Department of Environmental Health Sciences
UCLA School of Public Health
10833 LeConte Avenue
Los Angeles, CA 90095-1772

PB2001-100519

Inhalation and Sampling of Large Particles, 10-150 μm

PI: William C. Hinds, ScD, CIH

5 RO1/OH03196

Final Performance Report

December 23, 1998

Table of Contents

List of Abbreviations

AC	Alternating current
ACGIH	American Conference of Governmental Industrial Hygienists
CEN	Comite Europeen de Normalization
CMAD	Count median aerodynamic diameter
EPDM	Ethylene propylene polymer
IPM	Inhalable Particulate Matter
IPM-TLV	Inhalable Particulate Matter - Threshold Limit Value
ISO	International Standards Organization
Kr-85	Krypton-85
MMAD	Mass median aerodynamic diameter
NBS	National Bureau of Standards (now National Institute for Standards and Technology)
PVC	Polyvinyl chloride
TLV	Threshold Limit Value

List of Figures

List of Tables

Significant Findings

Specific Aim 1.

Measured orientation-averaged inhalability for mouth breathing agrees with ACGIH IPM criteria in the particle size range 0 - 30 µm, but is lower in the particle size range > 30 µm. Inhalability is not significantly affected by breathing rate over a range of tidal volumes from 0.72 to 1.62 L or by air velocity over the range 0.4 to 1.6 m/s. Average values of inhalability for d_a > 70 µm agree with theoretical estimates of the large particle limit for relative inhalability. Facing-the-wind inhalability showed a plateau from 20 to 116 µm at about 80% with no clear pattern for breathing rate or air velocity. All measurements of inhalability showed a decline in inhalability for the largest particle size, 141 µm, compared to 116 µm. To complete Specific Aim 1 it was necessary to redesign the aerosol delivery system and to develop a new ion generator design that reduced the electrostatic charge on the particle to acceptable levels.

Specific Aim 2.
Orientation-averaged nose inhalability was 4 - 7% for aerodynamic diameters of 40 to 140 µm. This is much less than orientation-averaged mouth inhalability for $d_a > 40$ µm. Facing-the-wind inhalability for nose breathing for $d_a > 50$ µm ranged from 2 to 27% and showed greater variability.

Specific Aim 3.
A liquid particle generation and measurement system was developed. It uses a vibrating orifice aerosol generator to generate oleic acid test aerosol droplets from a solution of oleic acid, uranine dye, acetone , and methanol. Aerosol charge is controlled by induced charge at the exit of the generator. The system has sufficient sensitivity for inhalability and sampler performance measurements with a 16 minute wind tunnel run.

Specific Aim 4.
Liquid particle inhalability measurements not yet done due experimental delays, see Introduction Section.

Specific Aim 5.
Measurement of personal sampler performance have been made for solid particles for eight configurations of personal samplers, including the effect of sampler orientation of the sampler inlet on the body. Analysis of the data are not yet complete. Preliminary results for 37-mm filter cassettes and the IOM personal inhalable sampler are given in the Body of the Report Section. A comparison study of a stationary simplified mannequin and a rotating full-sized mannequin has been conducted. Both show reasonable agreement with the ACGIH criterion, but show different trends in collection efficiency with air velocity.

Usefulness of Findings
For all Specific Aims.
Having more accurate and extensive data on inhalability for mouth and nose breathing, and personal inhalable sampler performance, will help industrial hygienist, researchers, persons setting occupational health standards, companies manufacturing personal sampling devices, and regulators.

Specific Aim 1.
Future measurements of inhalability will be simplified because of our data that shows that inhalability is insensitive to breathing rate and air velocity over the range tested. The concept of a large particle limit on inhalability introduced in this study provides a useful benchmark for exposure assessment and standard setting. The ion generator design for neutralizing high concentration, high charge aerosols will be useful to others working with such aerosols.

Specific Aim 2.
Nose inhalability data provide useful information, not previously available, for exposure assessment and standard setting.

Specific Aim 3.
The liquid particle generation and measurement system design will provide a useful method for others doing experimental studies of this type.

Specific Aim 5.
Data on the performance of personal samplers will be useful to industrial hygienist, researchers, persons setting occupational health standards, companies manufacturing personal sampling devices, and regulators. Data on advantages and limitations of the use of a stationary, simplified mannequin for personal sampler performance studies will help reduce the size, complexity, and expense of evaluating the performance of these samplers for large particles.

Abstract
This research seeks to better define particle inhalability, the fraction of ambient particles that are inhaled as a function of particle size, breathing conditions, and ambient air velocity and direction. Inhalation of large particles (10-150 μm) such as heavy metals, pesticides, radioactive materials, pharmaceuticals, wood dust, or corrosive materials, have a local or systemic toxicity that poses a health risk regardless of where in the respiratory tract they deposit. Inhalability is sensitive to the direction and velocity of the ambient air motion as well as particle size. This research also seeks to better define the collection characteristics of eight types of personal inhalable samplers as a function of particle size and air velocity. More complete information of inhalability and inhalable particle personal sampler performance is needed to correctly assess the health risks of exposure to large particles and to set occupational standards for such particles.

Measurements of inhalability and sampler performance were made for solid particles using an open cycle, closed-jet, low-velocity wind tunnel having a 1.6 × 1.6 m cross section. Tunnel air velocities were 0.4, 1.0, 1.6 m/s. A life-size, full-torso mannequin was modified to collect the airborne particles entering the mouth or nose. The inhalation path was connected to a mechanical breathing machine, which simulated human breathing with minute volumes of 14.2, 20.8, and 37.3 L. The mannequin was either facing the wind or rotated slowly (0.06 rpm) with respect to the wind direction. Personal samplers were attached to the mannequin in its breathing zone. Test aerosols were produced by resuspension and charge neutralization of nine sizes of sieved aluminum oxide powders. Mass median aerodynamic diameters of the test aerosols ranged from 7 to 141 μm. Dust concentration at the test section was determined by three isokinetic samplers. It ranged from 50 to 200 mg/m^3. Room turbulence was removed by screens and honeycomb panels at the tunnel inlet. Controlled turbulence was introduced by a biplanar lattice. At the test section air velocity was uniform to within 10% and dust concentration was uniform to within 15%.

Measured orientation-averaged inhalability for mouth breathing agrees with ACGIH IPM criterion in the particle size range 0 - 30 μm, but was lower for particles greater than 30 μm. Inhalability is not significantly affected by breathing rate over a range of tidal volumes from 0.72 to 1.62 L, or by air velocity over the range 0.4 to 1.6 m/s. Average values of inhalability for $d_a > 70$ μm agree with theoretical estimates of the large particle limit for relative inhalability. Facing-the-wind

inhalability showed a plateau from 20 to 116 μm at about 80% with no clear pattern for breathing rate or air velocity. All measurements of inhalability showed a decline in inhalability in the particle size range of 116 to 141 μm. Orientation-averaged nose inhalability was 4 - 7% for aerodynamic diameters of 40 to 140 μm. This is much less than orientation-averaged mouth inhalability for d_a > 40 μm. Facing-the-wind inhalability for nose breathing for d_a > 50 μm ranged from 2 to 27% and showed greater variability than orientation-averaged inhalability. A comparison study of the IOM inhalable sampler performance using a stationary, simplified mannequin and the rotating, full-sized mannequin found reasonable agreement with the ACGIH criterion for both, but showed different trends in collection efficiency with air velocity.

Body of Report with Conclusions

Introduction and Background

Inhalation of large particles, those with aerodynamic diameters from 10 to approximately 200 μm, represents an important potential occupational exposure route that has not been well characterized. Examples of materials having potential adverse health effects in this particle size range include heavy metals, pesticides, radioactive materials, wood dust, and corrosives. Generally, these materials can cause adverse health effects when inhaled regardless of where they deposit in the respiratory system.

Over the past ten years criteria have been recommended that define inhalable fraction in terms of particle size. The International Standards Organization (ISO) and the American Conference of Governmental Industrial Hygienists (ACGIH) have recommended criteria for the sampling of large particles, up to an aerodynamic diameter of 100 μm (ISO, 1981; ACGIH, 1985). Similar criteria have been adopted by the Comite Europeen de Normalisation (CEN) of the EEC. The ACGIH TLV committee has defined Inhalable Particulate Mass TLVs (IPM-TLVs) based on the ACGIH criteria (ACGIH, 1998).

The physics describing the process of inhaling large particles is extremely complex. Whether or not a large particle can be inhaled in a given situation depends on the aerodynamic particle size, direction and velocity of ambient air motion, breathing pattern of the worker, and on the geometry of the mouth, face, head, and torso. The presence of clothing or headgear may also affect inhalability. To reduce the number of variables and make results more tractable, inhalability results are usually given as "orientation averaged" results, that is, an average value with all horizontal wind directions equally represented.

At present there are no theoretical ways to predict inhalability with acceptable accuracy. Despite recent concern for this type of exposure, we have only limited data on what fraction of particles of a particular size, in the 10 - 200 μm size range, are inhaled for a given condition and even less information on the performance of personal samplers in this size range. There are several reasons why the data for inhalability and sampling performance for large particles are limited. First the process of inhalation or entry into a sampler takes place in the external environment with its complex and ever changing flow field around a person. This makes it very difficult to get meaningful and generalizable data from field measurements. The complexity of the flow field around a person renders theoretical solutions, even advanced programs run on supercomputers, ineffective at defining inhalability or sampler performance. Measurements of these parameters are best made under simulated industrial conditions, such as in a low velocity wind tunnel, where particle size, wind velocity and direction, and breathing rate can be carefully controlled.

Because of the complexity of the flow field around a worker, performance of IPM personal samplers must be evaluated under simulated use conditions, that is, attached to a mannequin in a wind tunnel where air motion and particle size can be controlled. There is also a need to evaluate the performance of traditional personal sampling devices to interpret existing exposure data in terms of inhalable criteria. Theoretical solutions for samplers of simple geometry have been obtained for isolated samplers. Such solutions, however, are not useful for predicting sampler performance when the sampler is mounted on a person because of the complex flow field around a person.

Previous work

Ogden and Birkett (1977, 1978) made the first inhalability measurements with a head and shoulders mannequin in a chamber and a small wind tunnel. Measurements were made for 10 - 30 µm particles at 0 to 2.75 m/s wind velocity. They used liquid particles and steady flow into the mouth. Results were averaged over all orientations with respect to the wind direction.

A study by Armbruster and Bruer (1982) used a head mannequin in a small tunnel at 1 to 8 m/s. A polydisperse coal dust aerosol was used. Coulter analysis of "inhaled" and free stream samples gave orientation averaged inhalability up to 60 µm. Three breathing rates were used.

A paper by Vincent and Mark (1982) provides the most extensive data. A full torso mannequin was used to obtain orientation averaged inhalability. Narrow distribution solid particles with a size range of 10 to 100 µm were used. Wind speeds ranged from 1 to 4 m/s and an inhalation-only breathing cycle was used.

Few data are available for the performance of area or personal samplers for particles larger than 30 µm. The available data on various "total" dust samplers show them to be highly variable, and dependent on whether they are isolated or mounted on a person. In general they do not sample either total dust or inhalable dust accurately.

The 37 mm open face and in-line plastic cassettes, commonly used in the United States, have been evaluated by Fairchild (1980) and McCawley (1983). Results indicate that these samplers oversample when used as isolated samplers at 2 Lpm and undersample when worn with the inlet facing down at an angle on a person. The air flow field near the sampler is quite different when a sampler is isolated or is attached to a person or a mannequin. Kenny et al (1997) gives results from a major CEN study on sampler performance of eight types of personal samplers for particle sizes up to 100 µm. They tested samplers on a mannequin at air velocities of 0.5, 1.0, and 4.0 m/s. All samplers tested showed significant departures from the ISO criterion at either high or low air velocity or both.

The samplers showing the closest agreement with inhalability data are an area and personal sampler developed at the Institute for Occupational Medicine (IOM) in Edinburgh, UK (Mark et al., 1985; Mark and Vincent, 1986). The area sampler operates at 3 Lpm. It has a rotating head with an inlet designed so that particles captured on the sides of the inlet can be weighed along with the filter. The personal sampler mounts on the chest with its 15 mm diameter inlet facing forward. Orientation averaged performance of these samplers are within 20% of the ACGIH inhalability curve over the size range of 10 to 100 µm.

Overall objective

The overall objective of this proposal is to improve our knowledge and understanding of the inhalation of large particles, those in the 10 to 150 µm aerodynamic diameter size range, and to evaluate current and modified personal samplers for their ability to sample these particles accurately under simulated industrial conditions.

Specific Aims

1) Using the UCLA low velocity wind tunnel, make measurements of inhalability (mouth) for solid particles as a function of ambient air velocity, orientation of the mannequin relative to the direction of air motion, aerodynamic particle size (10-150 µm), and mannequin breathing pattern (work rate).

2) Using the UCLA low velocity wind tunnel, make the measurements given in (1) for nose inhalation for a breathing pattern associated with a work rate of 34 W (208 kg-m/min) and an ambient air velocity of 1.0 m/s.

3) Develop a liquid particle aerosol generator that will produce monodisperse or narrow distribution liquid particles in the size range of 10 to 150 µm for use as a test aerosol in the wind tunnel. The set-up developed for Specific Aim (1) will be used to move the source back and forth and up and down to cover the full tunnel cross section.

4) Conduct measurements of inhalability (mouth and nose) for liquid particles as described in 1) and 2) above.

5) Evaluate the sampling performance of commercially available personal samplers for large solid and liquid particles as a function of ambient air velocity, orientation of the mannequin to the air motion, and aerodynamic particle size (10-150 µm). Samplers to be evaluated will include 37 mm in-line, 37 mm open-face, IOM personal, Marple personal cascade impactor, and modified 37 mm filter cassettes.

Accomplishments.

All specific aims have been completed except for the inhalation and sampling of liquid particles in Specific Aims 4 and 5. These were not completed because of delays, totaling nearly two years, due to our reassessment of the experimental system as described below.

Initial measurements of inhalability showed a leveling off for large particles at about 25%. Because our results differed significantly from those of other investigators, who found inhalability leveling off at about 50%, we embarked on a major reassessment of every aspect of our experimental system. We needed to be sure that the observed differences in inhalability were not due to any artifact or short coming in our experimental setup or procedures. Given the nature of the measurements and the experimental system this step was prudent and represents good scientific practice. We were able to identify two potentially significant problems in the experimental system that could have caused low measured inhalability, particle charge on the solid particles and uniformity of aerosol concentration.

To evaluate particle charge we had to develop a system to measure it. The Faraday-cup isokinetic sampler and the electrometer described in the Experimental Section were fabricated and purchased. Particle charge was found to be very high so a search was undertaken to find a way to reduce it to acceptable levels. This eventually led to the ion generator described in the Experimental Section.

A second problem was the design of the original multi-outlet aerosol distribution manifold could allow gaps between regions of uniform aerosol concentration in the vicinity of the mannequin. Several attempts to improve the manifold failed, so a different approach was taken. The three outlet nozzles were put adjacent to each other on a sliding nozzle assemble and driven back and forth as well as up and down as described in the Experimental Section. This worked well for both the solid and liquid particles. Another modification was changes to the mounting system for the mannequin. The base support was changed from a turntable to a hollow shaft supported by ball bearings. This eliminated the jerky motion and enabled the rotation to be controlled by a computer controlled stepping motor. The latter was located under the wind tunnel. Together these changes took nearly two years, but improved the experimental system's accuracy and reliability.

Experimental

A key feature of this research is a specially designed low velocity wind tunnel that allows the simulation of the air motion and turbulence that occurs in industrial settings. The details of the wind tunnel are given in Hinds and Kuo (1995). Main features and changes since Hinds and Kuo (1995) are summarized here.

The UCLA inhalable particle test facility is a low velocity open-cycle, closed-jet wind tunnel, shown in Figure 1. Its cross-section is 1.6 m square and its length is about 8 m. It is powered by a 11,000 cfm (310 m^3/s) fan. A radial blade damper on the fan inlet is used to control the air velocity in the tunnel over the range of 0.1 to 2 m/s. This range covers the air velocity found in most indoor occupational exposure environments.

The inlet section has a bell-mouth, a layer of screen, and a layer of honeycomb to provide a

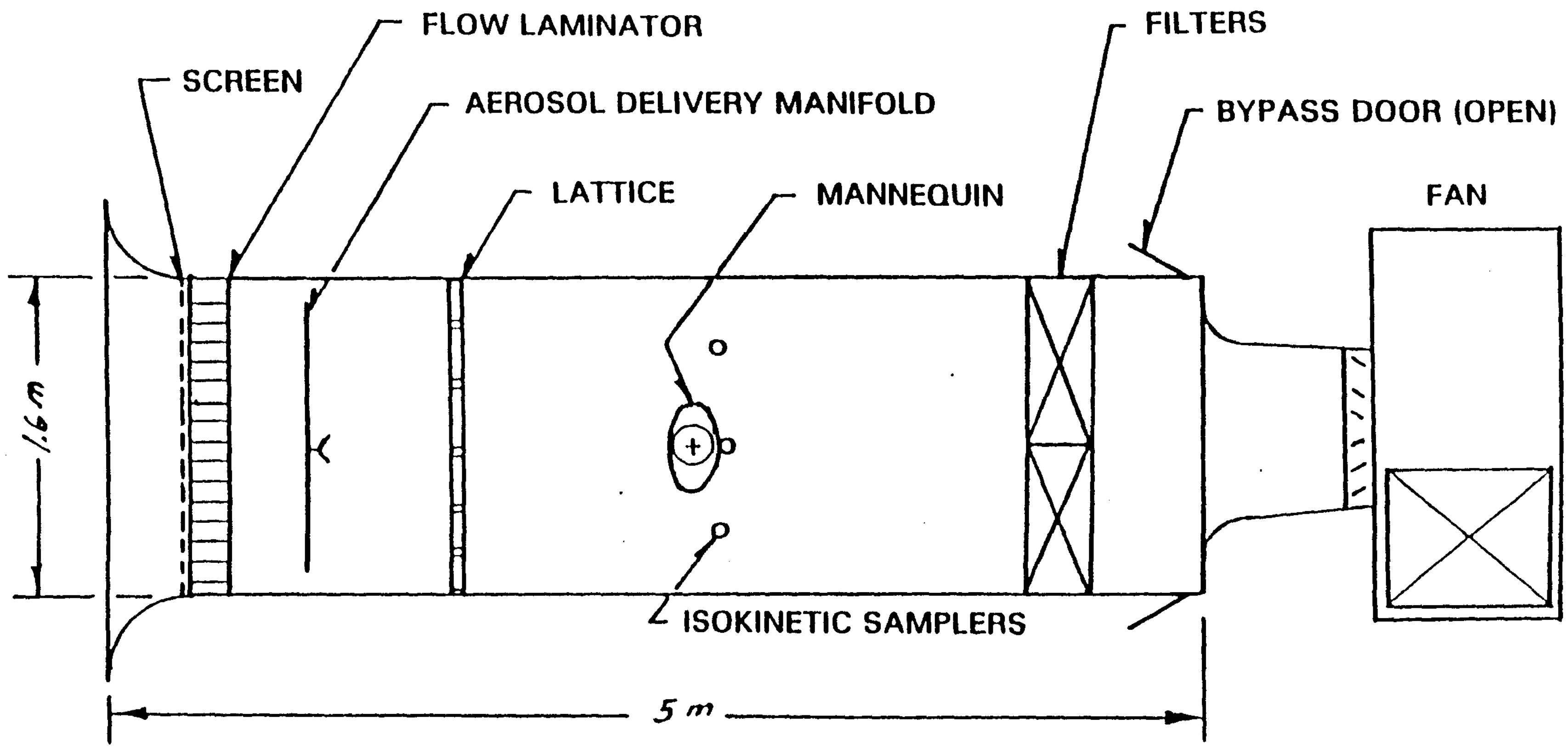

Figure 1. Diagram of low velocity wind tunnel.

uniform velocity profile and to remove room turbulence from the air stream. This is followed by the aerosol generation and delivery section, described below. The dust laden air passes through a wooden lattice (vertical and horizontal 25 × 25 mm strips on 130 mm centers) to add a controlled amount of turbulence to the air stream. The test mannequin and isokinetic samplers are positioned about 1 m downstream from the lattice. The final section contains an air cleaning filter bank, air flow control damper, fan, and muffler.

Air velocity in the tunnel is uniform to within 10% across the test section. Turbulence intensity can be controlled over the range of 4 to 14%. The results described here were obtained for turbulence intensities of less than 5%.

The test aerosol material was resuspended aluminum oxide optical abrasive powder. Nine sizes were used with mass median aerodynamic diameters (MMAD) ranging from 7 to 141 μm. The larger sizes were sieved to narrow the size distributions so that the geometric standard deviations for all sizes were less than 1.36. The dust was dispersed by three NBS type dust feeders (see Hinds, 1999) mounted on top of the wind tunnel. The aerosol passed through three 25 mm conductive rubber tubes to a traveling distribution nozzle assemble located in the tunnel. The nozzle moves back and forth every 6 seconds and up and down at 4 - 10 cm/s to cover the entire cross-section of the wind tunnel and produce a uniform concentration in the tunnel. Using a 11-point array of isokinetic sampling filter holders, the aerosol concentration at the test section was found to be uniform within ±15% over the central 80% of the cross-sectional area. Concentration was stable within 10% over time. Supply air to the aerosol generator was humidified to approximately 50% relative humidity to reduce electrostatic effects.

An ion generator was developed to neutralize the concentrated streams of large, highly charged, particles. Neutralization to less than ±10,000 charges per particle was necessary to prevent electrostatic sampling artifacts. Neutralization with radioactive sources would have required an impractically large source. The ion generator, shown in Figure 2, constructed from 21 and 32 mm PVC pipe, has four peripheral radial electrodes of 0.5 mm tungsten wire and a 2.0 mm diameter central electrode. The aerosol flowed through the ion generator along its axis. The ion generator was powered by a Richmond Static Control Model AB-250 power supply with adjustable output voltage of 0-8.5 kV. Performance of the ion generator was monitored with an isokinetic Faraday-cup sampler, shown in Figure 3, connected to a Keithley Model 6512 electrometer capable of 0.1 fA resolution. The sampler used a stainless steel 47-mm filter holder as the Faraday cup. The cup was insulated with Teflon inside a 90-mm diameter stainless steel enclosure with a 21-mm diameter inlet. The isokinetic sampling flow rate was 20.8 L/min for a tunnel velocity of 1.0 m/s.

This setup gave near real time measurement of the charge state of the aerosol in the wind tunnel. By adjusting the ion generator power supply, particle charge could be reduced to less than 2% of its original charge. Ion generator output was sufficiently stable to maintain the particle charge within ± 2% of the original charge over a 1 hr period as shown in Figure 4. These reduced charge levels are comparable to charge levels found on workplace aerosols (Johnston et al, 1985).

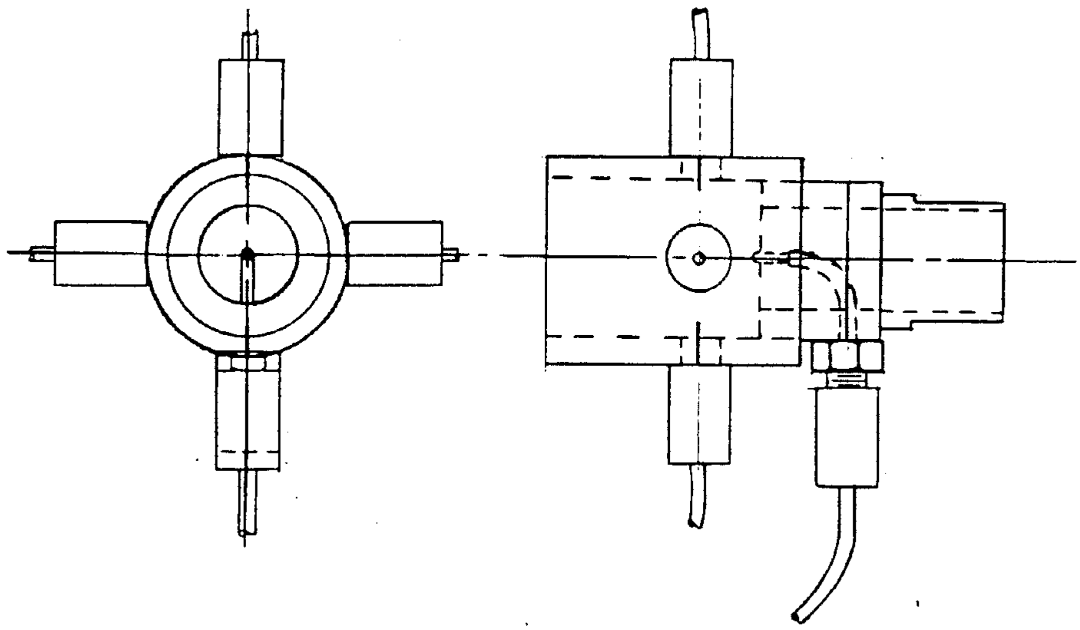

Figure 2. Diagram of ion generator.

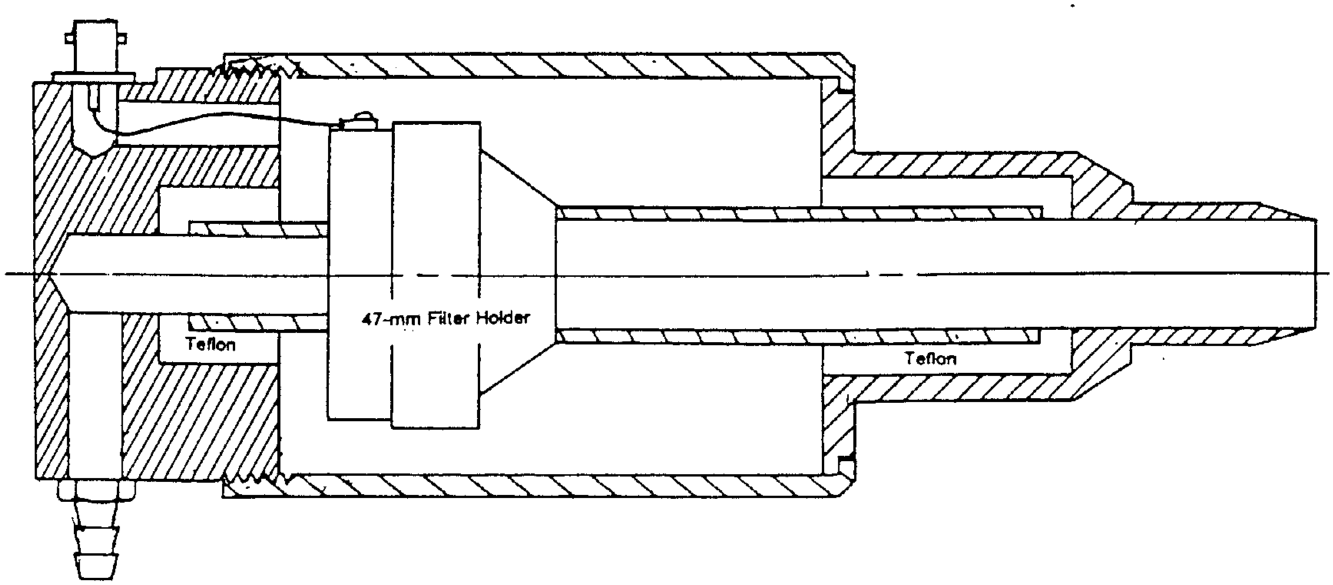

Figure 3. Diagram of Faraday-cup isokinetic sampler.

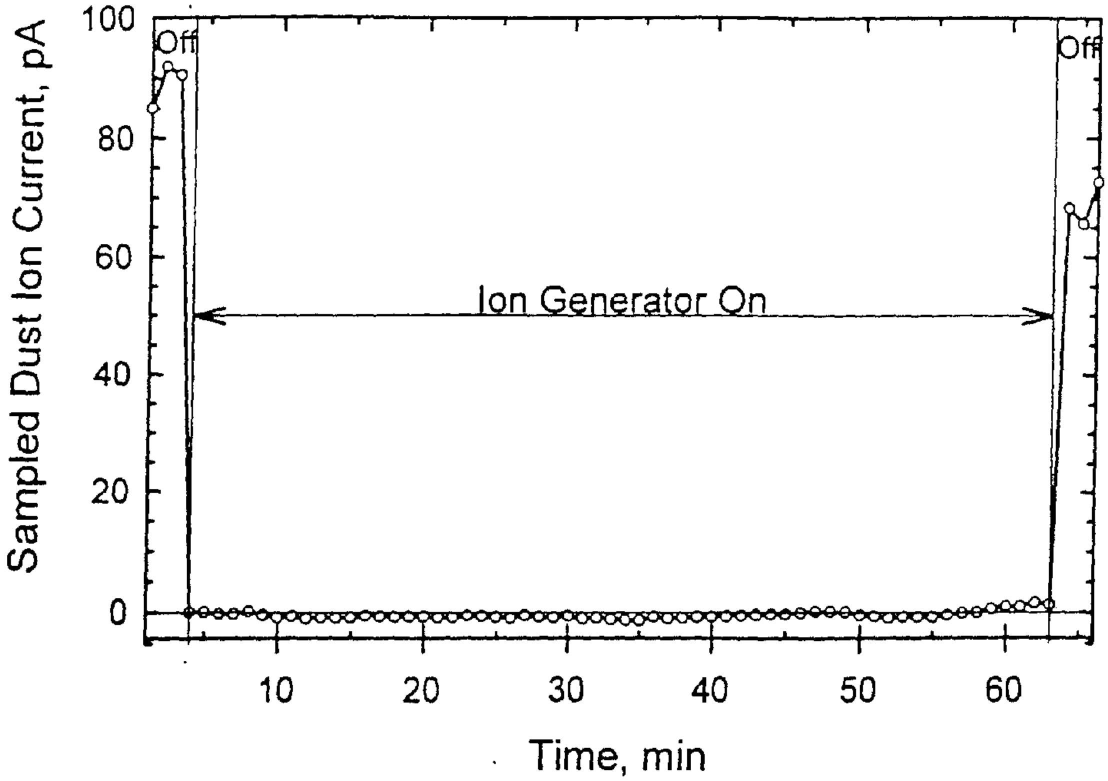

Figure 4. Effect of ion generator on particle charge.

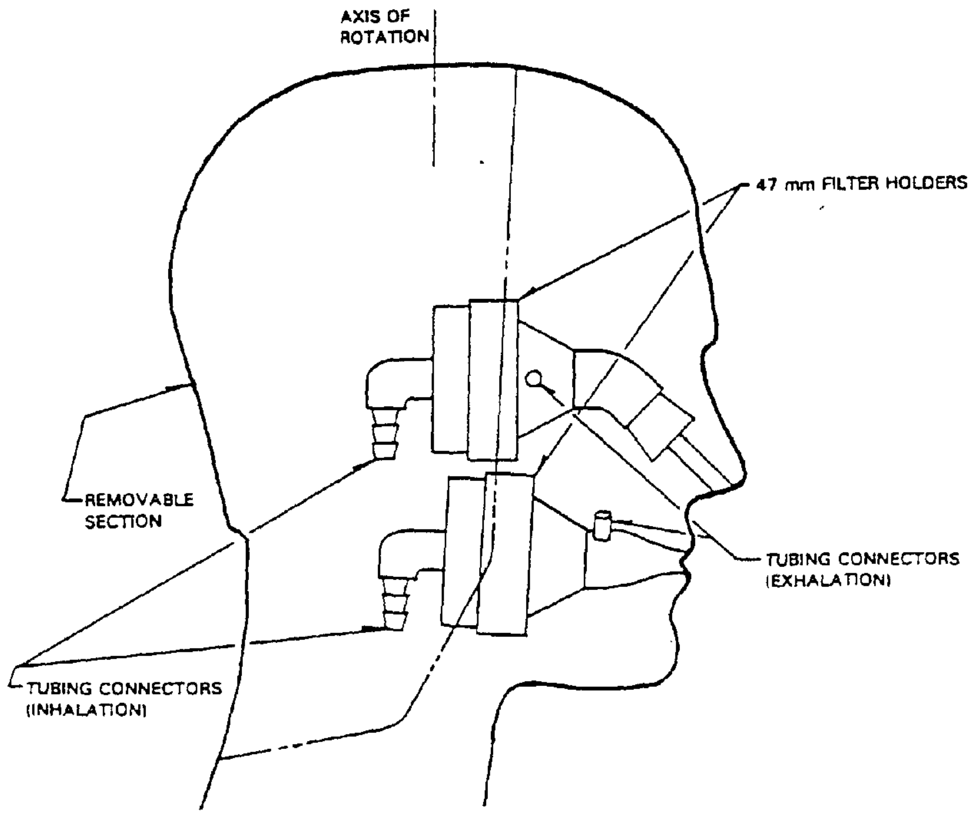

Figure 5. Diagram of mannequin's head.

Aerodynamic particle size was measured by an Aerosizer instrument (Amherst Process Instruments, Inc., Hadley, MA) and checked by direct measurement of settling velocities in air and water. The size distributions were measured by optical microscopy. Results for the nine particle sizes used are shown in Table 1.

Table 1. Size distributions of Al_2O_3 test aerosols.

Designation	CMAD (μm)	GSD	MMAD (μm)
GR 5.5 (Optical Powder)	6.2	1.27	7
GR 9.5 (Optical Powder)	12.9	1.36	17
GR 14.5 (Optical Powder)	19.6	1.21	22
GR 22.5 (Optical Powder)	28.0	1.35	37
GR 29.5 (Optical Powder)	40.6	1.34	52
GR 240	57.4	1.27	68
GR 180 and 240 + sieving at 270/325	77.0	1.16	82
GR 180 and 240 + sieving at 230/270	105.0	1.20	116
GR 180 and 240 + sieving at >230	134.4	1.13	141

Liquid particles were generated with a TSI, Inc. (St. Paul, Mn) vibrating orifice aerosol generator. The generator head was mounted in place of the nozzle assemble and scanned back and forth and up and down as describe above. The final liquid droplets are oleic acid with a fluorescein dye. Initially the oleic acid and dye are dissolved in acetone with about 10% methanol. The methanol in needed to dissolve the dye and the acetone is need for complete evaporation of the solvent by the time the particles get to the mannequin. Liquid particles were neutralized by a controlled induced charge as they left the vibrating orifice. The technique is based on that described by Reischl et al (1977).

A life-size, full-torso fiberglass mannequin was used to simulate a worker. The mannequin obstructs less than 11% of the tunnel cross-sectional area when it is facing-the-wind. It was designed to rotate a full 360° about the vertical axis. The mouth and nose openings connect to 47 mm filter holders mounted inside the head, as shown in Figure 5. The month opening is an oval 6 × 30 mm. The metal connecting tube, 35 mm long, connects the filter holder to the back half of the lips. Inhaled dust deposited on the short inlet connecting tubing is included with the filter sample. A mechanical breathing machine, located external to the tunnel, provides full cycle breathing with a pattern corresponding to that for the three work rates given in Table 2. A return line is connected to the filter inlet tube so that exhalation air is exhaled through the mouth or nose.

Table 2. Characteristics of the three breathing rates used.

Work Rate		Breathing Frequency	Minute Volume	Tidal Volume
(kg·m/min)	(W)	(min^{-1})	(L)	(L)
0	0	19.6	14.2	0.72
208	35	21.2	20.8	0.98
622	105	23.0	37.3	1.62

Personal samplers were positioned on the chest of the mannequin in the usual fashion as shown in Figure 6. Samplers used were the IOM personal IPM sampler (SKC, Inc.), Marple personal cascades impactor, and 37 mm filter cassettes with 4, 8, 16, and 33 mm inlets. All were operating at 2.0 Lpm. The inlet for the IOM sampler faces forward. The 4 and 33 mm-inlet, 37-mm cassettes were either mounted on a frame and facing forward or attached to the collar and hung down at an angle of 75 to 85° to the horizontal. The 8 and 16 mm inlet 37-mm cassettes were only tested facing forward. Tests were conducted at air velocities of 0.4, 1.0, or 1.6 m/s.

Inhalability and sampler performance were determined gravimetrically. Three isokinetic samplers were positioned on either side and above the head to measure the aerosol concentration in the tunnel as shown in Figure 6. Inhalability was calculated as the ratio of mass concentration determined by the mouth samplers to that determined by the isokinetic samplers. Sampler performance was calculated as the ratio of mass concentration determined by the personal samplers to that determined by the isokinetic samplers. Three replications were conducted at each test condition.

There were 36 run for each particle size and there were nine particle sizes for a total of 288 runs for solid particles. Each orientation-averaged run lasts 16 minutes and each facing-the-wind run lasts 8 minutes. There were two orientations with respect to the air motion, facing-the-wind and continuous rotation (orientation averaged). For mouth breathing there were three air velocities 0.4, 1.0 and 1.6 m/s and three breathing rates corresponding to sedentary, light work, and moderately heavy work. Each condition was repeated three times. Conditions were the same for nose breathing except only one air velocity and breathing rate was used. For each particle size and mannequin breathing rate runs were randomly sequenced.

As part of Specific Aim 5 we conducted a study comparing the use of a stationary simplified mannequin, as proposed by Witschger et al (1998), instead of the full-size, rotating mannequin, as used for all other test in this study. The simplified mannequin, shown in Figure 7, was fashioned from a plastic waste basket (Model 2956, Rubbermaid, Inc., Wooster, OH). It has a three-dimensional body with rounded corners. The dimensions are 33 cm wide x 20 cm deep x 20 cm high. During sampling, it replaced the full-size mannequin in the wind tunnel, but did not rotate.

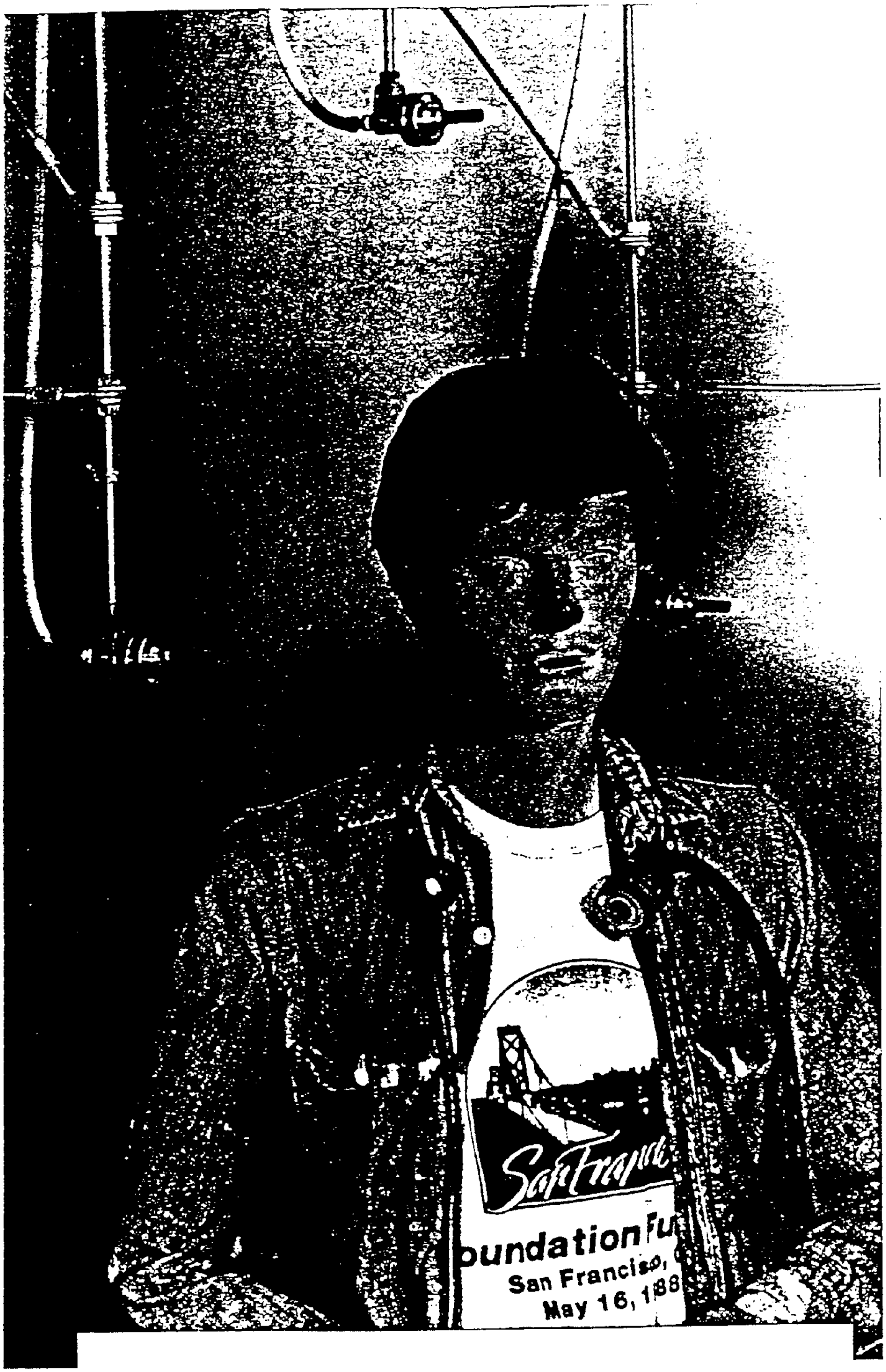

Figure 6. Photograph of mannequin and isokinetic samplers.

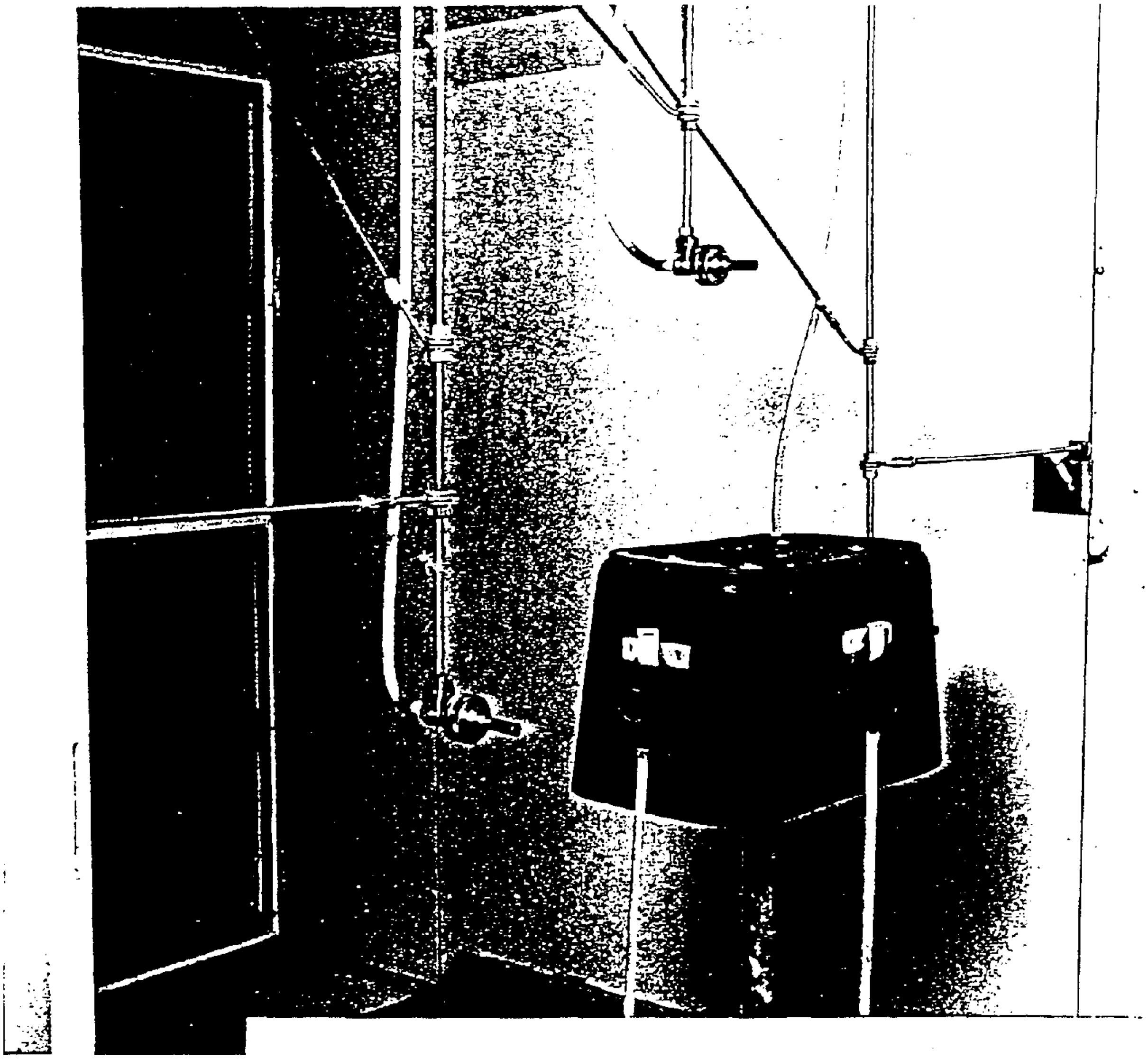

Figure 7. Photograph of simplified mannequin and isokinetic samplers.

To measure the aerosol concentration in the wind tunnel, three isokinetic samplers were positioned 30 mm to the sides and top of the head of the full-size mannequin or the "body" of the simplified mannequin.

Sampler performance for a commercially-available IOM personal sampler (Mark and Vincent, 1986) was evaluated by placing it either within the breathing zone of the full-size mannequin or in the center of each vertical side of the simplified mannequin. Orientation-averaged results for the simplified mannequin were then calculated using the values for 0°, 90° and 180° with respect to wind direction. The IOM samplers were operated at a sampling flow rate of 2.0 L/min and were fitted with 25-mm glass fiber filters.

Five narrowly-distributed particle sizes (GSD < 1.35) were used. The test dust was Al_2O_3 optical powder (General Abrasives/Treibacher, Inc., Niagra Falls, NY) and the aerodynamic diameters were 7, 22, 52, 82 and 116 µm. To minimize electrostatic effects, the supply air to the aerosol generator was humidified and an adjustable ion generator was used to mix unipolar ions with the aerosol stream (Hinds and Kennedy, 1998). The mass concentration in the wind tunnel ranged from 50-200 mg/m^3 and varied with the size of dust used.

Aspiration efficiency was determined by comparing the average mass concentration determined by the personal sampler(s) to that measured by the isokinetic samplers. The performance of the samplers on the simplified mannequin was then compared to the performance of the same sampler on the full-size mannequin. Using five sizes and three wind velocities gave a total of 15 sampling conditions. Three replications for each set of conditions were performed.

Results and Discussion

Specific Aim 1.

Figure 8 shows combined results for all orientation-averaged mouth inhalability runs. Also shown is the ACGIH and ISO inhalable fraction sampling criterion, which goes only to 100 µm and is undefined for larger particle sizes. The data show a similar shape to the criterion, but plateaus at an inhalability of about 30% at 80 µm. Also shown in Figure 8 is the theoretical large particle limit for relative inhalability for the three air velocities used. This is the expected relative inhalabilty for large particles that travel in a perfectly straight line. This assumes that inhalability is 100% when the mannequin is facing-the-wind and particles are traveling in horizontal straight lines. Neglecting particle settling the inhaled concentration is

$$C_I = \frac{Mass\,Inhaled\,/\,s}{Volume\,Inhaled\,/\,s} = \frac{C_m \times V \times A\,\cos\theta}{Q}$$

where C_m is the mass concentration, V the air velocity, A the mouth opening area, Q inhaled volumetric flow rate, and θ the angle in radians between the mouth axis and the wind direction. The relative inhalable fraction IF_{rel} is the ratio of the inhaled concentration relative to that for facing-the-wind. For continuous rotation

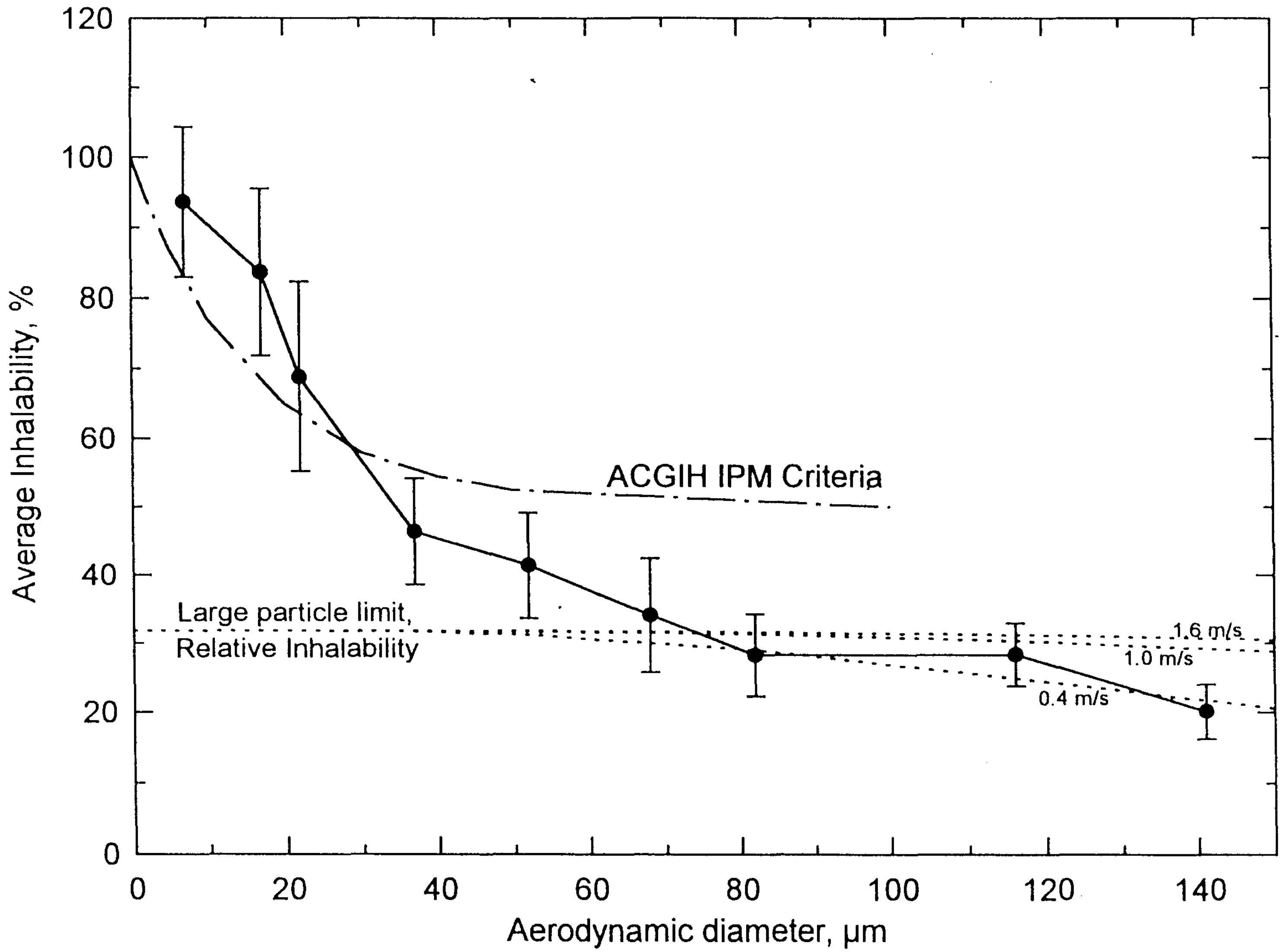

Figure 8. Orientation-averaged inhalability for mouth breathing. Combined data.

$$IF_{rel} = \frac{1/\pi \int_0^{\pi/2} C_I(\theta)\,d\theta}{C_I(\theta = 0^\circ)}$$

where IF_{rel} is 0 for $\theta > \pi/2$. For the largest particles at the lowest air velocities the particles do not travel horizontally so inhaled concentration is reduced by cos ϕ, where ϕ is the downward angle of the straight-line trajectory of the particle due to its settling velocity relative to the wind velocity.

$$\phi = \arctan\left(\frac{V_{TS}}{U}\right)$$

Inhalability results shown in Figure 8 show good agreement with the theoretical large particle limits for particles larger than 60 μm in aerodynamic diameter.

The reason for the inhalability leveling off at 30% instead of at 50% as found by other investigators is unclear, but some possible explanations follow. (1) Orientation-averaged inhalability is strongly influence by the large inhalability at a narrow range of angles around 0°. Continuous rotation gives the proper weight to this component whereas averaging measurements at fixed angles of 0°, 45°, 90°, etc. (as done by previous investigators) tends to give greater weight to the 0° inhalability condition. (2) Charge neutralization could have a significant effect on inhalability results. Previous investigators did not neutralize particle charge. They observed accumulation around the mouth, which may have been knocked off into the mouth by collision with incoming particles. Also they felt that particle may have bounced into the mouth. (3) In our experiments exhalation was through the mouth (or nose in the case of nose breathing). This creates a low concentration region in front of the mouth at the beginning of the next inhalation when facing the wind and thus could lower measured inhalability. Previous investigators did not exhale through the mouth. (4) Given the complexity of the experimental system, it is likely that inhalable fraction measurements are somewhat apparatus specific for unknown reasons.

Figure 9 shows the measured orientation-averaged inhalability at three air velocities. Breathing rate is the same for each line shown. Data at 0.4 m/s go only as far as 116 μm, because the settling effect precluded measurement of inhalability for larger particles at this low air velocity. There is no clear pattern with air velocity and within the accuracy of the measurements one can conclude that inhalability is independent of air velocity over the range 0.4 to 1.6 m/s.

Figure 10 shows orientation-averaged inhalability results for three breathing rates at an air velocity of 1.0 m/s. Again there is no clear pattern, although the middle breathing rate seems to give higher inhalability that the others for particles in the 60 - 116 μm range. It is unclear why this should be so.

Unlike previous investigators who only evaluated inhalability out to 100 μm, our results show a

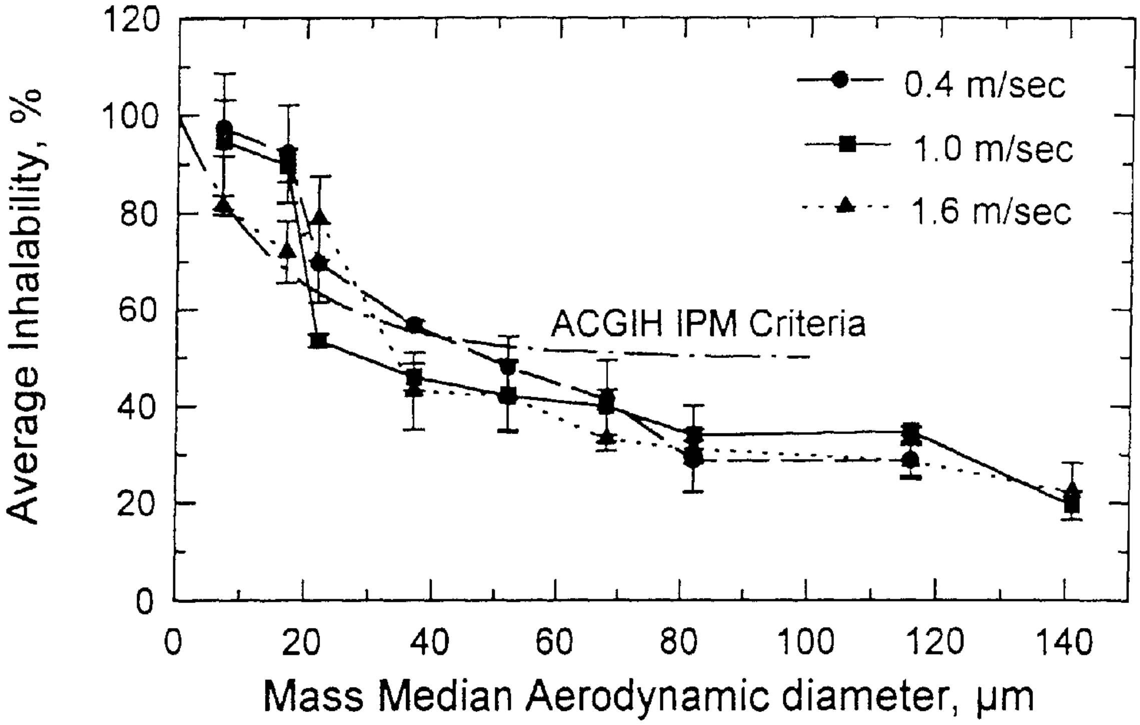

Figure 9. Orientation-averaged inhalability for mouth breathing at a tidal volume of 0.98 L.

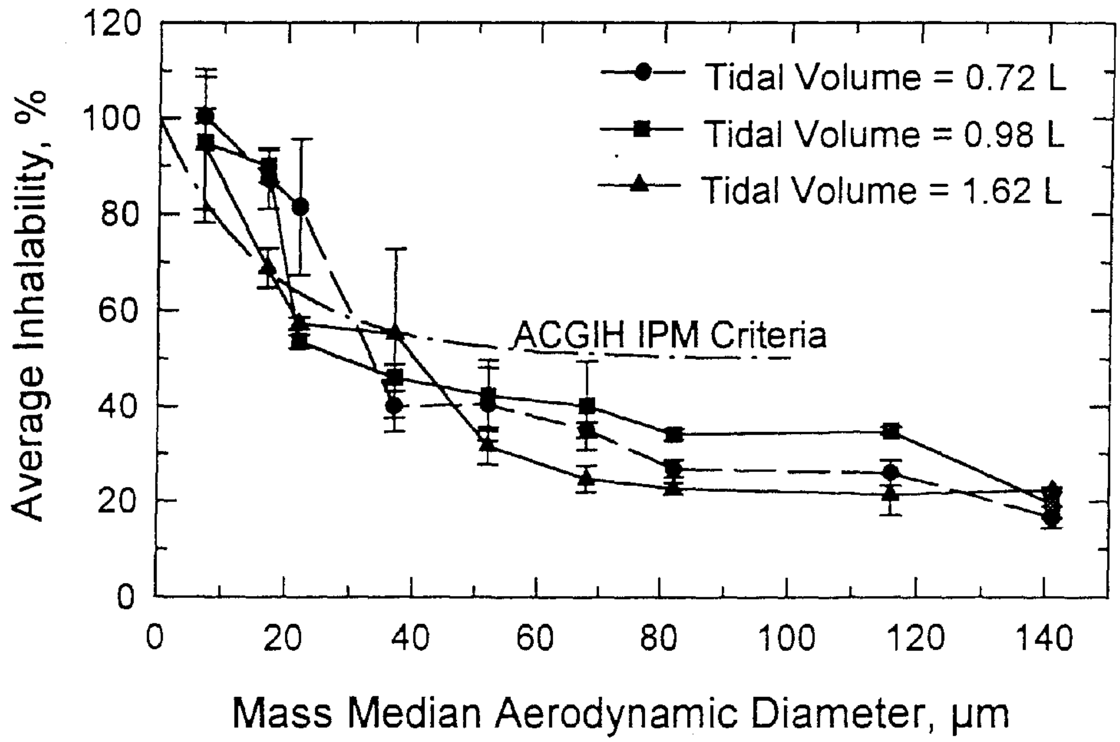

Figure 10. Orientation-averaged inhalability for mouth breathing at an air velocity of 1.0 m/s

consistent decrease in inhalability between the 116 μm and 141 μm aerodynamic sizes. This may be a manifestation of the theoretical decrease in inhalability expected for the largest particles described above.

Figures 11-13 shows inhalability results for the facing-the-wind orientation. Figure 11 gives combined results for all breathing rates and air velocities for mouth breathing. Similar combined results are also given for nose breathing. Results show more variability than for orientation-averaged results. The mouth breathing results show inhalability decreasing from approximately 100% for the smallest particles to about 80% for particles from 30 to 120 μm and decreasing further for larger particles. There are no published data in this size range to compare these results to.

Figure 12 shows the facing-the-wind inhalability for mouth breathing for three air velocities at the intermediate breathing rate. Inhalability for particles larger than 70 μm shows a pattern of greater inhalability at greater air velocity. This and the downward slope of the inhalability curves for particles larger than 116 μm may be a result of the settling velocity effect described above.

Figure 13 gives mouth inhalability results for facing-the-wind for three breathing rates at an air velocity of 1.0 m/s. One can not conclude from these results that breathing rate has any affect on inhalability. The results for the largest particle size show the consistent downward slope observed for other conditions.

Specific Aim 2.
Figure 14 shows measured orientation-averaged inhalability for nose breathing at the intermediate breathing rate and an air velocity of 1.0 m/s. Inhalability is high, nearly 100% for small particles, but drops abruptly in the 22 to 37 μm range to a nearly constant low value for all larger sizes. It is likely that the nose breathing inhalability for large particles is due to deflection of air and particles upwards and into the nose when facing-the-wind. This is supported by the facing-the-wind results shown in Figure 11, although there is considerably more scatter to the data when facing-the-wind. There are no published data for nose breathing inhalability in this size range for comparison.

For particles larger than 40 μm aerodynamic diameter there is a big difference between the ACGIH criterion and the nose breathing inhalability found here. For these particles the criterion is approximately ten times greater than our measurements of nose breathing inhalability. Our measurements of mouth inhalability are about five times greater than our measurements of nose breathing inhalability. The criterion is, of course, base on mouth breathing, but could greatly over estimate a workers exposure. Basing the criteria on mouth breathing is the appropriate and conservative approach where only a single criterion is used.

Specific Aim 3.
A liquid particle generation and measurement system has been developed. It is described in the experimental section of this report. The method works well and provides precise control of

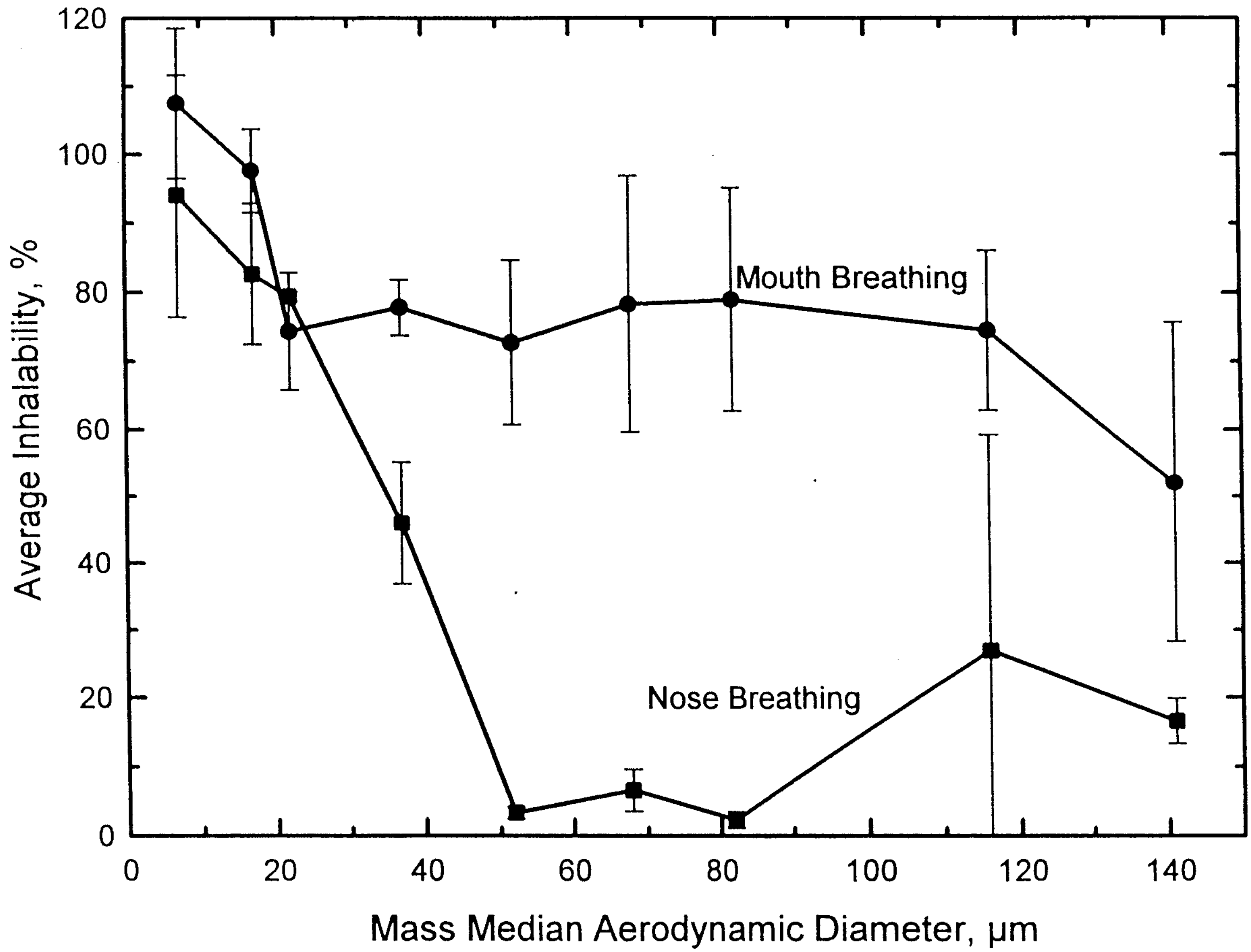

Figure 11. Facing-the-wind inhalability for mouth breathing. Combined data.

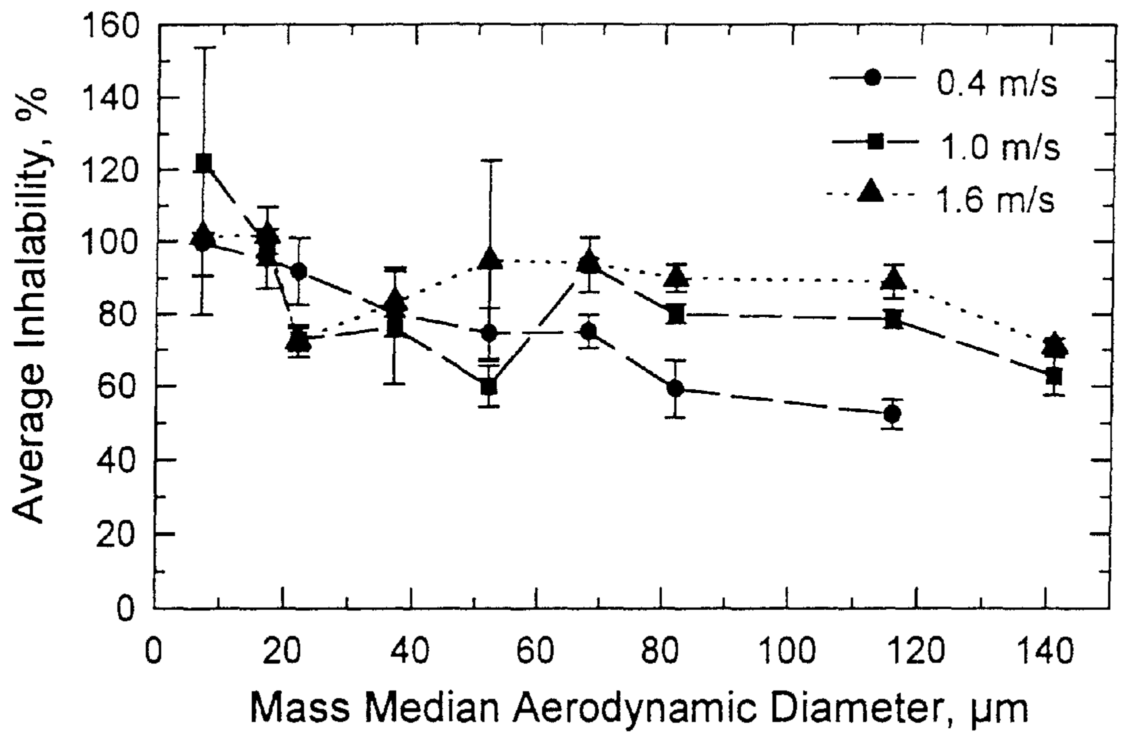

Figure 12. Facing-the-wind inhalability for mouth breathing at a tidal volume of 0.98 L.

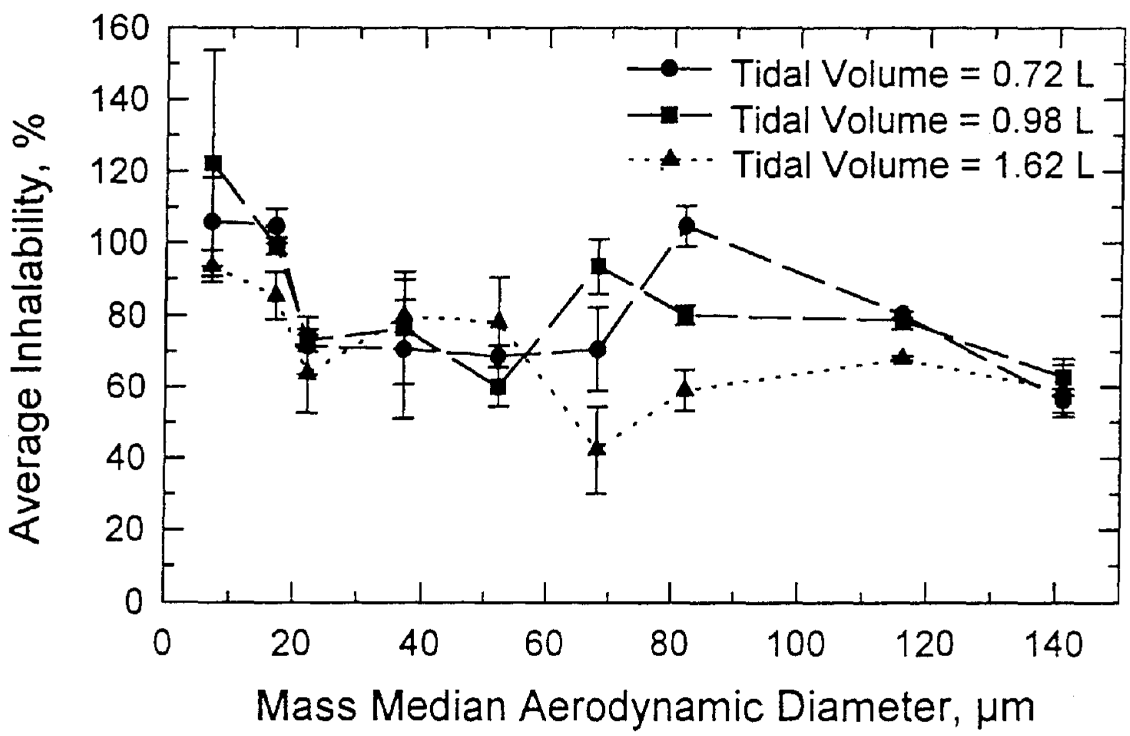

Figure 13. Facing-the-wind inhalability for mouth breathing at an air velocity of 1.0 m/s.

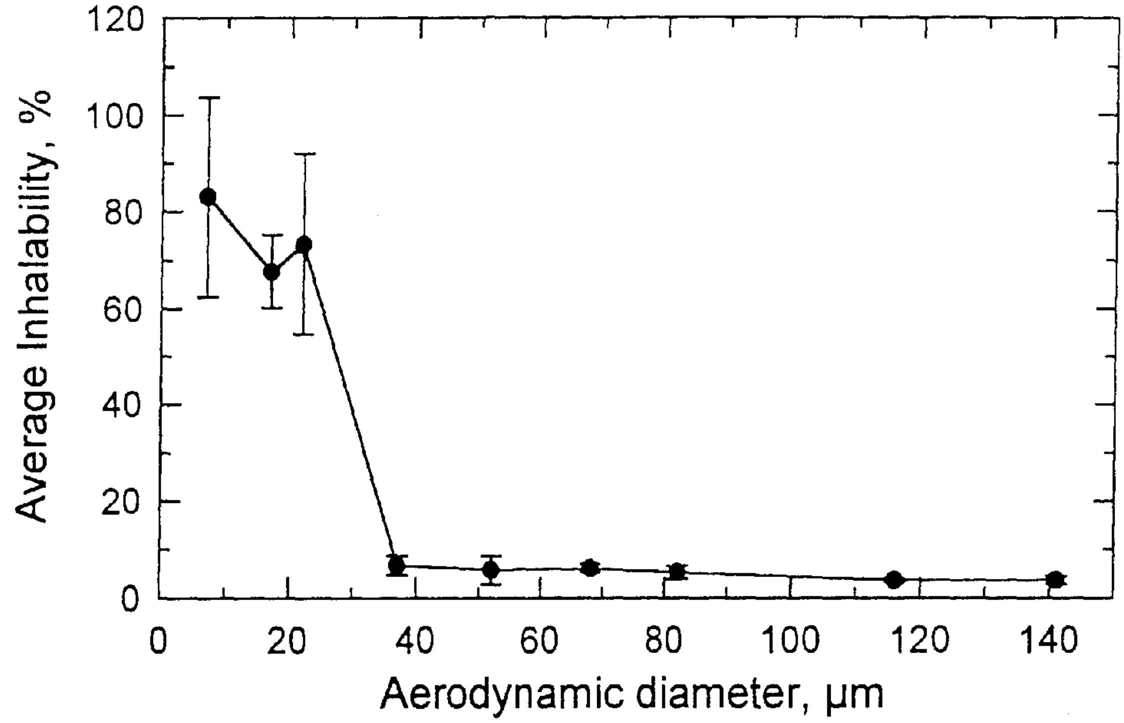

Figure 14. Orientation-averaged inhalability for nose breathing at a tidal volume of 0.98 L and an air velocity of 1.0 m/s.

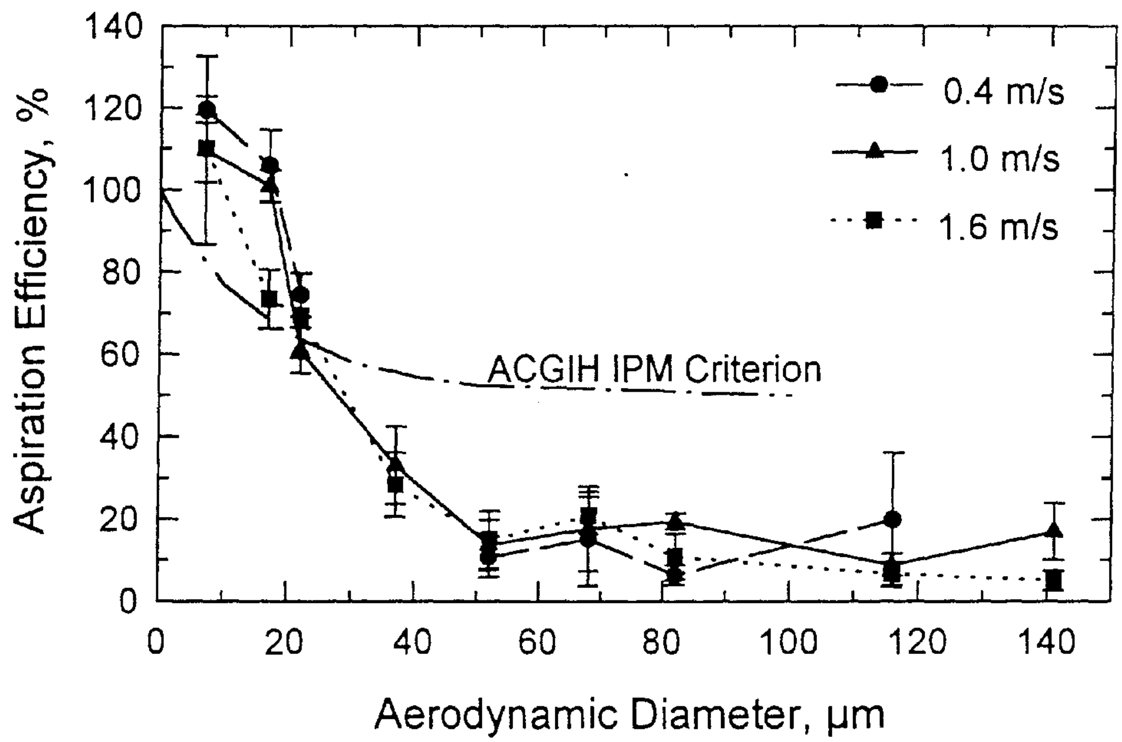

Figure 15. Sampling performance of 37-mm, in-line filter cassettes.

particle size and charge. The collected particles are extracted from the filter in methanol. The fluorescence of the extract is measured at 522 nm for an excitation wavelength of 493 nm. The method provides satisfactory sensitivity for evaluating inhalability and sampler performance for runs of 16 minutes.

Specific Aim 4.
Measurements of liquid particle inhalability have not been done because of the experimental delays described in the Introduction Section. The experiments will be conducted as time permits as part of the doctoral thesis work of Nola Kennedy. The same sequence of runs used for the solid particles will be used, but the number of particle sizes tested will be reduced.

Specific Aim 5.
Measurement of the sampler performance for solid particles for the eight personal samplers configurations have been completed. Analysis of these results is not yet complete, but will be completed in about two months.

Preliminary results for sampler performance are shown in Figures 15 and 16. Figure 15 shows sampler performance for 37-mm, in-line filter cassettes (4-mm inlet) sampling at 2 L/min. Samplers were in their customary orientation in the breathing zone, hanging down from the lapel. As shown in Figure 15, these cassettes significantly undersample for $d_a > 40$ µm. This is likely due to the hanging-down orientation on the mannequin.

Figure 16 shows IOM personal sampler performance at 2 L/min. The IOM sampler shows much better agreement with the ACGIH IPM criterion curve at 1.0 and 1.6 m/s than the 37-mm cassettes, but oversamples for $d_a > 80$ µm at 0.4 m/s.

Results for the comparison study of the full-sized rotating mannequin and the stationary simplified mannequin are complete. Sampler performance for the IOM personal sampler indicated reasonable agreement with the IPM sampling criteria whether the device was mounted on a full-size mannequin, Figure 16, or a simplified mannequin, Figure 17. The two testing configurations show opposite trends with respect to wind velocity (Figures 16 and 17).

Figure 16 shows that aspiration efficiency decreases with increasing wind velocity for samplers placed on the full-size mannequin. When samplers are placed on the simplified mannequin, there is an increase in aspiration efficiency associated with an increase in wind velocity, Figure 17. The effect associated with wind velocity is most significant for particles larger than 50 µm.

Statistical analysis of the data confirms that the aspiration efficiencies of the IOM personal sampler for the two testing configurations are not significantly different ($p < 0.05$) when the wind velocity is 1.0 m/s or less and are significantly different for a wind velocity of 1.6 m/s. Results for the simplified, stationary mannequin show less variability than for the full-sized rotating mannequin.

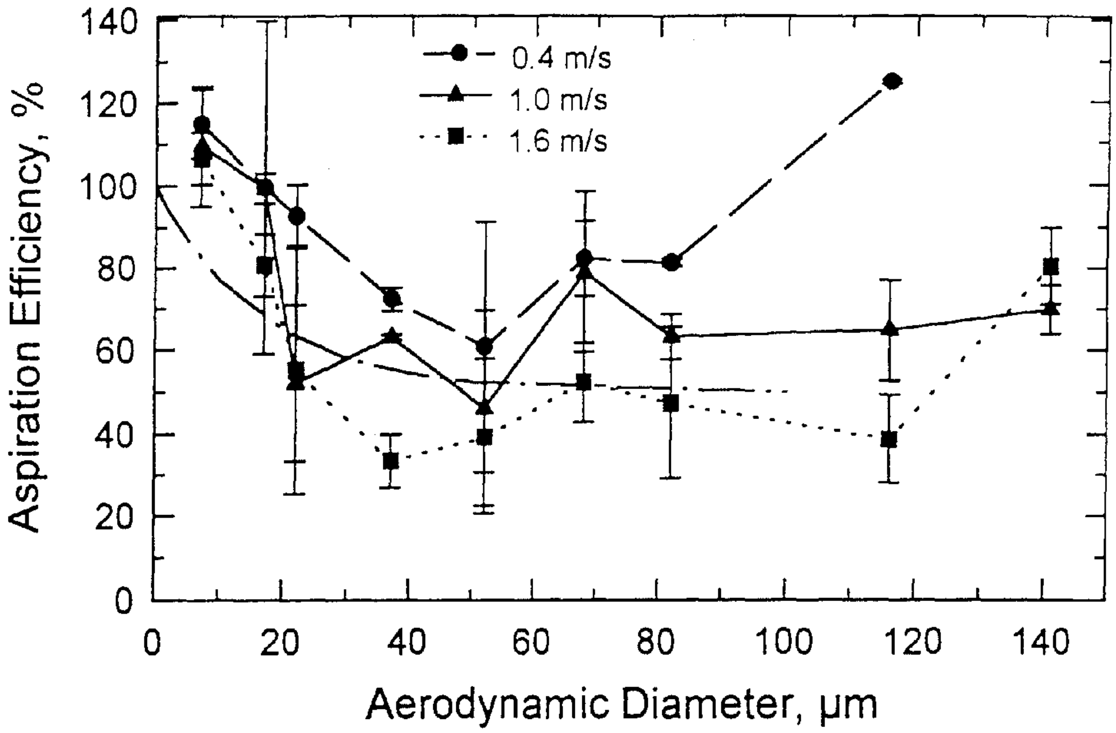

Figure 16. Sampling performance of IOM inhalable sampler on full-sized rotating mannequin.

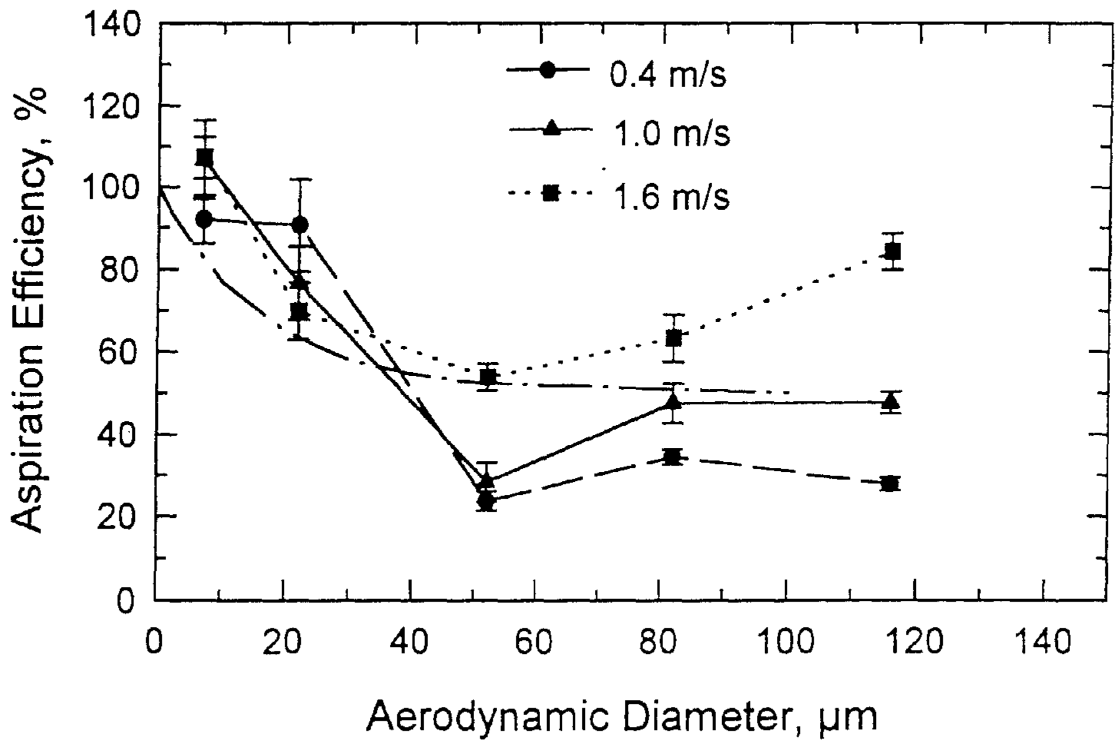

Figure 17. Sampling performance of IOM inhalable sampler on stationary, simplified mannequin.

The most obvious reason for the opposite trends in sampler performance between the simplified mannequin and the full-size mannequin is the difference in the shape of the "body" of the mannequin. Another possible bias may arise from the difference in methods used to obtain orientation-averaged results. While the rotating full-size mannequin actually allows sampling at all angles with respect to wind direction, the simplified mannequin relies on the averaging measurements at only three angles.

Conclusions

Main conclusions are summarized in the Significant Findings Section. We have made measurements of inhalability and sampler performance under carefully controlled conditions for a wider range of particle size and inhalation conditions than previous investigators. Measurements were made for both orientation-averaged and facing-the-wind conditions and for mouth breathing and nose breathing. We find evidence that inhalability does not level off at 50% for particles larger than 30 µm, but continues to decline with a plateau in the 80 to 120 µm size range. We have developed a system for making these measurements with liquid particles but have not made the measurements yet. We have made measurements of sampler performance for eight configurations of personal samplers, but have not yet finished analyzing the results.

Acknowledgments

The following people made significant contributions to the conduct of this research, doctoral student, Nola Kennedy, masters students, Jenny Wang and Karina Tatyan.

References

ACGIH: Particle Size-selective Sampling in the Workplace: Report of the ACGIH Technical Committee on Air Sampling Procedures. ACGIH, Cincinnati, Ohio. 1985

ACGIH: Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices, pp 83-86, 1998

Adachi M, Pui DYH, and Liu BYH: Aerosol Sci. Tech.18: 48-58, 1993.

Armbruster L and Breuer H: Investigation Into Defining Inhalable Dust. In: Inhaled Particles, Vol. V, (ed. Walton WH), Pergamon, Oxford, pp 21-32, 1982.

CEN: Workplace Atmospheres. Assessment of Performance of Instruments for Measurement of Airborne Particles. CEN/TC137/WG3/N125, 1993

Cooper DW and Reist PC: J. Colloid Interface Sci. 5:17-26, 1973.

Covert D, Wiedensohler A, Russell L: Aerosol Sci. Tech. 27:206-214, 1997.

Fairchild CI, Tillery MI, Smith JP and Valdez FO: Collection Efficiency of Field Sampling Cassettes. LA-8640-MS. Los Alamos Scientific Laboratory, 1980

Hinds WC: Sampler efficiencies: Inspirable Mass Fraction Chapt 5A in Particle Size-Selective Sampling in the Workplace. ACGIH Committee on Air Sampling Procedures, ACGIH, Cincinnati, Ohio, 1985

Hinds WC: Aerosol Technology. Wiley, New York, 1999.

Hinds WC and Kuo TL: Appl. Occup. Environ. Hyg. 10:549-556, 1995.

ISO: Ad Hoc Working Group to Technical Committee 146-Air Quality, International Standards Organization. Size Distributions for Particle Sampling. Am. Ind. Hyg. Assoc. J. 42(5): A64-A68, 1981.

John W: Particle Charge Effects. In: Generation of Aerosols (ed. Willeke K), Ann Arbor Science, Ann Arbor, MI, 1980.

Johnston AM, Vincent JH, and Jones AD: Ann. Occup. Hyg. 29:271-284, 1985.

Kenny LC, Aitkens R, Chalmers C, Fabries JF, Gonzalez-Fernandez E, Kronhout H, Liden G, Mark D, Riediger G, and Prodi V: A Collaborative European Study of Personal Inhalable Aerosol Sampler Performance. Ann. Occup. Hyg. 41:135-153, 1997.

Liu BYH and Pui DYH: J. Aerosol Sci. 5:465-472, 1974.

Mark D, Vincent JH, Gibson H, and Lynch G: A New Static Sampler for Airborne Total Dust in Workplaces. Am. Ind. Hyg. Assoc. J. 46:127-33, 1985.

Mark D and Vincent JH.: A New Personal Sampler for Airborne Total Dust in Workplaces. Ann. Occup. Hyg. 30: 89-102, 1986.

McCawley M, Burkhart J, Baron P and Dollberg: Testing of a Personal Filter Cassette with a Circumferential Orifice. Presented at American Industrial Hygiene Conference and Exposition, Philadelphia, PA, May 22-27, 1983.

Ogden TL, and Birkett JL: An Inhalable Dust Sampler For Measuring The Hazard From Total Airborne Particulate. Ann Occup. Hyg. 21:41-50, 1978.

Ogden TL, and Birkett JL: The Human Head as a Dust Sampler. In: Inhaled_Particles, Vol IV, (ed. Walton, WH), Pergamon, Oxford, pp 93-105, 1977.

Reischl G, John W and Devor W: Uniform Electrical Charging of Monodisperse Aerosols. J. Aerosol Sci. 8:55-65, 1977.

Romay FJ, Liu BYH, and Pui DYH: Aerosol Sci. Tech. 20:31-41, 1994.

Silverman L, Plotkin T, Sawyers T, and Yancey A: Air flow Measurements on Human Subjects with or without respiratory resistance at several work rates. Arch. Ind. Hyg. Occup. Med. 3:461, 1951.

Teague SV, Yeh HC, and Newton GJ: Health Physics 35:395-398, 1978.

Vincent JH, and Mark D: Applications of blunt sampler theory to the definition and measurement of inhalable dust. In: Inhaled Particles, Vol. V, (ed. Walton WH), Pergamon, Oxford, pp 3-19, 1982.

Witschger O, Willeke K, Grinshpun SA, Aizenberg V, Smith J, and Baron PA: Simplified Method for Testing Personal Inhalable Aerosol Samplers. J. Aerosol Sci. 29:855-874. 1998.

Yeh HC: Electrical Techniques. In: Aerosol Measurement, (eds. Willeke, Baron), Van Nostrand Reinhold, New York 1993.

Zamorani E and Ottobrini G: J. Aerosol Sci. 9:31-39, 1978.

List of Present and Future Publications

Hinds WC and Kuo TL: A low-velocity wind tunnel to evaluate inhalability and sampler performance for large dust particles. Appl. Occup. Environ. Hyg. 10:549-556, 1995.

Hinds WC: Inhalability and Sampler Performance for Large Particles. Proceedings of the International Conference on Aerosol Science and Technology, Taichung, Taiwan, R.O.C., October 28-30, 1993. J Aerosol Sci. 26:153, 1995. (Abstract).

Hinds WC and Kennedy NJ: An Ion Generator for Neutralizing Concentrated Aerosol Streams. Presented at American Association for Aerosol Research Annual Conference, Orlando, FL, October 14-18, 1996. (Abstract)

Kennedy N and Hinds WC: Inhalability of Large Solid Particles. Presented at American Association for Aerosol Research Annual Conference, Dever, CO, October 13-17, 1997. (Abstract)

Tatyan K and Hinds WC: Comparison study of a simplified mannequin versus a full size mannequin for testing IOM personal samplers. Presented at the American Industrial Hygiene Conference and Exposition, Atlanta, GA (Student Poster, Abstract) May 9-15, 1998.

Hinds WC, Kennedy NJ, and Tatyan K: Inhalability of large particles for mouth and nose breathing. Proceedings of the 1998 International Aerosol Conference, Edinburgh, Scotland, September 14-18, 1998. J. Aerosol Sci. 29:S277-S278, 1998.

Planned publications

Kennedy NJ, Tatyan K, and Hinds WC: Comparison study of a simplified mannequin versus a full

size mannequin for testing IOM personal samplers. To be submitted to Applied Occupational and Environmental Hygiene, 1999.

Hinds WC and Kennedy NJ: An Ion Generator for Neutralizing Concentrated Aerosols. To be submitted to Aerosol Science and Technology, 1999.

Hinds WC, Kennedy NJ, and Tatyan K: Inhalability of large particles for mouth and nose breathing.

Kennedy NJ and Hinds WC: Inhalability of Large Liquid Droplets.

Kennedy NJ and Hinds WC: Performance of personal samplers, comparison of solid and liquid droplets.