WIND TUNNEL TEST REPORT NO. 29

TEST OF THE RUPPRECHT AND PATASHNICK TEOM PM10 SAMPLER INLET, THE SATURATION MONITOR INLET, AND THE MARPLE PERSONAL INHALABLE PARTICLE SAMPLER AT 2 AND 24 KM/H

Prepared by:

D. W. VanOsdell

Research Triangle Institute
P. O. Box 12194
Research Triangle Park, NC 27709

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Project Officer
Kenneth A. Rehme

Atmospheric Research and Exposure Assessment Laboratory
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

ABSTRACT

Wind tunnel tests of the Rupprecht and Patashnick (R&P) 10-µm inlet for the TEOM Series 1400 PM-10 monitor have been conducted at 2 and 24 km/h. The purpose of the test was to compare the R&P inlet to the Sierra-Andersen (SA) 246b Dichotomous Sampler inlet. Simultaneously, the Saturation Monitor (SM) and Marple Personal Inhalable Particle Samplers (PIP) were tested. The test program was conducted in the EPA Aerosol Test Facility. The procedures used were those specified in 40 CFR Part 53 except that a reduced number of test particle sizes were used. All tests utilized liquid challenge particles, and tests were conducted at either 2 or 24 km/h.

Based on these limited tests, the R&P inlet appears to be functionally identical to the Andersen 246b Dichotomous Sampler Inlet. The cut-point was found to be about 9.8 µm at 2 km/h and 9.6 µm at 24 km/h (compared to 9.8 and 10.0 µm, respectively, for the SA 246b.)

Neither of the other samplers performed well under windy conditions. The SM was found to have cut-points at 2 and 24 km/h of about 14.4 µm and 8.6 µm, respectively. The Marple PIP, designed for indoor use, was found to have cut-points at 2 and 24 km/h of about 8.5 µm and 6.5 µm, respectively.

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SECTION 1
INTRODUCTION

This report documents a test of the SA 246B 10-μm inlet for the dichotomous sampler. The SA 246B has been commercially available for a number of years, and is widely used. It was originally tested by McFarland and Ortiz (1984) of Texas A&M University (TAMU) prior to the promulgation of the PM_{10} sampler performance specifications and test procedures in 40 CFR Part 53. McFarland and Ortiz tested the SA 246B with solid and liquid aerosols at wind speeds of 2, 8, and 24 km/h. They used liquid test particles that were approximately 5.4, 7.6, 9.8, 11.8 and 14.0 μm in aerodynamic diameter. Glass beads having 20 μm aerodynamic diameter were used as solid aerosol. The present work continued the test by adding 3, 5, 10, 15, and 25 μm liquid aerosol test results to the data set, along with 25 μm solid ammonium fluorescein aerosols at 8 and 24 km/h.

The purpose of the present test was to evaluate the SA 246B in the EPA Aerosol Test Facility (ATF), following the procedures set forth in 40 CFR Part 53, and compare the results to the earlier TAMU data. Should the agreement be satisfactory, the combined data set (TAMU and ATF) was to be used to evaluate the performance of the SA 246B.

SECTION 2

CONCLUSIONS

Based on this test of various size-selective inlets, the following conclusions are drawn:

1. The wind tunnel effectiveness performance of the R&P inlet is substantially the same as that of the SA 246b inlet at 2 and 24 km/h, and the inlet appears to meet the requirements of 40 CFR for a PM-10 inlet. Because 2 and 24 are the extremes of the measurement range, it can be reasonable inferred that the R&P inlet would also perform satisfactorily at 8 km/h.

2. As a PM-10 inlet, the SM was found to have an unsatisfactorily high cut-point at 2 km/h and an unsatisfactorily low cut-point at 24 km/h. While at some intermediate wind speed the SM may have a 10-µm cut-point, the magnitude of the cut-point change makes this inlet unsuitable for use on an PM-10 sampler.

3. The Marple PIP was also found to be unsuitable for outdoor use as a PM-10 size-selective sampler. The cut-point was too low in the presence of even 2 km/h winds, and was even worse at 24 km/h.

SECTION 3
EXPERIMENTAL PROCEDURES

The test procedures used in the EPA Aerosol Test Facility were the same as those used and reported previously. Individual tests met the requirements of 40 CFR Part 53. Because the test program was designed primarily to compare the R&P inlet to the SA 246b, only 2 wind speeds and about half the number of particle sizes called for in 40 CFR Part 53 were tested during the present work. A brief overview of the test procedures is given below, and details may be found in the report by VanOsdell, Chen, and Newsome (1988).

3.1 Wind Tunnel Arrangement.

Figure 1 gives an overview of the EPA Aerosol Test Facility and the wind tunnel. Flow in the wind tunnel was counter-clockwise. There are few flow obstructions, and a number of access doors are provided to allow all sections of the wind tunnel to be cleaned. The test aerosol was generated on top of the wind tunnel where indicated, and injected through a distributor into the 1.83 m square cross-section region below. The sampler test area is also indicated in Figure 1. At the test area the wind tunnel cross-section is 1.52 m wide by 1.22 m high. The blower downstream of the sampler test area is capable of driving the wind tunnel at speeds up to 50 km/h (1550 m^3/min).

Some wind tunnel arrangement details not shown on Figure 1 were required to achieve acceptable particle and velocity uniformity at the 3 wind speeds. A plywood baffle was placed about 1 m upstream of the 1.83 m square cross-section particle injection zone to promote mixing. The baffle was 1.22 m square and mounted in the center of the wind tunnel transverse to the air flow. A counter-flow fan, 0.4 m in diameter and centered in the cross-section, was operated about 1 m downstream from the injection zone to provide additional mixing.

At 24 km/h, the large blower in Figure 1 powered the wind tunnel, and the filter/chiller was not turned on except to clean the wind tunnel air for 30 min before beginning each day's testing. The large blower could not be slowed enough to power the

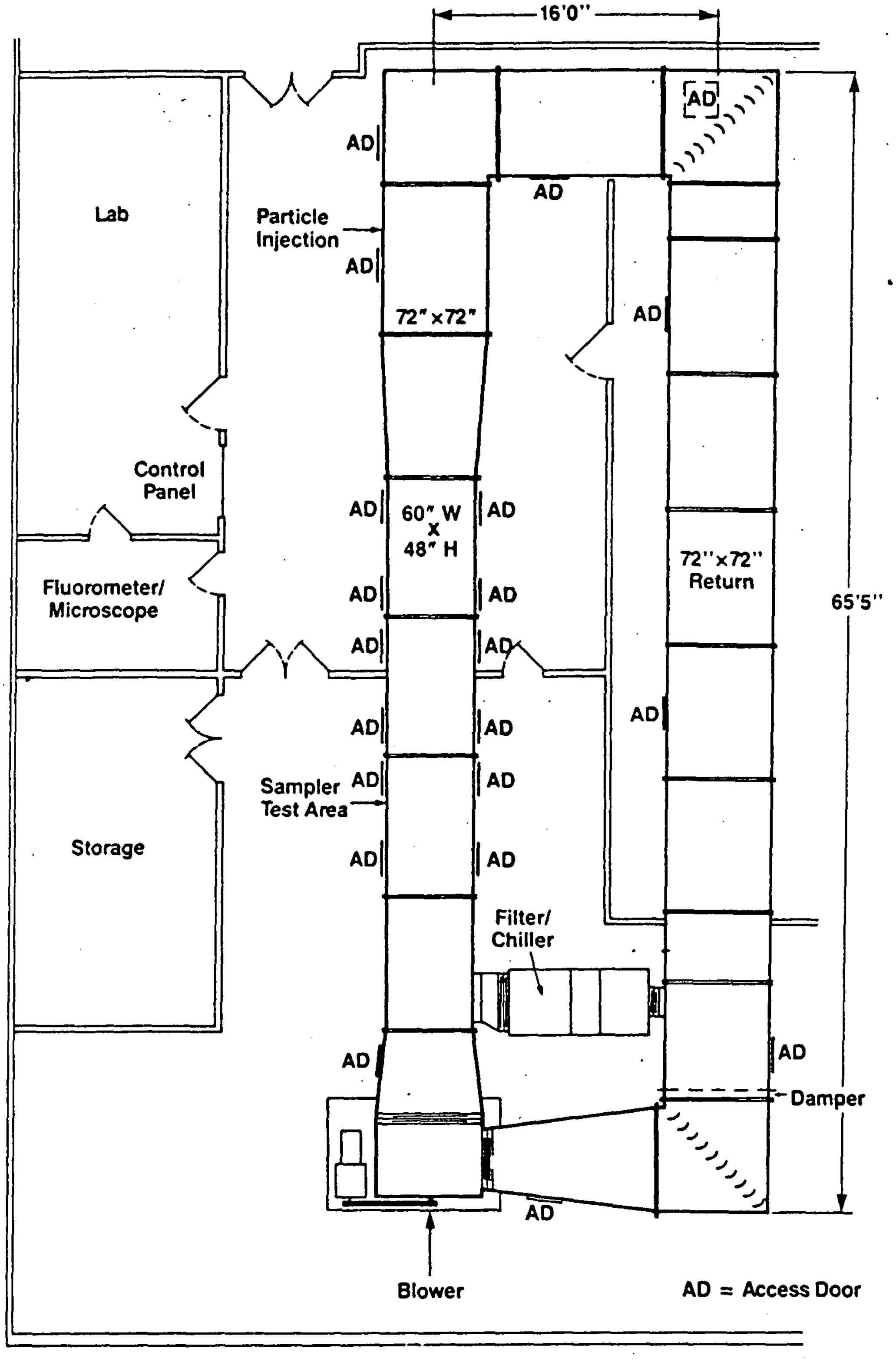

Figure 1. Aerosol Test Facility and Wind Tunnel.

Figure 1. Schematic Drawing of the EPA Aerosol Test Facility

wind tunnel at 2 km/h. To operate at 2 km/h, the damper indicated on Figure 1 was closed and the filter/chiller fan used to power the wind tunnel. To prevent flow channeling along the wall of the wind tunnel during the 2 km/h tests, a center-hole baffle was placed 2 m downstream of the sampler test area (and about 1 m upstream of the filter/chiller inlet.) This baffle blocked the wind tunnel except for the 30-cm square hole in its center, and provided a symmetric flow profile at 2 km/h.

The velocity uniformity and turbulence intensity in the wind tunnel were measured at each wind speed before beginning tests. The results are given in Table 1. The flow parameters are within acceptable limits for PM_{10} testing.

Table 1. Wind Tunnel Set-Up for 2 and 24 km/h

Mean Wind Speed	Baffle Arrangement	Mixing Fan	Velocity Uniformity	Turbulence Intensity in Test Zone
2 km/h	1.22 m^2 centered	On	± 5%	3 - 4%
24 km/h	1.22 m^2 centered	On	± 4%	4 - 5%

Note: Velocity uniformity was calculated as the deviation from the mean within the test zone. Velocity was measured with a hot-film probe.

3.2 Aerosol Generation.

The test was conducted with monodisperse test aerosols generated using a vibrating orifice aerosol generator (VOAG). The aerosol material, oleic acid, was tagged with uranine, a fluorescent dye, and the oleic acid and uranine were both dissolved in an ethanol carrier. The concentration of nonvolatiles (oleic acid and uranine) in the ethanol varied as required to obtain the desired particle size after the ethanol evaporated. Typical

VOAG operation utilized a 20 μm orifice, 0.165 mL/min feed rate, and a frequency of about 70 kHz. Particle size was calculated from the VOAG and particle solution parameters, and verified microscopically using Nye-Bar treated glass slides and a flattening coefficient determined by Olan-Figueroa et al. (1982). The liquid particles generated for the test had nominal diameters of 5, 9, 10, 12, and 25 μm.

The test aerosol was blown down into the wind tunnel through a dispersion manifold, and dispersed across the wind tunnel cross-section within the 10 m between the injection site and test zone. The uniformity of particle dispersion and particle challegne concentration were evaluated during each test using an array of four isokinetic samplers placed within the test zone and operated simultaneously with the samplers being tested. The results of a day's tests were rejected if the particle mass collected by each individual isokinetic sampler that day was not within +/- 10 percent of the mean particle mass from the 4 isokinetic samplers. The isokinetic samplers are described more fully below.

At 2 km/h the background aerosol was always negligible compared to the mass of aerosol captured by the samplers. At 8 and 24 km/h this was not always true. The test aerosol was generated at a fixed rate from the VOAG, and therefore the concentration of test aerosol was inversely proportional to wind speed. In addition, higher wind speeds have been shown to entrain more background particles. Thus increases in wind speed give inherently higher backgrounds while the available test aerosol concentration decreases. The aerosol background varies between days and at different times during each day too much to allow simple subtraction of the background. Rather, the background concentration was computed and used to indicate when data sets were suspect. At both 8 and 24 km/h, some 25 μm particle test runs were deleted as unreliable because the aerosol mass collected on the filters was too low compared to the background.

3.3 Sampler Position and Operation

The inlet of each sampler was positioned in the same axial plane of the wind tunnel (the same distance from the particle injection point.) That is, the upstream edges

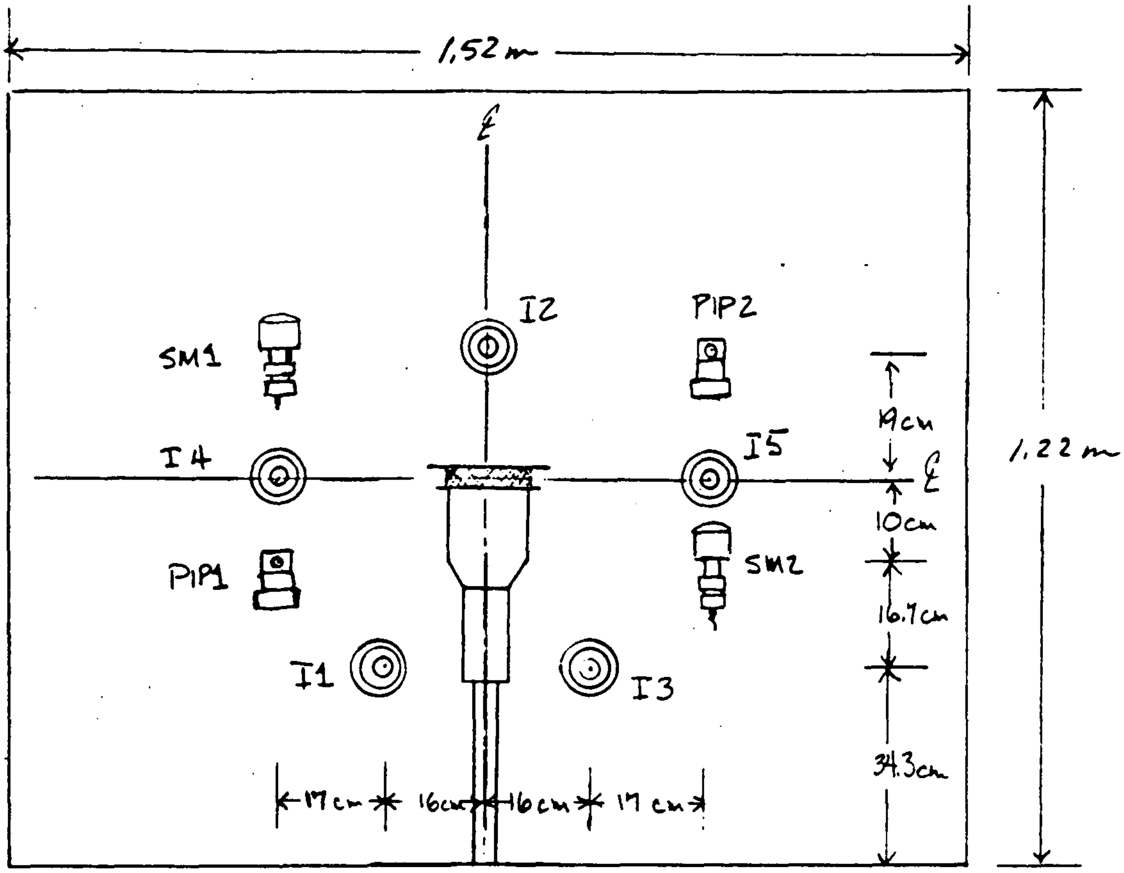

Figure 2. Position of samplers in Wind Tunnel.

Figure 2. Arrangement of Samplers in Wind Tunnel

of the R&P inlet, the SMs, and the PIPs were all in the same plane as the upstream ends of the isokinetic sampler nozzles. Figure 2 shows the arrangement of the samplers in the wind tunnel in a view along the direction of wind flow.

The isokinetic samplers were 47 mm filter holders fitted with sharp-edged conical nozzles, and were operated isokinetically. The suction pipe at the back of each sampler was clamped to a support frame to hold the sampler in position wiht the nozzle inlet about 25 cm upstream of the support frame. At 2 km/h, the nozzles' inlets were 2.94 cm in diameter and the samplers were operated at 22.6 L/min. At 24 km/h 1.22 cm diameter nozzles operated at 46.8 L/min were used. The flow rate through each sampler was controlled with a manual valve that was preset to the required flow rate. During a test, the total flow through each sampler was measured with a dry gas meter. The house vacuum manifold was used to draw the sample through the isokinetic samplers.

The R&P inlet was attached to a 3.2 cm OD aluminum riser tube and supported in the wind tunnel as shown in Figure 2. A 47 mm filter holder was mounted at the bottom of the tube, and a Gelman AE glass fiber filter collected the aerosol. The flow rate through the R&P inlet was controlled manually with a valve that was adjusted to the required 16.7 L/min prior to the test. During a test, the total flow measured using a dry gas meter. Suction was provided by the house vacuum manifold.

Saturation monitors 1 and 2 were positioned as shown in Figure 2. They were held in place using 3-fingered laboratory clamps that were themselves clamped to the support frame. Flow measurement was provided by calibrated mass flow meters and controlled manually using a valve. Valve adjustments were made as required to maintain the flowrate at 5 L/min. A PIPS pump system with a bleed valve was used as a vacuum source for the saturation monitors.

PIPS 1 and 2 were positioned as shown in Figure 2 and held in place using 3-fingered laboratory clamps attached to the support frame. The position of the inlet holes in the PIPs caps was not controlled. Flow through the PIPs was maintained at 10 L/min using the PIPs control system.

3.4 Inlet Tests

Three sequential tests of the inlets were conducted on the same day using the same test aerosol for most particle sizes. The R&P inlet, two SMs, two PIPs, and 4 isokinetic filter samplers were operated simultaneously during each of the three tests. The duration of each test was set to ensure that the aerosol mass captured on the sampler filters was sufficient to provide a reliable measurement. Most runs lasted 1 hour, but the 5 and 25 µm particle runs at 24 km/h were 3 hours long.

The sampling effectiveness for each sampler was computed as the ratio of the mass concentration measured by that sampler to the mass concentration measured by the closest isokinetic samplers. Table 2 identifies the isokinetic samplers used as the challenge concentration measurement for each sampler.

Table 2. Isokinetic Samplers Averaged for Challenge Concentration

Sampler	Isokinetic Samplers Averaged to Get Challenge Concentration
R & P 10 µm Inlet	Average of all 5
Saturation Monitor 1	2 and 4
Saturation Monitor 2	3 and 5
PIPS 1	1 and 4
PIPS 2	2 and 5

3.5 Analysis of Mass Collected on Filter Samples.

Following the EPA Aerosol Test Facility standard procedures, the uranine was extracted from the filters into 0.1 N NaOH solutions (liquid aerosol) or 0.1 N NH_4OH (solid aerosol) by soaking overnight. The mass of test aerosol collected on the filters was determined fluorometrically using standard ATF procedures. The nozzles of the isokinetic samplers were washed and the uranine found in the wash was added to the uranine collected on the filter to obtain the total challenge aerosol mass. The inlet sections of the R&P inlet, SMs, and PIPs were not washed to collect inlet losses.

3.6 Data Analysis

The raw effectiveness data from the samplers was analyzed using the PM_{10} data analysis normally used at the ATF. The three effectiveness values for each test were averaged to obtain a value at each test particle size. These effectiveness values were then input to the PM_{10} data analysis computer program (VanOsdell, Chen, and Newsome, 1988). For each sampler and wind speed, the effectiveness data were adjusted to account for the presence of multiplets of the primary challenge particle. A robust-spline curve (in log-normal space) was then fit to the multiplet-corrected data. The PM_{10} data analysis procedure outlined in 40 CFR Part 53 requires that the effectiveness-particle size data be fit with a smooth curve and that the ends of the curve be smoothly extrapolated to 100 percent at 1 μm and 0 percent at 50 μm, and this requirement has been implemented mathematically in the data analysis program. The program usually fits effectiveness data well, especially in the region of the cut-point, and it provides an impartial estimate of an inlet's performance parameters. (Because the curve fit is generated in log-normal space, values above 100 percent are suppressed.) The robust spline curve-fit process does not impose any preconceived functional form on the data. The D_{50}, expected mass collection for the PM_{10} ambient particle size distribution (40 CFR Subpart D, Table D-3), and expected mass ratio were all computed based on the robust-spline curve.

SECTION 4

RESULTS AND DISCUSSION

4.1 Effectiveness Results

A summary of the test program results is presented in Table 3. Most effectiveness values in Table 3 are the mean of three individual effectiveness determinations made during a given test. The Expected Mass and Mass Ratio to Ideal Sampler are values

Table 3. Summary of Multiplet Corrected R&P Test Results

	R&P Dichot	SM 1	SM 2	PIP 1	PIP 2
2 km/h D_{50}, µm	9.82	14.03	14.44	8.45	8.74
2 km/h Expected Mass, µg/m^3	148.0	184.3	184.2	131.6	133.6
2 km/h Mass Ratio to Ideal PM_{10} Sampler	1.028	1.281	1.280	0.914	0.929
24 km/h D_{50}, µm	9.58	8.36	8.89	6.57	6.32
24 km/h Expected Mass, µg/m^3	147.8	140.2	150.0	114.6	111.5
24 km/h Mass Ratio to Ideal PM_{10} Sampler	1.027	0.974	1.043	0.796	0.775

Note: All values computed using standard PM10 Data Reduction Program. All effectiveness values were corrected for multiplets.

used to compare PM_{10} samplers. The ideal sampler effectiveness performance curve and the ambient particle mass distribution are given in 40 CFR Part 53. The expected mass is obtained by multiplying the mass in each size fraction of the size distribution by the sampler's effectiveness and adding over the size distribution. The ratio is self-explanatory. The complete data sets for each wind speed are given in the Appendix. Also given in the Appendix are the test particle size parameters and the particle uniformity data for each test.

Figure 3 shows the data and curve-fits for the R&P inlet at 2 and 24 km/h. The data are seen to be well behaved, and the D_{50}, expected mass, and mass ratio values given in Table 3 provide good representations of the R&P sampler's behavior. Within the limits of this data set, the R&P 10-µm Inlet appears to easily meet the wind tunnel sampling requirements of 40 CFR Part 53. While the 8 km/h data were not gathered, the 2 and 24 km/h data span the limits of interest and at the most likely velocities for a sampler to fail the test procedure.

Figures 4 and 5 show the data and curves for the saturation monitors at 2 and 24 km/h. The saturation monitors oversampled 5-µm particles at both wind speeds. Because values above 100 percent do not exist in log-normal space, these points were treated as 99.99 percent in the data analysis.

The significance of the measured oversampling is unclear. The saturation monitors have not been tested in a quiesent atmosphere to determine the cut-point of the sampler's impactor. A wind tunnel test necessarily reflects both the sampling and the size-selective characteristics of an inlet. While theoretically possible, the physical shape of the saturation monitors does not appear likely to encourage the flow patterns that could cause oversampling. However, the 5 L/min flow rate of the saturation monitors, which is lower than the other sampling rates, caused the mass collected on the filter to be low. Consequently, measurement errors may have been significant. Contamination may have occurred and the variability in the fluorometry measurement would be much more important than it is normally. Fortunately, the potential errors become less significant as the test particle size increases, and the curves shown in Figures 4 and 5 should adequately represent the performance of the saturation monitors for particles larger than

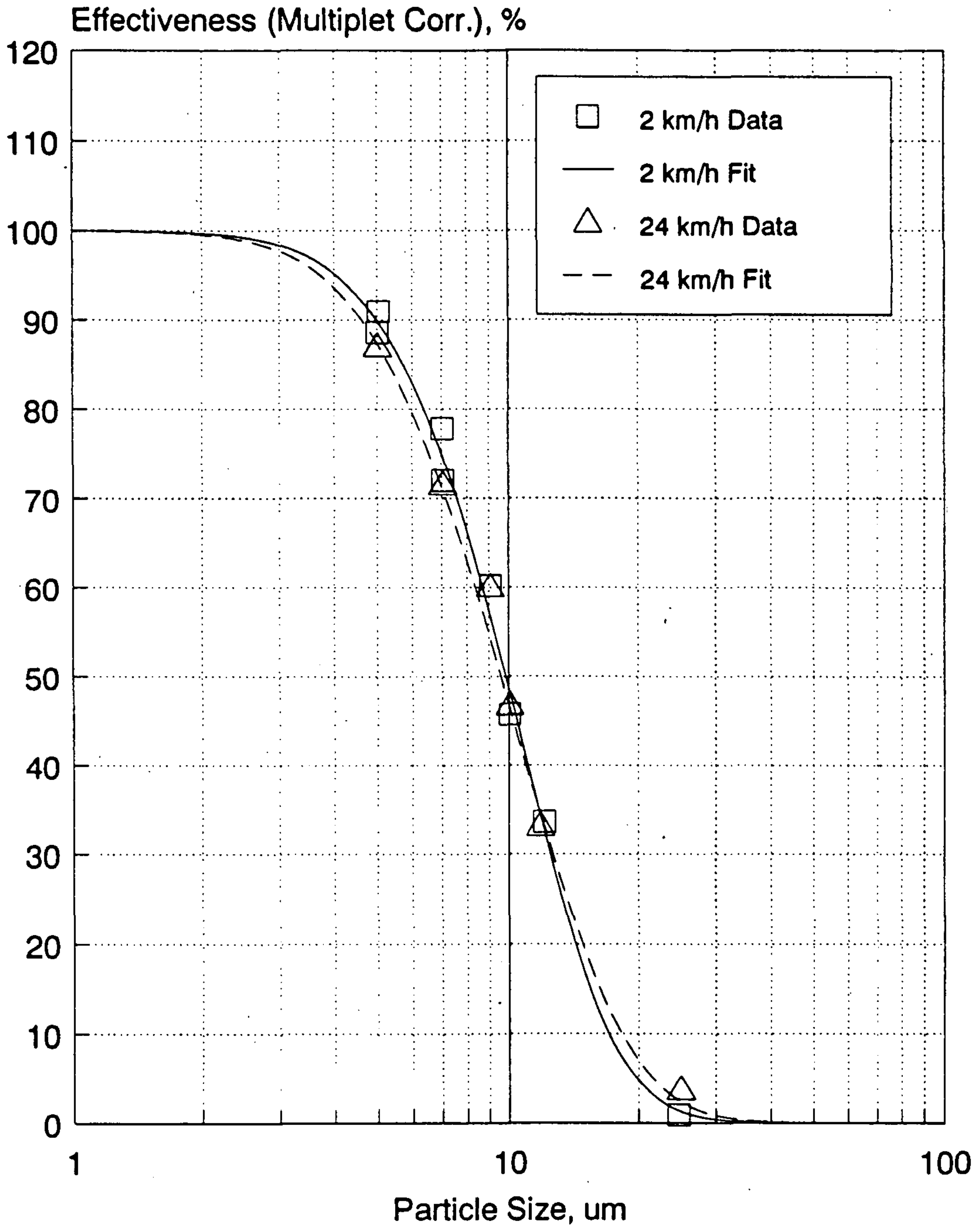

Figure 3. R&P 10-µm Inlet Performance at 2 and 24 km/h

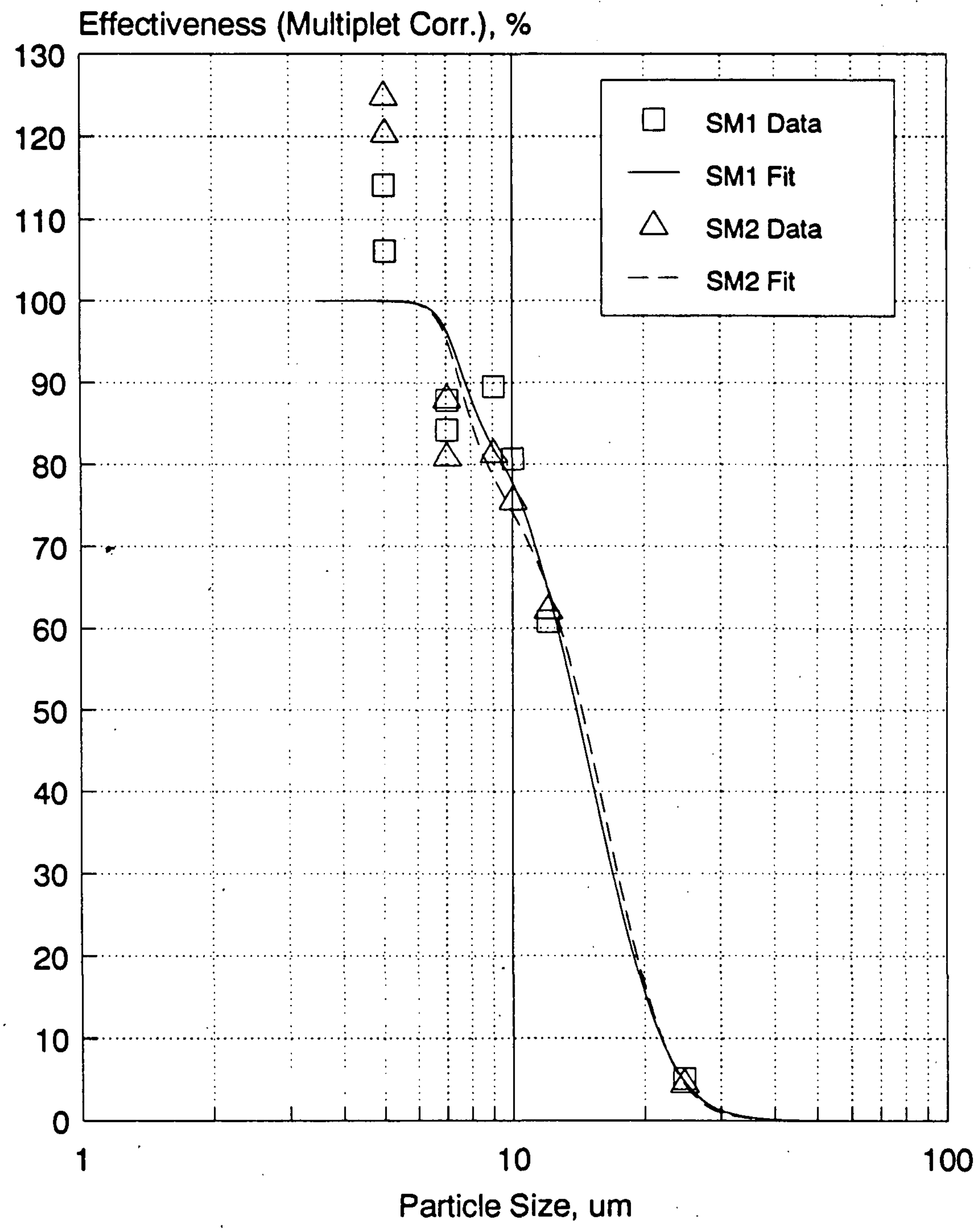

Figure 4. Saturation Monitor Performance at 2 km/h.

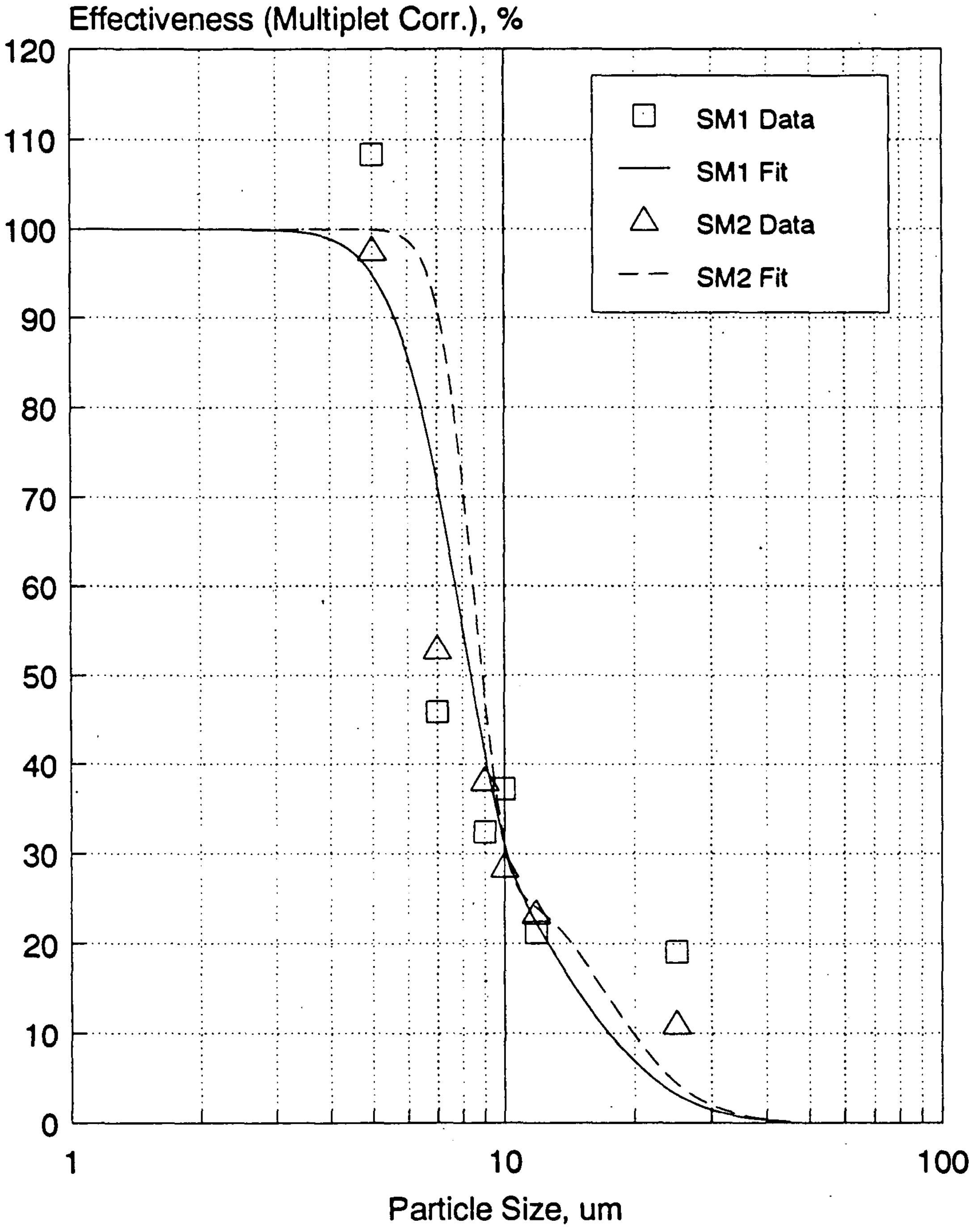

Figure 5. Saturation Monitor Performance at 24 km/h.

5 μm.

The data and effectiveness curves for the PIPS are shown in Figures 6 and 7 at 2 and 24 km/h, respectively. The cut-points measured for the PIPS in the wind tunnel are smaller than expected. PIPS cut-points have been measured in a wind-free chamber and found to be approximately 10 μm. The PIPS were designed as indoor size selective samplers, and not for use in wind. They do not have a wind screen. The sample is drawn into the region above the impactor jets through four 13 mm holes, and the impactor jets sample from that region. Wind entering through the inlet hole may simply jet across the sampler and out the other side. Under these conditions the air available to the impactor jets may become depleted of challenge particles. This explanation seems more likely at 24 km/h than at 2 km/h.

However, as was true of the saturation monitors, at 5 μm the mass collected by the sampler was relatively low. Thus the low effectivenss at 5 μm may have been caused by errors in the measurement. The very low effectiveness values at 24 km/h for 7 μm particles are unexplained. The tests were not repeated because the PIPS are not really suitable for application in any case.

4.2 Sampler Performance In Various Challenge Particle Size Distributions

The significance of the effectiveness curves in Figures 4 through 7 was addressed for the PM_{10} challenge particle size distribution in Table 3. The mass ratio compares the mass that the tested sampler would have collected to that the ideal PM_{10} sampler would have collected. Figure 8 is a presentation of all the sampler performance curves at 2 km/h. The PM_{10} ideal sampler curve was obtained from 40 CFR Part 53. Figure 9 presents the same information at 24 km/h. The R&P Inlet is fairly close to the ideal inlet at both 2 and 24 km/h. On the other hand, SM1 goes from collecting a great deal more aerosol than the ideal sampler at 2 km/h to overlapping performance at 24 km/h, and the PIP1 sampler goes from overlapping at 2 km/h to collecting a good deal less aerosol at 2 km/h.

The significance of the differences evident in Figures 8 and 9 can be evaluated by extending the mass ratio analysis to other challenge size distributions. Figure 10 is a

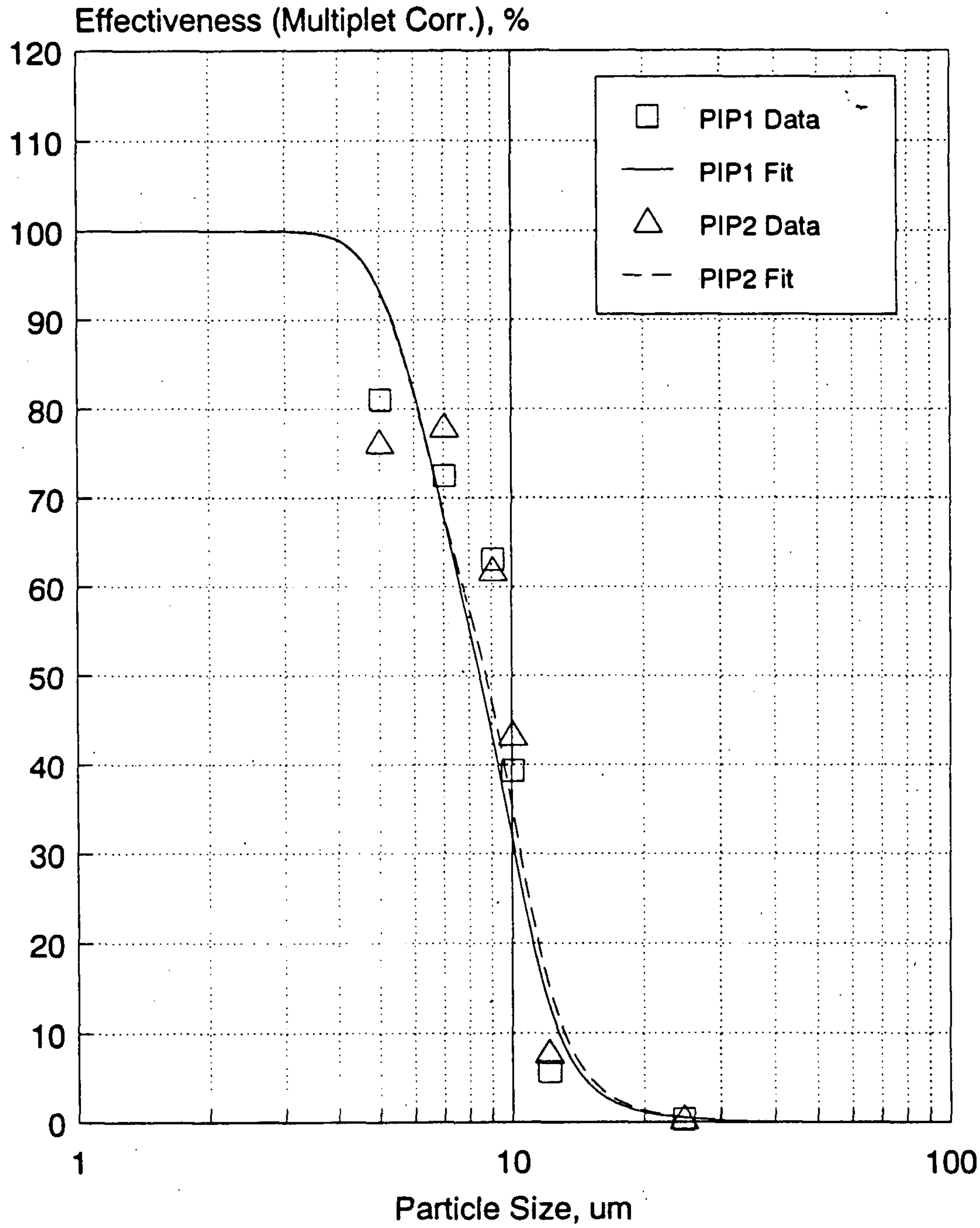

Figure 6. Performance of PIPS at 2 km/h.

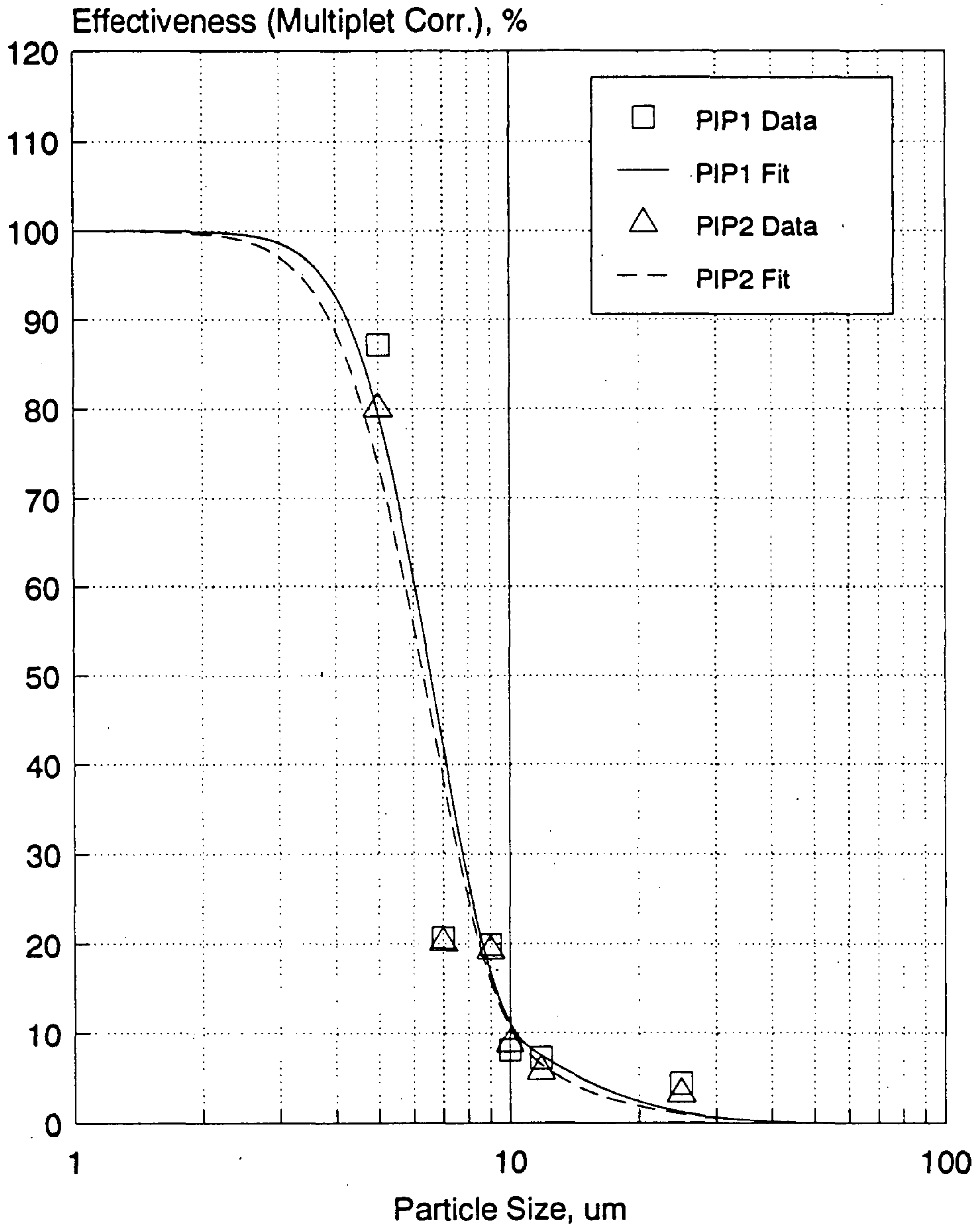

Figure 7. Performance of PIPS at 24 km/h.

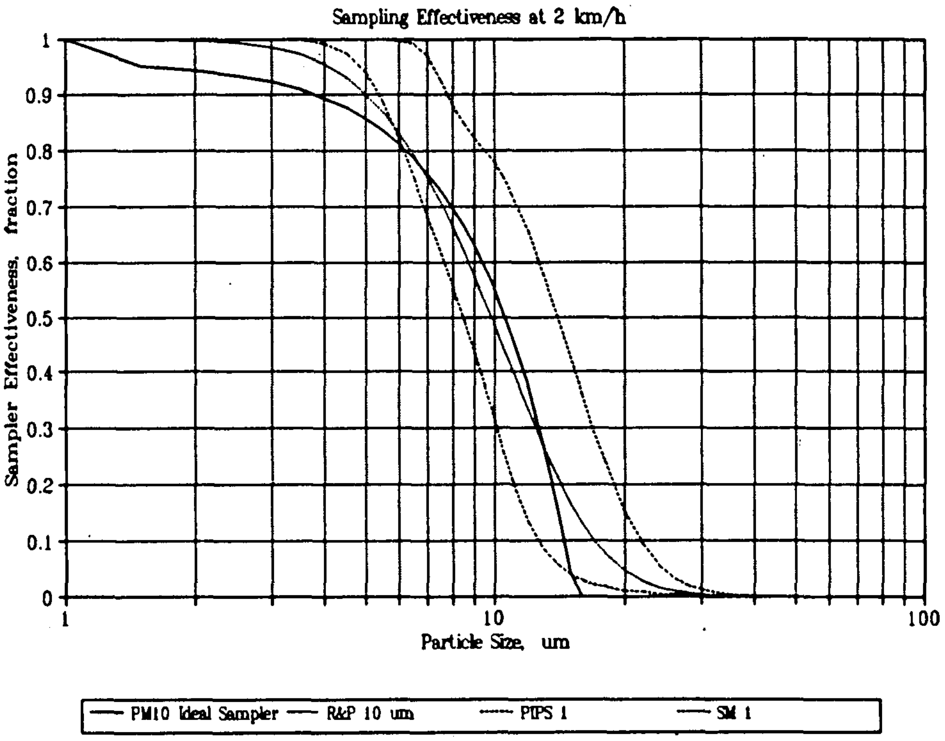
Sampling Effectiveness at 2 km/h
Sampler Effectiveness, fraction
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
10
100
Particle Size, um
PM10 Ideal Sampler
R&P 10 um
PIPS 1
SM 1

Figure 8.

Figure 8. Comparison of Tested and Ideal Samplers at 2 km/h.

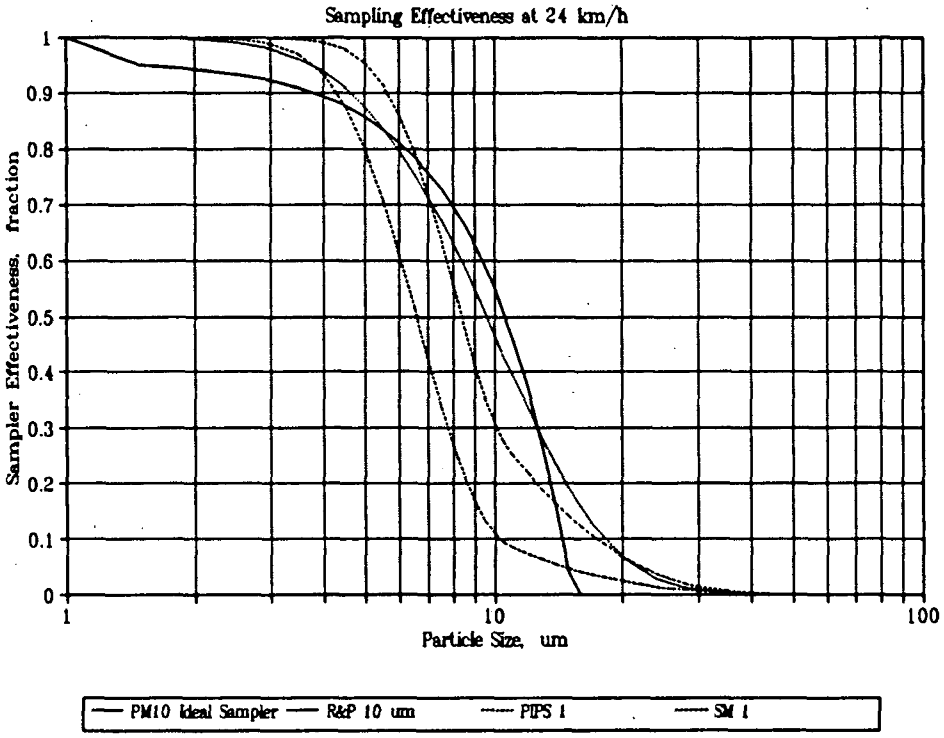
Sampling Effectiveness at 24 km/h
Sampler Effectiveness, fraction
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
10
100
Particle Size, um
PM10 Ideal Sampler
R&P 10 um
PIPS 1
SM 1

Figure 9.

Figure 9. Comparison of Tested and Ideal Samplers at 24 km/h.

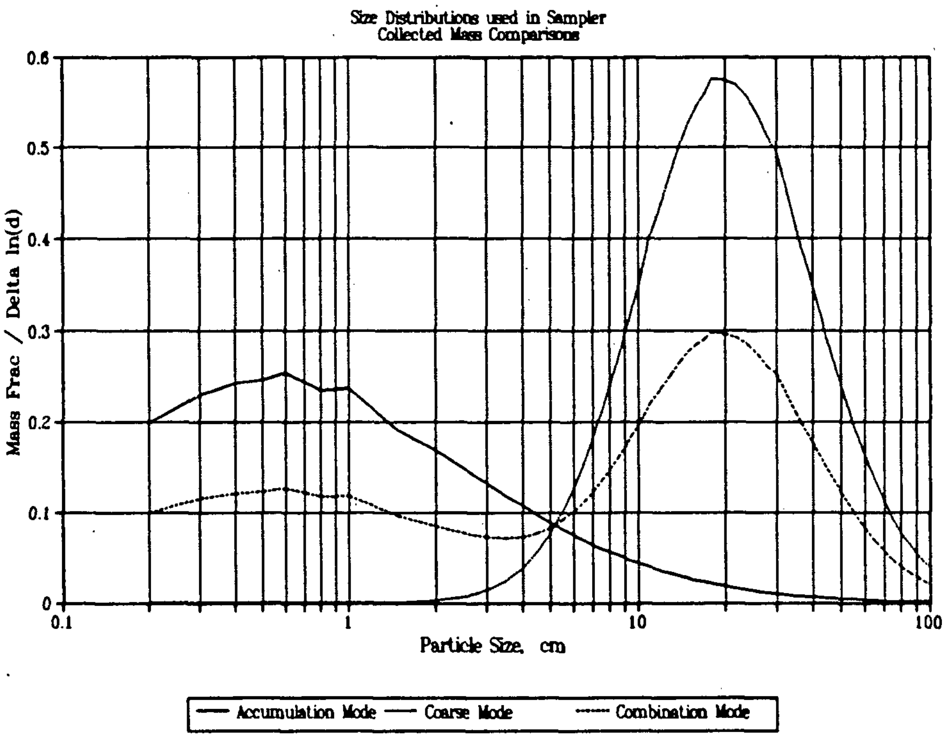
Size Distributions used in Sampler
Collected Mass Comparisons
Mass Frac / Delta ln(d)
0.6
0.5
0.4
0.3
0.2
0.1
0
0.1
1
10
100
Particle Size, cm
Accumulation Mode
Coarse Mode
Combination Mode

Figure 10.

Figure 10. Size Distributions for Sampler Comparison.

differential mass plot of two primary distributions and a third distribution formed by adding the primary distributions in equal proportions. The accumulation mode aerosol has an MMD of 0.5 μm and σ_g of 5.0, while the coarse mode aerosol has a MMD of 20 μm and σ_g of 2.0. This distribution was described by Lundgren and Paulus (1975). The primary and combined distributions were mathematically collected by the samplers to obtain quantities analogous to the mass ratios presented in Table 3. The effectiveness curve of the ideal PM_{10} sampler was obtained from 40 CFR Part 53. The effectiveness values for each size interval were multiplied by the mass in that interval and added to obtain a total relative mass collected by that sampler. This process was carried out for the ideal sampler, the R&P sampler, SM1, and PIP1 for all three distributions. (Collection of all the particles in a size distribution would give a relative mass of 1.0. The samplers collect only a portion of the distributions, so their relative mass collections were less than 1.0.) The relative mass collected by the tested samplers was then divided by that collected by the ideal sampler to obtain mass ratios for each sampler and size distribution. The results are given in Table 4.

As would be expected, Table 4 shows that all the samplers collect most of the fine mode aerosol. On the other hand, there are significant differences between samplers in the coarse mode aerosol collection. As they should, all samplers collected considerably less than 100 percent of the coarse aerosol. The R&P inlet and the ideal sampler collect about the same fraction of the coarse aerosol, and the results are the same at both wind speeds. The PIP1 sampler collected less coarse mode aerosol than the ideal sampler at both wind speeds, with the difference being especially large at 24 km/h. SM1, on the other hand, collected substantially more coarse mode aerosol than the ideal sampler at 2 km/h and about the same at 24 km/h. Thus the behavior of these two samplers in the wind depends greatly on both the size distributions to which they are exposed and the wind speed. Despite this, the overall performance on the combined size distribution is not as bad as the individual distribution results suggest it might be. SM1 at 2 km/h gave the greatest discrepancy, oversampling by 15 percent relative to the ideal sampler. At 24 km/h, the PIP1 sampler undersampled by 8 percent while SM1 was close. This calculation suggests that the wind dependent performance of a sampler is likely to be

Table 4. Relative Mass Collected and Mass Ratios for Artificial Size Distribution.

	Fine Mode REL. MASS	Coarse Mode REL. MASS	Comb. Size Dist. REL. MASS	Fine Mode RATIO	Coarse Mode RATIO	Comb. Size Dist. RATIO
Ideal Sampler	0.94	0.17	0.56			
R&P at 2 km/h	0.95	0.19	0.57	1.01	1.10	1.03
SM1 at 2 km/h	0.95	0.13	0.54	1.03	1.82	1.15
PIP1 at 2 km/h	0.97	0.31	0.64	1.01	0.76	0.97
Ideal Sampler	0.94	0.17	0.56			
R&P at 24 km/h	0.95	0.19	0.57	1.01	1.12	1.03
SM1 at 24 km/h	0.93	0.09	0.51	1.01	0.96	1.00
PIP1 at 24 km/h	0.95	0.17	0.56	0.99	0.51	0.92

fairly robust for the usual challenge aerosols, even if the performance curve deviates considerably from ideal performance.

SECTION 5

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