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PERFORMANCE CHARACTERISTICS OF $PM_{2.5}$ SAMPLERS IN THE PRESENCE OF AGRICULTURAL DUSTS

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Abstract

Tests in a controlled laboratory environment were performed on three $PM_{2.5}$ samplers: a FRM sampler with Wells Impactor Ninety-Six, a FRM sampler with Sharp-Cut Cyclone, and a High-Volume $PM_{2.5}$ Sampler. Three dusts were used for sampling: alumina, corn starch, and wheat flour. Ten replications were performed for each sampler in each dust for a total of ninety replications. Concentration measurements for the test samplers were compared to the "true" $PM_{2.5}$ concentrations, determined by multiplying the fraction less than 10 µm from the Coulter Counter PSD times the TSP concentration. The results showed the percent error of the $PM_{2.5}$ samplers increased with the MMD of the dust sampled. The hypothesis was that the $PM_{2.5}$ samplers used to monitor $PM_{2.5}$ concentrations in the ambient air will not accurately perform in an agricultural environment. It was concluded that the use of these $PM_{2.5}$ samplers would result in unfair regulation of the agricultural industry.

Introduction

In recent years, several studies have been published that associate daily mortality with concentrations of $PM_{2.5}$. These studies resulted in the revision of the National Ambient Air Quality Standards (NAAQS) by the Environmental Protection Agency, which was promulgated on July 18, 1997 and adopted on September 16, 1997. This revision included a new standard for fine particulates ($PM_{2.5}$), which is defined as particulate matter less than 2.5 µm in aerodynamic diameter.

The long-term $PM_{2.5}$ standard, assessed as the three-consecutive year arithmetic mean of annual averages, was set at 15 µg/scm. The short-term $PM_{2.5}$ standard, assessed as the 98^{th} percentile of 24-hour concentrations averaged over three consecutive years, was set at 65 µg/scm (EPA, 1997). However, while the agency based its standard on epidemiological data that linked mortality with particulate matter concentrations, laboratory studies using controlled human exposure did not produce physiological changes**.** This uncertainty about the mechanism of action was a key issue in the debate over the final $PM_{2.5}$ standards (Cooney, 1998). The debate made it all the way to the United States Supreme Court, and in February of 2001, the constitutionality of the 1997 Revisions to the Clean Air Act was unanimously upheld.

Shortly after the revision of the NAAQS, a $PM_{2.5}$ sampler was developed for the Federal Reference Method (FRM). This sampler, however, was mandated "by design" rather than "by performance," due to the limited performance data available for the sampler. An update published by the EPA (2000) states: "the requirement that these instruments rely on specific design elements, rather than performance criteria alone, is structured to produce greater measurement precision and to avoid the data measurement uncertainties experienced in the PM_{10} monitoring program." This lack of performance data, however, does not allow for a margin of error to be specified for the sampler. The designation "by design" then implies that the FRM $PM_{2.5}$ sampler is an accurate sampler.

The EPA seeks various methods for monitoring the concentrations of $PM_{2.5}$ in the ambient air. Methods that are determined to meet specific requirements for adequacy are designated as either reference or equivalent methods. This allows for their use by states and other agencies for determining attainment for the NAAQS. In 40 CFR Part 50 (EPA, 1997), the accuracy of a considered method is defined in a relative sense. The accuracy is defined as the degree of agreement between a subject field $PM_{2.5}$ sampler and a collocated $PM_{2.5}$ reference method audit sampler operating simultaneously at the urban monitoring site location of the subject sampler. In other words, the subject field $PM_{2.5}$ sampler is set next to a FRM $PM_{2.5}$ sampler in the presence of an urban dust, and if the results from both methods statistically agree, then the subject field $PM_{2.5}$ sampler is deemed accurate enough to become a reference or equivalent method.

EPA's focus is on urban environments, yet they also regulate agriculture. Urban dust has an MMD of 5.7 µm and a GSD of 2.25 (EPA, 1996). Agricultural dusts have a larger MMD than that of urban dust. Agricultural dusts such as grain dusts have a MMD ranging from 12 to 16 µm and a GSD ranging from 1.8 to 2.2 (Parnell et al., 1986), while cotton gin dusts have a range of MMDs from 20 to 23 µm and a GSD range of 1.8-2.0 (Wang, 2000). Since reference or equivalent methods are mandated in the presence of urban dusts, and not agricultural dusts,which have a much larger mass median diameter (Figure

1), agriculture could be directly impacted with the use of these methods. It is important to determine if there are differences between $PM_{2.5}$ samplers when sampling agricultural dusts.

Methods and Procedures

A controlled laboratory environment was used throughout this research. This set-up consisted of the samplers, operated within a dust chamber. This chamber included an external dust entrainment system. The temperature in the chamber ranged from 24°C – 29°C during testing periods.

Dust Chamber and Entrainment System

The dust chamber was constructed from particleboard and allowed for the testing of four samplers at once. The chamber consisted of a cubed body portion measuring 2.44 meters at each dimension, with two 45° transitions located on opposite ends of the cube. A single inlet blower located at the end of one transition was capable of moving air at a rate of 127.5 m^3/min through the chamber. A duct connected to the opposite transition allowed dust particles to travel around the outside of the dust chamber body and into the inlet of the fan, to be recirculated throughout the chamber (Figure 2). Perforated walls with 17.5% open area were located between each transition and the cube body of the chamber to act as air straighteners (Figure 3).

A dust feeder injected dust into the chamber. An aluminum disk with a diameter of 61 cm and a thickness of 2.54 cm was used to hold the dust. The disk had a radial rectangular groove, with a cross-sectional area of 2 cm^2, in which the dust was placed. A motor rotated the disk at adjustable speeds. A venturi tube was used to move the dust from the disk into the chamber through Teflon tubing. The suction side of the venturi tube was located over the groove. Air was passed through the venturi tube, and as the disk turned, dust moved into the system and was conveyed into the chamber through the tubing (Figure 4). It was released at a point close to the outlet of the fan, which helped eliminate the settling of the dust. Three dusts were used in this research: corn starch, wheat flour, and brown fused aluminum oxide (alumina).

Tests

Samplers that were tested were a FRM $PM_{2.5}$ sampler with a WINS preseparator, a FRM $PM_{2.5}$ sampler with a Sharp-Cut Cyclone (SCC), and a high-volume $PM_{2.5}$ sampler. Two total suspended particulate (TSP) samplers were also used in this research. One TSP sampler was used to determine the concentration of the dust present in the chamber for each test. The other TSP sampler allowed for a particle size distribution of the entrained dust to be found. A total of ten tests were run for each $PM_{2.5}$ sampler for each of the three dusts. Concentrations from each sampler were calculated for each test.

The particulates captured on the filters during testing were sized using the Coulter Counter Multisizer III (CCM) method. Results of a CCM PSD are particulate matter volume percent versus equivalent spherical diameter (ESD). To change these results to PM mass percent versus aerodynamic equivalent diameter (AED), an assumption must be made. The particle density for the different size particles is assumed to be constant. By entering the square root of the particle density into the CCM software, the resulting particle sizes can automatically be changed from ESD to AED. If the particles have a known shape factor, the square root of the particle density would also be divided by the square root of the shape factor (Mark et al., 1985).

Particulate materials from natural and manmade sources are often nonspherical in shape. The shape and size of particles greatly influence their mechanical properties. The drag force on a nonspherical particle is generally greater than that on a sphere of the same volume moving at the same velocity (Cheng et al., 1988). Therefore, the behavior of a particle is determined by particle size, shape and density. The dynamic shape factor (κ) relating sedimentation diameter to equivalent volume diameter can range from 1.0 to 2.0.

The alumina dust used in this research has an angular shape, not unlike that of a mineral dust such as quartz. Shape plays an important role in processes that concern the adhesion of particles to the collection surface of an impactor. The sharp edges of alumina, with their small local radii of curvature, would considerably reduce the adhesion forces compared to those of a sphere with an equivalent geometrical size. A mean shape factor for alumina dust was determined from the mass median diameter of the dust. The grade designation of the dust used in this research was F1200, which had a shape factor of 1.44 (Mark et al., 1985). A pycnometer was used to find the particle density for the alumina utilized in this research (3.91 g/cm^3).

No shape factor data for corn starch or wheat flour was available in the literature. For the purposes of this research, it was assumed that the particles of these two dusts were spherical, corresponding to a shape factor of one. The particle densities for corn starch and wheat flour were found using the pycnometer, and were 1.5 g/cm^3 and 1.46 g/cm^3, respectively.

Results

Inlet PSDs

In this research, a lognormal distribution was not the best representation of either the inlet or outlet PSDs. Inlet PSDs of all three dusts were found using the CCM. Figures 5, 6, and 7 show the PSDs for all three dusts. It can be seen that although a lognormal distribution might have represented the corn starch and alumina PSDs, it would not have been an appropriate fit for the wheat flour PSD

However, the purpose of the duct on the dust chamber was to recirculate smaller particles throughout the chamber, since the dusts contain only a very small percentage of particles smaller than 2.5 ⌈m. The TSP sampler has a cut-point of approximately 40 ⌈m, so the PSD found from the TSP filter should be representative of the dust entrained in the dust chamber. Figures 8, 9, and 10 show the PSDs of the dust being sampled inside the dust chamber.

Five representative TSP filters were chosen from each set of dust tests, in order to see if the dust distribution within the dust chamber varied throughout the testing. No variations were found, so an average of the five PSDs for each dust was used to represent that dust's inlet PSD. Table 1 shows a comparison between the PSD of the dust and the PSD of the PM captured on the TSP filter. It can be seen that the dust entrained in the dust chamber contained a larger percentage of smaller particles. It is hypothesized that this was a result from the recirculation process. The MMD represents the middle of a PSD: half of the mass on the filter is above the MMD and half is below. The addition of the smaller particles resulted in more mass in the lower half of the particle size ranges. This addition of mass shifted the MMD of the entrained dust PSD to the left. The PSDs of the corn starch and alumina entrained in the dust chamber also showed the trend of an increased GSD. However, the GSD of the wheat flour entrained it the chamber, as compared to the straight wheat flour, decreased. This may be explained by the larger particles in wheat flour settling out, which would decrease the width of the PSD. This hypothesis is also discussed in the concentration section.

Outlet PSDs

The outlet PSDs were found by sizing the PM captured on the filters for each $PM_{2.5}$ sampler with the CCM. The outlet PSDs varied dramatically between dusts for each sampler. Figures 11, 12, and 13 show a sample outlet PSD for each of the three dusts for the High-Volume $PM_{2.5}$ sampler, the FRM with SCC, and the FRM with WINS, respectively. For each sampler, the filters used when sampling the dusts with larger MMDs (corn starch and wheat flour) contained most of their mass in larger particles. The fine particulate on the filter was overwhelmed by the larger particles, inhibiting the calculation of a fractional efficiency curve for the samplers.

The mass on the filter was biased towards the larger particles. This phenomenon leads to the belief that there was a large amount of $PM_{2.5}$ in the ambient air; when, in fact, the "true" $PM_{2.5}$ concentration was much lower than what was measured. This was especially true of the dusts with larger MMDs (corn starch and wheat flour), which are representative of agricultural dusts.

Concentrations

The inlet concentrations for each test were found by dividing the mass captured on the TSP glass fiber filters by the volume of air that passed through the filters. The same process was used for each $PM_{2.5}$ filter to get the outlet concentrations. The inlet concentrations varied for each test, as well as between dusts. The mean and standard deviations for the inlet concentrations of each dust are shown in Table 2. The motor speed was set to turn the dust feeder disk at four revolutions per hour for corn starch and wheat flour. It was deduced from the lower inlet concentrations for wheat flour that the dust has larger particles that tend to settle out, instead of staying entrained throughout the chamber. For alumina, the dust feeder disk turned at approximately 1.5 revolutions per hour. Due to the high initial concentrations of alumina within the chamber, the motor speed had to be reduced. The higher concentration might be explained by alumina consisting of mostly smaller particles that stay entrained.

Another important factor affecting inlet concentrations is the shape factor of the particles in each dust. Wheat flour and corn starch have very similar particle densities (approximately 1.5 g/cm^3). Corn starch and wheat flour were fed into the dust chamber at the same rate; however, there was over three times the concentration of corn starch as wheat flour in the chamber. Shape factor is the obvious explanation. Nonspherical particles will settle more slowly than their equivalent volume spheres (Hinds, 1999). Wheat flour particles are most likely closer to spherical than those of corn starch. This would mean wheat flour has a smaller shape factor, close to one, while corn starch has a larger shape factor.

AED is converted from ESD by the square root of the particle density over the shape factor. For dusts that have the same particle density, one with a smaller shape factor would result in higher AEDs. Therefore, the wheat flour most likely has a larger MMD than reported, while the corn starch has a smaller MMD.

The average and standard deviations for the outlet concentrations are shown in Table 3. For every dust, the WINS measured the smallest outlet concentration, followed by the High-Volume $PM_{2.5}$ sampler. The FRM with SCC measured the largest. The same increasing pattern could be seen with the standard deviations.

Statistical Analysis

For each dust, the inlet concentrations were calculated for each trial. The outlet concentrations were calculated for each sampler as well. The inlet concentration varied between each test. This might be explained by the recirculation of dust in the chamber. Human error involved in the filling of the dust feeder may have also contributed. The outlet concentrations from each $PM_{2.5}$ sampler were normalized in order to compare results between samplers. For every trial, normalization was achieved by dividing the outlet concentration for each sampler by the corresponding inlet concentration. This gives a ratio of the $PM_{2.5}$ measured by each sampler over the TSP for each test.

A split-plot design was used to statistically compare the results from each sampler in each type of dust. The whole plot treatment was the ten tests that were ran for each dust and the whole plot experimental units were the three $PM_{2.5}$ samplers. The three test dusts were the subplot experimental units. This design allowed for comparisons between the samplers to be made, as well as the determination of any interaction between samplers and the dust sampled. Outliers in the normalized data were removed as to not bias the results of the analysis. Outliers were defined as any data points more than three standard deviations away from the mean. A SAS program was written to compare results between samplers and dusts.

Tests of fixed effects for the dust, samplers, and, most importantly, interaction between the dust and samplers were performed. The results indicated that there were significant interactions between dust and samplers with 95% confidence. Since there were significant interactions, the comparison of whole-plot means at a fixed level of the sub-plot factor could be made. These data were used to determine whether there were significant differences between the least-square means of the normalized results from the three samplers, while in the presence of the same dust.

All comparisons were made using a 95% confidence level. Results showed that while sampling alumina, there was significant difference between the means of the FRM with WINS and the other two samplers, but no difference between the means of the FRM with SCC and High-Volume $PM_{2.5}$ samplers. According to these results, if a FRM sampler with WINS, a FRM sampler with SCC, and a High-Volume $PM_{2.5}$sampler sampled simultaneously in an urban environment, the FRM with WINS results would not statistically agree with the other two samplers' results. However, the FRM with SCC and High-Volume $PM_{2.5}$ sampler would return results that statistically agree. This research showed that, according to the EPA's requirements for designation of a reference or equivalent method for monitoring $PM_{2.5}$ concentrations, neither the FRM with SCC nor the High-Volume $PM_{2.5}$ sampler would be adequate. Although the High-Volume $PM_{2.5}$ sampler is not an EPA-approved $PM_{2.5}$ sampler, the SCC (when used in conjunction with a FRM sampler) was designated by the EPA as an equivalent method and is currently used to monitor $PM_{2.5}$ concentrations in the ambient air.

The statistical analysis also showed there were significant differences between the mean results of all the samplers when sampling wheat flour. If these samplers simultaneously sampled in an agricultural environment, the concentration measurements from each sampler would differ. However, when sampling corn starch, there was no significant difference between the means. It should be noted the within-sample variations for the normalized data were large. Data in which between-sample variability is small relative to the within-sample variability is more likely to be presumed as statistically agreeing.

Discussion

Coulter Counter analysis of the PM captured on the TSP filters showed 0.46% $PM_{2.5}$ for corn starch, 0.92% $PM_{2.5}$ for wheat flour, and 5.34% $PM_{2.5}$ for alumina. Using the inlet concentrations, the "true" concentration of $PM_{2.5}$ in the ambient air can be found. For example, if a TSP sampler measured a total concentration of 1000 ⌈g/scm, and 10% was $PM_{2.5}$, there would be 100 ⌈g/scm of $PM_{2.5}$ in the ambient air. If an "ideal" $PM_{2.5}$ sampler samples at the same time as the TSP sampler, it should measure 100 ⌈g/scm. This research showed the tested $PM_{2.5}$ samplers are not "ideal," and would not measure the $PM_{2.5}$ concentration in the ambient air accurately.

To determine the accuracy of the tested $PM_{2.5}$ samplers, the error between the "true" $PM_{2.5}$ concentration and the concentration measurements from the samplers were calculated. The exact $PM_{2.5}$ concentration contained in each dust for every trial, found using the Coulter Counter data and the inlet concentrations, was considered to be the "true" $PM_{2.5}$ concentration. This was compared to the $PM_{2.5}$ concentration measurements for each $PM_{2.5}$ sampler in the corresponding trial. Table 4 shows the average percent error and standard deviation for every sampler in the three dusts. All of the samplers' concentration results exceeded the "true" $PM_{2.5}$ concentrations. The FRM with WINS sampled the best, followed by the High-Volume $PM_{2.5}$ sampler and FRM with SCC, respectively. Although the FRM with WINS performed better than

the other two tested $PM_{2.5}$ samplers, it still does not accurately monitor $PM_{2.5}$ concentrations in either urban or agricultural dusts. However, the error terms increased with the MMD of the dust, as did the standard deviation. The sampler's performance worsens when sampling agricultural dusts. This could be detrimental to the agricultural industry if these samplers were used to determine if an agricultural facility meets the NAAQS.

Methods for monitoring the concentration of $PM_{2.5}$ in ambient air are examined by the EPA. Methods that are determined to meet specific requirements for adequacy are designated as either reference or equivalent methods. However, the accuracy of a considered method is defined in a relative sense. The accuracy is defined as the degree of agreement between a subject field $PM_{2.5}$ sampler and a collocated $PM_{2.5}$ reference method audit sampler operating simultaneously at the urban monitoring site location of the subject sampler. If the results from both methods statistically agree, then the subject field $PM_{2.5}$ sampler is deemed accurate enough to become a reference or equivalent method. However, the samplers are not tested in the presence of agricultural dusts, which have much larger MMDs than urban dusts.

It is assumed that the performance characteristics of a sampler do not depend on the MMD of the ambient air. The results of this research show otherwise. The error terms for each of the three $PM_{2.5}$ samplers tested increased as the MMD of the sampled dust increased. The FRM with SCC, an equivalent method, measured over nineteen times (average) the actual concentration of $PM_{2.5}$ when sampling wheat flour. Errors such as these can be detrimental to agriculture. Most agricultural dusts contain very little, if any, particles with an AED of 2.5 ⌠m or smaller. EPA set the short-term $PM_{2.5}$ standard at 65 ⌠g/scm. If the EPA wished to monitor the concentration of $PM_{2.5}$ at the property line of a cotton gin, where the actual concentration of $PM_{2.5}$ was 10 ⌠g/scm, a FRM with SCC might be used. If the PM released by the cotton gin had an MMD similar to that of wheat flour, instead of measuring a property line concentration of 10 ⌠g/scm, it may measure 190 ⌠g/scm. If inaccurate measurements such as these continued, the cotton gin would exceed the short-term $PM_{2.5}$ standard. Since the government believes the facility is not meeting the NAAQS, it could impose fines, the addition of costly abatement equipment, or possibly even the closure of the facility in order to decrease the inaccurately measured property-line concentration of $PM_{2.5}$. These high additional costs are unfair to the ginner and can be avoided by the use of a more accurate method for sampling $PM_{2.5}$.

Inappropriate regulation of agriculture will continue as long as the EPA uses inaccurate $PM_{2.5}$ samplers to monitor concentrations of $PM_{2.5}$ at the property lines of agricultural facilities. A more appropriate sampling method needs to be implemented, as well as a better determination of reference or equivalent methods. The standard in which EPA determines the accuracy of a subject sampling method needs to be modified. Testing should be carried out in agricultural environments, as well as urban. Sampling in a controlled laboratory environment, in order to avoid the inaccurate sampling of agricultural dusts, should also be included.

Conclusion

Three FRM with WINS, FRM with SCC, and High-Volume $PM_{2.5}$ samplers were tested in a controlled laboratory environment. They were tested with controlled concentrations of three dusts: alumina, corn starch, and wheat flour. The MMDs increased with each dust, respectively.

The dust chamber used had a duct for recirculating dust throughout the chamber. It was hypothesized this duct would increase the amount of fine particulates available for sampling. It was observed from the PSDs of the dusts entrained in the chamber that there was an increase in the fraction of smaller particles when compared to the PSDs of the packaged dusts. The PSDs of the entrained dust also showed a decrease in the MMDs. It was also discovered the PSDs of the entrained dust were not appropriately represented by a lognormal distribution, as normally accepted.

The inlet concentrations for each dust were found for every test. The mean concentrations varied from dust to dust. It was hypothesized the variations were due to the shape factor of the dust particles. The shape factor of a particle helps describe the physical properties of the particle, such as settling rate and adhesion, and is important in the conversion of ESD to AED.

The shape factor of alumina particles was known; however, no shape factor data could be found in the literature for either corn starch or wheat flour particles. Corn starch and wheat flour have very similar particle densities. It was believed, because of the smaller concentrations of wheat flour in the chamber when fed at an equal rate as corn starch, that the wheat flour particles have a shape factor close to that of a sphere (1.0) and corn starch has a larger shape factor. The addition of a shape factor when converting ESD to AED can move a MMD to the left or right, which is important when classifying dusts.

The outlet concentrations were also found for each test. In order for the results to be statistically analyzed, the data were normalized by dividing the outlet concentration by the inlet concentration. The analysis showed there were significant interactions between dusts and samplers. It was concluded from the analysis that the results from the three tested samplers

statistically agreed when sampling in the presence of corn starch, but did not when sampling wheat flour. Also, in the presence of alumina dust, the FRM with SCC and the High-Volume $PM_{2.5}$ sampler statistically agreed, although neither results agreed with those from the FRM with WINS. The High-Volume $PM_{2.5}$ sampler is not mandated for government use, but the FRM with SCC is. According to these results, the FRM with SCC should not have met the EPA's accuracy requirements for a reference or equivalent $PM_{2.5}$ monitoring method.

The filters from the samplers used in this research contained a great amount of larger particles, as shown by the outlet PSDs for each test. It is believed that when sampling dusts with large MMDs (as agricultural dusts do), the larger particles overwhelm the preseparator, allowing them to penetrate. This may also cause smaller particles to be captured, instead penetrating the preseparator as they should. The larger particles on the filter, which have a greater mass, will lead to an inaccurate measure of the concentration of $PM_{2.5}$ in the ambient air.

The accuracy of the tested $PM_{2.5}$ samplers was determined by finding the error between the concentration measurements for the samplers and the "true" $PM_{2.5}$ concentrations. The percentage of $PM_{2.5}$ in the ambient air was taken from the inlet PSDs, and using the inlet concentrations, the "true" concentration of $PM_{2.5}$ in the air was found. This, along with the concentration measured by the sampler, was used to calculate the percent error for each test. Results showed the error and standard deviation increased as the MMD of the sampled dust increased. The WINS had the smallest error terms, followed by the High-Volume $PM_{2.5}$ sampler and the SCC, respectively. Standard deviations also increased in this pattern.

The results of this research showed as the MMD of a dust increased, the performance of the $PM_{2.5}$ samplers decreased. Subject field $PM_{2.5}$ samplers are tested by the EPA and their accuracy defined compared to the performance of a collocated FRM with WINS, when sampling simultaneously in an urban environment. If their results statistically agree, the subject sampler could be deemed as an equivalent or reference method used for monitoring the concentration of $PM_{2.5}$ in the ambient air.

The agricultural industry generates dusts with much larger MMDs than urban dusts. According to the results from these experiments, if any of the tested samplers were used to find property line concentrations for agricultural facilities, the concentration measurements would greatly exceed the true $PM_{2.5}$ concentration. This could prove detrimental to the agriculture industry. Inaccurate sampling of agricultural dusts would bring about the unneeded and unfair regulation of agriculture facilities, resulting in high, unnecessary costs. The EPA needs to implement a more appropriate sampling method for monitoring the $PM_{2.5}$ concentration in the ambient air, as well as a better determination of reference or equivalent methods. The EPA's standard for determining the accuracy of a subject method needs to be modified. Testing of subject methods should be performed in a controlled laboratory setting, as well as in both urban and agricultural environments.

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Table 1. Statistical comparison between PSD of straight dust and PSD of dust as sampled by TSP sampler.

	Straight Corn Starch	TSP Corn Starch	Straight Wheat Flour	TSP Wheat Flour	Straight Alumina	TSP Alumina
MMD (⌠m)	17.1	14.9	17.3	14.4	8.4	6.2
GSD	1.43	1.52	1.86	1.75	1.51	1.67
% < 2.5 ⌠m	0.06	0.46	0.92	0.92	1.23	5.34
% < 5.0 ⌠m	0.38	2.55	7.19	6.38	12.9	33.2
% < 10 ⌠m	9.11	17.7	25.7	28.9	69.7	87.7
% < 20 ⌠m	70.0	84.0	62.3	77.5	99.4	97.9
% < 50 ⌠m	100	100	100	100	99.8	100

Table 2. The mean and standard deviations for the inlet concentrations of the three dusts used in this research.

Dust	Mean Inlet Concentration (⌠g/scm)	Standard Deviation
Corn Starch	23719	3981
Wheat Flour	7116	1048
Alumina	33982	3107

Table 3. The mean and standard deviations for the outlet concentrations measured by the three $PM_{2.5}$ samplers, in each of the three dusts.

	Corn Starch		Wheat Flour		Alumina	
	Mean (⌠g/scm)	Std Dev	Mean (⌠g/scm)	Std Dev	Mean (⌠g/scm)	Std Dev
WINS	401	79	323	200	2862	365
SCC	702	339	1385	888	4337	2249
Hi-Vol $PM_{2.5}$	589	103	524	228	4274	652

Table 4. Average percent error between sampler's measured $PM_{2.5}$ concentration and actual $PM_{2.5}$ concentration in ambient air.

	Alumina		Corn Starch		Wheat Flour	
	Mean Error	Std Dev	Mean Error	Std Dev	Mean Error	Std Dev
WINS	51%	18	211%	82	444%	337
SCC	119%	110	585%	312	1771%	96
Hi-Vol $PM_{2.5}$	111%	25	467%	96	632%	311

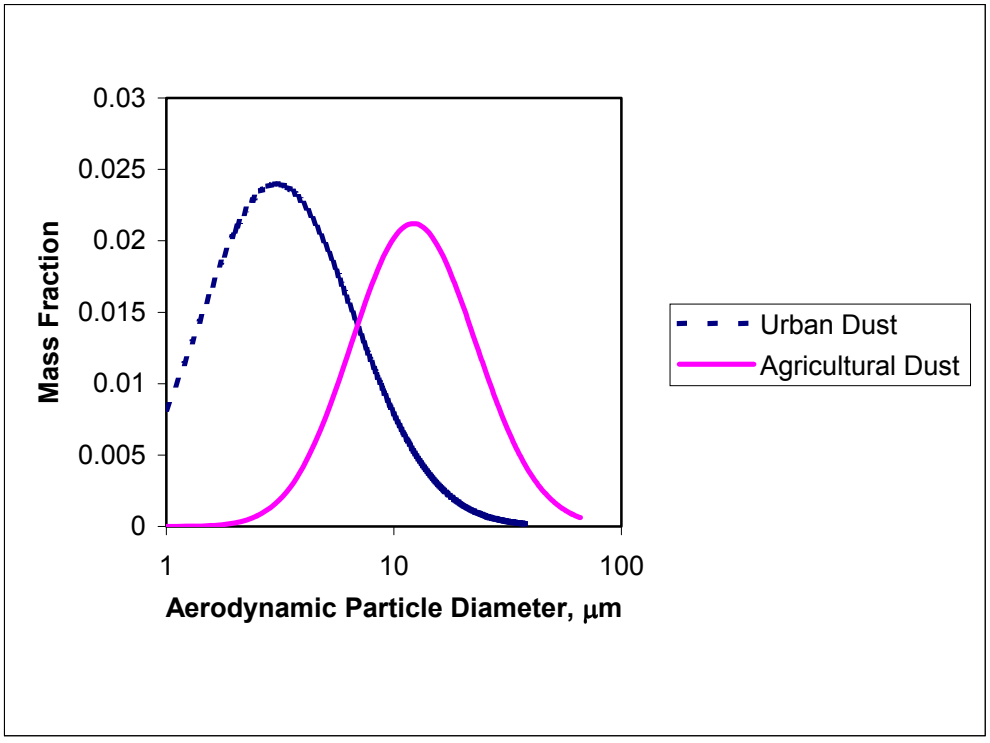

Figure 1. Particle size distributions of urban dust (MMD=5.7, GSD=2.25) and agricultural dust (MMD=18, GSD=1.9).

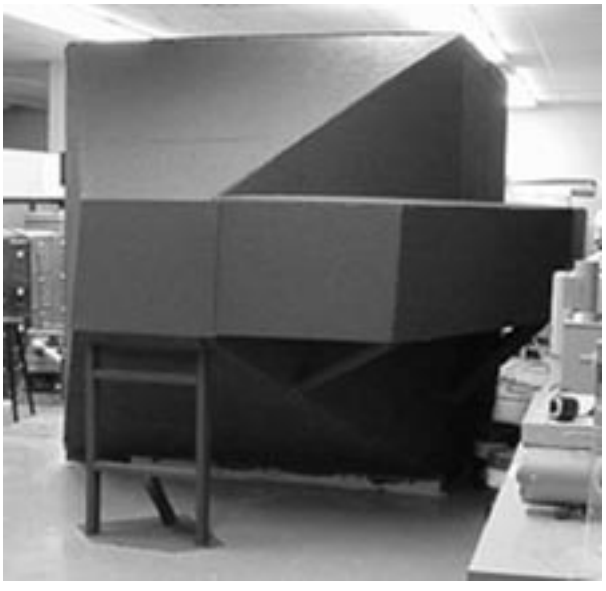

Figure 2. Back view of dust chamber showing one 45° transition and the connected duct.

Figure 3. Inside view of chamber, showing sampler set-up and air straightener located between one transition and cube body of chamber.

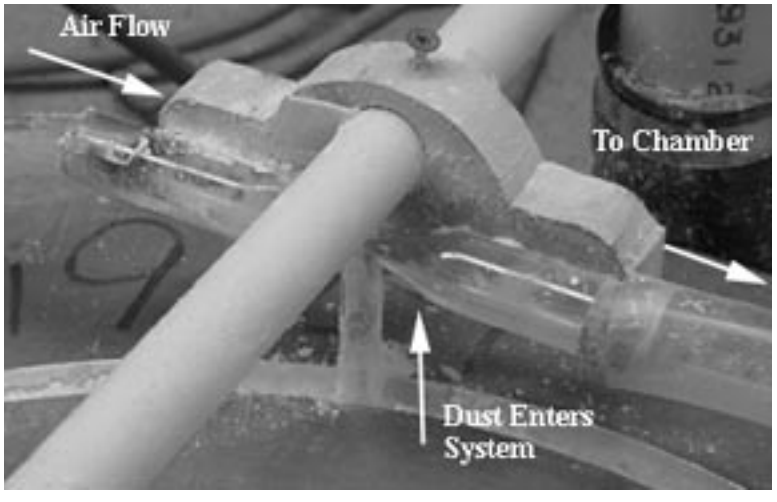

Figure 4. Venturi tube that is used to move dust from disk into chamber.

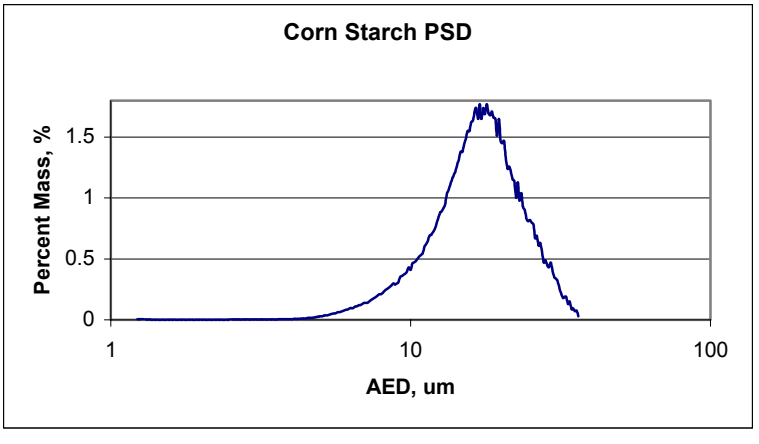

Figure 5. CCM PSD of corn starch.

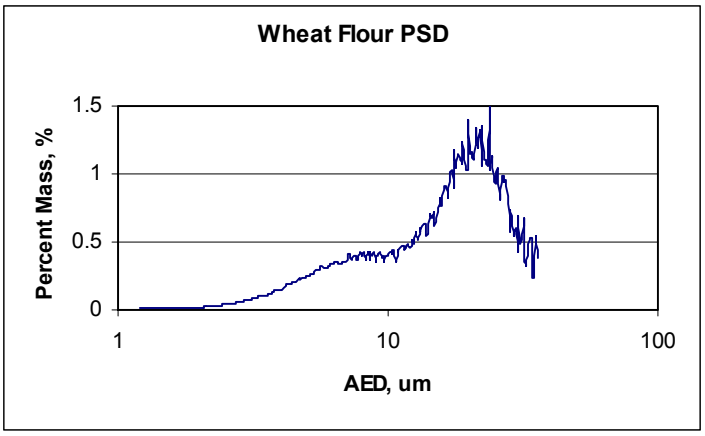

Figure 6. CCM PSD of wheat flour.

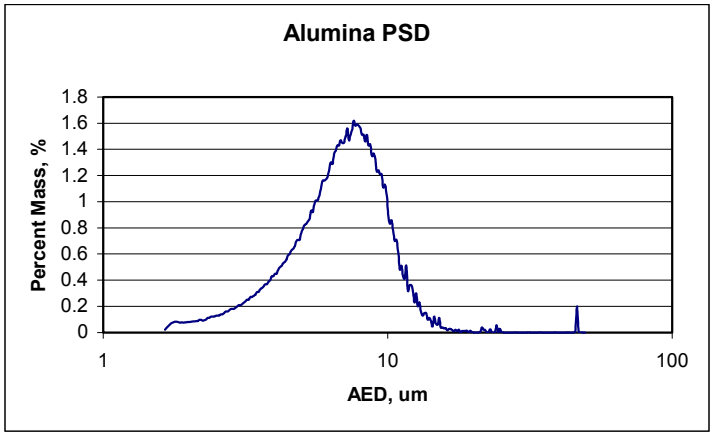

Figure 7. CCM PSD of F1200 brown fused aluminum oxide.

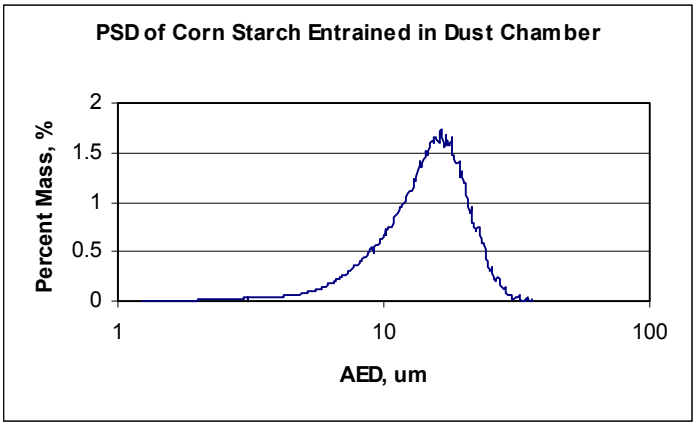

Figure 8. CCM PSD of corn starch as sampled by TSP sampler, representative of entrained dust.

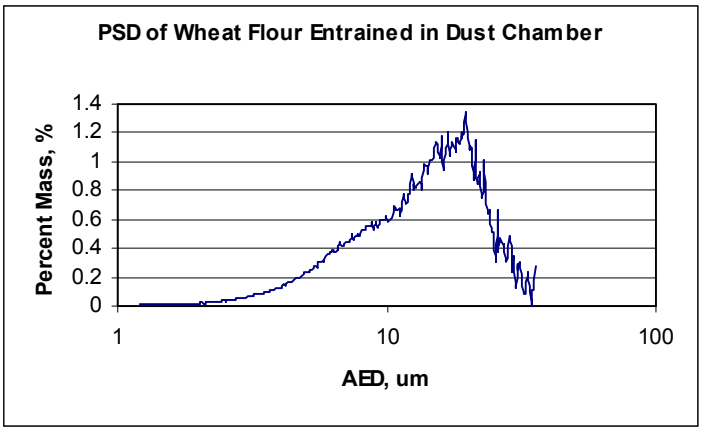

Figure 9. CCM PSD of wheat flour as sampled by TSP sampler, representative of entrained dust.

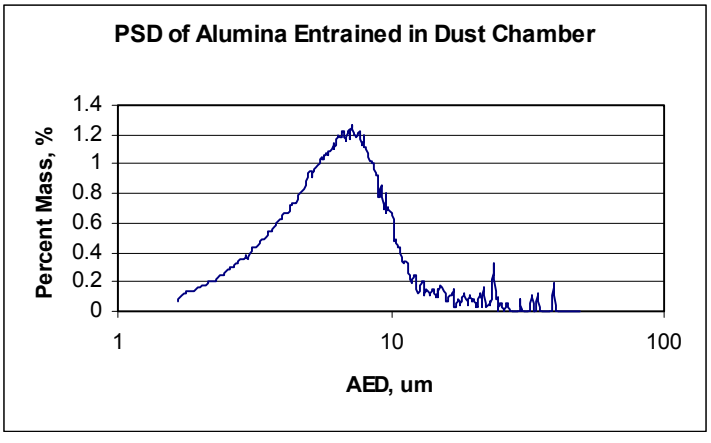

Figure 10. CCM PSD of alumina as sampled by TSP sampler, representative of entrained dust.

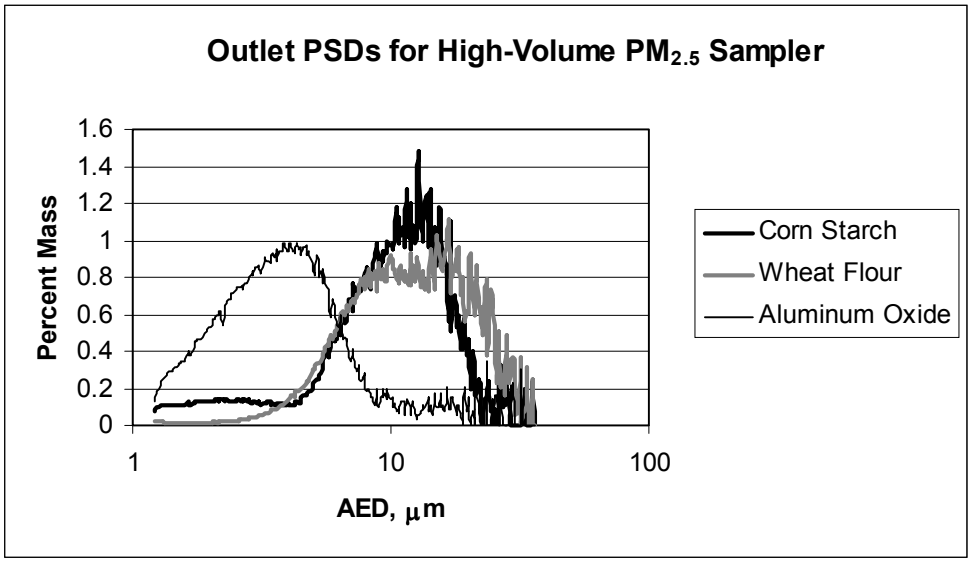

Figure 11. High-Volume $PM_{2.5}$ sampler outlet PSDs for each of the three dusts used in testing.

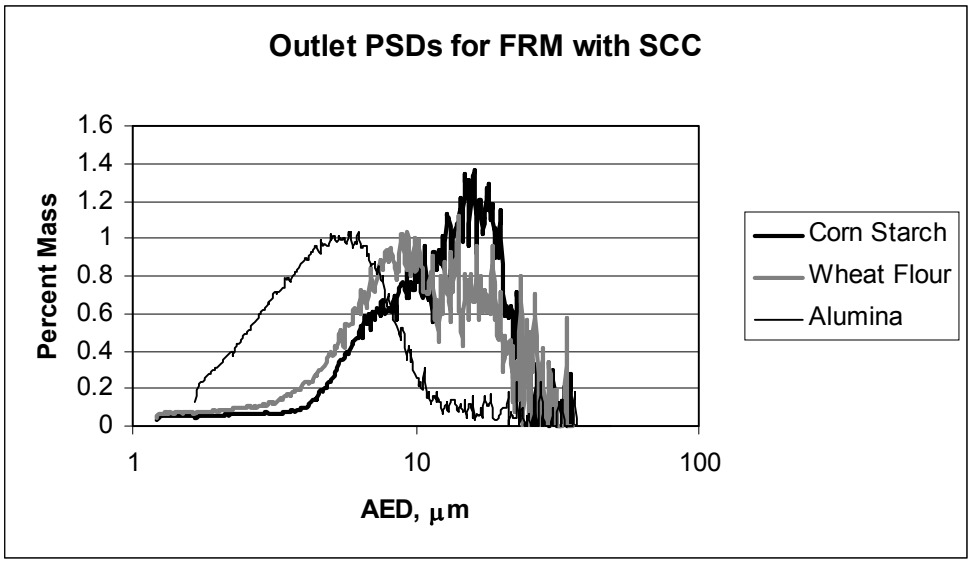

Figure 12. FRM with SCC outlet PSDs for each of the three dusts used in testing.

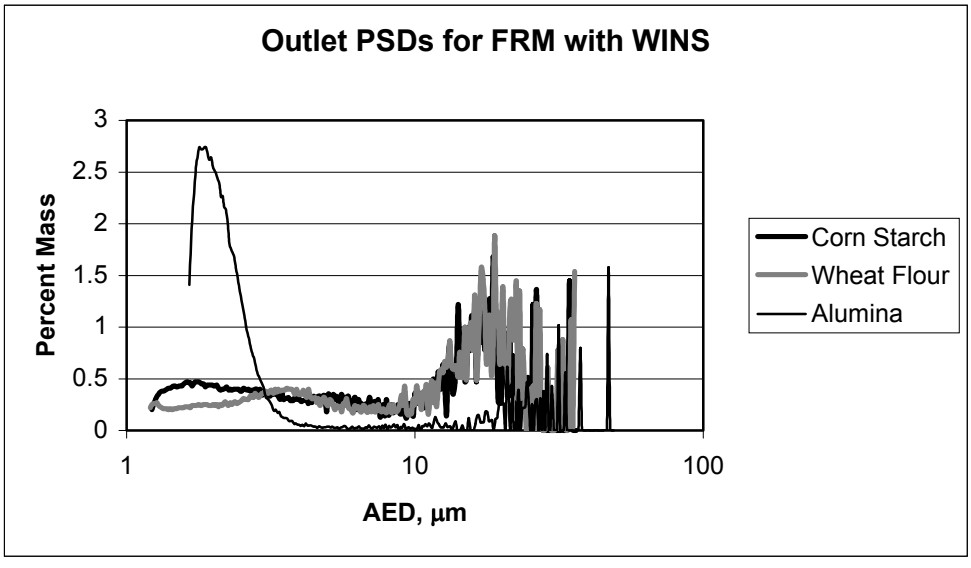

Figure 13. FRM with WINS outlet PSDs for each of the three dusts used in testing.