DEPARTMENT OF HEALTH AND HUMAN SERVICES

Public Health Service
Centers for Disease Control
and Prevention (CDC)

Memorandum

Date: January 16, 2004

From: Susan B. Board, Program Official
Office of Extramural Programs, NIOSH, E-74

Subject: Final Report Submitted for Entry into NTIS for Grant 5R01OH002984-06.

To: William D. Bennett
Data Systems Team, Information Resources Branch, EID, NIOSH, P03/C18

The attached final report has been received from the principal investigator on the subject NIOSH grant. If this document is forwarded to the National Technical Information Service, please let us know when a document number is known so that we can inform anyone who inquires about this final report.

Any publications that are included with this report are highlighted on the list below.

Attachment
cc: Sherri Diana, EID, P03/C13

List of Publications

Ramachandran G, Sreenath A, Vincent JH: Experimental Study of Sampling Losses in Thin-Walled Probes at Varying Angles to the Wind. Aerosol Science and Technology, in press, 2001

PUBLICATIONS (PUBLISHED OR EXPECTED)

Brixey, S.A., Paik, S., Evans, D.E. and Vincent, J.H. (2002), Experimental studies to develop new aerosol samplers and methods for their evaluation, Journal of Environmental Monitoring, 4, 633-641.

Brixey, S.A., Evans, D.E. and Vincent, J.H. (2003), New studies of the aspiration efficiencies of thin-walled probes placed at right angles to the wind, Journal of Aerosol Science, in preparation, to be submitted early 2004.

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Vincent, J.H. (2003), Progress towards a new standard protocol for the testing of personal aerosol samplers: an update of European Standard EN13205, Annals of Occupational Hygiene, in preparation, to be submitted mid-2004.

Title:	Methods For Developing And Testing Aerosol Samplers
Investigator:	James H. Vincent
Affiliation:	Michigan Univ
City & State:	Ann Arbor, MI
Telephone:	(734) 763-2417
Award Number:	5R01OH002984-06
Start & End Date:	9/1/1994-5/31/2003
Total Project Cost:	214403
Program Area:	
Key Words:	aerosols, sampling methods

Final Report Abstract:

Development and characterization of samplers whose performances mimic the inhalability of the human head will be an important step forward in exposure assessment for environmental and occupational aerosols. The current method for sampler characterization involves arduous experiments in large wind tunnels, of which only a few exist. Therefore a new, rapid and cost-effective method is needed, and the main objective of this research was to develop a set of scaling laws for aerosol sampling, leading to new methodology for aerosol sampler characterization in a small-scale wind tunnel using a direct-reading aerodynamic particle sizer (APS), which counts and sizes sampled particles. For this purpose, a prototype automated experimental system was designed and built, which included a novel approach to account for particle losses inside the sampler inlet. For this, the sampler entry was filled with a plug of porous plastic foam that smoothed the aspirated air flow and provided well-defined particle penetration into the instrument.

The first experiments with this system investigated the aspiration efficiency of a thin- walled probe at 90° to the wind, with the aim of gaining experience with the new apparatus and methodology with an aerosol sampling system that is simple yet still of considerable scientific interest to aerosol scientists. The results were in fair agreement with previously published data, but indicated some internal functional relationships not previously seen. For the main experimental study aimed at practical personal aerosol samplers, the scaling laws we developed enabled full-scale experimental conditions may be simulated by small-scale experiments. A key component was that not only are the sampler dimensions and air flows able to be scaled, but the particle size itself may be scaled as well. This allowed for particles in the range of the APS (up to 20 μm) to be used to simulate the behavior of much larger particles. These scaling laws were applied to experiments for testing the performance of three commercially-available personal aerosol samplers: the IOM personal inhalable aerosol sampler, the CIS inhalable aerosol sampler and the Button aerosol sampler. The results from these experiments provided validation of the scaling laws and were broadly consistent with what has been previously observed in large wind tunnels. Again, however, some additional functional relationships were observed that had not previously been seen by others. Despite some differences in sampler performance when compared to full-scale studies, it is concluded that the new testing method developed in this research will be an excellent starting point for the preparation of a standard protocol for the evaluation of practical aerosol samplers.

Finally, some experiments were carried out in the field, an aluminum smelter, to compare instruments derived from the new knowledge gained in this research, as well as in a previous NIOSH-funded project. Here, for instruments that compared well in our laboratory studies, agreement was less satisfactory in the field. It is possible that this may be associated with the fact that windspeeds in most workplaces are actually much lower than those in wind tunnel experiments (including not only our own but also most of the aerosol sampling research conducted by others).

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December 1st 2003

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Office of Extramural Programs,
National Institute for Occupational Safety and Health,
1600 Clifton Road,
Executive Park, Building 24, Room 1427,
MS E-74,
Atlanta, GA

Dear Adele,

Re: Final Report on 5 RO1-OH02984-06 "Methods for developing and testing aerosol samplers"

I am pleased to submit the Final Report on this NIOSH-funded project. I have enclosed two hard copies and one electronic copy on a CD-ROM. I hope that this meets the requirements for this part of the final close-out of this project.

I am very pleased at the progress we achieved in this research, and feel that it makes a substantial step forward towards how we might best protect workers from occupational aerosol exposures. I would welcome comments from anyone to whom you would wish to circulate the report.

Please let me know if there are any questions.

Yours sincerely,

James H. Vincent, Ph.D., D.Sc.
Professor and Chair, Department of Environmental Health Sciences

cc. Patrice Somerville

PB2005-105216

Final Report

on research carried out under

NIOSH-CDC Grant No. 5 RO1-OH 02984-06

entitled

METHODS FOR DEVELOPING AND TESTING AEROSOL SAMPLERS

by

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and

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Submitted December 2003

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ACKNOWLEDGEMENTS

The authors are grateful for the financial support of this research by the National Institute for Occupational Safety and Health through its Extramural Program in Occupational Health (Grant Number 5 RO1 OH02984-06). We are also grateful to the School of Public Health at the University of Michigan for providing basic facilities and infrastructure without which this work would not have been possible. In addition we are grateful for the technical support provided by machinists in the Department of Chemistry at the University of Michigan who helped design and build a number of items of equipment that were central to the work.

We would like to note our special appreciation of the opportunity, for the field study part of the project reported near the end of this report, to work closely with colleagues at the Norwegian National Institute for Occupational Health, Oslo. Special thanks are due to Dr. Yngvar Thomassen, who facilitated the collaboration and provided technical support both in the field study itself and in the subsequent quantitative analysis of samples in his laboratory.

Finally we appreciate very much the work of the administrative support teams in the Department of Environmental Health Sciences and elsewhere in the University who provided the guidance, administrative work and financial oversight that were essential to the success of the whole project.

ABSTRACT

Development and characterization of samplers whose performances mimic the inhalability of the human head will be an important step forward in exposure assessment for environmental and occupational aerosols. The current method for sampler characterization involves arduous experiments in large wind tunnels, of which only a few exist. Therefore a new, rapid and cost-effective method is needed, and the main objective of this research was to develop a set of scaling laws for aerosol sampling, leading to new methodology for aerosol sampler characterization in a small-scale wind tunnel using a direct-reading aerodynamic particle sizer (APS), which counts and sizes sampled particles. For this purpose, a prototype automated experimental system was designed and built, which included a novel approach to account for particle losses inside the sampler inlet. For this, the sampler entry was filled with a plug of porous plastic foam that smoothed the aspirated air flow and provided well-defined particle penetration into the instrument.

The first experiments with this system investigated the aspiration efficiency of a thin-walled probe at 90° to the wind, with the aim of gaining experience with the new apparatus and methodology with an aerosol sampling system that is simple yet still of considerable scientific interest to aerosol scientists. The results were in fair agreement with previously published data, but indicated some internal functional relationships not previously seen. For the main experimental study aimed at practical personal aerosol samplers, the scaling laws we developed enabled full-scale experimental conditions may be simulated by small-scale experiments. A key component was that not only are the sampler dimensions and air flows able to be scaled, but the particle size itself may be scaled as well. This allowed for particles in the range of the APS (up to 20 μm) to be used to simulate the behavior of much larger particles. These scaling laws were applied to experiments for testing the performance of three commercially-available personal aerosol samplers: the IOM personal inhalable aerosol sampler, the CIS inhalable aerosol sampler and the Button aerosol sampler. The results from these experiments provided validation of the scaling laws and were broadly consistent with what has been previously observed in large wind tunnels. Again, however, some additional functional relationships were observed that had not previously been seen by others. Despite some differences in sampler performance when compared to full-scale studies, it is concluded that the new testing method developed in this research will be an excellent starting point for the preparation of a standard protocol for the evaluation of practical aerosol samplers.

Finally, some experiments were carried out in the field, an aluminum smelter, to compare instruments derived from the new knowledge gained in this research, as well as in a previous NIOSH-funded project. Here, for instruments that compared well in our laboratory studies, agreement was less satisfactory in the field. It is possible that this may be associated with the fact that windspeeds in most workplaces are actually much lower than those in wind tunnel experiments (including not only our own but also most of the aerosol sampling research conducted by others).

SIGNIFICANT FINDINGS

We set out to develop a cost effective small-scale system and methodology for testing the aspiration efficiencies of aerosol samplers and validation against the latest particle size-selective sampling criteria for actual particle sizes up to 100 μm in aerodynamic diameter and over relevant ranges of actual sampler geometrical dimensions, flowrate and windspeed. This objective was met in large measure. A prototype new, automated testing system, designed around the application of a direct-reading aerodynamic particle sizer (APS) was designed and built. It was validated through experiments with a small range of personal aerosol samplers currently of interest to industrial hygienists.

An important part of the research, underpinning the apparatus and methodology referred to above, was the development and validation of appropriate scaling relationships for aerosol samplers, thus enabling scaling between small and large sampling systems, low and high windspeeds and sampling flowrates, and small and large particles. These were shown to be very effective in helping to design scaled laboratory experiments.

The final part of the project involved trials in workplaces with new aerosol samplers arising out of the new knowledge of the aerosol sampler scaling relationships, comparing them with pre-existing samplers that have already found practical application by industrial hygienists. Here, in a field trial carried out in Norway in an aluminum smelter, it was found that some of the correlations that were firmly established in the laboratory were not fully realized in the field. It was suggested that this may be due to the fact the windspeeds in actual workplaces tend to be lower than those corresponding to experiments in the laboratory, both in our research and most of that reported by others. This needs further work, and – indeed – is the subject of a new proposal.

USEFULNESS OF FINDINGS

The area of scientific research described by this research continues to be important in the field of environmental and occupational health. The international community has recently moved towards the adoption of health-related particle size-selective criteria for the measurement of exposure to aerosols that have been agreed upon by the International Standards Organisation (ISO), the American Conference of Governmental Industrial Hygienists (ACGIH) and the Comité Européen de Normalisation (CEN), as well as other national and international organizations (Vincent, 1999). In turn, such criteria will form the basis of a new generation of scientific occupational exposure limits which reflect the health-related exposures of workers more closely than those of the previous generation.

The research described in this report reflects significant progress towards the development of a rapid and cost-effective test method for the evaluating of personal aerosol samplers like those used by practicing industrial hygienists. This goal is not only the subject of the present NIOSH-funded project but also of a large multi-nations project funded by the European Community, reflecting the international interest in this subject. The significance of the findings of this research are represented by the application of our new knowledge into a new, 'demonstration'" aerosol sampler testing protocol.

GLOSSARY OF IMPORTANT SYMBOLS

θ	Angle of orientation with respect to the wind
A	Aspiration efficiency
A_{90}	Aspiration efficiency at 90° to the wind (for the thin-walled probes)
c	Particle concentration
c_0	Freestream particle concentration
c_{APS}	Particle concentration measured by the aerodynamic particle sizer
c_e	Particle concentration passing through the entry region of the sampler
c_s	Particle concentration passing through the plane of the sampler orifice
δ	Sampler orifice diameter
D	Bluff body diameter
d_{ae}	Particle aerodynamic diameter
d_f	Effective fiber diameter (for the porous plastic foam media)
E	Transmission efficiency
Fr	Froude number
G	Coefficient used in semi-empirical aspiration efficiency models
$I(d_{ae})$	Inhalability as a function of particle size
k_δ	Scaling factor for orifice diameter
k_{dae}	Scaling factor for particle diameter
k_U	Scaling factor for air velocity
η	Viscosity of air, 1.8134×10^{-5} kg/ms
N_g	Gravitational parameter (for the porous plastic foam media)
ρ	Density
ρ^*	Density of water, 10^3 kg/m^3
P	Particle penetration
P_{entry}	Particle penetration for the entry region of a sampler
P_{foam}	Particle penetration for the porous foam
$P_{sampler}$	Particle penetration for the portion of aerosol sampler in front of the filter/foam

THE PROPOSED RESEARCH

Summary of original proposal

Background

In general, the operation of aerosol samplers involves the aspiration of particle-laden air, selection of particles in the size range of health-related interest, and either collecting them onto a filter (for subsequent gravimetric or other assessment) or passing them through a sensing region (e.g., for real-time assessment, optically or by some other means). The efficiency with which particles are aspirated and collected in this system depends mainly on a combination of inertial and gravitational forces. The physical fluid and particle mechanical scenario is complicated. But research in recent years, including previous NIOSH-funded work in our own laboratory, has provided important new insights into the factors which govern aspiration efficiency (the primary index of sampler performance)

Current theoretical knowledge, based on the application of aerosol science to the behavior of particles in distorted flows near bluff bodies with aspiration, has now reached the point where it can provide strong guidance to the design and development of new aerosol samplers and to the interpretation of results obtained using existing ones. However confidence in such models has not yet reached the point where they can be applied directly to the design and implementation of new samplers without the need for the intermediate step of testing and validation in the laboratory. At present, such testing can be reliably carried out only for full-scale sampling systems in large wind tunnels (e.g., large enough to accommodate personal samplers mounted on life-sized mannequins) and for particles with aerodynamic diameter[1] in the range up to and exceeding 100 μm (i.e., the range typical of many workplace aerosols). But such tests are very difficult because of the problems of achieving uniform aerosol spatial and temporal distributions in the working sections of such large facilities. They are also very time-consuming and laborious, as has been borne out by previous studies directed by the Principal Investigator (e.g., Mark and Vincent, 1986; Vincent and Mark, 1990) and others (e.g., Kenny *et al.*, 1997). Inevitably, therefore, the cost is also very high, so much so that it is unlikely that such methods can be routinely applied to the testing of such intrinsically low-cost devices. In any case, the availability of resources and expertise to carry out such experiments is severely limited – where only about four laboratories in the world are presently suitably equipped.

From the preceding, it is clear that an alternative approach to sampler design, development and testing is essential if full implementation of the new aerosol standards is to be achieved. During the last two decades there has been great progress towards the setting of scientifically-based criteria for aerosol measurement in the workplace and elsewhere, led by the International Standards Organisation (ISO), the American Conference of Governmental Industrial Hygienists (ACGIH) and the Comité Européen

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[1] Particle aerodynamic diameter is defined as the diameter of a spherical particle of density 10^3 kg/m^3 that has the same falling speed in air as the particle in question.

Normalisation (CEN). All three bodies have moved during recent years towards international harmonization of particle size-selective criteria for health-related aerosol sampling, and these are summarized in a recent book published by ACGIH (Vincent, 1999). Such criteria are intended specifically as 'yardsticks' for the design of new sampling instrumentation. They focus attention firmly on the need for sampling to directly reflect the true physical nature of the human exposure. They identify firstly the inhalability of the human head itself, representing the efficiency, as a function of particle size, with which particles enter through the nose and/or mouth during breathing. This is the inhalable fraction. They then identify the thoracic and respirable fractions as subfractions of that inhalable fraction. Here, the thoracic fraction describes the probability that an inhaled particle may penetrate into the lung below the larynx, and the respirable fraction the probability of penetration down to the alveolar region. Each of the three conventions is represented by a single curve describing it as a function of particle aerodynamic diameter (Vincent, 1995). It is expected that these will form the basis of future occupational exposure limits (OELs) for aerosols.

The inhalable fraction is the most relevant to the research that was proposed. This is mainly because it is expected that this fraction will apply to most OELs for what is currently referred to as "total aerosol". In addition, the inhalable fraction is the starting point (or the 'envelope') for the other two fractions. Further, it is the most difficult to simulate in a sampling instrument since it is determined largely by physical (fluid and particle mechanical) factors outside the body of the sampler which are highly variable and largely uncontrolled.

Aims

Aerosol samplers are important to industrial hygiene through their role in the measurement (and hence regulation) of workers' exposures to airborne particles. Proposed new health-related aerosol standards require that such measurement should reflect the true physical nature of human exposure (i.e., the manner in which they are inhaled and penetrate into the respiratory tract). This, in turn, has stimulated the search for new generations of practical sampling devices, and development of these should be facilitated by the improved knowledge about their basic performance characteristics. However the actual development and implementation of such instruments is restricted by the current need to employ very sophisticated and time-consuming experimental test procedures in scarce, large wind tunnel facilities (and hence at great cost). The primary broad objective of the proposed research was therefore:-

- To develop a cost-effective, small-scale system and methodology for testing the aspiration efficiencies of aerosol samplers and validation against the latest particle size-selective sampling criteria for actual particle sizes up to 100 μm in aerodynamic diameter and over relevant ranges of actual sampler geometrical dimensions, flowrate and windspeed.

The specific objectives of the research were:-

- To use current new knowledge of the theory of aerosol sampling to develop scaling relationships between small and large sampling systems, low and high windspeeds and sampling flowrates, and small and large particles;
- To apply the scaling laws to an experimental system in which aerosol sampling systems of interest (including small personal samplers mounted in the 'breathing zone' of a large torso) are re-created at small-scale in a small wind tunnel and tested for experimental particle size ranges (up to 25 μm) that can be conveniently measured using currently-available direct-reading instrumentation (e.g., an aerodynamic particle sizer);
- To validate application of the scaling laws by comparing the results from selected small-scale systems (for particles up to 25 μm) with previously-obtained results from experiments conducted at full-scale in large wind tunnels (for particles up to 100 μm);
- To apply the validated scaling laws to the development of cost-effective protocols for the testing of proposed new samplers for the inhalable aerosol fraction;
- To use the new methods to aid the design and development of new and more effective samplers for the inhalable fraction; and
- To conduct trials in workplaces to compare exposures as measured with new samplers with those previously validated.

In such scaling laws, it is important to recognize that it is not only the physical dimensions and airflows that may be scaled but also – within the natural principles of physics and engineering – the particle size itself. Thus, as will be demonstrated in this report, experiments or tests carried out for particles of small size (say, up to just 25 μm) can be used to directly infer knowledge about what would happen for particles of large size (say, up to 100 μm or beyond). This indeed was a key component of what is proposed, opening the door to practical application of the rapid testing methods that were first identified during earlier NIOSH-funded research (RO1-OH 02984-02) (Vincent *et al.*, 1998). Thus this project would provide and validate the means to rapidly develop, test and deploy new aerosol sampling devices to meet the needs arising from implementation of the new particle size-selective occupational health standards.

TECHNICAL REPORT

1. Introduction

Aerosol samplers are important tools in the field of environmental and occupational health for the assessment of exposure to airborne particulates. The scientific basis of exposure itself is important in that it provides the basis for the setting of appropriate criteria for health-based aerosol standards and the measurement of exposure in relation to those standards. Aerosol sampling plays an essential role in exposure assessment, since it relates to the technical means by which a person's exposure to airborne particulates may be quantified. Sampling involves extraction of a volume of air and particles into a device so that the particles can be subsequently quantified by weighing, use of a direct-reading instrument, or some other means. Understanding of this process, in terms of aerosol science, requires the study of air and particle transport in the flow around a bluff body, particularly where there is aspiration (Vincent *et al.*, 1997).

There has been much progress made in the last twenty years towards setting scientifically-based criteria for the measurement of exposure to aerosols. The bodies primarily involved are the International Standards Organisation (ISO), the American Conference of Governmental Industrial Hygienists (ACGIH) and the Comité Européen de Normalisation (CEN), as well as other national and international organizations. These organizations have recently moved towards international standardization of particle size-selective criteria for health-related aerosol sampling, which have been recently published by ACGIH (Vincent, 1999). These criteria focus on the need for sampling to reflect the true nature of human exposure. First, they identify the inhalability of the human head, representing, as a function of particle size, the efficiency with which particles enter through the nose and/or mouth of exposed people during breathing. This is defined as the *inhalable fraction*. Both the thoracic and respirable fractions are then identified as subfractions of the inhalable fraction. The *thoracic fraction* represents the probability that an inhaled particle will penetrate into the lungs past the larynx, and the *respirable fraction* represents the probability of penetration to the alveolar region.

These criteria are important because personal aerosol samplers are used for regulatory purposes and in exposure assessment. For the sake of worker protection and accuracy of exposure assessment, aerosol samplers must be able to effectively represent the particle size-selective nature of human inhalation. The thoracic and respirable fractions are crucial because some aerosols are not harmful just when inhaled into the nose and mouth, but only when they penetrate further into the respiratory tract (when the health effect of concern is associated with particle penetration deeper into the respiratory tract, as opposed to toxic effects caused by the presence of the substance anywhere in the body). For an aerosol containing an inherently toxic substance, such as lead or cadmium, it is important to collect the inhalable fraction, since any of the substance that enters the body may potentially be harmful.

The inhalable fraction is the most relevant of the three health-based, particle size-selective criteria to the present research. It is of special interest because it contains both the thoracic and respirable fractions, and also because it is expected that this fraction will apply to most standards relating to what was previously referred to as "total aerosol". However, the inhalable fraction is the most difficult to simulate because it is largely influenced by physical factors outside of the sampling body, most of which are uncontrollable and, in many cases, unknown. These include complex flow shapes, instabilities, velocities, external winds, etc.

Presently, characterization of aerosol samplers can only be reliably performed in wind tunnels large enough to accommodate full-scale mannequins (Ogden and Birkett, 1977; Ogden *et al.*, 1977; Armbruster and Breuer, 1982; Vincent and Mark, 1982). There are very few wind tunnels in existence that are properly equipped to carry out these tests. The tests themselves have involved placing the sampler on a full-sized mannequin body in the working section of a large wind tunnel. Typically, narrowly-graded, nearly-monodisperse aerosols have been generated, delivered to the working section of the tunnel and collected by the aerosol samplers of interest. In such experiments, many experiments must be run to cover a range of relevant particle sizes and windspeeds. Yet it is very difficult in such systems to achieve the necessary uniform temporal and spatial distributions of aerosol in the working section of the large wind tunnel. Each individual experiment is time-consuming, requiring filters and sampler cassettes to be weighed before and after sample collection and long sampling durations for sufficient masses to be collected by the samplers. Characterization of a single aerosol sampler in this way may therefore require weeks of experiments, and the resultant large data scatter that has been experienced is difficult to control. All these factors make the cost of full-scale aerosol sampler characterization very high, leading to the conclusion that – in the longer run – it is impractical for routine use in sampler development.

There is therefore a need for a better method for aerosol sampler characterization that is less expensive, less labor-intensive and less time-consuming. The National Institute for Occupational Safety and Health (NIOSH) recognizes this need and has provided funding for this research. It is postulated initially that, by performing these experiments in a small wind tunnel, costs would be greatly reduced, and many more laboratories would be able to set up properly-equipped facilities. Even so, gravimetric tests with monodisperse aerosols as described is still time-consuming, even in a small wind tunnel. But the incorporation of a direct-reading instrument, such as an aerodynamic particle sizer (APS) which counts and sizes sampled particles, would allow for data to be collected simultaneously for many particle sizes and stored and analyzed digitally. Progress towards the development of a method of this type was made earlier by a research group at the University of Minnesota led by the Principal Investigator for the present research (Ramachandran *et al.*, 1998), and was used as a starting point for this work. It is known that the European Community has also recently been funding research that parallels this work, involving laboratories in the UK, France, Italy and Germany (Kenny, 1997).

The development of a method of the type alluded to also has important implications as a basis of a standard protocol for testing of aerosol samplers. Having a standard method would allow for more reliable and more rapid testing of aerosol samplers and would facilitate comparison of experimental results between different laboratories. A good example of a standardized protocol for the evaluation of aerosol samplers has been drafted by the Comité Européen de Normalisation (CEN) which could be used as a template for such a standard method (Liden, 1994; CEN, 2001).

Goals of the Research

The research described in this report set out to address the following primary broad objective (as already described in the proposal):-

- To develop a cost-effective methodology for testing the aspiration efficiencies of aerosol samplers using a small-scale system; validated against the latest particle size-selective sampling criteria for actual particle sizes up to 100 μm (aerodynamic diameter) over relevant ranges of actual sampler geometric dimensions, sampling flowrate and windspeed.

The more specific scientific objectives of the research included:-

- To develop scaling relationships between small/large sampling systems, low/high windspeeds, low/high sampling flowrates, and small/large particles;
- To apply scaling laws to an experimental system where aerosol sampling systems of interest are recreated at small-scale in a small wind tunnel and tested with particle sizes up to 20 μm, measured using an aerodynamic particle sizer (APS);
- To validate application of scaling laws by comparing the results from small-scale experiments to previously obtained results from full-scale experiments in large wind tunnels with particle sizes up to 100 μm;
- To apply validated scaling laws to the development of cost-effective testing protocols for new samplers proposed for the inhalable aerosol fraction; and
- To conduct a field study to evaluate how samplers emerging from this research and other recent related research performed under actual workplace conditions.

Other research

The work described in this report builds on what was learned during earlier NIOSH-funded research (RO1-OH 02984-02) (Vincent *et al.*, 1998). It also complements research carried out under a more recent NIOSH-funded project (RO1-OH 03687-03) (Vincent *et al.*, 2003). That other project was concerned with the development of new personal aerosol samplers, specifically inhalable aerosol samplers that could be operated at much lower sampling flowrates than the samplers that are currently used for this fraction.

2. Background

Health-based aerosol sampling criteria

The inhalable aerosol fraction is expressed quantitatively by an empirical equation which relates inhalability (I) to particle aerodynamic diameter (d_{ae}), thus

$$I(d_{ae}) = 0.5 \cdot \{ 1 + \exp(-0.06 d_{ae}) \} \quad (2.1)$$

The thoracic fraction (T) is defined as a fraction of the inhalable fraction, described by

$$T(d_{ae}) = I(d_{ae}) \cdot \{ 1 - F_T(d_{ae}) \} \quad (2.2)$$

where $F_T(d_{ae})$ is a cumulative log-normal function with its median at $d_{ae} = 11.64$ µm and has a geometric standard deviation (σ_g) of 1.5. Similarly, the respirable fraction (R) is defined as a subfraction of inhalability, thus

$$R(d_{ae}) = I(d_{ae}) \cdot \{ 1 - F_R(d_{ae}) \} \quad (2.3)$$

where $F_R(d_{ae})$ is a cumulative log-normal function with its median at $d_{ae} = 4.25$ µm and σ_g equal to 1.5 (Vincent, 1999).

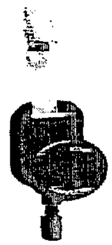
Personal aerosol samplers

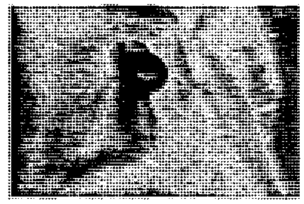
Industrial hygienists have recognized that the only way to obtain a truly representative measure of an individual worker's aerosol exposure is to place a small sampling device very close to the "breathing zone" of the worker. In this way, the sampler – provided it has the appropriate health-based particle size-selection characteristics – collects the same aerosol concentration as that experienced by the worker. Nowadays, personal sampling is widely viewed to be the only way to satisfactorily measure the exposure of workers to airborne particulates (Walton and Vincent, 1998).

There are many different designs of commercially-available personal aerosol samplers. They are all comprised of a sampling head of varying design in front of a filter where the particles are collected for gravimetric or chemical analysis. Generally they are attached by flexible tubing to a personal sampling pump that is worn on the belt. Since these samplers are meant to be worn in the breathing zone of the worker, they are generally equipped with a clip to attach it to the shirt collar or lapel.

The Institute of Occupational Medicine (IOM) personal inhalable aerosol sampler (from SKC, Inc., Eighty-Four, PA) – see Figure 2.1 below – was the first personal sampler developed specifically to collect the inhalable fraction (Mark and Vincent, 1986). Subsequent laboratory and field studies have shown that this sampler is indeed an effective inhalable aerosol sampler (Vaughan *et al.*, 1990; Kenny *et al.*, 1997). The IOM sampler has a simple design consisting of a removable filter cassette that has a 15-mm diameter sampling orifice which sits inside a 45-mm diameter sampling body. The required sampling flow rate is 2 L/min. This sampler is unique in that the entire filter cassette is weighed in order to quantify the amount of aerosol collected, rather than the filter alone. The IOM sampler was tested extensively during the course of this work.

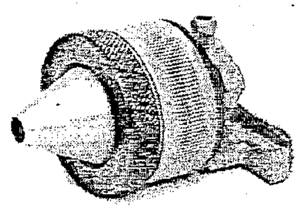
Figure 2.1: The IOM sampler





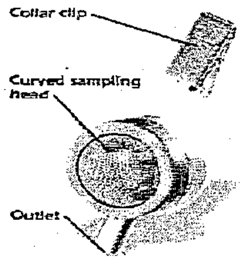
The conical inlet sampler (CIS, from BGI, Inc., Waltham, MA) was also studied in this work (see Figure 2.2 below). This sampler was designed in Germany, where it is known as the "GSP sampler". This sampler is operated at a flow rate of 3.5 L/min, and the aerosol collected is quantified by assessment of the filter only. It has been shown in some experimental studies to collect the inhalable fraction satisfactorily under certain environmental conditions (Kenny *et al.*, 1997).

Figure 2.2: The CIS sampler



The third sampler that was characterized in the current work is the Button Aerosol Sampler (from SKC, Inc., Eighty-Four, PA). It is shown below in Figure 2.3. For this instrument, the inlet was designed in the form of a curved porous stainless steel screen (with individual orifices of the order of 380 μm), aimed at minimizing the sensitivity of the sampling efficiency to wind velocity and direction, and providing uniform particle deposition on the filter (Aizenberg *et al.*, 2000; Li *et al.*, 2000). The recommended flowrate for this sampler is 4 L/min, and the aerosol collected is quantified by assessment of the filter only.

Figure 2.3: The Button sampler



Primary indices of aerosol sampler performance

People are exposed to particles by inhalation when the particles are drawn into the nose and/or mouth by aspiration. This process is strongly influenced by the way in which airborne particles are carried by air in the vicinity of the individual. So the concentration of aerosol inhaled (or aspirated) may not be the same as that originally in the inhaled air volume. Inhalation efficiency (I) is defined as

$$I = c / c_0 \qquad (2.4)$$

where c is the concentration of particles passing into the nose and/or mouth and c_0 is the concentration of particles originally contained in the aspirated air volume. Similarly, the aspiration efficiency of an aerosol sampler can be defined as

$$A = c_s / c_0 \qquad (2.5)$$

where c_s here is the concentration of particles passing directly through the plane of the sampling orifice. This is true for aerosol samplers for which the entire amount of aerosol that enters the plane of the sampling orifice is quantified, as is the case for the IOM sampler. However, it is important to note that the use of many commercially-available aerosol samplers, including the CIS and Button samplers, involves assessment of only the aerosol collected on the filter that is housed in the sampler, while any particles deposited on the inner surfaces in front of the filter are disregarded. Performance of this type of sampler is therefore best characterized by its "sampling efficiency", in which the aspiration efficiency is modified by the particle size-selective penetration characteristics of the portion of the sampler inside the entry but in front of the filter.

The aspiration or sampling efficiency of a particular aerosol sampler, expressed as a function of particle aerodynamic diameter, is the primary index of sampler performance and should match the appropriate health-based criterion (e.g., the inhalability criterion) in order that it may be said to provide a valid health-based assessment of personal exposure of inhalable aerosol.

Dimensionless quantities

Aspiration efficiency can be generally described as a function of several different dimensionless parameters relating to the movement of air and particles in the vicinity of the sampler, thus

$$A = \mathrm{f}\,\{\, St, R, r, \theta, Re_f, Re_p, Fr, \ldots \,\} \qquad (2.6)$$

where St is the Stokes' number, R the velocity ratio, r the dimension ratio, θ the angle of orientation of the sampler with respect to the wind, Re_f and Re_p the Reynolds' numbers relevant to the macroscopic bulk and microscopic particle air flows respectively, and Fr the Froude number. Here, R is the ratio of the freestream velocity (U) to the mean velocity of air passing through the plane of the sampler orifice (U_s), thus

$$R = U \,/\, U_s \qquad (2.7)$$

The dimension ratio (r) is the ratio of the sampler orifice diameter (δ) to the sampler characteristic dimension (D), thus

$$R = \delta \,/\, D \qquad (2.8)$$

The Stokes' number represents the inertial forces experienced by the particle in the flow field near the sampler body, and is expressed as

$$St = d_{ae}^{\,2} \rho^{*} U \,/\, 18\, \eta\, \delta \qquad (2.9)$$

where ρ^{*} is the density of water and η the viscosity of air. This quantity defines the ability of the particles to follow the air flow as may be influenced by inertial considerations.

Reynolds' number is a very important dimensionless quantity in the general field of fluid mechanics, reflecting the balance between inertial forces in the main body of the flow and the viscous forces close to the flow boundaries. In general it is given for air by

$$Re = d\, v \,/\, \rho\, \eta \qquad (2.10)$$

where d here is a characteristic dimension, v a relevant velocity, and ρ and η are the air density and air viscosity respectively. Re_f is the Reynolds' number pertaining to the macroscopic flow outside and around the sampler. Although it has been considered in some proposals for aerosol sampler scaling (e.g., Kenny *et al.*, 2000), many properties of air flows around bluff bodies are not very sensitive to Re_f for values above about 2,000 (e.g., Schlichting, 1979). So for the present work, where Re_f ranged from about 6,000 to 40,000 (see below), it is a reasonable starting assumption that Re_f may be initially neglected. Re_p is the Reynolds' number for the microscopic particle motion relative to the flow, and it is reasonable to assume that, within the range where particle motion follows Stokes' law (where typically $Re_p < 1$), this parameter too may be neglected in considerations of scaling in the present work.

The Froude number (Fr) describes the relative effect of inertia to gravity in particle motion. But for particle sizes in the range of interest in the research described here, gravitational forces are small in relation to inertial ones, so that effects relating to Fr may be neglected. In addition to the dimensionless quantities already identified, it is possible to define others that might, under certain conditions, be important (e.g., relating to the freestream turbulence or electrostatic effects). However, the overall effects of these are thought to be secondary in importance (Vincent, 1989), and so they are not further considered here.

In conclusion from the above, aspiration efficiency is considered in the first instance to be a function simply of the form

$$A = \mathrm{f}\,\{\, St, R, r, \theta \,\} \tag{2.11}$$

It should be further noted that the dimension ratio (r) is now known not to be as important in determining aspiration efficiency as was initially thought. Recent research in our laboratory (Paik and Vincent, 2002b) has shown that A does not change significantly for an aerosol sampler mounted on different sizes of bluff bodies, over a wide range of r. With this in mind, therefore, Stokes' number (St) and velocity ratio (R) are the only parameters that were scaled in this work.

As suggested by Equation (2.11), sampler orientation is also an important dimensionless variable that needs to be taken into account. In this work, all experiments involving personal aerosol samplers were 'orientation-averaged'. That is, the sampler and bluff body were continuously and slowly rotated throughout the experiments, instead of being placed at a fixed angle with respect to the wind. This is so that their performances may be compared to the inhalability criterion which itself was based on the aspiration efficiency of the human head for orientations averaged over 360° about a vertical axis. This in turn reflects the fact that, in general in the workplace, people have no preferred orientation with respect to any local air movement. There was one set of experiments for which more specific sampler orientation was studied, namely for thin-walled sampling probes placed at 90° to the air flow. Full details of all these experiments are given below, and Table 2.1 shows the ranges of St, R, r and θ that were investigated.

Parameter	Thin-walled probe	IOM Sampler	CIS sampler	Button sampler
St	2.8×10^{-4} to 3.7	5.1×10^{-5} to 0.29	1.9×10^{-4} to 0.62	2.5×10^{-4} to 0.20
R	2.8 to 54	5.3	0.43 to 3.4	3.7 to 29
r	1	0.125	0.067	0.21
θ	90°	orientation-averaged	orientation-averaged	orientation-averaged

Table 2.1: Range of scaled variables for sampler aspiration efficiency experiments.

Aspiration efficiency models

One possible approach towards describing the nature of air and particle flow near and into an aerosol sampler may involve solving the rigorous mathematical transport equations, requiring full description of flow fields and particle trajectories (e.g., Dunnett and Ingham, 1988; Dunnett and Vincent, 2000). But no complete mathematical model currently exists that can describe any except the simplest of sampling scenarios. So an alternative approach, favored by many aerosol scientists, is to describe the system of interest using semi-empirical physical models based on an understanding of broader features of air and particle transport. Such an approach has been described as the "impaction model" (Vincent, 1989). The simplest such model is for a thin-walled probe facing into the wind. For this scenario, aspiration efficiency may be described by

$$A = 1 + \alpha\,(R - 1) \tag{2.12}$$

where α is an impaction efficiency as a function of Stokes' number, taking values between zero and unity. Seminal work carried out by Belyaev and Levin (1974) established that

$$A = 1 - \{\, 1 / (1 + G \cdot St\,)\, \} \tag{2.13}$$

with the coefficient G given by

$$G = 2 + \{\, 0.62 / R\, \} \tag{2.14}$$

It has been shown that this model predicts aspiration efficiency well for thin-walled samplers facing the wind for a range of R-values from 0.03 to 11 (Lipatov *et al.*, 1986). Several attempts have been made to develop this model further to account for the effect of different sampler orientations with respect to the wind (Durham and Lundgren, 1980; Tufto and Willeke, 1982; Vincent *et al.*, 1986; Vincent, 1989; Hangal and Willeke, 1990). Vincent *et al.* suggested an expression which simplifies to

$$A_{90} = 1 + \{\, 1 + 4 \cdot G \cdot St \cdot R^{1/2}\, \} \tag{2.15}$$

when the sampler is pointed with its entry at 90° to the freestream. This is relevant to the current research because a number of experiments were carried out for thin-walled probes under this condition. In the original Vincent *et al.* work, a number of expressions for the coefficient G were considered and dependences on R, δ and θ were found to be not statistically significant. So as a constant value of G for the limited case of the thin-walled probe, Vincent *et al.* proposed G = 2.1 with a standard error of ±0.9, with the large standard error reflecting the significant scatter in the data available at that time.

More recently, Paik and Vincent (2002a) have experimentally investigated aspiration efficiency for thin-walled nozzles facing the wind for R-values ranging much more widely than before, from 0.5 to 50. Based on the new experimental data, they expanded the original Belyaev and Levin model by adding an additional term to the coefficient G, as follows

$$G = 2 + \{\, 0.62 / R\, \} - \{\, 0.9 \cdot R^{0.1}\, \} \tag{2.16}$$

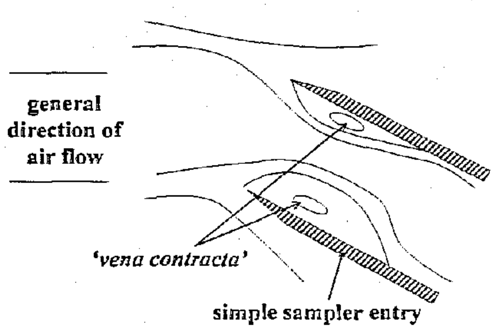
This was found to be in excellent agreement with all of the available experimental data, including both the earlier ones as well as the new data.

The discussion here has so far been concerned only with thin-walled sampling probes. These samplers are important because their simplicity allows insight into some of the fundamental issues relating to sampler performance that can then be translated to more complex configurations more relevant to practical aerosol samplers. Some progress has been achieved towards extension of the preceding models to samplers of more realistic shape, including blunt samplers at various orientations with respect to the wind (e.g., Vincent, 1987; Tsai and Vincent, 1993; Tsai *et al.*, 1995; Tsai *et al.*, 1996). However, such models do not feature in the present research, and so will not be elaborated further in this report.

Inlet effects

In designing an automated system by which to measure the aspiration efficiency of an aerosol sampler, the behavior of particles in the flow region very close to the sampler, both outside and inside the plane of the entry, becomes very important. This is the region where the external flow 'couples' with the internal flow. Here it has been shown that significant particle deposition losses may occur that are very difficult to account for (Sreenath *et al.*, 2001).

Figure 2.4: Air flow inside the sampler inlet



Such effects are associated with the flow separation that takes place just inside the sampler, manifested in the formation of the *vena contracta* (see Figure 2.4 above). Depending on the relative magnitudes of U and U_s, and on the sampler orientation, this may also be characterized by flow instability. Sreenath *et al.* showed that particle motion in this region of the flow is a complex function of particle size, windspeed, sampling flowrate and sampler orientation. Even for the relatively simple case of thin-walled probes that was studied, the flow is complex enough that there is little prospect of being able to effectively model the transport of particles through this region so that such effects may be accounted for. So it is still necessary to find an alternative way to quantify, or otherwise account for, particle losses in the inlet.

$$y = 54.86 \cdot St_{foam}^{2.382} + 38.91 \cdot N_g^{0.880} \qquad (2.20)$$

where Vincent *et al.* determined the coefficients by non-linear regression with respect to the data available at the time. Since it was originally developed, the model embodied in the preceding set of equations has been validated against a significant amount of new data from two different laboratories and has been confirmed as providing a good prediction of foam penetration (Kenny *et al.*, 2001).

Such foams are conventionally specified in terms of nominal porosity (Po), expressed in ppi or 'pores per inch' (the number of pores intersected per linear inch) which can be measured by microscopy. Vincent *et al.* showed that this in turn may be empirically related to the fiber diameter (d_f) by the empirical expression

$$d_f = 9633 \cdot Po^{-1.216} \qquad (2.21)$$

where d_f is again expressed in µm.

Overview

The research described in this report integrates all of the above ideas. The remainder of the report describes the development of the desired small-scale aerosol sampler testing system, along with an appropriate set of scaling laws to govern the translation of full-scale environmental conditions into those which may be created in a small wind tunnel. This will be followed by descriptions and interpretations of results from the subsequent aerosol sampler performance experiments.

3. Experimental design

Laboratory equipment

Wind tunnel: The wind tunnel utilized in this research had a test section with a square cross-sectional area of 0.3 x 0.3 m^2 (1 ft^2) (see Figures 3.1 and 3.2 below), which is much smaller than the large wind tunnels typically used to characterize aerosol samplers for industrial hygiene. Air was drawn through an inlet containing a bank of HEPA filters, passed through a honeycomb screen, and accelerated through a 6.25:1 contraction into the aerosol dispersion section. Test aerosol was introduced into the dispersion section and passed through a square-mesh turbulence grid, with bars 8.4 mm wide spaced 62 mm apart, and then into the test section. The purpose of the turbulence grid was to facilitate mixing of the aerosol and to establish well-defined turbulence in the test section. This particular grid size was chosen so that it was thin enough to provide a uniform velocity distribution downstream, yet wide enough to provide mixing of the aerosol. The grid provided 31% blockage, well within the recommended range for such grids suggested by Baines and Peterson (1951). The turbulence itself was described using equations developed by Baines and Peterson for turbulence intensity and length scale generated by flow through lattice-type grids or screens, yielding an intensity of 4.3% and length scale of 2.2 cm at the location of the upstream reference sampler and an intensity of 3.4% and length scale of 2.7 cm at the location of the test sampler. Downstream of the test section, the flow passed through a diffuser, through the cent-axial fan, and was discharged through another bank of HEPA filters. The fan was able to provide windspeeds in the test section ranging from 0 to 21 m/s. A velocimeter (VelociCheck, Model 8330, TSI Inc., St. Paul, MN) was used to measure the velocity distribution across the width of the test section. For windspeeds between 0.5 and 4.6 m/s, velocity varied by less than ±10% across the inner 0.2 meters (8 in.) of the test section (see below for further details).

Figure 3.1: Schematic of the wind tunnel

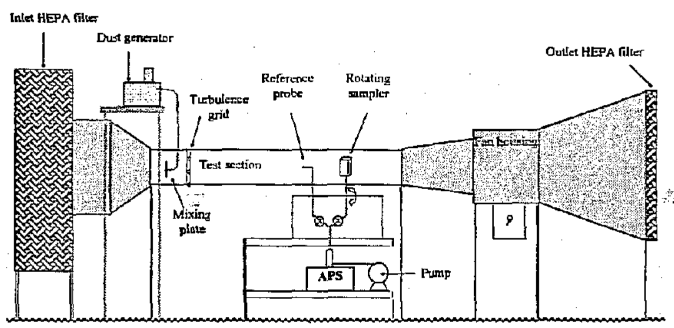


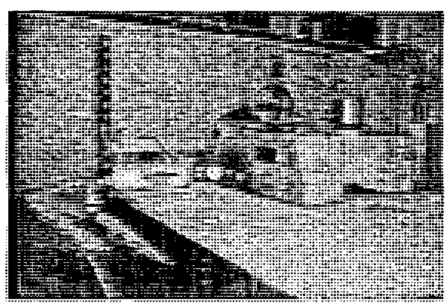
Figure 3.2: Photograph of the wind tunnel

Aerosols: Two types of aerosol were used for the experiments contained in this dissertation, mechanically generated from polydisperse glass beads and monodisperse fused alumina, respectively. The experiments using the APS and prototype testing system employed polydisperse glass beads, obtained from two different sources. The same grade of glass beads from the two sources were not significantly different from one another, with 80% of the mass comprised of particles of aerodynamic diameter between 13 and 44 μm (325 mesh, Class IV GL-0191, MO-SCI Corp., Rolla, MO; and 325 mesh, AQR, Cataphote Inc., Jackson, MS). The glass beads were stored in a heated oven (70°C) to reduce moisture content. The presence of moisture could cause agglomeration of the aerosol, which could tend to bias the results, since any agglomerated particles aspirated into the sampler could disaggregate before reaching the sensing region of the aerodynamic particle sizer. A 250 watt Krypton spot lamp was used to maintain an elevated temperature of the glass beads in the dust generator to reduce moisture absorption and agglomeration. The small set of gravimetric tests that was performed later in this work required a nearly monodisperse aerosol, because the particles were collected onto a filter and weighed. In order for this method to effectively characterize the sampler performance in terms of aspiration efficiency as a function of particle size, it is important to know the particle size or particle size distribution of the test aerosol. The dusts used for this purpose were narrowly-graded powders of fused alumina ("Duralum", Washington Mills Electrominerals, Manchester, England). These produced aerosols that were considered to be essentially monodisperse (geometric standard deviation < 1.3), and these have been widely used in this type of work since the 1980s (Mark *et al.*, 1985). The sedimentation diameter and specific gravity (3.96) obtained from the manufacturer were used to calculate the aerodynamic diameter, and Table 3.1 summarizes the grade, sedimentation diameter and aerodynamic diameter for the powders and resultant aerosols for the powders used in this research.

Manufacturer's grade	Mass median particle sedimentation diameter (μm)	Mass median particle aerodynamic diameter (μm)
F500	12.8	25.5
F400	17.3	34.4
F320	29.2	58.1

Table 3.1: Manufacturer's grade designation of fused alumina powders and the corresponding sedimentation and aerodynamic diameters.

Figure 3.3: Aerosol generator



Aerosol generation: Mechanical aerosolization was achieved using a belt-feed type aerosol generator (SAG 410, Topas, Dresden, Germany) (see Figure 3.3). The powder was placed into the hopper complete with its scraping mechanism. The dosing band ran below the hopper, and the scraper ensured constant filling of each segment on the belt, providing a constant feed of dust. The temporal stability of the aerosol concentration was crucial since the APS samples were not taken simultaneously but, rather, over a period of time, alternating between the reference and sampler (see below for further details). The feed rate, and consequently the particle concentration in the test section, were controlled by adjusting the belt speed. A Venturi-type injection nozzle, attached to an oil-less compressor and located at the end of the feeding belt sucked up the powder and so formed the aerosol. The compressor was operated at a pressure of 1.2 to 2.2 bar, corresponding to a total volumetric flowrate of air through the dust generator of approximately 50 to 100 L/min. The aerosol was injected into the wind tunnel just upstream of the turbulence grid, in the direction opposite to the air flow. A square 0.15 m x 0.15 m mixing plate was placed just behind the injection nozzle to aid in mixing the aerosol (as suggested by Stairmand, 1941). In order to ensure that the dust was not agglomerated, several samples of aerosol from the test section of the wind tunnel were collected onto glass microscope slides while the wind tunnel and dust generator were in operation. These slides were subsequently examined under an optical microscope, and no evidence of particle agglomeration was observed.

Aerosol neutralization: For some of the experiments, the dust was aspirated through a neutralizer (Model 3012, TSI Inc., St. Paul, MN) where the particles were neutralized to near Boltzmann equilibrium by exposing them to a dense cloud of bipolar ions from a radioactive source (2 mCi ^{85}Kr). The purpose of neutralization was to remove excess charge and to correct any asymmetry in the charge distribution (i.e., skewed towards either positive or negative). In a freshly mechanically-generated aerosol, it is well-known that particles may become highly charged (Vincent, 1995). However, most of the published studies to investigate the aspiration efficiency of aerosol samplers have not involved the use of neutralized aerosols (Mark and Vincent, 1986; Maynard *et al.*, 1999; Paik and Vincent, 2003). In our own research it was found that use of the neutralizer was, in itself, problematic. For example, the neutralizer became clogged easily, which often resulted in sudden changes in aerosol concentration in the test section over relatively short periods of time. With this in mind, we performed an investigation to determine the effect of neutralization on sampler performance and to assess whether or not it was really needed. The conclusion was that the neutralizer did not have a significant effect on sampler performance with this system (see below for more details). It should be noted, however, that all components of the wind tunnel, aerosol generation system and test system were electrically grounded to minimize effects due particle charging.

Porous plastic foam media: The porous plastic foams used in these experiments were made of reticulated polyurethane (polyester-based) and were obtained commercially in sheets 6 mm thick (Foam Engineers Ltd., Buckinghamshire, UK). These foams required a procedure for cutting, cleaning and preparing them for use. Initially, foams were cut using a sharp edged tube and a mallet. However this was not a very precise procedure, especially for smaller diameter foam plugs (< 10 mm). An improved better method was therefore devised which involved first placing a small sheet of the foam media in a shallow pan, adding enough melted paraffin wax to cover the foam, allowing time for the wax to cool and harden, and then cutting out plugs of the desired diameter with a sharp-edged tube. The wax was necessary to maintain the shape and structure of the foam during cutting, so that it could be cut to form regular cylinders, and the edges were not distorted. The wax was then melted, and the foam plugs were removed and washed with a cleaning solvent (Wax-Out Cleaning Solution, Fisher Scientific, Pittsburgh, PA) to dissolve any residual wax. After drying, the foam plugs were immersed in a 10% (by mass) mixture of petroleum jelly in xylene and dried to leave a uniformly greased surface. By greasing the foam media in this way, it was ensure that, during sampling, larger particles were prevented from bouncing off the foam fibers (see below for further details). Individual foam plugs were re-used several times. Between experiments, they were washed with detergent and hot water to remove collected particulate matter and the petroleum jelly coating, then dried and re-coated with fresh petroleum jelly solution. For this study, porous plastic foam of 20 ppi nominal porosity was characterized by digitally photographing a piece of the foam under epifluorescent conditions on an optical microscope (Olympus AX70) with 4X original magnification (the camera provided additional magnification). The photographs were then imported into Adobe PhotoShop, and fiber diameter measurements were made in terms of the widths (in pixels) of filamental elements at their midpoints. A separate digital photograph was taken in the same manner of a 200 μm scale bar, which was also measured in pixels, to quantify the fiber diameter measurements (see below for further details).

Aerodynamic particle sizer (APS): The Aerodynamic Particle Sizer (APS Models 3320/3321, TSI, Inc., St. Paul, MN) is a direct reading instrument in which particle size data are stored in 52 channels, from 0.5 to 20 μm. During the course of this research, papers appeared in the literature that questioned the accuracy of the APS Model 3320 for large particle sizes (Armendariz and Leith, 2002; Stein *et al.*, 2002). The manufacturer of the APS conceded that there was a problem in the design of the APS 3320 that caused small particles to recirculate in the sensing region, being first sized accurately and then counted as larger particles as their velocity decreased. So the manufacturer offered an upgrade to a model APS 3321 to correct the problem. Before proceeding with this upgrade in the present work, however, we performed a set of experiments to compare the performance of the APS 3320 to an upgraded APS 3321 from another research group in our Department (see below for the presentation of data and discussion). The conclusion was that the flaw in the APS 3320 did indeed have an effect on sampler performance results for some experimental conditions. So we then proceeded to upgrade our own instrument. Comparison of APS 3321 and multi-stage impactor particle size distributions by Peters and Leith (2003) has since confirmed that the newer APS 3321 does not produce 'phantom' particle counts. In our experiments, data from the APS were collected using Aerosol Instrument Manager software (Version 5.2, TSI, Inc., St. Paul, MN) on a laptop computer (Satellite 325 CDS, Toshiba America, Inc., Irvine, CA), with sample collection controlled through the software. In each run, alternating samples were taken, beginning with a reference sample. The duration of each sample was two minutes, spaced out every three minutes. The resultant data files were then exported to Microsoft Excel for further analysis, where a spreadsheet compared particle counts for the test sampler with those for the reference, leading to calculation of the average efficiency (penetration efficiency or sampling efficiency, depending on the experiment) for each particle size. Further details are given below.

Prototype test system design

Purpose: The purpose of the prototype test system was to collect samples (particle counts and particle size distributions) with the APS alternating between a reference probe and a test sampler, and to use the comparative data in order to calculate the aspiration efficiency of the test sampler. After considering all requirements, a system was designed and fabricated to perform these experiments (see Figure 3.4 for a schematic representation and Figure 3.5 for a photograph of the test system).

Figure 3.4: Diagram of automated measurement system

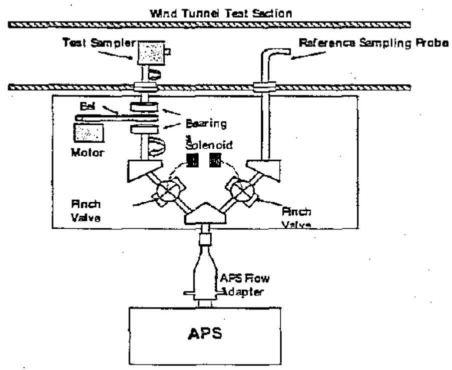
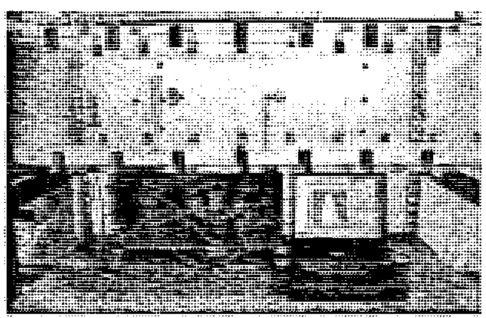


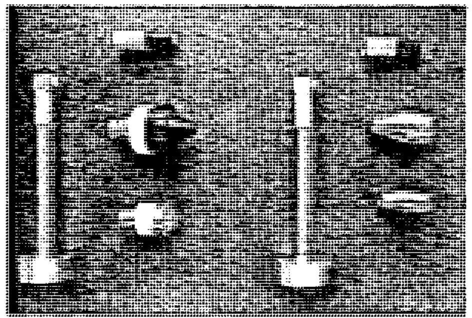
Figure 3.5: Photograph of automated measurement system



General design requirements: There were five key requirements in the design of this prototype test system:

- Particle penetration of reference and test sampling lines should be equal.
- Particle losses in reference and test sampling lines should be minimized.
- A set of automated valves to alternate air flow between the reference and test sampling lines was required.
- The test sampler must be able to be positioned at any angle to the wind (in the horizontal plane) or be continuously rotated by a motor.
- The test system must be connected to the APS by a flow adapter with a pump to add or remove air, depending on experimental conditions.

Figure 3.6: Sampling tubes and inlets



Sampling tubes and inlets: The majority of the system was constructed of ½-inch (outer diameter) stainless steel (SS) tubing. All components were mounted onto an aluminum plate backing, which rested on the bench below the test section of the wind tunnel. In order to meet the first design requirement listed above, the tubing connecting the reference probe to the APS and that connecting the test sampler to the APS was symmetrical and internally identical. Sampling probes (the portion of the sampling lines that protruded into the test section) were connected to the test system at the reference and test locations by flanges. Each sampling probe consisted of a 6 inch vertical piece of ½-inch stainless steel tubing, topped with a manufactured ½-inch stainless steel elbow, to which the appropriate test inlet could be attached (see Figure 3.6 above). The inlets were designed so that the reference and test arms were identical, at least until the corresponding sampler head and/or bluff body was attached. This design permitted identical porous foam plugs to be used in the sampler inlets, which allowed the penetration efficiency of the foam in the reference and test to cancel (see below). The specific inlet design for each set of experiments will be described in appropriate parts of this report. To render the data obtained using this test system comparable to full-scale experiments (which had been performed with the sampler mounted on a continuously rotating mannequin), our small-scale experiments required that the sampler be mounted on a continuously rotating scaled bluff body. To accomplish this, a motor with a speed of one rotation per minute was attached to the upper portion of the sampler line by a belt. In the design of the Y-connection (where the reference and sampler lines meet) two competing factors had to be balanced. To minimize particle losses between the sampler entry and the APS, the connecting tubing needed to be kept as short as possible. However, to avoid excessive losses due to gravity, the tubes were positioned vertically. The most appropriate compromise was to place the two arms of the Y-connection at 45° angles from the horizontal plane.

Valves: Sudden restrictions or large cavities in the tubing could contribute significantly to particle losses, and many types of valves were rejected for use in the system because they contained large cavities and/or sudden changes in internal geometry. The ideal valve would have the geometry of a tube when open and approximately the same diameter as the connecting stainless steel tube. For this reason, pneumatic pinch valves with ½-inch inner diameter silicone tubing were chosen to close off transmission lines when alternating between reference and test samples. The silicone tubing was flexible and the interior diameter of the system was kept close to constant through the valve when open. The short segments of silicone tubing in the valves were changed often to minimize effects of deformation on the transmission efficiency through the valves. Switching between the reference and sampler was accomplished by actuation of the two compressed air activated pinch valves by solenoids. The solenoids were controlled by a program written in Visual Basic (version 6.0) and installed on the laptop computer. Actuation of the valves was timed so that 30 seconds were allowed to elapse before and after each APS sample, before the valve closed.

APS flow adapter: The APS required a constant flowrate of 5 L/min, provided by an internal pump. In order to sample at flowrates larger or smaller than 5 L/min, an APS flow adapter was designed with additional ports, connected to an external pump, to either add or remove clean air from the system. This design was based on a previous flow adapter, which was designed so that addition of sampling ports close to the APS inlet did not distort the flow field at the APS entry (Sreenath, 1998).

Scaling

Describing aspiration efficiency in terms of dimensionless groups (as described earlier) allowed scaling according to basic engineering principles. In the context of this work, this refers to the scaling between different systems (e.g., large versus small, slow versus fast, etc.), and the way that air and particles behave in complex flow systems. This means that regardless of the physical size of the sampler in question, the aspiration efficiency should remain the same as long as St, R and θ remain the same. Kenny *et al.* (2000) have proposed scaling a sampling system by keeping St, R, r, θ and also Re constant between the full-scale and model-scale versions. However, this approach is unnecessarily restrictive. Keeping all of these variables constant would require the system to be scaled by the same factor all around. For example, if one wanted to simulate particle sizes up to 100 μm by using particles in the small-scale system of up to 20 μm, the sampler dimensions would have to be scaled down by a factor of 5 while the windspeed and sampling velocity were scaled up by a factor of 5. This gives little flexibility in designing the small-scale system. Since Re was not expected to have a significant effect on the aspiration efficiency, as long as it falls within the turbulent regime for the flow around the sampler, it was our working assumption that it need not be kept constant.

Parameters that were controlled in the experiments included the windspeed (U), sampling rate (U_s), sampler dimensions (D and δ) and particle size (d_{ae}). In order to keep R constant, U and U_s should be scaled by the same factor, k_U. Since it has been demonstrated that the dimension ratio, r, does not have a strong impact on aspiration efficiency, it was considered reasonable that the size of the bluff body on which the sampler is mounted could be chosen simply to suit the size of the wind tunnel (Paik and Vincent, 2002b). The scaling factor for the sampler orifice, δ, was scaled by the factor k_δ. As a result, the scaling factor for d_{ae} then became kd_{ae}. Since the Stokes' number is proportional to the square of the particle size multiplied by U/δ, thus

$$St \approx d_{ae}^2\, U / \delta \qquad (3.1)$$

then the basic scaling relationship for aerosol sampling is given by

$$k_{dae}^2 = k_\delta / k_U \tag{3.2}$$

In the present work, this allowed more flexibility in designing the actual small-scale system than would have been obtained from a more complete consideration of all the possible contributing factors, and this was especially important because of the need to consider the penetration characteristics of the porous plastic foam. Here, an important technical challenge was to ensure a significant number of particles 10 μm and larger penetrating through the foam and being counted by the APS. In the overall experimental design, the Vincent *et al.* foam penetration model was used in conjunction with the scaling relationships in the design of the small-scale experiments, thus to choose optimal experimental conditions in order to maximize foam penetration efficiency.

Bias tests

When conducting experiments in our small wind tunnel, the reference sampler was placed upstream of the test sampler. However it had earlier been discovered that there was a particle size and windspeed-dependent concentration difference, or bias, in the upstream and downstream positions (Paik, 2002). In order to account for this bias in our new experimental results, a separate bias test was conducted at the beginning of each set of experiments. For these bias tests, identical forwards-facing thin-walled sampling inlets (the same inlets used for the experiments) were used as the reference and test samplers, and a complete experimental run was performed. Eleven samples were collected in each sampling run, with the odd-numbered samples being reference and even-numbered being test. To calculate the five particle count ratios (downstream/upstream) from this run, sample 2 was divided by the average of samples 1 and 3, sample 4 was divided by the average of samples 3 and 5, and so on. This resulted in five separate ratios, which were averaged to give the bias for the experiments performed for that particular set of conditions. This method of determining bias also contained any bias that associated with any asymmetry in the sampling lines themselves.

It should be noted that some of the experimental results for orientation-averaged aspiration efficiency still contained a small bias (10% or less). It would be expected that, for the type of aerosol samplers used in this research, the aspiration efficiency for very small particles (less than 1 μm) should be unity. The reason for this assumption is that such small particles do not have sufficient inertia to cause their paths to deviate significantly from the streamlines of the air. Therefore, aspiration efficiency results that were significantly larger or smaller than unity for particles of $d_{ae} < 1$ μm, were considered to contain an unaccountable bias. The source of this bias in some cases was the subject of further investigation, and was discovered to be the result of a non-uniform particle concentration distribution over the cross-section of the wind tunnel (see below for further discussion).

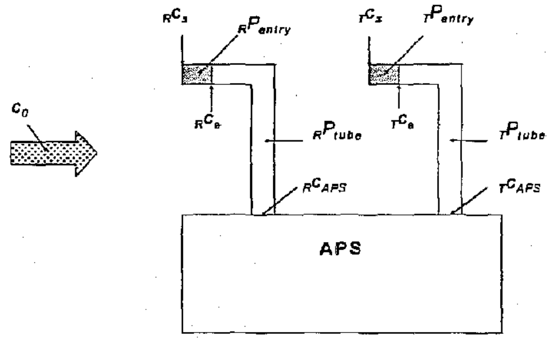
Experimental procedure

The procedure for conducting a given experiment was as follows:-

- Turn on APS (allow to warm up at least 15 minutes).
- Turn on pump connected to APS adapter, if a flowrate different from 5 L/min is required (allow to warm up at least 15 minutes).
- Turn on power strip on back of wind tunnel (power for laptop, valve-switching system, and motor to rotate test probe).
- Open main valve on compressed air tank.
- Make sure that solenoid valves are disconnected (wires labeled '*ref*' and '*test*').
- Connect laptop to power source, APS, and valve-switching system.
- Start up laptop.
- Turn on power strip for dust generator and lamp.
- Turn on dust generator and fill hopper with dust from oven.
- Turn on air compressor.
- Set up experiment inside test section.
- Check reference and test probe flowrates with Dry-Cal flowmeter. The easiest way to close a valve was to disconnect the valve-switching system from the laptop, then connect the solenoid of the valve you want to close. Use the small, color-coded valve to adjust flowrate.
- Record reference and test flowrates. Connect the valve-switching system to the laptop. Connect solenoids with the correct wires ('*ref*' on right, '*test*' on left).
- Turn on motor to rotate test probe, if running an orientation-averaged experiment, or position test probe at appropriate angle.
- Place lid on test section.
- Start wind tunnel (green '*Run*' button on controller).
- Place tip of Veloci-Chek probe in center of cross-section and adjust wind tunnel frequency to the appropriate windspeed. Record windspeed and frequency. Remove Veloci-Chek probe and be sure to plug hole in side of test section.
- Open '*Aerosol Instrument Manager*' on the laptop. ('*Shortcut to AIM*' icon on the desktop). Open a new file. Select '*Run*' then '*Properties*' from the taskbar. In the '*Properties*' window under '*Data Settings*' enter the particle density (optional). In the '*Properties*' window under '*Scheduling*' enter sample length of 120 seconds, to repeat every 3 min.
- Open the valve-switching program ('*G-valve*' icon on the desktop).
- Start dust generator. Set feed rate (push in small yellow button and adjust with '*Belt Speed*' knob). Turn control knob to '*2*' to feed dust. (Control knob at '*1*' is compressed air only.)
- Record belt speed and pressure.
- Click '*Start*' on G-valve.
- After 30 seconds start AIM software (click on green button on taskbar or go to '*Run*' and '*Start data collection*').
- Stop AIM software after sample number 11 (approximately 33 minutes).
- Turn off dust generator and wind tunnel and remove lid from test section.
- Repeat, starting at step 11.

Calculation of test sampler aspiration efficiency

Figure 3.7: Schematic of sampling arrangement – see Equations (3.3) to (3.8)



The following set of equations describes the transmission efficiency (E) of particles from the wind tunnel test section, through the sampler, and to the APS, where they are measured (see Figure 3.7 above). In the following equations the subscripts 'R' and 'T' denote the reference and test, respectively:-

$$ {}_TE = \frac{{}_Tc_{APS}}{c_0} = \frac{{}_Tc_{APS}}{{}_Tc_e}\frac{{}_Tc_e}{{}_Tc_s}\frac{{}_Tc_s}{c_0} = {}_TP_{tube}\cdot {}_TP_{entry}\cdot {}_TA \qquad (3.3) $$

$$ {}_RE = \frac{{}_Rc_{APS}}{c_0} = \frac{{}_Rc_{APS}}{{}_Rc_e}\frac{{}_Rc_e}{{}_Rc_s}\frac{{}_Rc_s}{c_0} = {}_RP_{tube}\cdot {}_RP_{entry}\cdot {}_RA \qquad (3.4) $$

Dividing Equation (3.3) by Equation (3.4) gives

$$ \frac{{}_TE}{{}_RE} = \frac{{}_Tc_{APS}}{{}_Rc_{APS}} = \frac{{}_TP_{tube}\,{}_TP_{entry}\,{}_TA}{{}_RP_{tube}\,{}_RP_{entry}\,{}_RA} \qquad (3.5) $$

In these equations, c_0 and c_s are as previously defined, c_e is the particle concentration at the interface between the entry and the tube, c_{APS} is the concentration measured by the APS, P_{entry} is the particle penetration through the entry, P_{tube} is the penetration of the tubing from the entry to the sensing region of the APS, and A is the aspiration efficiency itself.

Since foam plugs were placed in both the reference probe entry and the sampler entry, and the tubing behind the foam plugs was identical for both reference and sampler, then ${}_RP_{entry} = {}_RP_{foam}$, ${}_TP_{entry} = {}_TP_{foam}$ and ${}_RP_{tube} = {}_TP_{tube}$. Substituting these relationships into Equation (3.5) and rearranging gives

$$ {}_TA = \frac{{}_Tc_{APS}\,{}_RP_{foam}}{{}_Rc_{APS}\,{}_TP_{foam}}\cdot {}_RA \qquad (3.6) $$

The foam penetration model could have been used to determine ${}_RP_{foam}$ and ${}_TP_{foam}$. However for all experiments the foam plugs in the reference and test sampling tubes were identical, so it can be said that ${}_RP_{foam} = {}_TP_{foam}$, and the relationship is further simplified to

$$_{T}A = \frac{_{T}c_{APS}}{_{R}c_{APS}} \cdot {_{R}A} \tag{3.7}$$

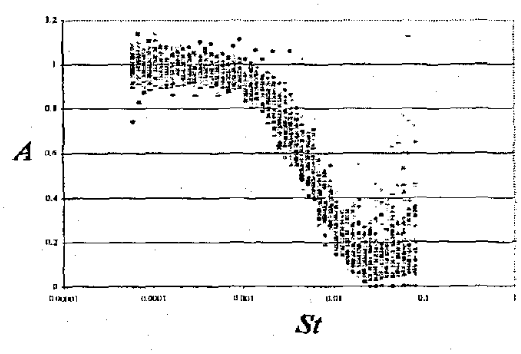
The aspiration efficiency of the thin-walled reference probe, $_{R}A$, was determined using the thin-walled probe model discussed earlier and in Paik and Vincent (2002a). Therefore, the only remaining unknown was the sampler aspiration efficiency, which was the desired quantity to be determined.

Determination of the aspiration efficiency of the test sampler, $_{T}A$, was the desired endpoint of the exercise. It involved several steps. Bearing in mind that time-of-flight data were reported by the APS for fifty-one separate particle size bins in the range of d_{ae} from 0.542 to 19.81 μm, data were collected for fifty-one particle sizes simultaneously. Then separate aspiration efficiency values were calculated for each particle size in order to produce an overall aspiration efficiency curve. For the first step, the ratio of test sampler particle counts to reference particle counts, $_{T}c_{APS}/_{R}c_{APS}$, was calculated for each of the five test samples. This was done by dividing each test sample, $_{T}c_{APS}$, by the average of the reference sampler values before and after the particular sample in question. As already mentioned, typically, eleven such samples were collected in each sampling run, with the odd-numbered samples being reference samples and the even-numbered being the test samples. To calculate the five particle count ratios from this run, sample 2 was divided by the average of samples 1 and 3, sample 4 was divided by the average of samples 3 and 5, and so on. Each of these ratios was then multiplied by the calculated reference probe aspiration efficiency and divided by the downstream/upstream bias calculated from the corresponding bias test (c_{down}/c_{up}).

$$_{T}A = \frac{_{T}c_{APS}}{_{R}c_{APS}} \cdot \frac{_{R}A}{bias} \tag{3.8}$$

Therefore, each sampling run provided five individual aspiration efficiency values for each particle size recorded by the APS. Because the aspiration efficiency was calculated in this way, the shape of the actual particle size distribution of the test aerosol was not important so long as it did not change significantly within the time frame of three APS samples (which was approximately 10 minutes). The particle size distribution was monitored to ensure that this was true for all sampling runs, and, in fact, the measured particle size distribution in the test section of the wind tunnel was very consistent.

Figure 3.8: Example of a complete data set for one run



An example of a complete single set of sampler aspiration efficiency data is shown above in Figure 3.8 This data set exhibits a spread typical of all the experiments described in this research. Each set of aspiration efficiency data presented in later chapters comprises of an equivalent number of data points. For subsequent presentation purposes, these data were averaged, and the mean aspiration efficiency value for each particle size was plotted. All sampler aspiration efficiency data sets presented in this report also contain error bars representing the standard error, which was calculated as the standard deviation divided by the square root of the number of samples in the data set (n). A trend that can be seen when examining aspiration efficiency data collected using this test system is that, in general, there are significantly larger error bars associated with the larger particle sizes, especially those greater than about 15 μm. The cause can be attributed to the fact that, while there were many small particles counted in each sample, fewer of these large particles were present in the test aerosol, and these large particles were more readily deposited in the porous foam and on the walls of the tubing in their journey from the freestream air to the APS. As a result, there was less certainty in aspiration efficiency measurements for large (versus small) particle sizes. All aspiration efficiency data presented in this report were calculated by the method described above, with the exception of the foam penetration studies described below and the small number of gravimetric test results for the IOM sampler in (also described below). Because an older version of the APS, the Model 3310, was used for the foam penetration experiments, corrections were required for 'phantom' particle counts. This was accomplished by a computer macro written in Microsoft EXCEL. Calculation of aspiration efficiency for the gravimetric tests was quite simple. The ratio of the mass of aerosol collected in the test sampler to that collected in the isokinetic reference sampler was divided by an correction factor (0.79) to account for the particle concentration difference between the downstream and upstream positions, similar to the bias used in the APS experiments. This correction factor was experimentally determined by another researcher in this small wind tunnel for a windspeed of 2.5 m/s (Paik, 2002).

4. Preliminary experiments and system characterization

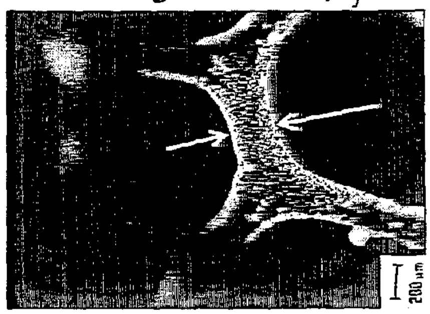
Introduction

We carried out a series of experiments in order to characterize the experimental set-up and its components. These involved characterization of the porous plastic foam media, verification of the APS calibration, evaluation of velocity and aerosol concentration profiles across the test section of the wind tunnel, effect of aerosol neutralization on results, and comparison of results obtained with APS Models 3320 and 3321.

Characterization of porous plastic foam

The porous plastic foam that was used in the majority of the sampler aspiration efficiency experiments had a nominal porosity of 20 ppi (pores per inch) (Foam Engineers Ltd., Buckinghamshire, UK). In order to determine the exact porosity of this foam, it was digitally photographed under an optical microscope and the widths of the inter-connecting pieces, or fibers, of the foam were measured (see earlier for a description of the method). A micrograph close-up is shown in Figure 4.1, indicating the equivalent 'fiber' diameter, d_f. Forty measurements were made of fiber diameter from twenty-five digital photographs. The mean value for d_f was found to be 239 μm with a standard deviation of 16 μm. The porosity calculated using Equation (2.21) was 20.9 ± 0.3 ppi, which is very close to the manufacturer's nominal value of 20 ppi.

Figure 4.1: Micrograph of foam media showing'fiber' width, d_f



Foam penetration study

Purpose: Two types of foam penetration tests were carried out. The first was performed to determine the penetration efficiency of nominal 20 and 30 ppi foams in order to compare them to the published model (Vincent *et al.*, 1993). The purpose of the second was to determine how well the foam penetration model could predict the particle penetration of foam with a changing cross-sectional area.

Experimental design: Experiments for this part of the research were performed in a small-scale wind tunnel at the Health and Safety Laboratory in Sheffield, UK, during the month of February, 2001. The closed-loop wind tunnel there had a cross-section of 1.0 m x 1.0 m. Reference and test sampling lines were located side-by-side in the center of the working section. A pair of manually-operated ball valves was used to alternate sampling between the reference and test lines. An older version of the APS (Model 3310, TSI, Inc., St. Paul, MN) was used to collect samples, and data were recorded on a laptop computer. Data were analyzed using a macro in Microsoft EXCEL. The purpose of the macro was to calculate the ratio of test to reference counts, with a correction to eliminate 'phantom' particle counts from the data. The APS 3310 has been shown to produce such erroneous particle counts as a result of the presence of more than one particle at a time in the path of the laser beams in the instrument and, therefore, requires a correction (Sreenath *et al.*, 1999). To test the penetration of 20 and 30 ppi foams, a simple experimental set-up was used. Forward-facing 10-mm ID stainless steel tubes were attached to the reference and test sampling lines. The reference contained no foam, while a 10-mm diameter plug of foam was inserted into the test sampling tube, with a foam thickness of 12 mm. Both the 20 and 30 ppi foams were tested under low and high flow conditions (0.8 and 5 L/min). The experimental conditions are summarized in Table 4.1. To determine how well the foam penetration model could predict the penetration of foam with a changing cross-sectional area, required a special sampling tube. For this purpose, a 10-mm ID stainless steel tube was modified to allow a section of 25-mm diameter foam, between 12 and 24 mm thick, to be inserted into an expansion in the tube. A forwards-facing 10-mm ID stainless steel tube with no foam was used as the reference. A photograph of the sampling tubes, which were attached forward-facing to the test sampling line, is shown below in Figure 4.2, and a schematic drawing in Figure 4.3. Experimental conditions are summarized in Table 4.3. For all of the above experiments, foam plugs were prepared by washing with detergent and warm water and rinsing with ultra-pure water.

Test Number	Foam (ppi)	Q (L/min)	U_s (m/s)	U (m/s)	d (mm)	t (mm)
P1	20	0.8	0.17	1.0	10	12
P2	20	5.0	1.1	1.0	10	12
P3	30	0.8	0.17	1.0	10	12
P4	30	5.0	1.1	1.0	10	12

Table 4.1: Experimental conditions for simple foam penetration tests, where d is the overall diameter of the foam plug and t is its thickness.

Results and discussion: The results for the foam penetration study did not, ultimately, greatly influence the trajectory or the outcome of the rest of the research described in this report. So, for conciseness, the full results of this part of the work are not reported here. It suffices to say that, for the simplest case where the foams were ungreased, there was strong evidence of larger particles' penetration through the foam plugs due to bounce or re-entrainment. This phenomenon has also been reported for ungreased foams by other workers (e.g., Kenny *et al.*, 2001). Fortunately, the problem disappeared when the foams were greased prior to use with petroleum jelly, and the results then fell into good agreement with the model of Vincent *et al.* (1993) described earlier. Some experiments were also carried out to examine how well the model predicted particle penetration for foam plugs of changing cross-section. It was shown that a modified version of the model based on combining the separate penetration efficiencies for the two plug sections (see Figures 4.2.and 4.3) agreed well with what was observed experimentally. This finding, although not ultimately important to the course of the present work, may be important in some future work if we were to consider placing plugs of such foam media inside the entries of samplers without constant cross-section (e.g., the CIS inhalable aerosol sampler, see Figure 2.2).

Figure 4.2: Photograph of sampling tubes and inlets used to examine effect of changing inlet cross-section

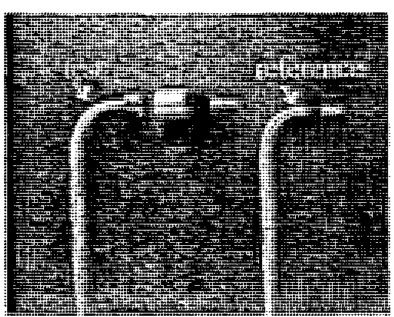
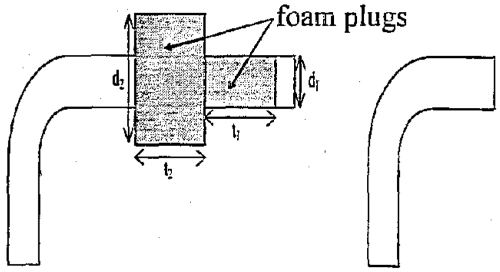


Figure 4.3: Schematic of sampling tubes and inlets (see Figure 4.2)



Verification of APS calibration: In order to be assured that the APS was functioning properly, the calibration was periodically checked against NIST-traceable particle size standards. These were obtained in the form of polystyrene latex (PSL) spheres of nominal diameter 3, 5 and 10 µm (3.063 ± 0.027, 5.030 ± 0.034 and 10.15 ± 0.06 µm, respectively) suspended in water (Duke Scientific Corp., Palo Alto, CA). Pre-cleaned glass microscope slides were prepared by applying several drops each of isopropyl alcohol and the three PSL standards. The slides were allowed to dry and were then stored in a closed microscope slide case. To check the APS calibration, a clean paintbrush was used to brush the PSL spheres directly into the inlet of the APS, while collecting a 20-second sample. Typically, differences between the APS particle size classification and the PSL standard were less than 10%, and such differences were considered acceptable.

Velocity and aerosol concentration profiles

Purpose: The purpose of this series of experiments was to characterize the aerosol spatial distribution in the test section of the wind tunnel. To accomplish this, the velocity and aerosol concentration distributions were measured over the cross-section of the wind tunnel. Several experiments were also conducted to verify that the Topas dust generator was providing a stable aerosol output.

Experimental design: For the first set of experiments, experiments were performed to characterize the mixing in the test section at windspeeds of 2 and 4.6 m/s, both with and without compressed air through the dust generator. For the second set, total aerosol counts at the reference probe location were measured over the course of two hours. For each such experiment, two-minute averaged samples were collected and recorded by the APS every three minutes. The third set of experiments involved using the APS to measure the total aerosol counts at locations over the cross-section of the wind tunnel. This was accomplished via a small, 5-mm diameter thin-walled tube, facing directly into the wind, into a port in the side of the wind tunnel, just in front of the reference sampler position. A 20-second sample was collected with the APS at each location.

Results and discussion: Velocity profiles for several sets of experimental conditions were examined, for various windspeeds and with and without air input from the dust generator. In general, the air velocity distribution was seen to be uniform to within 10 to 20% across the inner eight inches of the test section, indicating that the turbulence grid effectively distributes the air flow uniformly across the tunnel and – importantly – suppresses the effect of the mixing plate. The same trend was seen at both the reference and test sampler positions, indicating that the presence of the upstream reference probe did not have a significant impact on flow conditions in the vicinity of the test sampler. It is of course not surprising that the injection of air from the dust generator did not significantly impact the velocity distribution since it comprised only a very small proportion (0.2 to 0.9%) of the total air flow in the wind tunnel. Aerosol concentration was examined as a function of time, also for various windspeeds, using the APS. Here we found some slow drift in the concentration over the sampling time for both windspeeds, as well as some occasional 'spikes', notably for the higher windspeeds examined. We believe that these were due to the sudden dislodging of powder that had built up on the inner walls of the aerosol injection tube. However, neither the slow concentration drift nor the 'spikes' were of significant concern since we were able to show that their effects would largely cancel out during the averaging process during each given sampling run.

Comparison of sampler aspiration efficiency results obtained with neutralized and non-neutralized aerosols

Purpose: The purpose of these experiments was to determine the effect of aerosol neutralization on results for aerosol sampler performance. Experiments were initially begun with aerosols neutralized using the ^{85}Kr source, as described earlier. But we found that the neutralizer was easily clogged with powder, making it difficult to use and causing the aerosol concentration in the wind tunnel to decrease over time. Some published laboratory studies of aerosol sampler performance did not utilize neutralized aerosol, under the assumption that there was no significant effect of particle charging on sampler performance (Mark and Vincent, 1986; Maynard *et al.*, 1999; Paik and Vincent, 2003). However, for the present work, before deciding on which approach to take, we investigated the effect of aerosol neutralization on aspiration efficiency measurements.

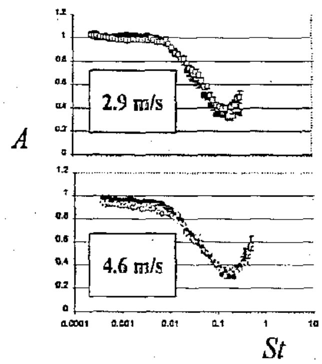
Experimental design: A set of experiments was conducted in which the only difference was the use of the ^{85}Kr neutralizer. These involved measurements of the aspiration efficiency of the IOM sampler at two windspeeds, 2.9 and 4.6 m/s, both with and without neutralizer use. Table 4.2 summarizes the experimental conditions used. The results were plotted in the form of aspiration efficiency versus Stokes' number.

	IOM 2.9 m/s	IOM 4.6 m/s
δ (mm)	11	11
D (mm)	88	88
U (m/s)	2.9	4.6
U_s (m/s)	0.55	0.87
Q (L/min)	3.2	5.0
R	5.3	5.3

Table 4.5: Experimental conditions for neutralizer comparison and APS comparison tests.

Results and discussion: Figure 4.4 (see below) shows the experimental results from this study. It is seen that there is very little difference between the results for neutralized and non-neutralized aerosol respectively. Any differences are small and are well within the variability we have come to expect for this type of experiment. The conclusion, therefore, is that neutralization of test aerosol is not required for experiments of the type envisioned for this research. So the use of the neutralizer was discontinued.

Figure 4.4: Measured aspiration efficiency for an IOM-like sampler for neutralized and non-neutralized test aerosols



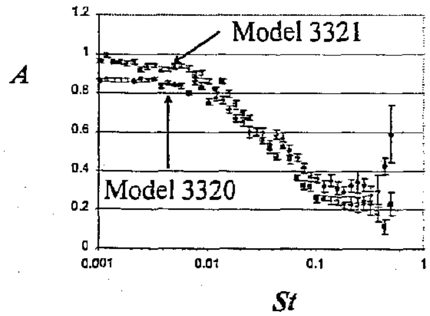
solid symbols for neutralized aerosol, open symbols for non-neutralized aerosol

Comparison of sampler aspiration efficiency results obtained with APS Models 3320 and 3321

Purpose: The purpose of these experiments was to compare aspiration efficiency results for experiments performed with the prototype test system, using two different APS Models, the earlier 3320 and the more recent 3321. Recent studies had shown that there were particle counting errors with the Model 3320 (Armendariz and Leith, 2002; Stein *et al.*, 2002) and, as mentioned earlier, the manufacturer had responded by offering an upgrade to a Model 3321 to correct the problem. But before the Model 3320 originally intended for use in this research was upgraded, its performance was compared to a Model 3321, borrowed from our colleagues in the Department of Environmental Health Sciences Air Quality Laboratory. Prior to this study, some of the experiments in our research program had been completed, so it was important to determine what effect the APS itself may have had on the results.

Experimental design: Two sets of experiments were run in which the only difference was the model number of the APS employed. Again, these involved experiments with the IOM sampler. Aspiration efficiency results from the two experiments were compared.

Figure 4.5: Measured aspiration efficiency for IOM-like samplers using two different APS models



Results and discussion: The results of these experiments are shown above in Figure 4.5 plotted – as before – in the form of aspiration efficiency versus Stokes' number. Apart from the slight biases observed for small particles (attributable to the slight non-uniformities in aerosol spatial distribution), there is seen to be good agreement between the results for the two APS models for *St* up to about 0.4 (corresponding to $d_{ae} < 17$ μm). But beyond this point, the data sets diverge, with results from the Model 3320 clearly increasing while those for the Model 3321 tend to level out. The decision was therefore made to upgrade our original Model 3320 to the new Model 3321, and to disregard all previously acquired Model 3320 results for particles larger than 15 μm in aerodynamic diameter. According to the manufacturer and other researchers, the measurement chamber inside the Model 3320 contained a region of recirculating flow, which allowed for some very small particles (of the order of 1 μm) to recirculate and be subsequently re-counted as much larger particles (Stein *et al.*, 2002). This explains the observed increase in aspiration efficiency measured by the Model 3320 for large particles and justifies the exclusion of such data. Meanwhile, the recent study of Peters and Leith (2003) supports the view that the design change of the aerosol measurement chamber (for the Model 3321) has indeed corrected the problem of erroneous large particle counts.

Conclusions from this part of the research

This portion of the work was directed towards characterizing several components of the experimental system, specifically the porous plastic foam media, the dust generation system and the APS. It was concluded that the Vincent *et al.* (1993) mathematical model for particle penetration through porous foams provides a good prediction of foam penetration, even for portions of foam with changing cross-sectional area. It was shown that while the wind velocity across the test section was quite uniform, the aerosol concentration distribution was less so. For the latter, however, the observed variations of up to ±20% were deemed to be satisfactory for most of the experiments that will be reported. Regarding the aerosol delivery system itself, the effect of concentration temporal fluctuations on the experimental results that will be reported was considered to be minimal. It was also concluded that the effect of the neutralizer on the results of experiments like those described in this report was minimal, so that the use of the neutralizer could safely be discontinued.

Finally, experiments were conducted to determine the effect of counting errors in the APS Model 3320 on sampler aspiration efficiency. It was determined that, as had been reported by other workers, there was an overestimation of aspiration efficiency for particles larger than 15 μm in aerodynamic diameter. Our original Model 3320 was therefore promptly upgraded to Model 3321 to correct the problem, and all data for particles of 15 μm and larger obtained using the Model 3320 were discarded.

5. Aspiration efficiency of a thin-walled probe at ninety-degrees to the wind

Purpose

This portion of the overall body of work was carried out in order to provide validation of the experimental system and method described above. However, the study of thin-walled probe aspiration efficiency is interesting in its own right. Many researchers have studied the aspiration characteristics of a thin-walled sampling probe oriented at angles up to ninety-degrees to the wind, and semi-empirical models have been developed to predict aspiration efficiency for such conditions (Durham and Lundgren, 1980; Davies and Subari, 1982; Vincent *et al.*, 1986). These studies covered a range of velocity ratio (R) from 0.2 to 2. The current work set out to test the aspiration efficiency of a ninety-degree, thin-walled probe for a much larger range of R.

Experimental design

Figure 5.1: Experimental set-up for most of the 90° thin-walled probe study

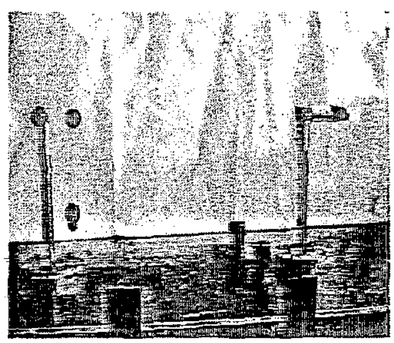
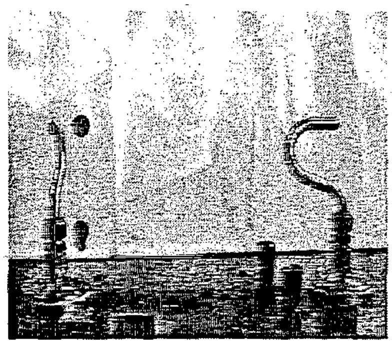


Figure 5.2: 'Goose-neck' probes used in part of 90° thin-walled probe study



The majority of these tests were carried out using thin-walled probes with inlet diameters of 11 mm. The experimental set-up is shown above in Figure 5.1. For these experiments, the inlet of the test probe, when oriented at 90° to the wind, was located 2.25 inches to the left or right of center in the wind tunnel, and sampling was termed "off-axis". To accomplish these experiments, a bias test was first conducted with both the reference and test probes facing forward, directly into the wind. Following the bias test, the test probe was turned through 90°, a 6-mm thick plug of greased 20 ppi foam was placed into each sampling inlet, and a series of experimental runs was performed with the test probe alternating between facing right and facing left. Experimental conditions were varied to provide R-values of 2.75, 11.0 and 54.3, and are summarized in Table 5.1.

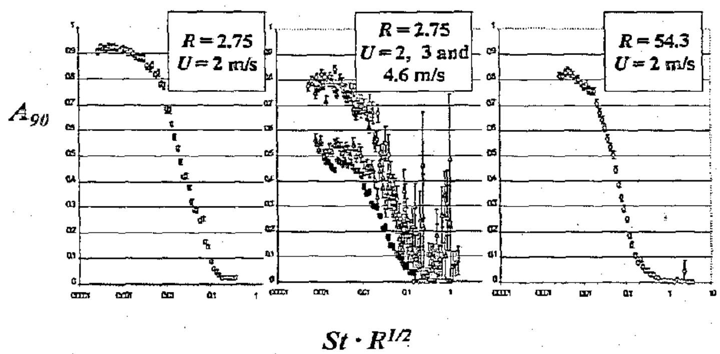
	$R = 2.75$	$R = 11$ (2 m/s)	$R = 11$ (3 m/s)	$R = 11$ (4.6 m/s)	$R = 54.3$
d (mm)	11	11	11	11	11
U (m/s)	2.0	2.0	3.0	4.6	4.6
U_s (m/s)	0.73	0.18	0.27	0.42	0.08
Q (L/min)	4.15	1.04	1.56	2.38	0.48
R	2.75	11.0	11.0	11.0	54.3

Table 5.1: Summary of experimental conditions for 90° thin-walled probe experiments.

After completing the experiments described, we carried out one additional test, for $R = 2.75$, with a new pair of sampling probes. Here we employed a pair of 'goose-necked', thin-walled sampling probes of the type widely used in stack sampling, where, by virtue of this design, the inlet of the tube was always positioned on the axis of rotation, regardless of inlet orientation. This experimental set-up is shown above in Figure 5.2.

Results

Figure 5.3: Original aspiration efficiency data for thin-walled probes at 90° to the wind



Original results for the 90° thin-walled probe experiments using the probes shown in Figure 5.1 are shown in Figure 5.3. Here, aspiration efficiency is plotted as A_{90} versus $St{\cdot}R^{1/2}$, consistent with the form suggested by the theoretical model described by Equation (2.15) (Vincent *et al.*, 1986; Stevens, 1986). The error bars shown represent the estimated standard error. All the data sets are seen to exhibit a bias for small particles between the upstream (reference) and the downstream (test) probes, ranging from about 10% for $R = 2.75$ to greater than 50% for some of the experiments for $R = 11$. It considered likely that such biases derived from the off-axis positioning of the test sampler inlet when oriented at 90° to the wind. Under this assumption, the data were therefore corrected to force aspiration to unity for particles with $d_{ae} < 0.9$ μm, based on the physical reality that the aspiration efficiency must tend towards unity for small enough particle inertia. This correction was achieved by taking the average of the first eight aspiration efficiency values in each data set (in the range 0.542 μm < d_{ae} < 0.898 μm), and dividing the aspiration efficiency of the entire data set by this number. The corrected results are shown below in Figures 5.4. In an effort to verify the preceding, an additional set of experiments were carried out using the 'goose-necked' probes shown in

Figure 5.2. Figure 5.5 shows experimental data for the original (corrected as indicated) and goose-necked sampling probes, respectively, for $R = 2.75$. The excellent agreement between the two data sets supports the validity of the bias correction that was applied in Figure 5.4.

Figure 5.4: Corrected aspiration efficiency data for thin-walled probes at 90° to the wind

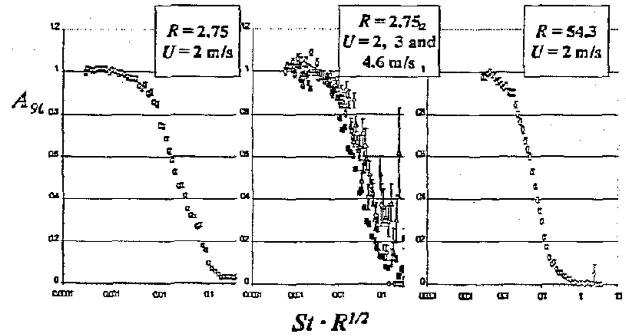
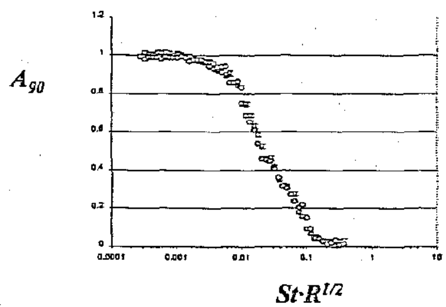


Figure 5.5: Comparison between results for off-axis (open symbols) and on-axis sampling for the 'goose-neck' probes (shaded symbols)



As seen in Figure 5.4, the results for R-values of 2.75 and 54 appear to be well-behaved, in that they are reproducible over the course of many sampling runs, resulting in relatively small standard error. In general, they follow the expected trend. But there are significant differences in the A_{90}-values as measured for $R = 2.75$ and 54 respectively. The three separate sets of experiments for $R = 11$ for the windspeeds of 2, 3 and 4.6 m/s show much greater variability than those for R-values of 2.75 and 54. This is due to the combination of a smaller number of sampling runs for each set of experimental conditions (25 individual measurements of A_{90}, instead of 50) and low APS particle counts.

Discussion

Figure 5.6 shows previously-published results from three different laboratories for a thin-walled sampling probe oriented at ninety-degrees with respect to the wind (Durham and Lundgren, 1980; Davies and Subari, 1982; Vincent *et al.*, 1986). Here, the shaded area encompasses 92% of the individual experimental data points. Aspiration efficiency data from the present work (corrected as indicated above) are compared to these published results in Figure 5.7. This shows that, for the most part, although our new data fall within the range encompassed by the three previous studies, they tend to fall towards the lower side of the shaded area.

Figure 5.6: A_{90} versus $St \cdot R^{1/2}$ from other workers

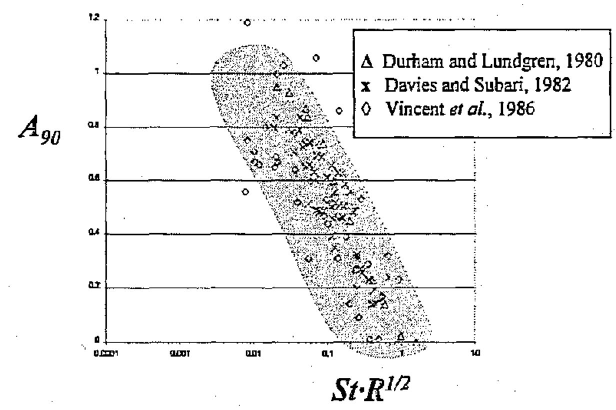


Figure 5.7: A_{90} from present work as compared to those of previous studies (shaded area)

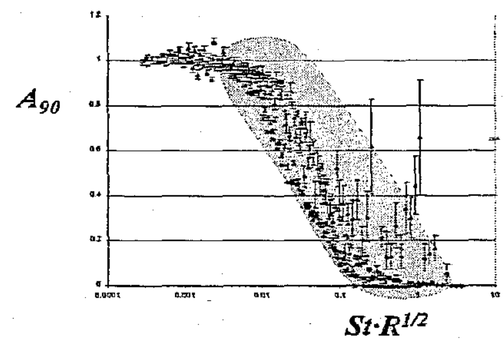
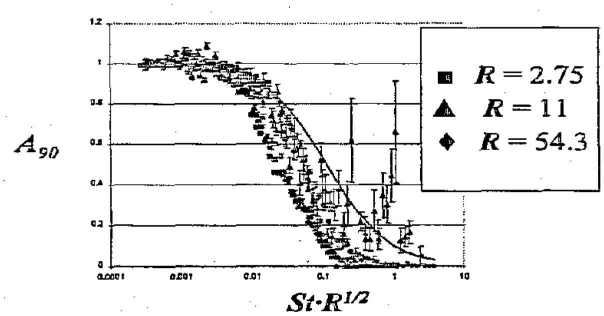


Figure 5.8: A_{90} measured in the present work compared to the model of Vincent *et al.* (1986)



The aspiration efficiency model for a thin-walled probe at ninety-degrees to the wind is represented by Equation (2.15) shown earlier (Vincent *et al.*, 1986). The new experimental data from the present research study are compared to the model in Figure

5.8, and it is seen that agreement with theory is qualitatively good but quantitatively less so. Closer inspection of this graph reveals that our data suggest a clear trend of increasing A_{90} for increasing R, whereas no such trend could be detected in the earlier published studies. This is likely due to the limited range of R-values examined in those earlier studies and the large degree of scatter in those data. Examination of the new data therefore points to the possibility of a further dependence on R beyond that included in the model.

An important feature of the model in Equation (2.15) is the coefficient G which, it is recalled, could only be described as a constant based on the earlier data (i.e., G = 2.1). This deserves closer inspection. To do this, we may re-write Equation (2.15) in the form

$$\frac{1}{A_{90}} = \{ 4 \cdot G \cdot St \cdot R^{1/2} \} + 1 \} \qquad (5.1)$$

where $(1/A_{90})$ is a linear function of $(St{\cdot}R^{1/2})$ with a slope of G. With this in mind, linear regressions were performed, using the new experimental data, to estimate G for the various R-values examined. The results of these analyses are shown in Table 5.2. Here we see that the range of estimated G-values are very different from the original G = 2.1. In addition, there is no obvious correlation with R. Since each set of experiments covered different ranges of particle sizes, it is likely that there is – at least – an additional dependence on St. Unfortunately the current data set does not cover a sufficient range of experimental conditions to allow any useful conclusions to be drawn about these relationships.

R	U (m/s)	Range of d_{ae} (μm)	G
2.75	2.0	0.5 to 3.3	5.83
2.75	2.0	0.5 to 8.4	11.8
2.75	2.0	0.5 to 20	37.2
11	2.0 to 3.0	0.5 to 7.2	7.28
11	4.6	0.5 to 7.2	29.9
54.3	4.6	0.5 to 3.8	7.37
54.3	4.6	0.5 to 7.8	16.9
54.3	4.6	0.5 to 20	15.3

Table 5.2: Summary of calculated values for G from linear regression of the results for the ranges of particle sizes indicated. Note that the larger scatter in data for R = 11 and larger particles prevented reliable regression.

Conclusions from this part of the research

Aspiration efficiency for a thin-walled probe at 90° with respect to the wind has been measured for a range of experimental conditions. The results fell within the range of measured aspiration efficiency from three published studies, and show similar trends as a function of $St{\cdot}R^{1/2}$, the quantity identified in the theoretical model of Vincent *et al.* (1986). But quantitative agreement with the model is less good. Attempts to develop additional functional relationships (e.g., on other combinations of St and R) to explain the detailed internal trends revealed by these experiments have not so far been successful.

Overall, however, these experiments have provided valuable information about the performance of the prototype testing system we have developed, and have contributed to the validation of the method. The data collected using this method are well-behaved, in that they generally follow the expected trend and are highly reproducible between repeated runs for the same experimental conditions. Further, they do not exhibit the large variability that was characteristic of the earlier studies, and so enable examination of detailed behavior and trends not previously possible.

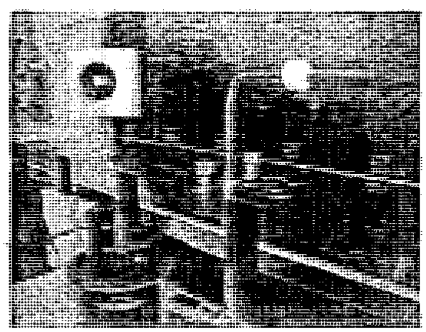
6. Orientation-averaged aspiration efficiency of IOM-like aerosol samplers

Purpose

Experiments were carried out to determine the aspiration efficiency of a scaled-down version of the commercially-available IOM personal inhalable aerosol sampler (SKC, Inc.), to validate the scaling relationships and prototype experimental system. To accomplish this, six different scaling scenarios were developed, all designed to be equivalent to the same set of equivalent full-scale sampling conditions. At the conclusion of the study, a small set of gravimetric tests was performed in the small wind tunnel with a full-size IOM sampler to determine the aspiration efficiency for particle sizes outside of the range of the APS experiments.

Experimental design

Figure 6.1: Photograph of the test and reference sampler set-up for testing IOM-like samplers mounted on a rectangular bluff body



The way in which the IOM sampler is generally used in occupational hygiene practice reflects actual aspiration efficiency, as discussed earlier in this report. This is because, in the routine use of this instrument, the entire sampling cassette is weighed, as opposed to weighing only the filter as is the standard procedure for most other commercially-available aerosol samplers. In this way, all particles that cross the plane of the sampling orifice of the IOM are accounted for. For this reason, the design of the sampling inlets for the experiments utilizing the prototype test system and APS was quite simple. An 11-mm ID thin-walled probe was fitted with an 88-mm square bluff body (44-mm deep) mounted onto it, designed to mimic the aspiration characteristics of an IOM sampler recessed into a small bluff body. The set-up for the test and reference samplers respectively is shown above in Figure 6.1. Previous work performed in our laboratory has demonstrated that, when mounting the IOM sampler on a small bluff body, a positive bias in aspiration efficiency was observed due to the significant protrusion of the sampler out from the bluff body (Paik, 2002). Recessing the sampler into the body, so that the front surface was nearly flush with that of the bluff body, eliminated this sampling bias and more closely represented the way in which samplers would be used in the workplace, where the sampler would not project out significantly from the worker's body relative to the size of that body. An identical 11-mm thin-walled sampling probe, without a bluff body, provided the reference. Greased 20 ppi foam plugs were inserted into the inlets of both the reference and test sampling probes, placed so that the front face of each foam plug was exactly flush with the leading edge of the sampling probe.

This design provided a small-scale approximation of an IOM sampler, with k_δ, the factor by which the inlet diameter was scaled with respect to full-scale, equal to 1.36. For this scaled sampler design, six separate scaling scenarios were developed to be equivalent to full-scale conditions of an IOM sampler with a volumetric sampling flowrate of 2 L/min and an external windspeed of 1 m/s. These are summarized in Table 6.1. These chosen conditions were chosen because of the availability of published data from full-scale wind tunnel studies for these conditions (Mark and Vincent, 1986; Kenny *et al.*, 1997). The purpose of performing a relatively large number of experiments, all simulating the same full-scale conditions, was to test the validity of the scaling relationships earlier in this report.

	Full-Scale	0.73 m/s	1.0 m/s	1.5 m/s	2.0 m/s	2.9 m/s	4.6 m/s	Gravimetric
δ (mm)	15	11	11	11	11	11	11	15
D (mm)	300	88	88	88	88	88	88	120
U (m/s)	1.0	0.73	1.0	1.5	2.0	2.9	4.6	2.5
Q (L/min)	2.0	0.79	1.1	1.6	2.2	3.2	5.0	5.0
k_{dae}	1	1	1.17	1.43	1.67	2.0	2.5	1.58
k_δ	1	1.36	1.36	1.36	1.36	1.36	1.36	1
k_U	1	1.36	1	0.66	0.49	0.34	0.22	0.40

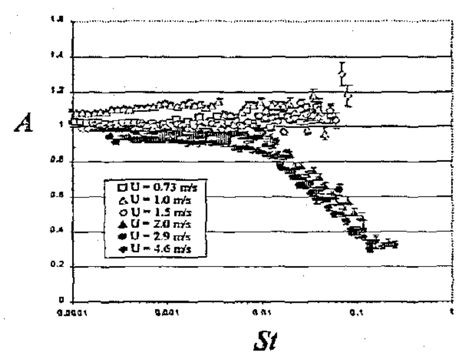
Table 6.1: Summary of experimental conditions for scaled IOM sampler experiments, in which δ = orifice diameter, D = bluff body width, U = freestream wind velocity, Q = sampling flow rate, k_{dae} = scaling factor for particle size, k_d = scaling factor for inlet diameter, and k_U = scaling factor for windspeed. [Note: Scaling factors are here expressed as full-scale/small-scale].

Towards the end of this part of the experimental program, a small set of gravimetric tests was performed to test the aspiration efficiency of the IOM sampler for several large particle sizes which were outside the range of the APS, even allowing for the scaling of particle size in the experiments. For the gravimetric tests, nearly-monodisperse aerosols were generated utilizing narrowly-graded powders of fused alumina. Actual particle sizes for the aerosols thus generated were 26, 34 and 58 μm mass median aerodynamic diameter, and these were used to simulate full-scale particle sizes of 41, 54 and 92 μm, respectively. For these experiments, two full-size IOM samplers were recessed into opposing sides of a 120-mm square bluff body. The reference was provided by a 6-mm ID thin-walled sampling tube fitted onto the front of a 25-mm filter holder. This reference sampler was operated isokinetically, meaning that the sampling velocity was equal to the external wind velocity, providing an aspiration efficiency equal to unity. Because there was concern over the validity of data obtained in this small wind tunnel at low windspeed (see below), it was decided to run these particular experiments at a windspeed of at least 2 m/s. A windspeed of 2.5 m/s was chosen because a correction factor for particle concentration differences between the upstream and downstream positions had already been established for this wind velocity in this wind tunnel (Paik, 2002).

Results and discussion

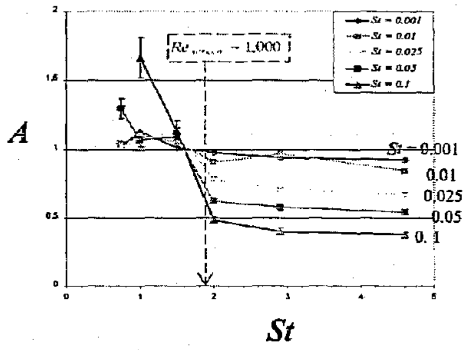
Results obtained using the prototype new testing system: Results from the IOM sampler experiments using the prototype new, automated testing system, scaled to a be equivalent to a full-scale windspeed of 1m/s, are shown in Figure 6.2, where it is recalled that all data for particles larger than d_{ae} = 15 μm obtained using the APS Model 3320 were eliminated for the reasons stated earlier. It was expected that all six data sets presented in Figure 6.2 would follow the same trend and scale well together. But it is clear that there are two distinct trends exhibited by these data sets. For the three lower windspeeds, 0.73, 1 and 1.5 m/s, aspiration efficiency is seen to be close to unity for *St* up to about 0.03, from which point it increases. For the three higher windspeeds, 2, 2.9 and 4.6 m/s, aspiration efficiency shows a decreasing trend starting at $St \approx$ 0.01. The latter trend was expected, based on both theory and available published experimental data, but the former was quite surprising (Mark and Vincent, 1986; Tsai *et al.*, 1995; Tsai *et al.*, 1996; Kenny *et al.*, 1997). These data were therefore more closely examined in an attempt to determine the why the data sets diverged.

Figure 6.2: Aspiration efficiency for IOM-like samplers for the 6 scaling scenarios in Table 6.1



Effect of windspeed on aspiration efficiency: The data sets described above were re-plotted in the form of aspiration efficiency versus freestream windspeed (*U*) for a range of *St* (see Figure 6.3 below). This graph shows a clear transition in the results for *U* somewhere in the range from 1.5 to 2 m/s. It is recalled from the earlier discussion that these experiments were not controlled for Reynolds' number. So now the possibility must be considered that the observed transition may be due to a transition in the characteristics of the flow outside of the sampler, as represented by *Re*.

Figure 6.3: Results from Figure 6.2 re-plotted in the form of *A* versus windspeed (*U*)



Approximate Reynolds' numbers relevant to the flow around the sampler bluff body for the freestream windspeeds studied ranged between 4,600 and 28,500, compared to an equivalent *Re* for full-scale experiments (on a 300 mm-wide mannequin) of 21,200. The observed transition in our new experimental results is seen to occur for *U* between about 1.5 and 2 m/s, corresponding to a Reynolds' number somewhere in the range from 9,400 and 12,700. This would appear to be high compared to related flow transitions noted elsewhere in experimental fluid mechanics. Since there is no explanation to be found for a flow transition to occur in this high range of Reynolds' number, it was considered that the flow transition may have been associated with some other property of the flow in our experiments, perhaps the role of the upstream turbulence screen. Here the appropriate Reynolds' number for *U* from to 1.5 to 2 m/s lay between 890 and 1,200. This seems more plausible. In the search for some supporting concrete information, we carried out some flow visualization studies of the flow through the screen, using smoke tracer and a digital camera operated in 'movie mode'. But unfortunately this did not yield any conclusive new information. Although the suggestion of the role of the screen therefore remains speculative, it was decided to run all future experiments in this wind tunnel at a freestream windspeed of 2 m/s or higher, and to consider only earlier data obtained at windspeeds in this range for further analysis or discussion. Consequently, the scaled IOM sampler data that were accepted for further consideration includes only those for these conditions, and those for lower windspeeds were removed. Inspection of Figure 6.2 reveals that the results for freestream windspeeds of 2, 2.9 and 4.6 m/s, all scaled to simulate a full-size IOM sampler at a full-scale windspeed of 1 m/s, agree very well with one another. The data are also well-behaved, in that aspiration efficiency is close to unity for small *St* and then decreases with increasing *St*. The aspiration efficiency seems to begin to level off at approximately 0.35 for *St* greater than 0.1. Performing these scaled experiments at increasing windspeeds and sampling flow rates succeeded in extending the range of *St* and, effectively, particle size for which aspiration efficiency could be measured with the APS. To further extend the range of *St* for which aspiration efficiency could be measured, would have required experiments with ever-increasing windspeeds and sampling flow rates. But this was eventually limited due to the progressively smaller particle penetration efficiency for the porous foam media placed in the sampler inlets.

Therefore, to assess the aspiration efficiency of the IOM sampler for larger *St*, we decided to extend the effective particle size range by performing a series of gravimetric tests with relatively monodisperse aerosols.

<u>Results obtained using the gravimetric method</u>: Figure 6.4 shows results obtained in our small wind tunnel where aspiration efficiency for the scaled IOM sampler was measured by gravimetric assessment of nearly-monodisperse aerosols. These have allowed the range of *St* covered to be extended considerably. It is seen that the results are reasonably consistent with the trend exhibited by the ones obtained using our new prototype automated measurement system, although perhaps lying somewhat higher than expected.

Figure 6.4: Results for aspiration efficiency from scaled gravimetric tests

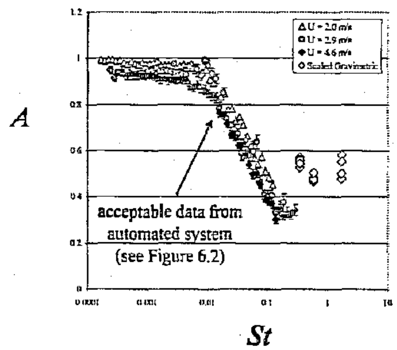
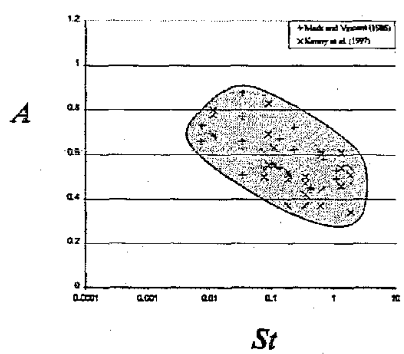


Figure 6.5: Data from earlier studies for the scaled conditions summarized in Table 6.1



<u>Comparison of experimental results with published data and the inhalability criterion</u>: Published results for the orientation-averaged aspiration efficiency of the IOM sampler at full scale in a large wind tunnel and at an external windspeed of 1 m/s are shown in Figure 6.5 (Mark and Vincent, 1986; Kenny *et al.*, 1997). Both of the studies cited were completed using gravimetric methods, in relatively large wind tunnels and with the samplers mounted on full-size mannequins. In order to facilitate comparison between the

published results and those from the current work, the shaded area on the graph encompasses all the actual data.

Figure 6.6: Comparison between current (from Figure 6.4) and earlier data (from Figure 6.5)

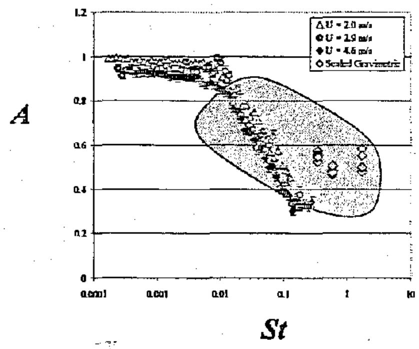
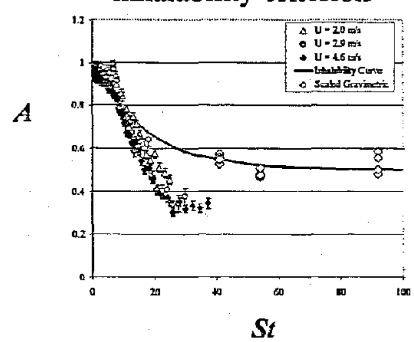


Figure 6.6 combines the results from the current work with the shaded representation of the published data. When viewed in this way, it can be observed that, for the most part, the results from our scaled experiments fall within the range of those full-scale data. But for *St* greater than about 0.05, results from scaled experiments tend towards the lower side of – and a few data points from the present study actually fall outside of – the range encompassed by the full-scale data. It seems possible, therefore, that the prototype testing system and method utilizing the APS may have underestimated the aspiration efficiency for particles of relatively large *St*, in comparison to gravimetric methods. This is supported by comparison with the earlier published data of Mark and Vincent and of Kenny *et al.* and also with the present gravimetric data. At present there is no obvious explanation for the difference. However, the question is raised about the extent to which the modification of the air flow entering the sampler, by the insertion of the foam plugs in the present experiments, might be responsible for such a difference. It is possible that the presence of the porous foam causes a change in the airflow pattern outside of – but very close to – the sampler, and that this in turn may influence the aspiration efficiency (i.e., compared to that for the same sampler with no foam insert).

Figure 6.7: Comparison between new experimental data for the IOM sampler and the inhalability criterion



Finally, the full range of IOM aspiration efficiency data were compared to the inhalability criterion (see Figure 6.7 above). This time, aspiration efficiency is plotted as a direct function of equivalent full-scale particle aerodynamic diameter, consistent with the way in which the inhalability criterion is defined (e.g., Vincent, 1999). The latter was calculated by multiplying the actual particle aerodynamic diameter reported by the APS by the scaling factor, k_{dae}, for each scaling scenario. These scaling factors are given above in Table 6.1. The overall conclusion is that the IOM sampler is quite effective at capturing the inhalable aerosol fraction. Aspiration efficiency of particles in the range of d_{ae} from 20 to 40 μm is seen to be underestimated in relation to inhalability by the scaled IOM sampler using the the prototype testing system. However, when these data are combined with the gravimetric assessment for large particle sizes, it may be reasonably concluded that the IOM is indeed an effective inhalable aerosol sampler.

Conclusions from this part of the research

The main purpose of this portion of the research was to provide validation of the scaling relationships that were developed and of the prototype testing system. This was achieved by comparing results obtained in the small wind tunnel with published results from experiments performed by others in large wind tunnel facilities. A secondary purpose was to further characterize the IOM sampler and compare its performance with the inhalability criterion. Six different scaling scenarios were developed that were designed to be equivalent to the same full-scale conditions. Excellent correlation was found between results from the three different sets of experimental conditions that employed windspeeds of 2 m/s or greater, but the aspiration efficiency from the other three scaling scenarios, that employed windspeeds of less than 2 m/s, exhibited very different behavior. It was concluded that there was some type of flow transition that affected the sampler aspiration efficiency results. But our flow visualization study did not reveal any useful information to help identify the cause. In the absence of a concrete explanation for this behavior, and to avoid this effect in the testing of other samplers, it was decided that all future experiments would be performed for windspeeds of 2 m/s and higher.

Aside from the unexpected observed windspeed effect, there was excellent agreement between results for small-scale windspeeds of 2, 2.9 and 4.6 m/s. This provided good evidence that the scaling relationships developed for this experimental system were valid. The actual values of aspiration efficiency results from the prototype automated system fell somewhat below expectations at larger *St*-values, and below the trend reflected in the past and our new gravimetric results. One possibility is that the presence of the porous foam plugs in the sampler inlet may have altered the air flow just outside the plane of the sampler entry.

Finally, it was concluded from our new studies that the IOM sampler is indeed effective in capturing the inhalable aerosol fraction, supporting all the previous work reported for this instrument.

7. Orientation-averaged sampling efficiency of the CIS and Button samplers

Purpose

A series of experiments was carried out to evaluate the sampling efficiency of the commercially-available CIS inhalable aerosol sampler (BGI Inc., Waltham, MA) and Button Aerosol Sampler (SKC Inc., Eighty Four, PA), respectively. These samplers are described earlier in this report, and both have been proposed as plausible candidates for the inhalable fraction. The purpose of these experiments was to further explore the scaling relationships and to examine the prototype experimental system using the APS – also to characterize these two aerosol samplers for a range of relevant conditions. For this purpose, scaling scenarios were developed for each of the samplers to simulate three full-scale external windspeeds. Comparison of results with published data for wind tunnel studies from other laboratories, provided the basis for evaluating the performance of the prototype testing system.

Experimental design

Figure 7.1: Experimental set-up for testing the CIS sampler

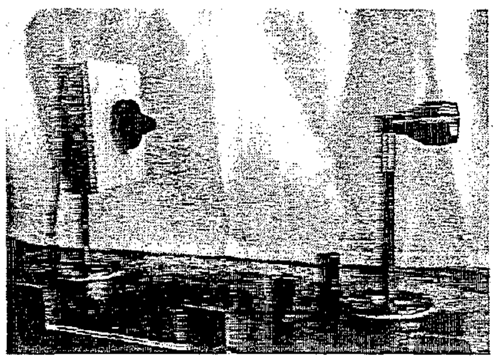
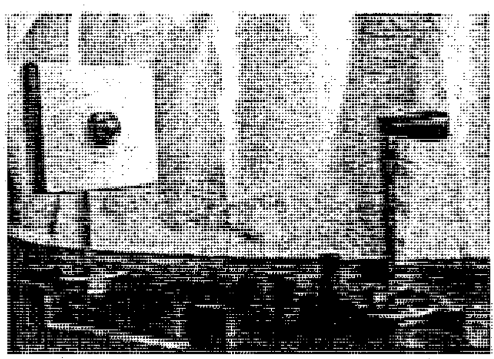


Figure 7.2: Experimental set-up for testing the Button sampler



The designs of the sampling inlets for the CIS and Button samplers were quite different from that for the IOM sampler. In particular, neither of these instruments is recommended for use in a way that reflects true aspiration efficiency. Instead, only the aerosol collected on the filter inside the sampler is quantified, and any aerosol inside the sampler in front of the filter is disregarded. In order to produce results with the prototype testing system that would be comparable to gravimetric studies, any particles deposited inside the sampler inlet in front of the location of the filter must be excluded from the experimental determination of what is therefore the sampling efficiency. To accomplish this, identical stainless steel inlets were attached to the reference and test sampling lines, and the CIS or Button sampling head was attached to a PTFE collar that was fitted onto the test inlet. The experimental set-up in the wind tunnel for the CIS sampler tests is shown in Figure 7.1, and the set-up for the Button sampler tests is shown in Figure 7.2. The CIS sampling entry (with a single orifice) had an inner diameter of 31.8 mm, which tapered – at an angle of 15° – down to 11 mm at the point where the inlet was attached to the sampling line. The multi-orifice inlet for the Button sampler measured 21.6 mm ID, which tapered – at 15° – down to 11 mm at the point where the inlet was attached to the sampling line. The shallow taper in both sampler types was considered necessary to minimize the loss of particles and disturbance to the air flow in the contraction. The entry diameter of each inlet was designed so that the cross-sectional area was equal to the area of the filter through which air would be drawn, inside the actual CIS or Button sampling device, respectively. In this way, the sampling velocity (U_s), through the porous foam that was inserted into the inlet was equal to what the face velocity through the filter would be if the actual sampling device was operated at the same flow rate.

Figure 7.3: Schematic of set-up for testing the CIS and Button samplers, indicating key parameters

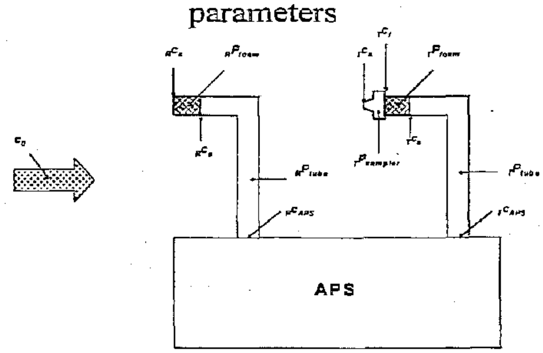


Figure 7.3 shows a schematic representation of the experimental system, with the relevant parameters labeled. The *sampling efficiency* for either of these two samplers may be represented by

$$ {}_TE = \frac{{}_Tc_{APS}}{c_0} = \frac{{}_Tc_{APS}}{{}_Tc_e} \cdot \frac{{}_Tc_e}{{}_Tc_f} \cdot \frac{{}_Tc_f}{{}_Tc_s} \cdot \frac{{}_Tc_s}{c_0} = {}_TP_{tube} \cdot {}_TP_{foam} \cdot {}_TP_{sampler} \cdot {}_TA \qquad (7.1) $$

$$ {}_RE = \frac{{}_Rc_{APS}}{c_0} = \frac{{}_Rc_{APS}}{{}_Rc_e} \cdot \frac{{}_Rc_e}{{}_Rc_s} \cdot \frac{{}_Tc_f}{{}_Tc_s} \cdot \frac{{}_Rc_s}{c_0} = {}_RP_{tube} \cdot {}_RP_{foam} \cdot {}_RA \qquad (7.2) $$

leading to

$$ \frac{{}_TE}{{}_RE} = \frac{\dfrac{{}_Tc_{APS}}{c_0}}{\dfrac{{}_Rc_{APS}}{c_0}} = \frac{{}_Tc_{APS}}{{}_Rc_{APS}} = \frac{{}_TP_{tube}\,{}_TP_{foam}\,{}_TP_{sampler}}{{}_RP_{tube}\,{}_RP_{foam}} \cdot \frac{{}_TA}{{}_RA} \qquad (7.3) $$

Sampling efficiency may be defined as

$$ {}_TS = {}_TP_{sampler} \cdot {}_TA \qquad (7.4) $$

which, when substituted into Equation (7.3), along with the assumptions that ${}_RP_{foam} = {}_TP_{foam}$ and ${}_RP_{tube} = {}_TP_{tube}$ gives

$$ {}_TS = \frac{{}_Tc_{APS}}{{}_Rc_{APS}} \cdot {}_RA \qquad (7.5) $$

This therefore provides the means to determine sampling efficiency for the CIS and Button aerosol samplers using the prototype new test apparatus.

In these experiments, the porous foam was located some distance behind the plane of the sampler entry, in the position that the filter would normally occupy in the sampler as used in practice. Because the foam is recessed into the sampler in this way, it is not likely that the presence of the foam would negatively influence the sampling efficiency, as was suggested for the case of the IOM sampler experiments discussed in the previous section. In fact, the presence of the foam in the CIS and Button sampler experiments may well cause the flow characteristics and, hence, sampling efficiency as utilized in the small wind tunnel to better simulate that of a sampler as employed in practice for exposure assessment.

Results and discussion for the CIS sampler

Orientation-averaged sampling efficiency data for the CIS sampler are shown in Figures 7.4, 7.5 and 7.6. They are plotted as a function of *St* for equivalent full-scale external windspeeds of 4, 1 and 0.5 m/s, respectively. Results from the current work are plotted along with those from published studies of other researchers for the same windspeed but in larger wind tunnels (Kenny *et al.*, 1997; Aizenberg *et al.*, 2000; and Li *et al.*, 2000). All the cited reports involved gravimetric assessments of sampling efficiency. The Kenny *et al.* and Aizenberg *et al.* studies were published as orientation-averaged sampling efficiency. The results from the Li *et al.* study were presented separately for three discrete sampler orientations with respect to the wind, 0°, 90° and 180° respectively, and the orientation-averaged sampling efficiency was estimated by assuming equal weightings between the contributions for the three orientations.

CIS Sampler	Full-scale	Small-scale (1)	Small-scale (2)
δ (mm)	8	8	8
D (mm)	300	120	120
U (m/s)	4.0	2.0	4.0
Q (L/min)	3.5	1.75	3.5
k_{dae}	1.0	0.71	1.0
k_{δ}	1.0	1.0	1.0
k_U	1.0	2.0	1.0

Table 7.1: Conditions for CIS sampler experiments equivalent to full-scale wind velocity of 4 m/s.

In our study, Figure 7.4 shows the sampling efficiency of the CIS sampler for a full-scale windspeed of 4 m/s and for two separate experiments. The first involved scaling both the sampling flowrate and windspeed downwards by a factor of two, while the second was conducted just at the recommended flowrate for the CIS sampler (3.5 L/min) and a single windspeed of 4 m/s (see Table 7.1 for experimental conditions). It is evident from Figure 7.4 that there is excellent agreement between the two data sets. This is important, because it demonstrates that the scaling relationships are indeed valid. These data also exhibit excellent agreement with Kenny *et al.* data for a windspeed of 4 m/s. From this data set, one may conclude that the prototype experimental system and method are quite effective in determining sampling efficiency.

Figure 7.4: Measured aspiration efficiency for CIS sampler for equivalent full-scale windspeed $U_{fs} = 4$ m/s

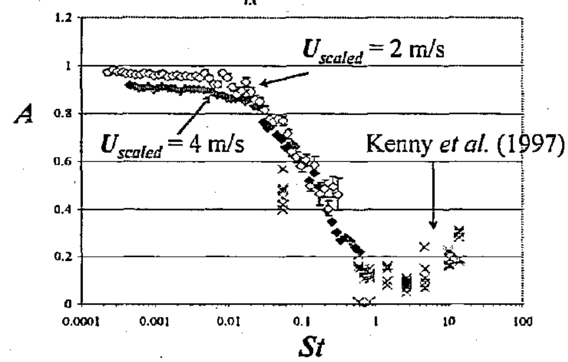


Figure 7.5: Measured aspiration efficiency for CIS sampler for equivalent full-scale windspeed $U_{fs} = 1$ m/s

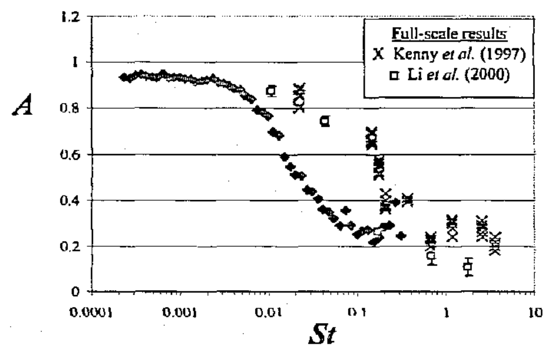


Figure 7.6: Measured aspiration efficiency for CIS sampler for equivalent full-scale windspeed $U_{fs} = 0.5$ m/s

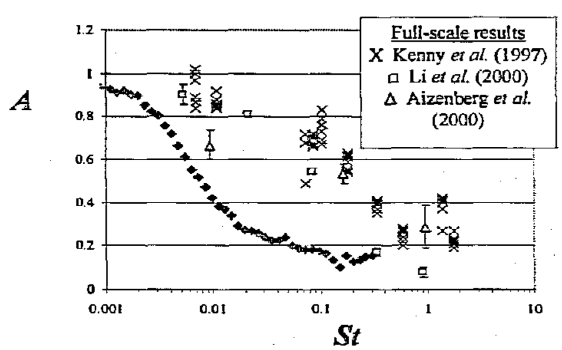


Figure 7.5 shows our results for scaled conditions chosen to match an equivalent full-scale windspeed of 1 m/s. This was accomplished by operating the system at twice the full-scale windspeed (2 m/s) and twice the recommended CIS flowrate (7 L/min) (see

be very different from one another. However, it is seen that sampling efficiency falls progressively and significantly below the inhalability curve for d_{ae} greater than about 4 µm. All this suggests that the CIS sampler is therefore not a good choice for the health-related assessment of personal aerosol exposure. But this is not quite consistent with the results from the gravimetric studies cited (see Figure 7.8 above). Here a different picture emerges in which the CIS appears to be a reasonable choice for the inhalable fraction for environments characterized by low windspeeds (say about 0.5 m/s, which corresponds to a high proportion of workplaces), but not for higher windspeed conditions.

Figure 7.7: Summary of the new, scaled results for the CIS sampler (from Figures 7.4 to 7.6), shown compared with inhalability

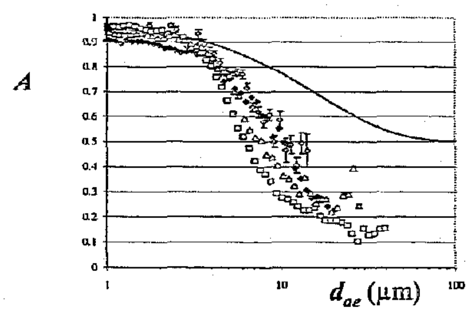
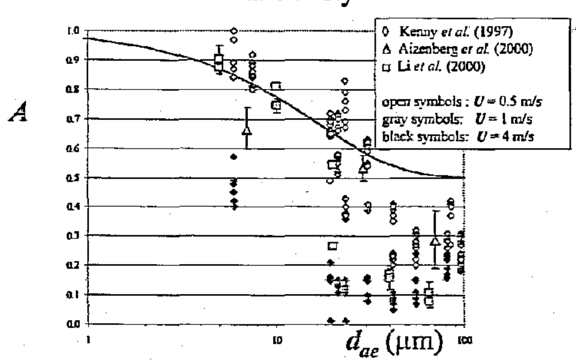


Figure 7.8: Summary of earlier, full-scale results for the CIS sampler, shown compared with inhalability



Results and discussion for the Button sampler

The experimental conditions for the tests with the Button sampler for equivalent full-scale windspeeds of 0.5, 2 and 4 m/s are summarized below in Tables 7.4 to 7.6.

Button sampler	Full-scale	Small-scale
δ (mm)[2]	25	25
D (mm)	300	120
U (m/s)	0.5	2.0
Q (L/min)	4.0	16.0
k_{dae}	1.0	2.0
k_{δ}	1.0	1.0
k_U	1.0	0.25

Table 7.4: Conditions for Button sampler experiments equivalent to full-scale wind velocity of 0.5 m/s.

Button sampler	Full-scale	Small-scale (1)	Small-scale (2)
δ (mm)	25	25	25
D (mm)	300	120	120
U (m/s)	2.0	2.0	4.0
Q (L/min)	4.0	4.0	8.0
k_{dae}	1.0	1.0	1.4
k_{δ}	1.0	1.0	1.0
k_U	1.0	1.0	0.50

Table 7.5: Conditions for Button sampler experiments equivalent to full-scale wind velocity of 2 m/s.

Button sampler	Full-scale	Small-scale
δ (mm)	25	25
D (mm)	300	120
U (m/s)	4.0	4.0
Q (L/min)	4.0	4.0
k_{dae}	1.0	1.0
k_{δ}	1.0	1.0
k_U	1.0	1.0

Table 7.6: Conditions for Button sampler experiments equivalent to full-scale wind velocity of 4 m/s.

Measured orientation-averaged sampling efficiency data for the Button sampler are shown in Figures 7.9, 7.10 and 7.11 as a function of *St* for equivalent full-scale external windspeeds of 0.5, 2 and 4 m/s, respectively. There are fewer published studies of orientation-averaged sampling efficiency available for this sampler (compared to the IOM sampler and even the CIS sampler). But some data are available from Aizenberg *et al.* (2000) and Li *et al.* (2000).

[2] For the Button sampler, the orifice diameter for the purpose of this table (also in Tables 7.5 and 7.6) is defined as the diameter of the hemispherical screen of the sampler's inlet, and this is what was used for the calculation of *St*.

Figure 7.9: Measured aspiration efficiency for Button sampler for equivalent full-scale windspeed $U_{fs} = 0.5$ m/s

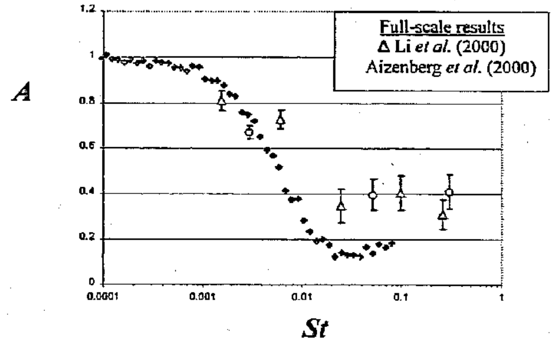


Figure 7.10: Measured aspiration efficiency for Button sampler for equivalent full-scale windspeed $U_{fs} = 2$ m/s

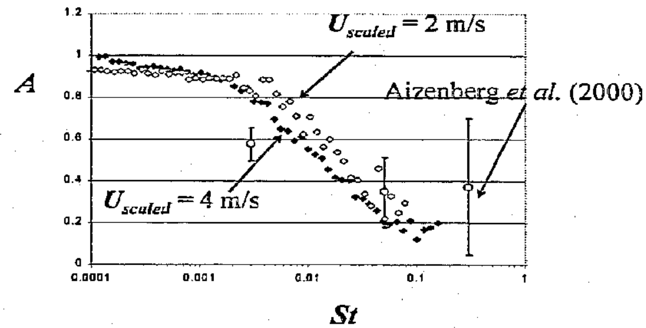
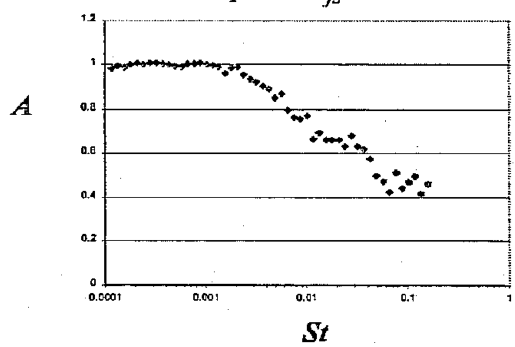


Figure 7.11: Measured aspiration efficiency for Button sampler for equivalent full-scale windspeed $U_{fs} = 4$ m/s



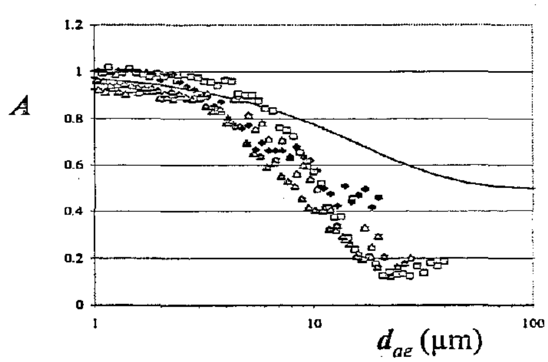
The first data set for the Button sampler, shown in Figure 7.9, was scaled to match an equivalent full-scale windspeed of 0.5 m/s. This was accomplished by operating the system at four times the windspeed (i.e., $k_U = 0.25$ such that U in the wind tunnel was 2 m/s) and four times the recommended Button flowrate (4 x 4 L/min = 16 L/min) (see Table 7.4 for experimental conditions). When compared to data from Aizenberg *et al.* and Li *et al.* for equivalent conditions, the results from the prototype testing system are seen to correlate well for *St*-values in the range from about 0.001 to 0.01, but are somewhat lower than the published data for *St* larger than about 0.02. However, considering the performance of the CIS sampler with the prototype testing system for the same value of k_U (= 0.25), the performance of the Button sampler with the prototype testing system looks quite promising.

Sampling efficiency for the Button sampler for an equivalent full-scale windspeed of 2 m/s was determined in two separate experiments. The first scaled the sampling flowrate and windspeed up by a factor of two, while the second was simply operated at the recommended sampling flowrate (4 L/min) and a windspeed of 2 m/s (see Table 7.5). It is evident, from Figure 7.10, that there is very good agreement between the two data sets. This was important, because it demonstrates yet again, as for the IOM and CIS samplers, that the scaling relationships described earlier are indeed valid. These data also show good agreement with the Aizenberg *et al.* data for a windspeed of 2 m/s. From this data set, it may be concluded that the prototype experimental system and method are indeed quite effective in accurately determining sampling efficiency.

The final set of experiments for the Button sampler were not scaled, but simply run at the recommended sampling flowrate of 4 L/min and a windspeed of 4 m/s (see Table 7.6) The results are shown in Figure 7.11. Unfortunately, for this case there are no available other data for equivalent conditions with which to compare our new results. In Figure 7.11 it is seen that sampling efficiency is close to unity for *St*-values up to about 0.02, and then decreases to approximately 0.5 and seems to begin to level out for *St* in the range from 0.05 to 0.1.

All three sets of scaled Button sampling efficiency data may be considered to be well-behaved, in that the sampling efficiency for very small particles is close to unity and the standard error for all of the data is quite small. There were only a limited amount of data available for comparison, but agreement between our new results and those other data seems to be fair.

Figure 7.12: Summary of the new, scaled results for the Button sampler (from Figures 7.9 to 7.11), shown compared with inhalability



Finally, as for the other samplers tested (see above), the sampling efficiency results for the Button sampler are compared directly with the inhalability criterion (see Figure 7.12).

Here, the scaling factors used for calculation of equivalent full-scale particle aerodynamic diameter were as given in Tables 7.4 to 7.6. When viewed in this way, we see that the results for the three full-scale windspeeds are in good agreement with one another. However, all the results appear to fall significantly below the inhalability curve for equivalent full-scale particle aerodynamic diameter values greater than about 5 μm. From these results, therefore, it does not appear that the Button sampler would be an acceptable inhalable aerosol sampler for windspeeds of 2 or 0.5 m/s. For the higher windspeed of 4 m/s, however, it is possible from the results in Figure 7.11 that the Button sampler may be acceptably close to the inhalability criterion if it could be shown that the sampling efficiency for particles of d_{ae} greater than 20 μm continues to level out for larger particle sizes. Extending the range of particle diameter tested by performing a series of gravimetric tests, similar to those given in the previous section for the IOM sampler, would provide valuable information on the suitability of this sampler for high windspeed environments. But no such experiments were performed during the research described in this report.

Conclusions from this part of the research

This portion of the research was aimed towards the further exploration of the prototype testing system and method, as well as the characterization of the CIS and Button aerosol samplers for a range of equivalent full-scale external windspeeds. First, it was established that the testing system could indeed be used to assess samplers like the CIS and Button, for which it is sampling efficiency is measured, as opposed to the more ideal aspiration efficiency (as for the IOM sampler). All the sampling efficiency data collected in this study are seen to be well-behaved, as evidenced by sampling efficiency for very small particles tending towards unity and with small variability for the entire range of data.

The experiments for both the CIS and Button samplers, that involved two separate scaling scenarios which were equivalent to the same full-scale conditions, demonstrated that the scaling relationships developed in the whole body of the present research work are well-founded. But when compared with published data from other laboratories, the CIS sampler exhibited good agreement only for the highest equivalent full-scale windspeed. But for equivalent full-scale windspeeds of 0.5 and 1 m/s, sampling efficiency appears to be underestimated for most of the range of *St* studied. Our new sampling efficiency results for the Button sampler agreed quite well with the limited amount of published data that was available.

Overall, our new results suggest that the CIS sampler is not an acceptable inhalable aerosol sampler for any of the conditions tested. However the results of other workers are more equivocal, suggesting the possibility that the CIS sampler might be acceptable at low windspeeds. By contrast, for the Button sampler the results suggest that the sampler may be an acceptable inhalable aerosol sampler only for higher windspeeds.

8. Field studies with full-scale and scaled-down IOM samplers

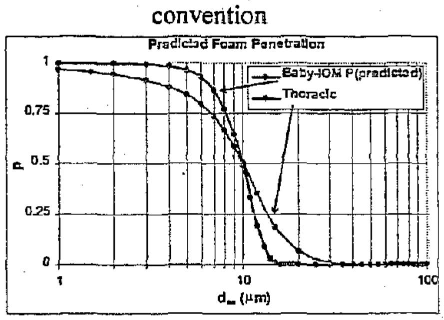
Purpose

A field study was carried out to provide some initial experience with samplers derived not only from the present project but also the one previously reported under NIOSH Grant Number RO1 OH 03687-03 (Vincent *et al.*, 2003), and to examine how results obtained using these compared with earlier samplers aimed at the same aerosol particle size fraction. This part of the research was carried out during March 2003 at an aluminum smelter in Norway. It was a collaborative effort with researchers from the Norwegian National Institute for Occupational Health, Oslo, with whom the Principle Investigator has collaborated on other, similar projects.

The samplers

Four different samplers were used in the field study, falling into two categories. The first category included two samplers already available commercially: the 2 L/min IOM inhalable aerosol sampler (SKC Inc., Eighty Four, PA) and the 1.6 L/min thoracic cyclone (BGI Inc., Waltham, MA), respectively. The second category included two new devices: the new, low-flowrate, 0.22 L/min 'Baby-IOM' inhalable aerosol sampler and its corresponding thoracic version – the 'Baby-Thoracic-IOM' – respectively. Both the latter two instruments derived from the present body of work, in particular from application of the aerosol sampling scaling laws we have developed (see preceding sections). The Baby-IOM inhalable aerosol sampler is based directly on the original IOM. In this version, however, the 15-mm orifice is replaced by a new 5-mm orifice formed by the insertion of a stainless steel insert pressed into the entry of the stainless steel filter cassette. The Baby-Thoracic-IOM sampler is based on the same new instrument, but now a 45-ppi cylindrical porous plastic foam plug of diameter 5 mm and length 3.5 mm was inserted into the entry with its face flush with the plane of the sampler entry (see Vincent *et al.*, 2003). This porous foam plug was chosen to provide a close match with the thoracic convention, as shown in Figure 8.1, where the predicted penetration curve was obtained using the model of Vincent *et al.* (1993).

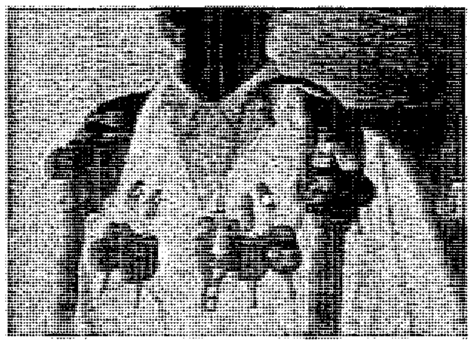
Figure 8.1: Predicted penetration of foam plug shown in comparison with the thoracic convention



Set-up for field study

In the field study, 4 original inhalable IOM samplers were used, together with 2 of each of the small-scale inhalable and thoracic versions (Baby-IOM and Thoracic-Baby-IOM), and also a BGI thoracic cyclone. To simulate the use of these samplers as personal samplers, they were all placed on the torso of a life-size mannequin, and the whole set-up was built so that it could be taken to workplaces. The set-up is shown below in Figure 8.2.

Figure 8.2: Mannequin set-up for field sampler studies, also showing placement of the test samplers



The mannequin was dressed in a hard-hat, shirt and laboratory coat. Over the laboratory coat was placed military webbing straps and a belt, normally used for attaching pouches and the like, but in this instance held the samplers and tubing in place. The flowrates for all the samplers were maintained by a rotary pump and a set of critical orifices.

The workplaces studied

The field study was carried out in an aluminum smelter at Karmøy on the west coast of Norway, south of Bergen and adjacent to Haugesund. The basis for all modern primary aluminum smelting is the Hall-Héroult process, in which alumina is dissolved in an electrolytic bath of molten cryolite (sodium aluminium fluoride) within a large carbon or graphite lined steel container known as a "pot". An electric current is passed through the electrolyte at low voltage, but very high current, typically 150,000 amperes. The electric current flows between a carbon anode (positive), made of petroleum coke and pitch, and a cathode (negative), formed by the thick carbon or graphite lining of the pot. Molten aluminum is deposited at the bottom of the pot and is siphoned off periodically, taken to a holding furnace, often but not always blended to an alloy specification, cleaned and then generally cast. A typical aluminum smelter consists of around 300 pots, and produces about 125,000 metric tons of aluminum annually. There are two main types of aluminum smelting technology, "Söderberg" and "Pre-bake". Söderberg technology uses a continuous anode which is delivered to the cell (pot) in the form of a paste, and which bakes in the cell itself. By contrast, pre-bake technology uses multiple anodes in each cell which are pre-baked in a separate facility and attached to rods that suspend the anodes in the cell.

In our study, the mannequin was situated close to and facing one of the aluminum pots in either of the two types of process rooms. The mannequin remained stationary as no suitable turntable was available. There were also restrictions on movement within the plant and the availability of a suitable power supply for the pump linked to the critical orifices, ensured that the mannequin remained at each of the two locations. Samples were collected for 12 working shifts at each of the 2 locations over a period of 10 days. The first location was within the pre-bake process area, and the second location was within the Söderberg process area.

Sampling, sample extraction and analysis

The samplers were run for as close to a whole working shift as possible. Flowrates were measured pre and post-sampling. Samplers were capped pre and post-exposure to and from the preparation room next to the plant. The IOM variant samplers utilised 25-mm 5-μm PVC membrane filters (Millipore). Upon completion of a sampling period, samplers were carefully disassembled with gloved hands, and the filters (and foam plugs where used) were placed into individual clean centrifuge tubes. The inner surfaces of the IOM variant filter cassettes were washed with a small quantity (5 to10 ml) of distilled de-ionised ultra-pure water to account for small quantities of material deposited inside the sampler but not caught on the filter. The BGI thoracic cyclone utilised a 37 mm-filter cassette, which was pre-assembled at the National Institute of Occupational Health laboratories in Oslo Norway, before making their journey to the Karmøy plant. In addition to the actual samples taken in this way, blanks were taken for each sampler for each sampling shift.

Upon return of the samples, all samples and blanks were acid digested in their individual respective centrifuge tubes and centrifuged. The extracts analyzed by inductively coupled plasma mass spectrometry (ICP-MS). Beryllium was used as an internal standard and small corrections were made to account for volumetric deviations. Samples were thus reported as aqueous concentrations expressed as parts per million. These were converted, with the appropriate flowrate information, to give airborne mass concentrations expressed as $\mu g/m^3$ of aluminum (as Al). Other metals were also provided in this analysis but, since aluminum was the primary focus of interest in the field study, results for the others are not reported here. All the analyses were carried out in the laboratories of the Norwegian National Institute of Occupational Health.

Results and discussion

The masses collected by all the samplers exposed during the field study were corrected using the corresponding blank samples (directly by subtraction). The comparison between the IOM inhalable aerosol sampler and the Baby-IOM inhalable aerosol sampler is shown below in Figure 8.3. The comparison between the BGI cyclone and the Thoracic-Baby-IOM aerosol sampler is shown in Figure 8.4. Results are shown separately for the Söderberg and pre-bake locations, respectively, and are shown for aluminum as represented by total Al. The first feature of the graphs in these figures is that the aerosol concentrations are significantly lower in the pre-bake area than in the Söderberg area.

Figure 8.3: Comparison between results for IOM sampler and Baby-IOM sampler (in μg/m³ of Al)

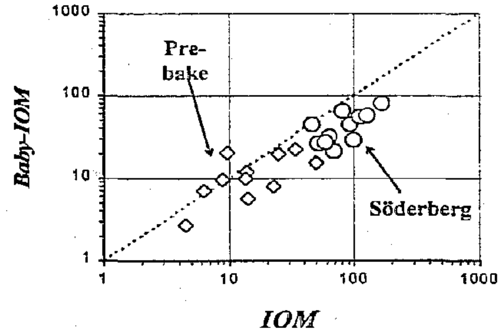
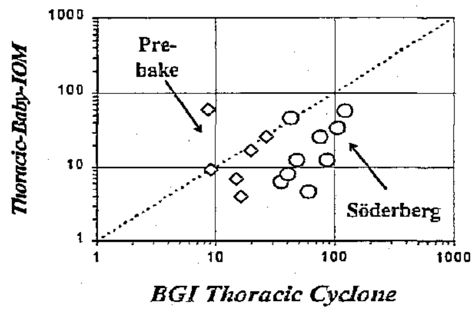


Figure 8.4: Comparison between results for the BGI thoracic cyclone and Thoracic-Baby-IOM sampler (in μg/m³ of Al)



It is clear from Figure 8.3 that the Baby-IOM sampler consistently samples a higher aerosol concentration than the IOM itself. It is also clear from Figure 8.4 that the data are much more scattered for the thoracic fraction than for the coarser inhalable fraction, and that the Thoracic-Baby-IOM consistently samples a higher concentration than the BGI thoracic cyclone. For the purpose of this report, the data for each comparison were analyzed by simple linear least squares regression with the line forced through the origin of coordinates (which is justified on the basis that zero concentration – when it occurs – should be recorded as such by both instruments). The results are as follows:-

$${}_{\text{Pre-bake}}\text{Baby-IOM} = (0.518 \pm 0.093) \cdot {}_{\text{Pre-bake}}\text{IOM}$$

$${}_{\text{Söderberg}}\text{Baby-IOM} = (0.475 \pm 0.042) \cdot {}_{\text{Söderberg}}\text{IOM}$$

$${}_{\text{Pre-bake}}\text{Thoracic-Baby-IOM} = (0.369 \pm 0.237) \cdot {}_{\text{Pre-bake}}\text{Thoracic-Cyclone}$$

$${}_{\text{Söderberg}}\text{Thoracic-Baby-IOM} = (0.281 \pm 0.064) \cdot {}_{\text{Söderberg}}\text{Thoracic-Cyclone}$$

where there were 12 pairs of data records for each comparison and where the uncertainties indicated are standard errors. Here it is shown that the Baby-IOM undersampled with respect to the IOM in the workplaces where the tests were carried out, and the Thoracic-Baby-IOM undersampled with respect to the BGI thoracic cyclone. It is be noted that the number of data points shown for the thoracic sampler pairs is less than for the inhalable sampler pairs. This is because a significant number of data records had to be removed because the masses collected were recorded as negative, and so were unusable. This, not surprisingly, reflects the overall lower aerosol concentrations for the thoracic fraction versus those for the inhalable fraction.

In the context of the present research, the comparison between the Baby-IOM sampler and the full-scale IOM sampler are the most significant. The fact that the Baby-IOM undersamples by as much as a factor of about x2 is not consistent with what was found in our laboratory studies. It is recalled that, in our laboratory studies, where the small-scale Baby-IOM emerged from considerations of scaling of the performance of the full-scale IOM, we had found excellent agreement. So the findings from experiments in the field provide are surprising. Since the scaling laws were derived from physical considerations, and we have every reason to believe them to be correct, we are led to consider whether the environmental conditions in the field are in fact equivalent to those which pertained to the laboratory studies that have made up the bulk of this report.

This brings us to consideration of the windspeeds that are encountered in actual workplaces, as compared to those which have traditionally been employed in wind tunnel studies of aerosol sampler performance by most workers (including ourselves). Nearly all the published literature on industrial hygiene-directed aerosol sampling based on laboratory studies in wind tunnels has been concerned with full-scale windspeeds equal to or greater than 0.5 m/s. This is partly because the original motivation for much such research was its application in relation to underground mining where, because of the need for high ventilation levels, local windspeeds tend to be quite high. In addition, it is widely acknowledged among aerosol scientists that wind tunnel studies using large particles at lower windspeeds are very difficult to execute due to the problems in achieving uniform aerosol spatial distribution under such conditions. However, it is now known that windspeeds in most workplaces are much lower than the ranges of windspeeds used in most aerosol sampler studies like those cited in this report. Surveys reported by Berry and Froude (1989) and Baldwin and Maynard (1998) reveal that actual windspeeds in workplaces rarely exceed 0.2 to 0.3 m/s and more typically are less than 0.1 m/s. With this in mind, although local windspeeds were not measured during the field study described in this report, it is not unreasonable to expect that they too would be as low as those reported in the above citations. So the question is raised as to whether the scaling laws that worked so well in our laboratory studies might or might not apply for the different windspeed regime encountered in the field.

Conclusions from this part of the research

A field study was carried out at a Norwegian aluminum smelter, in which new samplers derived from both the present and earlier NIOSH-funded research were compared with existing instruments. This was done using samplers of the different types mounted on the full-sized torso of a mannequin that was taken to locations in the smelter. The most important finding was that new samplers that had been shown to perform well in the laboratory, following a plausible set of physical scaling laws that had been developed, did less well in the field. Although no firm evidence was found to explain this discrepancy, it is noted that the windspeed conditions in the field may well have been quite different than those for which the laboratory studies were carried out. In particular, we now know that windspeeds in actual workplaces often tend to be much lower than originally expected, and are certainly lower than those applied to most of the wind tunnel studies that have been carried out to examine aerosol sampler performance in the laboratory. This points to the need for new research to explore sampler performance for this range of conditions. Aerosol scientists acknowledge the difficulty in performing such experiments, but a new experimental approach has recently been proposed by the Principal Investigator by which to carry out such studies. This will be reported at a future date.

9. Towards a new protocol for the testing of personal aerosol samplers

Based on the work described here, considerable progress has been made towards a new protocol for aerosol testing procedures that embody the desired features identified at the outset of the project, in particular for personal samplers intended for collecting the inhalable aerosol fraction. The prototype new automated testing system looks very promising as a basis for a future aerosol sampler testing system. But, as can be seen from the scientific discussion in the preceding sections of this report, there remain some outstanding scientific questions that need to be answered before such a system can be fully endorsed. In particular, some of the observed inconsistencies between results obtained with the new system and those obtained by the more conventional gravimetric approach are still unexplained. So there is still some way to go. Meanwhile, however, we have provided new knowledge that can help identify a way forward. Firstly, it is an extremely important result from our research that aerosol sampling systems and their evaluation can be reliably scaled with respect to physical dimensions, windspeeds, sampling flowrate, orientation and particle size. Secondly, we have shown that a rapid evaluation system can be developed around direct-reading particle sizing and counting instrumentation. Thirdly, the finding from earlier research carried out in our laboratory, showing the weak role of bluff body size on sampler aspiration efficiency (Paik and Vincent, 2002b), provides the basis for simpler experimental systems than were previously thought to be necessary. All these findings are directly valuable in the search for improved protocols for the evaluation of the performances of aerosol samplers. We may therefore identify an – at least – intermediate step towards an improved test protocol.

The CEN approach

A particularly good model for such a protocol is the one developed by the Comité Européen de Normalisation (CEN) (CEN, 2001). In the CEN model, for any given sampler to be tested, the first step is a critical review of the sampling process for the instrument in question. This is intended to identify factors that may influence the performance of the sampler, including particle size, windspeed, aerosol composition, filter material, etc. This is essential in the process of sampler evaluation, determining under what conditions the sampler will need to be tested. Three options are then presented for the testing of samplers: (a) the laboratory testing of samplers with directly respect to sampling conventions; (b) the laboratory comparison of instruments; and (c) the field of comparison of instruments. The second and third of these involves the identification and use of an existing aerosol sampler that is known and agreed to be capable of accurately sampling the appropriate health-based aerosol fraction as a reference sampler. For the inhalable fraction, for example, the IOM sampler has, perhaps, been most consistently shown to be the best candidate currently available for this role (e.g., Bartley, 1998). The test sampler of interest is then operated alongside the reference sampler, and the mass of aerosol collected in the test sampler is compared to that in the reference. In the laboratory, these experiments should be performed for the range of relevant environmental conditions, as identified in the critical review, and appropriately scaled. In the field, the comparisons should be carried out for as wide a range of conditions as possible pertaining to the field site(s) in question. For the latter, it is clear that the results can only be considered useful for future application in the same – or demonstrably similar – sites. So this approach may be of limited general value. The first test method identified by CEN is the one that is directly relevant to the present project.

An improved approach

The features contained in the CEN model for laboratory testing with respect to sampling conventions may be adapted as a framework for the application of the new knowledge gained from our research. An outline, based on the CEN document as a starting point, is provided in Appendix at the back of this report. It contains the following ingredients:-

- **Statement of principle**
- **Description of the experimental test method**
    - <u>Test conditions</u>
        - test variables
        - particle size
        - windspeed
        - wind direction
        - aerosol composition
        - sampled mass
        - aerosol charge
        - specimen variability
        - flowrate variations
        - surface treatments
    - <u>Experimental requirements</u>
        - environmental conditions (temperature and humidity)
        - test aerosol
            - choice of monodisperse or polydisperse
            - measurement of particle size
        - reference samples
        - windspeed range and variability
        - number of samplers to be tested simultaneously
        - sampling pumps

- **Calculation methods**
  - Nomenclature
  - Calculation of the actual sampled concentration
  - Calculation of ideal sampled concentration
  - Calculation of sampler bias
  - Application of a sampler correction factor
  - Calculation of uncertainty in the estimated sampler bias
  - Calculation of sampler accuracy
- **Test report**

In summary, the sampler performance is characterized fully for a representative range of particle sizes, windspeeds and sampler orientations (where sampling is usually orientation-averaged, as has been the case in the most of the research described in this report). The resultant data are used to construct an 'average' performance curve (aspiration efficiency or sampling efficiency, depending on the recommended mode of operation of the sampler) as a function of particle aerodynamic particle diameter. Then the sampling efficiency curve is compared directly to the sampling convention (e.g., inhalability curve) by calculating the measured sampled mass fraction for a set of log-normal particle size distributions. This calculated mass is then compared with the equivalent results for a hypothetical ideal sampler that perfectly matches the convention. The two sets of calculated results are then used to construct a mathematical 'map' of the collected mass biases that would be found when the sampler is used over relevant ranges of conditions. Any given sampler can then be classified according to its ability to sample more or less closely to the desired criterion.

10. Conclusions from and implications of the research

The work described in this report has been a scientific research study which was intended to further the understanding of the nature of aerosol sampling, particularly as it applies to the need for exposure assessment in the workplace and ambient environments in relation to the latest health-based aerosol exposure standards. The research combined aspects of aerosol science and fluid mechanics together with considerations of occupational and environmental health. It relates to the current interest in the United States and the international occupational health community in the practical applications of the growing body of work on aerosol sampling science.

Achievement of the research objectives

In the original proposal, a set of specific research objectives was given, along with a primary broad objective (see first part of this report). These objectives are again presented here along with an examination of how they have been met.

The primary broad objective: This was to develop a cost-effective, small-scale system and methodology for testing the aspiration efficiencies of aerosol samplers and validation against the latest particle size-selective sampling criteria for actual particle sizes up to 100 μm in aerodynamic diameter and over relevant ranges of actual sampler geometrical dimensions, flowrate and windspeed. This objective was met in large measure. A prototype new, automated testing system, designed around the application of a direct-reading aerodynamic particle sizer (APS) was designed and built. It was validated through experiments with a small range of personal aerosol samplers currently of interest to industrial hygienists (i.e., the IOM, CIS and Button samplers) for aerosols with equivalent full-scale particle aerodynamic diameters up to 40 μm. Examination of larger particle sizes in this system were not possible due to the experimental constraints associated with particle penetration through the porous plastic foam media which were employed to assist with the coupling between the air flow outside and just inside the sampler under test. For such larger particle sizes, therefore, it is suggested that a small number of gravimetric tests, using narrowly-graded powders to produce nearly-monodisperse aerosols can provide information to complement the main body of data obtained using the new system. It was shown that such experiments could be performed quite quickly, such that – under practical testing conditions – the additional tests that would be required could be carried out with relatively little extra work.

The first specific objective: This was to use current new knowledge of the theory of aerosol sampling to develop scaling relationships between small and large sampling systems, low and high windspeeds and sampling flowrates, and small and large particles. Such scaling laws were developed by reference to knowledge of the physics of both aerosol and fluid mechanics. They were based on the identification of a number of dimensionless groups of variables, relating for example to the roles in particle transport of particle inertia, relative dimensions and relative air velocities and sampler orientation. Many other dimensionless groups were considered but eventually neglected, including in particular the Reynolds' numbers for the macroscopic and microscopic air flows in the overall system, reflecting the balance between fluid mechanical inertial and viscous forces.

The second specific objective: This involved applying the new system of scaling relationships to an experimental system in which aerosol sampling systems of interest (including small personal samplers mounted in the 'breathing zone' of a large torso) were re-created at small-scale in a small wind tunnel and tested for experimental particle size ranges (up to 25 μm) that could be conveniently measured using direct-reading instrumentation such as the aerodynamic particle sizer (APS). This was successfully carried out through extensive experiments with the prototype new, automated testing system, both for idealized thin-walled probes oriented at 90° to the freestream and for the range of personal aerosol samplers already referred to. In general, this validation was successful. However there was one clear and notable exception. It did appear that there was an additional, unexpected role of the air velocity in the wind tunnel during some of the personal aerosol sampler experiments, specifically for windspeed less than 2 m/s. This pointed to an effect associated in some way with the Reynolds' number associated with the macroscopic air flow in the overall system. Although it was hypothesized that this might relate to the nature of the air flow through the turbulence-generating mixing screens upstream of the wind tunnel working section, we were not able to identify conclusive evidence for this, nor indeed for any other factor. However, in view of the

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First and foremost, this research has been a scientific study that was aimed towards improving the understanding of the physics of aerosol sampling and employing that knowledge in the development of a new aerosol sampler testing system capable of rapidly testing new and existing samplers for health-based aerosol exposure assessment. Substantial progress has been made towards that ultimate goal. However, as in any piece of research of this type, a number of questions remain that will require further investigation, in particular if the scaling laws we have developed and the prototype new, automated testing system are eventually to be incorporated explicitly into future aerosol sampler testing protocols.

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APPENDIX

The following outline describes possible ingredients of a new protocol for testing of aerosol samplers. It follows the structure of Annex A "*Laboratory testing of samplers with respect to sampling conventions*" in the European standard EN 13205 (2001) "*Workplace atmospheres – assessment of performance of instruments for measurement of airborne particle concentrations*". The purpose of such a protocol is to identify and fully describe a standard set of procedures that can be consistently applied by everyone and anyone for the testing, evaluation and – ultimately – classification of aerosol samplers on the basis of their abilities to collect appropriate health-related aerosol fractions.

Although the narrative given below may not be exactly the same as the original, it applies similar formatting in order to facilitate comparison for the reader that wishes to do so. Explanations, where appropriate, are given in footnotes. Finally, as in the main body of this report, reference is made only to samplers for the inhalable fraction. So references that are made to samplers for the thoracic and respirable fractions, which appear in the original EN 13205, are not given here. It is important to note that what is present here does not represent an actual *proposed* standard protocol for aerosol sampler testing, but rather a *step on the way* towards the evolution of such a protocol.

1. Principle

The purpose of the laboratory experiments is to determine the sampling efficiency of a given candidate sampler as a function of particle aerodynamic diameter over the relevant size range, and also as a function of any other relevant variables. The sampling efficiency values are compared to the target sampling convention. Mathematical modeling is used to estimate the concentrations that would be sampled from a range of ideal log-normally distributed aerosols, using both the measured sampler efficiency and the target sampling convention. From these data, the sampler bias and precision are estimated.

2A. Test method using monodisperse test aerosols

The sampling efficiency values are calculated by comparing the aerosol concentrations measured using the sampler under test, with reference samples of the ambient aerosol concentration. An experimental design shall be devised that takes account of appropriate aerosol sampler physical scaling relationships[3] and also gives due attention to randomisation of the data and to estimation of the main effects. The design, and its associated statistical model, shall be explained in a test report.

2A.1. *Test conditions*

Experiments to candidate test samplers for the inhalable fraction shall be carried out in a wind tunnel or aerosol chamber. Personal inhalable samplers intended for use outdoors or

[3] Scaling of sampler performance with respect to the appropriate variables was demonstrated during the present research.

Electric charge	O	Charged or neutralised aerosol, conducting or insulating sampler	Choose and document	A.2.2.7
Sampler variability	C'	Inhalable: one or more specimens		A.2.2.8
Flowrate variation	C'	Design flowrate ±10% for inhalable samplers, at one windspeed	≥ 3	A.2.2.9
Collection surface	O	Choice of materials (e.g filters, foams) and details of any surface treatments to be stated		A.2.2.10

2A.2.1. Particle size

For inhalable aerosol samplers, the largest equivalent full-scale particle size tested shall be no smaller than 90 μm, but may be smaller in reality if scaling of physical variables is appropriately carried out.[5]

2A.2.2. Windspeed

The 'outdoor workplace' range of windspeeds shall also apply to samplers intended for use in forced ventilation (equivalent full-scale > 1 m/s). The highest equivalent full-scale windspeed value recommended here may be altered if the critical review identifies a more suitable upper limit, depending on the intended use of the sampler. Again, testing may be carried out at different windspeeds by the application of appropriate scaling laws.[6]

2A.2.3. Wind direction

In accordance with the definition of the inhalable convention, the effects of wind direction shall be averaged out by rotating the mannequin (if used) or samplers during the course of each test run, either slowly and continuously, or stepwise with four or more steps. For static (or area) samplers, an exception to this requirement may be made when the sampler is designed such that its inlet always takes up a preferred orientation to the external wind, or is omnidirectional, or when its use is limited to fixed sampling positions with respect to forced ventilation.

2A.2.4. Aerosol composition

Particles used for tests to classify samplers should be spherical (solid or liquid), or approximately isometric. The degree of agglomeration of the test aerosol itself may be verified by the visual microscopic inspection of particles collected by elutriation onto slides placed in the working section of the wind tunnel or test chamber used.[7]

2A.2.5. Sampled mass

The purpose of the test is to determine any dependency of the sampler efficiency curve on the sampled mass for the particle size of interest, not to evaluate analytical errors. If a

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[5] Again, scaling laws were developed during the present research that described the roles not only the main macroscopic variables (sampler size, windspeed, etc.) but also particle size.

[6] Again, by the use of scaling laws developed during the present research.

[7] This was shown during the present and earlier research (Vincent *et al.*, 2003) to be a convenient and effective means of checking.

test is carried out, a maximum concentration and sampling time relevant to the intended measurement tasks should be chosen.

2A.2.6. Aerosol charge

If the sampler is non-conducting it should be tested with a neutralised aerosol, unless it can be demonstrated – or argued from the peer-reviewed scientific literature – that the results for aerosols charged during mechanical generation and dispersal into the test system are not significantly different.[8] Electrostatic influences should be reduced where possible, by choosing samplers made from conducting materials, cleaning them thoroughly, and earthing them during all tests.

2A.2.7. Specimen variability

This is optional for inhalable aerosol samplers.

2A.2.8. Flowrate variations

For inhalable samplers, the sampling flowrate should be within ±10% of the recommended value, or of the value used in the tests after appropriate scaling.[9] The flow dependence should be tested at the windspeed most representative of the conditions of use. Tests to obtain this information need not be carried out where reliable data are available in the published literature.

2A.2.9. Surface treatments

Examples of surface treatments are the greasing and cleaning of collection substrates, the neutralising of filters and foams, and the method of sampler cleaning. Differences between the surface treatments actually tested and those recommended in the sampler's instruction manual shall be clearly stated and explained.

2A.3. *Experimental requirements*

The experimental system shall have the following characteristics:

2A.3.1. Environment

The experiments shall be carried out in an environment with temperature between 15 °C to 25 °C, atmospheric pressure 960 hPa to 1050 hPa and relative humidity 20 % to 70 %, unless the sampler is to be used in more extreme environments, in which case the conditions of use should be reproduced as closely as possible. A full description of the test environment shall be given in the test report, and the actual conditions existing at the time of testing documented.

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[8] This was shown to be the case during the present research, at least for any effects relating to aspiration efficiency.

[9] Using the scaling laws developed during the present research.

2A.3.2. Test aerosols

Tests should be carried out using nearly-monodisperse aerosols. When nearly-monodisperse test aerosols are used, a single experiment gives rise to a single measurement of sampling efficiency at a single nominal aerodynamic diameter covering the range of interest. Therefore nine different aerosols should be used in order to obtain sampling efficiency values corresponding to nine particle sizes (as recommended in Table A1). Correction factors for particle shape and particle density, where used, shall be determined for each aerosol or obtained from appropriate reliable literature.[10]

2A.3.3. Particle aerodynamic diameter

The choice of aerosol depends on the availability of a suitable method for the measurement of mass median particle aerodynamic diameter for the individual aerosols generated and used for testing or of appropriate valid pre-existing data. Such properties should be measured independently unless data are available in the peer-reviewed literature to provide the necessary information for aerosol generated from a particular substance in a particular way.[11] If it is decided to conduct experimental calibration of the test aerosols, this may be done by any method having a unique, monotonic calibration curve over the appropriate particle size range. Full details of the calibration method shall be stated, particularly where correction factors for particle density, particle shape or other test aerosol characteristics are used. The particle aerodynamic diameter values measured shall be those pertaining to the Stokes regime, and their precision (including uncertainty in any correction factors used) shall be determined and stated in the test report.

2A.3.4. Particle size distribution and monodispersity

For tests on inhalable samplers, the nearly-monodisperse test aerosols shall have geometric standard deviation less than 1.50.

2A.3.5. Spatial and temporal distribution of test aerosol

The test aerosols should be spatially homogeneous to within ±20% with respect to both particle size distribution and concentration over the region of the test system occupied (or projected) by the test sampler system. Mass concentration should not vary or change over time by more than ±25%. The aerosol concentration and particle size distribution during the tests should be carefully chosen for compatibility with the limitations of the particle aerodynamic diameter measurement method, and shall be documented. The aerosol particle size distribution and concentration shall be sufficient to ensure that analytical errors in the measurement of the sampled aerosol are less than 2% for analysis by weighing or chemical methods, and less than 1% for analysis by particle counting.

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[10] This section of the protocol refers only to methods where nearly-monodisperse test aerosols are used for the testing of inhalable aerosol samplers. A new section is added (see below) that deals specifically with the application of polydisperse aerosols coupled with direct reading particle sizing and counting instrumentation.

[11] As was the case in some of the experiments described in this report.

2A.3.6. Reference samplers

Reference samples shall be collected with thin-walled sharp-edged probes operating isokinetically in the case of a wind tunnel, or in the case of an aerosol chamber by any method for which it can be demonstrated that the sampling efficiency is unity for all particle sizes of interest. Alternatively, anisokinetic operation of reference may be applied provided that an appropriate validated aspiration efficiency model is identified and used for the correction of reference aerosol concentrations.[12] Reference probes shall be situated at representative positions within the area in which the test samplers are placed, so that spatial variations in the test aerosol can be identified. The method used to calculate the sampler efficiency shall be clearly stated, and should take into account where possible temporal and spatial variations in concentration. The method used to estimate the reference concentration shall have relative standard deviation lower than 10%.

2A.3.7. Windspeed

The actual values of wind speed (or any other environmental variable) during the test runs, scaled or otherwise, shall not differ by more than 10% from the target value over the spatial area in which test specimens are situated. Where a wind tunnel is used the blockage by the mannequin or samplers shall be less than 20 %. The turbulence length scale and intensity in the wind tunnel shall be estimated[13] if possible and documented in the test report. The values should be kept constant for each of the test windspeeds.

2A.3.8. Positional and interference effects

Several sampler specimens may be tested together provided they are not so close that they interfere with one another. The experimental design shall be capable of isolating and eliminating any positional effects from the experiment. Samplers shall be tested together with their appropriate holders; the plane of the inlet with respect to vertical shall be orientated as in field sampling. The positions and orientations used shall be documented. The positions at which personal samplers are placed on a mannequin or other bluff body during testing shall be representative of where they are designed to be used, unless it can be shown – or argued from the peer-reviewed literature – that such positional effects are not significant.

2A.3.9. Test report

The test report shall contain details of the methods used to process and analyse the samples taken during the tests, and of the procedures used to clean samplers between experimental runs.

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[12] Recent research in our laboratory under an earlier NIOSH-funded project has yielded an accurate mathematical model by which the aspiration efficiency of thin-walled reference sampling probes can be corrected for anisokinetic conditions over a wide range of such conditions (Vincent *et al.*, 2003; Paik and Vincent, 2002b).

[13] Turbulence intensity and length scale are difficult to measure, and require sophisticated equipment. However it is well-known that, for grid-generated turbulence in a wind tunnel, these may be estimated reliably from the empirical equations proposed by Baines and Peterson (1951), as was done during the present research.

2A.3.10. Pumps and flowrate
Samplers should be tested together with suitable, properly maintained pumps. For test purposes the sampler volumetric flowrates shall be carefully adjusted and measured, using a bubble flowmeter or gasmeter, and recorded. The pumps used shall meet general requirements (e.g., EN 1232), and any more stringent requirements specified in the instruction manual for the sampler. Samplers with an integral pump or air mover shall be tested under flow conditions having the same characteristics as the integral pump or air mover.

2B Test method using polydisperse test aerosols

The sampling efficiency values are calculated by comparing the aerosol concentrations measured using the sampler under test, with reference samples of the ambient aerosol concentration. An experimental design shall be devised that permits the application of polydisperse aerosols and appropriate direct reading instrumentation such that rapid acquisition of sampler efficiency data can be achieved within a single experiment, as opposed to the multiple experiments that would be needed using the approach described in 2A. Also as for the approach described in 2A, this method should also take account of appropriate aerosol sampler scaling relationships. If, for the specific method chosen, scaling does not permit simulation of the full desired range of equivalent full-scale particle size, then the results may be supplemented at larger particle sizes by data points obtained using the method described above in 2A.[14] The design, and its associated statistical model, shall be explained in the test report.

2B.1 *Test conditions*

Same as in 2A.

2B.2 *Test variables*

Same as in 2A.

2B.2.1. Particle size
For inhalable aerosol samplers, the equivalent full-scale particle size tested shall range from 0 to 90 μm. But appropriate scaling laws can be used to narrow this range for the purpose of testing. Such application of scaling laws may enable the application of direct-reading instrumentation for the accurate rapid-detection, sizing and counting of particles in the test system.[15]

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[14] As indeed was the case in the research described in the main body of this report.

[15] Currently-available direct-reading particle counters operate efficiently only for particles with aerodynamic diameter up to no greater than about 20 μm.

2B.2.2. Windspeed
Same as in 2A.

2B.2.3. Wind direction
Same as in 2A.

2B.2.4. Aerosol composition
Not relevant.[16]

2B.2.5. Sampled concentration
The sampled aerosol concentration must be in the range that is (a) large enough to provide sufficient individual particle counts across the whole range of particle size of interest, in order that particle concentration may be defined with sufficient statistical accuracy, but (b) not so large that particle counting artifacts may occur due to counting coincidences or other apparent 'phantom' particles.[17]

2B.2.6. Aerosol charge
Same as in 2A.

2B.2.7. Specimen variability
Same as in 2A.

2B.2.8. Flowrate variations
Same as in 2A.

2B.2.9. Surface treatments
Same as in 2A.

2B.3 *Experimental requirements*

The experimental system shall have the following characteristics:

2B.3.1. Environment
Same as in 2A.

2B.3.2. Test aerosols
Tests should be carried out using polydisperse, preferably non-agglomerated test aerosols with continuous particle size distribution and ample particles throughout the range of particle aerodynamic diameter at least from 0 to 20 μm.

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[16] Direct reading instruments relevant to this application count and size particles only in terms of the individual airborne particulate entities, whether agglomerated or not.

[17] The particle coincidence or 'phantom' artifacts referred to are a function of the specific direct reading instrument used.

2B.3.3. Particle aerodynamic diameter
The direct-reading instrumentation used should be capable of providing particle size information specifically in terms of particle aerodynamic diameter. Alternatively, however, an instrument that provides particle size in terms of some other metric would be acceptable provided that it can either be calibrated in terms of particle aerodynamic diameter or the particle size it provides can be converted to particle aerodynamic diameter by the application of other information (e.g., particle density or shape) according to established aerosol science principles. If the latter approach is adopted, full details of the conversion method shall be stated in the test report.

2B.3.4. Spatial distribution of test aerosol
Same as in 2A.

2B.3.5. Reference samplers
Same as in 2A.

2B.3.6. Windspeed
Same as in 2A.

2B.3.7. Positional and interference effects
The experimental design shall be capable of isolating and eliminating any positional effects from the experiment. In this method, only one sampler can be tested in any given test. Its position and orientation used shall be documented. The position at which a personal sampler is placed on a mannequin or other bluff body during testing shall be representative of where they are designed to be used.

2B.3.8. Experimental procedure
Any test method involving the use of a direct-reading instrument to determine sampling efficiency must require consideration of the flow interface between the air movement outside the sampler inlet to that inside the sampler inlet. It will also be necessary to account for the particle losses that will occur after passing through the inlet but before arrival at the sensing zone of the direct-reading instrument. This must apply to both the sampler being tested and the reference sampler. The method must therefore either take quantitative account of such particle losses, or it must be designed so that such losses cancel out between the test and reference sampler respectively. In addition, sampler flowrates appropriate to the sampler being tested (after appropriate scaling) and the reference sampler may need to take account of the flowrate specified for the direct-reading instrument used, such that appropriate flow matching may be required (e.g., by the addition or subtraction of air from the sampler air flow).[18] The overall method that is

[18] This was addressed during the present research by the use of a suitable flow adaptor

used should be shown to provide results that are equivalent, after appropriate scaling, to those that would be obtained using the method described in 2A.[19]

2B.3.9. Test report
Same as in 2A.

3. Calculation, analysis, evaluation and reporting

The EN 13205 protocol contains detailed information on calculation methods, analysis of results, sampler evaluation and reporting of the results (as outlined in the main body of this report). These will apply to the modified protocol suggested here, and so the details are not repeated.

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[19] These design considerations were addressed in the main part of the present research project. This research identified one method that might be appropriate for the desired application. It has addressed and resolved most of the technical issues outline in this Appendix, although – as the report shows – there are some remaining questions that must be answered.

PUBLICATIONS (PUBLISHED OR EXPECTED)

Brixey, S.A., Paik, S., Evans, D.E. and Vincent, J.H. (2002), Experimental studies to develop new aerosol samplers and methods for their evaluation, *Journal of Environmental Monitoring*, 4, 633-641.

Brixey, S.A., Evans, D.E. and Vincent, J.H. (2003), New studies of the aspiration efficiencies of thin-walled probes placed at right angles to the wind, *Journal of Aerosol Science*, in preparation, to be submitted early 2004.

Brixey, S.A., Evans, D.E. and Vincent, J.H. (2003), Experimental studies of IOM-like aerosol samplers using a new rapid evaluation method, *Aerosol Science and Technology*, in preparation, to be submitted early 2004.

Brixey, S.A., Evans, D.E. and Vincent, J.H. (2003), Experimental studies of a range of candidate personal inhalable aerosol samplers using a new rapid evaluation method, *Annals of Occupational Hygiene*, in preparation, to be submitted early 2004.

Evans, D.E., Thomassen, Y. and Vincent, J.H. (2003), Comparison between inhalable and thoracic aerosol samplers in aluminium smelting workplaces, *Journal of Environmental Monitoring*, in preparation, to be submitted early 2004.

Vincent, J.H. (2003), Progress towards a new standard protocol for the testing of personal aerosol samplers: an update of European Standard EN13205, *Annals of Occupational Hygiene*, in preparation, to be submitted mid-2004.