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ABSTRACT

Measurements were conducted to assess the MiniVol $PM_{2.5}$ sampler performance for various particle preseparator configurations including flat and cup impaction stages. Laboratory measurements were conducted to determine the impactor collection efficiency as a function of particle size. Impactor cut points - the aerodynamic particle diameter exhibiting 50% collection efficiency - were 2.5 µm (± 10%) for the flat stage and 3.0 µm for the cup stage. Collection efficiency curves for cascade (tandem) impactor configurations (PM_{10} followed by $PM_{2.5}$) generally agreed with the single stage results. In all cases the collection efficiency curves exhibited the classical sigmoidal shape, albeit less steep than required for $PM_{2.5}$ Federal Reference Method (FRM) samplers. Field data was collected at urban sites in St. Louis using MiniVol samplers collocated with a $PM_{2.5}$ FRM sampler to quantify the MiniVol sampler precision and accuracy. Collocated sampler precision was 6% and 10% for MiniVol cascade impactors with flat $PM_{2.5}$ stages and cup $PM_{2.5}$ stages, respectively (N=31). Both of these MiniVol configurations were deemed statistically equivalent to the FRM when the reported ambient mass concentrations were corrected for field blank values (N=15).

INTRODUCTION

In July 1997, the U.S. Environmental Protection Agency (USEPA) revised the particulate matter National Ambient Air Quality Standard (NAAQS) to include an indicator for particulate matter smaller than 2.5 µm aerodynamic diameter ($PM_{2.5}$). Monitoring for the purposes of NAAQS compliance requires the use of a Federal Reference Method (FRM) monitor; however, there is a need to supplement such sampling with additional measurements using, e.g., saturation monitors. Indeed, applications include saturation monitoring for optimal FRM monitor siting, to support control strategy development, and research into $PM_{2.5}$ emission rates from various sources.

The MiniVol Portable Air Sampler (Airmetrics, Inc., Springfield, OR) has been used in a variety of particulate matter sampling applications for Inhalable Particulate, PM_{10} and recently also $PM_{2.5}$.[1,2] Tropp et al.[3] and Lamoree[4] contain several references to studies which have used the MiniVol sampler. USEPA's Saturation Monitoring Repository (SMR) provides MiniVol samplers on loan for certain monitoring applications. The MiniVol is lightweight, inexpensive, and relatively easy to operate. For $PM_{2.5}$ sampling, it features a 2.5 µm cut point inertial impactor operating at a flow rate of 5 LPM. Airmetrics has marketed a variety of particle preseparator configurations for achieving this cut point: (1) the original arrangement of a single $PM_{2.5}$ jet with a flat impaction stage; (2) a single $PM_{2.5}$ jet with a cup impaction stage; and (3) a cascade (tandem) impactor arrangement with a PM_{10} impactor upstream of the $PM_{2.5}$ impactor. Single impactor and cascade impactor preseparator geometries are shown in Tropp et al. (Figures 2 and 3, respectively).[3] Although the MiniVol does not meet the design specifications required for designation as a $PM_{2.5}$ regulatory monitor, it is potentially useful for saturation monitoring and other particulate matter sampling studies. The MiniVol $PM_{2.5}$ impactor assembly appears to be based on accepted, generic design criteria for impactors[5]; however, its performance has not been characterized robustly.

The overall scope of this study was to evaluate the performance of the MiniVol $PM_{2.5}$ sampler by using laboratory testing and field measurements. This paper presents results obtained for: laboratory measurements to determine MiniVol $PM_{2.5}$ impactor collection efficiency as a function of particle size, including data for the flat impaction stage, cup impaction stage, and cascade impactor arrangement; and measurements at fine particulate matter-dominated urban sites using MiniVol samplers collocated with a $PM_{2.5}$ Federal Reference Method monitor.

LABORATORY EVALUATION OF THE MINIVOL $PM_{2.5}$ IMPACTOR

Approach

Particle collection efficiency curves for the MiniVol $PM_{2.5}$ impaction assembly were measured by challenging the impactor with a series of monodisperse aerosols of known size and at a controlled flow rate. The collection efficiency was calculated by measuring the concentration of particles upstream and downstream of the impactor. Particle removal by impaction is governed by the particle Stokes number, STK defined as[6]:

$$STK = \frac{\rho_p d_p^{\,2} U C_c}{9 \mu D_j}$$

where ρ_p is the particle density (1000 kg/m^3 for aerodynamic particles), d_p is the particle diameter, U is the gas velocity at the jet exit, C_c is the Cunningham slip correction factor, μ is the gas viscosity (1.81×10^{-5} kg/m/s for air at 20°C), and D_j is the jet diameter (0.290 cm for the MiniVol $PM_{2.5}$ impactor). The Cunningham slip correction factor is defined as $C_c = 1 + 2.52\lambda/d_p$ where λ is the mean free path (0.066 μm for air at 20°C).[6] The square root of the Stokes number ($\sqrt{STK}$) is proportional to d_p for $C_c = 1$ (i.e. $\lambda << d_p$); thus, collection efficiency curves are often plotted as a function of $\sqrt{STK}$. Since the Stokes number is a function of both particle size and gas velocity, the collection efficiency can be measured for a range of $\sqrt{STK}$ numbers by varying the particle size and/or the gas flow rate. This approach is valid assuming "dimensional similitude" holds for the range of operating conditions used to measure the collection efficiency. Patel et al.[7] have demonstrated that the particle collection efficiency trends for relatively large particles can be determined using smaller particles and a higher flow rate (that is, dimensional similitude is *operationally* preserved in this regime).

The MiniVol impactor is designed to achieve an aerodynamic particle cut point of 2.5 μm for aerodynamic particles at a flow rate of 5 LPM. This corresponds to $\sqrt{STK} = 0.42$ for the MiniVol sampler geometry. The ideal collection efficiency curve would be a step function at this value of $\sqrt{STK}$, indicating complete collection of particles larger than 2.5 μm and no removal of particles smaller than 2.5 µm. In reality, certain factors cause the collection efficiency to have a sigmoidal-shaped appearance. In such cases, the √STK number corresponding to the cut point is the value at which the collection efficiency is 50%.

Experimental Method

The experimental apparatus shown in Figure 1 was used to suspend monodisperse particles in an air stream, control the flow rate of aerosol through the MiniVol impactor, and measure particle concentrations upstream and downstream of the impactor. Polystyrene latex (PSL) spheres (Duke Scientific, Palo Alto, CA) were used for all collection efficiency measurements. A constant-output atomizer (TSI Model 3076, St. Paul, MN) suspends droplets of an aqueous PSL suspension into a stream of dried, filtered air. The aerosol subsequently passes through a charge neutralizer (TSI Model 3054) and silica gel radial diffusion dryer, and enters a sampling plenum. An aerosol stream is drawn from the plenum at a controlled flow rate using a rotameter, needle valve, and vacuum pump. A test section upstream of these flow control devices houses the MiniVol impactor assembly. A laser optical particle counter (Particle Measuring Systems, model LAS-X, Boulder, CO) records the particle size distribution for aerosol drawn from isokinetic sampling ports located in the test section upstream and downstream of the impactor. The particle collection efficiency is defined as $\eta = 1 - x_{down}/x_{up}$, where x_{down} and x_{up} are the particle counts measured at the downstream and upstream probes, respectively. Standard deviations, σ_η, for the collection efficiency at each √STK were calculated by propagating the standard deviations of each upstream/downstream data set within a given run.

Repeat measurements were conducted for all operating conditions to reduce the uncertainty in the calculated collection efficiencies. In general, repeat measurements of the collection efficiency were conducted on separate days with the impactor assembly typically removed, cleaned, greased and re-inserted into the test section between such runs. Weighted mean collection efficiencies and weighted standard deviations were calculated for the replicate data.[8] Figure 2 shows a typical collection efficiency curve obtained in this study. Error bars are presented as 2σ which is approximately equal to the 95% confidence interval. Error bars are not provided on the remaining figures in this paper to increase the readability of the figures; however, they were taken into consideration when interpreting the data. The particle diameter, d_p, along the top x-axis corresponds to aerodynamic particles at the MiniVol design flow rate of 5 LPM; this labeling convention will be used for the figures throughout this paper.

It is important to note that these experiments characterize the MiniVol impactor assembly performance for the idealized condition of a relatively well-defined flow field upstream of the impactor assembly. In contrast, field operation of the MiniVol sampler may be affected by complex flow patterns in the short space between the rain cap and impactor assembly.

MiniVol Impactor Particle Collection Efficiency Curves

Collection Efficiency as a Function of Impaction Stage Greasing

In inertial impaction, particle size separation is achieved by having large particles collect on the impaction stage. However, it is possible particles may have enough energy to bounce off the impaction stage, thereby biasing mass concentration measurements. This particle bounce phenomenon can be significantly reduced by applying grease to the impaction stage.[9] To determine the influence of impactor stage greasing on collection efficiency, both the flat and cup stages were tested with various amounts of applied grease.

Prior to each run, the impactors were cleaned with hexane and treated with a grease solution. The various greasing procedures are defined as follows: (1) “no grease” - no grease was applied to the stage after cleaning; (2) “light grease” – a dilute solution of Apiezon grease (1 inch/100 mL hexane) was applied to the center of the impaction stage until the solution freely flowed over the stage edges; (3) “heavy grease” - a concentrated solution of Apiezon grease (4 inches/100 mL hexane) was applied to the stage in the following sequence: three drops placed at the center of the stage; a total of three drops applied near the stage edges; and after the initial application was allowed to evaporate, an additional six drops were applied at the center of the stage; and (4) “very heavy grease” – a thin coat of Apiezon grease - without hexane - was applied directly to the stage surface. The light grease method most closely resembles the recommended procedure in the MiniVol Operation Manual.[10] The manual calls for 2-3 drops, but 6-8 drops are actually needed for the solution to flow over the edges of the stage.

Figure 3 shows the collection efficiency results for the flat stage configuration; qualitatively similar trends were obtained for the cup stage. The unacceptably low collection efficiency for larger $\sqrt{STK}$ in the absence of grease demonstrates the need for applying grease. Similarly, the “light” method does not provide sufficient collection efficiencies for the flat stage as the collection efficiency is less than 90% at large $\sqrt{STK}$ values. For the cup stage (not shown) both the “light” and “heavy” greasing procedures yielded relatively good collection for large $\sqrt{STK}$. In summary, the “heavy” greasing protocol is superior to the “light” protocol for the flat stage while the “light” greasing protocol is an adequate method for preparing the cup impaction stage.

Collection Efficiency for Flat Stage and Cup Stage $PM_{2.5}$ Impactors (No Cascade)

Patel et al.[7] present collection efficiency curves for: four presumably identical $PM_{2.5}$ flat stage impactors; four presumably identical $PM_{2.5}$ impactor jets paired with the same flat stage; and three presumably identical cup stages paired with the same $PM_{2.5}$ jet. Collection efficiency curves for the flat stage impactors all had the same basic shape exhibited by the “heavy grease” curve in Figure 3 with cut point values $\sqrt{STK} = 0.39\text{-}0.46$ ($d_p = 2.3\text{-}2.7$ μm). Using the same stage and four different jets narrowed the spread in the cut point data to $\sqrt{STK} = 0.43\text{-}0.46$ ($d_p = 2.5\text{-}2.7$ μm). This suggests that small differences in the jets likely account for some of the observed differences in collection efficiency curves between different impactors. Collection efficiency curves for the three cup stages with the same $PM_{2.5}$ jet exhibited good reproducibility; however, the cut point was $\sqrt{STK} = 0.50$ ($d_p = 3.0$ μm) which is significantly greater than the design value of $\sqrt{STK} = 0.42$ ($d_p = 2.5$ μm).

Collection Efficiency for Cascade (PM_{10} followed by $PM_{2.5}$) Impactors

A relatively recent variation on the MiniVol $PM_{2.5}$ impactor design calls for a PM_{10} impactor upstream of the $PM_{2.5}$ stage impactor (i.e. a cascade or tandem impactor configuration). Collection efficiency curves were developed for this configuration using both flat and cup $PM_{2.5}$ impactors with light grease applied to cup stages and heavy grease applied to flat stages. Figure 4 displays these curves along with curves for the single-impactor configurations and the USEPA design specification curve for $PM_{2.5}$ FRM monitors.[11] For both the flat and cup $PM_{2.5}$ stage impactors there is excellent agreement between the curves for single impactor and cascade configurations except at $\sqrt{STK}$ below ~0.3 where collection appears to be amplified for the cascade arrangement. Neither the cut point nor the basic shape of the collection efficiency curves change significantly with the addition of the PM_{10} impactor ($\sqrt{STK}$ = 0.46 and 0.45 for the single and cascade flat stage, respectively, and $\sqrt{STK}$ = 0.50 and 0.52 for the single and cascade cup stage, respectively). This is logical since the PM_{10} impactor should not collect any particles below 10 μm; therefore, it should not improve the collection of particles in the 2-5 μm range. Figure 4 clearly demonstrates the different cut points for the flat stage (d_p = 2.5 μm) and cup stage (d_p = 3.0 μm) impactors as reported in the previous section. Collection efficiency curves for both MiniVol impactors are less steep than the FRM design specification curve.

FIELD STUDIES OF MINIVOL $PM_{2.5}$ SAMPLER PERFORMANCE

While previous studies have evaluated the performance of MiniVol PM_{10} samplers (see references in Topp et al.[3] and Lamoree[4]), relatively little data is available to describe the MiniVol $PM_{2.5}$ sampler performance for measuring 24-hour average mass concentrations with the tandem impactor configuration. One exception is the work of Tropp et al. who investigated MiniVol $PM_{2.5}$ sampler performance for "best-case" sampling conditions; six runs were included in their statistical data analysis.[3]

To determine the MiniVol sampler performance under actual field conditions, a series of collocated sampling runs was conducted over several months in 1997 and 1998. Ambient particulate matter mass concentrations determined from multiple samplers on the same day, at the same location, and subjected to "identical" ambient conditions were used to quantify both the precision and accuracy of the MiniVol sampler. Precision was based on a comparison between two identically configured, collocated MiniVol samplers. Accuracy was determined with respect to a dichotomous sampler (Graseby-Andersen Model 241, Smyrna, GA) and a USEPA-approved $PM_{2.5}$ Federal Reference Method sampler (Rupprecht & Patashnick Co., Inc. Partisol-FRM 2000, Albany, NY). Data for the dichotomous sampler is presented and discussed elsewhere.[12] The Partisol $PM_{2.5}$ FRM provides an *operational* definition (indeed, also a *regulatory* definition) for measuring $PM_{2.5}$ mass concentrations because the cut point is not a step function. For the purposes of this paper, MiniVol accuracy is expressed in terms of its relative performance compared to the Partisol $PM_{2.5}$ FRM.

Sampling was conducted for three specific sites at two geographic locations; each site would be classified as "best-case" locations using the criteria of Tropp et al.[3] Site "A" was located on the roof of a one-story building (the Radiochemistry building) on the campus of Washington University, immediately west of the City of St. Louis. Sampling was conducted from 11/1/97 through 12/16/97. This site was located approximately 50 meters south of a four-lane principal arterial roadway which separates the campus from an urban residential area and was generally unobstructed. It is characterized as a fine particulate matter-dominated location with an average dichot $PM_{2.5}/PM_{10}$ ratio of 72 ± 8%.

Site "B" was located on the roof of a three-story building (City of St. Louis Municipal Garage) in downtown St. Louis. The sampling period ran from 1/27/98 through 3/7/98. The site was located several hundred meters north of heavily traveled Interstate 64 and was surrounded by high rise buildings to the north, east, and west. There was a 1-meter-high wall at the edge of the roof, approximately 3 meters to the west of the sampling equipment. Site B was also dominated by fine particulate matter (average dichot $PM_{2.5}/PM_{10}$ ratio of 66 ± 10%), and presumably presented complex wind patterns that were expected to challenge the samplers.

Site "C" was located on the roof of a three-story building (Urbauer Hall) on the campus of Washington University, approximately 100 meters east of site A. Sampling was performed from 5/23/98 through 6/26/98. Several nearby buildings were of approximately the same height, and the four-lane roadway was now 100 meters to the north. The wind patterns around site C were largely unobstructed. Like site A, site C was dominated by fine particulate matter (average dichot $PM_{2.5}/PM_{10}$ ratio of 60 ± 11%), and was chosen in light of its accessibility for the initial set of tests conducted with the Partisol FRM.

Experimental Method

Collocated samplers were operated for a series of 24-hour periods to determine the daily-average ambient $PM_{2.5}$ mass concentration. All samples were collected on PTFE filters (47 mm diameter, 1 μm nominal pore size, Gelman Sciences, #R2PL047, Ann Arbor, MI) and gravimetric analysis was performed using a balance with microgram precision (Analytical Technology, Inc., Cahn Model C-35, Boston, MA). Gravimetric analysis procedures were generally consistent with USEPA protocols for microbalance operation and filter weighing and handling.[13] Specifically, filters were weighed twice before and twice after sample collection. For at least 24 hours prior to each set of weighings, the filters were equilibrated in a humidity chamber maintained at 40-45% relative humidity. In accordance with recent revisions to the particulate matter NAAQS monitoring regulations, reported particulate matter mass concentrations were *not* corrected to standard temperature and pressure (STP).

Preparation of the MiniVol samplers included cleaning and greasing the impactor stages and setting the flow rate. Prior to each run, all of the impactors were disassembled and cleaned with hexane. Impactors were then re-greased according to the protocols discussed earlier in this paper. MiniVol sampler flow rates were set to 5 LPM for the average temperature and pressure forecasted for the sampling period using a NIST-traceable rotameter (Gilmont Instruments, Inc., GF-4340, Barrington, IL) connected to a PVC adapter machined to attach to the MiniVol preseparator adapter. This approach to setting the flow rate neglects differences between the ambient conditions at the time of deployment and the average conditions forecasted for the sampling period; in general, such corrections were deemed small.

At the sampling site, all of the MiniVol samplers were placed in a straight line with 30-40 centimeters spacing. They were suspended from a 2-meter high PVC framework with inlets at approximately the same height as the dichotomous sampler and Partisol FRM inlets, which were located within 3 meters of the MiniVol samplers. Sampling was performed every second or third day, with the samples usually being recovered within 1-2 days following each run. The numbers and configurations of samplers at sites A and B were identical; four operational MiniVol samplers and one field blank were collocated with a single dichotomous sampler and the meteorological station. The Partisol $PM_{2.5}$ FRM was not available for use until the start of sampling at site C.

All of the MiniVol samplers used the cascade impactor arrangement with flat PM_{10} stages. Samplers 1019 and 1020 used cup $PM_{2.5}$ impaction stages and were configured and prepared according to the manufacturer's latest recommendations.[10] Samplers 1507 and 1508 used flat $PM_{2.5}$ impaction stages with heavy grease application, which was found to give the best results in a laboratory characterization as described earlier in this paper. MiniVol samplers 1507 and 1508 were manufacturer's version 4.2, while 1019 and 1020 were version 4.1. The same sampler body, impactor jet, and impaction stage combinations were used for all runs. Separate field testing showed that the MiniVol performance is dictated by the preseparator assemblies and not the sampler bodies.[12]

Field Study Results

MiniVol Sampler Precision

Summary statistics for ambient particulate matter mass concentrations and collocated sampler precision are presented in Table 1. Figure 5 shows scatter plots for the collocated MiniVol samplers of identical configuration. By visual inspection, the flat $PM_{2.5}$ impaction stages appear to have better precision than the cup $PM_{2.5}$ impaction stages. In particular, there appears to be a bias between the cup $PM_{2.5}$ impaction stages and also a large difference in reported mass concentration at high values.

Table 1 demonstrates the range and variation in ambient fine mass concentration obtained from each sampler type over the course of the study. Data is shown only for days during which *all* of the samplers operated normally; no outliers were removed from this data set and no corrections for field blank values were applied. During some runs, one-or-more samplers failed QA/QC criteria (e.g., filter housing not securely sealed, filter severely damaged by water or ice accumulating in the filter housing, filter dropped during handling) and these runs are excluded from Table 1. The average, standard deviation, and coefficient of variation are given for the ambient mass concentrations recorded by each sampler or pair.

The collocated precision in Table 1 gives a valid measure of the precision, or reproducibility, among identical samplers regardless of ambient concentration variations. This precision was calculated as a pooled standard deviation – a method that assumed each daily concentration had a common variance which was unaffected by the magnitude of the values on each day.[12] Table 1 reveals a collocated MiniVol sampler precision of about 6% for the cascade impactor with flat $PM_{2.5}$ impaction stage and about 10% for the cascade impactor with cup $PM_{2.5}$ impaction stage. The data set includes 31 runs for each configuration. It appears that the flat impaction stage configuration provides modestly better precision than the cup impaction stage for the conditions of this study. Using the full data set (that is, including all data where collocated samplers of a given configuration passed QA/QC regardless of whether all deployed samplers passed QA/QC), the collocated precision over about 40 runs was 8-9% for both sampling configurations. In comparison, Tropp et al.[3] reported a precision of about 7% for the tandem configuration with cup impaction stages; six runs were included in their statistical data analysis with $PM_{2.5}$ concentrations in the range 10-16 $\mu g/m^3$.

MiniVol Accuracy Compared to the Partisol FRM

Figure 6 shows scatter plots of the $PM_{2.5}$ mass concentration for each MiniVol sampler versus the Partisol FRM. The MiniVol data was not corrected for field blank values and outliers were removed from the data set as described below. By visual inspection, it is apparent that both MiniVol configurations - a cascade impactor with flat $PM_{2.5}$ impaction stage and a cascade impactor with cup $PM_{2.5}$ impaction stage - yield higher fine particulate matter mass concentrations than the Partisol FRM. Qualitatively similar results were obtained for a comparison between the MiniVol samplers and the dichotomous sampler.[12]

The performance of different samplers was compared using a method involving linear regression of one sampler against another.[14] Standard linear regression results were used to correlate the performance of different samplers. If the slope was within three standard errors of unity, the intercept was within three standard errors of zero, and the correlation coefficient was greater than 0.90, the samplers were considered "equivalent". If the slope was not within three standard errors of unity but the other two conditions were met, the performance of the sampler was considered "predictable", but not equivalent. In this way, the linear regression parameters provided a means to determine the values that would be obtained by one sampler from those of another. It should be stressed that these are not USEPA's criteria for Federal Reference Method equivalency. Furthermore, the results are constrained to the sampling conditions (e.g., concentration range) for the data set collected in this study. An additional metric for comparison is the average difference between the two samplers. If this value was greater than the collocated precision between the two samplers (as defined by Mathai et al.[14] rather than the pooled standard deviation used in the *MiniVol Sampler Precision* section) and the samplers would otherwise be equivalent, the sampler in question was considered "biased" in relation to the other sampler. Table 2 summarizes the metrics for comparing samplers.

Table 3 displays the results of this analysis using the Partisol FRM as the independent variable. These calculations did not include outliers, which were determined to be days on which the difference between the two samplers exceeded three times the collocated precision of those two samplers. No runs (N=16) were classified as outliers for the data with no field blank corrections. None of the MiniVol samplers demonstrated equivalence to the Partisol FRM. All of the data sets either failed the intercept criterion or were biased based on the average difference criterion. The samplers that failed because of the intercept criterion would have also been found biased due to the average difference criterion. Additionally, all of the intercepts and average differences were greater than zero. These facts suggest the MiniVol samplers had a systematic positive bias over the entire range of observed ambient mass concentrations. Qualitatively similar results were obtained for the MiniVol sampler compared to the dichotomous sampler.[11] Tropp et al. reported less than 2.5% bias (high) for the $PM_{2.5}$ MiniVol sampler with tandem cup configuration compared to a prototype FRM; however, the study included only six runs with a relatively narrow spread in ambient mass concentration (10-16 $\mu g/m^3$).[3]

In response to these findings, the MiniVol mass concentrations were subsequently corrected with the field blank measurement and the regression analysis was repeated. The field blank was a MiniVol sampler configured with a cup $PM_{2.5}$ impactor in a cascade arrangement (identical to sampler 1019 and 1020) and was collocated with the rest of the MiniVol samplers. The pump on the field blank sampler was not turned on, but the unit was exposed to the ambient environment for the same time period as the other samplers. No field blank was available for the FRM, but this is of lesser concern in light of its inlet geometry and the higher filter mass loadings due to larger air volumes sampled. The procedure for correcting the MiniVol mass concentrations involved starting with the data as presented in Table 1, then subtracting the field blank mass from each MiniVol for each sampling period. Outliers were then removed from these corrected values as previously described; in this case, 1-2 runs were deemed outliers depending on the sampler configuration. Scatter plots are presented in Figure 7 for the MiniVol versus Partisol mass data and regression results are summarized in Table 3.

The field blank-corrected MiniVol data in Table 3 presents a much different story than the uncorrected data. All four MiniVol samplers were deemed equivalent to the Partisol FRM, albeit with a worse collocated precision between the cup $PM_{2.5}$ impaction stage samplers and the FRM than between the flat $PM_{2.5}$ impaction stage samplers and the FRM. Equivalent performance was also observed when outliers were not removed from the data set.

The fact that the field blank is collecting enough mass to significantly affect the accuracy of the MiniVol likely stems from the MiniVol's simple inlet geometry, low sampling flow rate (which results in relatively low particulate mass loadings on the filter), and relatively extensive filter handling requirements. In the latter case, recent modifications to the preseparator should reduce filter handling issues; we are currently evaluating the effect of these design revisions. A drawback of the MiniVol's compact size is that the distance between the sampler inlet and the filter is rather short - even for the cascade geometry - compared to other samplers. Additionally, the inlet does not have an elaborate physical barrier to reduce the penetration of low-inertia particles that may enter the inlet while the pump is not running. Given the short distance to the filter, these particles could conceivably pass by the impactors and deposit on the filter (we shall refer to this phenomenon as "passive sampling"). In contrast, the Partisol FRM has a PM_{10} cyclone inlet which provides a barrier to passive sampling. While correcting the MiniVol raw data using a field blank appears to solve this problem (at least for the conditions of this study), the burden of conducting field blanks with every run significantly increases the sampling and gravimetric analysis requirements. Furthermore, the field blank method used in this study accounts for passive sampling over the entire ambient exposure time. Ideally, this correction would account for passive sampling only during the time period that the samplers are not operating.

SUMMARY AND CONCLUSIONS

The MiniVol $PM_{2.5}$ sampler was evaluated by conducting both laboratory and field measurements for "best-case" conditions. Laboratory particle collection efficiency measurements for the particle preseparator assembly were conducted using well-defined entry flow and no initial particulate matter loading on the impaction surface; the latter minimizes particle bounce effects which might arise in the field for heavy particulate matter loading and relatively dry environments. The MiniVol $PM_{2.5}$ impactor with a flat impaction stage featured a critical particle size (50% collection efficiency) of 2.5 μm while the cup stage geometry yielded a cutoff near 3.0 μm. Thus, the flat stage is preferred over the cup stage based on performance for the idealized laboratory conditions. The tandem impactor configuration did not affect the critical particle size but did increase the collection of smaller particles in the preseparator assembly.

Field studies were conducted using the tandem impactor configuration at urban sites which featured relatively low coarse particulate matter contributions. The flat $PM_{2.5}$ stage exhibited slightly improved precision compared to the cup $PM_{2.5}$ stage. Both configurations were deemed equivalent to a collocated Federal Reference Method monitor when the MiniVol mass concentration data was corrected for field blank values and were biased high in the absence of field blank corrections.

Both the cup impaction stage and tandem configuration were designed to improve sampler performance for dry, windblown dust conditions; this study was not designed to challenge the sampler for such environments. However, the particle collection efficiency data generated in this study suggests that additional field measurements are needed to determine whether the shift in the critical particle size for the cup impaction stage has a substantive effect on observed mass concentrations when a significant coarse particulate matter component is present.

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REFERENCES

1. Claiborne, C.; Mitra, A.; Adams, G.; Bamesberger, L.; Allwine, G.; Kantamaneni, R.; Lamb, B.; Westberg, H. *Atmos. Environ.* **1995**, *29*, 1075-1089.
2. Lamoree, D.P.; Turner, J.R. In *$PM_{2.5}$: A Fine Particle Standard*; Chow, J., Koutrakis, P., Eds.; AWMA Publication VIP-81; Air & Waste Management Association: Pittsburgh, PA, 1998; pp 605-618.
3. Tropp, R.J.; Jones, K.; Kuhn, G.; Berg, N.J. Jr. In *$PM_{2.5}$: A Fine Particle Standard*; Chow, J., Koutrakis, P., Ed.; AWMA Publication VIP-81; Air & Waste Management Association: Pittsburgh, PA, 1998; pp 215-225.
4. Lamoree, D.P. M.S. Thesis, Washington University in St. Louis, 1999.
5. Marple, V.A.; Willeke, K. In *Aerosol Measurement*; Lundgren, D.A., Harris, F.S. Jr., Marlow, W.H., Lippmann, M., Clark, W.E., Durham, M.D., Eds.; University of Florida: Gainesville, FL, 1979; pp 90-107.
6. Hinds, W.C. *Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles*; John Wiley: New York, 1982.
7. Patel, P.D.; Hill, J.S.; Turner,J.R. in preparation.
8. Bevington, P.R;. Robinson, D.K *Data Reduction and Error Analysis for the Physical Sciences*; McGraw-Hill: New York, 1992.
9. Chow, J.C. *J. Air Waste Manage. Assoc.* 1995, *45*, 320-382.
10. Airmetrics, Inc. *MiniVol Portable Air Sampler: Operation Manual (version 4.2)*; Airmetrics, Inc.: Springfield, OR, 1997.
11. Federal Register **1997**, 62, 38763-38854.

12. Hill, J.S.; Patel, P.D.; Turner, J.R. in preparation.
13. USEPA *Quality Assurance Guidance Document 2.12: Monitoring $PM_{2.5}$ in Ambient Air Using Designated Reference of Class I Equivalent Methods*, U.S. Environmental Protection Agency, 1998.
14. Mathai, C.V., Watson, J.G.; Rogers, C.F.; Chow, J.C.; Tombach, I.; Zwicker, J.O.; Cahill, T.; Feeney, P.; Eldred, R.; Pitchford, M.; Mueller, P.K. *Environ. Sci. Technol.* **1990**, *24*, 1090-1099.

Table 1. Summary of sampling data at each site, including only those days when all deployed samplers passed QA/QC criteria. No outliers were removed from the data set for the purposes of the table, and field blank corrections were not applied. Standard Deviation and Coefficient of Variation reflect the day-to-day environmental conditions and not the sampler performance.

Location	Samplers	# of days	Minimum ($\mu g/m^3$)	Maximum ($\mu g/m^3$)	Average ($\mu g/m^3$)	Standard Deviation ($\mu g/m^3$)	Coefficient of Variation (%)	Collocated Precision ($\mu g/m^3$)	Collocated Precision (%)
Site A	1507 & 1508	6	15.4	18.8	17.0	1.6	9	0.69	3.8
	1019 & 1020	6	14.9	18.1	16.5	1.3	8	0.51	3.1
Site B	1507 & 1508	10	6.1	33.5	18.6	9.4	51	1.88	7.2
	1019 & 1020	10	6.7	40.1	20.5	11.5	56	2.93	9.5
Site C	1507 & 1508	15	8.1	35.2	18.7	7.6	41	0.96	6.7
	1019 & 1020	15	10.1	38.4	20.8	7.9	38	2.07	11.9
	FRM	15	5.9	31.1	16.4	7.6	47	N/A	N/A
Overall	1507 & 1508	31	6.1	35.2	18.3	7.4	40	1.30	6.4
	1019 & 1020	31	6.7	40.1	19.9	8.4	42	2.21	9.9
	FRM	15	5.9	31.1	16.4	7.6	47	N/A	N/A

Table 2. Statistical measures for comparing sampler performance.

	equivalent	predictable	biased	uncorrelated/failed
Slope within three standard errors of unity	YES	NO	YES	*
Intercept within three standard errors of zero	YES	YES	YES	*
Correlation coefficient greater than 0.9	YES	YES	YES	*
Average difference smaller than collocated precision	YES	YES	NO	*

(*) “uncorrelated” if correlation criterion not met, regardless of other criteria; “failed” intercept criterion not met.

Table 3. Regression of the MiniVol data - both raw and corrected for field blank values - against the Partisol FRM. All data collected at sampling site C.

	# of days	Slope	Intercept ($\mu g/m^3$)	Correlation Coefficient	Avg. Diff. ($\mu g/m^3$)	Collocated Precision ($\mu g/m^3$)	Correlation
Without Field Blank Correction...							
MiniVol 1507	16	1.00 +/- 0.05	2.61 +/- 0.85	0.985	2.59	2.04	failed
MiniVol 1508	16	0.97 +/- 0.04	2.54 +/- 0.73	0.988	2.10	1.68	failed
Average 1507 &1508	16	0.99 +/- 0.04	2.58 +/- 0.68	0.990	2.35	1.81	failed
MiniVol 1019	16	1.01 +/- 0.07	3.20 +/- 1.20	0.971	3.31	2.66	biased
MiniVol 1020	16	1.00 +/- 0.07	5.32 +/- 1.19	0.971	5.34	3.98	failed
Average 1019 &1020	16	1.00 +/- 0.05	4.26 +/- 0.99	0.980	4.33	3.23	failed
With Field Blank Correction...							
MiniVol 1507	14	0.94 +/- 0.06	0.86 +/- 1.05	0.979	-0.13	1.10	equivalent
MiniVol 1508	15	0.94 +/- 0.06	-0.07 +/- 1.06	0.976	-0.99	1.34	equivalent
Average 1507 &1508	14	0.93 +/- 0.05	0.73 +/- 0.87	0.985	-0.44	1.00	equivalent
MiniVol 1019	15	1.01 +/- 0.09	-0.61 +/- 1.65	0.953	-0.45	1.70	equivalent
MiniVol 1020	15	1.00 +/- 0.07	1.75 +/- 1.28	0.970	1.67	1.75	equivalent
Average 1019 &1020	15	1.00 +/- 0.07	0.57 +/- 1.30	0.970	0.61	1.38	equivalent

Figure 1. Experimental setup for measuring the MiniVol $PM_{2.5}$ impactor collection efficiency as a function of particle size using monodisperse polystyrene latex particles.

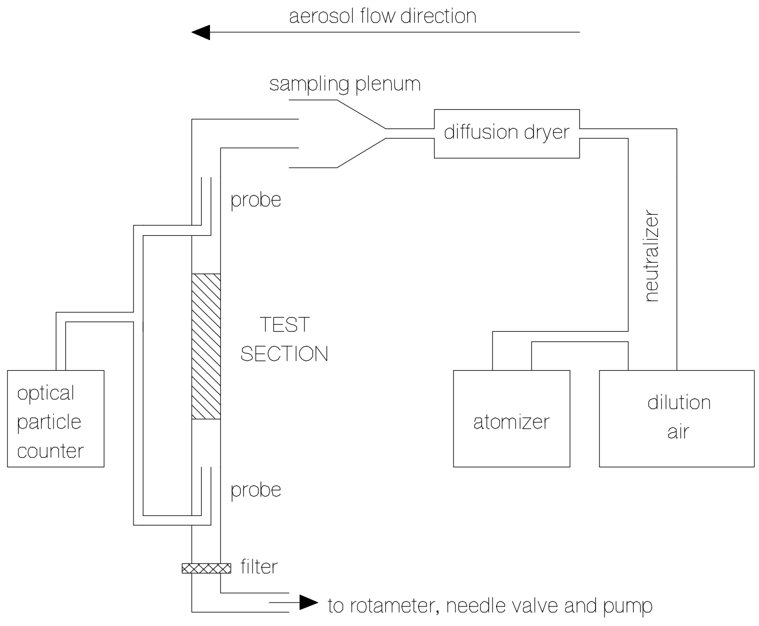

Figure 2. A typical particle size collection efficiency curve for laboratory testing of the MiniVol impactor assembly. Error bars are 2σ as derived from repeat measurements weighted by their respective propagated uncertainties.

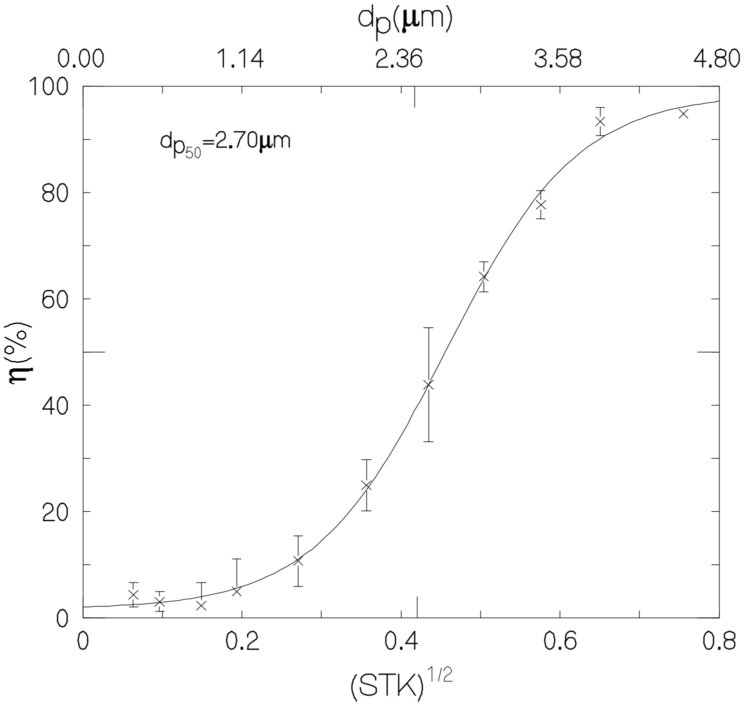

Figure 3. Particle collection efficiency as a function of impactor stage greasing protocol for the flat $PM_{2.5}$ stage.

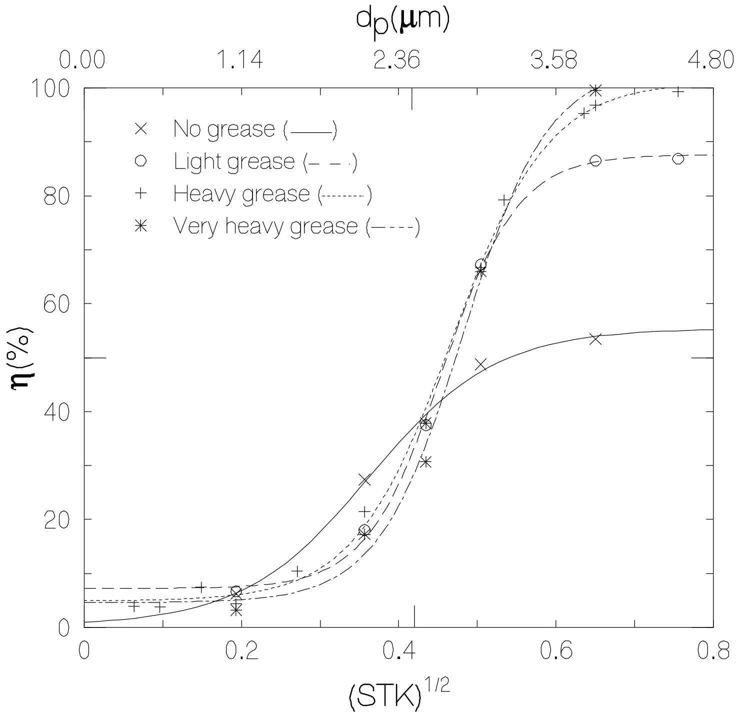

Figure 4. Collection efficiencies for two cascade impactor arrangements.

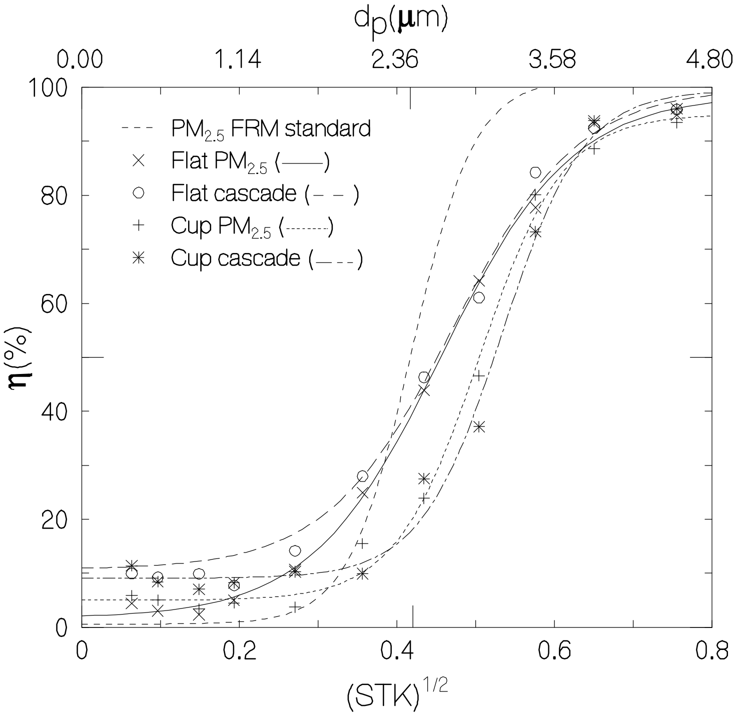

Figure 5. Scatter plots for collocated MiniVol samplers with cascade preseparator assemblies and: (a) flat $PM_{2.5}$ impaction stage, samplers 1507 and 1508; and (b) cup $PM_{2.5}$ impaction stage, samplers 1019 and 1020. No outliers were removed from the data sets and field blank corrections were not applied.

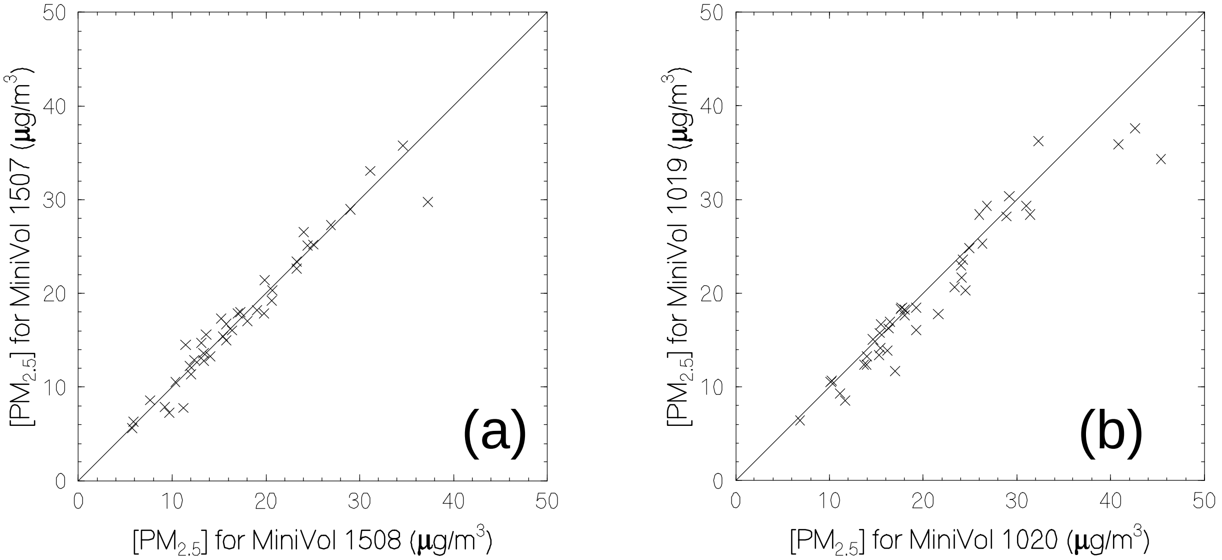

Figure 6. Scatter plots for MiniVol sampler PM$_{2.5}$ mass concentration versus Partisol FRM sampler PM$_{2.5}$ mass concentration. (a), (b): cascade impactor with flat PM$_{2.5}$ impaction stage; and (c), (d): cascade impactor with cup PM$_{2.5}$ impaction stage. MiniVol data was not corrected for field blank values.

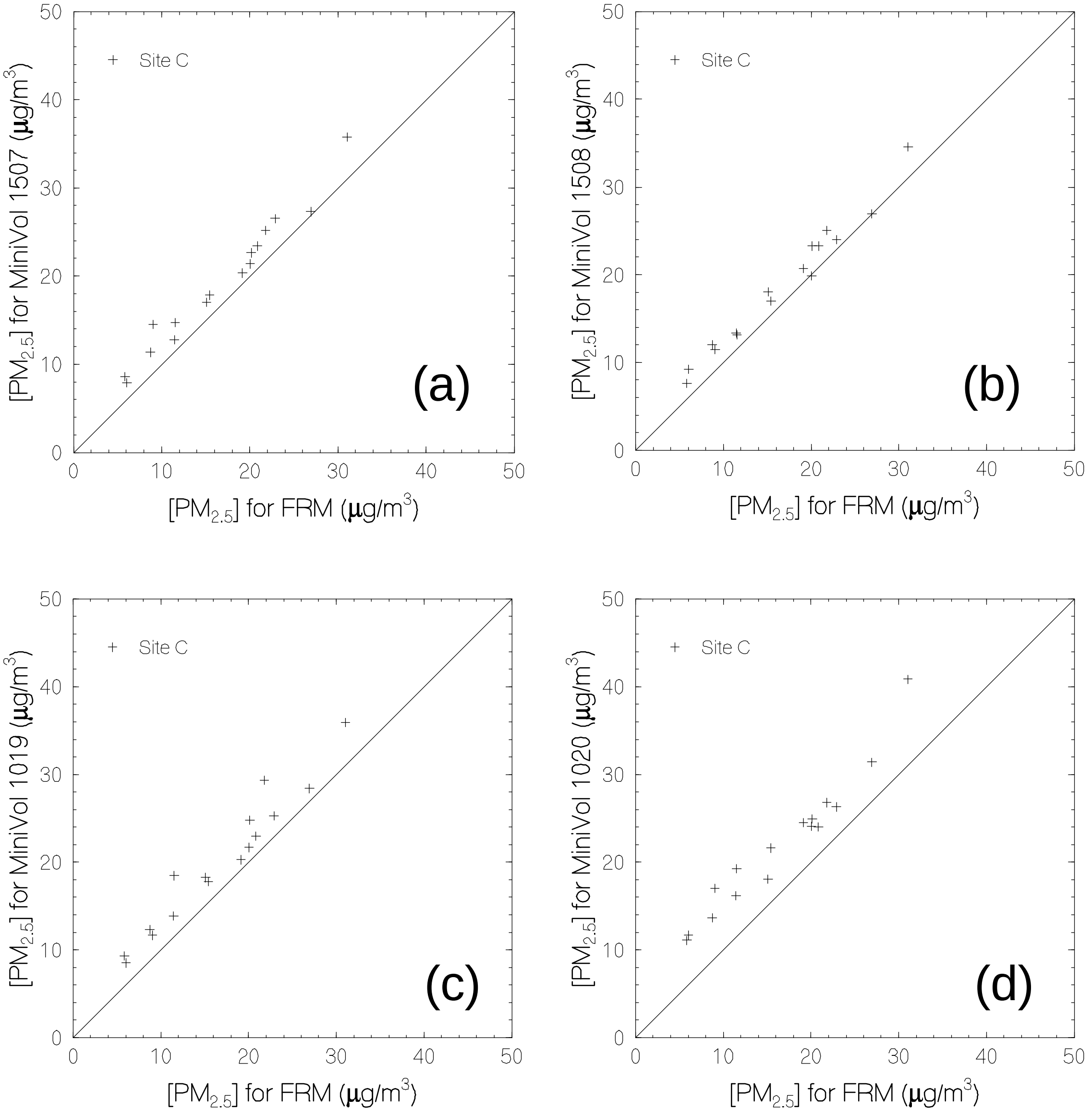

Figure 7. Scatter plots for field blank corrected MiniVol sampler $PM_{2.5}$ mass concentration versus Partisol FRM sampler $PM_{2.5}$ mass concentration. (a), (b): cascade impactor with flat $PM_{2.5}$ impaction stage; and (c), (d): cascade impactor with cup $PM_{2.5}$ impaction stage.