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# Development of a Large Particle Aerosol Distribution System for Testing Manikin-Mounted Samplers

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**ABSTRACT.** Personal samplers used to determine the inhalable fraction of workplace dust are tested while mounted on a manikin, which simulates a worker. To understand the mechanisms affecting the performance of such samplers, researchers must measure the airflow around the body where the samplers are mounted. Therefore, wind tunnel facilities to determine both airflow conditions around samplers and sampling efficiency are needed.

A wind tunnel system was developed that was large enough to accommodate the top half of a life-sized manikin and employed a laser Doppler velocimeter for velocity measurements around the manikin. For generating particles up to 70  $\mu\text{m}$ , an aerosol generation system, using a two-dimensional scanning system to cover an extended area, was developed and tested. The generation system had carriages with linear bearings mounted on rod assemblies for scanning in the horizontal and vertical directions. Screw drives, powered by stepper motors under computer control, moved the carriages in a preprogrammed pattern. The generation system was characterized for its ability to generate uniform concentrations of aerosols over an extended area at wind speeds of 0.5 and 2 m/s and particle sizes of 7 and 70  $\mu\text{m}$ . Uniformity of concentration over the area studied, in the absence of the manikin, was 10% relative standard deviation (RSD) or better, except for 7  $\mu\text{m}$  particles at a wind speed of 0.5 m/s where some nonuniformity was observed. The uniformity under these conditions was improved by rearranging the distances between components in the wind tunnel.

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## INTRODUCTION

Testing of personal aerosol samplers for inhalable dust has involved manikin-mounted samplers in a wind tunnel or in the work environment to simulate samplers worn on a worker (Botham et al. 1991; Chung et al. 1992; Chung et al. 1987; Kenny et al. 1997; Mark and Vincent 1987). To understand the mechanisms affecting personal sampler performance, it is desir-

able to make measurements of both the airflow around the samplers mounted on the manikin and the sampling efficiency of the samplers. For the measurement of airflow, laser Doppler velocimetry has a number of advantages. These include measurement of the airflow without the measurement device interfering with the airflow, and the ease with which a large number of measurements can be made at precise distances from

an object in a repeatable manner. Measuring the sampling efficiency requires an aerosol generation system that can produce uniform concentrations over an extended area, including the area where the samplers are located, and the area where reference isokinetic samplers can be located without the flow being affected by the manikin. For large particles, it is not possible to generate an aerosol over an extended area by using a single fixed generator with a fixed aerosol distribution system because settling and impaction of particles in the generation and distribution system will result in large losses and nonuniformity of concentration. In achieving a uniform concentration over an area, other researchers have tried 2 different approaches. One approach uses a limited number of generators set in a linear array, while moving the line of generation to cover the area of interest (Hinds and Kuo 1995). The other approach uses multiple generators covering an area (Kenny 1995). Both of these approaches have problems of overlapping outputs from multiple generators and the

operation and maintenance associated with multiple generators.

In the development of the generation system described in this paper, a different approach was taken. A single generator was used to achieve constant concentration over an extended area by moving the point of generation in 2 dimensions to cover the wind tunnel cross section. This approach avoided the problems of overlapping of outputs from multiple generators and the associated maintenance problems. With this approach, aerosol particles of 7 and 70  $\mu\text{m}$  aerodynamic diameter were generated over an area of nearly the cross section of the wind tunnel (2.23  $\text{m}^2$ ).

### MATERIALS AND METHODS

*Wind tunnel.* The wind tunnel for testing manikin-mounted personal samplers is shown in Figure 1a. The wind tunnel has a 1.83 m wide by 1.22 m high cross section and a total length of 7.24 m. It employs a recirculating design with high efficiency particulate air (HEPA) fil-

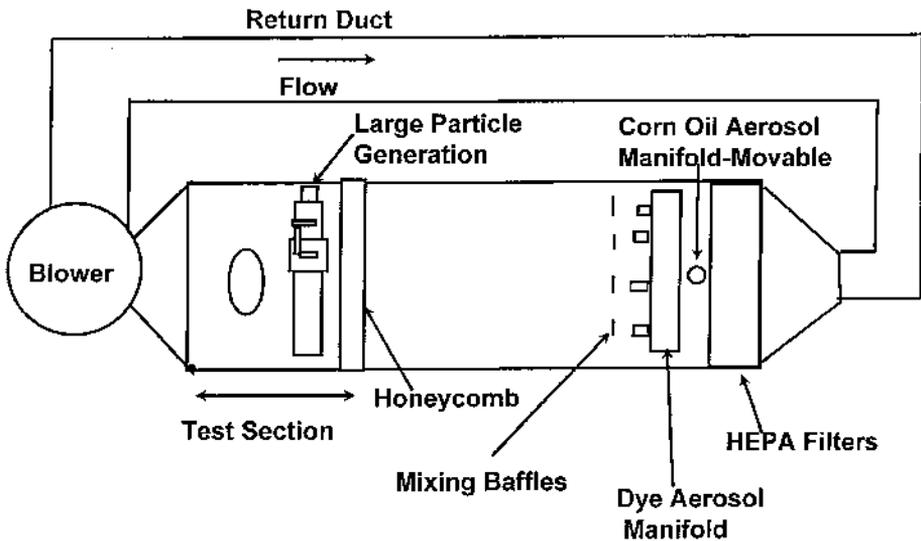


FIGURE 1a. Overall diagram of the wind tunnel (top view), showing location of test section, recirculation duct, and aerosol generation systems.

tration at the inlet and is capable of wind speeds from 0.5 to 3 m/s. The longitudinal component of free stream turbulence intensity was 3–5% without the manikin in the tunnel. If the vertical scanning component of the large particle generation system (which will be described later) was directly in front of the velocity measurement point, the turbulence intensity was 10–15%. The wind tunnel uses a number of types of aerosol generation systems that will be described in another section.

Figure 1b shows a diagram of the test section of the wind tunnel. When the manikin was present, it was located in this section of the wind tunnel. There was also an optional removable rotating table on which the manikin rotated for experiments in which the orientation

was averaged. For experiments to examine the performance of personal samplers, the personal samplers were mounted on the manikin and isokinetic reference samplers were mounted on both sides of the manikin. For experiments to determine the uniformity of concentration in the wind tunnel such as those presented in this paper, the manikin was replaced by a set of vertically spaced reference isokinetic samplers. An aerosol generation system for use with large particles was located in the test section and will be described in more detail. The honeycomb flow straightener was originally located 60 cm from the generation system. However it was observed that some of the generated aerosol could reach the flow straightener at the 0.5 m/s wind speed, so its position was changed to 90 cm

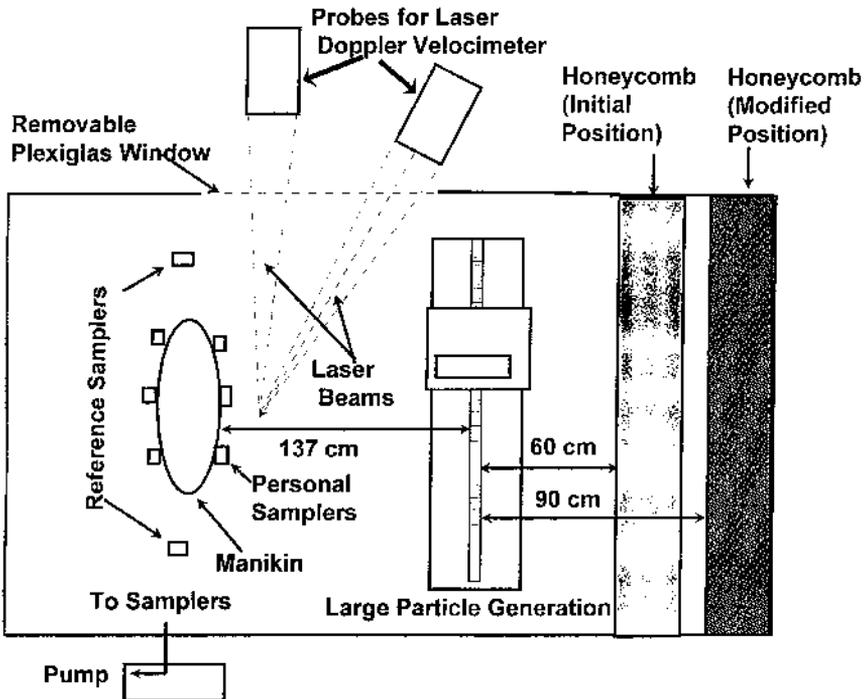


FIGURE 1b. Test section of the wind tunnel (top view), showing location of honeycomb flow straightener, large particle generation system, manikin, and probes for laser Doppler velocimeter. The position of the honeycomb was changed for some of the experiments.

from the generation system to improve uniformity. Figure 1a shows the location of the probes used with the laser Doppler velocimeter (LDA, 3D FiberFlow System, Dantec Electronics, Inc., Mahwah, NJ). For use with the manikin, the velocimeter used beam expanders and spherical 10 cm diameter lenses with 1200 mm focal lengths. With this optical configuration, the measurement volume would have a  $286 \mu\text{m}$  diameter with a 9.1 mm length. The probes were mounted on an optical bench, which was moved by a precision 3 component traverse system. This system measured the flow velocity in the wind tunnel and the airflow around the manikin and other test bodies. Because laser Doppler velocimeter employed 2 separate probes with a total of 6 beams, it was able to measure 3 components of velocity. It was necessary to align the beams from the 2 different probes to be sure that their measurement volumes overlapped as much as possible. Some measurements made with this system are described in Witschger et al. 1998. The recirculating design of the wind tunnel made it possible to make velocity measurements around the manikin when the plexiglas window of the wind tunnel was removed. Distortion of the laser beams of the velocimeter by the window made 3 component velocity measurement difficult, so removal was needed to improve velocity measurement. It was found that removal of the window did not affect the airflow in the middle of the wind tunnel for the range of velocities that were studied.

*Reference Samplers.* The isokinetic reference samplers employed sharp-edged, thin-walled inlets (Figure 2a). The inlets were 80-mm long

brass tubes with an inside diameter of 1.0 cm. The inlet tube was attached to a 25-mm filter holder with a tapered plastic cone. The reference samplers were operated isokinetically and isoaxially, and the collected aerosol was sampled onto glass fiber filters (Type A/E, Gelman Sciences, Ann Arbor, MI). The flow rates for the reference samplers were 2.4 L/m at a wind velocity of 0.5 m/s and 9.5 L/m at a wind velocity of 2 m/s. The aerosol deposited in the inlet was carefully washed from the inlet tube onto a 25-mm membrane filter (Type VM-1, Gelman Sciences, Ann Arbor, MI) with distilled water, so that the total weight of aerosol entering the sampler was determined. The filters in the reference samplers and the filters containing the dust washed from the reference samplers were weighed with a balance with  $2 \mu\text{g}$  sensitivity (model AT20 Mettler Toledo Inc., Hightstown, NJ). The arrangement of the reference samplers used for assessing the uniformity of concentrations is shown in Figure 2b. The position of the manikin is also shown in this figure. For the data given in Tables 1–5, the manikin was not present. To determine the concentration when personal samplers were mounted on the manikin, one reference isokinetic sampler was placed on each side of the manikin (about 20 cm from the manikin). These reference samplers were the same distance from the floor of the wind tunnel as the personal samplers on the manikin (about 40 cm).

### *Aerosol Generation Systems*

*Small Particle.* The wind tunnel had 3 different aerosol generation systems associated with it.

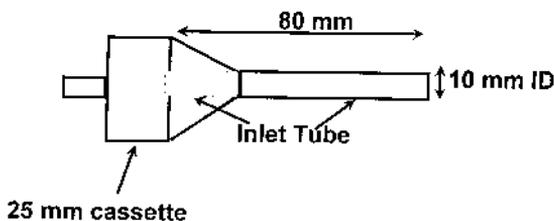
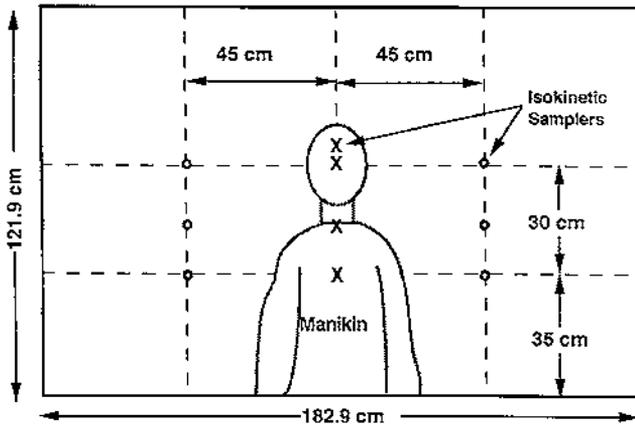


FIGURE 2a. Isokinetic sampler showing inlet tube and filter holder.



**FIGURE 2b.** Arrangement of isokinetic samplers in the wind tunnel for assessment of uniformity of concentration. Also shown is the position of the manikin when it was present.

Two of them were located directly downstream from the HEPA filters and generated particles  $< 10 \mu\text{m}$  (Figure 1a). A dye aerosol generation system produced a uranine aerosol having a  $7\text{-}\mu\text{m}$  mass median aerodynamic diameter that was used for sampler testing. This generation system used an ultrasonic nebulizer located in a  $15.2\text{-cm}$  i.d. chamber on the top of the wind tunnel. The generated aerosol was dried and transported into the tunnel through a  $15.2\text{-cm}$  i.d. flexible duct. The aerosol distribution system consisted of a manifold having 2 sets of 4 evenly spaced outlets. One set of outlets was located directly above the other. Each outlet of the manifold was followed by a  $26.4\text{-cm}$  disk to mix the output from outlet of the manifold with the flow in the wind tunnel. This distribution system was developed to produce a uniform cloud of aerosol in the test section of the wind tunnel and was used in a study of respirable dust samplers using a uranine aerosol (Smith and Bartley 1996). The corn oil particle generation system generated small particles for use as a seed aerosol with the laser Doppler velocimeter. The laser Doppler velocimeter determines velocity by measuring the transit time of small particles through its measurement volume. The corn oil generation system used a Collision nebulizer, which was located outside the wind tunnel, to produce a corn oil aerosol

having a size of  $0.7 \mu\text{m}$  count median aerodynamic diameter. The size was measured with an Aerodynamic Particle Sizer (APS33, TSI Inc, St. Paul, MN). The nebulizer was connected by flexible tubing to a manifold which consisted of a  $2.5\text{-cm}$  i.d. pipe that was  $118\text{-cm}$  long with holes evenly spaced at  $5\text{-cm}$  intervals along its length. The manifold was mounted vertically in the wind tunnel. This vertically mounted manifold allowed the aerosol to be produced over a limited vertical area. The pipe could be moved along the width of the wind tunnel so that different areas could be covered. This movable manifold allowed the concentration of the seed aerosol to be maximized for a given test zone.

*Large Particle.* The aerosol generation and distribution system for use with larger particles was located in the test section of the wind tunnel (Figures 1a and 1b) and is shown in Figure 3a. The dust source was a rotating brush generator (Palas RBG-1000, Palas GmbH Karlsruhe, Germany) that fed dust from a cylindrical reservoir onto a rotating brush from which the dust was dispersed by air at a high velocity. For this study, the generator used a  $28\text{-mm}$  reservoir, a feed rate of  $20\text{ mm/h}$ , and a dispersion airflow rate of  $70\text{ L/m}$ . This would give a volumetric feed rate of  $12.3\text{ cm}^3/\text{h}$ . The mass feed rate would be determined by the density of the material being

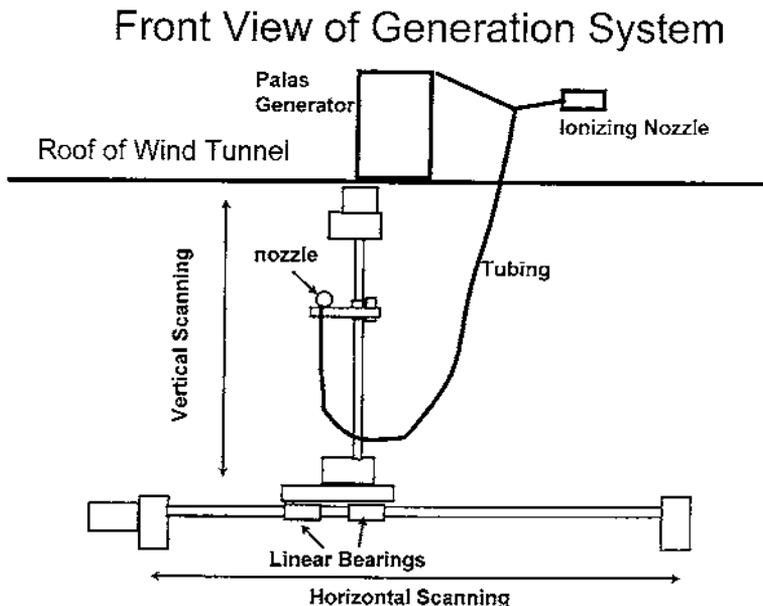


FIGURE 3a. Overall diagram of large particle generation system showing location of generator on top of the wind tunnel, horizontal and vertical scanning components, and nozzle where aerosol exits system into the wind tunnel.

generated in the reservoir of the generator. The aerosol was produced from a powder of graded aluminum oxide, available in a number of sizes ranging from slightly under  $10\ \mu\text{m}$  to well over  $100\ \mu\text{m}$  (Mark et al. 1986). The particles used in these experiments had a  $7\text{-}\mu\text{m}$  mass median aerodynamic diameter (MMAD) with geometric standard deviation (GSD) of 1.5 at the lower end and a  $70\ \mu\text{m}$  MMAD with a GSD of 1.4 at the upper end of particle size. The  $70\ \mu\text{m}$  particles were the largest size that could be characterized for these experiments. These aerosols were characterized by sedimentation analysis on the bulk material (Model 5000, Sedigraph, Micromeritics Instrument Corp., Norcross, GA).

It is important to minimize the charge on aerosols used to assess sampling efficiency. The first attempt to adjust the charge on the aerosol involved mixing the generated aerosol with air containing bipolar ions from an ionizing nozzle, as shown in Figure 3a. It was hoped that there would be sufficient ions present in the

bipolar mixture to neutralize any charges on the produced aerosol. The bipolar ions were generated by using an ionizing nozzle and controller (Model AN-6 nozzle and AFC-2 controller, Richmond Static Control Services, Inc., Palm Springs, CA) and mixed with the dust coming from the Palas generator to neutralize the aerosol that was produced. The Palas generator and neutralizer were located outside the wind tunnel, and the generated dust was transported through Tygon<sup>®</sup> tubing ( $7.9\ \text{mm}$  ID,  $244\ \text{cm}$  long) into the wind tunnel, where it went through a nozzle into the flow. After development of a charge assessment system, it was found that this system was not effective in adjusting the charge on the aerosol. Therefore, a system was developed where positive and negative ions were added separately to the aerosol shortly before it exited the nozzle into the wind tunnel, which required the use of a device to assess the level of charge, so that the charge could be adjusted. The charge assessment device is shown in Fig-

ure 3b, and the neutralization system is shown in Figure 3c. The charge assessment system measured the current from particles collected on a conductive silver membrane filter. The filter was

mounted inside a 25 mm filter cassette, which was isolated from ground and was mounted inside a grounded conducting cylinder to shield the filter from electric fields. The aerosol was

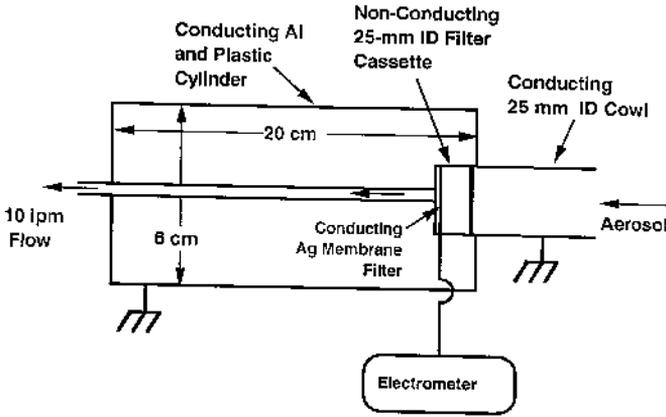


FIGURE 3b. Charge assessment system. The aerosol is sampled through the conducting cowl, and the current from the aerosol collected on the filter is measured with the electrometer.

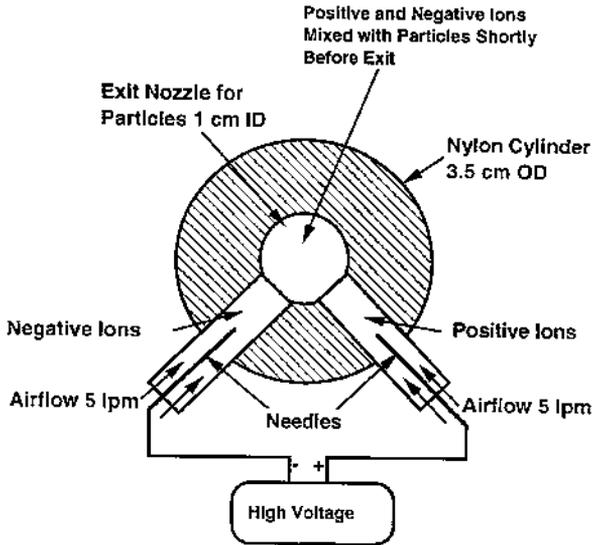


FIGURE 3c. Exit nozzle charge neutralization system (cross section through area where ions added). Positive and negative ions produced from high voltage discharge at the needles are mixed with the aerosol a short distance before it exits the nozzle.

sampled through a 25-mm, grounded, conductive, plastic cowl that also helped to shield the filter. The current from the filter was measured with an electrometer (Model 642, Keithley Instruments, Cleveland, OH) that was attached to a chart recorder. To adjust the charge on the aerosol, the exit nozzle of the generation system was redesigned so that positive and negative ions were generated separately and mixed directly with the generated particles a short distance before the particles exited the nozzle. The ions were generated by a high voltage DC discharge from needles that were mounted on the nozzle. Air continuously passed over these needles to provide a continuous source of ions. The high voltage was generated using a power supply that is used for ionizing nozzles (Model AFC-2 controller, Richmond Static Control Services, Inc, Palm Springs, CA). The ratio of positive to negative ions was adjusted with this power supply; a process that was repeated before every experiment when the charge was adjusted. The charge assessment system determined if equal numbers of positively and negatively charged particles were present.

The nozzle in the large particle generation system was pointed in opposition to the major airflow in the wind tunnel. The nozzle in

the wind tunnel scanned over a given area in the wind tunnel using a 2 component scanning system. The horizontal component (Figure 3d) used a 167.6 cm (66 in.) quick slide (Thomson Industries, Inc., Port Washington, NY), which consisted of a carriage which rides on two 2.5 cm (1 in.) rods using linear bearings. The rods were mounted in an endblock that held them in position. The vertical component employed a similar 106.7 cm (42 in.) quick slide that had a 5.1 cm (2 in.) wide carriage and used 1.4 cm (0.75 in.) diameter rods. The horizontal component and vertical components used screw drives (Nook Industries, Inc, Cleveland, OH) driven by stepper motors (Model PJ 80 for horizontal axis and PJ 50 for vertical axis, Kollmorgen Motion Technologies Group, Radford, VA), controlled by programmable controllers (Model SMC-400 Kollmorgen Motion Technologies Group, Radford, VA), and connected to a computer through a serial port. These controllers used computer commands written in BASIC to control the motion. These programs could be changed to generate different patterns of motion. A typical pattern of motion is as follows: The initial movement is in the horizontal direction. The length of this movement is programmed and can be varied. At the end of each horizontal movement,

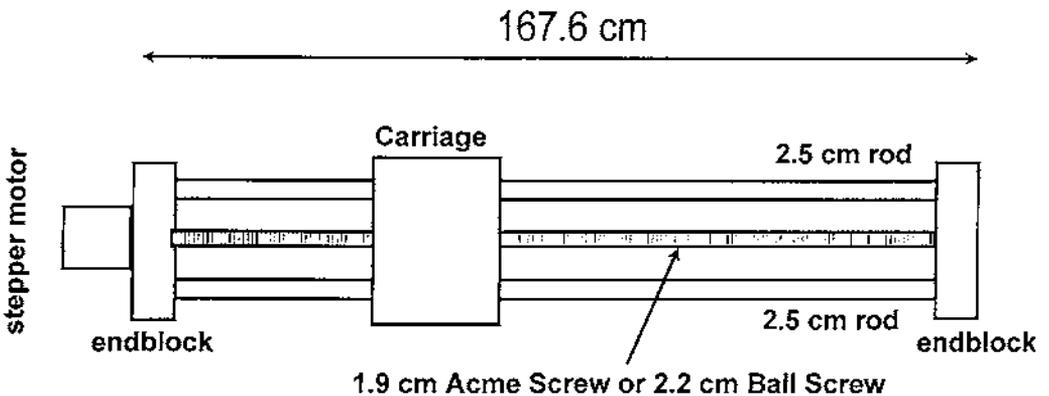


FIGURE 3d. Horizontal scanning component of generation system showing rods, carriage, lead screw, and motor.

the nozzle is moved down a given distance (e.g., 3.81 cm) and then moved horizontally in the opposite direction. When the entire area is covered, the nozzle is returned to the starting position and the run is terminated or the area to be covered is scanned again. The vertical and horizontal starting position of the movement pattern can be varied by putting the nozzle at a different position to start the scan. The length of the scan in the horizontal direction can be adjusted by changing the preprogrammed value, and the width of the vertical scan can be adjusted by adjusting the number of steps of the scan in the program. For the experiments whose results are presented in Tables 1–5, the scanned area was 127 cm (50 in.) in the horizontal direction and 64.8 cm (25.5 in.) in the vertical direction, and the scan was symmetrical because it started and ended at the same distance from each side of the wind tunnel. The 127-cm horizontal length of the scan is the longest scan that can be conveniently done with the present system because of the length of the rods and the width of the carriage. It is desirable to use the longest scan possible that will place the reference samplers as far from the manikin as possible. The 64.8 cm width of the scan in the vertical direction was used to adequately cover both the chest area and breathing zone of the manikin. The vertical position of the start of the scan was 88 cm from the wind tunnel floor, except for the run for 70  $\mu\text{m}$  particles at a wind speed of 0.5 m/s which started at 108 cm to compensate for increased gravitational settling of these large particles. The time for each horizontal segment of the scan was about 2 min, for a total of 49 min for the whole area.

## RESULTS AND DISCUSSION

The results from air velocity measurement around the manikin using the laser Doppler system were presented in a previous paper (Witschger et al. 1998). Briefly, air velocity measurements were made on the chest area of the manikin, and the manikin was oriented at

0° (facing the wind), 90° (side to the wind), and 180° (back to the wind) at speeds of 0.5 and 2 m/s. With the manikin at 0° to the wind, the air velocity decelerated as it approached the manikin, reaching 30% of the free stream velocity at a distance of 5 cm. Since the earlier paper was written, the laser Doppler system has been modified to take velocity measurements even closer to the body. These measurements indicate that the air velocity can be as low as 10% of free stream velocity at a distance of 1 cm from the manikin. With the manikin at 90° to the wind, a slight acceleration of the flow was observed as it passed around the manikin. Measurements were only made as close as 7 cm from the manikin. Many personal samplers are located closer than 7 cm from the manikin, so it is important to make measurements closer to the manikin. With the manikin at 180° to the wind (the wind blowing from the back of the manikin), the flow in front of the manikin was turbulent as determined by visualization of the flow with smoke and measurements of the velocity with the laser Doppler velocimeter. The average velocity in the chest area of the manikin was low, but fluctuated around the low average velocity. The laser Doppler velocimeter system is now being modified to allow measurements to be made closer to the manikin, and more measurements of airflow will be made in future studies.

The uniformity of aerosol concentration over a given test area depended on the particle size and the wind speed of the experiment, as well as the area covered by the scan of the distribution system, and the distance from the distribution system to the area where measurements were made. Experiments were done for wind speeds of 0.5 and 2 m/s and particle sizes of 7 and 70  $\mu\text{m}$ . At least 2 experiments were performed at each condition, and the distribution of concentrations over the test area and overall RDS of replicate experiments were in close agreement. However, the average concentration varied by as much as 20% from experiment to experiment, so that results shown in the following tables are from one of the experiments per-

formed. The results for the experiments that examined the uniformity of concentration are shown in Tables 1–5. For each sample taken during an experiment, the horizontal position of the corresponding sampler is given in the first row of the table and the vertical position of the sampler is given in the first column of the table. The concentration measured by the sampler is given in the body of the table. At the bottom of each table, the average concentration for samplers located at various horizontal positions is given, and at the side of each table, the average concentration for samplers at various vertical positions is given. These average concentrations are given as an assessment of the uniformity of concentration measured by these samplers. For the data given in the Tables 1–5, the manikin was not present since these experiments were performed to examine uniformity in the absence of the manikin.

At the 70  $\mu\text{m}$  particle size, the RSD of all the concentration measurements was approximately 10% for wind speeds of 2 m/s and 0.5 m/s (Tables 1 and 2). Part of this variation was due to the analysis of the samples since the entire quantity of dust collected by each isokinetic sampler had to be assessed. This involved washing the

inside of the sampler onto a preweighed membrane filter. Also, removal of the filter from the sampler could have resulted in some loss of collected sample. For the experiment with 0.5 m/s wind velocity, the point at 65 cm vertical height was not used in determining the mean and standard deviation since it was desired to determine the variation in the area where the aerosol concentration was constant. The value of the measured concentration was lower at this point probably due to settling. Seventy  $\mu\text{m}$  particles settle at 15 cm/s. If it is assumed that the particles have to travel 1.5–2 m after generation before they arrive in the test area, then they would settle for about 3 s before arriving in the test area. They would therefore settle 45 cm in this time period. Since the area scanned by the generation system was started at 108 cm vertical position (instead of 88 cm, as used in the other experiments), positions higher than 60 cm might be expected to receive less exposure. Because of settling, the area where the personal aerosol samplers were located on the manikin and the breathing zone of the manikin were exposed to different concentrations for 70  $\mu\text{m}$  particles at 0.5 m/s wind speed. There may also have been some variation with position along the horizon-

**TABLE 1. Uniformity of concentration for samplers at various positions in the wind tunnel 70  $\mu\text{m}$  particles, wind speed = 0.5 m/s, and vertical starting position of scan of 108 cm. The horizontal length of the scan was 127 cm (centered in the wind tunnel), and the scan was 64.8 cm wide in the vertical direction covered in 3.8 cm increments.**

Sampler Position	Horizontal <sup>b</sup>			Mean(SD) <sup>c</sup>
	Vertical <sup>a</sup>	46 cm (left)	0 cm	
65 cm			5.76 mg/m <sup>3e</sup>	
60 cm		7.56 mg/m <sup>3</sup>	7.07 mg/m <sup>3</sup>	7.39(0.28)
50 cm		7.25 mg/m <sup>3</sup>	8.64 mg/m <sup>3</sup>	7.99(0.70)
35 cm		7.71 mg/m <sup>3</sup>	9.36 mg/m <sup>3</sup>	8.68 mg/m <sup>3</sup>
Mean(SD) <sup>d</sup>		7.51(0.24)	8.35(1.17)	8.11(0.57)

Overall mean = 7.99 mg/m<sup>3</sup>; overall standard deviation = 0.76 mg/m<sup>3</sup>.

<sup>a</sup>Vertical position of sampler relative to floor of wind tunnel.

<sup>b</sup>Horizontal position of sampler relative to center of wind tunnel.

<sup>c</sup>Mean concentration (standard deviation) for row of samplers at indicated vertical position.

<sup>d</sup>Mean concentration (standard deviation) for column of samplers at indicated horizontal position.

<sup>e</sup>Not included in overall mean and overall standard deviation.

**TABLE 2. Uniformity of concentration for samplers at various positions in the wind tunnel 70  $\mu\text{m}$  particles, wind speed = 2 m/s, and vertical starting position of scan of 88 cm. The horizontal length of the scan was 127 cm (centered in the wind tunnel), and the scan was 64.8 cm wide in the vertical direction covered in 3.8 cm increments.**

Sampler Position	Horizontal <sup>b</sup>				
	Vertical <sup>a</sup>	47 cm (left)	0 cm	50 cm (right)	Mean(SD) <sup>c</sup>
65 cm			2.99 mg/m <sup>3</sup>		
60 cm		3.05 mg/m <sup>3</sup>	2.63 mg/m <sup>3</sup>	3.29 mg/m <sup>3</sup>	2.99(0.33)
50 cm		2.87 mg/m <sup>3</sup>	2.87 mg/m <sup>3</sup>	3.21 mg/m <sup>3</sup>	2.98(0.19)
35 cm		2.24 mg/m <sup>3</sup>	2.95 mg/m <sup>3</sup>	3.06 mg/m <sup>3</sup>	2.75(0.44)
<b>Mean(SD)<sup>d</sup></b>		2.72(0.42)	2.86(0.16)	3.18(0.12)	

Overall mean = 2.92 mg/m<sup>3</sup>; overall standard deviation = 0.30 mg/m<sup>3</sup>.

<sup>a</sup>Vertical position of sampler relative to floor of wind tunnel.

<sup>b</sup>Horizontal position of sampler relative to center of wind tunnel.

<sup>c</sup>Mean concentration (standard deviation) for row of samplers at indicated vertical position.

<sup>d</sup>Mean concentration (standard deviation) for column of samplers at indicated horizontal position.

**TABLE 3. Uniformity of concentration for samplers at various positions in the wind tunnel 7  $\mu\text{m}$  particles, wind speed = 0.5 m/s, and vertical starting position of scan of 88 cm. The horizontal length of the scan was 127 cm (centered in the wind tunnel), and the scan was 64.8 cm wide in the vertical direction covered in 3.8 cm increments.**

Sampler Position	Horizontal <sup>b</sup>				
	Vertical <sup>a</sup>	47 cm (left)	0 cm	50 cm (right)	Mean(SD) <sup>c</sup>
75 cm			6.68 mg/m <sup>3</sup>		
65 cm		5.85 mg/m <sup>3</sup>	7.10 mg/m <sup>3</sup>	7.58 mg/m <sup>3</sup>	6.80(0.73)
50 cm		5.11 mg/m <sup>3</sup>	6.56 mg/m <sup>3</sup>	6.93 mg/m <sup>3</sup>	6.20(0.96)
35 cm		3.31 mg/m <sup>3e</sup>	4.48 mg/m <sup>3</sup>	5.05 mg/m <sup>3</sup>	4.28(0.89)
<b>Mean(SD)<sup>d</sup></b>		4.76(1.31)	6.20(1.17)	6.52(2.32)	

Overall mean = 6.15 mg/m<sup>3</sup>; overall standard deviation = 1.07 mg/m<sup>3</sup>.

<sup>a</sup>Vertical position of sampler relative to floor of wind tunnel.

<sup>b</sup>Horizontal position of sampler relative to center of wind tunnel.

<sup>c</sup>Mean concentration (standard deviation) for row of samplers at indicated vertical position.

<sup>d</sup>Mean concentration (standard deviation) for column of samplers at indicated horizontal position.

<sup>e</sup>Not included in overall mean and overall standard deviation.

tal axis, but the measurements within the area still had an RSD < 10%.

At 7  $\mu\text{m}$  particle size, the distribution of concentrations was different at wind velocities of 0.5 and 2 m/s. At 0.5 m/s, the RSD was about 17% and there was evidence of concentration differences from one side of the wind tunnel to the other and from lower to higher locations (Table 3). At 2 m/s, the concentration was uniform with an RSD of about 3% and no appar-

ent variation in concentration due to position (Table 4). The nonuniformity observed at 0.5 m/s may have been caused by interaction between the flow from the nozzle of the generation system and the honeycomb flow straightener and possible mixing problems at the lower wind speed. To improve the uniformity at 7  $\mu\text{m}$  and 0.5 m/s, the honeycomb was moved 30 cm further from the generation system, back toward the HEPA filters, in the wind tunnel. The data

**TABLE 4. Uniformity of concentration for samplers at various positions in the wind tunnel 7  $\mu$ m particles, wind speed = 2 m/s, and vertical starting position of scan of 88 cm. The horizontal length of the scan was 127 cm (centered in the wind tunnel), and the scan was 64.8 cm wide in the vertical direction covered in 3.8 cm increments.**

Sampler Position	Horizontal <sup>b</sup>				
	Vertical <sup>a</sup>	47 cm (left)	0 cm	50 cm (right)	Mean(SD) <sup>c</sup>
75 cm			2.67 mg/m <sup>3</sup>		
65 cm		2.76 mg/m <sup>3</sup>	2.72 mg/m <sup>3</sup>	2.65 mg/m <sup>3</sup>	2.71(0.05)
50 cm		2.74 mg/m <sup>3</sup>	2.73 mg/m <sup>3</sup>	2.77 mg/m <sup>3</sup>	2.75(0.02)
35 cm		2.83 mg/m <sup>3</sup>	2.92 mg/m <sup>3</sup>	2.85 mg/m <sup>3</sup>	2.87(0.04)
Mean(SD) <sup>d</sup>		2.78(0.05)	2.76(0.11)	2.76(0.10)	

Overall mean = 2.76 mg/m<sup>3</sup>; overall standard deviation = 0.082 mg/m<sup>3</sup>.

<sup>a</sup>Vertical position of sampler relative to floor of wind tunnel.

<sup>b</sup>Horizontal position of sampler relative to center of wind tunnel.

<sup>c</sup>Mean concentration (standard deviation) for row of samplers at indicated vertical position.

<sup>d</sup>Mean concentration (standard deviation) for column of samplers at indicated horizontal position.

**TABLE 5. Uniformity of concentration for samplers at various positions in the wind tunnel. Wind tunnel modified by moving honeycomb 30.5 cm further from generation system. 7  $\mu$ m particles, wind speed = 0.5 m/s, and vertical starting position of scan of 88 cm. The horizontal length of the scan was 127 cm (centered in the wind tunnel), and the scan was 64.8 cm wide in the vertical direction covered in 3.8 cm increments.**

Sampler Position	Horizontal <sup>b</sup>				
	Vertical <sup>a</sup>	47 cm (left)	0 cm	50 cm (right)	Mean(SD) <sup>c</sup>
75 cm			6.29 mg/m <sup>3</sup>		
65 cm		6.85 mg/m <sup>3</sup>	7.06 mg/m <sup>3</sup>	6.60 mg/m <sup>3</sup>	6.84(0.23)
50 cm		6.21 mg/m <sup>3</sup>	7.13 mg/m <sup>3</sup>	6.62 mg/m <sup>3</sup>	6.66(0.46)
40 cm		5.18 mg/m <sup>3</sup>	6.23 mg/m <sup>3</sup>	6.01 mg/m <sup>3</sup>	5.81(0.56)
Mean(SD) <sup>d</sup>		6.08(0.84)	6.68(0.48)	6.41(0.35)	

Overall mean = 6.41 mg/m<sup>3</sup>; overall standard deviation = 0.58 mg/m<sup>3</sup>.

<sup>a</sup>Vertical position of sampler relative to floor of wind tunnel.

<sup>b</sup>Horizontal position of sampler relative to center of wind tunnel.

<sup>c</sup>Mean concentration (standard deviation) for row of samplers at indicated vertical position.

<sup>d</sup>Mean concentration (standard deviation) for column of samplers at indicated horizontal position.

from these uniformity experiments are shown in Table 5. The overall uniformity was improved and the uniformity from one side of the wind tunnel to the other was also improved. However, there still appeared to be some nonuniformity from the lower to the higher positions in the wind tunnel, and the lower positions had a lower concentration. In these experiments the lowest sampling positions were moved from 35 to 40 cm to determine if the concentration was constant in this reduced range of height. How-

ever, the concentration was still not constant over this reduced height range. In order to obtain constant concentrations over the chest area and breathing zone of the manikin, it is necessary to locate the manikin at a higher position so that both the chest region where the samplers are located and the breathing zone are in a region of relatively constant concentration (for samplers located above 50 cm, the standard deviation is about 5% of the mean value). However, it is not necessary to correct concentra-

tions for the nonuniformity from one side of the wind tunnel to the other. A number of future experiments are planned where the wind tunnel system will be used to examine the sampling efficiency of personal samplers mounted on the manikin.

## CONCLUSION

Uniform exposure of samplers in a wide area can be obtained by scanning the source over the area using a two-dimensional scanning system. The uniformity of the particle concentration over a test area depends on the area scanned, particle size, wind velocity, and distance from the scanned area to the area where samples are taken. It is necessary to check the uniformity of concentration in a given area to be sure that the uniformity meets the needs of the experiment. Some modifications to the original arrangement of components in the wind tunnel improved uniformity when the RSD of measurements was > 10% (e.g., 0.5 m/s with 7  $\mu$ m particles). The uniformity was found to depend on the arrangement of the space between the honeycomb and nozzle of the generation system.

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*DISCLAIMER: Mention of company names or products does not constitute endorsement by the Centers for Disease Control and Prevention.*

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