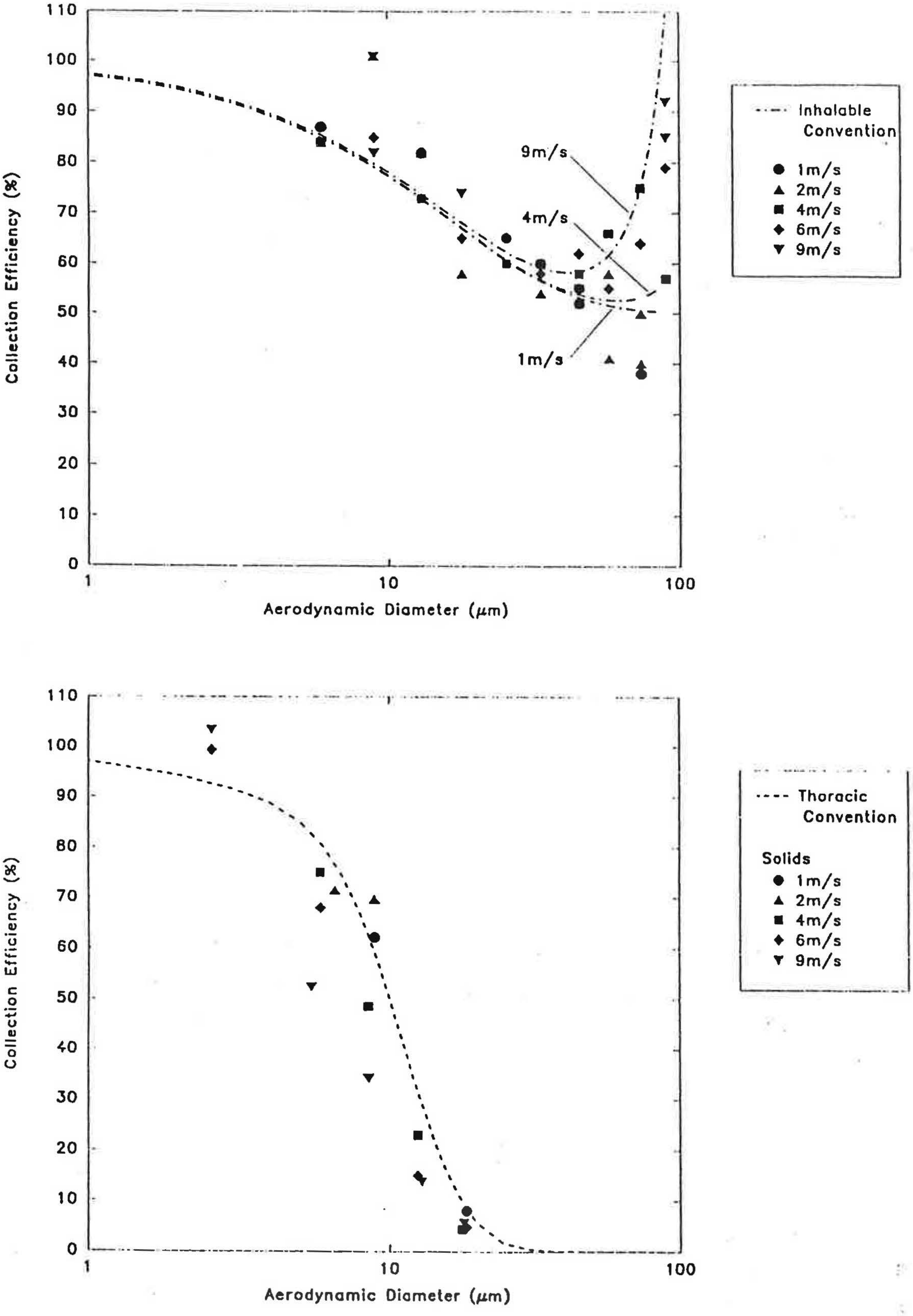
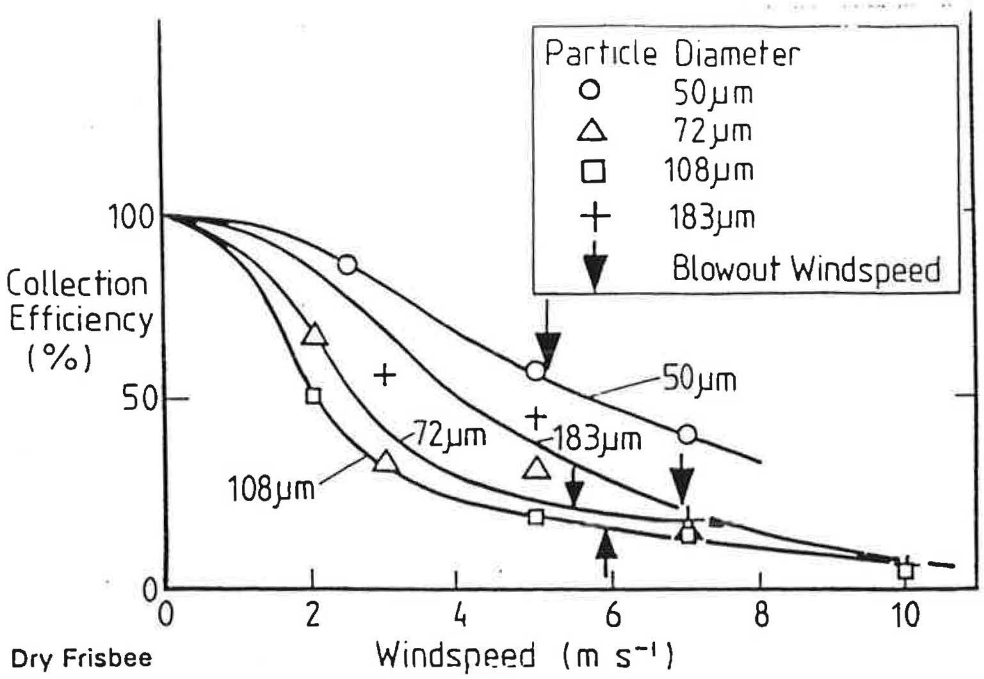
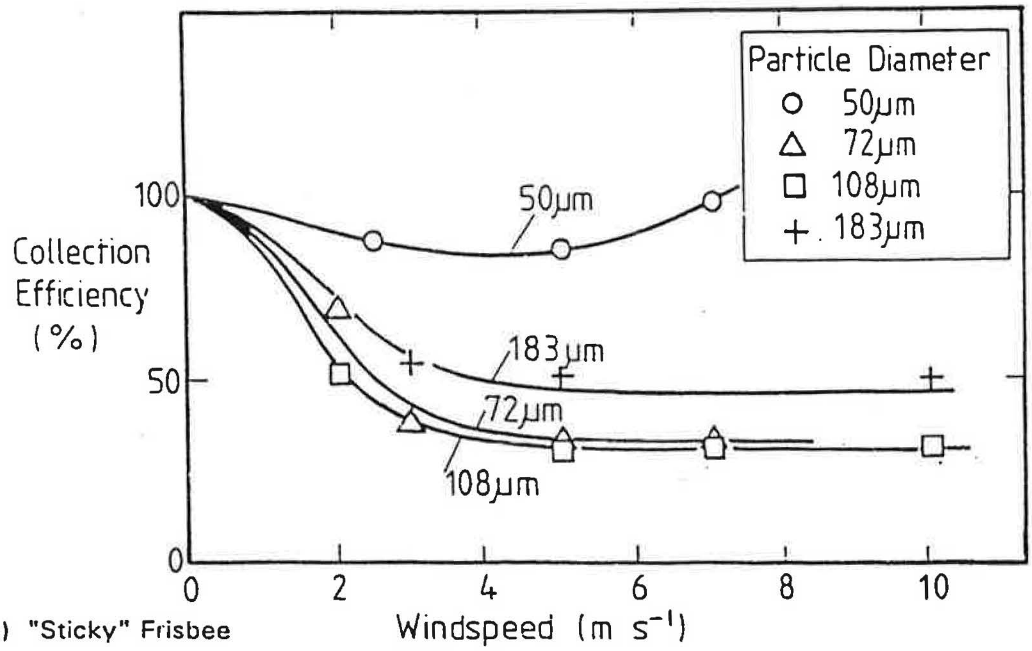


Figure 13. Performance of IOM sampler; a) inhalable dust, b) thoracic dust

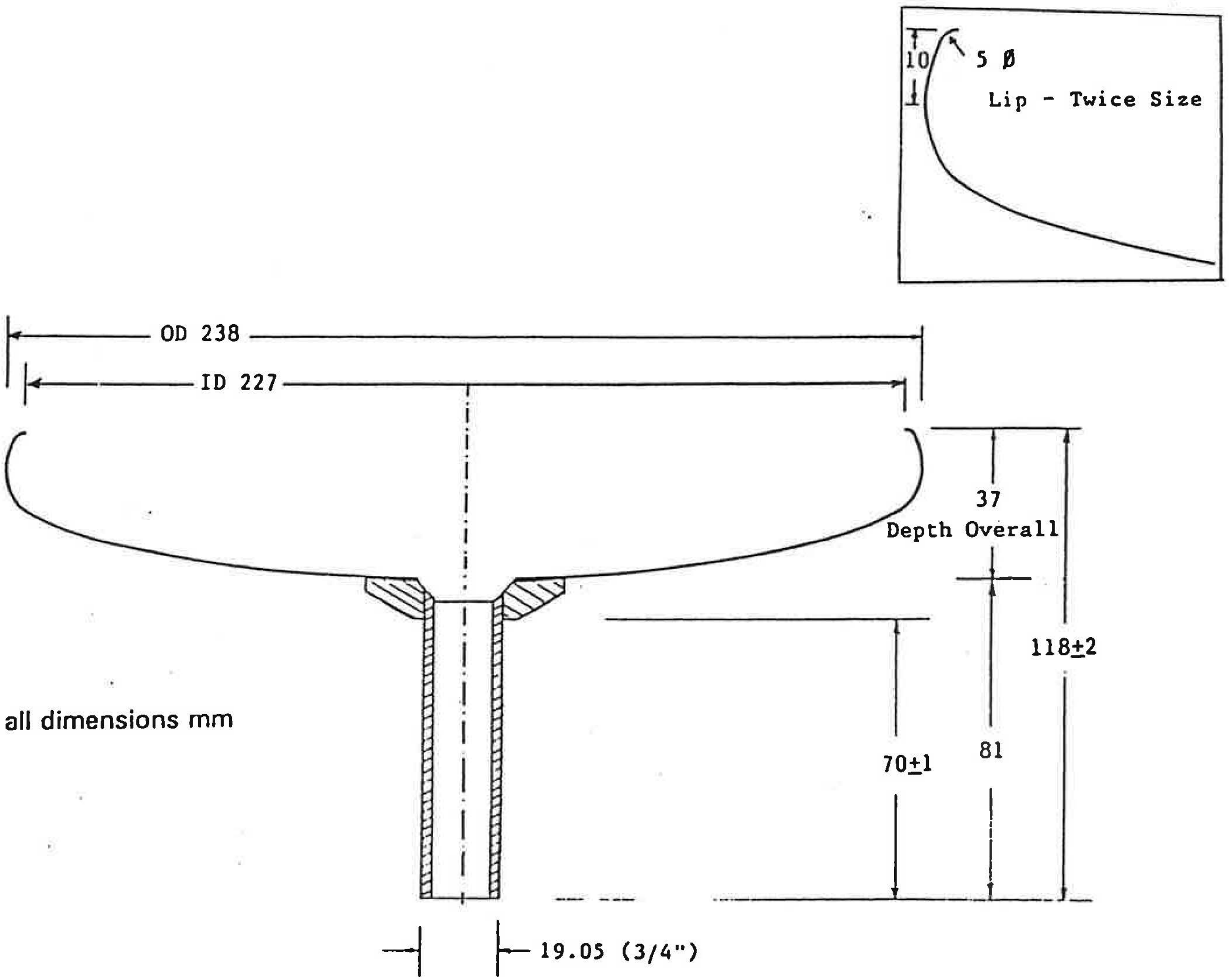


a) Dry Frisbee



b) "Sticky" Frisbee

Figure 14. Performance of inverted frisbee gauge



all dimensions mm

Figure 15. Section through metal frisbee

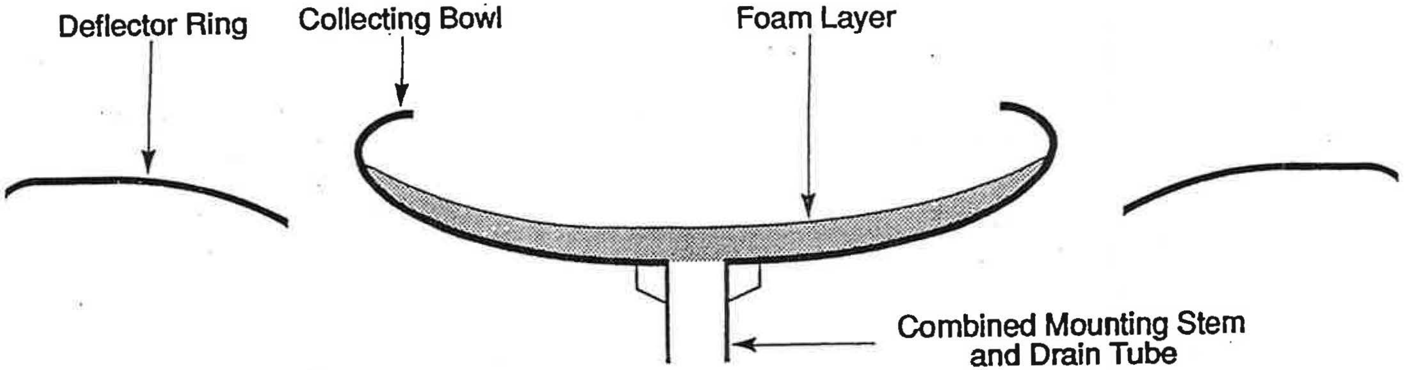
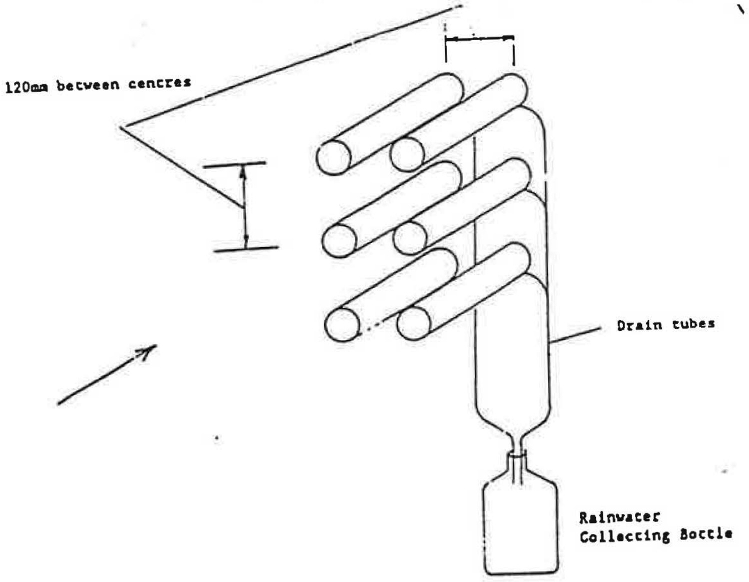
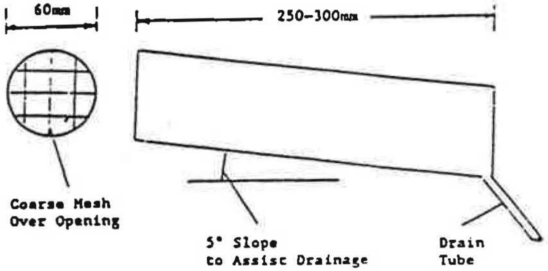


Figure 16. Cross Section Through the Collecting Head of the Improved Design of Deposition Gauge



Layout of Sampling Tubes



Individual Sampling Tube

vii) Small Cylindrical Collector with flare

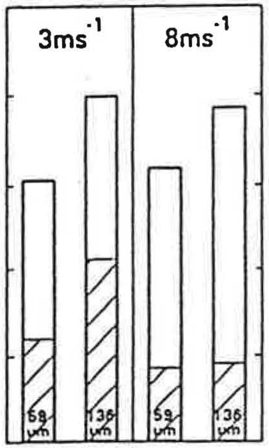


Figure 17. Tentative Design for a Closed Container Flux Gauge.

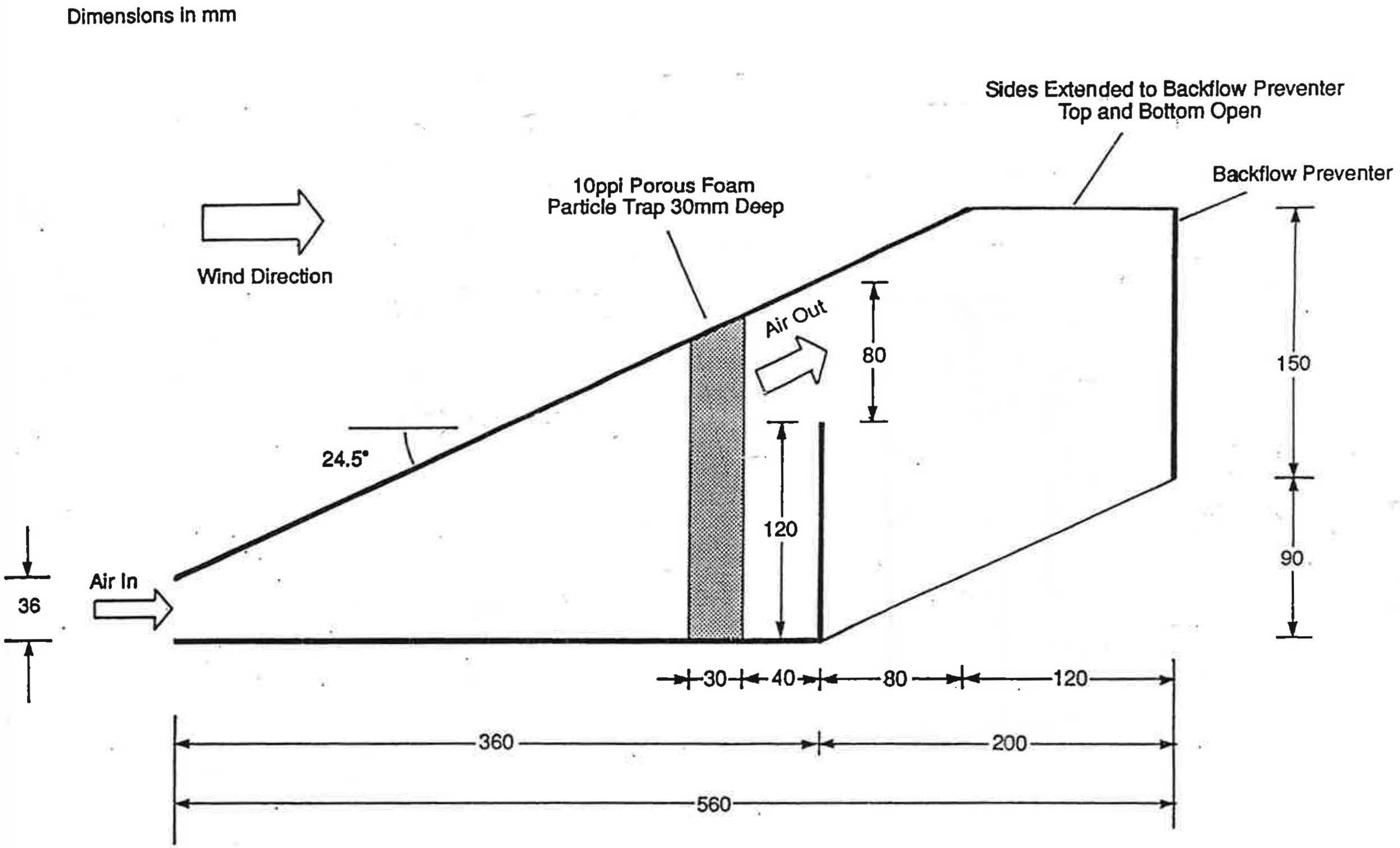


Figure 18. Cross Section Through the Improved Design of Flux Gauge

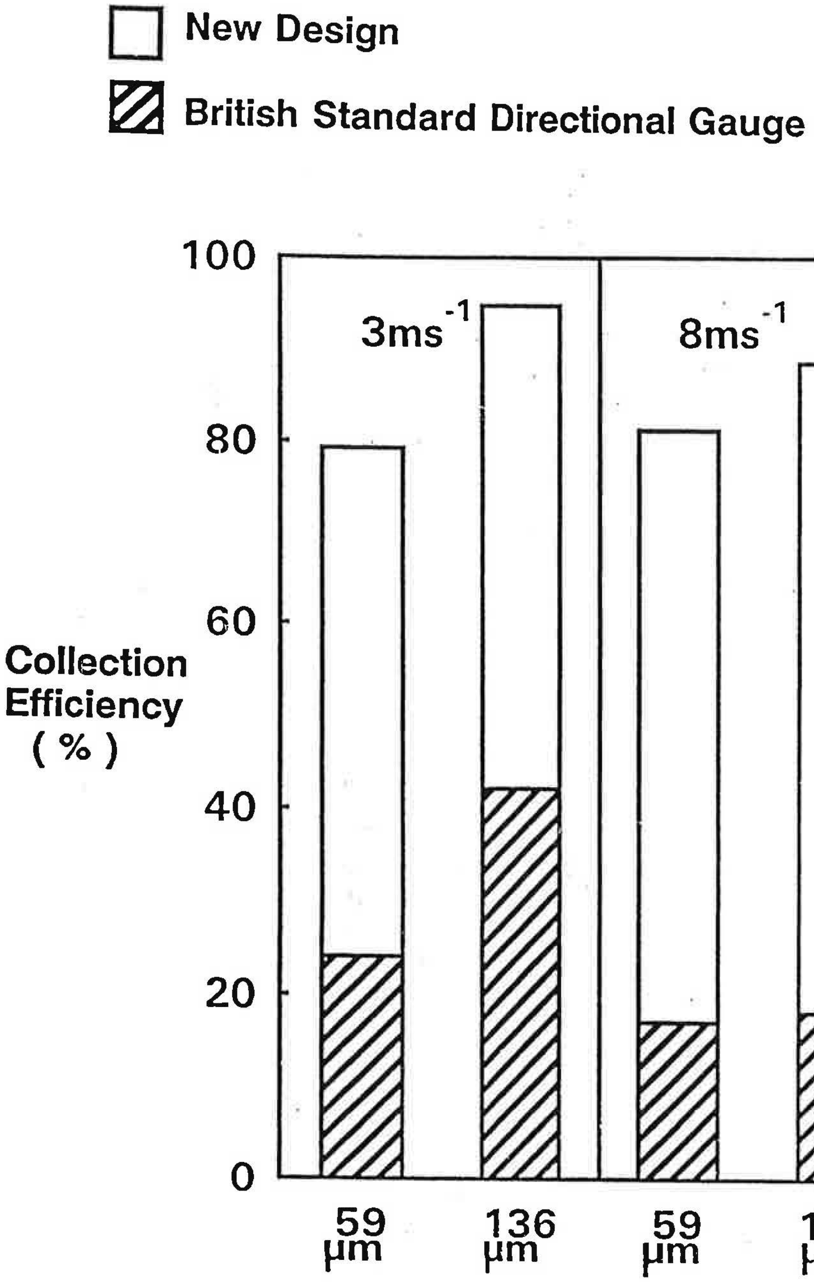


Figure 19. Performance of the Improved Design of Flux Gauge