EA - NCAS Box 2

Desktop Study of Methods for the Monitoring of Particulate Emissions from Positively Pressurised Baghouses

ENVIRONMENT AGENCY

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Preface

The monitoring of emissions to atmosphere from positively pressurised baghouses, commonly used within the UK steel industry, poses practical difficulties which environmental regulators and the industry have attempted to overcome, but with limited success so far. As a result, the level of compliance monitoring which can currently be practised is limited.

British Steel Engineering Steels and the Environment Agency's National Compliance Assessment Service have jointly funded a study to identify practical options for continuous or semi-continuous monitoring of such emissions. The study has been undertaken by British Steel's Swinden Technology Centre, Rotherham, under the guidance of a steering committee comprising :

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Executive Summary

Within the UK steel industry, some large bag filters are operated with extraction fans upstream of the filter itself. Such filters are termed positively pressurised baghouses and monitoring the emissions from these plants poses practical difficulties because the waste gases are emitted through a vent at the apex of the baghouse roof, rather than through a conventional stack or outlet duct. British Steel Engineering Steels and the Environment Agency jointly commissioned this report into techniques which may be developed to quantify emissions of particulate material and to check the operation of such filters. The report considers over a dozen potential methods of monitoring, some using existing techniques and others requiring the development of novel monitoring methods.

A two-dimensional model of the top part of one baghouse geometry was developed using computational fluid dynamics (CFD). This exercise concluded that there may be no single position within a typical baghouse where a sample which is equally representative of the emissions from the whole width of the plant can be taken. The most suitable sampling position will be at one of the points across the width of the vent throat where the velocity is a maximum.

Initially, potential techniques were assessed to determine their suitability for achieving the objectives of the study, their overall cost and practicability of operation. In addition, an assessment of the likelihood of successful application of each technique, bearing in mind the current status of the technology, was made. The initial evaluation suggested that three techniques were worthy of more detailed assessment.

The first of these is the use of an obscuration meter to monitor the reduction in the intensity of a light beam transmitted along the length of the baghouse vent, which can be related to dust concentration. Secondly, an extraction duct could be used to continuously withdraw a composite sample from several positions along the length of the vent and bring the sample to an accessible location where the particle concentration can be measured by conventional means. Thirdly, one or more triboelectric probes, which monitor the small electrical charges acquired by particles as they pass through a gas stream and relate the measured current to dust concentration, could be installed in the roof vent. The obscuration meter and triboelectric probes would need to be calibrated in-situ to provide quantified emissions data, and so a fourth technique, extracting a sample through permanently installed narrow bore tubing, has also been evaluated as a calibration method.

The detailed assessment concluded that all three suggested techniques (using the permanent narrow bore tubing method for calibration where necessary) could be used for quantitative monitoring of emissions from positively pressurised baghouses. Consideration of the sources of measurement error concluded that the errors would probably not exceed -44 % to +52 % so long as at least six sampling positions were used.

Each of the techniques has advantages and disadvantages and the final choice of monitoring method for any particular application may depend on the weight given to these other factors. The obscuration meter gives a more representative result than the other methods and is more likely to detect short term emissions attributable to torn or fallen bags. The continuous extraction duct can be used to measure baghouse emissions other than particulates by substituting a different analysis method. The in-situ triboelectric probes provide data attributable to individual compartments, rather than to the whole baghouse, and the effect of spurious readings from off-stream compartments can be minimised. Different operators may therefore choose different solutions, depending on their particular requirements.

Contents

List of Appendices

List Of Figures

1 Introduction

Particle removal from industrial waste gas streams can be effected by a number of different types of equipment, including electrostatic precipitators, cyclones, scrubbers and filters. In most instances, the cleaned waste gases are then discharged to atmosphere through a stack or outlet duct, in which measurements of the residual particulate concentration can be made to quantify the emission and to check on the satisfactory operation of the gas cleaning plant.

Within, for example, the steel industry, some large bag filters are operated with extraction fans upstream of the filter itself. The gas is cleaned by a large number of filter bags, and the waste gases collect in a chamber in the roof of the baghouse and are emitted through a vent at the apex of the roof. Such filters are termed positively pressurised baghouses, and the general layout of such a plant is shown in Figure 1. In these plants, there is no outlet duct in which measurements of dust levels escaping the filter can be made in a conventional manner. British Steel Engineering Steels and the Environment Agency jointly commissioned this report into novel techniques which may be used to quantify emissions and check the operation of such filters. The report considers over a dozen potential methods of monitoring, some using existing technology and others requiring further development work.

Positively pressurised baghouses in the steel industry are typically used to clean gases extracted from processes creating fine metal fume, such as in electric arc furnace direct and indirect extraction systems and in blast furnace casthouse extraction systems. Such installations clean large volumes of air (between 200 and 800 actual m^3/s) at temperatures up to about 130 °C. The inlet dust loadings are variable, depending on process operation, but typical outlet dust loadings for plants in good condition are between 2 and 20 mg/m^3. The baghouses themselves are up to 50 metres long, 15 metres wide and 25 metres high. For cleaning and maintenance purposes, the filter is divided into a number of separate compartments (between 12 and 24), which exhaust into a common chamber above the bags; each compartment contains several hundred filter bags. Generally, the width of the baghouse is divided into two parallel compartments, as shown in Figure 1. At the apex of the baghouse roof, a ridge vent up to three metres wide runs along the length of the filter and the emissions from the baghouse escape to atmosphere through this vent. The applications discussed in this report have been developed with such plants in mind, but they are not plant specific, and positively pressurised baghouses of different dimensions and operating parameters are not excluded.

Bag filters in good condition would be expected to remove a very high proportion of inlet particulates, with residual concentrations no greater than 20 mg/m^3 on average[1]. Poor performance may be due to general deterioration of the bags with age, or to a few bags which are torn, have fallen from their support, or have become detached from the gas distribution plate. Emissions attributable to poor performance are minimised by isolation of parts of the filter where torn or fallen bags are detected until the bags can be replaced, and by replacement of all bags at intervals chosen to prevent significant general deterioration.

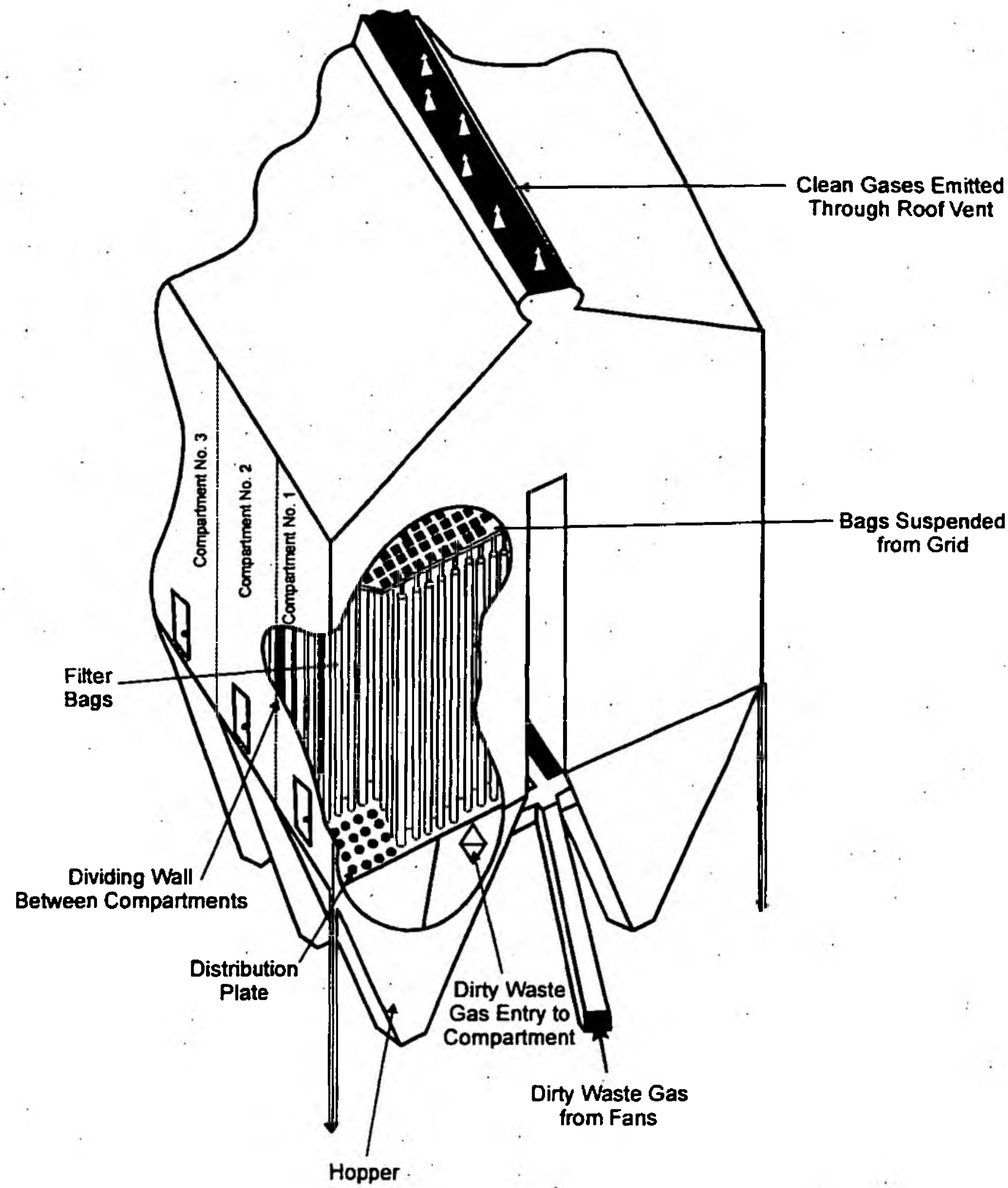


FIG. 1 GENERAL LAYOUT OF BAGHOUSE

2 Objectives and Methodology

Prior to the commencement of the study, meetings took place between personnel from the Environment Agency, British Steel Engineering Steels and Swinden Technology Centre to agree the objectives, scope and methodology to be employed.

2.1 Objectives of the Study

The overall aim of the study was to evaluate potential techniques for continuous or semi-continuous monitoring of average particulate emissions from positively pressurised baghouses. This would include estimation of the worst-case accuracy of selected techniques.

Specific objectives were to develop techniques which would:

- improve on existing monitoring methods.
- quantify the general background dust level emitted by a correctly functioning, well maintained, positively pressurised baghouse.
- detect long term changes in baghouse performance, either by continuous monitoring or by regular discrete measurement.
- quantify the annual mass emission of particulates from a positively pressurised baghouse. Most of the techniques presented here measure particulate concentration, and so to derive mass emission rates, information on waste gas flows will also be required. The measurement of waste gas flows has not been considered in this study.
- apply to a range of sites, not be specific to one plant.
- demonstrate consistent operation over a long time period at the standard of performance demanded by the regulators.

The detection of torn or fallen bags was not a specific objective of the monitoring considered in this study.

2.2 Programme of Work

The programme of work was split into five different phases, which are detailed below.

1. Undertake a literature search to identify potential techniques and current state of the art. This would include a review of the techniques and methods employed in the rest of the UK and abroad.
2. Develop proposed options for measurement techniques. This phase could deliver several potential options which extend or apply the current state of art to positively pressurised baghouses. At this stage, schematic arrangements for apparatus and procedure would be outlined.
3. Undertake an evaluation of the options identified in Phase 2. Estimate the expected accuracy of the techniques proposed. This stage would include two-dimensional modelling of fume flow above the compartments in a baghouse.

4 Cost out and evaluate in greater detail the most promising methods identified in Phase 3. Estimate the expected accuracy of these methods.

5 Document the desk-top study.

3 State of the Art

The current state of the art of monitoring emissions from baghouse vents has been determined from the following sources :

3.1 Swinden Technology Centre

Swinden Technology Centre provides environmental monitoring expertise to British Steel and has been involved in previous exercises to measure and quantify emissions from vents on a number of different types of plant, including positively pressurised baghouses. Four techniques have been employed, as detailed below :

(A) Isokinetic gravimetric sampling at a single position above the filter bags within a compartment or in the throat of the vent. This is a much simplified version of the US EPA Method 5D[2] and can be expected to give results applicable only to the position measured, not to the whole baghouse. Temporary scaffolding may be required to gain access to the sampling position.

(B) Non-isokinetic gravimetric sampling at one or several positions above the filter bags within a compartment or in the throat of the vent using a permanent narrow bore sample line (typically, a length of copper tube). The sample line is brought down to an accessible location where a gravimetric sampler can be set up when required. Attempts to check this method against (A) when emissions were high (bags deliberately removed to increase emissions) were unsuccessful - but this may have been because of poor mixing in the baghouse roof. When emissions were normal, both (A) and (B) gave similar results[3].

(C) Short term continuous monitoring (for periods up to about six hours) using anemometer, thermocouple and particulate measurement device. Dust concentrations were measured with either a hand-held obscuration meter (about 1 cm path length) or a short path obscuration meter mounted on a frame (50 cm path length) at the vent exit, calibrated by reference to simultaneous near-isokinetic gravimetric sampling at the same position[4]. Temporary scaffolding is required to gain access to the top of the vent, and this technique is very labour intensive.

(D) Gravimetric sampling using a high-volume sampler designed for ambient air measurements at a single position above the filter bags within a compartment. Attempts to check this method against (A) were unsuccessful - but this may have been because of poor mixing in the baghouse roof[5]. Access into the compartment is required to set up the sampler.

3.2 Other UK Steelmakers

Amongst the membership of the UK Steel Association, two other techniques have been employed :

(E) Continuous monitoring of obscuration across the vent exit from each compartment[6] or along the length of the vent[7]. This technique operates successfully as an indicative measurement, warning of torn or fallen bags, but has not been calibrated to give a quantitative reading.

(F) Continuous extraction of a composite sample drawn from four positions within a single compartment[6]. The continuous extraction duct was brought down to an accessible location where a triboelectric probe was set up to continuously monitor particulate concentration. Indicative results from this technique were similar to those from (E), but attempts to calibrate the triboelectric probe against isokinetic sampling were unsuccessful.

3.3 Other World Steelmakers

A study published by the International Iron and Steel Institute[8] on environmental technology for electric arc furnace plants shows that the majority of steelmakers outside the UK use suction (negatively pressurised) bag filters, with the fan downstream of the filter and emissions to atmosphere through a stack. Monitoring of emissions can be undertaken in the stack by conventional methods. The main exception is the United States (see section 3.7 below).

A reference[9] to a method of monitoring emissions from the roof vent of the building housing a Basic Oxygen Steelmaking plant referred to a technique similar to (C) above.

3.4 Other Metals Industries

A search of the METEDEX index, covering published articles relating to the metals industries over the past thirty years, revealed only the reference[9] to BOS roof monitoring (see section 3.3 above).

3.5 Other UK Industry

A search by the Environment Agency of techniques employed by other Part A processes did not locate any methods additional to those described above.

3.6 Standards

The only recognised standard method relating to emissions from positively pressurised baghouses is the US EPA Method 5D[2], which involves :

(G) Isokinetic gravimetric sampling over a large number of positions above the filter bags within a compartment or in the throat of the vent. The method specifies minimum numbers of sampling positions per test; for instance if sampling above the bags in a filter with 24 compartments, a minimum of 96 measurements would be required (twelve of the compartments should be monitored and eight sampling positions per compartment used). Temporary scaffolding may be required to gain access to the sampling positions, and this technique is very labour intensive.

The method recommends that at least twelve (or half the total number of compartments, if greater) compartments should be monitored, and that these should be evenly distributed within the baghouse.

3.7 Legislators

The Environment Agency provided contacts with the authors of European environmental technology guidance notes (BREF notes) and with the US EPA. The former[10] confirmed that most European countries use suction bag filters with emissions through stacks, monitored by obscuration meters. The US EPA provided information[11] on another technique, which is said to be employed in the United States:

(H) Triboelectric probes fitted at one position above the filter bags within a compartment or in the throat of the vent. The probes may be fitted with fins to increase the area covered.

3.8 Internet

Searches were conducted on the Internet. The only relevant site found was the US EPA Emission Measurement Centre (*http://www.epa.gov/ttn/emc*), which contained details only of techniques (G) and (H) above.

3.9 Discussion

The table below summarises some attributes of the eight existing techniques identified in sections 3.1 to 3.8.

Technique	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Suitable for continuous monitoring	No	No	No	No	**Yes**	**Yes**	No	**Yes**
Suitable for regular spot monitoring (semi-continuous)	No	**Yes**	No	No	#	**Yes**	No	#
Gravimetric sample	**Yes**	**Yes**	**Yes**	**Yes**	No	*	**Yes**	No
Representative sample	No	No	No	No	**Yes**	No	**Yes**	No

\# these techniques are inherently continuous measurements
* depends on the technique selected for measurement of the composite sample

Only three of the existing techniques - obscuration meter (E), continuous extraction duct (F) and in-situ triboelectric probe (H) - would be suitable for continuous monitoring, and another one - permanent narrow bore tube **(B)** - could be used for regular spot monitoring, since once the sample line is in place, access for sampling is simple. Obscuration meters and triboelectric probes are commercially available systems, the narrow bore tube method has been prototyped on large steelworks baghouses, but the continuous extraction duct would require considerable further development to produce a fully functional system. The other four techniques are not thought suitable for regular monitoring because of the difficulty in providing safe access for the required sampling exercises. Further, two of these other techniques are very labour intensive.

If the measurement technique selected is to provide a quantifiable result, then measurements should either be undertaken gravimetrically, or by a method that can be calibrated against a gravimetric measurement. Direct gravimetric measurement methods are not ideally suited to continuous monitoring, since there will be a requirement to change the collection medium at regular intervals. In most cases, it will also be necessary to weigh these to obtain the dust concentration, and so results will not be available immediately. In addition, the outcome will be an average result over a period, rather than a continuous measure of concentration variation, though as discussed in section 9.4, this may not be a significant disadvantage. These disadvantages do not apply to spot sampling, and so gravimetric sampling is suitable for semi-continuous monitoring techniques.

Calibration of non-gravimetric analysis methods may not be a straightforward exercise, since gravimetric samples must be taken from close to the position where measurements are made. In addition, techniques such as obscuration meters and triboelectric probes can be affected by some characteristics of the dust or the gas stream. Such characteristics include particle size distribution, density and colour of the particles and gas velocity, and these may not remain constant over time.

As discussed in section 4 below, mixing of the gases between the top of the bags and release to atmosphere may be poor, depending on the geometry of the baghouse, and it may not be possible to obtain a wholly representative sample when using a measurement technique reliant on sampling or measurement at only one or a few positions. Only two of the existing techniques - obscuration meter (E) and US EPA Method 5D (G) - will give a representative sample in a typical baghouse, though further development of some of the other techniques may make them more representative, as discussed in section 6.

3.10 Conclusions

Eight existing techniques for monitoring emissions from baghouse vents have been identified. Only four of these are thought suitable for continuous or semi-continuous monitoring, and will be further evaluated in section 6 along with ideas for new techniques.

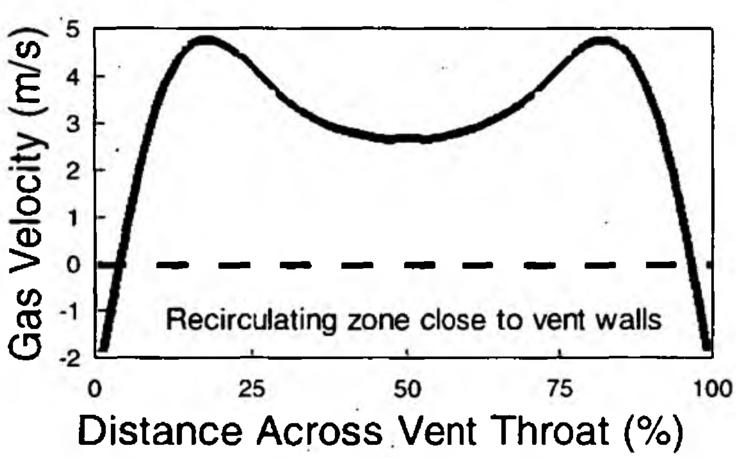
4 Flow Distribution

In order to achieve satisfactory cleaning efficiencies, gas velocities through filter media in baghouses must be low, and the upward velocity of the gas stream entering the space above the bags in a typical installation is less than 2 m/s. The gas velocity increases as it rises into the narrowing roof space, but even at the throat of the vent, a typical velocity may be only 4 to 8 m/s. Such flows do not promote mixing of the gases rising to the vent, and so may make it difficult to obtain a representative sample when using a measurement technique reliant on sampling or measurement at only one or a few positions.

To investigate the magnitude of potential flow maldistribution, a two-dimensional model of the top part of a typical baghouse has been developed using computational fluid dynamics (CFD). This exercise examined only one baghouse geometry, which was expected to exhibit the greatest flow maldistribution, and so the results represent a worst case situation. Details of the modelling exercise are included in Appendix A, and Figure 2 below illustrates the predicted distribution of velocity in the vent throat.

FLOW DISTRIBUTION IN VENT THROAT

FIGURE 2



The conclusion of the modelling study is that there may be no position within a typical baghouse where a sample which is equally representative of the emissions from the whole width of the plant, or even of one compartment, can be taken. The most suitable sampling position will be at one of the points across the width of the vent throat where the velocity is a maximum. If samples are taken at, for instance, 20% of the distance across the vent throat, then they may only be indicative of the emissions from half the compartments in the baghouse, though provided that there is no systematic difference between the two halves of the filter, this may be adequate to represent emissions from the whole plant.

5 Isokinetic Sampling

The accuracy of any particulate measurement technique which extracts a sample from a gas stream, rather than measuring in-situ, may be affected by any difference between the sampling velocity and the gas velocity. If the velocity at which gas is drawn into the sampling device is greater than the undisturbed gas velocity at the same point, then large particles with relatively high momentum may not follow the gas streamlines and some will not enter the sampler, resulting in a concentration measurement which is lower than the true value. The opposite is true when the sampling velocity is lower than the gas velocity - the measured concentration of large particles will be greater than the true value. To avoid these errors, gas sampling in ducts[12] is generally undertaken isokinetically, i.e. the sampling velocity is set equal to the gas velocity.

As particle size, and hence momentum, decreases, the errors in non-isokinetic sampling also decrease. Methods for estimating the magnitude of these errors are described in Hawksley *et al.*[13], and Figure 3 shows the variation of likely error with sampling velocity and particle size for a nozzle diameter of 15 mm, particle density 4200 kg/m³, undisturbed air velocity 5 m/s and air at 100 °C (density = 0.95 kg/m³, viscosity = 2.1 x 10^{-5} kg/m/s). Appendix B details the method used to calculate the data for Figure 3.

ERRORS FROM NON-ISOKINETIC SAMPLING

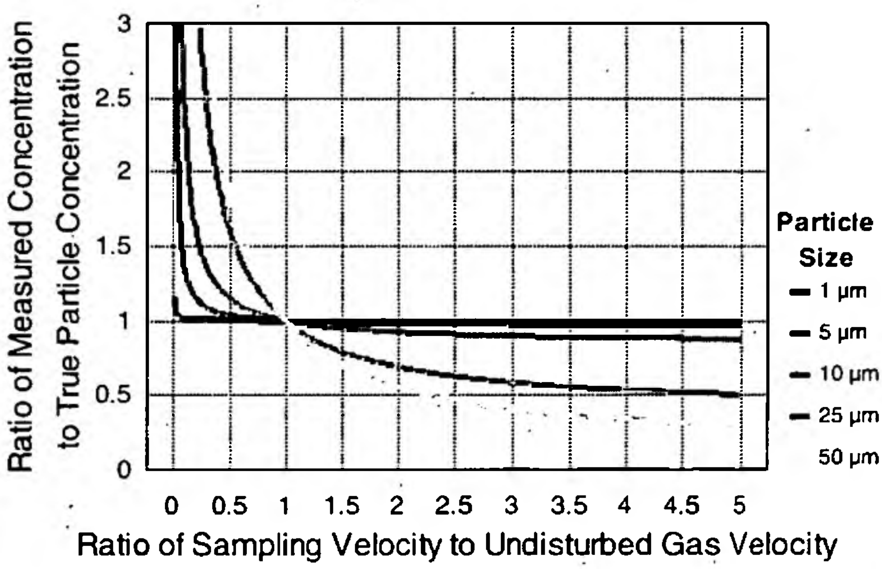


FIGURE 3

At least 90 % of the fine metal fume typically treated by bag filters in the steel industry is below 10 µm diameter, and around 80 % is below 2.5 µm. Figure 3 shows that for such particles, non-isokinetic sampling errors are generally small, and so maintaining the sampling velocity at the gas velocity may not be critical to the accuracy of the measurement, though wherever possible, sampling rates should be close to isokinetic. Sampling at a higher velocity than the undisturbed gas flow gives rise to lower errors than sampling at a lower velocity.

In applications outside the steel industry, it is possible that larger particles may be encountered, and non-isokinetic sampling errors may then become more significant. However, bag filters are generally employed to clean gases containing fine dusts - larger particles may be removed with cyclones or other techniques - and so it is not expected that this problem will arise.

6 Development and Initial Assessment of Potential Methods

This section describes a number of potential techniques for continuous or semi-continuous quantitative monitoring of particulate emissions from positively pressurised baghouses, some developed from existing methods (see section 3) and some ideas for new techniques. These techniques are then evaluated to assess their suitability for achieving the objectives of the study (see section 2), their overall cost and their practicability.

6.1 Development of Existing Methods

Three of the existing techniques identified in the literature search were considered suitable for continuous or semi-continuous monitoring (see section 3.10). These are further described in the following sections.

6.1.1 Permanent Narrow Bore Tube (B)

Permanent sample lines (prototypes are 15 mm diameter copper tubing) could be installed in the vent throat; the number of lines depending on the accuracy required. In the throat, the tube may simply be open-ended, directed to face the gas flow, or a T-piece may be fitted to extract a composite sample from several positions. The line would terminate at an easily accessible location, and at intervals gravimetric sampling equipment would be connected to the lines and measurements undertaken.

6.1.2 Obscuration Meter (E)

An obscuration meter comprises a light source and a detector some distance away. Particulates passing between the two reduce the intensity of light detected and this change can be related to dust concentration. Obscuration meters could be installed either across the width of the baghouse roof vent to monitor emissions from two compartments or, if a sufficiently powerful light source is used, along the length of the vent to determine emissions from a series of compartments. Calibration of such an instrument with simultaneous gravimetric sampling would be required to allow quantification of the emissions.

6.1.3 In-situ Triboelectric Probe (H)

Triboelectric probes monitor the small electrical charges acquired by particles as they pass through a gas stream. These charges are imparted to the probe either by impact (DC probes) or by induction (AC probes). The resulting current can be measured and related to dust concentration. When monitoring large particles, such devices can only be used where the gas velocity exceeds about 3 m/s and does not vary by more than ±10 %[14]; though for small particles this limitation may not apply[15]. Several probes could be installed in the vent throat; the number will depend on the accuracy required. Calibration of such instrumentation with simultaneous gravimetric sampling would be required to allow quantification of the emissions.

6.2 Development of New Methods

A number of novel ideas for methods to undertake continuous or semi-continuous monitoring of particulate emissions from positively pressurised baghouses have been considered. Most of these methods would require calibration against a gravimetric measurement, but calibration techniques have not been specifically addressed at this stage. The methods are further described in the following sections.

6.2.1 Continuous Extraction Duct (F)

Although already used on a small scale[6] in one installation in the UK, a considerable amount of further development would be required to produce a fully functional monitoring system based on continuously extracting a composite sample. The sample could be continuously drawn from several positions along the length of the baghouse vent, through a duct of around 150 mm diameter. The collection duct should be designed to withdraw equal gas volumes from each position, and to operate at close to isokinetic sampling rates. The duct would be brought down to an accessible location where particulate concentration would be measured; any suitable measurement method could be utilised. If regular gravimetric sampling were used, then this technique would be similar to the permanent narrow bore tube method (B) and so this option will not be considered further. Instead, it is assumed that an instrument such as a triboelectic probe, obscuration meter or ß-gauge would be used to continuously measure particulate concentration. Sample ports would be provided to allow calibration of the selected monitor against gravimetric sampling.

Since the volume of waste gas withdrawn may be several cubic metres per minute, consideration must be given to the safe discharge of this gas after measurement. Discharging the gas into the "dirty" side of the baghouse, upstream of the filter bags, would subject the monitoring system to fluctuating pressures, which may affect the set-up of the flows in the collection duct. Hence the waste gas should either be returned to the "clean" side of the baghouse, or exhausted to atmosphere at a safe location.

6.2.2 Optical Monitoring - External (I)

A bank of lights could be positioned above and external to the baghouse roof vent. A camera up to 100 metres away would be aimed at these lights and as particles emerge from the vent, the lights would be partially obscured. This would be registered by the camera, which would effectively function as an obscuration meter, but using several light sources to cover a large area of the vent, rather than just one beam of light. Additional lights positioned on the baghouse could be used as a reference to eliminate the effect of atmospheric conditions.

6.2.3 Infra-Red Monitoring - External (J)

An infra-red camera up to 100 metres from the baghouse could be used to observe the warm waste gases emerging from the baghouse roof vent. Particles in the gas stream would emit infra-red radiation, which would be detected by the camera, and this may be related to dust concentration.

6.2.4 Optical Monitoring - Internal (K)

Similar in principle to the external option (I), but with lights and camera inside the baghouse. A bank of lights could be positioned internally across each end of the baghouse, above the filter bags. Cameras would also be mounted on each end wall, aimed at the lights on the opposite wall. The cameras and lamps would function as obscuration meters covering a plane above the bags.

6.2.5 Vibrating Rod (L)

A rod could be installed in the vent throat and the natural frequency of oscillation of the rod measured. As dust collected on the rod, the frequency would change and this change may be related to the mass of dust which has settled (in a similar manner to the operation of the TEOM ambient air monitors), and to the dust concentration in the waste gas stream.

6.2.6 Continuous Wire (M)

A continuous wire could be stretched between pulleys along the length of the baghouse. Dust would collect on the wire, and at intervals the pulleys could rotate and the dust would be scraped off the wire onto a balance. The incremental mass of dust which has settled would be recorded and related to dust concentration.

6.2.7 Moving Trolley (N)

A trolley could be mounted on rails in the void below the baghouse vent. Instruments could be mounted on the trolley and moved to sample at any desired location within the plant. The trolley would either move steadily along the vent to provide semi-continuous coverage of the whole filter, or sample at specific locations within the baghouse to measure emissions from a particular position.

6.3 Other methods

Three further methods were suggested, but rejected without detailed consideration as explained below :

(O) LIDAR equipment detects light reflected from species within the atmosphere in a manner analogous to RADAR. No such equipment is available for purchase, having to be purpose built at a cost of £500,000 to £750,000. The equipment is available for hire, but this is not considered acceptable when regular checks may be required, and the cost of building is prohibitively expensive for a technique which is unproven in this application.

(P) Particle counting equipment is generally for use in clean rooms and vacuum chambers and is considered unsuitable for this application.

(Q) TEOM monitors can continuously monitor airborne particulate concentrations, but currently available models are designed for concentrations typically found in ambient air. Development of types for stack sampling is proceeding, and when these are available they could be used in the same way as other continuous particulate monitors, for instance to measure dust concentration in the continuous extraction duct system (F). A disadvantage of the TEOM over triboelectric or obscuration monitors is that it will require regular changes of the collection medium.

6.4 Initial Assessment

Each of the ten potential techniques in sections 6.1 and 6.2 has been assessed to determine its suitability for achieving the objectives of the study, its overall cost and the practicability of operation. In addition, an assessment of the likelihood of successful application, bearing in mind the current status of each technology, has been made. These assessments are included in Appendix C, and are summarised in the table below :

	Permanent Narrow Bore Tube	Obscuration Meter	Continuous Extraction Duct	In-Situ Triboelectric Probe	Optical Monitoring - External	Infra-Red Monitoring - External	Optical Monitoring - Internal	Vibrating Rod	Continuous Wire	Moving Trolley
Technique	**B**	**E**	**F**	**H**	**I**	**J**	**K**	**L**	**M**	**N**
Achievement of Objectives										
Quantifies general background dust level	A	B	A	B	C	C	C	C	C	A
Detects long term changes in performance	A	A	A	A	A	A	A	B	B	A
Quantifies annual particulate mass emission	B	B	A	B	C	C	C	C	C	B
Cost										
Cost of developing technique to practical state	A	A	A	A	C	B	C	C	A	B
Capital cost (including installation)	A	A	B	B	C	B	C	B	B	B
Operating costs	C	B	A	A	A	A	A	A	A	C
Practicability										
Ease of calibration	A	B	A	B	B	C	B	C	C	A
Representative sampling	B	A	B	B	A	A	A	B	A	A
Continuous operation	C	A	A	A	A	A	A	A	B	C
Stability of operation	A	A	A	A	A	C	B	A	A	A
Maintenance requirements	A	A	A	A	A	A	B	A	B	B
Likelihood of Success										
Amount of initial design work	A	A	B	A	C	C	C	C	B	B
Requirement for prototype	A	A	A	A	B	B	B	B	C	A
Likelihood of further development being required	A	A	A	A	C	C	C	C	B	B

A = most favourable; C = least favourable

6.5 Discussion and Conclusions

Of the existing techniques, none is considered entirely suitable, but the obscuration meter or in-situ tribolelectric probe (E and H) could be developed further to largely achieve the objectives of the study. Using these techniques, the measurement would be undertaken within the baghouse vent and in-situ calibration would be required. The permanent narrow bore tube (B) may be a suitable calibration technique, and so this has also been included in the detailed assessment.

With the exceptions of the continuous extraction duct and moving trolley (F and N), most of the novel techniques developed in section 6.2 are considered to be difficult to calibrate, and hence may not achieve the objective of quantifying the emissions from a baghouse. These techniques also have a high risk of failure, since significant development work would be required, and they will not be further considered in this study. The novel moving trolley is not considered to have significant advantages over other sampling techniques, and will also not be further considered in this study. The continuous extraction duct could be developed further to largely achieve the objectives of the study and so will be carried forward to a more detailed evaluation.

A further assessment of the three possible continuous monitoring techniques (obscuration meter, continuous extraction duct and in-situ triboelectric probe) and a calibration technique (permanent narrow bore tube) is detailed in section 7 below.

7 Detailed Assessment

This section of the report considers the four methods selected in section 6.5 in more detail. In all cases it will be assumed that monitoring will be undertaken at one of the positions of maximum velocity across the width of the vent throat, ascertained from an initial velocity traverse. The design of baghouse ridge vents means that there will generally be two positions of maximum velocity in the throat (as illustrated in Figure 2). Provided that there is no systematic difference between the two halves of the filter (as might arise, for instance, if all the compartments on one side of the filter are fitted with new bags whilst the other half has older bags), then the analysis in section 9.1 demonstrates that monitoring at just one of the positions will be adequate to represent emissions from the whole plant. The assessment of errors also suggests that a minimum of six sampling positions should be used along the vent throat, and that accuracy would be improved by using twelve or more positions.

Current (July 1998) cost data for all the selected techniques are provided in Appendix D, and section 7.5 summarises the data in the form of total costs for one typical baghouse.

7.1 Obscuration Meter

Previous work undertaken by Swinden Technology Centre[7] has demonstrated that an obscuration meter installed along the length of a baghouse vent is sensitive enough to detect the increased emissions caused by torn bags when a compartment is returned to service after cleaning. In conventional through-beam obscuration meters used to monitor stack emissions, the reduction in light intensity as particles pass between the light source and the detector can be linearly related to average dust concentration along the light path (see section 7.1.1). It is envisaged that with suitable calibration, a long path obscuration meter monitoring along the vent could be used to quantify the average dust concentration in the waste gases leaving the baghouse. Calibration is further discussed in section 8.1.

The accuracy of through-beam obscuration meters is quoted as the product of the minimum detectable change in dust concentration and the length of the light path, and is typically[15] 5 mg/m^2. Hence for a 50 m baghouse, the accuracy would be expected to be aboutt $\pm$0.1 mg/m^3, and for a 20 m long vent $\pm$0.25 mg/m^3. Obscuration meters using laser light may show an improvement in sensitivity.

The correct alignment of the light source and detector is critical to the operation of the obscuration meter. Since the path length may be up to 50 metres, small deflections as the baghouse warms up or cools down could produce a significant misalignment and so careful consideration must be given to the mounting arrangements to prevent this.

During a bag cleaning cycle, or when a compartment is taken off-stream for maintenance, the air flow through a compartment ceases. Even if the mean particle concentration in the gases emitted to atmosphere remains the same when one compartment is taken off-stream, the mean concentration along the light path may change because a portion of the light beam crosses the off-stream compartment. The obscuration meter output may therefore change, even though the actual particle concentration has not changed, but this effect is not expected to cause problems in the overall monitoring system, so long as no more than 20% of the compartments along the length of the light beam are off-stream.

Such an obscuration meter would be expected to monitor the general background dust level emitted by a positively pressurised baghouse and to detect long term performance changes. With suitable calibration, the emissions could be quantified to demonstrate compliance with performance standards and to estimate particulate mass emission rates. Short term emissions attributable to torn or fallen bags will also be detected if the plume intersects the light beam. The technique is not plant-specific, and so it meets the objectives of the study detailed in section 2.1.

7.1.1 Theory of Operation

The Beer-Lambert Law relates the attenuation of light intensity to the mean concentration of particulates along the light path :

$$I = I_0 \, e^{-kc}$$

where the meaning of the symbols used is detailed in the table below.

The value of the factor k is sensitive to particle characteristics such as size distribution, density and colour, and these may vary with process operation. The transmission is defined as I / I_0, and hence :

$$T = e^{-kc} \qquad \text{or} \qquad 1 / T = e^{kc}$$

Finally, the extinction is defined as ln (1 / T) and so :

$$E = k\,c$$

The above theory demonstrates that the extinction should be linearly related to the average dust concentration along the path of the light beam, so long as the factor k does not vary greatly. This is confirmed by instrument manufacturers[15], and means that the obscuration meter may be adequately calibrated by a single measurement. If the mean particulate density over a period of time can be established, then the factor k can be calculated and the obscuration meter can be used to quantify the concentration of particulates in the waste gases passing through the baghouse vent.

		Units
c	average concentration of particulates along the path of the light beam	mg/m^3
E	extinction	-
I	measured light intensity	-
I_0	light intensity when light path is clear of particulates	-
k	constant	m^3/mg
T	transmission	-

7.2 Continuous Extraction Duct

The continuous extraction duct method can be split into two separate areas. The duct and extraction fan collect a composite sample of the waste gas stream from along the length of the baghouse vent and transport it to a suitable measurement location. In a separate step, the particulate material in the duct can be measured by any conventional analysis technique, as illustrated in Figure 4. The duct may be designed to draw a sample along the whole length of the vent, or it may be T-shaped to draw the samples along half the vent length and extract the sample from the centre of the duct (labelled "Alternative route" in Figure 4). In large baghouses, it may not be possible to design a duct which can operate over the whole vent, and two ducts may be required in such installations.

During a bag cleaning cycle, or when a compartment is taken off-stream for maintenance, the air flow through a compartment ceases and the gas drawn from a position above the compartment being cleaned will not be typical of emissions to atmosphere. The volume of waste gas extracted from this position will continue to be the same as from the positions located above operating compartments, and so the composite sample will not be exactly representative of overall emissions to atmosphere. This effect is not expected to cause problems in the overall monitoring system, so long as no more than 20% of the compartments along the length of the light beam are off-stream.

Such a system would be expected to monitor the general background dust level emitted by a positively pressurised baghouse and to detect long term performance changes. The particulate analysis equipment could be calibrated against a gravimetric technique to quantify the emissions to demonstrate compliance with performance standards and to estimate particulate mass emission rates. Short term emissions attributable to torn or fallen bags may not be detected if mixing in the baghouse roof is poor, since the proportion of the total waste gases sampled will generally be less than 0.1 %. Since the particulate analysis is separate from the waste gas collection, the composite sample could also be analysed for other gaseous or particulate species. The technique is not plant-specific, and so it meets the objectives of the study detailed in section 2.1.

Calibration of the selected particulate analysis technique can easily be undertaken if sample ports are provided in the duct to allow gravimetric sampling. It should be noted that continuous techniques such as obscuration meters or triboelectric probes used in this technique may be affected by changes in particle characteristics as described in sections 7.1.1 and 7.3.

7.2.1 Design Calculations for Collection Duct

The design of the continuous extraction duct must take into account the following requirements :

- The number of sampling positions along the length of the duct should be sufficient to produce a representative composite sample. It is recommended that a minimum of six positions are used, and that these should be equally distributed between the compartments monitored (hence if there are eight compartments, either eight orsixteen positions should be used with one or two above each compartment).
- The transport velocity along the extraction duct should be sufficient to minimise particle settling.
- The sampling velocity through each inlet should be approximately equal to the undisturbed gas velocity in the vent throat; typical velocities will be 4 - 8 m/s.
- The sample volume flow through each inlet in the duct should be approximately equal to maintain representative sampling.

- The diameter of the inlets should not be so small as to be easily blocked by dust build-up. It is recommended that a minimum diameter of 25mm is used.

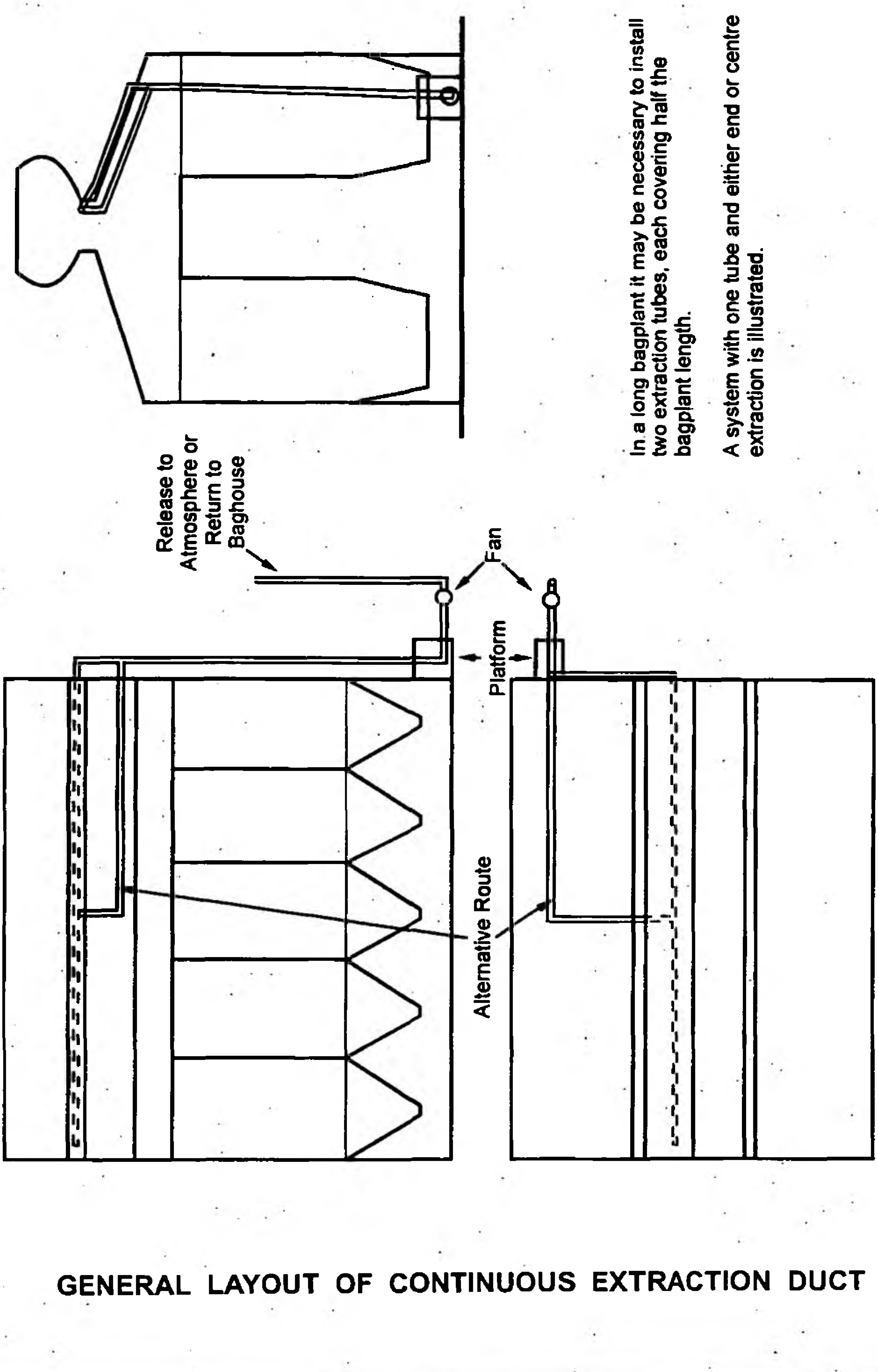


FIG. 4 GENERAL LAYOUT OF CONTINUOUS EXTRACTION DUCT

To achieve the above criteria may require a complex design, and some compromises will have to be made. The diameters of the inlets may need to vary to ensure equal volume flows through each as pressure changes along the length of the duct. A stepped tube, rather than one of constant diameter, may be necessary to maintain the required transport velocity along the whole length. Appendix E details the equations used to design the continuous extraction duct, and gives an example that can be used as a guideline for design in other baghouses.

7.3 In-Situ Triboelectric Probe

To obtain a representative result, several matched triboelectric probes could be placed along the length of the baghouse vent to provide continuous monitoring. The number of probes considered necessary would depend on the baghouse size and the coverage required (see Figure 5); it is recommended that a minimum of six probes are used. It is envisaged that with suitable calibration, triboelectric probes monitoring in the vent could be used to quantify the dust concentration in the waste gases leaving the baghouse. Calibration is further discussed in section 8.3.

Where triboelectric probes are used to monitor large particles, the output is sensitive to changes in gas velocity (the variation must be no more than ±10 %), and the velocity should be greater than 3 m/s. In cases where these criteria are not met, an array of fans would be required to accelerate the gases over the probe and provide satisfactory monitoring performance. The design of such an array is discussed in Appendix F. During normal operation, the velocity in the vent throat for typical baghouses in the steel industry is greater than 3 m/s, though in other plants this may not always be the case. Variations in velocity will occur when compartments are taken off line for maintenance or cleaning, or when the required extraction volume passing through the filter changes as process operations dictate. The magnitude of likely variations in velocity should be taken into consideration when considering the suitability of this technique in any particular application. Where triboelectric probes are used to monitor small particles, the dependence of the output results on gas velocity is reduced[15].

Although there is a theoretical basis for the DC triboelectric system, a similar basis for the AC system does not exist. In practice, AC probes have been found to be more reliable than the DC version. The response of the triboelectric probe to changes in particulate concentration is almost linear[16] so long as the waste gas and particle characteristics remain constant, so that a single point calibration will be adequate. The calibration is sensitive to particle characteristics such as size distribution and density and also to waste gas velocity, and these may vary with process operation.

The minimum detectable dust concentration for the triboelectric probes assessed by Warren Spring Laboratory[16] was below 5 mg/m^3. Further details of the use of triboelectric probes in monitoring emissions from baghouses can be found in reference 17.

During a bag cleaning cycle, or when a compartment is taken off-stream for maintenance, the air flow through a compartment ceases. The waste gas velocity above the compartment will fall and readings from a triboelectric probe located above the compartment being cleaned will be unreliable (unless a fan array is used, but even in this case the measured concentration will not be representative of emissions to atmosphere). This cyclic effect is not expected to cause problems in the overall monitoring system, as the input from probes located above compartments which are off-stream could be disregarded if information on the effected compartments is available. Hence the in-situ triboelectric probe system can be made less sensitive than the other techniques to compartments being taken off-stream.

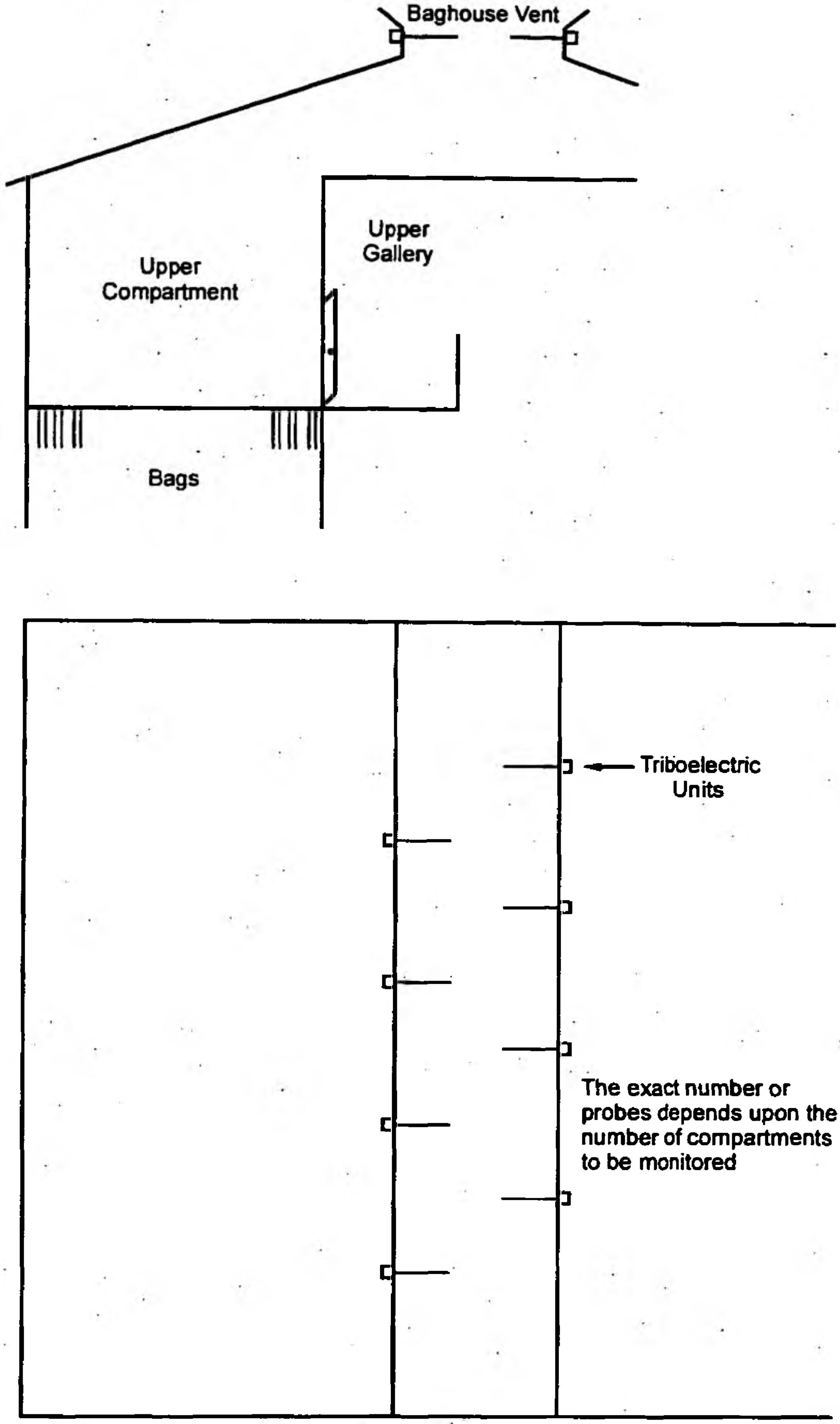


FIG. 5 EXAMPLE LAYOUT OF TRIBOELECTRIC PROBES

Such a system would be expected to monitor the general background dust level emitted by a positively pressurised baghouse and to detect long term performance changes. With suitable calibration, the emissions could be quantified to demonstrate compliance with performance standards and to estimate particulate mass emission rates. Short term emissions attributable to torn or fallen bags may not be detected if mixing in the baghouse roof is poor, since the proportion of the total emission area monitored will be very low. The technique is not plant-specific, and so it meets the objectives of the study detailed in section 2.1.

7.4 Permanent Narrow Bore Tube (Calibration Method)

Discussion of this technique will generally be limited to its application as a calibration method for either the obscuration meter or the in-situ triboelectric probe. A minimum of six continuous lengths of narrow bore tube would be installed leading from suitable locations in the vent throat through connectors in the baghouse wall, providing a permanent, safe method of extracting particulate samples from within an operating bag filter. The location of tubes would be determined by the application. It is recommended that to calibrate an obscuration meter, the tubes should be equally distributed between the compartments monitored. For calibration of triboelectric probes, narrow bore tubes should be located close to each probe requiring calibration. External to the filter compartments, gravimetric sampling trains could be set up when measurements were required; this is illustrated in Figure 6. In the throat, the tube may simply be open-ended, directed to face the gas flow, or a T-piece may be fitted to extract a composite sample from several positions, see Figure 6. Prior to sampling, the line should be cleaned using compressed air to remove any particulate material which has deposited within the tube since the previous measurement exercise.

It is not envisaged that the waste gas velocity at the sampling point would be measured for each sampling exercise, and so the only data available would be the results of the initial velocity traverse undertaken to locate the most suitable measurement position. Rigorous isokinetic sampling will therefore not be possible, but since the diameter of particles emitted from positively pressurised baghouses is expected to be predominantly below 10 µm, the error introduced by non-isokinetic sampling will be small (see section 5 and Figure 3).

Depending on the frequency of measurements, such a system would be expected to quantify the general background dust level emitted by a positively pressurised baghouse and to detect long term performance changes. It is doubtful whether the results would be acceptable to demonstrate compliance with performance standards or to reliably estimate particulate mass emission rates. Short term emissions attributable to torn or fallen bags may not be detected if mixing in the baghouse roof is poor, since the proportion of the total waste gases sampled will be very low. Since the particulate analysis is separate from the waste gas collection, the samples could also be analysed for other gaseous or particulate species. The technique is not plant-specific. This technique does not fully meet the objectives of the study detailed in section 2.1. In the context of this study, it is suggested that the permanent narrow bore tube method be used as a means of calibrating other continuous measurement methods, rather than being a prime method of emissions monitoring.

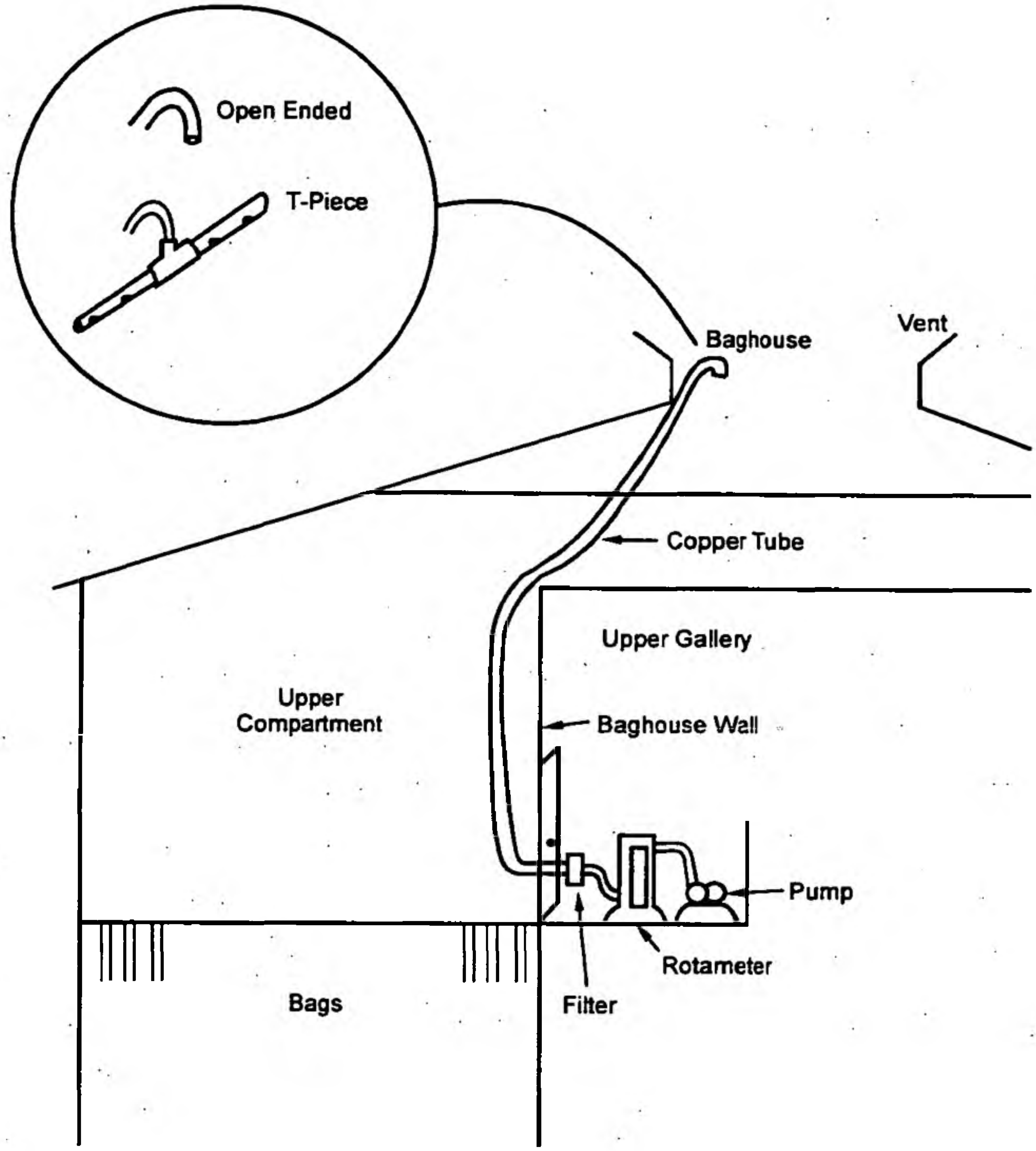


FIG. 6 GENERAL LAYOUT OF PERMANENT NARROW BORE TUBES

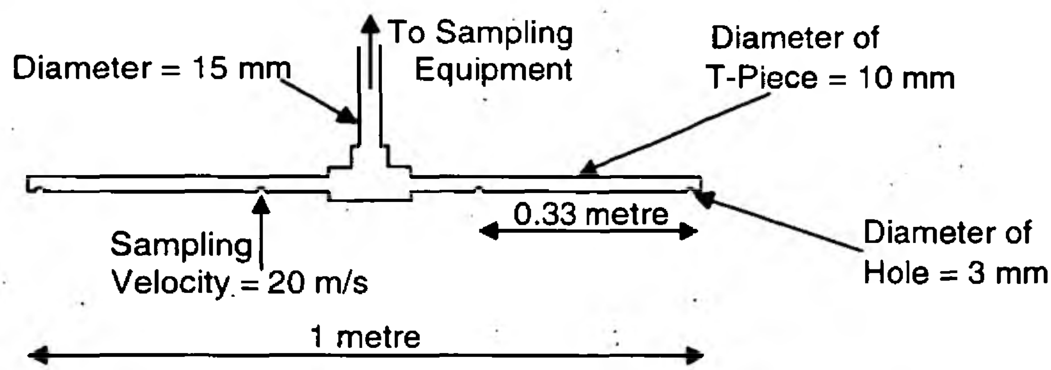
7.4.1 Design Calculations

Typical velocities at a sampling position in the vent throat will be between 4 and 8 m/s. Near-isokinetic sampling through an open ended, 15 mm internal diameter tube will therefore require a sampling rate of between 7×10^{-4} and 1.4×10^{-3} m^3/s at actual temperature (about 35 to 70 litres/minute at ambient temperature). For an open ended tube, the velocity within the tube is the same as the sampling velocity, and gravitational settling during sampling is not expected to be a problem, so long as there are no long horizontal sections of tubing. Particle drop-out at bends in the tube should be minimised by keeping bend radii large relative to the tube diameter, and is not expected to be a problem, especially since small particles will generally follow the gas flow, rather than being thrown to the outside of the bend.

If a T-piece is used, rather than an open ended tube, the design must consider similar factors to those described in Appendix E for the continuous extraction duct. Since the T-Piece will not be used continuously, and will be cleaned with compressed air prior to each use, the limitations on transport velocity and size of the entry holes can be relaxed. As an example of the design of a T-piece, consider a situation where the upward gas velocity is 5 m/s, the gas temperature is 100 °C, density is 0.95 kg/m^3 and viscosity is 2.1×10^{-5} kg/m/s. The dimensions of one possible design are shown in Figure 7. The Reynolds number of the gas stream entering a 3 mm diameter hole is 2,714 and C_0 is estimated to be 0.8. The pressure drop across each hole is calculated to be 297 N/m^2. The maximum gas velocity within the T-piece is 3.6 m/s, Re_d is 1,629 (laminar flow), f = 0.0098 and Δp = 16 N/m^2. The sampling maldistribution is less than 3 % and the total sample flowrate is 34 litres/minute.

POSSIBLE DESIGN OF T-PIECE FOR PERMANENT NARROW BORE TUBES

FIGURE 7



7.5 Typical Costs

Appendix D details budget cost information for the selected methods. The data used was obtained in 1998, and is presented here for general guidance. The table overleaf illustrates the total budget cost for one example of monitoring a typical baghouse with 24 compartments. The compartments are arranged in four rows of six, with two separate vents to monitor. For the purposes of this example, it is assumed that only one half of each vent will be monitored.

For monitoring by obscuration meter, two separate units would be required at a cost of £5,000 to £7,000 each. To this must be added the cost of installing permanent narrow bore tubes for calibration.

For the continuous extraction duct, costs for some further detailed design work and testing of the flows have been included, since this will be site-specific. The construction and installation of each duct and fan will cost £9,000 to £10,000, depending on the final design. In addition, the cost of the selected particulate analysis method must be added; triboelectric probes would cost £3,000 per vent.

If in-situ triboelectric probes were used, then the cost would depend largely on the number of probes required. In this example, a total of twelve probes have been assumed, at a cost of between £2,050 and £2,900 each. To this must be added the cost of installing permanent narrow bore tubes for calibration.

Installation costs for each method include electrical wiring and connection of instrumentation outputs to a PLC. For the continuous extraction duct, fan starters are also included in the installation costs. Costs of any scaffolding required to install the equipment have not been included.

For calibration of the obscuration meters, it has been assumed that twelve permanent narrow bore tubes will be installed in each vent, at a cost of £300 each. For the in-situ triboelectric probes, only one probe in each vent will be calibrated, and only one tube with a T-piece will be installed in each vent, the rest of the probes being matched (see section 8.3). The calibration costs reflect the personnel time involved in undertaking gravimetric sampling exercises to determine the average particulate concentration over a period of time. Using the permanent narrow bore tubes for calibration, it is estimated that the cost of measuring up to four tubes would be £2000, and for up to eight tubes the cost would be £3,000 per exercise. The particle analysis equipment associated with the continuous extraction duct would be calibrated by conventional means.

	Obscuration Meter	Continuous Extraction Duct	Triboelectric Probes
Capital and Installation			
Design and pre-installation testing		£3,000	
Instrumentation	£10,000 (2 units)	£6,000 (2 units)	£28,800 (12 units)
Construction of extraction ducts		£20,000 (2 units)	
Installation	£3,000 (2 units)	£8,000 (2 units)	£8,000 (12 units)
Provision of permanent narrow bore tubes for calibration	£7,200 (24 units)		£700 (2 units)
Total Budget Capital Cost	**£20,200**	**£37,000**	**£37,500**
Calibration Costs	£9,000 (24 units)	£1,500	£2,000 (2 units)

7.6 Conclusions

The three continuous methods proposed meet the objectives detailed in section 2.1. The permanent narrow bore tube method may not meet these objectives, but could be a useful calibration method for the obscuration meter or in-situ triboelectric probe. Each of the techniques has advantages and disadvantages and the final choice of monitoring method for any particular application may depend on the weight given to these other factors.

The obscuration meter gives a more representative result than the other methods and is more likely to detect short term emissions attributable to torn or fallen bags.

The continuous extraction duct can be used to measure baghouse emissions other than particulates by substituting a different analysis method. If it is envisaged that species other than particulates will be monitored, the materials of construction must be chosen to be inert to the species of interest.

If the permanent narrow bore tube method is installed to calibrate the obscuration meter or in-situ triboelectric probe, then this too can be used to obtain samples for other analyses, though several such tubes would be required to obtain a representative sample.

The in-situ triboelectric probe is less affected by off-stream compartments than the other methods.

8 Calibration

Both obscuration meters and triboelectric probes, when in a conventional duct, are commonly calibrated using isokinetic gravimetric sampling methods and both are amenable to single point calibration. The permanent narrow bore tube calibration method suggested here is novel, but if the baghouse is in good condition at the time of calibration, there are no interfering effects from broken bags (particularly for the obscuration meter) and the averaging time for the calibration is chosen with care, an adequate calibration should be possible.

Obscuration meters and triboelectric probes, whether used in the baghouse vent or as the analysis stage of the continuous extraction duct, may be affected by cyclic changes in particle or gas characteristics from different process operations, such as charging and tapping a furnace. Hence to obtain a calibration representing average emissions, the calibration should be undertaken over a number of complete furnace cycles.

8.1 Obscuration Meter

The obscuration meter would be installed to monitor along the whole length of a baghouse vent. A minimum of six gravimetric samples would be required along the length of the beam, and these would be obtained simultaneously to calibrate the obscuration meter. The average dust concentration measured from all the samplers would be compared to the average obscuration meter output over the same period to calculate the calibration factor.

8.2 Continuous Extraction Duct

Before installation of the collection duct, the fan should be run and flows at each inlet measured to confirm the design calculations. If significant deviations from representative sampling are discovered at this stage, then modifications to the inlet diameters may be required to correct this.

Sample ports must be provided in an accessible section of the duct to allow calibration of the selected monitoring equipment against gravimetric sampling.

8.3 In-Situ Triboelectric Probe

To provide monitoring of the whole baghouse, several triboelectric probes would be positioned down the length of the plant. If the probes are matched by the manufacturer, then only one probe will require calibration, and the rest will then have similar characteristics. A gravimetric sampling device (either an open-ended permanent narrow bore tube or one with a 'T' piece) would be positioned near to one of the probes for periodic calibration. The average dust concentration would be compared to the average triboelectric output over the same period to calculate the calibration factor.

9 Sources of Error and Measurement Inaccuracy

The overall accuracy of the measurement of particulate concentration may be affected by four types of error. Firstly, as the measurement is not made on the whole emission from the baghouse, then the fraction which is measured may not be representative of the overall emission. Secondly, if dust-laden gas is physically extracted from the gas stream, non-isokinetic sampling may yield a sample with a different composition from the undisturbed waste gas at that position. Thirdly, the measurement technique selected may not accurately measure the particulate concentration in the gas stream presented to it. And finally, even if all the above errors could be eliminated, the instantaneous particulate concentration may not be representative of the long term emission performance owing to random effects. These errors are further discussed in the following sections.

9.1 Non-representative Sampling

For the continuous extraction duct and the in-situ triboelectric probe, which sample or measure at a limited number of positions, if the concentration of particulates in the gas stream is not uniform then there will be errors due to unrepresentative sampling. For the obscuration meter, a more representative sample is measured, but since the obscuration meter must be calibrated using a limited number of samples, the overall effect of flow maldistribution may be similar

This effect has been investigated using the results of the CFD modelling (see Appendices A and G), with the conclusion that in a worst case, then even at the most suitable sampling position, emissions from some parts of the baghouse may be over-represented by a factor of four and emissions from other parts of the plant under-represented by a factor of six. Again, making some worst case assumptions, it is estimated that the error bounds will not exceed -44 % to +136 % for a single sampling position, and will not exceed -44 % to +58 % for at least six sampling positions.

From the analysis reported in Appendix G, it is recommended that a minimum of six sampling positions are used along the length of the baghouse vent. Provided that there is no systematic difference between the two halves of the filter, then monitoring at only one position across the width of the vent will be adequate to represent emissions from the whole filter.

9.2 Non-isokinetic Sampling

For the continuous extraction duct, which draws a sample from the gas stream for measurement, there may be some error due to sampling at a different velocity to the undisturbed gas velocity at the same point. The obscuration meter and triboelectric probes measure particulate concentrations in-situ, but since they must be calibrated with an extractive technique, they will be subject to similar errors from non-isokinetic sampling. These errors have been discussed in section 4, and for fine fume will be small, say no greater than 10 %.

9.3 Inaccuracy of Measurement Technique

Any measurement technique will have its inaccuracies, from weighing errors for gravimetric methods to non-linear response for triboelectric probes. Other examples of potential measurement errors include particle drop-out in sampling ducts and changes in response of triboelectric probes when velocities change. Errors for any particular technique can be obtained from equipment manufacturers, but it is expected that these inaccuracies will be small in comparison with non-representative sampling errors.

Also included within this type of error will be errors in calibration, where a long path obscuration meter is calibrated against gravimetric samples taken along the light path. Since the samples would be taken at a limited number of positions, the calibration error for the obscuration meter may be of the same order as the non-representative sampling error for the continuous extraction duct or in-situ triboelectric probe. It is recommended that calibration should only be undertaken when the filter is in good condition (i.e. no discernable emissions from torn or broken bags), which should reduce the maldistribution of particulate concentration, resulting in a lower error than the worst case result derived in Appendix G.

9.4 Random Errors

Measurements at any instant in time may be affected by factors that are outside the scope of the measurement technique, but which mean that the measurement made is not representative of the long-term performance of the filter. Examples include variation in dust loading to the filter owing to process operations such as charging and tapping a furnace, the effect of gusts of wind or changes in wind direction on flow patterns within the baghouse, and different degrees of bag cleaning per cleaning cycle. For this reason, it is recommended that the measurements are averaged over at least one full furnace cycle and over at least three full filter cleaning cycles (whichever is the longer) before being reported. In order to establish a reliable emissions trend, not significantly affected by random error, it may be advantageous to report daily or weekly average particulate concentrations.

9.5 Overall Accuracy

The overall error may depend on the technique being used, since different methods will be affected by different types of error. The overall error can be assessed as :

$$\varepsilon_{overall} = \sqrt{\varepsilon^2_{non-representative} + \varepsilon^2_{non-isokinetic} + \varepsilon^2_{measurement} + \varepsilon^2_{random}} = \sqrt{\varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_3^2 + \varepsilon_4^2}$$

If it is assumed that non-isokinetic sampling errors (ε_2) are no greater than 10 %, errors in the actual particulate measurement (ε_3) are negligible, and that random errors (ε_4) are minimised by applying a long averaging time to the measurements, then the estimated error is dominated by the effects of non-representative sampling. If six sampling positions are used, as recommended above, the overall error of each technique can be estimated.

For the obscuration meter, ε_1 will be less than the -43 % to +51 % calculated for spot sampling methods in Appendix G, ε_2 for the calibration exercise is estimated as 10 %, ε_3 will be dominated by the non-representative error during the calibration exercise, which again will be less than the -43 % to +51 % calculated in Appendix G, because calibration should be undertaken only when the filter is in good condition, and ε_4 is negligible. The overall error is not expected to be greater than -44 % to +52 %.

For the continuous extraction duct, ε_1 will be around -43 % to +51% (see Appendix G), ε_2 is estimated as 10 %, ε_3 and ε_4 are both negligible and the overall error is not expected to be greater than -44 % to +52 %.

For the in-situ triboelectric probe, ε_1 will be around -43 % to +51 % (see Appendix G), ε_2 for the calibration exercise is estimated as 10 %, ε_3 and ε_4 are both negligible and the overall error is not expected to be greater than -44 % to +52 %.

Hence for all three of the continuous monitoring techniques, the worst case error is estimated to be around -44 % to +52 %.

10 Conclusions

Three continuous monitoring methods have been proposed that meet the objectives detailed in section 2.1. Each of the techniques has advantages and disadvantages and the final choice of monitoring method for any particular application may depend on the weight given to these other factors.

The obscuration meter gives a more representative result than the other methods and is more likely to detect short term emissions attributable to torn or fallen bags.

The continuous extraction duct can be used to measure baghouse emissions other than particulates by substituting a different analysis method.

The in-situ triboelectric probe is less affected by off-stream compartments than the other methods.

The obscuration meter and in-situ triboelectric probe could be calibrated using permanent narrow bore tubes to extract a sample for gravimetric analysis. These tubes too could be used to obtain samples for other analyses by substituting a different analysis method.

The worst case error for all three of the continuous monitoring techniques is estimated to be around -44 % to +52 %.

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APPENDIX A

Computational Fluid Dynamic Modelling Study

In order to achieve satisfactory cleaning efficiencies, gas velocities in baghouses must be low, and mixing of the gases rising to the vent may be poor. To investigate the magnitude of potential flow maldistribution, a two-dimensional model of the top part of a typical baghouse has been developed using the Fluent / UNS CFD code. The geometry chosen is expected to exhibit greater flow maldistribution than other geometries, and so the results represent a worst case situation. Figure A1 shows the dimensions input to the model; the upward flow from the bags is simulated by 30 identical entry points along the base of the model. For the plant modelled, the mean upward velocity at the top of the bags is approximately 1.2 m/s, but the model was also run using velocities of 0.6 m/s and 3 m/s to investigate the sensitivity of the solution to the input conditions. Except for the magnitude of the calculated velocities, the model predictions were virtually unchanged as the input velocity was altered. Figure A2 illustrates the calculated velocity vectors for an input velocity of 1.2 m/s, and it is noteworthy that the upward component of velocity in the throat of the vent ranges from 2.6 m/s in the centre to a peak of 4.6 m/s, plus a recirculating zone with downward flow at the wall. This has implications for the siting of any monitor or sampling probe in the throat of the vent.

Figure A3 illustrates the behaviour of a plume of gas from bags in the centre of one compartment. The Figure shows the fraction of the gas above the bags which entered the model through one of the thirty entry points. If mixing were perfect, then the fraction of this gas at the vent throat would be , but the model results predict that the actual fraction could range from 0 to 13.5 %, depending on the position in the throat at which a sample was taken. Similar studies on plumes of gas from the bags near the external wall of the compartment and from near the centre of the baghouse showed even greater maldistributions.

It follows that there is no position within this baghouse where a sample which is equally representative of the emissions from the whole width of the plant, or even of one compartment, can be taken. In particular, it is not satisfactory to take one sampling position in the centre of the vent to represent the emissions from both compartments, since at this point velocities are low and over 40 % of the waste gas entered through the bags nearest the centre of the baghouse. Thus to give complete coverage of the two compartments, two sampling positions would be required and the CFD model has been extended to determine the most suitable position available. Figure A4 shows the areas within the baghouse where the fraction of gas from one of three particular parts of the compartment is no more than a factor of four different from the well-mixed solution (in this example, where the fraction is between 0.8 and 13.3 %). Again, there is no position where this condition is satisfied for bags across the whole width of a compartment, but the most suitable position is at approximately 75 - 80 % of the width of the vent throat (with a second sampling position at about 20 - 25 % by symmetry). At this position, emissions from the centre of the compartment are over-represented (13.5 % compared to the well mixed solution of 3.3 %), emissions from near the external wall are almost correctly represented (about 2.5%), and emissions from near the centre of the baghouse are under-represented (less than 0.5%).

The above results are presented for only one worst case baghouse geometry, but the considerable resources required to undertake the modelling make it undesirable to repeat the CFD modelling exercise for every individual case. Since the positions of peak velocity are also at approximately 20% and 80 % of the throat width, it is recommended that a survey of velocity variation across the vent throat is undertaken, and samples taken from positions where the peak velocities are found.

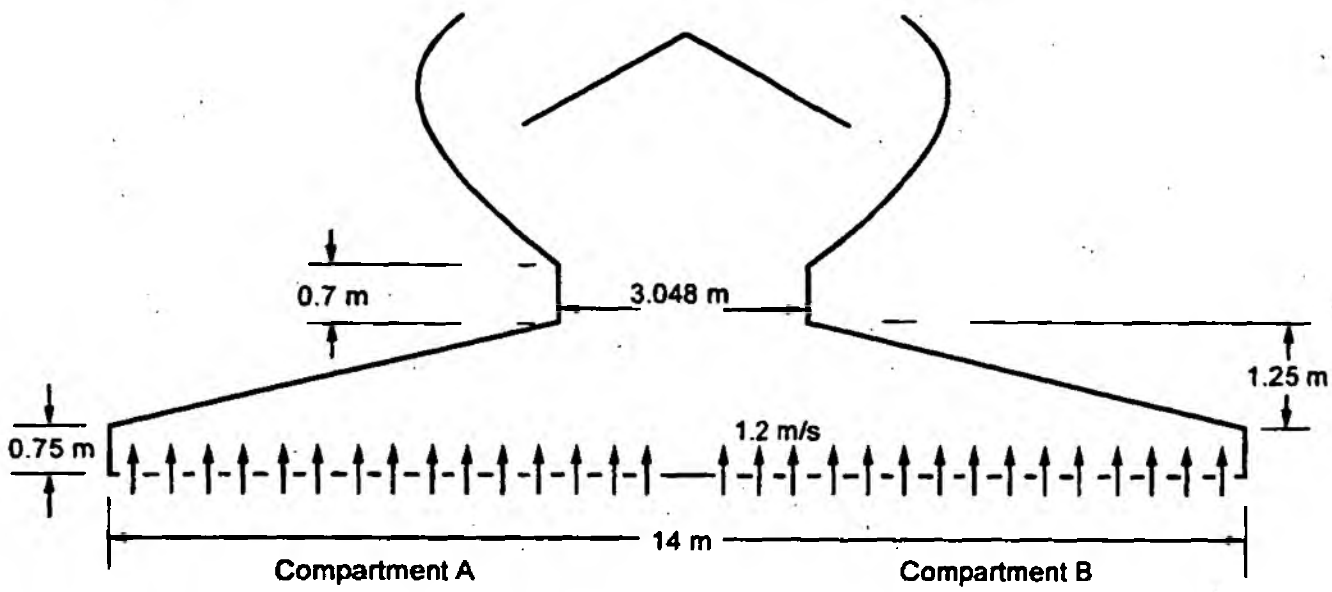


FIG. A1 GEOMETRY OF CFD BAGHOUSE MODEL

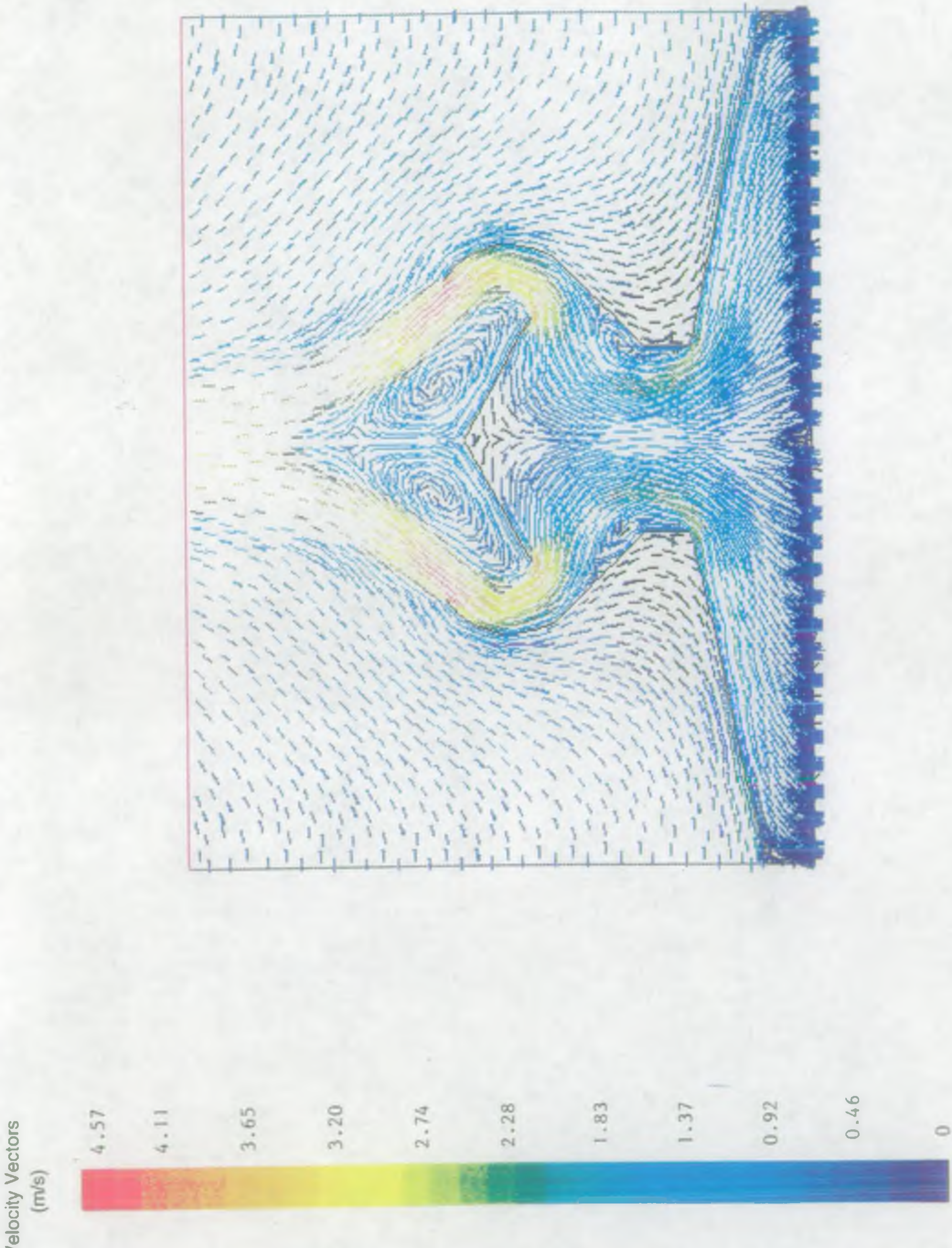


FIG. A 2 CALCULATED VELOCITY VECTORS

FIG. A 3 TRAJECTORY OF PLUME EMITTED FROM CENTRE OF COMPARTMENT

Shaded areas represent the region where the plume from one entry point accounts for between 0.8 and 13.3% of the waste gas

- Plume from Centre of Baghouse
- Plume from Centre of Compartment
- Plume from External Wall of Baghouse

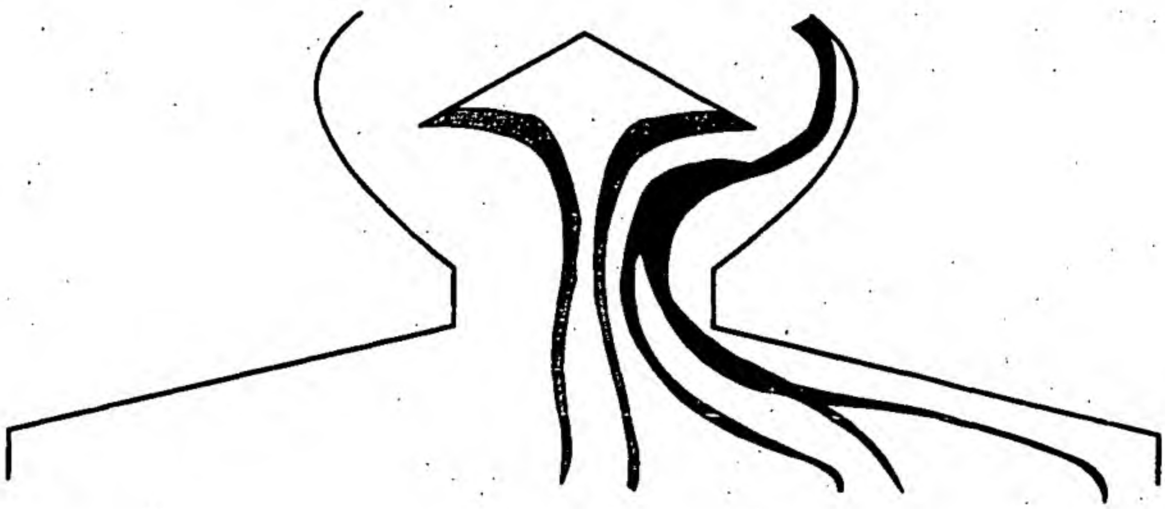


FIG. A 4 DETERMINATION OF SAMPLING LOCATION

Calculation of Errors from Non-Isokinetic Sampling

Hawksley *et al.*[13] detail a method for calculation of the errors which may arise from non-isokinetic sampling.

The Stokes' velocity of a spherical particle is defined as :

$$v = (\sigma - \rho)\ g\ d^2 / 18\ \mu$$

where the meaning of the symbols used is detailed in the table below.

The distance the particle would theoretically travel in accelerating from rest to the same velocity as air flowing past it, termed the range of the particle, is given by :

$$\lambda = v\ V / g$$

The average length of upstream disturbance as gases approach a nozzle is a function of the nozzle diameter and design. For one particular nozzle design[18], an empirical relationship has been derived :

$$L = 0.06032 - 1.612\ D$$

The proportion of the particles which are not carried with a deflected gas stream is :

$$\alpha = \lambda / L\ (1 - e^{-L/\lambda})$$

The sampled mass flow of particles per unit area is thus :

$$m_S = c\ (1 - \alpha)\ V_S + c\ \alpha\ V$$

And the measured particulate concentration is :

$$c_S = c\ \{\ (1 - \alpha) + \alpha\ V / V_S)$$

Figure 3 in the main report illustrates an example of the effect of non-isokinetic sampling.

		Units
c	true concentration of particulates in gas stream	mg/m³
c_S	measured particulate concentration	mg/m³
d	diameter of an equivalent spherical particle	m
D	diameter of sampling nozzle	m
g	acceleration due to gravity	m/s²
L	length of upstream disturbance as gases approach a nozzle	m
m_S	mass flow of particles per unit area collected by sampler	mg/m²/s
V	velocity of undisturbed gas stream at sampling location	m/s
V_S	velocity at sampling nozzle	m/s
α	proportion of particles which are not carried with a deflected gas stream	-
λ	range of particle	m
μ	absolute viscosity of gas	kg/m/s
v	Stokes' velocity of particle	m/s
ρ	density of gas	kg/m³
σ	density of particle	kg/m³

Initial Assessment of Potential Monitoring Methods

Technique : Permanent Narrow Bore Tube (B)

Achievement of Objectives	
Quantifies general background dust level	Yes - several tubes required for representative quantification.
Detects long term changes in performance	This is not a continuous technique, but could be used for regular spot monitoring. This would detect long term performance changes and may be adequate to quantify annual mass emissions, depending on the monitoring frequency.
Quantifies annual particulate mass emission	
Cost	
Cost of developing technique to practical state	Technique already developed.
Capital cost (including installation)	Materials and fabrication costs are low (copper tubing would typically be used). Installation is not difficult; electrical power is required at the location where the sampling equipment is to be set up.
Operating costs	Personnel costs involved in regular surveys could be high.
Practicability	
Ease of calibration	Gravimetric technique; may be used to calibrate other techniques.
Representative sampling	Depends on the number of tubes installed.
Continuous operation	No.
Stability of operation	Stable - no electronics or moving parts.
Maintenance requirements	Cleaning out of tube with compressed air prior to sampling.
Likelihood of Success	
Amount of initial design work	A little if a T-piece is to be designed, otherwise virtually none.
Requirement for prototype	Already prototyped by Swinden Technology Centre.
Likelihood of further development being required	Technique already developed.

Technique : Obscuration Meter (E)

Achievement of Objectives	
Quantifies general background dust level	So long as the technique is adequately calibrated.
Detects long term changes in performance	Yes.
Quantifies annual particulate mass emission	So long as the technique is adequately calibrated.
Cost	
Cost of developing technique to practical state	Technique already developed.
Capital cost (including installation)	Instrument cost is not excessive. Installation requires mounting brackets and electrical power at the baghouse vent.
Operating costs	Low, apart from extensive calibration exercise.
Practicability	
Ease of calibration	Difficult to obtain representative samples from the path of the light beam. Response to particulate concentration is linear.
Representative sampling	Yes.
Continuous operation	Yes.
Stability of operation	Such instruments are designed for stable operation.
Maintenance requirements	Routine cleaning of optics.
Likelihood of Success	
Amount of initial design work	Little.
Requirement for prototype	None.
Likelihood of further development being required	Possible development of suitable calibration method.

Technique : Continuous Extraction Duct (F)

Achievement of Objectives	
Quantifies general background dust level	Yes.
Detects long term changes in performance	Yes.
Quantifies annual particulate mass emission	Yes.
Cost	
Cost of developing technique to practical state	Small-scale version (one compartment) already prototyped.
Capital cost (including installation)	Materials and fabrication costs fairly low, but installation may require considerable work to provide suitable support within the baghouse roof. Electrical power required for the fan and particulate analysis equipment.
Operating costs	Low.
Practicability	
Ease of calibration	Access for calibration of chosen particulate analysis technique against gravimetric sampling is easy.
Representative sampling	Depends on tube design.
Continuous operation	Yes.
Stability of operation	Stable.
Maintenance requirements	Low.
Likelihood of Success	
Amount of initial design work	Tube must be carefully designed to ensure representative sampling and to minimise particle drop-out in the tube.
Requirement for prototype	The flows through each inlet can be checked before the tube is installed in the baghouse vent.
Likelihood of further development being required	Some correction of flows may be required, but this can be achieved before final installation.

Technique : In-situ Triboelecric Probe (H)

Achievement of Objectives	
Quantifies general background dust level	So long as the technique is adequately calibrated.
Detects long term changes in performance	Yes.
Quantifies annual particulate mass emission	So long as the technique is adequately calibrated.
Cost	
Cost of developing technique to practical state	Technique already developed.
Capital cost (including installation)	Several instruments would be required, but cost per instrument is low. Installation requires electrical power at baghouse vent.
Operating costs	Low, apart from calibration exercise.
Practicability	
Ease of calibration	Calibrated by gravimetric sampling through an adjacent narrow bore tube. Response to particulate concentration is linear.
Representative sampling	Depends on the number of probes installed.
Continuous operation	Yes.
Stability of operation	Such instruments are designed for stable operation.
Maintenance requirements	Low.
Likelihood of Success	
Amount of initial design work	Little.
Requirement for prototype	None.
Likelihood of further development being required	Low.
Other Comments	Such instruments require a minimum velocity of 3 m/s. If the velocity at the measuring position is too low, then a bank of fans may be required to increase the local velocity.

Technique : Optical Monitoring - External (I)

Achievement of Objectives	
Quantifies general background dust level	Only if the technique can be calibrated.
Detects long term changes in performance	Yes.
Quantifies annual particulate mass emission	Only if the technique can be calibrated.
Cost	
Cost of developing technique to practical state	Both hardware and software may need to be developed.
Capital cost (including installation)	Hardware includes camera, image analysis equipment and suitable weatherproofing. Installation requires electrical power at baghouse vent and at camera location.
Operating costs	Low.
Practicability	
Ease of calibration	Very difficult. Response to particulate concentration may not be linear.
Representative sampling	Yes.
Continuous operation	Yes.
Stability of operation	Stable.
Maintenance requirements	Routine cleaning of lamps and camera.
Likelihood of Success	
Amount of initial design work	Testing required to establish the feasibility of the proposed method.
Requirement for prototype	Yes.
Likelihood of further development being required	High.
Other Comments	Image analysis will need to resolve small differences in light intensity (say 1 in 4000).

Technique : Infra-Red Monitoring - External (J)

Achievement of Objectives	
Quantifies general background dust level	Only if the technique can be calibrated.
Detects long term changes in performance	Yes.
Quantifies annual particulate mass emission	Only if the technique can be calibrated.
Cost	
Cost of developing technique to practical state	Significant.
Capital cost (including installation)	Hardware includes camera, image analysis equipment and suitable weatherproofing. Installation requires electrical power at camera location.
Operating costs	Low.
Practicability	
Ease of calibration	Very difficult. Response to particulate concentration may not be linear and may depend on temperature.
Representative sampling	Yes.
Continuous operation	Yes.
Stability of operation	May be affected by temperature of the gases leaving the baghouse vent.
Maintenance requirements	Routine cleaning of camera.
Likelihood of Success	
Amount of initial design work	Testing required to establish the feasibility of the proposed method.
Requirement for prototype	Yes.
Likelihood of further development being required	High.

Technique : Optical Monitoring - Internal (K)

Achievement of Objectives	
Quantifies general background dust level	Only if the technique can be calibrated.
Detects long term changes in performance	Yes.
Quantifies annual particulate mass emission	Only if the technique can be calibrated.
Cost	
Cost of developing technique to practical state	Both hardware and software may need to be developed.
Capital cost (including installation)	Hardware includes camera and image analysis equipment. Installation requires electrical power at baghouse vent.
Operating costs	Low.
Practicability	
Ease of calibration	Very difficult. Response to particulate concentration may not be linear.
Representative sampling	Yes.
Continuous operation	Yes.
Stability of operation	Camera operation may be affected by high temperatures.
Maintenance requirements	Routine cleaning of lamps and camera within baghouse.
Likelihood of Success	
Amount of initial design work	Testing required to establish the feasibility of the proposed method.
Requirement for prototype	Yes.
Likelihood of further development being required	High.
Other Comments	Image analysis will need to resolve small differences in light intensity (say 1 in 4000).

Technique : Vibrating Rod (L)

Achievement of Objectives	
Quantifies general background dust level	Only if the technique can be calibrated.
Detects long term changes in performance	Probably.
Quantifies annual particulate mass emission	Only if the technique can be calibrated.
Cost	
Cost of developing technique to practical state	Both hardware and software may need to be developed.
Capital cost (including installation)	Sophisticated electronics required to detect oscillation frequency.
Operating costs	Low.
Practicability	
Ease of calibration	Difficult in-situ. Calibration would have to be established at prototype stage. Response to particulate concentration may not be linear.
Representative sampling	Depends on the number of probes installed.
Continuous operation	Yes.
Stability of operation	Stable so long as electronic components are not subjected to high temperatures.
Maintenance requirements	Low.
Likelihood of Success	
Amount of initial design work	Testing required to establish the feasibility of the proposed method.
Requirement for prototype	Yes.
Likelihood of further development being required	High.

Technique : Continuous Wire (M)

Achievement of Objectives	
Quantifies general background dust level	Only if the technique can be calibrated.
Detects long term changes in performance	Probably.
Quantifies annual particulate mass emission	Only if the technique can be calibrated.
Cost	
Cost of developing technique to practical state	Low.
Capital cost (including installation)	Installation may require careful planning to ensure unobstructed path.
Operating costs	Low.
Practicability	
Ease of calibration	Very difficult. Response to particulate concentration may not be linear.
Representative sampling	Yes.
Continuous operation	Semi-continuous, but the intervals between measurements may be sufficiently small to make it virtually continuous.
Stability of operation	Stable so long as moving parts and balance are not subjected to high temperatures and dust levels.
Maintenance requirements	Balance will need regular cleaning.
Likelihood of Success	
Amount of initial design work	Moderate.
Requirement for prototype	Yes, to demonstrate that the technique works.
Likelihood of further development being required	Moderate.

Technique : Trolley (N)

Achievement of Objectives	
Quantifies general background dust level	Yes.
Detects long term changes in performance	This is not a continuous technique, but could be used for regular spot monitoring. This would detect long term performance changes and may be adequate to quantify annual mass emissions, depending on the monitoring frequency.
Quantifies annual particulate mass emission	
Cost	
Cost of developing technique to practical state	Moderate.
Capital cost (including installation)	Installation may require careful planning to ensure unobstructed path.
Operating costs	Personnel costs involved in regular surveys could be high.
Practicability	
Ease of calibration	Can carry gravimetric sampling equipment for in-situ calibration.
Representative sampling	Yes, over a period of time.
Continuous operation	No. Intended to be moved over time to monitor different parts of the plant.
Stability of operation	Stable.
Maintenance requirements	Moderate - moving and flexing parts are subjected to high temperatures and dust levels.
Likelihood of Success	
Amount of initial design work	Moderate.
Requirement for prototype	None.
Likelihood of further development being required	Possibly.

Cost of Particulate Monitoring Equipment

The following budget costs for the four techniques discussed in section 7 in the main report were obtained in July 1998 and are presented here for general guidance. Quotations for specific instruments were obtained from manufacturers, but do not necessarily reflect the exact models which may be available in the future, and may not include every manufacturer. A more complete list of manufacturers of particulate monitoring equipment can be found in reference 19.

Obscuration Meter

Two quotations were obtained for long path, through-beam obscuration meters, suitable for monitoring along the length of a baghouse vent :

Codel 101E/E50	£ 4,725
Erwin Sick SM 56	£ 7,000

Continuous Extraction Duct

The drawings attached as Figure D1 were submitted to a contractor familiar with steel industry baghouses to obtain quotations for fabrication and installation, including fans, of a number of different configurations. The budget costs provided are summarised below :

Configuration	Vent Length	Budget Cost
A, 2 off T-Piece	50 m (25 m per T-Piece)	£17,000
B, 1 off T-Piece	50 m	£10,600
C, 1 off T-Piece	30 m	£10,000
D, 2 off Single Tube	50 m (25 m per Tube)	£16,000
E, 1 off Single Tube	50 m	£ 9,500
F, 1 off Single Tube	30 m	£ 8,900

In addition, particle analysis instrumentation is required. For a scattered light obscuration meter, suitable for measuring low particle concentrations over a short light path, a typical cost would be :

Erwin Sick RM 210 (range 0-20 mg/m³)	£ 8,200

Alternatively, for a single triboelectric probe suitable for measuring particulate concentrations in a duct, a typical cost would be :

PCME DT 270 (range 0.01-1000 mg/m³)	£ 2,900

In-Situ Triboelectric Probe

When several triboelectric probes are used, the cost per probe may be reduced :

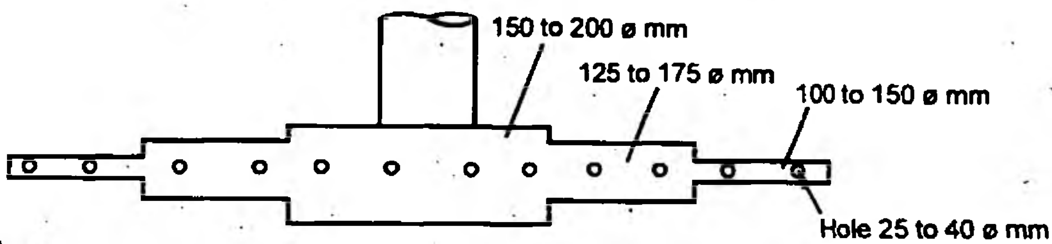
PCME DT 270 (range 0.01-1000 mg/m³)

Basic probe	£ 2,900
Probe with expansion box and card	£ 2,600
Probe with card (maximum 2 per system)	£ 2,050

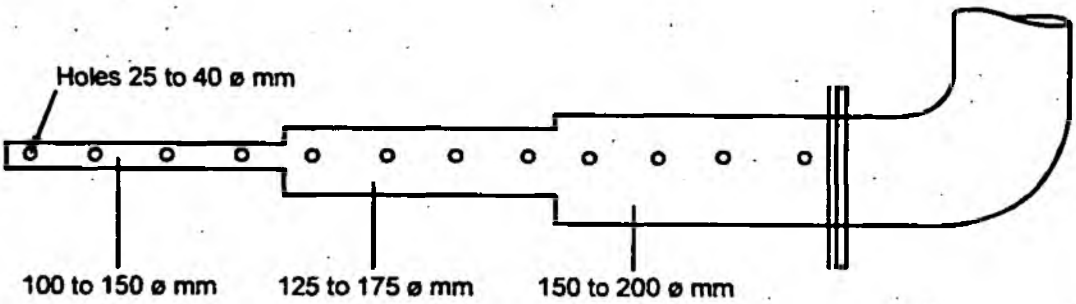
Hence for four probes, the total cost is £9,600.

Permanent Narrow Bore Tube

Fabrication and installation of an open-ended tube is estimated as £300 per tube, or £350 for a tube with a T-piece.



Configuration						
A	4 m	4 m	8 m	4 m	4 m	2 off per 50 m bagplant
B	8	8	16	8	8	1 off per 50 m bagplant
C	5	5	10	5	5	1 off per 30 m bagplant



Configuration				
D	8 m	8 m	8 m	2 off per 50 m bagplant
E	16	16	16	1 off per 50 m bagplant
F	10	10	10	1 off per 30 m bagplant

Detail of extraction tube
View from beneath tube,
i.e. entry holes face the
upward gas flow

FIG. D1 DRAWINGS SUBMITTED FOR BUDGET COST QUOTATION

APPENDIX E

Design of Continuous Extraction Duct

This appendix details the equations necessary for the design of a duct to continuously sample from a number of positions in the baghouse vent to produce a representative composite sample. Only the design of the collection part of the duct is considered here; the design of the rest of the duct bringing the composite sample to a suitable sampling location and discharging the sample safely is uncomplicated. All equations are taken from reference 20, and the numbering used here is the same as in this reference. Symbols are defined in the table at the end of this appendix.
The constraints on the design are :

- A minimum of six positions, equally distributed between the compartments monitored.
- The transport velocity along the duct should be sufficient to prevent particle settling.
- The sampling velocity through each inlet should be close to the undisturbed gas velocity in the vent throat
- The sample volume flow through each inlet in the duct should be approximately equal.
- The diameter of each inlet should be a minimum of 25 mm.

Transport Velocity

Particles travelling along a horizontal section of duct will fall under gravity, and may settle out at the bottom of the duct if the transport velocity is too low. The required velocity is a function of the downward velocity of the particles, the diameter of the duct and the length of the duct. If it is assumed that spherical particles fall at their terminal velocity, ν, then if the particle Reynolds number, $Re_p = \rho\ d\ \nu\ /\ \mu$, is less than 0.1, the downward velocity can be found from Stokes' equation :

$$\nu = (\sigma - \rho)\, g\, d^2 / 18\mu \qquad (6\text{-}232)$$

For $0.1 < Re_p < 1000$, equations (6-229) and (6-233) must be solved iteratively :

$$v = \sqrt{\frac{4(\sigma - \rho)\, g\, d}{3\rho\, C_D}} \qquad (6\text{-}229)$$

$$C_D = \left[\frac{24}{Re_p}\right]\left[1 + 0.14\, Re_p^{0.7}\right] \qquad (6\text{-}233)$$

For $Re_p > 1000$, equations (6-234) or (6-235) would be used instead, but it is unlikely that such high Reynolds numbers will be found in applications where the continuous extraction duct is to be used.

Having determined the downward velocity of the particles, the proportion that could fall to the bottom of the duct over a length λ is $\left[\frac{v}{V_t}\right]\left[\frac{\lambda}{D}\right]$. It should be noted that these particles will not necessarily be lost from the gas stream, since they could be re-entrained, either immediately or at a later time. If it is assumed that each inlet along the length of the duct will generate sufficient turbulence to redistribute the particles, then the relevant length scale is the distance between inlets. The transport velocity, V_t should be chosen to prevent a significant proportion of particles from settling out in the duct.

Sampling Velocity

Ideally, the sampling velocity, V_s, should be equal to the undisturbed gas velocity in the vent throat; however, this requirement may not be compatible with other constraints. The magnitude of the errors which may be introduced by non-isokinetic sampling is discussed in Appendix B and illustrated in Figure 3 in the main report. For small particles, say less than 10 µm diameter, then the sampling velocity can be up to five times greater than the gas velocity without undersampling by more than 15 %.

Sampling Maldistribution

Large pressure drops along the collection duct would mean that the pressure across the inlets would differ, and so the volume flow through each inlet would not be the same. To avoid this maldistribution, the tube should be designed so that the variation in pressure along the duct is small in comparison to the average pressure drop across each inlet. The percentage variation in flow between the first and last inlets can be estimated as :

$$\text{Percentage maldistribution} = 100 \left[1 - \sqrt{\frac{\Delta p_o - \Delta p}{\Delta p_o}} \right] \qquad (6\text{-}150)$$

The pressure drop across each inlet, provided that the area of the inlet is small compared to cross-sectional area of the duct, is given by :

$$\Delta p_o = \rho V_s^2 / 2 C_0^2 \qquad (6\text{-}149)$$

The discharge coefficient, C_0, is a function of the Reynolds number of the gas passing through the inlet, $Re_i = \rho\, i\, V_s / \mu$. Figure 10-20 in reference 20 shows the variation of C_0 for orifice meters with for Reynolds numbers; for Re_i greater than about 20,000, the discharge coefficient can be taken as 0.62.

The pressure drop along the collection duct is given by :

$$\Delta p = \left[\frac{4 f L}{3 D} + 2K \right] \left[\frac{\rho V_e^2}{2} \right] \qquad (6\text{-}148)$$

The pressure recovery factor, K, for such ducts is close to 1.0 and the friction factor, f, is a function of the Reynolds number, $Re_d = \rho D V_e / \mu$. If the flow along the duct is turbulent ($4{,}000 < Re_d < 100{,}000$), the friction factor for smooth-walled tubes can be calculated from the Blasius equation :

$$f = 0.079 / Re_d^{0.25} \qquad (6\text{-}37)$$

For laminar flow ($Re_d < 2{,}100$), the friction factor can be calculated from the Hagen-Poiseuille equation :

$$f = 16 / Re_d \qquad (6\text{-}35)$$

For intermediate values of Re_d, the friction factor is uncertain and equation (6-37) should be used, but will probably overestimate the value of f.

Example

Assume that a 30 metre long baghouse, divided along its length into twelve compartments, is to be monitored using a continuous extraction duct. The particle diameter is 10 µm, particle density

4200 kg/m³, undisturbed gas velocity 5 m/s and the gas at the vent is air at 100 °C (density = 0.95 kg/m³, viscosity = 2.1 x 10^{-5}kg/m/s).

First, it is decided to have twelve inlets (one above each compartment) in the collection duct, and so they will be spaced 2.5 metres apart. Initially, it will be assumed that the duct diameter is 150 mm.

The particle terminal velocity calculated from equation (6-232) is about 0.011 m/s, which equates to a particle Reynolds number of 0.005. Hence equation (6-232) is applicable and the particle settling velocity can be taken as 0.011 m/s. If the particles had been larger, then equation (6-232) might not have been applicable; for instance 50 μm particles would give v = 0.27 m/s and Re_p = 0.62 using equation (6-232). The Reynolds number is now greater than 0.1, and equations (6-233) and (6-229) must be solved instead to give v = 0.25 m/s and Re_p = 0.56.

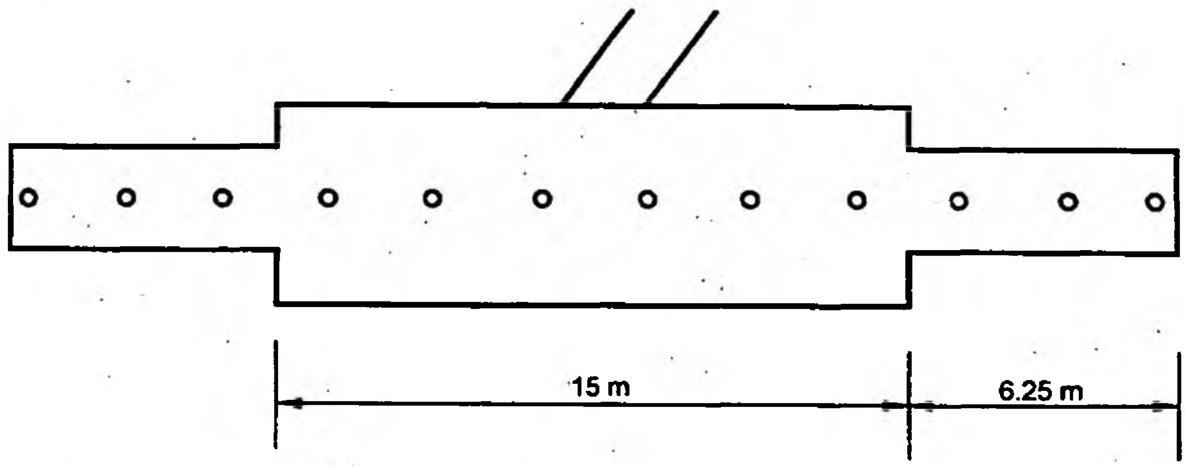
As a first iteration, assume that the transport velocity should be about 10 m/s along the whole length of the duct. For a duct diameter of 0.15 m, the proportion of the particles that could fall to the bottom of the duct between inlets (a distance of 2.5 m) is 2 %, which is acceptable. To maintain this constant transport velocity in the collection duct, the duct would have to change diameter at each inlet point, but such a design would be unnecessarily complex. Instead, it will be assumed that only two different diameters will be used, as shown in Figure E1a. The total sample volume flow in this instance will be of the order of $2 \times 10 \times \pi D^2/4$ = 0.35 m³/s, or 0.03 m³/s through each of the twelve inlets. To achieve a transport velocity of 10 m/s after the first inlet, the diameter of the smaller section of the duct should be around 60 mm.

The diameter of the inlets can now be chosen to give a sampling velocity which is not too different from the undisturbed gas velocity (5 m/s). An inlet diameter of 50 mm gives V_s = 15 m/s and V_s / V = 3, which is acceptable in terms of non-isokinetic sampling errors. If the inlet diameter is 50 mm, then the diameter of the smaller duct section will need to be increased from the 60 mm suggested above. A diameter of 75 mm will be chosen.

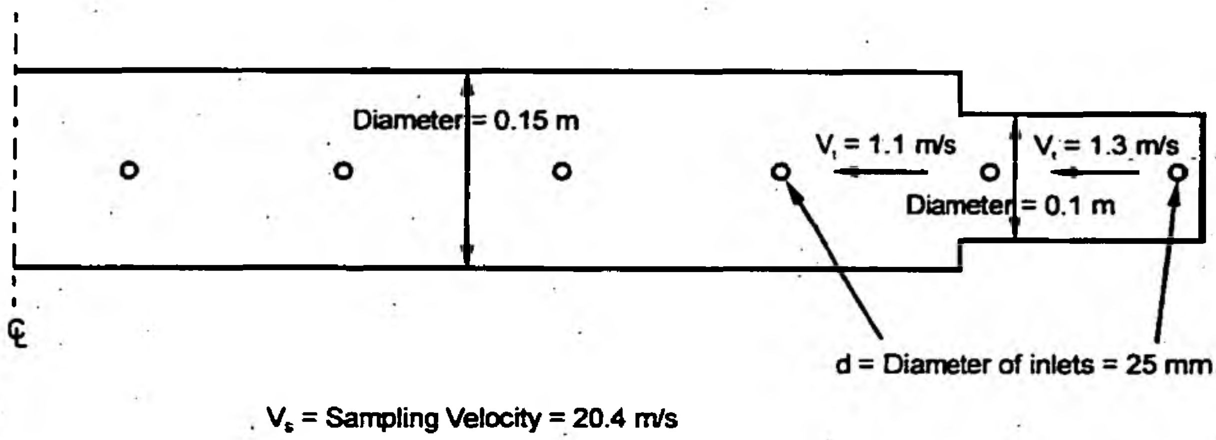
Now the sampling maldistribution must be checked. Considering first the larger diameter duct se ction (L = 7.5 m, D = 0.15 m), the maximum velocity in the duct is 10 m/s, giving a Reynolds number of 67,857, which is within the range where the Blasius equation (6-37) applies. Hence the friction factor is 0.0049 and the pressure drop along this duct section is 110 N/m². For the smaller duct section (L = 6.25 m, D = 0.075 m), V_e = 20 m/s, Re_d = 67,857, f = 0.0049 and Δp = 483 N/m². To complete the calculation of pressure drop along the collection duct, the loss of pressure across the change in cross-section should also be calculated, but as a first approximation, the pressure drop between the first and last inlets is 593 /m².

Considering now the pressure drop across the inlets (V_s = 15 m/s, i = 0.05 m), the Reynolds number is 33,929 and so C_0 can be taken as 0.62. This gives Δp_0 = 278 N/m². Since this is only about half the calculated change in pressure along the collection duct, it would be expected that there would be large variations in the sampled flow between the inlets closest to the T-piece and those at the furthest ends of the duct, which is not acceptable.

Hence a further design iteration is necessary. To reduce the sampling maldistribution, the pressure drop across each inlet must be increased relative to the pressure drop along the duct. The pressure drop across an inlet cannot be increased without increasing the sampling velocity, which may be undesirable since non-isokinetic sampling errors will then increase. Reducing the pressure drop along the duct requires a reduction in the transport velocity, which may increase the proportion of dust settling out in the duct. Hence any solution must be a compromise between these different constraints.



(a) (D0934E09)



(b) (D0934E09)

FIG. E 1 (a and b) DESIGN OF CONTINUOUS EXTRACTION DUCT

One suggested solution is illustrated in Figure E1b. The volume flow through each inlet is 0.01 m³/s, giving V_s = 20.4 m/s and V_s / V = 4.1, which is still acceptable in terms of non-isokinetic sampling errors. Re_i = 23,040, C_0 = 0.62 and Δp_0 = 513 N/m². The velocity at the end of the smaller duct section (L = 2.75 m, D = 0.1 m) is 2.5 m/s, giving Re_d = 11,520, f = 0.0076 and Δp = 7 N/m². For the larger duct section (L = 11 m, D = 0.15 m), V_e = 3.4 m/s, Re_d = 23,040, f = 0.0064 and Δp = 15 N/m², giving a total pressure drop along the collection duct of about 22 N/m². The percentage maldistribution is around 2 %, which is acceptable. In this design, the transport velocities are lower than would be ideally required, and dust fall-out may become a problem.

This example illustrates the difficulties in designing a duct to continuously sample from a number of positions in the baghouse vent to produce a representative composite sample.

		Units
C_D	drag coefficient	-
C_0	discharge coefficient	-
d	diameter of an equivalent spherical particle	m
D	diameter of extraction duct	m
f	Fanning friction factor	-
F	total sample volume flow	m³/s
g	acceleration due to gravity	m/s²
i	diameter of inlet	m
K	pressure recovery factor for inlet	-
L	length of collection duct	m
Δp	pressure drop along collection duct	N/m²
Δp_0	pressure drop across inlet	N/m²
Re_d	Reynolds number of gas stream in collection duct	-
Re_i	Reynolds number of gas stream passing through inlet	-
Re_p	Reynolds number of particle	-
V	velocity of undisturbed gas stream at sampling location	m/s
V_e	maximum velocity of gas stream in collection duct	m/s
V_s	velocity at sampling nozzle	m/s
V_t	transport velocity along the duct	m/s
λ	length scale	m
μ	absolute viscosity of gas	kg/m/s
ν	Stokes' velocity of particle	m/s
ρ	density of gas	kg/m³
σ	density of particle	kg/m³

APPENDIX F

Design of Fan Box to Increase Local Velocity for Triboelectric Probes

This appendix presents the general principles of fan box design for use with a triboelectric probe. The objective is to increase the local gas velocity to above 3m/s or to maintain a constant velocity if the volume of waste gas treated by the baghouse is variable.

Example

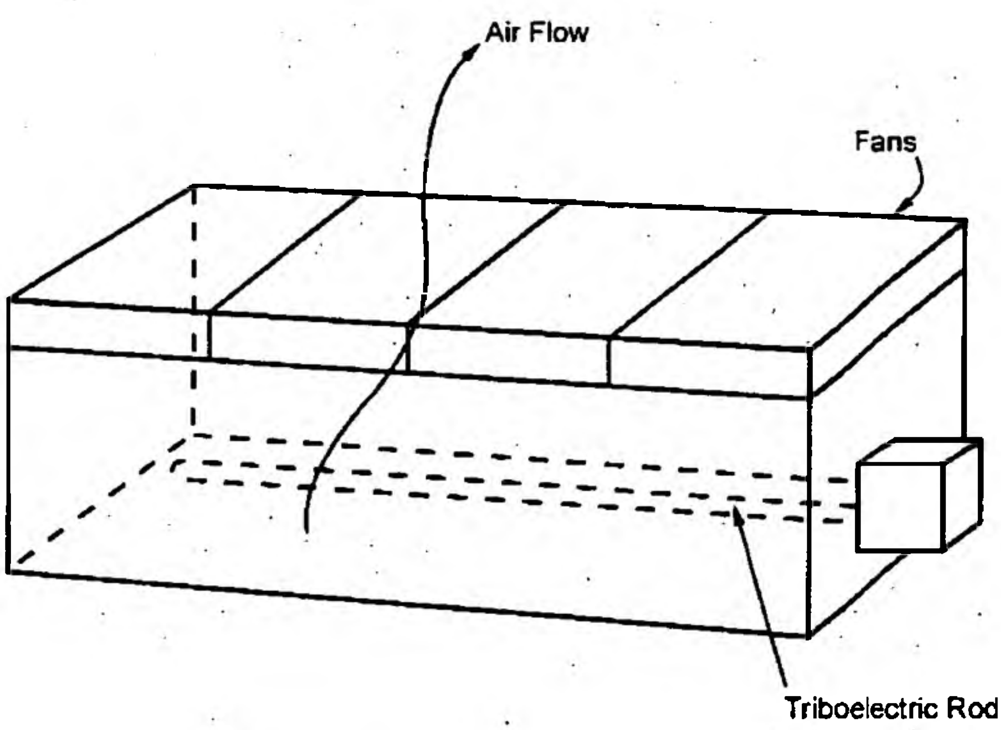
Consider a medium pressure, plate axial fan, a typical example of which can be obtained from the Farnell catalogue, No. 7003742. This is a 0.32m square fan, 0.3m deep, continuously rated up to 70°C, and capable of extracting 1300m^3/h (0.361m^3/s). Similar fans are available from other suppliers and manufacturers.

Over the fan area (0.32m x 0.32m) the average flow velocity is $0.316 / 0.32^2 = 3.5$ m/s, which is above the minimum requirement of 3m/s. The number of fans in a fan box will be determined by the length of the triboelectric probe.

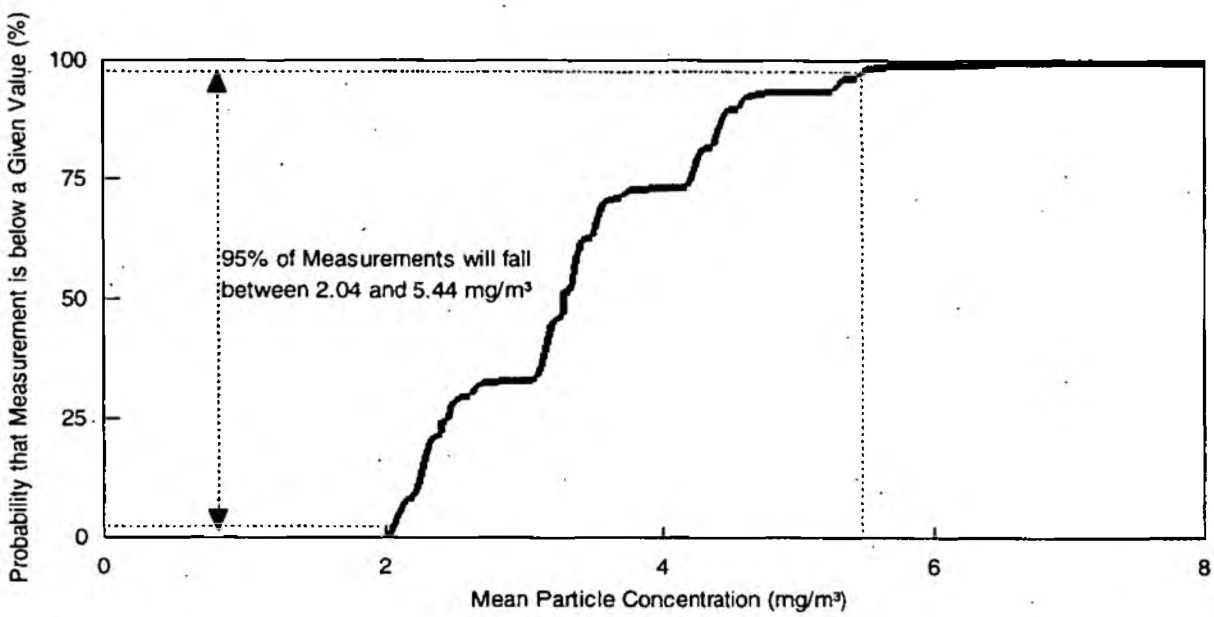
Because the triboelectric method of dust monitoring uses a charge transfer mechanism, it is important to use the fans to "pull" the waste gases over the probe (as illustrated in Figure F1), rather than to "push" the gas and particulates over the probe. As the waste gas passes through the fan, some particles will impact on the blades and lose their charge, thus modifying the charge monitored by the triboelectric probe if this is downstream from the fan box.

FAN BOX DESIGN

FIGURE F1



Estimation of Errors from Non-Representative Sampling



The CFD study (see Appendix A) concluded that there may be no position within the baghouse where a sample which is equally representative of the emissions from the whole plant can be taken. If the concentration of particulates in the gas stream is not uniform then errors will be introduced due to this unrepresentative sampling. This has implications for the accuracy of any measurements, which have been assessed with the following assumptions :

- The background particulate concentration is 2 mg/m^3.
- The particulate concentration from one of the thirty entry points across the baghouse width in the CFD model is 50 mg/m^3.
- The distribution of flow within the baghouse is as described in Appendix A. There are no random fluctuations over the monitoring timescale, and no variation of particulate concentration along the length of the baghouse.

If two samplers are positioned at approximately 20 - 25 % (Sampler 1) and at 75 - 80 % (Sampler 2) of the width of the vent throat, then the sampled particulate concentrations can be estimated for various different positions of the high particulate entry point, as in the table below :

Entry Point (% of width)	Measured particulate concentration (mg/m^3)			
	Sampler	1	2	Average

3	The CFD model predicts that emissions from this area will account for about 2.5 % of the measured emission at Sampler 1, with the other 97.5 % attributable to emissions from other areas of the compartment. 0.025 x 50 + 0.975 x 2 = 3.2 Virtually none of this high particulate level emission will be detected by Sampler 2, located on the opposite side of the vent.	3.20	2.00	2.60
25	0.135 x 50 + 0.865 x 2 = 8.48	8.48	2.00	5.24
47	0.005 x 50 + 0.995 x 2 = 2.24	2.24	2.00	2.12
53		2.00	2.24	2.12
75		2.00	8.48	5.24
97		2.00	3.20	2.60
True average particulate concentration (mg/m³)				**3.60**

Hence with the above assumptions, sampling at only one position may give a result between 2 and 8.5 mg/m³, depending on the position of the high particulate level entry point in relation to the sampling position. The true average particulate concentration is 3.6 mg/m³; the error bounds are thus -44 % to +136 %. Using two samplers, one at 20 - 25 % and one at 75 - 80 % across the vent throat, and averaging the two results would reduce the range of the measurements to between 2.1 and 5.2 mg/m³, and the error bounds to -41 % to +46 %.

The sensitivity of this estimate of error to the initial assumptions has also been tested and the following table shows the results of the sensitivity analysis. The error bounds depend on the number of sampling positions used, and on the ratio of the high particulate concentration to the background level. Using two samplers rather than one makes little difference to the minimum measured concentration, but reduces the maximum error by a factor of about three. The greater the non-uniformity of particulate concentration, the greater the likely measurement error.

Background Particulate Concentration (mg/m³)		2	0.5	0.5	20
Particulate Level from One Entry Point (mg/m³)		50	50	5	200
True Average Particulate Concentration (mg/m³)		3.6	2.15	0.65	26
One Sampling Position	Minimum Measurement (mg/m³)	2	0.5	0.5	20
	Maximum Measurement (mg/m³)	8.5	7.2	1.1	44.3
	Error bounds (% of true value)	-44 to +136	-76 to +234	-23 to +70	-23 to +70
Two Sampling Positions	Minimum Measurement (mg/m³)	2.1	0.6	0.5	20.5
	Maximum Measurement (mg/m³)	5.2	3.8	0.8	32.2
	Error bounds (% of true value)	-41 to +46	-71 to +79	-21 to +24	-21 to +24

The above analysis overestimates the potential measurement errors for three reasons :

- The results are based on CFD modelling of only one baghouse geometry, which is expected to exhibit greater flow maldistribution than other geometries, and so a worst case situation is represented.

- The results are based on steady-state modelling, with no random fluctuations. If the measurements are averaged over a time period of several hours or longer, then random effects would be expected which will tend to make the mean measured emission closer to the true concentration.

- The results are based on a two-dimensional modelling exercise, with high particulate level emissions originating from only one position across the width of the plant. If the distribution of emissions also varies along the length of the plant, then sampling at a number of positions down the length will give a more representative result than a single measurement.

The last of these effects can be accounted for in the following manner. Assume that as a worst case, there is one high particulate level entry point across the width at each sampling position, and that the location is randomly distributed. Binomial theory can be used to determine the likely distribution; for instance if it is assumed that emissions can come from one of the six entry points previously described, the table below shows the probability that a given number of the samples monitored will emanate from any one of these six positions across the baghouse width.

		Probability that r samples will emanate from the same one of the six entry points (%)												
	when r =	0	1	2	3	4	5	6	7	8	9	10	11	12
Number of Samples along length of Baghouse	1	83.33	16.67											
	3	57.87	34.72	6.94	0.46									
	6	33.49	40.19	20.09	5.36	0.80	0.06	< 0.01						
	12	11.22	26.92	29.61	19.74	8.88	2.84	0.66	0.11	0.01	< 0.01	< 0.01	< 0.01	< 0.01

So, for instance, if there are six monitoring positions along the length of the baghouse, the chances of the particulate concentration at all of them being 8.48 mg/m³ (given the assumptions discussed above) is less than 0.01 %. The average of the six measured values will lie somewhere between 2 and 8.48 mg/m³, and these possible measurements form a distribution, which is illustrated in the Figure overleaf.

FREQUENCY DISTRIBUTION OF RESULTS FROM CONTINUOUS EXTRACTION DUCT

FIGURE G1

Disregarding the most extreme values, we can say that at the 95 % confidence level, the average of the six particle concentration measurements will lie between 2.04 and 5.44 mg/m³.

Thus using six sampling positions along the length of the baghouse would be expected to reduce the error bounds to -43 % to +51 %. The 95 % error bounds for different numbers of sample positions have been determined by a similar analysis and are shown in the table below, both for the situation where samples are taken from only one position across the baghouse vent, and where samples are taken at both of the positions of maximum velocity.

Total Number of Sampling Positions in Baghouse	95 % error bounds	
	One Sampling Position across Width	Two Sampling Positions across Width
1	-44 % to +136 %	
3	-44 % to +78 %	
6	-43 % to +51 %	-41 % to +46 %
12	-39 % to +34 %	-37 % to +21 %
24	-31 % to +21 %	-28 % to +14 %

This demonstrates that if emissions are randomly distributed within the baghouse, and if six or more sampling positions are used in a vent, the improvement in accuracy by sampling at both positions of maximum velocity rather than just one is much reduced.

In most real situations, the likely measurement error will be less than the theoretical value previously derived, largely due to random fluctuations and to the fact that the particulate maldistribution is unlikely to be as extreme as assumed in the example. Using two samplers across the vent throat rather than one will reduce errors, but if at least six sampling positions are used, the improvement in accuracy is small. Errors from non-representative sampling will increase as the non-uniformity of particulate concentration increases.

A pessimistic estimate of the error for non-representative sampling, using one sampler located at about 20 - 25 % or at 75 - 80 % of the width of the vent throat, is that the error bounds will not exceed -44 % to +136 %. If six or more samplers are used, the error bounds would be expected not to exceed -43 % to +51 %.