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Literature Review on Aerosol-Sampling Devices for Respiratory Field Studies

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Literature Review on Aerosol-Sampling Devices for Respiratory Field Studies

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LITERATURE REVIEW ON AEROSOL-SAMPLING DEVICES
FOR RESPIRATORY FIELD STUDIES

by

Carol R. Sutcliffe

ABSTRACT

As part of the first phase of a Respirator Field Performance Factor project for the Occupational Safety and Health Administration/Nuclear Regulatory Commission, a critical review of the literature available on respirator protection studies was completed. Little information was available on experimental conditions, and when the information was available, each study was different in how the aerosol measurements were made and in which parameters were controlled. Under these conditions it is difficult to compare results obtained from different investigators.

The literature was also surveyed for characteristics desirable in an aerosol-sampling inlet in order to representatively sample respirable particles. Available ambient aerosol samplers were critically reviewed for their performance characteristics. Recommendations are made to avoid the pitfalls present in many respirator field studies and to help standardize these studies.

I. INTRODUCTION

The Industrial Hygiene Group at the Los Alamos National Laboratory is involved in a Respirator Field Performance Factor project for the Occupational Safety and Health Administration/Nuclear Regulatory Commission (OSHA/NRC). As part of the first phase of that study, a critical literature review on the parameters and performance characteristics of "commonly used" samplers in respirator protection studies was completed. The purpose of the study was to determine the best method for sampling the ambient aerosol and the aerosol inside the respirator in order to determine respirator field performance factors. We were interested in what was known about aspiration efficiencies and particle losses in each of these samplers and in any information available on the effect of sampling flow rate, orientation, and wind speed or turbulence.

It was soon evident, as far as respirator studies were concerned, that very little documentation was available on sampling design. Most reports gave only a cursory description of their sampling protocol without providing inlet parameters such as diameter, orientation, or flow rate. Because of this lack of information, the review was broadened somewhat to include studies on the efficiency of available inlet configurations and on samplers available for ambient or turbulent aerosol sampling.

II. RESPIRATOR STUDIES

The common practice in respirator studies is to determine the extent of protection by comparing the ambient aerosol concentration with the aerosol concentration on the inside of the respirator. This provides a Protection Factor (PF) for the respirator:

$$PF = \frac{\text{Exposure in absence of respirator}}{\text{Exposure with use of respirator}} .$$

The efficiency of the respirator is then given by (1-1/PF) x 100 percent. Upon the development of respirator fit methods, the term PF was adopted to indicate the face-to-facepiece fit of a particular respirator to a wearer. The current trend now is to use the term Fit Factor (FF) instead of PF for this last item. In this review, because the original papers used PF instead of FF, we will do likewise.

PFs are determined under three general experimental situations: with the respirator fitted to a manikin or mold under either continuous or cycled flows in an aerosol fit or test chamber, with man tests in an environmental chamber under controlled conditions, or with man tests in field studies under limited-control conditions. The problem of comparing the PFs determined under these different situations can be easily seen. Different variables are being held constant in the different situations, and even the parameters being measured are not always the same.

Some fairly extensive field studies have been performed on different types of respirators, but little data are available on the sampling protocol. Some efficiencies of respirators from these studies are shown in Table I. The American Iron and Steel Institute[1] conducted a study from July 1--October 31, 1972, to determine necessary controls needed in coke-producing operations. They compiled data from other studies of respiratory protection in coke-producing operations and conducted limited studies themselves. In most cases, no experimental details were given, only the efficiencies of the respirators.

The Bendix Corporation[2] also conducted a broad study of respirators used in paint-spraying operations throughout the country during 1975-1976. Respirator use in this study was voluntary, and respirators were provided, maintained, and repaired by the management of each plant. Fitting was not provided, but limited instruction was provided to the test subjects. Respirator fit checks varied from good to extremely poor. One major problem associated with this study was that the ambient and in-respirator samplings were obtained by different methods. Ambient sampling consisted of a 1-L/min flow rate through a 37-mm open-face filter cassette located on the lapel of the subject. Respirator sampling consisted of a 1-L/min flow through a 13-ga stainless steel needle protruding through the bottom of the mask, with the aerosol collected on a 13-mm filter. These vastly different sampling designs probably introduce sampling bias, so the two concentrations cannot be properly compared.

A joint field study by the Los Alamos National Laboratory and the New Mexico Health Department[3] (1967) was initiated to evaluate the effectiveness and acceptability of respirators for protection in New Mexico uranium mines. A basic performance criterion of an overall efficiency of 90 percent or greater was established taking into account the filter efficiency and the reliability of the face seal. A minimum performance goal of 95 percent collection efficiency for the respirator filter and an allowable 5 percent facepiece leakage were allowed. The primary purpose of the study was to determine if there were commercially available filter media other than the ultrahigh-efficiency filters with low initial- and final-breathing resistance and good dust-loading characteristics.

One of the major purposes of testing the overall efficiency was to determine the maximum protection that could be obtained if a uranium operator maintained a satisfactory respirator program. This included training and fitting of the respirator before a worker entered the contaminated atmosphere. The sampling procedure included a custom-made 1-inch-diameter by 3/8-inch-thick filter holder with a 13-ga hypodermic needle attached to the holder. The filter holder was mounted from inside the facepiece by pushing the needle through the soft rubber body of the facepiece, which permitted the sample to be collected in the breathing zone. A sampling hose was attached to the needle and led to a personal air sampler worn on the belt. The ambient dust sample was collected with a standard 1-inch filter holder attached to the lapel with the sampling hose leading to a second personal air sampler on the belt. Even though the air-sampling rate for both units was approximately 2 L/min, the collection characteristics were different because of the difference in inlet diameters.

A total of 64 respirator efficiency tests were made ranging from 5 to 59 minutes. Tests were made on 15 men involved in a variety of operations. The total included nine respirator efficiency tests made by a team of men in the engineering department of one of the mining companies using Los Alamos equipment. The results were comparable with those obtained by Los Alamos. The men were instructed to carry on their normal duties with the normal amount of talking or head turning during the time that they wore the respirator. The results of the respirator efficiency tests are shown in Table I. The results of 17 respirator efficiency tests made from 5 to 6 minutes indicated the efficiency ranged from 95-96.5 percent. The results of 10 respirator efficiency tests with a duration ranging from 10 to 59 minutes indicated an average efficiency ranging from 96-99 percent. These comparisons may indicate that the respirator face seal improves with increased wearing time. This is possibly due to the respirator becoming properly seated and perhaps to the perspiration seal.

The efficiencies of several respirators in removing the airborne radon daughters that were attached to dust in underground Colorado mines were reported by Martz and Schiager[4] in February 1968. The protection afforded to working uranium miners by dust respirators was estimated by comparison with *in vivo* counting of the internally deposited radon-daughters active dust present in the respiratory systems of miners at the end of the working shift. The mean protection efficiency obtained was 85.2 ± 13.8 percent, based on *in vivo* counts of 21 miners.

In 1972 Los Alamos National Laboratory[5,6] made quantitative fit tests on many of the Bureau of Mines approved disposable (or single-use) quarter-mask and half-mask dust respirators on the market. The main purpose of this National Institute for Occupational Safety and Health (NIOSH)-sponsored study was to evaluate the proposed concept of an anthropometrically selected test panel and the two quantitative man-test systems developed for use by the NIOSH.

The respirators were tested by two basic methods. One method was to measure the overall performance or efficiency of the respirator by equipping the facepiece with a normal approved dust filter and measuring the penetration with a sodium chloride (NaCl) aerosol having a Mass Median Aerodynamic Diameter (MMAD) of 0.6 μm. The second method was to measure only the facepiece leakage. This was done by replacing the dust filter with a high-efficiency filter(s) and performing quantitative fit tests with a 0.8-μm MMAD polydispersed dioctyl phthalate (DOP) aerosol. The same 16 men were used to test all of the respirators with both methods. The test subjects performed seven exercises during the test, which included smiling and coughing. The data were analyzed using (1) the average of all seven exercises and (2) only the basic five exercises. These two methods were used because there was still some question as to whether a smile and a cough should be included in the exercises designed to simulate work conditions. The results of measurement of overall respirator performance and the measurement of facepiece leakage only when equipped with a high-efficiency filter are shown in Table I.

TABLE I

RESPIRATOR STUDIES

Investigator Respirator	Aerosol (Particle Size)	Particle Concentration (mg/m^3)	Test Period (h)	Number of Tests	Respirator Mounting	Range Efficiency (mean)
American Iron and Steel[1] (1972)						
Bethlehem (W.A. Burgess) (1967)						
MSA Dustfoe 66 (old)	Coke (NG)	NG	NG	3	Manikin On Larry Car	82.7-86.7
MSA Custom Cumfo (S Filter)			"	3	"	88.3-94.6
MSA Custom Cumfo (H filter)			"	3	"	76.8-96.1
MSA Dustfoe 77			"	3	"	45.9-89.6
Willson Monomask 600A			"	3	"	72.6-88.7
(1971)						
MSA Dustfoe 66 (new)[a]			"	7	"	91.5-99.2
Willson Monomask 600A			"	5	"	33.2-97.5
MSA Dustfoe 66 (old)			"	2	"	45.0-68.5
W.A. Bugess (1971)						
A.O. Disposable Dust Mist	Coke (NG)	NG	3-4	3	Manikin In Larry Car	95.9-98.5
Welsh 7165	"		3-4	3	"	93.0-98.5
A.O. Dust/Mist	"		4	4	Man Test (Field)	65.3-88.3
Welsh 7165	"		4	4	"	62.7-94.4

[a] A facepiece design change and filter improvement.

TABLE I (Cont.)

Investigator Respirator	Aerosol (Particle Size)	Particle Concentration (mg/m^3)	Test Period (h)	Number of Tests	Respirator Mounting	Range Efficiency (mean)
W.A. Burgess (1970)						
AISI PAPR Supplying (MSA Custom Comfo)	Coke (NG)	NG	NG	5	Man Test Working Conditions (Field)	93.3-98.7
AISI PAPR Supplying (Acme Duo Seal)	"	"	"	5	"	94.8-97.6
AISI Helmet (Shroud outside tied)	"	"	"	2	"	99.0
AISI Helmet (Not tied)	"	"	"	3	"	92.3-96.0
U.S. Steel (1972)						
A.O. Dust/Mist	Coke (NG)	NG	8	7	Man Test (Field)	(90.0*)
Welsh 7165	"	"	"	7		(80.0*)
Bendix Corporation[2] (1973-1976)						
MSA 85556	Paints (Metals-Majority Small:1-5 μm)	NG	NG	11	Man Test (Field Conditions)	69.1-100.0
AO 5051	"	"	"	3		24.0-75.0
Binks Air Hood (P/N 40-29 Supplied Air)	"	"	"	1		100.0
Cesco (P/N 70-440)	"	"	"	1		55.7

TABLE I (Cont.)

Investigator Respirator	Aerosol (Particle Size)	Particle Concentration (mg/m^3)	Test Period (h)	Number of Tests	Respirator Mounting	Range Efficiency (mean)
DeVilbiss MPH-529 (canvas head, supplied air)	"	"	"	7	"	67.4-96.3
Pulmosan C251	"	"	"	2	"	64.9-96.4
Safeline 5211	"	"	"	2	"	51.1-54.2
Welsh 7511	"	"	"	2	"	72.0-88.2
Welsh 7531	"	"	"	3	"	97.8-100.0
Willson GA-2, Supplied Air	"	"	"	1	"	83.6
Wilson 841 CP	"	"	"	2	"	81.8-94.0
Willson 941 CP	"	"	"	1	"	100.0
Willson 1221-14	"	"	"	3	"	90.0-96.2
Los Alamos[3] (1967)						
1/2 Mask (English Wool)[b]	Radon Daughter Attached to Mine Dust (NG)	NG	.08 to 1	18	Man Tests (Field Conditions)	93-99
1/2 Mask (E Wool)	"	"	"	8	"	94-99
1/4 Mask (E Wool)	"	"	"	16	"	95-99
1/4 Mask (E Wool)	"	"	"	20	"	92-98
1/2 Mask (Fume)	"	"	"	6	"	93-98
1/4 Mask (Dust)	"	"	"	3	"	80-92

[b] Filter type.

TABLE I (Cont.)

Investigator Respirator	Aerosol (Particle Size)	Particle Concentration (mg/m^3)	Test Period (h)	Number of Tests	Respirator Mounting	Range Efficiency (mean)
Los Alamos[5,6] (1973)						
MSA Dustfoe 66	NaCl (.6 μm)	~14 mg/m^3	NG	16	Man Test, Environ-mental Chamber	89.0-97.1
MSA Dustfoe 77	"	"	"	"	All Exercises	69.0-96.0
A.O. 3030	"	"	"	"	"	81.0-93.4
A.O. 2090	"	"	"	"		70.0-96.0
W560	"	"	"	"	"	79.0-99.5
P264-7	"	"	"	16	"	77.0-95.2
GL-2000	"	"	"	"	"	79.0-98.3
Welsh 7100	"	"	"	"	"	82.0-98.4
3M 8710	"	"	"	"	"	83.1-94.0
A.O. Dust Demon	"	"	"	"	"	72.4-88.6
Welsh 7165	"	"	"	"	"	88.0-97.3
A.O. 6030	"	"	"	"	"	79.0-98.0
Comfel. "f"	"	"	"	"	"	83.1-96.3
Welsh 750	"	"	"	"	"	94.7-98.9
MSA Dustfoe 66	DOP (.8 μm)	~25 mg/m^3	NG	16	Man Test Chamber	86.4-99.6
MSA Dustfoe 77	"	"	"	"	All Exercises	86.9-99.85

TABLE I (Cont.)

Investigator / Respirator	Aerosol (Particle Size)	Particle Concentration (mg/m^3)	Test Period (h)	Number of Tests	Respirator Mounting	Range Efficiency (mean)
A.O. 3030	"	"	"	"	"	85.3-<99.99
A.O. 2090	"	"	"	"	"	85.4-<99.99
Willson 560	"	"	"	"	"	89.0-99.95
AO 6030	"	"	"	"	"	96.9-99.98
Comfo	"	"	"	"	"	91.0-<99.99
Welsh 7500	"	"	"	"	"	96.0-<99.99
Eastern Associated Coal[7,8] (1974)						
A.O. R2090	Coal Dust	2.02	NG	32	Man Test Field	(80.4*)
MSA Dustfoe 66	"	1.51	"	47	"	(73.7*)
MSA Dustfoe 77	"	1.70	"	37	"	(82.8*)
Welsh 7100	"	1.62	"	20	"	(89.1*)
Welsh 7400	"	1.35	"	19	"	(70.6*)
Revoir, A.O. Corp.[9] (1974)						
Single-Use Respirator						
A. A.O. Dust Demon (Nonapproved) Valveless	Silica (4-6μm)	50-60	1.5	6	Sealed To Mold In Chamber	73.6-71.0
B. 3M 8710(Approved) Valveless (Part II, Title 30)	"	"	"	"	"	99.4-99.8
C. Welch 7165 (Approved), With Valve (Title 21B)	"	"	"	"	"	99.6-99.9

TABLE I (Cont.)

Investigator Respirator	Aerosol (Particle Size)	Particle Concentration (mg/m^3)	Test Period (h)	Number of Tests	Respirator Mounting	Range Efficiency (mean)
A. A.O. Dust Demon (Nonapproved) Valveless	Coal Dust (1.2 μm)	50-100	.5	6	Man Test Chamber	95.6-91.9
B. 3M 8710 (Approved) Valveless (Part II, Title 30)	"					94.8-99.9
C. Welch 7165 (Approved) With Valve (Title 21B)	"					96.9-99.8
A. A.O. Dust Demon (Nonapproved) Valveless	Cotton Dust	1-20	2 hrs	5	Man Test Field	87.5-94.7
B. 3M 8710 (Approved) Valveless (Part II, Title 30)	"	"	"	6	"	95.5-98.8
C. Welch 7165 (Approved) With Valve (Title 21B)	"	"	"	5	"	92.7-98.3
Kaiser Aluminum[10] (1981)						
Disposable Respirator 3M 8706	Coke (Total Particulates)	NG[c]	NG	10		(94.4*)
9906	"	"	"	25		(99.4*)
9910	"	"	"	25		(99.5*)
Treaftis et.al[11] (1981)						
Racal AH-1	Coal Dust	3-38	8	5	Manikin In Chamber	(~100*)
	Silica	9-176		21		(99*)
Racal AH-5	Silica	9-176		5		(99*)
White et al[12] (1982)						
Racal AH-3 and AH-5 Air Purifying	Silica (Total Particulate)	NG	8 (Summed two 4-h Periods)	22	Man Test Field	57.5-99.6
	Pb	NG	8	33	Man Test Field	21.9-98.8

[c] Not given.

Harris et al.[7,8] of the Eastern Associated Coal Corporation looked at respiratory protection in the coal-mining industry (1970-1973). The ambient sampler was a 10-mm cyclone connected to a filter cassette located generally on the pocket (though the location varied and the cassette was sometimes on the machine being operated) and oriented upward at a 90° angle to the body. This orientation may have presented problems with particles from the clothing falling into the sampler. The respirator aerosol sampler consisted of a short piece of rubber tubing located near the bottom of the respirator, connected to a 10-mm cyclone and filter assembly. The time during which the respirator was worn was not controlled, but the time not worn was measured by a thermistor located in the respirator. The researchers determined an effective protection factor

$$EPF = \frac{\text{Concentration in ambient air}}{\text{Concentration in respirator}}$$

because they were essentially measuring worker exposure and not the efficiency of the respirator. This is due to the fact that while the respirator was not being worn, the in-respirator sampler was measuring ambient aerosol concentrations, not what was being filtered through the respirator. They obtained a range of EPFs but averaged all factors, despite differences in respirators, job classification, and time the respirator was worn. They also measured a True Protection Factor (TPF) using the best possible fit of respirator and having the respirator worn continuously during measurements. These TPFs were significantly higher than the EPFs as shown below:

MEAN AVERAGE OF SIX RESPIRATORS	
EPF	74 to 78
TPF	89 to 91

W. H. Revoir[9] of the American Optical Corporation looked at three dust respirators under continuous flow conditions sealed to a mold, in man tests in a fit chamber, and in field studies in a cotton textile plant. For the field studies, ambient concentrations were sampled through a tubular extension (100 mm long x 33-mm diameter) pointed downward and located on the shoulder. Although this direction was chosen such that cotton fibers would not settle out into the inlet, biases could have occurred due to orientation. The sampling flow rate was 1 L/min and collection was onto an open-face filter. In-respirator sampling was through a tube connected to the hat worn by the subject. The flow rate was 2 L/min and collection was on a closed-face filter. As can be seen from the above descriptions, the ambient and in-respirator sampling setups were different in inlet design, sampling flows, and means of collection. It has been reported in the literature that open-faced and closed-face filter assemblies have different collection characteristics.[13]

An evaluation of the Racal Airstream helmets, models AH-1 and AH-5, was provided by Treaftis et al.[11] in 1981. They used a manikin in a fit chamber and sampled from inside the respirator through a port in the mouth at a continuous flow of 80 L/min. It should be noted that without the cyclic flow associated with breathing, this type of sampling may not be comparable with concentrations inhaled by a person. Both coal dust and silica aerosols were studied. When the silica aerosol concentration was greater than 25 mg/m^3, even though the respirator was 99 percent efficient, levels of silica present in the respirator were greater than the 0.1 mg/m^3 Threshold Limit Value (TLV) for total insult dust concentrations typical of those used by NIOSH to approve respirators under 30 CFR Part 11.

Another study of the Racal helmets, models AH-3 and AH-5, was provided by White et al.[12] in both a foundry and a battery plant. They obtained a wide range of PFs in part because they were measuring individual exposure as opposed to protection provided by the respirator. Nevertheless, they averaged all their data to obtain a mean PF. They also averaged the data obtained from the two different respirators despite the fact that they function under quite different principles. The sampling procedure used by these investigators also suffered from poor design. Air continuously flows from the top of the helmet out the bottom at approximately 6.5 cfm (184 L/min), and the sampling inlet was oriented 180° with respect to this flow. Sampling bias probably occurred due to particles being diverted around the inlet and not entering the sampling inlet. Even though the ambient-sampling inlet was oriented in the same manner outside the helmet, it would not be expected to be exposed to the same continuous flows as inside the helmet, though turbulence might at times approach these values.

After reviewing the literature, there are several conclusions that can be drawn from the field studies for evaluating respiratory protection. Most studies conducted thus far contain notable flaws. For instance, there is a distinct lack of information provided about the experimental parameters, so the results presented cannot be compared with results obtained from other studies. Because of the complexity and inadequate control of many variables, improper experimental design, inadequate validation, and nonreproducibility, it is impossible to determine from the literature the protection afforded during periods of respirator usage.

In most cases, a personal exposure factor is obtained rather than an indication of protection provided while the worker is wearing the respirator because of the lack of control over many variables. This determination (personal exposure factor) has some purpose, but averaging the numbers to determine a mean PF is misleading. It may be more appropriate to give a range so the minimum protection afforded may be known. More care should be taken in analyzing the results obtained from respirator studies. Only numbers acquired under similar controls and conditions should be averaged to obtain a mean PF.

Recommendations

Several recommendations can be made from this review. First, decide whether measurements are to be made of the adequacy of respirator protection being provided to the workers under the conditions of the test or of respirator performance. To determine respirator performance, we must identify the purpose of the tests and specify constraints. Workers cannot be allowed to remove their respirators during the course of the study. If the respirator is uncomfortable, then that should be noted and shorter studies conducted or the respirator modified. Alternatively, sampling can be interrupted during the time the respirator is not worn. To improve reproducibility, it would be better to compare workers in similar jobs and exposed to similar ambient concentrations. In addition, the test site should have a high-enough ambient aerosol concentration to permit accurate measurement of the aerosol penetrating (or leaking around) the respirator.

Second, the respirators should be provided, maintained, and repaired by the group conducting the experiments. This is the only way that adequate consistency in the type and condition of the respirators being tested can be maintained. In addition, the experimenter should provide fitting and instruction on respirator use. An observer should be present during the testing to confirm that the conditions of the test are being met.

The most important consideration is the method of sampling. Very difficult conditions exist for representatively sampling aerosols both inside and outside the respirator. The air in the respirator is extremely turbulent because of the inhalation and exhalation by the test subject. Because of this turbulence, orientation of the inlet probably does not make much difference, but the inlet should be located near the breathing zone and mouth area. The sampling unit for the ambient measurements should be as close to the breathing zone as possible or in supplied-air respirators close to the air intake, since this more accurately represents the air flowing into the respirator. Turbulence here is also a problem owing to the change in air flow and eddy currents associated with the movement of the test subject. The sampling inlet is best oriented pointing down as opposed to pointing up, where particles can settle or fall into the sampler, or perpendicular to the body, where large particles can be driven into the sampler. With the sampling inlet pointing downward, it should be placed far enough away from the body (a couple of centimeters) to avoid complex air currents.

Both inside and outside samplers should be of the same type. They should sample only respirable particles (<10 μm), since these are the particles of interest. The inlet parameters should correspond to those found most efficient in sampling respirable particles as described in the next section.

III. SAMPLING INLETS

The inlet is a vital component of the sampler, but many samplers possess inlets that have not been vigorously tested. A well-designed inlet must be capable of representatively sampling all particles of interest in an atmosphere with nearly the same efficiency independent of sampling conditions. No general solution exists for the very complex problem of obtaining representative aerosol samples. The following are some of the numerous factors that can cause an error in the concentration of particles being sampled: particle size (which affects sedimentation rate), particle inertia, and impaction properties; sampling-head geometry, orientation, and velocity; and the strength and direction of external flows. All have an effect on how particles are sampled. It is impossible to design an inlet that is not affected by these factors, but it is possible to design an inlet where some of these factors may be ignored or a correction factor applied for a certain range of particle sizes. This section reviews inlets that have been evaluated either experimentally or theoretically in order to determine which inlet may best sample respirable particles (<10 μm) under the turbulent conditions prevalent inside respirators.

Representative sampling is strongly dependent on particle size. At the extremes, small particles have low inertia and therefore follow the flow lines into the sampling orifice, and large particles with high inertia enter the probe in straight trajectories independent of flow lines. Watson[14] found particles below 4 μm to be measured independently of sampling speeds in the range 0.5-2.0 times the wind speed. Wicks and Duckler[15] and later Gill et al.[16] found collection of particles with diameters greater than 50 μm to be independent of aspiration rate. Within the particle range 4-50 μm, aerosol sampling is affected by aspiration rates and external wind velocities, so the sampling design must be sufficiently analyzed to guarantee representative sampling.

The inlet design most prevalent in both theoretical and experimental studies is the cylindrical tube. It appears in various forms such as thin wall, thick wall, blunt edge, sharp edge, round edge, and side port. The ideal shape is a probe with infinitely thin walls. The nearest practical approach is tubing ground to a knife edge at a small cone angle. It is difficult to determine how far from ideality one may venture, but Walter[17] reported erratic concentration measurements obtained with a thick-walled tube ground to a knife edge. Belyaev and Levin[18] observed that the rebound of a particle from the tip of a nozzle into the probe causes less than 5 percent error if the edge thickness is less than 5 percent of the nozzle inside diameter and if the taper angle is less than 15 percent. A round nose probe gives considerable distortion of the flow lines even when sampling isokinetically.[19]

A number of studies have been focused on the diameter of the inlet. In general, the smallest size possible is desired in order to keep aerodynamic disturbances at a minimum. Davies[20] performed a theoretical evaluation of sampling with small tubes, large tubes, and an orifice in a large sampling head. Small tubes are considered to give the same results independent of orientation and are capable of 100 percent sampling efficiency in calm conditions if the inlet radius (r) meets the specifications of Table II. Calm conditions are assumed when the aspiration velocity (U_i) is much larger than the terminal velocity of a particle (V_s). However, U_i must not be so large that the stop distance (d_s) of the particle near the orifice is comparable with the radius of the orifice. If, for a certain particle size and aspiration rate, the radius of a small tube is greater than the left-hand figure in Table II, the particle inertial effects are negligible. If the inlet radius is less than the right-hand figure, the sedimentation effects are negligible and orientation is not a factor. It has been shown[21] that when $r = 5d_s$ the excess concentration of particles in front of the orifice due to inertia is only 1.6 percent, the sampling error must be less than this.

With small tubes in a wind, conditions in Table II apply when $U_0 \leq 1/2\ V_0$. Table III shows the upper limit of allowable wind speed for a particle at different sampling rates. When wind speeds are higher than those listed, inertial effects cause distortion of trajectories, and gravitational effects cause a fall in efficiencies. Levin[22] calculated the efficiencies of sampling by a point sink in a wind (Table IV). These results can also be applied to a tube of small finite radius.

TABLE II

PERMISSIBLE RADII OF TUBES (cm) FOR SAMPLING AEROSOLS IN CALM CONDITIONS[20]

Aspiration Rate Q (cm^3s^{-1})	1	10	10^2	10^3	10^4	10^5
Particle Diameter (μm)	Permissible Radii (cm)					
1	0.033-1.9	0.071-6.0	0.15-19	0.33-60	0.71-190	1.5-600
2	0.051-1.0	0.11-3.2	0.23-10	0.51-32	1.1-100	2.3-320
5	0.093-0.41	0.20-1.3	0.43-4.1	0.93-13	2.0-41	4.3-130
10	0.15-021	0.31-0.65	0.68-2.1	1.5-6.5	3.1-21	6.8-65
20	(0.23-0.10)	(0.50-0.33)	(1.1-1.0)	2.3-3.1	5.0-10.3	11.0-31
50	(0.42-0.042)	(0.90-0.13)	(1.9-0.42)	(4.2-1.33)	(9.0-4.2)	(19-13.3)
100	(0.63-0.023)	(1.4-0.071)	(2.9-0.23)	(6.3-0.71)	(14-2.3)	(29-7.1)
200	(0.89-0.014)	(1.9-0.037)	(4.1-0.14)	(8.9-0.37)	(19-1.4)	(41-3.7)
500	(1.26-0.008)	(2.7-0.025)	(5.8-0.08)	(12.6-0.25)	(27-0.80)	(58-2.5)

Note:
If the radius of the tube is greater than the left-hand value, then error due to particle inertia is negligible. When the radius is smaller than the right-hand value, the settlement of particles produce a negligible effect. For the entries in parentheses the two criteria cannot be met simultaneously. These entries may be sampled satisfactorily by selecting a radius greater than the left-hand value and positioning the tube so the plane of the orifice is vertical.

TABLE III

VALUES OF WIND VELOCITY NOT TO BE EXCEEDED FOR EFFICIENT SAMPLING[20]

Aspiration Rate Q ($cm^3 s^{-1}$)	10^{-1}	1	10	10^2	10^3	10^4	10^5
Particle Diameter (μm)				U_o($cm\ s^{-1}$)			
1	170	370	800	1700	3700	8000	17000
10	9	19	41	88	190	410	880
20	4	8	16	37	80	160	370
50	1	2.3	5	11	23	50	110
100	0.5	1	2	5	10	20	50
200	0.2	0.5	1	2	5	10	20
500	0.1	0.25	0.5	1	2.5	5	10

Note:

Sampling obtained with a "small tube" (radii meeting both criteria of Table II) and in calm air.

TABLE IV

EFFICIENCY OF SAMPLING AEROSOLS BY A POINT SINK IN A WIND[20]

$Q(cm^3 s^{-1})$	10^1				1					10					
$U_o(cm\ s^{-1})$	50	100	200	500	50	100	200	500	1000	50	100	200	500	1000	2000
Particle Diameter (μm)	Percent Efficiency														
1	99	97	91	60	99	99	97	89	89	100	100	99	97	90	72
2	96	88	68	—	99	97	90	61	—	99	99	97	87	72	—
5	76	35	—	—	92	78	41	—	—	98	93	80	28	—	—
10	—	—	—	—	70	—	—	—	—	91	74	29	—	—	—
20	—	—	—	—	—	—	—	—	—	63	—	—	—	—	—
50	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
100	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

$Q(cm^3 s^{-1})$	10^2							10^3							10^4						
$U_o(cm\ s^{-1})$	50	100	200	500	1000	2000	5000	50	100	200	500	1000	2000	5000	50	100	200	500	1000	2000	5000
Particle Diameter (μm)	Percent Efficiency																				
1	100	100	100	99	97	91	65	100	100	100	100	99	97	89	100	100	100	100	100	99	97
2	100	99	99	96	88	68	—	100	100	100	99	97	90	61	100	100	100	99	99	97	87
5	99	98	94	76	35	—	—	100	99	98	92	78	41	—	100	100	99	98	93	80	28
10	97	92	76	—	—	—	—	99	98	93	71	—	—	—	99	99	93	91	74	30	—
20	80	66	—	—	—	—	—	96	89	70	—	—	—	—	99	97	92	63	—	—	—
50	32	—	—	—	—	—	—	82	40	—	—	—	—	—	93	80	46	—	—	—	—
100	—	—	—	—	—	—	—	—	—	—	—	—	—	—	71	30	—	—	—	—	—

If a tube is needed to sample in an arbitrary orientation in a wind, Table V gives the maximum tube radius allowed.[7] For example, if 10-μm particles are sampled in a wind with a velocity of 100 cm/s, then from Table IV a sampling velocity of 100 cm^3/s will give an efficiency of 97 percent. From Table V, with these conditions, the maximum allowable radius is 0.06 cm. Table II, however, lists the minimum acceptable radius as 0.68 cm in order to be free of particle inertia errors. Therefore, 10-μm particles cannot be sampled at 100 cm^3/s in a wind at 100 cm/s with an efficiency of 97 percent.

TABLE V

MAXIMUM PERMISSIBLE TUBE RADIUS r FOR SAMPLING IN ARBITRARY ORIENTATION IN A WIND[20]

Q ($cm^3 s^{-1}$)	1	10^2	10^4	10^5
U_o ($cm\ s^{-1}$)		r(cm)		
10	0.018	0.18	1.8	5.6
50	0.008	0.08	0.8	2.5
100	0.006	0.06	0.6	1.8
200	0.004	0.04	0.4	1.3
500	0.0025	0.025	0.25	0.8

Large tubes must face the wind in order to sample representatively. When the mean velocity in the inlet (U_i) is equal to the wind velocity (U_o), an accurate sample is obtained ($C/C_o = 1$). For light particles, when $U_o/U_i \neq 1$ and $U_i > 0$, C/C_o will still equal 1, but for heavier particles, $C/C_o = U_o/U_i$. The error due to departure from equal velocity conditions is increased when the tube radius exceeds 0.63 cm and is reduced for smaller tubes.

A small orifice in a large suction head was also discussed by Davies.[20] Gravitational settling of particles causes a larger error in sampling compared with small tubes because of dust shadows produced by the large head. In calm air conditions, the limits of tube radius listed in Table II holds. With the orifice near the top of the head, settlement of particles is least when F, the flow per unit length of orifice, exceeds $(3 + 2\sqrt{2})\,\pi\, V_s D$ (D is the diameter of the sampling head). With the orifice in the bottom of the head, no sample is taken until F exceeds $V_s D$. The efficiency of sampling is given by

$$1 - \frac{V_s D}{F} \quad .$$

Efficiency, therefore, depends on the size of the head and not the orifice. In a crosswind, particles may be driven upon the windward side and efficiency falls. The effect is small when d_s, because of the wind, is small compared with the diameter of the head ($U_0 \tau < D$).

Sampling efficiency is primarily affected by three variables: the inlet diameter (D_i), the inlet velocity (U_i), and the particle diameter (D_p). These can be related to two dimensionless quantities, the Stokes number (St) and the relative settling velocity (V_s'). Using Davies' criteria to obtain 100 percent sampling efficiency in calm conditions, St should be <0.032 and $V_s' < 0.04$. Agarwal and Liu[23] have performed calculations that show Davies' criteria to be too strict. They have determined that to obtain a sampling efficiency of 90 percent, the product of (St) (V_s') need only be smaller than 0.1. Therefore, for a $V_s' < 0.04$, St need only be <2.0 in order to sample with an efficiency of at least 90 percent.

Belyaev and Levin[24] showed, experimentally and theoretically, the effect of varying R (U_0/U_i) on the aspiration coefficient (C/C_0) (Fig. 1) for various-sized particles. Several others have also evaluated the effect of orientation on aspiration coefficient according to particle size (Figs. 2 and 3).[14, 25] Durham and Lundgren[25] used a thin-walled tube inlet to relate the aspiration coefficient as a function of both orientation and R (Fig. 4).

Most theoretical studies and some experimental studies have focused on the aspiration coefficient that considers the efficiency of sampling only to the face of the inlet. Tufto and Willeke[26] performed some experiments with a thin-walled inlet tube to determine sampling efficiencies that include particle losses all the way to the measuring

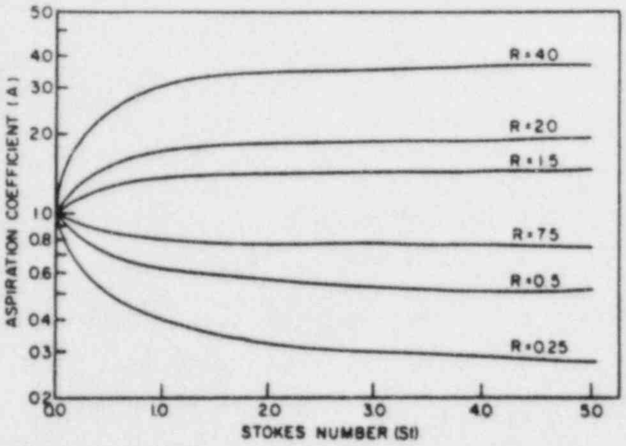


Fig. 1.

Aspiration coefficient at a function of Stokes number (St) and velocity ratio ($R = U_o/U_i$).[24,25]

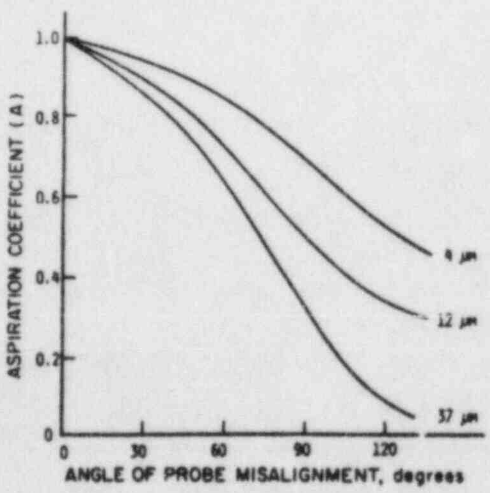


Fig. 2.

Error due to misalignment of probe to flow stream.[14,25]

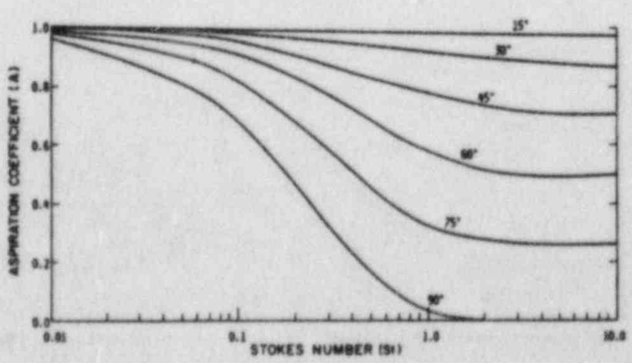


Fig. 3.

Predicted aspiration coefficient vs. Stokes number for angles of 15, 30, 45, 60, 75, and 90.[25]

medium. They considered effects of orientation of the inlet, R, and particle size. Figures 5 through 8 show the results of these experiments.

Deposition of particles on the internal surface of the inlet tube is a function of velocity and particle size. For a particle with an Re < 2000, the flow deposition is governed by Brownian diffusion. Figure 9 shows probe lengths allowing only 1 percent loss by deposition of particles for three different inlet diameters and particle sizes.[19] The length of the probe only becomes important when using small-diameter probes to sample small particles at low-velocity flows. If losses by sedimentation are to be reduced, residence time in the tubing should be reduced by increasing flow velocities by using small-bore tubing. Flows, however, must remain laminar.

When Re > 2000, flow becomes turbulent at some distance from the inlet and the deposition process is due to particles being projected to the walls by turbulent action. Figure 10 indicates lengths of probes giving 1 percent reduction in particle concentration.[19] For turbulent flow, deposition in the tubing is decreased by increasing the bore size of the tube. Any sharp bends under either laminar or turbulent flow should be avoided since particles will depart from following stream lines.

Lundgren and Calvert[27] did some experiments and calculated theoretical correction factors for sampling biases in a cylindrical tube with a side inlet probe and a cylindrical tube with an end inlet probe, sampling at 90° to the flow (Fig. 11). They compared sampling efficiencies with a conventional isokinetic sampler oriented into the flow. Under all sampling conditions, the side inlet probe's geometry will result in a disturbance of the flow field. Sampling biases in both probes were found to depend on both R and St to the extent shown in Figs. 12 and 13. For the side inlet probe with R = .7, inlet-sampling bias will be less than 5 percent over the range St = 0 to .15, whereas at R = 1, the error becomes about 20 percent at St = .15. Therefore, with a side port probe or a blunt edge probe of any type, slight undersampling (R < 1) is recommended. Wall losses due to inertial impaction when the airflow must change direction were found to be a function of St (Fig. 14). Experimental results showed representative sampling could only be obtained when St values were low.

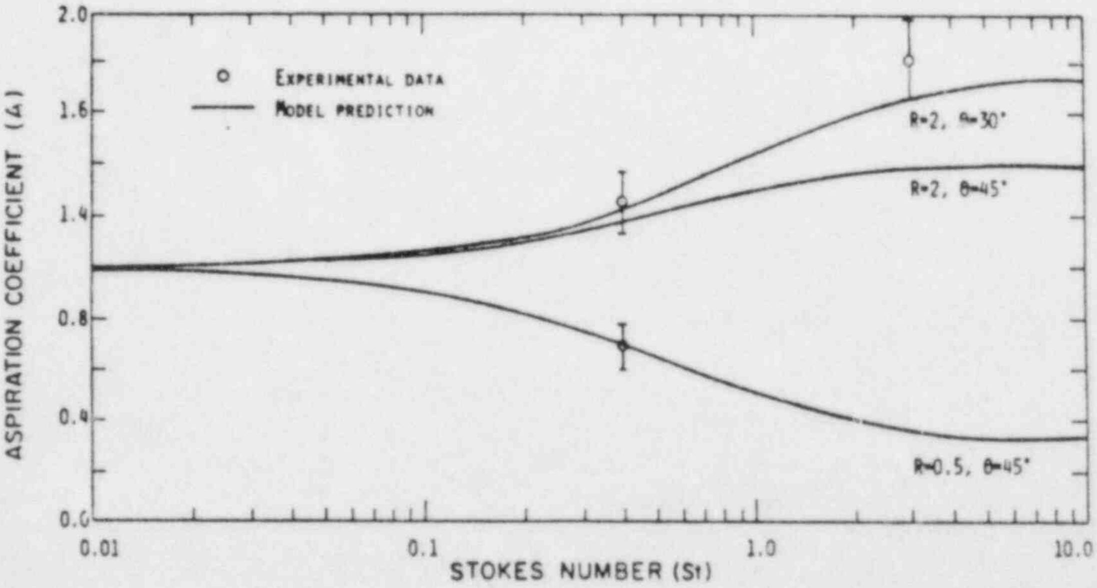


Fig. 4.

Aspiration coefficient vs. Stokes number for a 45° misalignment at R = 2.0 and R = 0.5 and for a 30° misalignment at R = 2.0.[25]

The effect of varying inlet geometries on the 10-mm nylon cyclone on collection efficiencies was investigated by Pickett and Sansone.[28] They pointed out that the 10-mm cyclone with a 2-mm-square orifice did not meet Davies'[20] criteria for inlet dimensions for nonbiased sampling of aerosols. In comparing the 10-mm cyclone with cyclones modified with inlets to conform to Davies' permissible radii, they found no difference between the collection efficiencies. Davies[29] responded that although his criteria were determined for small tubes in calm air conditions, the

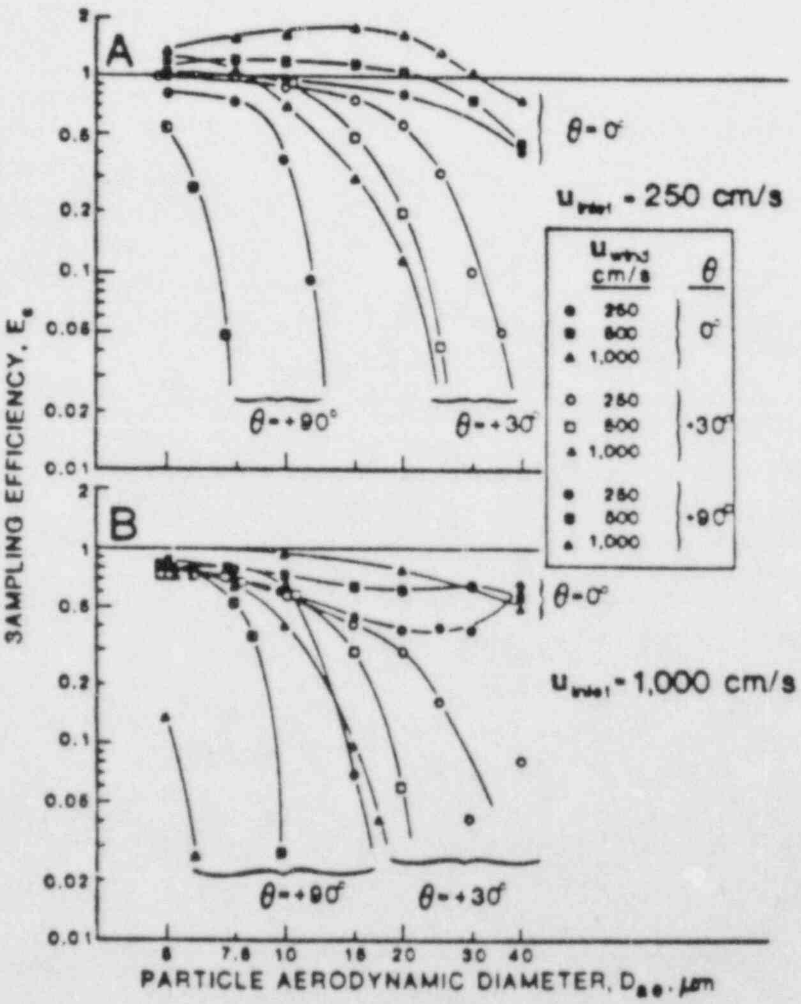


Fig. 5.

Sampling efficiency of a thin-walled inlet tube at constant inlet velocity. L = 20 cm, i.d. = 0.565 cm, o.d. = 0.635 cm (1/4 inch). A: inlet velocity = 250 cm/s. B: inlet velocity = 1 000 cm/s.[26]

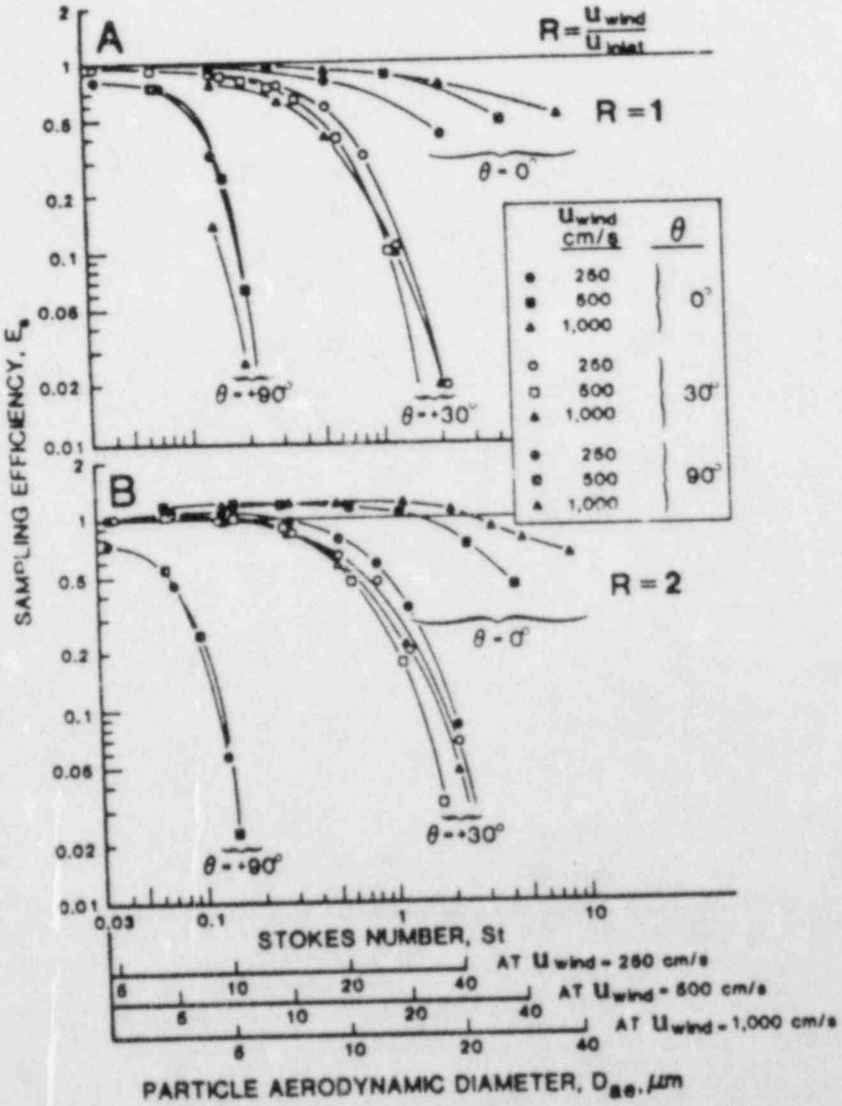


Fig. 6.

Sampling efficiency of a thin-walled inlet tube at constant sampling ratio.[26] L = 20 cm, i.d. = 0.565 cm, o.d. = 0.635 cm (1/4 inch). A: R = 1. B: R = 2.

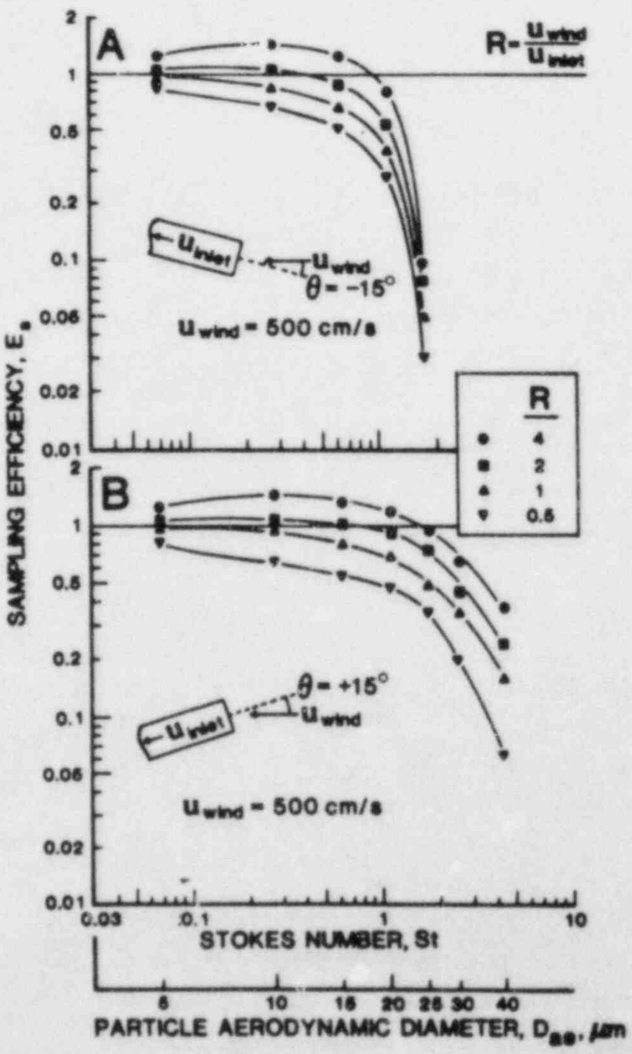


Fig. 7.

Sampling efficiency of a thin-walled inlet tube for downward vs. upward sampling.[26] L = 20 cm, i.d. = 0.565 cm, o.d. = 0.635 cm (1/4 in.). A: Upward sampling at θ = -15°. B: Downward sampling at θ = +15°.

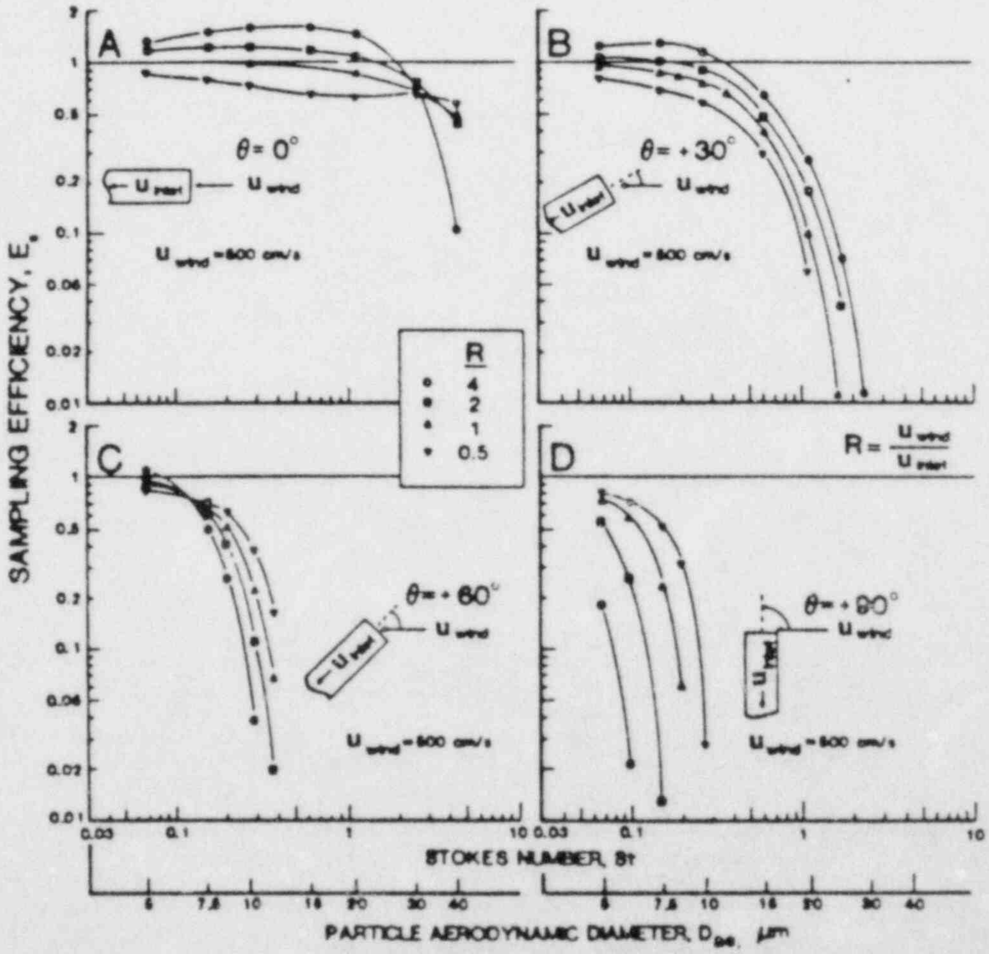
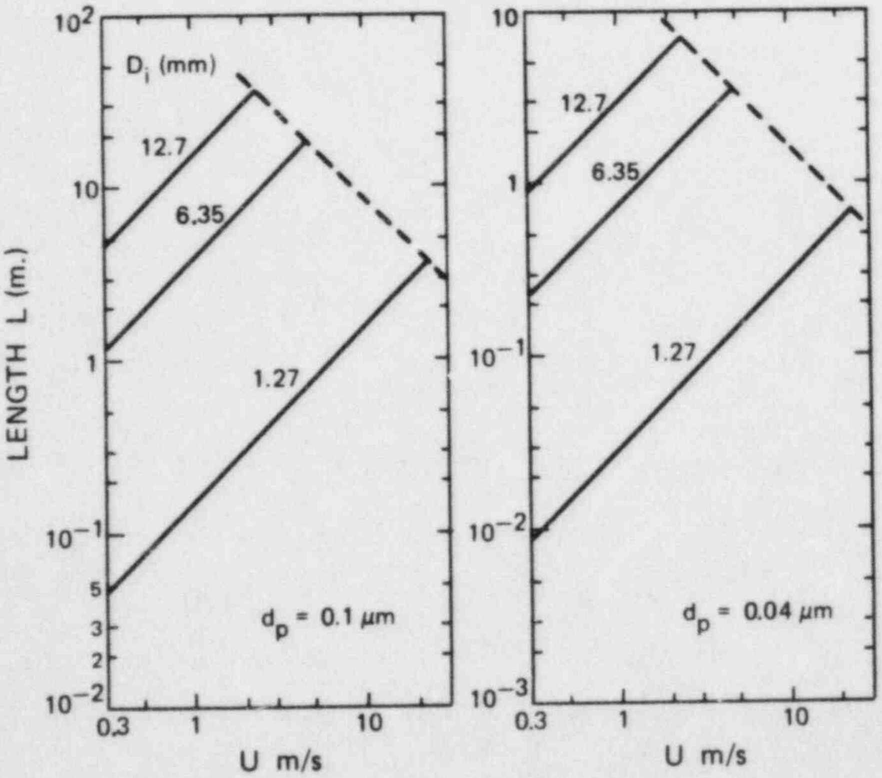


Fig. 8.

Sampling efficiency of a thin-walled inlet tube at constant wind velocity and different angles.[26] L = 20 cm, i.d. = 0.565 cm, o.d. = 0.635 cm (1/4 inch). A: θ = 0°. B: θ = +30°. C: θ = +60°. D: θ = +90°.



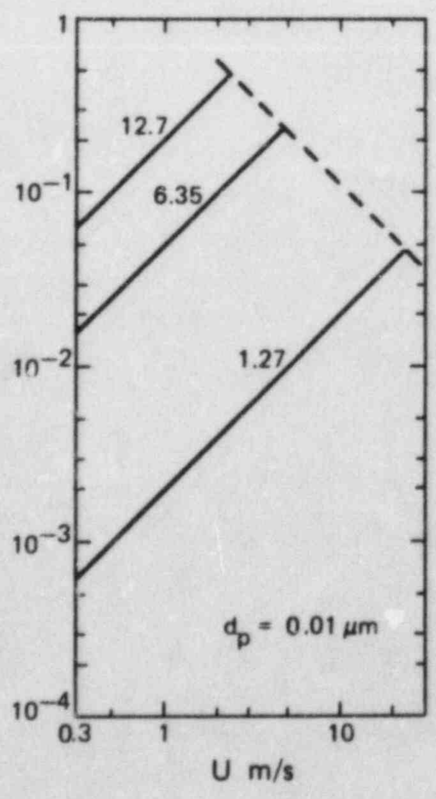
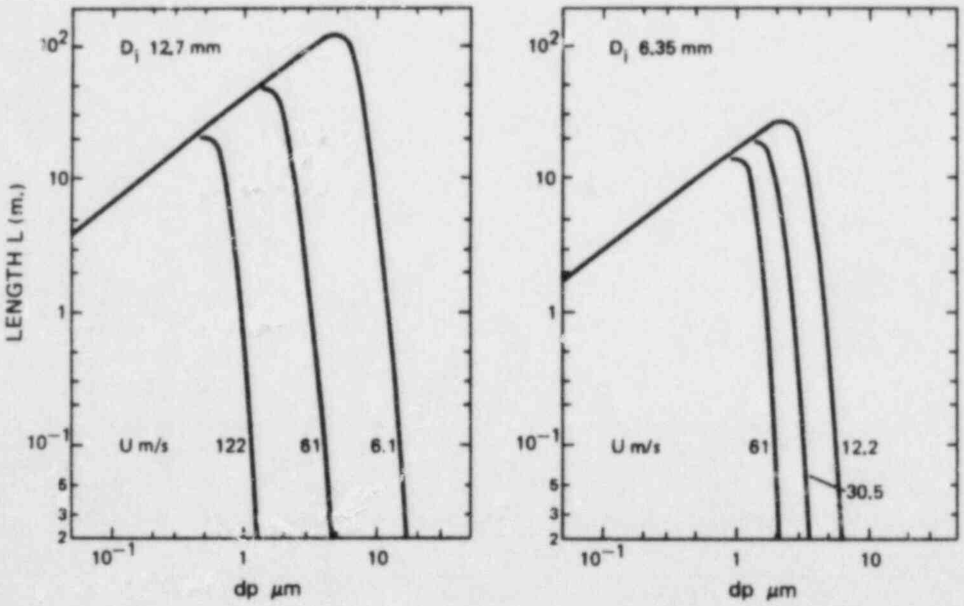


Fig. 9.

Effect of deposition in laminar flow[19]--length of probe for 1 percent reduction in particle concentration calculated for unit density spheres in air at 760 mm Hg and 20°C--laminar flow limit, Re = 2000.



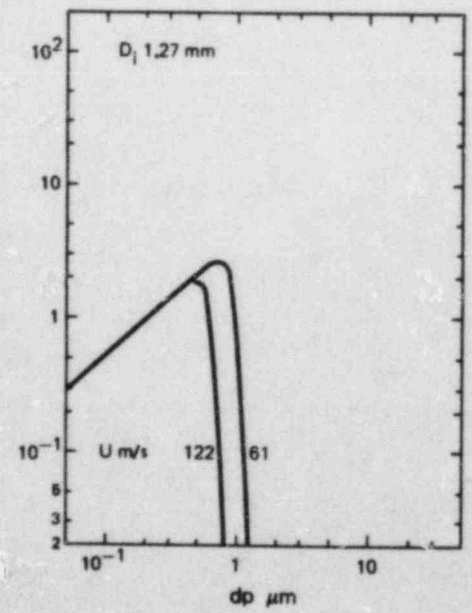


Fig. 10.

Effect of deposition in turbulent flow[19]--length of probe for 1 percent reduction in particle concentration calculated for unit density spheres in air at 760 mm Hg and 20°C.

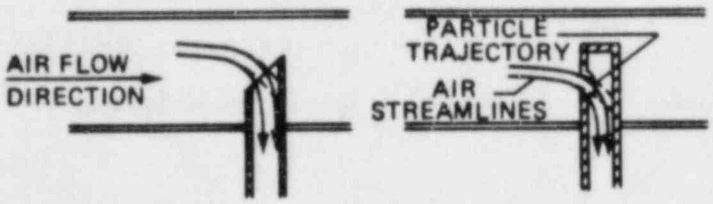


Fig. 11.

Impaction loss in a side port probe.[27]

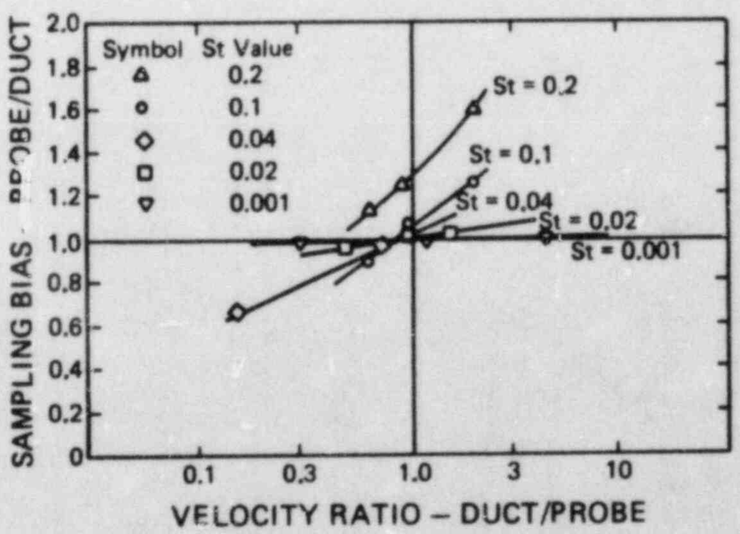


Fig. 12.

Side port probe--bias versus velocity ratio.[27]

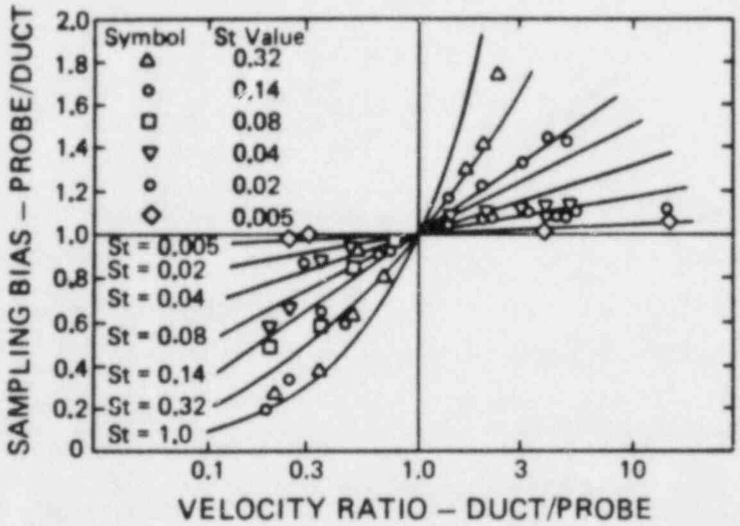


Fig. 13.

Straight inlet probe--bias versus velocity ratio.[27]

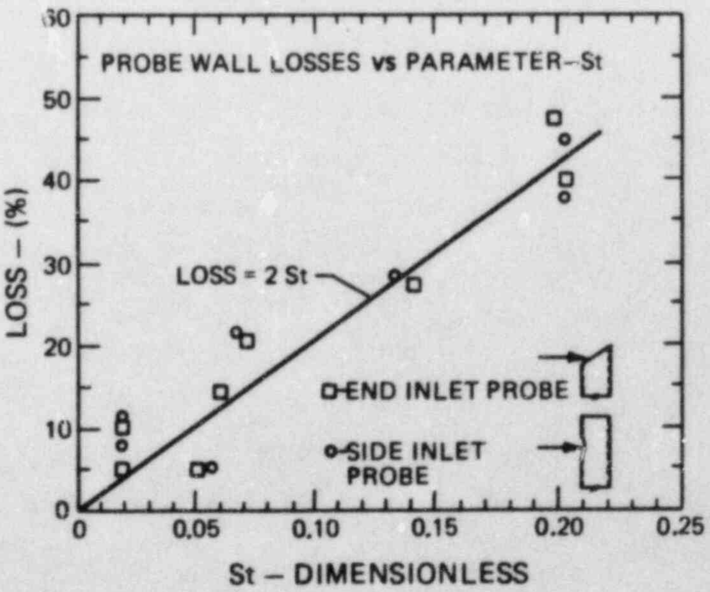


Fig. 14.

Wall loss versus St for side port probe.[27]

velocity (825 cm/s) in the square orifice of the nylon cyclone was so high that gravitational error was of no significance. He calculated the percentage of error due to inertia and found detected losses would not exceed 11 percent and would be primarily in the coarse particles. Davies was doubtful that Pickett and Sansone would have detected losses this small.

Bien and Corn[30] also used Davies' criteria for inlet radius to critique commonly used samplers in industrial hygiene. They found that samplers, in general, do not representatively sample particles up to 10 μm at the specified sampling rate according to Davies' calculation (Table VI). It should be pointed out that Davies' criteria are generally accepted as being too stringent, and these samplers probably perform better than shown in Table VI.

Liu et al.[31] conducted a fairly intensive study on two sampling inlets for use in respirators. They used a manikin with a breathing machine and tested a full- and half-mask powered air-purifying respirator. The focus of the experiments was not the protection afforded by the respirator but the sampling efficiencies of Inlets I and II (Figs. 15-17). Only the particles penetrating the entire inlet and reaching the collection filter were considered sampled. Efficiencies were determined by dividing the aerosol concentration found on the filter by the aerosol concentration found on the filter plus inlet (Table VII). It was found that Inlet I was not as efficient at sampling 2- to 10-μm-diameter particles as Inlet II, so further studies on Inlet I were not conducted.

Efficiencies of sampling inlets are typically determined by comparing the concentration obtained from an experimental inlet with that obtained by an inlet of 100 percent efficiency. Liu states this is an impossibility in a respirator, so he estimated efficiency by particles collected on the filter to particles that settle on the outer and inner surfaces of the inlet. Particles that settle on the outer surface may come from two sources--impaction of particles due to flow into the inlet and those due to turbulence. Therefore, some error exists in this method. The aerosol was blown into the mask from a vibrating orifice monodisperse aerosol generator, but they did not state what the target concentration was or how it compared with what was actually measured.

TABLE VI

CHARACTERISTICS OF SOME COMMONLY USED SAMPLING INSTRUMENTS

Inlet/Sampler	Inlet Diameter (cm) Di	Sampling Rate (L/m) Q	Inlet Velocity (cm/s) Ui	Stokes Number St	Reynolds Number Re	Relative Settling Velocity Vs	Max Dp Representively Sampled μm, AED
Pickett and Sansone[28]							
10-mm Nylon Cyclone	Square .2 (Equivalent Circle .226)	2	825	2.5		3.64×10^{-4}	
Modified Cyclone	1.2	2	29.5	1.5×10^{-2}		1.02×10^{-2}	
	Square 1.0 (equivalent 1.13)	2	33.3	2.0×10^{-2}		9.01×10^{-3}	
Bien and Corn[30]							
DEL Electrostatic Precipitator	6.1	750	428	4.3×10^{-2}		7.0×10^{-4}	8.4
MSA Electrostatic Precipitator	3.6	85	139	2.4×10^{-2}		2.2×10^{-3}	11.2
Andersen Cascade	1.8	28	183.4	6.2×10^{-2}	2153	1.6×10^{-3}	6.9
Standard GS Impinger	1.2	28	413	2.1×10^{-1}	3240	7.2×10^{-4}	3.8
Half-Inch Cyclone	.41	10	1262	1.9		7.3×10^{-4}	1.3
Half-Inch Cyclone	.41	8	1010	1.5		2.4×10^{-4}	1.4
Midget Impinger	.36	2.8	458	.78	1078	6.5×10^{-4}	1.8
MRE Elutriator	.10	2.4	5093	31.1		5.9×10^{-5}	.31
10-mm Cyclone	.226	2.0	831	2.2	1320	3.1×10^{-4}	1.2
10-mm Cyclone	.226	1.7	706	1.9		4.2×10^{-4}	1.3
10-mm Cyclone	.226	1.4	582	1.6		5.2×10^{-4}	1.4
Microimpinger	.36	.56	91.7	.16		3.3×10^{-3}	4.5

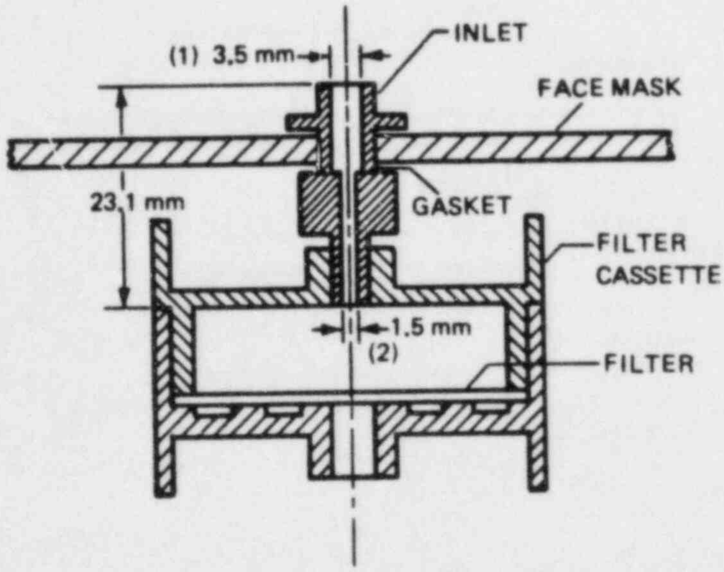


Fig. 15.

Schematic diagram of Inlet I.[31]

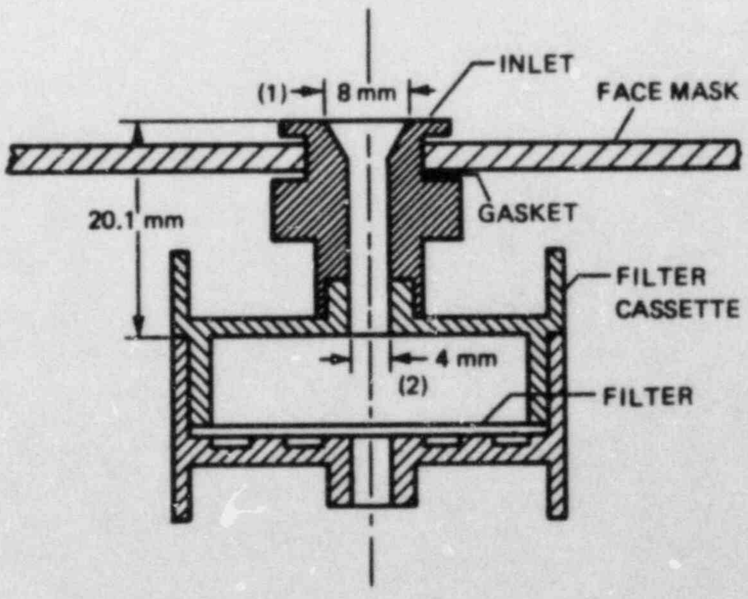


Fig. 16.

Schematic diagram of Inlet II.[31]

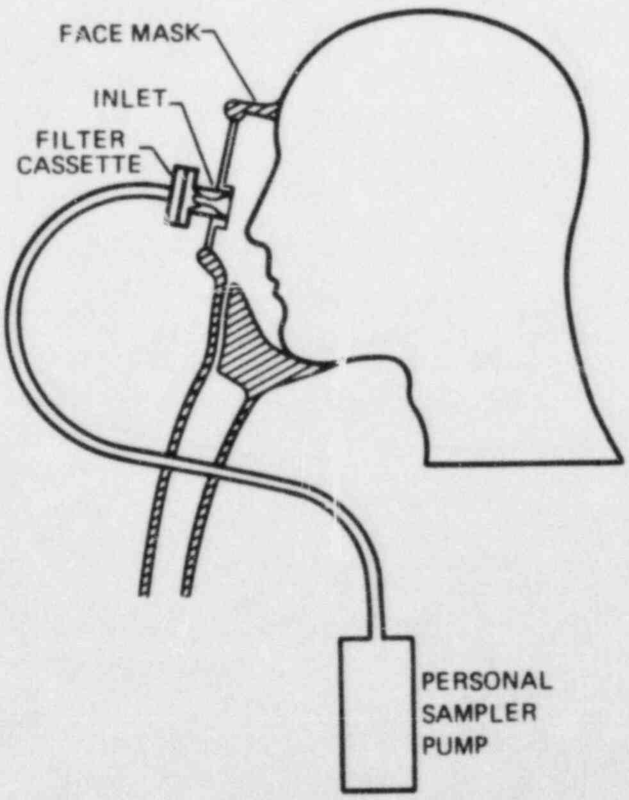


Fig. 17.

Schematic diagram of in-mask aerosol-sampling system.[31]

TABLE VII

CHARACTERISTICS OF LIU INLETS[31]

Liu's Inlet	Inlet Diameter (mm) Di	Sampling Rate (L/m) Qs	Inlet Velocity (cm/s) Ui	Breathing Rate (L/m) Qb	Stokes Number St	Reynolds Number Re	Efficiency d_p: % Eff.
Inlet I	(1) 3.5	1	173.2	24	.3		full 2μm: 93.4
		2	346.5		.6		5μm: 71.0
		4	692.8		1.2		10μm: 32.0
	(2) 1.5	1	1082.7		3.82	928	
		2	2165.4		7.65	1886	
		4	4330.8		15.29	3772	
Inlet II							
	(1) 8.1	1	32.3	24	.024		full
		2	64.7		.049		2μm: 100 10μm: 100
		4	129.2		.097		
	(2) 4.1	1	126.2	40	.188	339	full 2 and 5μm: 100 10μm: 92-98
		2	252.5		.377	678	
		4	505.0		.753	1358	half 10μm: 72-77

Liu et al.[31] obtained good reproducibility in his experiments. The design seemed to work well and the collection filter was fairly close to the inlet. Inlet II appears to be the inlet of choice in this review. It is hard to determine because the diagrams are not drawn to scale, but Inlet II may sit too close to the inner surface of the mask to eliminate turbulence and eddies due to airflow contact with a surface.

IV. AMBIENT SAMPLERS

Many instruments and techniques have been developed to collect and measure respirable (<10-μm-diameter) particles. An ambient aerosol sampler must effectively transport the particle size of interest with consistent or predictable losses independent of fluid mechanics (wind speed, three-dimensional direction, and turbulence intensity and scale) and environmental conditions (precipitation, airborne debris, insects, etc.).

Filters generally have high mass efficiencies[32] (90 percent to 100 percent) though they tend to have penetration losses (10 percent to 100 percent) for small particle sizes (<.5 μm).[33,34] Membrane filters have high pressure drops and tend to develop loading problems at high concentrations.[35] Besides their high collection efficiency, filters are simple, have a high surface retention, facilitate recovery and analysis of particles, and can be used in particle-size analysis.[36]

Inertial separators (cyclones, cascade impactors, etc.) can operate as selective samplers with a specific cutoff size.[37] They have good mass-collection efficiencies[38] but are difficult to calibrate, are inefficient for particles below 1 μm (unless they include a filter as a final stage), involve difficult particle recovery, and require analysis that is often complex. An example of an inertial separator is a cascade impactor with a six-stage sampler and 400 separation orifices.[39] Its main disadvantages include considerable departure from equal mass collection at each hole on stages 1 and 2. The orifices are small, so particles deposited on the collection plate pile up in mounds. Collection efficiencies of several stages are shown in Figs. 18-20, along with the cutoff diameters for each stage as shown in Table VIII. A compact cascade impactor is available for personal sampling.[40]

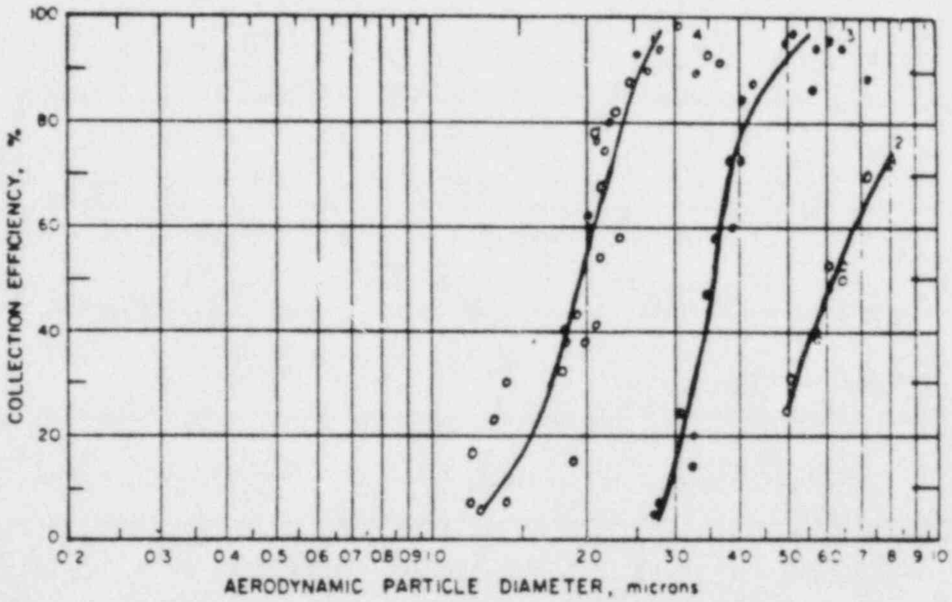


Fig. 18.

Andersen sampler collection efficiency curves (least squares fit) and data points for stages 2 to 4: optical microscope-methylene blue aerosol data.[39]

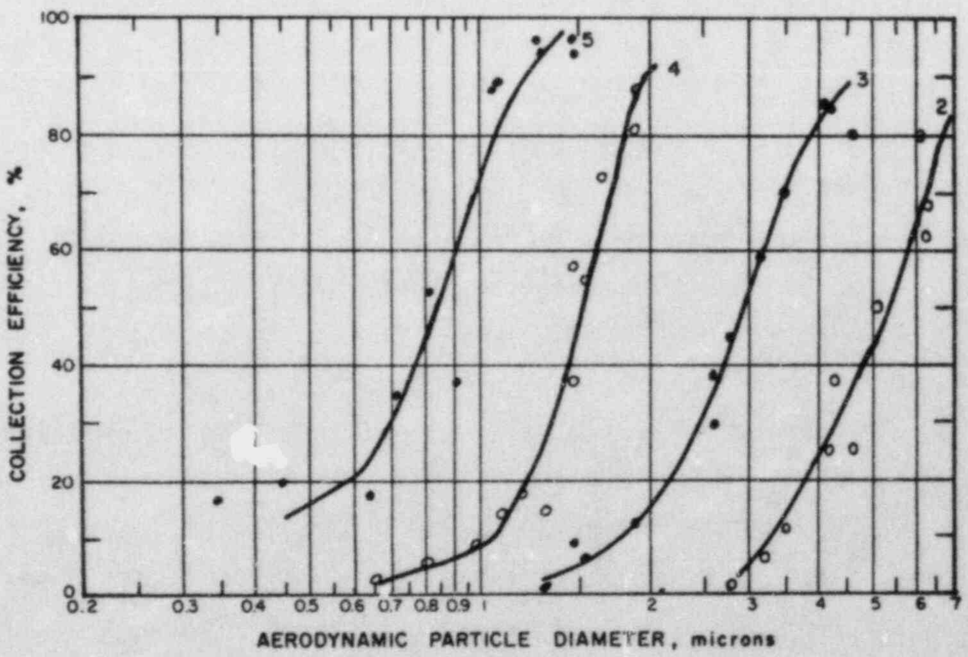


Fig. 19.

Andersen sampler collection efficiency curves (least squares fit) and data points for stages 2 to 5: electron microscope-methylene blue aerosol data.[39]

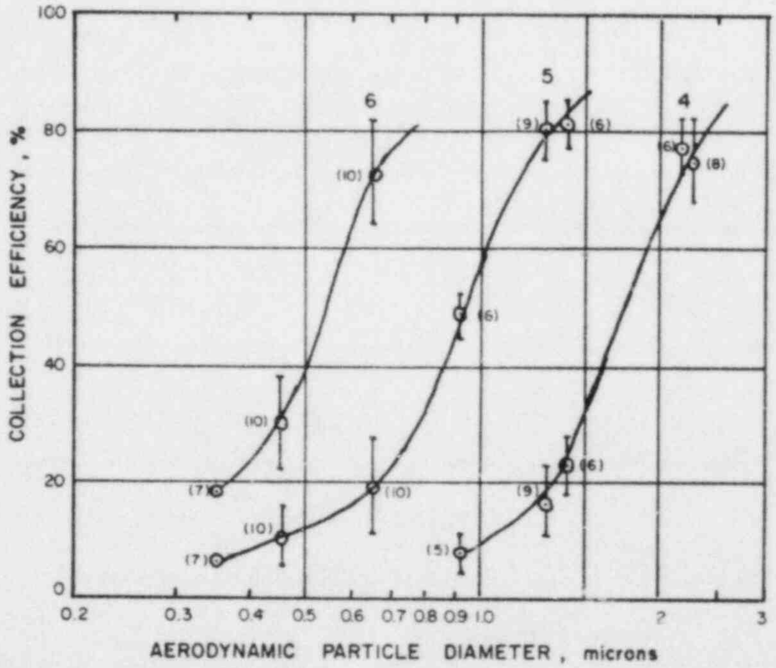


Fig. 20.

Andersen sampler collection efficiency curves (least squares fit) with mean and standard deviations of data points for stages 4 to 6: polystyrene latex aerosol data.[39]

TABLE VIII

ANDERSEN SAMPLER AERODYNAMIC EFFECTIVE CUTOFF DIAMETERS[39]

(μm)

Stage	Methylene Blue Aerosol, Optical Microscope	Methylene Blue Aerosol, Electron Microscope	Polystyrene Latex Aerosol	May[41]
2	6.2	5.35		5.5[a]
3	3.6	2.95		3.5
4	2.0	1.53	1.75	2.0
5		0.86	0.92	1.1
6			0.54	

[a]Modified stage.

Electrostatic particle samplers (concentric, parallel, and point to plane) usually handle large quantities of air with little pressure drop, and most have a high mass-collection efficiency. Several disadvantages of these systems include costly design and operation, a tendency to delineate particles according to mobility, production of ozone, and production of explosions when certain gases are present.[36]

Thermal participators have a uniformly high efficiency for particles below 5 μm.[42,43] Particles are easily recovered and analyzed by being directly deposited on an electron microscope grid; however, thermal precipitators are capable of only low flow rates and have a limited capacity for particle collection. Large particles are not sampled properly because isokinetic sampling cannot be achieved and because of inertial sedimentation losses. Most units are bulky, but a portable unit capable of operating 8 h is available.[44]

Elutriators are similar to inertial separators but operate at normal gravitational conditions with either a vertical or horizontal flow direction.[45] They are limited in analyzing small particles (<1 μm), but they have negligible airflow resistance, so only a small personal pump is required. These problems are due to build-up of material in the plates of a horizontal elutriator, and orientation is critical in controlling size cutoff points.

Both Liu and Piu[46] and Wedding[47] reviewed the history of ambient sampling inlets for inhalable particles. Table IX lists the characteristics of several ambient air samplers and their particle diameters that are sampled at 50 percent efficiency (η_{50}). Since isokinetic sampling is usually difficult in the field, these samplers are usually omnidirectional and sample anisokinetically. The "rotational cowl" sampler (Fig. 22) was developed to change direction in response to the wind and was kept at a fixed inlet velocity of 1.9 km/h. Thus, except for calm air conditions, this sampler operated subisokinetically most of the time. Tests by Wedding[47] showed at 5.5 km/h wind speed; particles of 15-μm diameter were sampled with an 82 percent efficiency.

A wind shield or baffle is often used to minimize the effect of wind on the inlet efficiency. If a tube is placed within a cylindrical wind shield of radius r, and r is sufficiently large, particle impaction on the wind shield can be prevented for particles of the same size traveling

TABLE IX

CHARACTERISTICS OF AMBIENT AEROSOL SAMPLERS AND INLETS

Sampler/Inlet	Sampling Flow Rate	Test Wind Speed (km/h)	D_{50} or D (efficiency, %) (μm)	Figure	Literature Reference
Standard Hi-Vol: 0°,45° Sampler	1.42 m³/ min (50 cfm)	13.65	12,18		Wedding et al.[48]
Standard Hi-Vol: IRPM Sampler		2,8,24	>30,31,16.5	21	McFarland[49]
Rotating Wind and Impactor Sample	0.566 m³/ min (20 cfm)	4.55 5.5	15(~100) 15(82)	22	Wedding et al.[48] Schmel[50]
Virtual Impactor Inlet	Primary inlet 201 L/min (7.10 cfm) Secondary inlet 14 L/min(.49 cfm)	8.03 27.4	15(30.1),20(16.9), 25(7.2) 15(6.3),20(6.51) 25(2.9)	23	Dzubay[51]
Rockwell International Sampler	0.88 m³/min (31 cfm)	5.49,21.95 43.89 5.49,21.95, 43.89	0°: 24,13.5,13.5 45°: >35,14.5,14.5	21	Wedding et al.[52]
Southern Research Institute Inlet		9,46,68 9,46,68	5(39,30,20) 12(35,12,35)	24	Bird et al.[53]
Beckman Inlet	16.67 L/min (.59 cfm)	2 8 24	15.5 13 10.5	25	McFarland[49]
Sierra Inlet	16.67 L/min (.59 cfm)	0 5 15 40	11 22 15 9.5	25	Wedding et al.[54]
Size Selective Hi-Vol Sampler	1.13 m³/min (40 cfm)	2 8 24	13.4 14.4 12.5	27	Wedding (unpublished)
Prototype dichotomous sampler inlet		5.5 16.5	17.5 13.5	28	Dzubay et al.[51] Wedding et al.[48]
Liu and Pui Sampler	16.7 L/min	9	13.3	29	Liu and Pui[46]

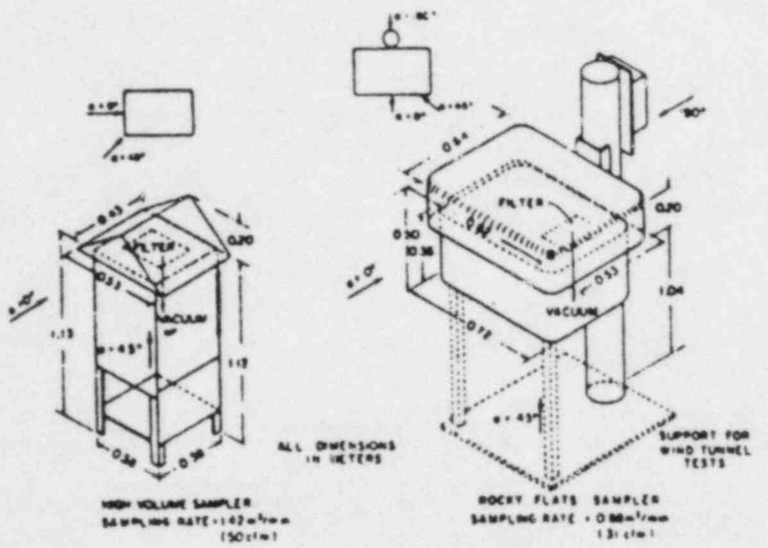


Fig. 21.

Standard (11-1/2 x 14 in.^{2}) Hi-Vol[55] and Rocky Flats (Rockwell International) sampler.[47, 52]

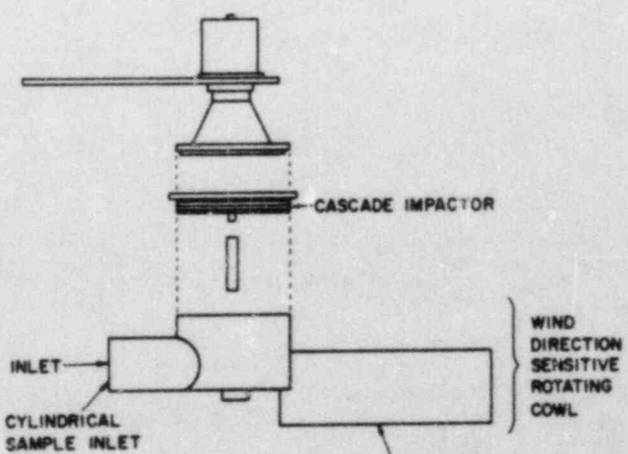


Fig. 22.

Rotating cowl and impactor.[47, 50]

at the same speed.[46] Unbiased sampling can take place from the relatively calm air region within the wind shield. No systematic study has been conducted on the actual performance of the wind shield, however.

The virtual impactor inlet (Fig. 23) and SRI inlet (Fig. 24) did not work well.[56] The Sierra 244E (Fig. 25) varied in D_{50} by more than a factor of 2 in the range of wind speeds of 0 to 40 km/h.[54] Wedding[57] developed an inlet with a cyclone fractionator and later revised it to sample 10-μm particles at 50 percent efficiency (Fig. 26). This inlet exhibited no wind speed dependence and no particle bounce problems. Liu and Piu[46] also developed a new inhalable-particle ambient aerosol-sampling inlet (Fig. 29). The inlet was designed for a sampling flow rate of 16.7 L/min and contained a circular top to keep out rain and snow and an internal impactor to remove coarse particles above 15 μm. Figure 30 shows the efficiency of this inlet.

V. AEROSOL-SAMPLING RECOMMENDATIONS FOR RESPIRATOR FIELD STUDY

This review indicates that there is insufficient information to design a sampling probe for inside the respirator facepiece that will insure the collection of a representative sample or ensure an aspiration efficiency that is the same for the samples collected on both sides of the respirator. The best approach, based on this review, would seem to be use of the Liu et al.[31] sampling probe in both locations. Both samplers would relate only to the respirable fraction to limit the sample to the size range to where aspiration problems are minimized. This can be accomplished by drawing both samples through 10-mm nylon cyclones.

Several additional points should also be considered. There may be flow-rate effects in determining the concentration inside the facepiece. These effects would relate to both the breathing rate of the worker and the sampling rate. There will be concentration effects, both with respect to the magnitude of the ambient concentration and the variability in time and space. The difficulty in defining breathing zone is part of this problem, because the breathing zone of someone shoveling coal will be different from the breathing zone of a lathe operator. The ambient

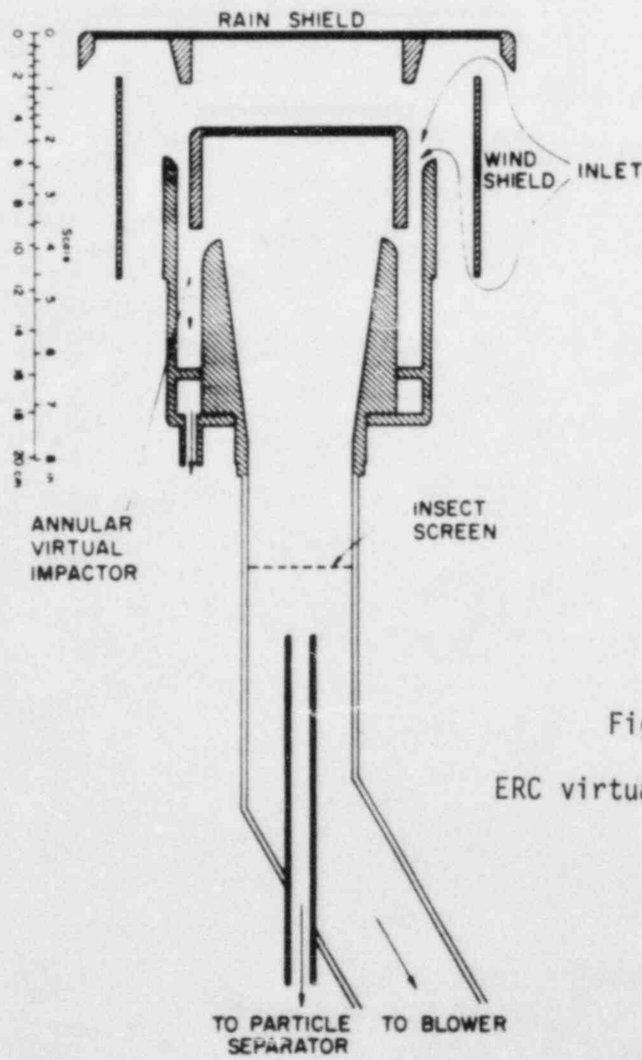


Fig. 23.

ERC virtual impactor.[47]

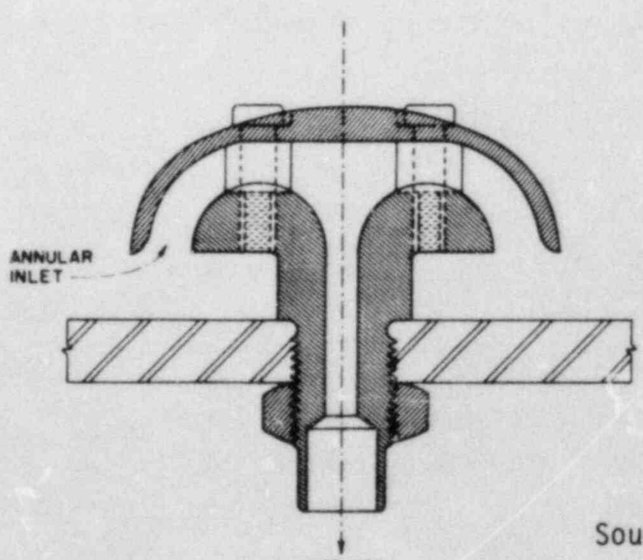


Fig. 24.

Southern Research Institute inlet.[47, 53]

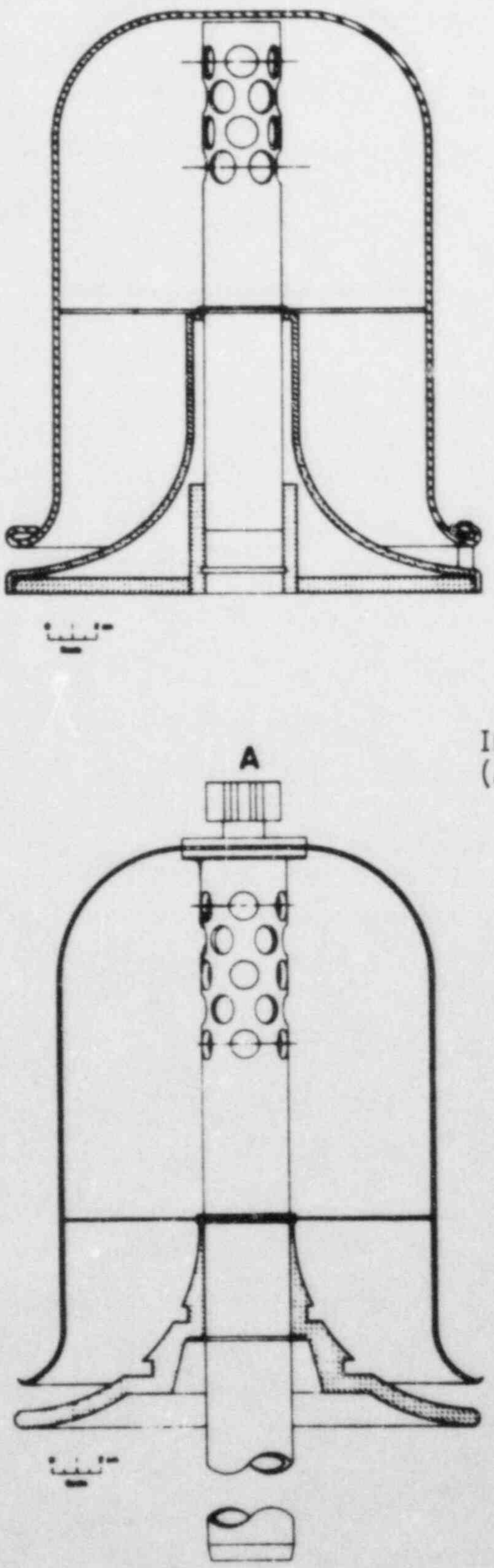


Fig. 25.

Inlets for the dichotomous virtual impactor: (A) Sierra 244E and (B) Beckman.[47,49]

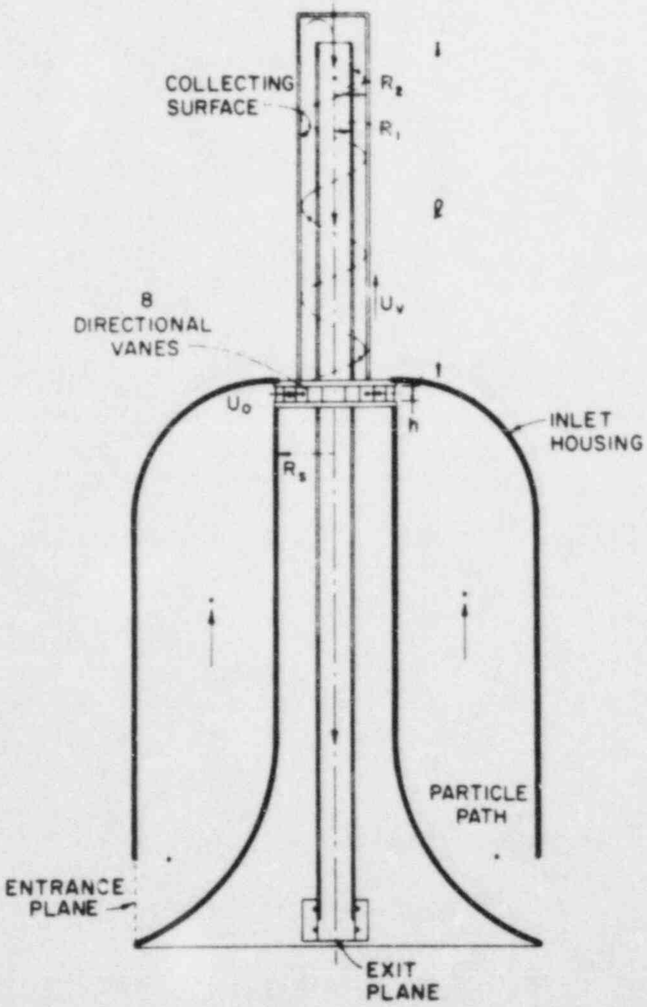


Fig. 26.

Wedding IP inlet section view; not to scale.[47, 57]

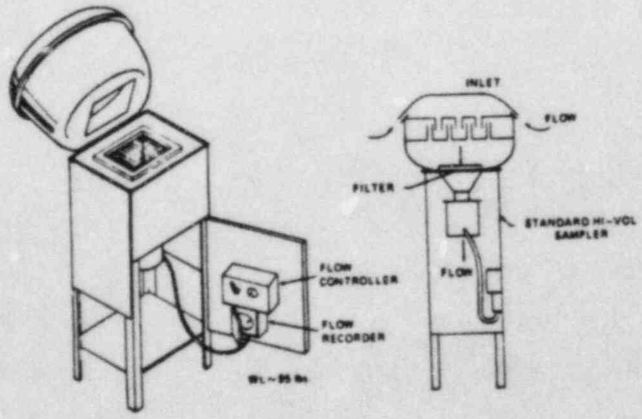


Fig. 27.

Size-selective Hi-Vol.[47, 49]

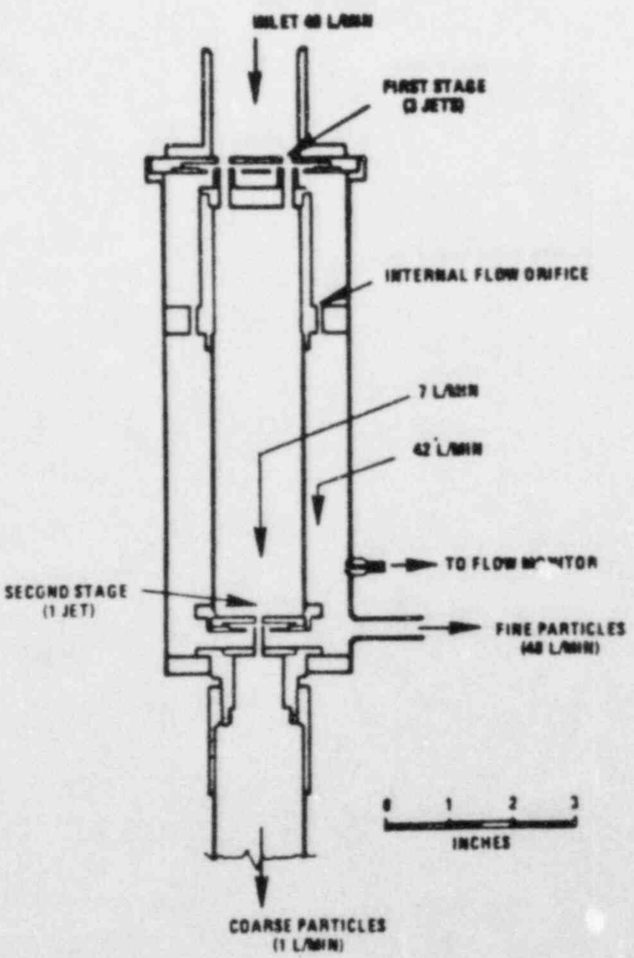


Fig. 28.

Drawing of dichotomous sampler with two substages.[51]

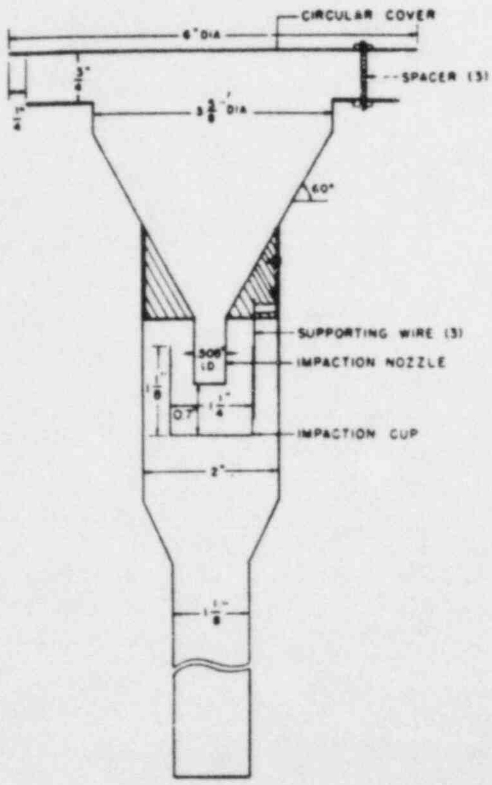


Fig. 29.

The University of Minnesota aerosol inlet for inhalable particles.[46]

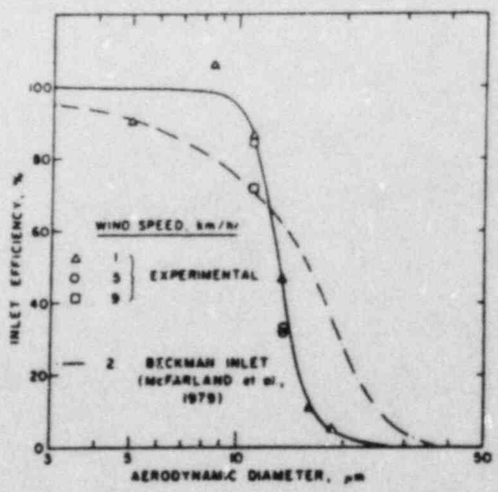


Fig. 30.

Experimental inlet efficiency for the University of Minnesota inlet and its comparison with the Beckman dichotomous sampler inlet.[46]

sample should probably be collected near the respirator inlet so as to represent the contaminant concentration just before being removed by the respirator filter.

Conditions will be different inside the facepiece of the respirator. The temperature will probably be higher and the humidity will be higher. The humidity can have significant effects, including changes in particle size for some materials, changes in analytical sensitivity for determining face side concentrations, and calibration of flow measurement and regulation methods. It may be necessary to use an absorbent or heater on the sample line to prevent condensation of water vapor.

We need a very careful definition of what we are trying to measure. This review indicates that previous studies have measured many different parameters, but none seem to have measured the same parameter on both sides of the respirator. Most of the studies seem to illustrate pitfalls to be avoided in this study. A well-defined objective is required with this study. It is apparent that it is impossible to arrive at any general conclusions from previous studies about actual workplace protection provided by respirators.

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GLOSSARY

i.d. = Inside diameter
o.d. = Outside diameter
Q = Aspiration rate (cm^3/s)
F = Flow per unit length of orifice (cm^2/s)
V_s = Terminal velocity of the particle
V_s' = Relative settling velocity = V_s/U_i
d_s = Stop distance = $(Q/4\pi)^{1/3}$
U_o = Wind velocity (cm/s)
U_i = Air velocity at inlet (cm/s)
V_o = Particle velocity (cm/s)
ρp = Particle density
μ_{air} = Viscosity of air
γ = Kinematic viscosity of gas

$R = \frac{U_o}{U_i}$ = velocity ratio

Aspiration coefficient = $\frac{C}{Co}$

D_p = Particle diameter
D_i = Diameter of sampling inlet
D = Diameter of sampling head

τ = Particle relaxation time = $\frac{(D_p)^2 \rho p}{18\mu_{air}}$ K (for spherical particles)

K = Cunningham slip correction factor

St = Stokes number = $\frac{\tau U_o}{(D_i/2)}$

Re = Reynolds number = $\frac{U_o D_p}{\gamma}$

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As part of the first phase of a Respirator Field Performance Factor project for the Occupational Safety and Health Administration/Nuclear Regulatory Commission, a critical review of the literature available on respirator protection studies was completed. Little information was available on experimental conditions, and when the information was available, each study was different in how the aerosol measurements were made and in which parameters were controlled. Under these conditions, it is difficult to compare results obtained from different investigators.

The literature was also surveyed for characteristics desirable in an aerosol-sampling inlet in order to representatively sample respirable particles. Available ambient aerosol samplers were critically reviewed for their performance characteristics. Recommendations are made to avoid the pitfalls present in many respirator field studies and to help standardize these studies.

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