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16. Abstract (Limit: 200 words) Flow visualization and tracer gas studies were conducted in a wind tunnel with a mannequin, to examine the phenomenon of boundary layer separation as it relates to a worker's breathing zone concentration. A simple conceptual model was used which was based on mass transport by vortex shedding. This model provided a reasonable estimate of the mannequin breathing zone concentration. An empirical model was developed which then related the measured concentration to the distance from the source to the breathing zone for conditions where the contaminant was released downstream in a uniform flow. The results of the mannequin experiments suggested that boundary layer separation plays a significant part in determining the concentration of contaminant in the breathing zone. The interaction of the separated boundary layer with a contaminant source downstream of a person in uniform flow can pull contaminant back into the breathing zone of the person. The amount of contaminant observed in the breathing zone was much less when the mannequin was positioned such that the air could flow from the side. The turbulent mixing zone was formed more to the side of the mannequin and thus has less opportunity to interact with the contaminant source. These results suggested that in situations such as paint booths where a worker is immersed in a uniform flow, a higher level of control may be achieved by standing to the side of the workpiece.

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THE IMPACT OF BOUNDARY LAYER SEPARATION ON LOCAL EXHAUST DESIGN AND WORKER EXPOSURE

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Abstract - The phenomenon of boundary layer separation is an important factor in determining a worker's breathing zone concentration. This paper presents the results of flow visualization and tracer gas studies, conducted in a wind tunnel with a mannequin, designed to examine this phenomenon. A simple conceptual model based on mass transport by vortex shedding, provides a reasonable estimate of the mannequin breathing zone concentration. An empirical model is developed which relates the measured concentration to the distance from the source to the breathing zone, for the situation when the contaminant is released downstream in a uniform flow. Applications of the results are discussed.

INTRODUCTION

One of the more serious threats to employee health is the inhalation of toxic airborne materials produced by various industrial processes. Once inhaled, these contaminants may give rise to a number of deleterious health effects. Occupational health professionals constantly seek ways to reduce these exposures to acceptable levels. Typically, in an industrial environment, it is desirable to remove the contaminant as close to its source as possible, before it has a chance to escape into the general workroom air. This is often accomplished through the use of local exhaust ventilation (LEV).

The size, shape, and configuration of an LEV system are as varied as the industrial processes they are designed to control. However, all LEV systems have one particular design parameter in common - capture velocity. Capture velocity is defined as the "air velocity at any point in front of the hood, or at the hood opening, necessary to overcome opposing air currents and to captue the contaminated air at that point by causing it to flow into the hood" [1].

Empirically determined equations for calculating the air flow necessary to provide a specific capture velocity have appeared in the literature since Dalla Valle's[2] work in the 1930's. Since that time, several investigators have approached the determination of centerline capture velocity from both the empirical and theoretical standpoint[3-13]. As a basis for the LEV design process, capture velocity has several drawbacks. Deficiencies include: 1) the inability to account for the effect of cross drafts or other air disturbances, 2) the uncertainty involved in shaping the hood and distributing face velocity for the most efficient capture of contaminant[14], 3) the inability to accommodate hot sources or obstructions in the flow, [15] 4) difficulty in application to large contaminant sources, [13] and 5) the inability to predict contaminant concentration in the vicinity of the worker[16].

The most fundamental deficiency in designing an LEV system to provide a specific capture velocity is that it does not tell the designer how effective he or she will be in achieving the overall goal of reducing the concentration of contaminant in the employee's breathing zone. Even when the target capture velocity is achieved, a method does not exist which relates this velocity to the breathing zone concentration. Similarly, a designer who wishes to reduce employee exposure below a specified action level does not have a method for quantitatively determining the ventilation required to do so. One cannot say, for example, that if a particular capture velocity is provided, a certain level of protection is achieved.

Clearly, a method of LEV design that somehow relates design parameters to breathing zone concentration would be most useful in employee protection. However, before such a design method can be developed, it is necessary to understand how the air drawn past the worker can interact with the contaminant source and give rise to concentrations in the breathing zone.

Analytic models describing flow fields into exhaust hoods[13,16,17] use potential theory as the theoretical basis. In potential flow the air is inviscid, incompressible (constant density) and irrotational (negligible local angular velocity)[18]. These assumptions are valid in the free field where an object is not present to obstruct the flow. While these models have certain applications, instances arise when the worker becomes a significant obstacle in the path of air flowing into the hood.

An object (such as a person) in the flow field calls into question the validity of potential theory in two ways. First, by its very presence, the object is a physical obstruction to the flow of air into the hood. As such it perturbs the boundary conditions for the solution of Laplace's equation. Second, and most important for the discussion here, when fluid flows past a blunt body, a boundary layer is formed on the surface of that body. A portion of the fluid adheres to the surface of the object and thus, near the surface, the motion of a thin layer of the fluid is retarded by frictional forces. Within this layer, fluid velocity increases from zero (at the surface) to the velocity of the free stream (external frictionless flow). This thin layer is called the boundary layer, and is a region in which the viscosity plays a major role, thus violating the inviscid assumption of potential theory.

As fluid approaches a blunt object, e.g. a circular cylinder, a boundary layer forms on the upstream side as depicted in Figure (1). If the flow is frictionless, fluid particles experience increasing acceleration on the upstream side of the cylinder and increasing deceleration on the downstream side. According to Bernoulli's equation this results in decreasing pressure on the upstream side and increasing pressure on the downstream side. Outside the boundary layer the flow is nearly frictionless while inside large frictional forces exist due to the large velocity gradient across the layer.

Consider a fluid particle in the boundary layer moving around the cylinder adjacent to the surface. Because of the high frictional forces inside the layer, the particle uses a large portion of its kinetic energy circumventing the upstream side of the cylinder. Not enough kinetic energy is left to allow it to continue on its path around the body into the area of increasing pressure on the downstream side. It eventually stops and, because of the increasing pressure in the direction of flow (adverse pressure gradient), it begins moving in the opposite direction (reverse flow). A vortex forms, grows in size, separates from the cylinder surface, and moves downstream.

The point at which separation occurs depends on several factors, one of the most important being the laminar or turbulent nature of the boundary layer. Separation occurs sooner in laminar flow than in turbulent flow. Turbulent flow is more resistant to the adverse pressure gradient and separates farther along the downstream side. This results in a broad wake for laminar flows and a narrower one for turbulent flows(18). The critical Reynold's number for transition to a turbulent boundary layer on a smooth circular cylinder is on the order of 3×10^5 (19).

The practical importance of this zone of reverse flow is evident when one considers an employee working in a typical position relative to LEV. Employees are normally instructed to position the work between themselves and the source of local exhaust. In this orientation, the worker becomes an obstruction in the flow field and boundary layer separation may occur as the air flows past the worker. Thus, this zone of reverse flow and turbulent mixing develops immediately downstream of the worker. If the source of contaminant is located within this zone, it will be drawn back toward the worker giving rise to significant concentrations of contaminant in the breathing zone. Air entrained into this mixing zone by the vortex formation ultimately determines the concentration of contaminant in it.

The effect of reverse flow on breathing zone concentration was studied by Ljungqvist(20) using a smoke diffuser. The diffuser was placed in a uniform air flow of approximately 0.25 m/s (50 fpm). With no obstruction in the flow, the smoke moved directly toward the LEV source. However, when a test person was placed between the diffuser and the source of air flow, the smoke was clearly directed back toward the person's breathing zone. Ljungqvist attributes this phenomenon to the stationary wake produced by the person in the air flow. He states that individuals in the flow field create two kinds of vortices; the wake caused by the body itself and those arising from movements of the body. He concludes that either of these two wake structures can completely destroy the intended beneficial effect of an LEV system and that no consideration appears to be given to this problem in standard ventilation design.

In studying push-pull ventilation systems, Hampl and Huges[21] also demonstrate the effect of a person in the flow field of a ventilation system. They observed the collection of smoke by a standard LEV hood with various orientations of air jets used as "pushing" air streams. For each orientation where a test mannequin obstructed the pushing jets, smoke was observed in the area in front of the mannequin. However, when the jet was placed between the smoke and the mannequin, no smoke was observed in the breathing zone and all smoke was captured by the hood. They conclude that the "push jet should be located so that the air impinging on the worker or other obstruction should be minimized".

Van Wagenen[22] studied the effects of positive air flow (blowing rather than exhausting air) on concentrations of various contaminants in a welder's breathing zone. He demonstrates that when directional air flow comes from directly behind the welder, concentrations of fume in the breathing zone are equal to or higher than the breathing zone concentration without any air flow at all. He attributes this to the eddy and convective currents around the welder's body. He also notes that positive air flow at 90^o to the welder's position significantly reduces breathing zone concentration compared to the case without any air flow.

The inability of current design procedure to predict breathing zone concentration is a serious obstacle to optimal LEV design. Understanding the interaction of the reverse flow vortices (formed by the separating boundary layers) with a contaminant source downstream of a worker and how this process transports contaminants into and out of the breathing zone is an important factor in making this prediction. A thorough understanding of this phenomenon is needed in order to develop models of contaminant concentration within the breathing zone. The purpose of this research is to develop a mathematical relationship to estimate breathing zone concentration as a function of the contaminant flow rate and local exhaust design parameters.

THEORY

The theoretical basis for estimating the concentration of pollutant released in a separated, near-wake zone is extremely complex. The governing equations include the Navier-Stokes, continuity, and species conservation equations. Successful three-dimensional, high-Reynolds number, numerical simulations of near-wake separation bubbles have not been reported, to our knowledge. The most successful approach seems to be a combination of dimensional analysis and wind tunnel experimentation in the area of estimating pollutant concentrations down wind of simple rectangular cubes[23]. This approach has been pursued primarily in regard to tackling the problem of re- entrainment of pollutants discharged from buildings[24]. Research suggests the mechanism of contaminant removal from the recirculation zone may be either turbulent diffusion, or vortex shedding, depending on whether the flow is more nearly two or three-dimensional[25].

A simple conceptual model based on treating the worker as a two-dimensional circular cylinder is presented here with the assumption of vortex shedding as the principal contaminant removal mechanism. A recirculation zone is hypothesized to exist downstream of the cylinder (worker), and a point source of contaminant is releasing tracer gas at a flow (Q_s) within the zone. Contaminant is being removed from the zone by the alternate shedding of vortices. The average steady-state concentration (C_{st}) within the zone is:

$$C_{st} = \frac{Q_s}{Q_v} \tag{1}$$

where Q_s is the contaminant flow into the zone, and Q_v is the air flow out of the mixing zone.

Recall that vortices form on the downstream side of an object in uniform flow, grow, and separate into the freestream. As vortices move away from the body, a regular, alternating pattern of shedding is noted. The frequency with which these vortices are shed is described by a dimensionless quantity called the Strouhal number (S):

$$S = \frac{fD}{U} \tag{2}$$

where f is the frequency of vortex shedding, D is the diameter of object, and U is the velocity of fluid stream. The Strouhal number remains constant at about 0.21 for Reynolds numbers from 400 to about 200,000[26]. In an industrial setting, Reynolds numbers around workers will almost always fall below 200,000.

Solving equation (2) for f and substituting 0.21 for S gives the frequency with which these vortices are shed downstream:

$$f = \frac{0.21U}{D} \tag{3}$$

The frequency is from one side of the cylinder only and the vortices are formed alternately first on one side of the cylinder then on the other. The total frequency at which a vortex is shed from either side of the cylinder is twice the frequency from a single side, or $2f$. The air entrained into the near-wake region is proportional to this total frequency and the volume of the eddies shed.

If the dimensions (volume) of these vortices were known, an estimate of the rate at which contaminant is removed from the zone (via vortex shedding) could be obtained. A first order approximation for the volume of such a vortex is based on the concept of the formation region. The formation region is the zone immediately downstream of the cylinder and extends until fluid from outside the wake crosses the wake axis[27]. Studies[28,29] suggest that the formation region is approximately a cylinder diameter wide in the range of Reynold's numbers studied here. If one assumes the height of the formation region is as tall as the cylinder (H) and one half the volume is cleared with each vortex shed[25], then the vortex volume (V) is:

$$V = \frac{\pi}{8} D^2 H \tag{4}$$

Since:

$$Q_v = 2fV \tag{5}$$

a simple approximation for the average steady state concentration is:

$$C_{st} = \frac{19 Q_s}{\pi U H D} \tag{6}$$

The principal assumption of this approach is that vortex shedding is the predominant mechanism in contaminant removal from the breathing zone of a worker. In contrast to this convective-air-movement approach is the idea of contaminant removal by turbulent diffusion. Many researchers studying the transport of contaminant in the wake downstream of a bluff body consider turbulent diffusion to be the most important consideration[30-32].

MATERIALS AND METHODS

In an attempt to obtain an empirical estimate of the size and nature of this reverse flow zone, a visualization study was conducted. A continuous source of smoke was achieved by blowing room air through a suction flask containing titanium tetrachloride. A dense smoke was forced out of the flask, through several feet of tygon tubing, and out of a 0.64 cm (0.25 in.) diameter glass tube mounted on a ring stand. Thus, a cloud of white smoke could be continuously generated. Figure (2) illustrates this smoke source in a uniform air velocity of approximately 0.5 m/s (100 fpm).

An anthropometric mannequin was also placed in the flow in two different orientations (A and B). In orientation A, the air flow comes from behind the mannequin (typical orientation of worker with respect to LEV). The effect of the mannequin on the smoke source in this orientation is depicted in figure (3). In orientation B, the smoke source is still in front of the mannequin, but the uniform air flow comes from the side of the mannequin rather than from behind. Figure (4) illustrates the behavior of the smoke with the mannequin in orientation B.

To study quantitatively the impact of this turbulent mixing zone on worker exposure, a separate experiment was designed to examine the breathing zone concentration of a tracer gas contaminant. As with the smoke, the mannequin was positioned in orientations A and B. In each orientation the source of contaminant was placed in front of the mannequin. In orientation A, the source of contaminant was between the mannequin and the LEV source. Thus, the opportunity existed for the separated boundary layer to interact with the source and pull contaminant back toward the mannequin. In orientation B, with flow at 90°, the turbulent zone was formed to the side of the mannequin with less of a chance for interaction with the source.

Exposure comparisons between the two orientations were made by placing a contaminant source at specified distances from the mannequin in each orientation and monitoring the breathing zone concentration. Curves were obtained by plotting breathing zone concentration as a function of the distance (Z) from the source to the mannequin's chest along a line parallel to the wind tunnel floor. To determine any effects due to velocity, these concentration versus distance curves were obtained at three different wind tunnel velocities.

The experiments were carried out in a wind tunnel 1.52 m high X 1.52 m wide X 2.44 m deep (5 ft. X 5 ft. X 8 ft.). The tunnel was equipped with an airfoil and honeycomb at the entrance to reduce turbulence. The rear wall of the tunnel consisted of peg board with 0.64 cm (0.24 in.) holes. This board served to create a perforated plenum for better air distribution across the tunnel. The average air velocity in the wind tunnel was determined by obtaining a velocity profile at three different tunnel depths. Each profile consisted of twenty equally spaced points at a tunnel cross section for a total of sixty measurements. The arithmetic mean of all velocity values was taken as the average tunnel velocity. Measurements were obtained with a calibrated "hot wire" anemometer. A blast gate was installed in the duct leading to the tunnel to regulate air flow.

Data were taken at wind tunnel velocities of; 0.25 m/s (49 fpm), 0.77 m/s (152 fpm), and 1.35 m/s (265 fpm). [Note: Since the tunnel was calibrated without the mannequin in place, these velocities have been adjusted in proportion to the amount of tunnel cross section blocked by the mannequin, approximately 6%]. These velocities were selected to give Reynolds numbers in the same range as those for air flowing around a worker in a uniform flow such as a spray booth. The Reynolds numbers associated with these velocities are 3368, 10,443, and 18,343 respectively. The diameter used to calculate the Reynolds numbers is the breadth of the mannequin chest as measured just under the armpits (20.3 cm (8 in.)).

The anthropometric mannequin used was a commercial mannequin 1.04 m (3.42 ft.) tall and 20.3 cm (8 in.) wide at the chest. One end of a 0.64 cm (0.25 in.) rubber hose was inserted into the back of the mannequin's head and mounted in the mouth about 10.2 cm (4 in.) from the top of the head. The other end of the hose was connected to a Mobile Infrared Analyzer (MIRAN) located outside of the tunnel. In this manner the MIRAN samples from the "breathing zone" of the mannequin.

Sulfur hexafluoride (SF_6) was the tracer gas selected for this experiment. The gas was metered from a certified-standard, gas cylinder of 10% SF_6 through a 0.64 cm (0.25 in.) diameter ceramic sphere. The sphere was mounted on a ring stand approximately 0.69 m (2.25 ft.) from the floor of the wind tunnel. Pores in the sphere allow the gas to diffuse in all directions. The flow of pure SF_6 was 2.36 X 10^{-7} m^3/s (0.0005 cfm) in all experiments.

The mannequin was placed on the centerline of the wind tunnel about 0.6 m (2 ft.) from the tunnel face in the typical orientation with respect to exhaust (i.e. facing the rear of the tunnel). The SF_6 diffuser was also placed on the centerline of the tunnel at a distance of 1.27 cm (0.5 in.) downstream of the mannequin. Thus the source of contaminant was between the mannequin and the source of exhaust.

The tunnel velocity was set at 1.35 m/s (265 fpm) (corrected velocity) and the SF_6 flow at 2.36 X 10^{-7} m^3/s (0.0005 cfm). The system was allowed to equilibrate for 10 minutes, then the breathing zone concentration, as measured by the MIRAN, was logged and integrated over a 10 minute period with a data logger. In this manner, a time weighted average concentration was obtained for that 10 minute period at the given distance. After the logging period, the SF_6 source was turned off and the tunnel was allowed to purge for 10 minutes. After the purging period the SF_6 diffuser was moved 2.54 cm (1 in.) downstream and the process was repeated. Thus, concentrations were obtained at distances ranging from 1.27 cm to 45.72 cm (0.5 in. to 18.0 in.). The experiments were repeated at 0.77 m/s (152 fpm) and then 0.25 m/s (49 fpm).

A repeat of the entire procedure was conducted with the mannequin in orientation B, i.e., with air flowing from the side. The contaminant source was again moved incrementally outward, away from the mannequin's body, and the breathing zone concentration measured for each distance.

RESULTS

The results of the smoke experiment are shown in Figures (3) and (4). When the smoke source was within about 0.31 m (12 in.) of the mannequin in orientation A, the majority of the smoke was drawn back toward the mannequin and swirled within the breathing zone. As the distance between the smoke source and the mannequin increased beyond 0.31 m

(12 in.), the amount of smoke drawn back toward the mannequin decreased. However, the effect of the turbulent zone on the smoke source could still be observed out to distances of about 0.46 m (18 in.). In orientation B, with flow coming from the side, virtually none of the smoke was drawn back into the mannequin's breathing zone (Figure (4)). The smoke moved downstream in basically the same pattern as that from the unobstructed source.

Results for the quantitative experiments are given in Figures (5), (6), and (7) which plot breathing zone concentration as a function of the distance from the source to the mannequin. The upper curve represents flow coming from behind the mannequin (typical worker orientation A) and the lower curve plots each of the same points with flow coming from the side (orientation B). Note from these plots the significant difference in breathing zone concentration between the two orientations. At each velocity, the breathing zone concentration was much greater with the mannequin oriented in the typical position with respect to LEV than when orientated with flow coming from the side. As with the smoke, this effect was particularly pronounced out to distances of at least 0.31 m (12 in.).

Figure (8) illustrates the data (orientation A) plotted in dimensionless terms. The horizontal axis is a dimensionless distance term, R/D where R is the straight line distance from the mannequin's mouth to the SF_6 source and D is the width of the mannequin at the chest. The vertical axis is the natural logarithm of another dimensionless term, C_{bz}/C_{wm}, where C_{bz} is the measured breathing zone concentration and C_{wm} refers to the overall "well mixed" concentration within the tunnel (source flow/tunnel flow).

Plotting the data in this manner effectively collapses the concentrations observed at all three velocities on to a single line. A least-squares regression analysis of this data gives the following empirical formula:

$$C_{bz} = 695 C_{wm} (0.135)^{R/D} \tag{7}$$

with an $r^2 = 0.94$. Thus, for this data set, most of the variability in breathing zone concentration can be explained by the factors considered in this study. Knowing the distance from the mannequin to the source, the mannequin width, the source flow and the tunnel flow, the breathing zone concentration can be predicted with reasonable accuracy.

The theoretical predictions of the steady state concentration (C_{st}) in the mixing zone given by eq.(6) are compared with the average measured breathing zone concentration (C_{bz}) within one body distance (i.e. 8 inches) in Table I. This average measured value is calculated as the arithmetic mean of the readings taken out to 8 inches from the mannequin's body, at a given velocity. As the data shows, agreement is quite good with the error ranging from +11% to a -17% and correlated with Reynolds number.

DISCUSSION

With the mannequin in orientation A, i.e., uniform air flow from behind, the effect of the separated boundary layer is noted at distances of at least 0.31 m (12 in.) in both the smoke and the SF_6 experiments. Assuming that a linear extrapolation to a person 0.5 m (20 in.) at the chest is appropriate, this would indicate that a significant amount of contaminant could be drawn back toward a worker from a contaminant source as far away from the body as 0.75 m (30 in.). Thus, boundary layer separation is likely to be important in virtually any operation in which the source of contaminant is handled, and a nearly uniform air flow is present e.g. spray painting.

On the other hand, when the mannequin is positioned with flow coming from the side, the turbulent zone formed by the separated boundary layer has less opportunity for interaction with the source. This is reflected by the fact that virtually no smoke and very little SF_6 is detected in the breathing zone of the mannequin in this orientation.

At each velocity, the peak concentration occurs at a source distance of about two inches. At this distance the source is essentially in the hands of the mannequin. The peak is most probably due to the effect of additional turbulent air motion around the hands and arms of the mannequin.

The reasonable agreement between the theoretical prediction of eq.(6) and the average of the measured breathing zone concentration within one body width is encouraging. The results suggest the importance of vortex shedding. The fact that eq.(6) overestimates at low velocity (Reynolds number) and underestimates at high velocity may reflect the growing importance of turbulent diffusion and enhanced transport. Further research is underway to evaluate and model the mechanisms of transport into and out of the mixing zone.

CONCLUSIONS

The mannequin experiments suggest that boundary layer separation plays a significant part in determining the concentration of contaminant in the breathing zone. The interaction of the separated boundary layer with a contaminant source downstream of a person in uniform flow can pull contaminant back into the breathing zone of the person. This is indicated by the higher concentration measured when the mannequin is in the typical worker position with the air flow coming from behind and the contaminant source downstream. The amount of contaminant observed in the breathing zone is much less when the mannequin is positioned such that the air could flow from the side. The turbulent mixing zone is formed more to the side of the mannequin and thus has less opportunity to interact with the contaminant source.

These results suggest that in situations such as paint booths where a worker is immersed in a uniform flow, a higher level of control may be achieved by standing to the side the workpiece rather than with the back to the flow. One should be cautious when extrapolating to real life situations, however. A stationary mannequin and a passive source were studied in this experiment. In industrial situations, workers are seldom stationary and contaminant sources are not typically passive, i.e., contaminant usually issues from the source with some momentum and direction. In addition, the influence of other obstructions, i.e. workpieces and machinery, and the boundary layers associated with them must also be considered. Although these restrictions may limit the applicability of the results; it appears that improvement in contaminant control is possible by considering worker orientation with respect to air flow.

The ability to draw one line through all the data with such a high correlation indicates that some consistent mechanism(s) such as vortex shedding and/or turbulent diffusion are at work removing contaminant from the reverse flow zone. While the simple model presented in eq.(6) and the approximate agreement with data does not in itself confirm vortex shedding as the mechanism, it does provide a reasonably accurate conceptual model. If vortex shedding is, in fact, the significant mechanism, the model previously discussed must be expanded to consider the three-dimensional nature of the problem. Recent visualization studies using the test smoke indicate that air flowing down over the mannequin's head into the mixing zone plays an important part in determining the dimensions of, and concentrations in, the mixing zone.

A theoretically complex problem relating to the effect of the separated boundary layer on breathing zone concentration is introduced when the freestream velocity is no longer uniform but accelerating. This is the case in the majority of industrial situations involving hoods for such operations as welding, manual powder transfer, etc. In front of a hood it would be expected that the additional acceleration given to the air as it moves around the object would alter the characteristics of the turbulent zone. It is possible that this additional acceleration may act to decrease the size and influence of this downstream vortical mixing zone. Additionally, air flows into a hood from all directions, causing velocity vectors in three dimensions as opposed to the two dimensional uniform flow situation studied here. Further research into this phenomenon is presently underway.

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Table I. Comparison between Theoretical and Measured Average Concentrations in the Separated Boundary Layer

WIND TUNNEL VELOCITY (fpm)	THEORETICAL CONCENTRATION FROM EQ. #6 (ppm)	MEASURED CONCENTRATION (AVERAGE VALUE) (ppm)	ERROR
49	27.2	24.5	+11%
152	8.8	8.3	+1%
265	5.0	6.0	-17%

FIGURE CAPTIONS

Figure 1 - Boundary layer separation around a circular cylinder in uniform flow. Adapted from reference 18.

Figure 2 - Smoke source in an unobstructed uniform velocity of 100 fpm.

Figure 3 - Smoke source placed downstream of mannequin in orientation A (uniform velocity of 100 fpm). Arrow indicates direction of air flow.

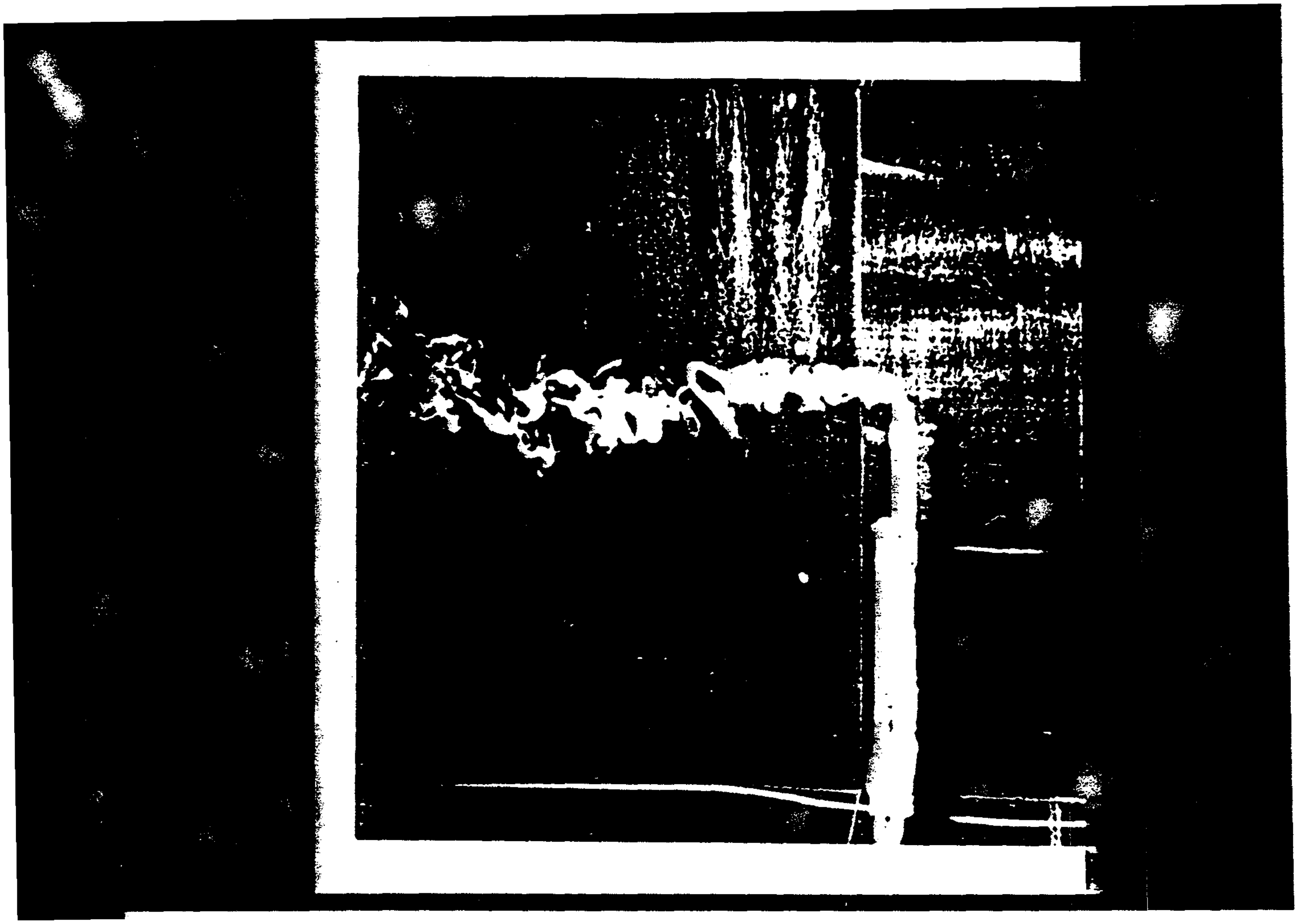
Figure 4 - Smoke source placed downstream of mannequin in orientation B (uniform velocity of 100 fpm).

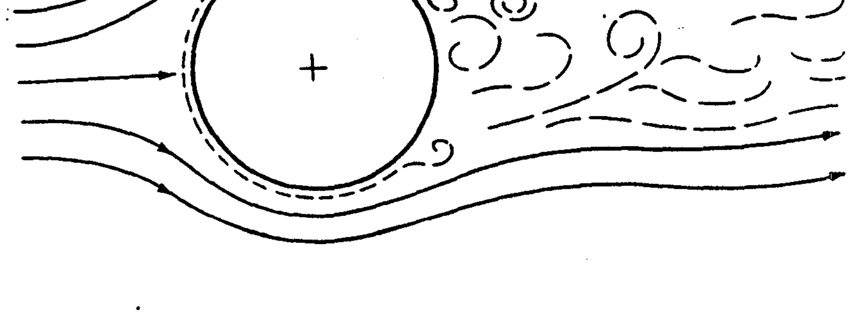
Figure 5 - Plot of SF_6 concentration as a function of source distance for the typical position (orientation A) and the situation when air flow is from the side at 90° (orientation B) in a uniform velocity of 49 fpm.

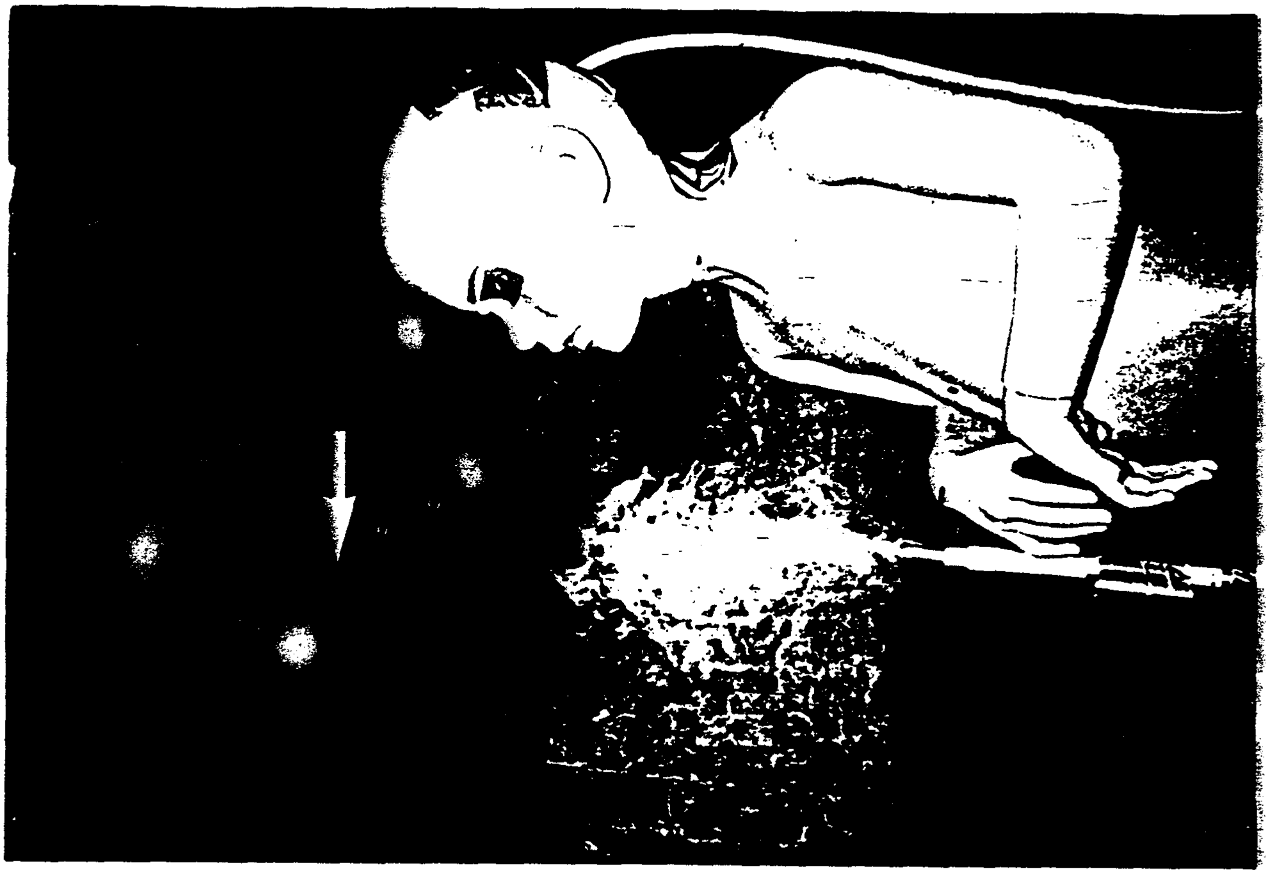
Figure 6 - Plot of SF_6 concentration as a function of source distance for the typical position (orientation A) and the situation when air flow is from the side at 90° (orientation B) in a uniform velocity of 152 fpm.

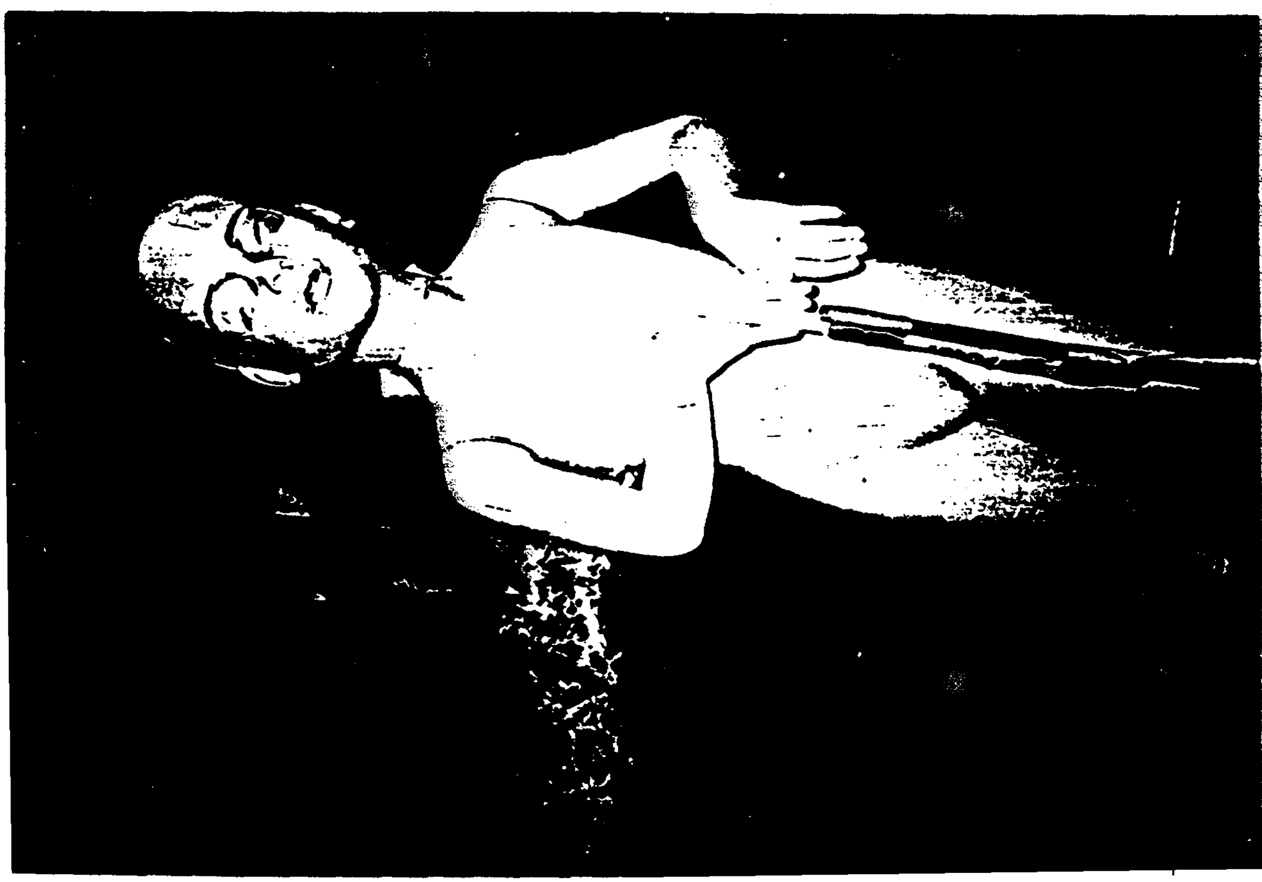
Figure 7 - Plot of SF_6 concentration as a function of source distance for the typical position (orientation A) and the situation when air flow is from the side at 90° (orientation B) in a uniform velocity of 265 fpm.

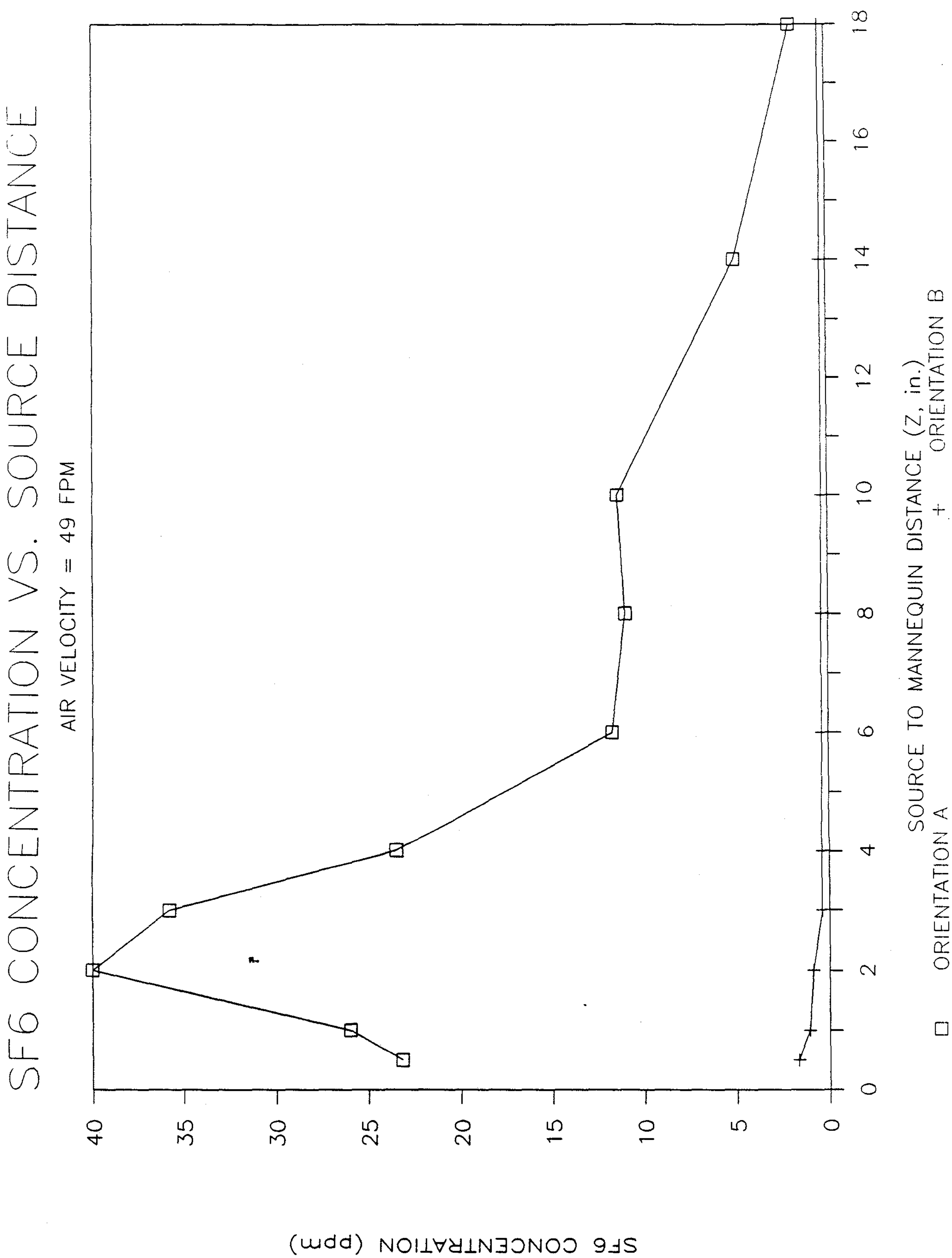
Figure 8 - Semi-Log plot of dimensionless concentration as a function of dimensionless source distance (orientation A) for different wind-tunnel flows (Q_h).



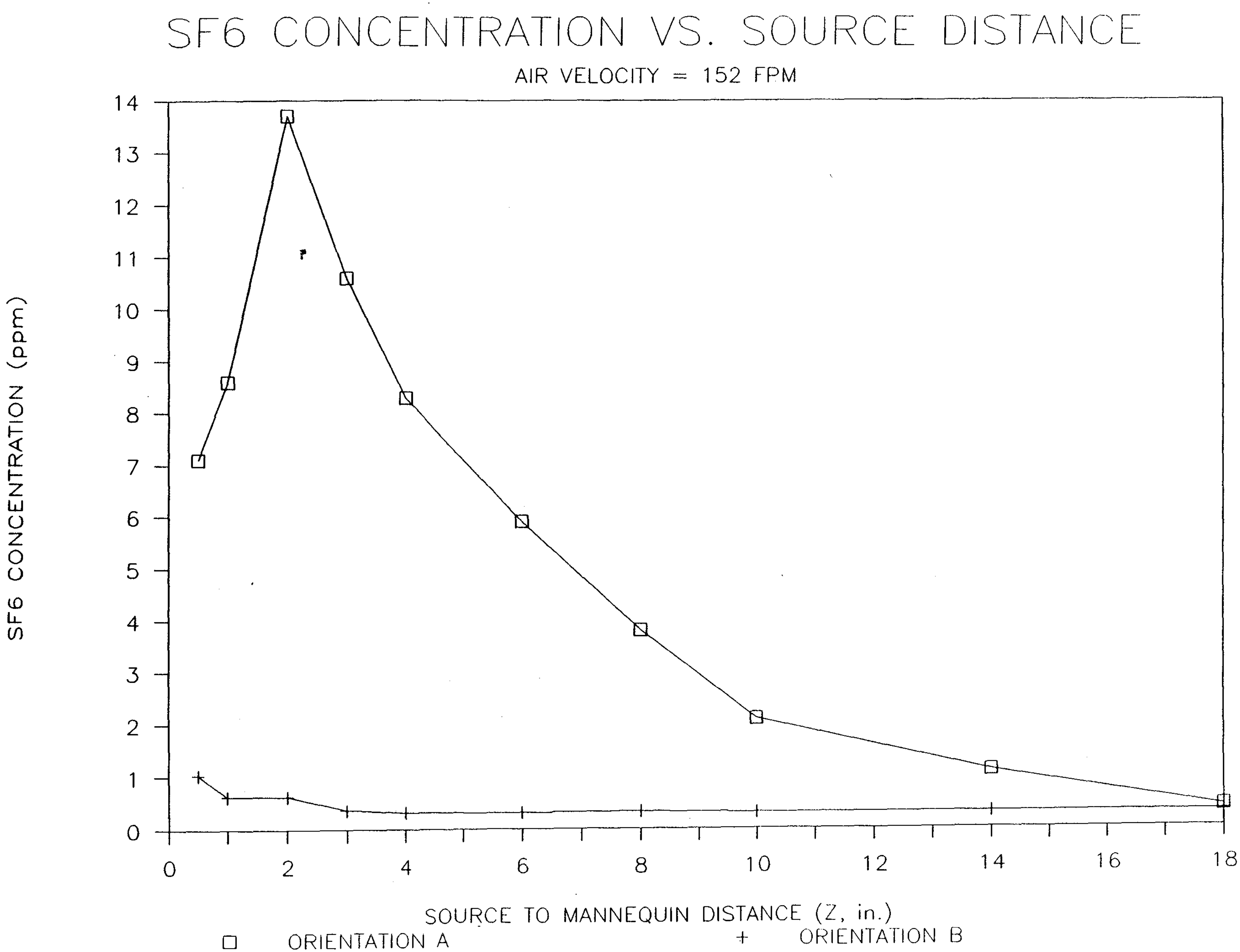


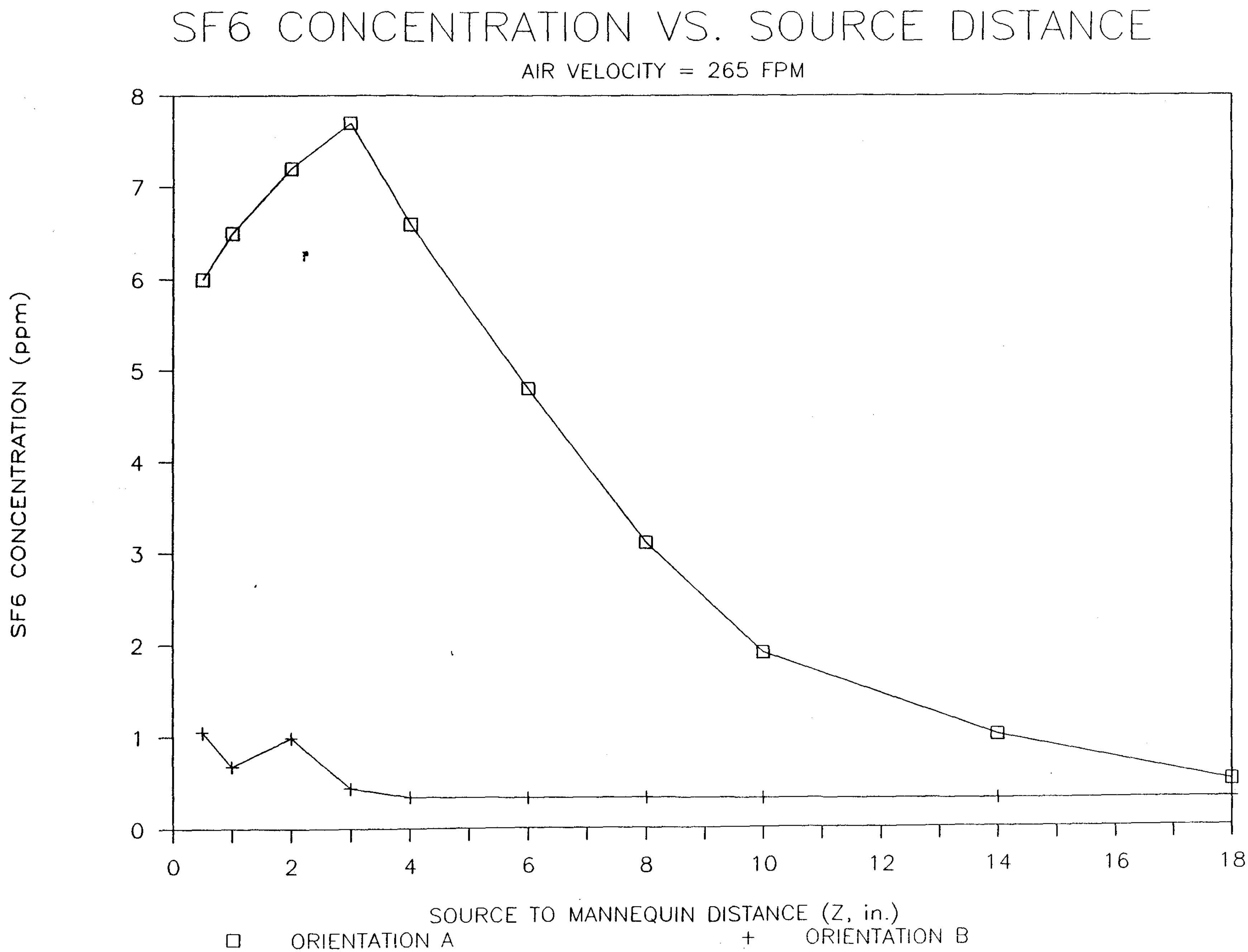


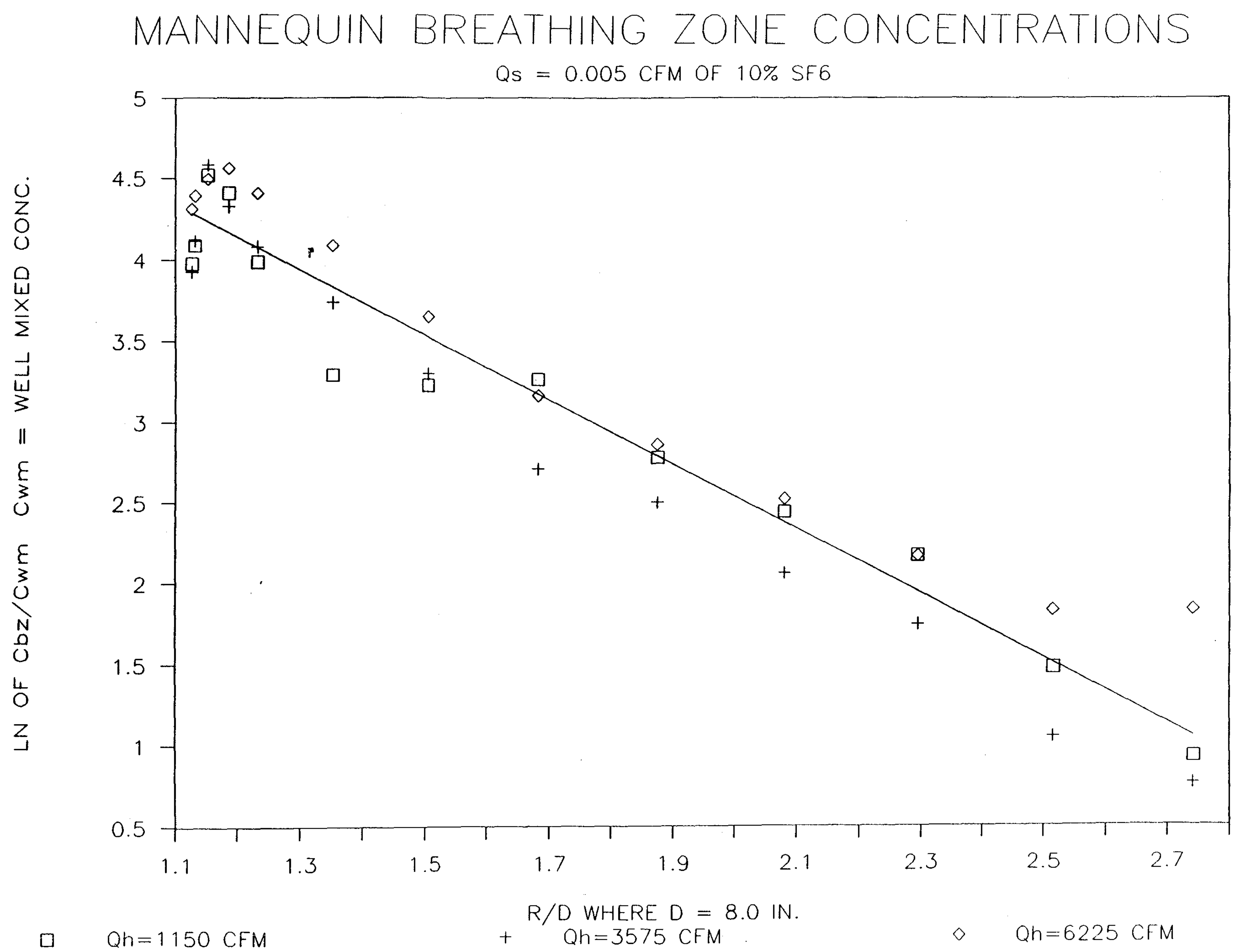




SF6 CONCENTRATION VS. SOURCE DISTANCE
AIR VELOCITY = 49 FPM
SF6 CONCENTRATION (ppm)
SOURCE TO MANNEQUIN DISTANCE (Z, in.)
ORIENTATION A
ORIENTATION B
0
5
10
15
20
25
30
35
40
0
2
4
6
8
10
12
14
16
18


SF6 CONCENTRATION VS. SOURCE DISTANCE
AIR VELOCITY = 152 FPM
SF6 CONCENTRATION (ppm)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
0
2
4
6
8
10
12
14
16
18
SOURCE TO MANNEQUIN DISTANCE (Z, in.)
ORIENTATION A
ORIENTATION B


SF6 CONCENTRATION VS. SOURCE DISTANCE
AIR VELOCITY = 265 FPM
SF6 CONCENTRATION (ppm)
0
1
2
3
4
5
6
7
8
0
2
4
6
8
10
12
14
16
18
SOURCE TO MANNEQUIN DISTANCE (Z, in.)
ORIENTATION A
ORIENTATION B


MANNEQUIN BREATHING ZONE CONCENTRATIONS
Qs = 0.005 CFM OF 10% SF6
LN OF Cbz/Cwm   Cwm = WELL MIXED CONC.
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
1.1
1.3
1.5
1.7
1.9
2.1
2.3
2.5
2.7
R/D WHERE D = 8.0 IN.
□ Qh=1150 CFM
+ Qh=3575 CFM
◇ Qh=6225 CFM