In-Mask Aerosol Sampling For Powered Air Purifying Respirators

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B.Y.U. LIU[A], K. SEGA[A]*, K.L. RUBOW[A], S.W. LENHART[B] and W.R. MYERS[B]

[A]Particle Technology Laboratory, Mechanical Engineering Department, University of Minnesota, Minneapolis, MN 55455-0111;
[B]U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, Division of Safety Research, Morgantown, WV 26505

A system for sampling aerosols in the facepiece of a powered air purifying respirator has been described. The system consists of a sampling inlet mounted on the respirator facepiece, a filter cassette and a personal sampling pump. The theoretical and practical considerations leading to the design of the sampling inlet have been discussed and experimental data presented showing the efficiency of the inlet as a function of particle size and sampling flow rate. The in-mask sampling system has been designed for powered air purifying respirators.

Introduction

Risks to human health through exposure to potentially harmful airborne contaminants are encountered daily by individuals in many occupations. Often respirators are used to reduce a particular job's health risk to a safe level, and protection factor values have been assigned to various respirator classes as guidance for respirator selection. Assigned protection factors are not based upon actual field measurements of workplace protection factors,[1] but rather upon the results of quantitative fit tests which have been performed under controlled laboratory conditions. The extent to which the results of quantitative fit tests predict a respirator's protective capabilities during actual use has not been established.

In an effort to study the performance of respirators in the workplace, NIOSH has initiated a program to evaluate respirator performance under actual use conditions. The reliability of the information produced by this research is strongly dependent upon the sampling techniques used to estimate contaminant concentrations inside the facepieces of test respirators. Therefore, this article addresses one aspect of the NIOSH respirator research program: the design of a high efficiency sampling system for the collection of contaminant particles within the facepiece of a powered air purifying respirator.

Theoretical and Practical Considerations in the Design of an In-Mask Aerosol Sampling System

For reason of practicality, it was decided to design the in-mask sampling system around the standard, commercially available plastic filter cassette (Model M000 037 A0, Millipore Corporation, Bedford, MA 01730). The filter cassette is located on or near the facepiece to minimize particle loss in the tubing between the inlet and the cassette. The sampling flow rate is limited to 1 to 4 liters per minute because of the availability of sampling pumps in this flow range.

The above considerations led to the design of the sampling system shown in Figure 1. The system consists of a stainless steel inlet probe secured to the facepiece of the respirator, a filter cassette and a personal sampling pump. The theoretical considerations leading to the design of the inlet probe are described below.

The entry of particles into an inlet opening under a suction flow is affected by several variables, all of which can cause
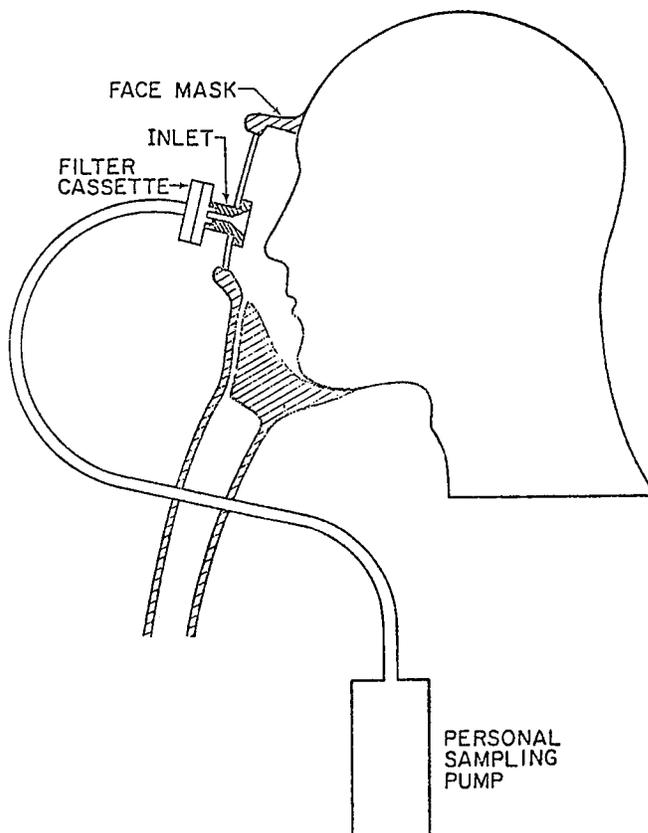

Figure 1 — Schematic diagram of in-mask aerosol sampling system.

particle loss at the inlet. The principal loss mechanisms of concern are sedimentation and inertial impaction, including inertial impaction caused by the turbulent fluid motion. These mechanisms are important for large particles, particularly those at or near the upper respirable size limit of 10 μm. Browian diffusion is generally unimportant over the entire respirable size range, down to a particle size of 0.01 μm, if reasonable inlet sizes (thickness of diffusion boundary layer small compared to tube radius) and sampling flow rates are used. Therefore, an inlet designed to minimize particle loss by sedimentation and inertial impaction for large particles can be expected to perform well for particles of all sizes in the respirable range.

Consider the sampling system shown in Figure 1. A sampling efficiency for the inlet can be defined as follows:

Inlet efficiency =

$$\frac{\text{Aerosol concentration sampled by the filter}}{\text{Aerosol concentration in the original sampled volume}} \quad \text{(1)}$$

The sampling efficiency of a vertical inlet tube under calm air conditions has been studied by a number of investigators including Davies[2] and Agarwal and Liu.[3] They showed that the efficiency is primarily a function of the dimensionless particle settling speed,

$$V_s' = V_2/U \quad \text{(2)}$$

and the dimensionless Stokes number

$$St = \frac{\tau U}{(D/2)} \quad \text{(3)}$$

where V_s is the terminal settling speed of the particle, U is the average fluid velocity in the inlet tube, τ is the particle relaxation time and D is the diameter of the inlet. For particles settling in accordance with the Stokes law,

$$V_s = \tau g \quad \text{(4)}$$

and
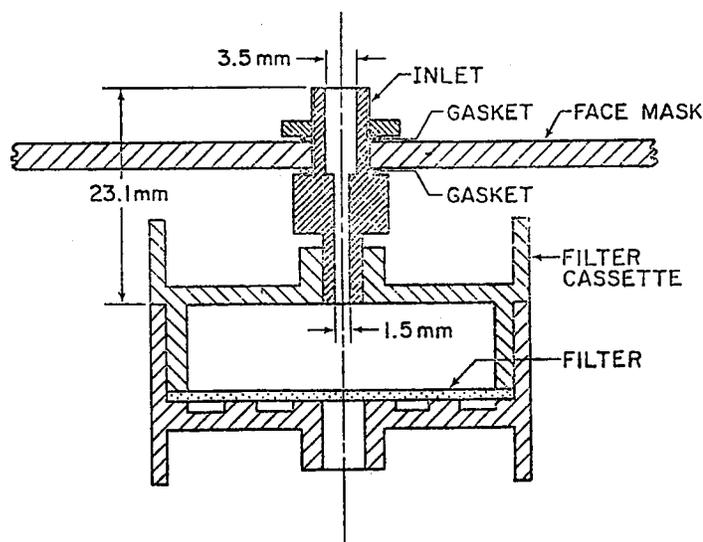
$$\tau = \frac{D_p^2 \, \rho_p}{18 \, \mu} \quad \text{(5)}$$

where g is the acceleration of gravity, D_p is the particle diameter, ρ_p the particle density and μ is the viscosity of air. Davies suggested that perfect sampling, i.e. inlet efficiency of close to 100%, can be obtained if the following criteria are met:

$$\begin{aligned} St &< 0.032 \\ V_s' &< 0.04 \end{aligned} \quad \text{(6)}$$

The Agarwal and Liu criteria for perfect sampling are considerably less stringent and can lead to orders-of-magnitude differences in the values of St and V_s' for perfect sampling.

The above theoretical criteria can provide some general guidance for inlet design, but they cannot be used rigorously to predict the actual inlet performance. The reasons are as follows: first, these criteria are derived assuming calm air conditions. Within the facepiece of a respirator, the air is quite turbulent. Secondly, the theoretical inlet efficiency defined is based on aerosol penetration through the inlet opening only, i.e. all particles passing through the inlet opening are considered to be sampled, ignoring losses on the way to the filter.

In spite of these limitations, theoretical and experimental studies on inertial impaction have shown that inertial effects are generally important only when the Stokes number is of the order of unity or larger, whereas for small Stokes numbers, say below about 0.1, inertial effects are often negligible. Similarly, the effect of particle sedimentation is generally negligible when the dimensionless settling speed, V_s' is small compared to 1.0.

At a given sampling flow rate, the diameter of the inlet tube affects St and V_s' in different ways. A large tube diameter would give rise to a small Stokes number and a large V_s', while a small tube diameter would give rise to a large Stokes number and a small V_s'. An appropriate intermediate tube size can often be found to keep both St and V_s' reasonable for practical inlets.

Figures 2 and 3 show the two sampling inlets developed and tested in the present study. The corresponding values of St, V_s' and the Reynolds number, Re, for these inlets are
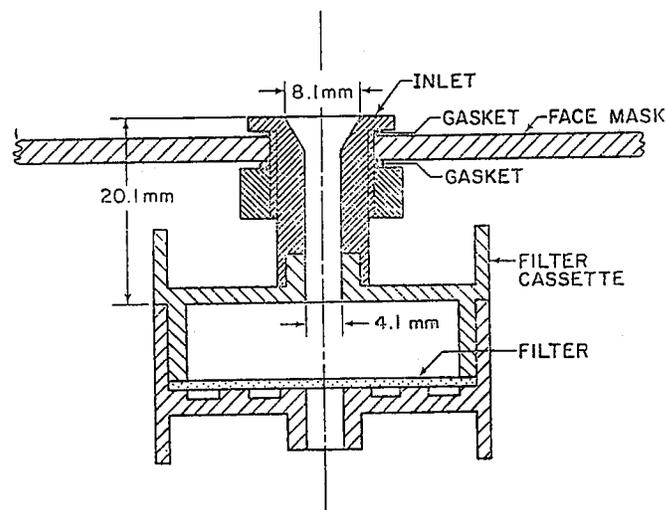

Figure 2 — Schematic diagram of Inlet I.

Figure 3 — Schematic diagram of Inlet II.

TABLE I
Stokes Number, St, Dimensionless Settling Speed, V_s' and Reynolds Number, Re, for Two Experimental Inlets (Dp = 10 μm)

	Inlet I			Inlet II		
Qs, L/min	1.0	2.0	4.0	1.0	2.0	4.0
St[A] (D=3.5 mm)	0.30	0.60	1.20	0.024	0.049	0.097
(D=1.5 mm)	3.82	7.65	15.29			
V_s'[B]		1.72×10^{-3}	8.62×10^{-4}	4.31×10^{-4}	9.32×10^{-3}	4.66×10^{-3}	2.33×10^{-3}
Re[C]		928	1856	3712	339	678	1356

[A]The Stokes number is calculated using the diameters of 3.5 mm and 1.5 mm for Inlet I and the diameter of the inlet opening, 8.1 mm, for Inlet II.

[B]V_s' is calculated using diameters of 3.5 mm for Inlet I and 8.1 mm for Inlet II.

[C]The Reynolds number is calculated using diameters of 1.5 mm for Inlet I and 4.1 mm for Inlet II.

shown in Table I for sampling flow rates of 1, 2 and 4 liters per minute. Both inlets are designed to allow the standard plastic filter cassette to be attached directly to them to form a tight seal. Inlet I of Figure 2 is a small inlet, which plugs into the inlet opening of the filter cassette while Inlet II of Figure 4 is a larger inlet. The latter inlet also provides a tapered entrance and a smooth internal surface.

The values of St and V_s' in Table I show that for both inlets, the value of V_s' is quite small for all three flow rates considered. Therefore, sedimentation is unlikely to be a problem for either inlet. For Inlet I, two Stokes numbers are shown, corresponding to the internal diameters of 3.5 mm and 1.5 mm, respectively. The large Stokes number shows that for this inlet, inertial deposition is likely to be a problem both at the entrance to the inlet and in the interior of the inlet where the flow passage expands from 1.5 to 3.5 mm. For Inlet II, the maximum Stokes number at the entrance is only 0.097. This, coupled with the tapered entrance that provides a smooth and gradual transition for the flow, should make this inlet an inherently more efficient inlet for the in-mask sampling of aerosols, as the data presented below will show.

Experimental Studies

The evaluation of these inlets was accomplished by means of the experimental system shown in Figure 4. The system consists of a powered air purifying respirator to which the sampling inlet is attached. The respirator is mounted on a manikin head, which is connected via a tube in the manikin's mouth to a breathing machine. The aerosol is injected into the flexible hose between the powered blower unit and the facepiece of the respirator as shown in the diagram.

Two powered air-purifying respirators were used, one containing a full facepiece and the other, a half facepiece. Each respirator is composed of a powered blower unit (containing a blower, two high efficiency filters and a battery pack), a flexible hose with an average diameter of 2.5 cm and a facepiece. The blower unit, when fully charged, was found to provide an air flow of 115 liters per minute.

A breathing machine was used to simulate the human breathing cycle. The machine contains four cam-driven pistons (diameter = stroke = 10.16 cm) moving inside four cylinders. The cylinders can be used individually or in paral-
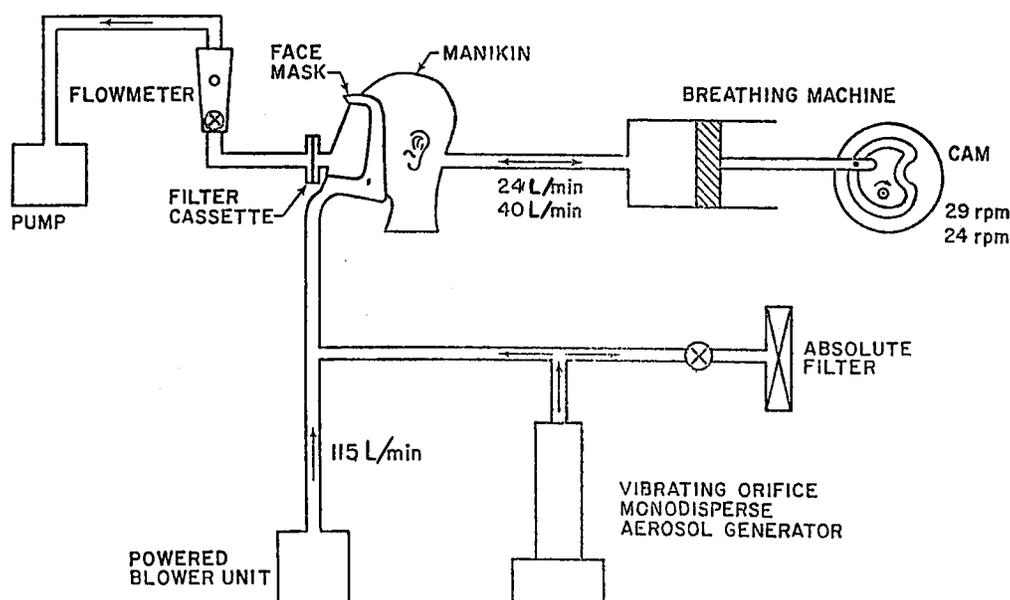

Figure 4 — Experimental system for determining the efficiency of sampling inlets.

TABLE II
Percent Aerosol Penetration Through Inlets I and II as a Function of Particle Size (Full Mask; Sampling Flow Rate, Q_s = 2 L/min; Minute Volume, Q_b = 24 L/min)

D_p =	\multicolumn{3}{c}{Inlet I}		\multicolumn{3}{c}{Inlet II}		
	2.0 μm	5.0 μm	10.0 μm	2.0 μm	5.0 μm^A	10.0 μm^A
	\multicolumn{3}{c}{Penetration}		\multicolumn{3}{c}{Penetration}	
Run 1	91.3	71.1	30.7	100	98.3	97.4
Run 2	95.0	70.4	32.2	100	97.1	99.1
Run 3	93.8	71.6	33.2	100	99.0	98.2
Average	93.4	71.0	32.0	100	98.1	98.2

^{A}For Inlet II and 5 and 10 μm diameter particles, there was no particle deposit on the front face of the inlet. The small amount of material deposited on the inlet was entirely on the inside surface of the inlet tube.

lel to provide the needed breathing volume. In the preliminary experiments comparing the two inlets, the machine was operated at 29 rpm and only one cylinder was used. This provided a minute volume of 24 liters per minute. In the final experiments for the full evaluation of Inlet II, the machine was operated at 24 rpm and with two cylinders operating in parallel to provide a minute volume of 40 liters per minute, corresponding to the breathing rate of an average worker engaged in a moderate level of work.

The aerosols used in these experiments were generated by a vibrating orifice monodisperse aerosol generator described by Berglund and Liu.[4] The device produces monodisperse aerosols by the controlled disintegration of a liquid jet. Particles of 2.0, 5.0, 8.0 and 10.0 μm aerodynamic equivalent diameters were used. The particles generated were oleic acid droplets with a small amount of uranine dye added to allow the droplet mass to be measured by the sensitive fluorometric technique.

The experimental procedure consisted of first starting the breathing machine and the powered blower unit of the respirator and adjusting the sampling flow to the desired value with the aerosol generator turned off. The aerosol generator was then turned on and connected to the system. After an appropriate sampling period, ranging from about 15 minutes to one hour, the aerosol generator was turned off. The sampling pump and the powered blower unit were then

turned off. The inlet probe and filter cassette were removed from the facepiece and the filter in the cassette was taken out and immersed in 50 mL of a wash liquid. The uranine concentration in the wash liquid was measured with a fluorometer. The aerosol deposited on the front face of the inlet was then wiped off with a wet cotton swab, which was also immersed in a wash liquid to measure the uranine concentration. The particle deposit on the inside surface of the inlet was removed by soaking the entire inlet in the wash liquid and measuring the uranine concentration. By this procedure the fraction of particles deposited on the front face of the inlet, the inside of the inlet and on the filter was determined. The detailed procedure of aerosol generation and measurement, including the conversion of the geometrical diameter of the particles to aerodynamic diameter is the same as that described in the paper by Liu and Pui.[5]

Results and Discussion

The results of the preliminary experiments comparing the performance of Inlets I and II are shown in Table II. The aerosol penetration through each inlet was obtained by di-

TABLE III
Percent Aerosol Penetration Through Inlet II as a Function of Sampling Flow Rate, Q_s, and Particle Size (Full Mask; Minute Volume, Q_b = 40 L/min)

Dp	Q_s =	1 L/min	2 L/min	4 L/min
		Penetration
2 μm		100	100	100
5 μm	Run 1	100	100	100
	Run 2	100	100	100
	Average	100	100	100
10 μm	Run 1	100	97.6	91.0
	Run 2	100	97.8	92.9
	Average	100	97.7	91.9

TABLE IV
Percent Aerosol Penetration Through Inlet II as a Function of Sampling Flow Rate and Particle Size (Half-mask; Minute Volume, Q_b = 40/Lpm)

Dp	Q_s =	1 L/min	2 L/min	4 L/min
		Penetration
2 μm		100	100	100
5 μm	Run 1	100	100	100
	Run 2	100	100	100
	Average	100	100	100
8 μm	Run 1	69.6	79.9	84.2
	Run 2	70.1	82.5	85.7
	Run 3	70.0		
	Run 4	70.5		
	Average	70.1	81.2	85.0
10 μm	Run 1	75.3	76.1	72.5
	Run 2	68.9	77.4	72.0
	Average	72.1	76.7	72.2

viding the mass of aerosol collected on the filter by the total mass of aerosol collected on the inlet (the sum of aerosol mass on the front surface and on the inside surface) and on the filter. For Inlet I, the penetration decreased from 93.4% for 2 μm diameter particles, to 32.0% for the 10 μm diameter particles. For Inlet II, the penetration remained high for all three particle sizes used. The maximum penetration was 100% for the 2.0 μm particles, decreasing only to 98.2% for the 10 μm particles.

In light of these results, further evaluation was then limited to Inlet II. The additional experiments performed were made with a minute volume of 40 liters per minute and sampling flow rates of 1, 2, and 4 liters per minute. Both the full facepiece and the half facepiece were used. The results are shown in Tables III and IV. The penetration is seen to remain essentially at 100% for 2.0 and 5.0 μm diameter particles. However, for the 10 μm particles, the penetration varied between 91.9% and 97.7% for the full facepiece and between 72.3% and 76.7% for the half facepiece. The difference in performance of the same inlet on the two facepieces is probably due to the different airflow velocity and patterns in the two facepieces due to their different design and size. The full facepiece has a rather large internal space. Air is introduced in the facepiece through the chin connection and is distributed uniformly along the inside surface of the facepiece, thereby minimizing fluid turbulence. In the case of the half facepiece, the air is introduced through the chin connection directly into the breathing zone. This creates a great deal of turbulence in a small volume, thus contributing to the increased particle deposition by turbulent impaction.

More detailed performance characteristics of Inlet II for different sampling flow rates and particle sizes are shown in Table V. The table gives the fractional particle mass deposited on the front surface of the inlet, the inside surface of the inlet and the filter. Only the average values are shown, since the experiments were quite repeatable and the individual runs did not differ significantly from each other. For the full facepiece, there is essentially no particle deposition on the inside surface of the inlet and the external deposition is also quite small even for particles as large as 10 μm. For the half facepiece, there is increased particle deposition for the larger particle sizes, both on the inside and outside surfaces of the inlet. This increased deposition can be attributed to the increased fluid turbulence in the half facepiece.

The data in Table V provide information on the relative amounts of material deposited on the inlet surfaces and on the filter. The actual inlet efficiency, as defined by Equation (1), could not be determined. In the usual procedure of inlet efficiency measurement, the true aerosol concentration is measured by sampling the aerosol through a reference inlet whose efficiency is known, a priori, to be 100%. An isokinetic probe is usually used as the reference inlet when the flow has well defined speed and direction, as in wind tunnel testing of inlets.[5] However, in the present case, the complicated airflow pattern within the facepiece of a respirator makes it impossible to use isokinetic sampling and there is no other inlet system available that can serve as a reference inlet to determine the true aerosol concentration. Therefore, an alternative procedure had to be devised.

TABLE V
Deposition and Penetration of Aerosols Through Inlet II (Minute Volume, Q_b = 40 L/min)

Sampling Flow Rate Q_s	Particle diameter D_p, μm	% of Particles deposited on front face of inlet, f_1	% of Particles deposited on inside surface of inlet, f_2	% of Particles deposited on filter, f_3	Penetration $p_1 = f_3$	Penetration $p_2 = \dfrac{f_3}{f_2 + f_3}$
Full Mask						
1 L/min	2	0	0	100	100	100
	5	0	0	100	100	100
	10	0	0	100	100	100
2 L/min	2	0	0	100	100	100
	4	0	0	100	100	100
	10	0	2.3	97.7	97.7	97.7
4 L/min	2	0	0	100	100	100
	5	0	0	100	100	100
	10	0	8.1	91.9	91.9	91.9
Half-mask						
1 L/min	2	0	0	100	100	100
	5	0	0	100	100	100
	8	24.5	5.4	70.1	70.1	92.8
	10	21.9	6.0	72.1	72.1	92.3
2 L/min	2	0	0	100	100	100
	5	0	0	100	100	100
	8	14.8	4.0	81.2	81.2	95.3
	10	17.4	5.9	76.7	76.7	92.9
4 L/min	2	0	0	100	100	100
	5	0	0	100	100	100
	8	11.8	3.2	85.0	85.0	96.4
	10	13.4	14.4	72.2	72.2	83.4

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The procedure finally adopted is based on the observation that inefficient aerosol sampling is always associated with particle loss on the inlet surfaces. When aerosol particles are lost by impaction on the inlet surface, the resulting concentration reaching the filter is reduced. Similarly, when particles are lost by Brownian diffusion to the walls of the inlet tube, the resulting aerosol concentration reaching the filter is similarly lower. The absence of particle deposition on the inlet surfaces, therefore, can be taken as evidence that 100% sampling efficiency has been achieved. This is clearly the case for Inlet II for 2.0 and 5.0 μm diameter particles. In the case where there is particle deposition on the inlet surface, only an estimate of the inlet efficiency can be obtained.

To estimate the actual inlet efficiency from the experimental data, we note that a parcel of fluid when drawn into an inlet opening may lose some of the particles by impaction on the front surface of the inlet. Once inside the inlet, additional loss can occur by impaction on the inside surface. The fraction reaching the filter is by definition the inlet efficiency according to Equation (1). However, not all particles found deposited on the outside surface of an inlet probe will come from the flow drawn into the inlet. Some deposited particles may come from the external flow circulating in the facepiece and not drawn into the inlet opening. Therefore, the actual inlet efficiency, η, should lie within the following limits:

$$P_1 < \eta < P_2 \tag{7}$$

$$\text{where} \qquad P_1 = \frac{m_3}{m_1 + m_2 + m_3} \tag{8}$$

$$P_2 = \frac{m_3}{m_2 + m_3} \tag{9}$$

and m_1, m_2, and m_3 are, respectively, the mass of aerosol particles deposited on the front face of the inlet, the inside surface of the inlet and the filter. The values of P_1 and P_2 derived from the experimental data obtained in the present study are given in Table V.

The results in Table V show that in the case of the full facepiece, there is no particle deposition on the external surfaces of the inlet. Consequently, in this case, $\eta = P_1 = P_2$. The actual inlet efficiency is 100% for 2 and 5 μm diameter particles. The efficiency shows only a slight decrease to 97.7% for 10 μm particle size at a sampling flow rate of 2 liters per minute and to 91.8% at a sampling flow rate of 4 liters per minute. The results in Table V for the case of the half-mask show that although the inlet efficiency remains at 100% for the 2 and 5 μm particles, there is some uncertainty in the actual inlet efficiency for the larger particle sizes because of the difference between P_1 and P_2. However, the uncertainty is not large. For the half-mask at a 10 μm particle size and at a flow of say, 2 liters per minute, the actual efficiency should lie in the range of 76.7 to 92.9%, with an estimated average efficiency of 84.8%.

The results of the present study shows that an inlet system, when properly designed, can have high efficiency for aerosol sampling in the facepiece of a powered air purifying respirator. The study also shows that in spite of the lack of a reference inlet with known 100% efficiency, the efficiency of an experimental inlet can be established to a sufficiently high degree of accuracy for aerosol sampling in the facepiece of a powered air-purifying respirator.

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