ENGINEERING OF PM_{10} AND $PM_{2.5}$ SAMPLERS

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Abstract

Agricultural operations including cotton ginning are encountering difficulties with complying with air pollution regulations across the cotton belt. It is likely that these problems will continue and get more severe. EPA has interpreted that the concentration limit on the property line must be less than the National Ambient Air Quality Standard (NAAQS). For PM_{10} and $PM_{2.5}$, the 24-hour NAAQS are 150 µg/m^3 and 65 µg/m^3 , respectively. The logical question by those who are being regulated is how accurate are the concentration measurements of PM_{10} and $PM_{2.5}$? Both PM_{10} and $PM_{2.5}$ samplers have pre-separators that remove the dust particles larger than the size to be sampled allowing the smaller particle to pass on to the filter. These pre-separators are not 100% efficient. In other words dust particles larger than 2.5 and 10 microns penetrate the pre-separator to the filter and dust particles less than 2.5 and 10 microns are captured by the pre-separator. Hence, there is some error in the measurement of PM_{10} and $PM_{2.5}$ concentrations when sampling with EPA approved samplers. The purpose of this paper is to quantify this potential measurement error with the goal of impacting the regulatory process. For example: if a measurement of 151 µg/m^3 were made at the property line of a cotton gin and the potential error for a PM_{10} sampler was 10%, an argument could be made that this measurement should not be a violation of the property line concentration limit since a 150 µg/m^3 concentration measured with an EPA approved sampler could be as high as 165 µg/m^3 and this 151 µg/m^3 could be as low as 136 µg/m^3.

Introduction

EPA approved samplers are used to measure particulate matter (PM) concentrations in ambient air. The two size fractions that are regulated are PM less than 10 micrometers (PM_{10}) aerodynamic equivalent diameter (AED) and PM less than 2.5 micrometers ($PM_{2.5}$). The design of Federal Reference Method (FRM) PM_{10} and $PM_{2.5}$ samplers consists of a pump that moves a constant flow rate of air plus PM through a pre-separator. In theory, the pre-separator separates the PM larger than the size to be sampled allowing the smaller PM to penetrate. The air plus the smaller PM passing through the pre-separator is subsequently filtered. The net mass of PM_{10} or $PM_{2.5}$ captured by the filter divided by the total volume of air sampled is a measure of the concentration.

One method of determining whether a new sampler design used to measure PM_{10} or $PM_{2.5}$ concentrations is measuring the same PM as the FRM sampler is to co-locate samplers and compare results. If the resulting measured concentrations are not significantly different, then the samplers are assumed to be operating the same. In other words, if sampler 'x' measures the same concentration as an FRM sampler, then sampler 'x' could be approved as an FRM sampler. On the surface, this would seem to be an acceptable method. However, the resulting measured concentrations with two samplers with very different cut points and slopes can be very nearly the same for PM with one particle size distribution (PSD) and be dramatically different when sampling PM with another PSD. This problem is exacerbated for PM with larger MMDs. PM from agricultural operations will typically have a high MMD compared to PM encountered in urban areas.

FRM PM_{10} and $PM_{2.5}$ Sampler Performance Characteristics

For the FRM PM_{10} ($PM_{2.5}$) sampler, an ideal pre-separator (virtual cut) would separate all PM larger than 10 :m (2.5:m) , allowing all PM less than 10 :m (2.5:m) to penetrate to the filter. It is not possible to engineer a pre-separator to obtain a virtual cut at 10 :m (2.5:m). The engineering description of the performance of a pre-separator is the fractional efficiency curve. This is a mathematical description of the percent mass captured versus particle size. The fractional efficiency curve is most commonly represented by a lognormal distribution with a slope and a cut-point. The cut-point is the particle size where 50% of the PM is captured and 50% penetrates to the filter. The slope is the ratio of the 84.1% and 50% particle sizes ($d_{84.1}/d_{50}$) or the ratio of the 50% and 15.9 % particle sizes ($d_{50}/d_{15..9}$) from the fractional efficiency curve. If the slope of the fractional efficiency curve is greater than 1.0 for any PM_{10} ($PM_{2.5}$) sampler, a fraction of the PM larger than 10 :m (2.5:m) penetrates the pre-separator to the filter and a fraction of the PM smaller than 10:m (2.5:m) is captured by the pre-separator. Fractional efficiency curves are usually assumed to be constant, independent of the particle size distribution of the PM being sampled, and log-normally distributed. *Two parameters define a pre-separator fractional efficiency curve: cut-point (d_{50}) and slope of the penetration curve ($d_{84.1}/d_{50}$).* These parameters are typically assumed to be constant.

Particle Size Distributions (PSD)

The particle size distributions (PSD) of PM in the ambient air consist of PM mass versus particle size. PSDs are typically represented by a lognormal distribution with mass median diameter (MMD) and geometric standard deviation (σ_g). An

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MMD is the particle size where 50% of the PM is larger or smaller from the PSD. The σ_g is the $d_{84.1}/d_{50}$ or $d_{50}/d_{15..9}$ ratio obtained from the PSD. The MMD and σ_g are similar to the *cut-point (d_{50}) and slope of the fractional efficiency curve ($d_{84.1}/d_{50}$),* respectively and are determined by a similar process but these values are characteristics of the ambient PM and are independent of the performance characteristics of the pre-separator.

Hinds (1982) points out that the lognormal distribution "is the most common distribution used for characterization aerosol particle size". EPA (1997) presented an "idealized distribution" that included separate distributions for fine (MMD=0.4 µm, σ_g = 1.5) and coarse mode (MMD= 4.9 µm, σ_g = 2.0) particulate matter. (See figure 1.) Wilson and Suh (1997) published sampling data illustrating a PSD for PM collected "in traffic" at the General Motors Proving Ground illustrating the "mechanically generated" fraction having an MMD = 4.6 µm and a , σ_g = 1.49. They state that the lower limit of coarse particles ($PM_{2.5-10}$) as 1 µm. They also published data utilizing dichotomous samplers where the two fractions, $PM_{2.5}$ and $PM_{10-2.5}$ were measured with one instrument for Philadelphia in the summer of 1992 and 1993 where the PM2.5 fraction was two-thirds the total of the PM_{10} concentration. This result suggests that variations of PM_{10} can be dominated by variations of $PM_{2.5}$ in some locations.

The ambient PSD that may be encountered throughout the U.S. will vary. If the primary source of PM in the ambient air is "mechanically generated" as is the case for almost all agricultural PM, the PSD will have a higher MMD. Figure 2 illustrates the lognormal distributions of ambient PM with MMDs of 5, 10 and 20 µm and a σ_g = 2.0

PM_{10} Pre-Separator Performance Characteristics

The resulting measurement of PM_{10} is a function of the ambient PSD and the fractional efficiency of the sampler. Parnell et al (1999) reported the logic used by EPA in 1987 when changing from the regulation of total suspended particulate matter to PM_{10}. The human respiratory system works like a pre-separator with a cut-point of 10 µm AED and a slope of 1.5 (ISO, 1981). Since it is not possible to engineer a sampler having a pre-separator with exactly these performance standards, EPA established performance standards: the pre-separator was required to have a cut-point of 10 ± 0.5 µm and a slope of 1.5 ± 0.1. (See Figure 3.) Hence, any sampler design that functions within these limits can potentially be an EPA approved PM_{10} sampler. In addition, all FRM PM_{10} samplers should be assumed to operate in this range. What this means is that a PM_{10} measurement with a FRM PM_{10} sampler will have a range of values that will meet the acceptable performance standard. It is a hypothesis of this paper that a SAPRA should not view that a measurement of 151 µg/m^3 PM_{10} is in violation of the 150 µg/m^3 PM_{10} NAAQS standard. If this is true, then what should be the range that would be a violation of the NAAQS?

Procedure

The process used to perform the engineering analysis of PM_{10} and $PM_{2.5}$ samplers was as follows:

1. Determine the measured concentration of PM having a uniform distribution between 0 and 20 µm and a concentration of 100 µg/m^3 by an FRM PM_{10} sampler with the ideal, upper, and lower operating characteristics, i.e. d_{50} = 10µm, slope = 1.5 and d_{50} = 10.5µm, slope = 1.6 d_{50} = 9.5µm, slope = 1.4, respectively. (See Tables 1-3.)
2. Determine the measured concentration of PM having a lognormal distribution (MMD = 25µm, GSD = 2) and a concentration of 100 µg/m^3 by an FRM PM_{10} sampler with the ideal, upper and lower operating characteristics, i.e. d_{50} = 10, slope = 1.5 and d_{50} = 10.5, slope = 1.6 d_{50} = 9.5, slope = 1.4, respectively. (See Tables 4-6.)
3. Determine the measured concentration of PM having a uniform distribution between 0 and 5µm and a concentration of 100 µg/m^3 measured with a:
   - WINS Impactor $PM_{2.5}$ sampler with operating characteristics described by Peters and Vanderpool (1996) of d_{50}= 2.5, slope = 1.18;
   - WINS Impactor $PM_{2.5}$ sampler with operating characteristics described by Buch (1999) of d_{50}= 2.7, slope = 1.32; and
   - IMPROVE sampler with operating characteristics described by Buch (1999) of d_{50}= 3.8, slope = 1.63. (See Tables 7-9.)
4. Determine the measured concentration of PM having a lognormal distribution (MMD = 10µm, GSD = 2) and an ambient concentration of 100 µg/m^3 for the three operating characteristics described in 3 above. (See Tables 10-12.)

For the PM_{10} analysis (Tables 1-6), 2µm increments were used for the size ranges. For the $PM_{2.5}$ analysis (Tables 7-12), 0.5µm increments were used for the size ranges. The fractional efficiencies used for each increment were calculated for the mid-point of each range. When lognormal PSDs were analyzed, the fraction of PM on the upper limit of each size range were calculated using the appropriate lognormal distribution and the net mass in each size range was calculated. The mass captured was calculated by multiplying the net mass in each size range times the factional efficiency for that size range. The mass entering minus the

mass captured by the pre-separator was the mass penetrating to the filter.

Results

Tables 13-16 are a summary of the results of this analysis. The analysis with the uniform distribution was performed to illustrate the range measurements that would occur independent of the PSD of the ambient PM. The public assumes that a PM_{10} sampler only samples PM less than 10µm. Error 1 in Table 13 illustrates that an FRM PM_{10} sampler will sample up to 12.6% more than the true concentration of PM_{10}. In other words, if the true concentration of PM_{10} were 150 µg/m^3, the sampler can measure as much as 169 µg/m^3. Error 2 illustrates the range of sampling results that would occur if the ideal measurement were d_{50} = 10 and slope = 1.5. The sampler would be as much as 5.4% higher or 6.8% lower than the concentration that would be measured if the sampler were operating ideally.

Table 14 illustrates the error that occurs if the ambient PM had a PSD characterized by MMD =25µm and a GSD=2. Error 1 in Table 14 illustrates that an FRM PM_{10} sampler will sample up to 120% more than the true concentration of PM_{10}. In other words, If the true concentration of PM_{10} were 150 µg/m^3, the sampler can measure as much as 330 µg/m^3. Error 2 illustrates the range of sampling results that would occur if the ideal measurement were d_{50} = 10 and slope = 1.5. The sampler would be as much as 29% higher or 27% lower than the concentration that would be measured if the sampler were operating ideally. Note that by merely changing the PSD, we have an FRM PM_{10} sampler that will measure more than double the true concentration of PM_{10}. As the MMD increases, the measured PM_{10} concentration increases. The PSD of PM associated with agricultural operations will typically have a larger MMD than PM in urban environments.

In contrast to the PM_{10} standard where EPA has established performance standards, the $PM_{2.5}$ NAAQS is based upon sampling with a sampler that is a $PM_{2.5}$ sampler "by design". In other words, whatever is measured by a $PM_{2.5}$ sampler is $PM_{2.5}$. For this standard, the ideal is a true measurement of $PM_{2.5.}$ Table 15 illustrates the error associated with two reported performance characteristics of the WINS Impactor sampler [Peters and Vanderpool (1996) and Buch (1999)] and the IMPROVE sampler [Buch (1999)]. Using a uniform distribution which theoretically removes any effects associated with the ambient PM PSD, the PM2.5 measurement could as much as 49% higher using the IMPROVE than the true concentration of $PM_{2.5}$. Usually concentrations of $PM_{2.5}$ are significantly lower than PM_{10} concentrations. For a true $PM_{2.5}$ concentration of 8 µg/m^3, the IMPROVE sampler would measure 11.9 µg/m^3 if the ambient PM PSD were uniformly distributed. Note that if this sampler were being evaluated by the co-locating results procedure, it could be easily concluded that the IMPROVE sampler were operating the same as a WINS Impactor.

Table 16 shows the results if the samplers with these different operating characteristics were sampling ambient PM with a lognormal distribution (MMD=10 and GSD =2). This PSD is not atypical of PM that might be associated with many agricultural operations. The IMPROVE could measure a concentration in excess of 1400% of the true $PM_{2.5}$ concentration and the WINS Impactor could result in a measured concentration of 150% higher than the true $PM_{2.5}$ concentration. In other words, If the true concentration of $PM_{2.5}$ concentration were 50 µg/m^3 , the WINS Impactor could measure 125 µg/m^3 and the IMPROVE could measure 785 µg/m^3 if the ambient PM PSD were characterized as having a lognormal distribution with an MMD=10 and GSD=2. The proposed NAAQS for $PM_{2.5}$ is 65 µg/m^3. This type of engineering analysis has not been reported in the literature. It is a concern of the authors that many of the scientists conducting research on health effects of PM_{10} and $PM_{2.5}$ are assuming that the samplers are precise measures of the PM they are sampling. In reality, the measurement errors can be quite large and are highly dependent upon the PM PSD. This is especially true of agricultural dusts that have relatively high MMDs when compared to PM sampled in urban environments.

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Table 1. Engineering analysis of the performance of a FRM PM_{10} sampler with the fractional efficiency curve defined by d_{50} = 10 µm and slope =1.5 for a uniform distribution of the PSD (0,20) and a total concentration of 100 µg/m^3 .

Range µm	dj µm	nj fraction	mj µg/m^3	nj*mj µg/m^3	PM_{10} µg/m^3
0--2	1.00	0.00	10.00	0.00	10.00
2--4	3.00	0.00	10.00	0.01	9.99
4--6	5.00	0.04	10.00	0.44	9.56
6--8	7.00	0.19	10.00	1.90	8.10
8--10	9.00	0.40	10.00	3.97	6.03
10--12	11.00	0.59	10.00	5.93	4.07
12--14	13.00	0.74	10.00	7.41	2.59
14--16	15.00	0.84	10.00	8.41	1.59
16--18	17.00	0.90	10.00	9.05	0.95
18--20	19.00	0.94	10.00	9.43	0.57
			Totals=	46.56	53.44
			Mass less than 10µm =		50.00

Note: dj = mid-size particle diameter of range,
nj = fractional efficiency of pre-separator for particle diameter dj,
mj= % PM mass in size range j,
nj*mj = mass pf PM captured by pre-separator,
PM_{10} = mass of PM penetrating the preseparator.

Table 2. Engineering analysis of the performance of a FRM PM_{10} sampler with the fractional efficiency curve defined by d_{50} = 9.5 µm and slope =1.4 for a uniform distribution of the PSD (0,20) and a total concentration of 100 µg/m^3.

Range µm	dj µm	nj fraction	mj µg/m^3	nj*mj µg/m^3	PM_{10} µg/m^3
0--2	1.00	0.00	10.00	0.00	10.00
2--4	3.00	0.00	10.00	0.00	10.00
4--6	5.00	0.03	10.00	0.29	9.71
6--8	7.00	0.18	10.00	1.83	8.17
8--10	9.00	0.44	10.00	4.38	5.62
10--12	11.00	0.67	10.00	6.70	3.30
12--14	13.00	0.82	10.00	8.25	1.75
14--16	15.00	0.91	10.00	9.13	0.87
16--18	17.00	0.96	10.00	9.58	0.42
18--20	19.00	0.98	10.00	9.80	0.20
			Totals=	49.96	50.04
			Mass less than 10µm =		50.00

Table 3. Engineering analysis of the performance of a FRM PM_{10} sampler with the fractional efficiency curve defined by d_{50} = 10.5 µm and slope =1.6 for a uniform distribution of the PSD (0,20) and a total concentration of 100 µg/m^3 .

Range µm	dj µm	nj fraction	mj µg/m^3	nj*mj µg/m^3	PM_{10} µg/m^3
0--2	1.00	0.00	10.00	0.00	10.00
2--4	3.00	0.00	10.00	0.04	9.96
4--6	5.00	0.06	10.00	0.58	9.42
6--8	7.00	0.19	10.00	1.95	8.05
8--10	9.00	0.37	10.00	3.73	6.27
10--12	11.00	0.54	10.00	5.41	4.59
12--14	13.00	0.68	10.00	6.76	3.24
14--16	15.00	0.78	10.00	7.77	2.23
16--18	17.00	0.85	10.00	8.48	1.52
18--20	19.00	0.90	10.00	8.97	1.03
			Totals=	43.68	56.32
			Mass less than 10µm =		50.00

Table 4. Engineering analysis of the performance of a FRM PM_{10} sampler with the fractional efficiency curve defined by d_{50} = 10.5 µm and slope =1.6 for a lognormal PSD distribution (MMD= 25µm, GSD = 2) and a total concentration of 100 µg/m^3 .

Range µm	dj µm	nj fraction	mj µg/m^3	Δmj µg/m^3	nj*Δmj µg/m^3	PM_{10} µg/m^3
0--2	1.00	0.00	0.00	0.01	0.00	0.01
2--4	3.00	0.00	0.00	0.40	0.00	0.39
4--6	5.00	0.06	0.02	1.56	0.09	1.47
6--8	7.00	0.19	0.05	3.03	0.59	2.44
8--10	9.00	0.37	0.09	4.30	1.60	2.70
10--12	11.00	0.54	0.14	5.17	2.80	2.38
12--14	13.00	0.68	0.20	5.66	3.83	1.83
14--16	15.00	0.78	0.26	5.84	4.54	1.30
16--18	17.00	0.85	0.32	5.79	4.91	0.88
≥18	19.00	0.90	0.37	68.23	61.21	7.03
			0.63	100.00	0.00	20.44
					mass less than 10 µm =	9.30

Table 5. Engineering analysis of the performance of a FRM PM_{10} sampler with the fractional efficiency curve defined by d_{50} = 10 µm and slope =1.5 for a lognormal PSD distribution (MMD= 25µm, GSD= 2) and a total concentration of 100 µg/m^3 .

Range µm	dj µm	nj fraction	mj µg/m^3	Δmj µg/m^3	nj*Δmj µg/m^3	PM_{10} µg/m^3
0--2	1.00	0.00	0.00	0.01	0.00	0.01
2--4	3.00	0.00	0.00	0.40	0.00	0.39
4--6	5.00	0.04	0.02	1.56	0.07	1.50
6--8	7.00	0.19	0.05	3.03	0.57	2.46
8--10	9.00	0.40	0.09	4.30	1.71	2.59
10--12	11.00	0.59	0.14	5.17	3.07	2.11
12--14	13.00	0.74	0.20	5.66	4.20	1.47
14--16	15.00	0.84	0.26	5.84	4.91	0.93
16--18	17.00	0.90	0.32	5.79	5.24	0.55
≥18	19.00	0.94	0.37	68.23	64.36	3.87
			0.63	100.00	0.00	15.87
					mass less than 10 µm =	9.30

Table 6. Engineering analysis of the performance of a FRM PM_{10} sampler with the fractional efficiency curve defined by d_{50} = 9.5 µm and slope =1.4 for a lognormal PSD distribution (MMD= 25 µm, GSD = 2) and a total concentration of 100 µg/m^3 .

Range µm	dj µm	nj fraction	mj µg/m^3	Δmj µg/m^3	nj*Δmj µg/m^3	PM_{10} µg/m^3
0--2	1.00	0.00	0.00	0.01	0.00	0.01
2--4	3.00	0.00	0.00	0.40	0.00	0.40
4--6	5.00	0.03	0.02	1.56	0.04	1.52
6--8	7.00	0.18	0.05	3.03	0.56	2.48
8--10	9.00	0.44	0.09	4.30	1.88	2.42
10--12	11.00	0.67	0.14	5.17	3.46	1.71
12--14	13.00	0.82	0.20	5.66	4.67	0.99
14--16	15.00	0.91	0.26	5.84	5.33	0.51
16--18	17.00	0.96	0.32	5.79	5.55	0.24
≥18	19.00	0.98	0.37	68.23	66.89	1.34
			0.63	100.00	0.00	11.61
					mass less than 10µm =	9.30

Table 7. Engineering analysis of the performance of a FRM $PM_{2.5}$ sampler with the fractional efficiency curve defined by d_{50} = 2.5 µm and slope =1.18 for a uniform distribution of the PSD (0,5) and a total concentration of 100 µg/m^3 .

Range µm	dj µm	nj fraction	mj µg/m^3	nj*mj µg/m^3	$PM_{2.5}$ µg/m^3
0--.5	0.25	0.00	10.00	0.00	10.00
.5--1	0.75	0.00	10.00	0.00	10.00
1--1.5	1.25	0.00	10.00	0.00	10.00
1.5--2	1.75	0.02	10.00	0.15	9.85
2--2.5	2.25	0.26	10.00	2.62	7.38
2.5--3	2.75	0.72	10.00	7.18	2.82
3--3.5	3.25	0.94	10.00	9.44	0.56
3.5--4	3.75	0.99	10.00	9.93	0.07
4--4.5	4.25	1.00	10.00	9.99	0.01
4.5--5	4.75	1.00	10.00	10.00	0.00
			Total =	49.31	50.69
			Mass less than 2.5 µm =		50.00

Table 8. Engineering analysis of the performance of a FRM $PM_{2.5}$ sampler with the fractional efficiency curve defined by d_{50} = 2.7 µm and slope =1.32 for a uniform distribution of the PSD (0,5) and a total concentration of 100 µg/m^3.

Range µm	dj µm	nj fraction	mj µg/m^3	nj*mj µg/m^3	$PM_{2.5}$ µg/m^3
0--.5	0.25	0.00	10.00	0.00	10.00
.5--1	0.75	0.00	10.00	0.00	10.00
1--1.5	1.25	0.00	10.00	0.03	9.97
1.5--2	1.75	0.06	10.00	0.59	9.41
2--2.5	2.25	0.26	10.00	2.56	7.44
2.5--3	2.75	0.53	10.00	5.27	4.73
3--3.5	3.25	0.75	10.00	7.48	2.52
3.5--4	3.75	0.88	10.00	8.82	1.18
4--4.5	4.25	0.95	10.00	9.49	0.51
4.5--5	4.75	0.98	10.00	9.79	0.21
				44.03	55.97
			Mass less than 2.5 µm =		50.00

Table 9. Engineering analysis of the performance of a IMPROVE sampler with the fractional efficiency curve defined by d_{50} = 3.8 µm and slope =1.63 for a uniform distribution of the PSD (0,5) and a total concentration of 100 µg/m^3.

Range µm	dj µm	nj fraction	mj µg/m^3	nj*mj µg/m^3	$PM_{2.5}$ µg/m^3
0--.5	0.25	0.00	10.00	0.00	10.00
.5--1	0.75	0.00	10.00	0.00	10.00
1--1.5	1.25	0.01	10.00	0.11	9.89
1.5--2	1.75	0.06	10.00	0.56	9.44
2--2.5	2.25	0.14	10.00	1.41	8.59
2.5--3	2.75	0.25	10.00	2.54	7.46
3--3.5	3.25	0.37	10.00	3.74	6.26
3.5--4	3.75	0.49	10.00	4.89	5.11
4--4.5	4.25	0.59	10.00	5.91	4.09
4.5--5	4.75	0.68	10.00	6.76	3.24
				25.93	74.07
			Mass less than 2.5 µm =		50.00

Table10. Engineering analysis of the performance of a FRM $PM_{2.5}$ sampler with the fractional efficiency curve defined by d_{50} = 2.5 µm and slope =1.18 for a lognormal PSD distribution (MMD= 10, σ_g = 2) and a total concentration of 100 µg/m^3.

Range µm	dj µm	nj fraction	mj µg/m^3	mj µg/m^3	nj*mj µg/m^3	PM2.5 µg/m^3
0--.5	0.25	0.00	0.00	0.00	0.00	0.00
.5--1	0.75	0.00	0.00	0.04	0.00	0.04
1--1.5	1.25	0.00	0.00	0.27	0.00	0.27
1.5--2	1.75	0.02	0.01	0.71	0.01	0.70
2--2.5	2.25	0.26	0.02	1.27	0.33	0.94
2.5--3	2.75	0.72	0.04	1.86	1.33	0.52
3--3.5	3.25	0.94	0.07	2.39	2.25	0.13
3.5--4	3.75	0.99	0.09	2.83	2.81	0.02
4--4.5	4.25	1.00	0.13	3.17	3.17	0.00
≥4.5	4.75	1.00	0.16	87.46	87.46	0.00
			0.84	100	97.37	2.63
					Mass less than 2.5 µm =	2.29

Table 11. Engineering analysis of the performance of a FRM $PM_{2.5}$ sampler with the fractional efficiency curve defined by d_{50} = 2.7 µm and slope =1.32 for a lognormal PSD distribution (MMD= 10, σ_g = 2) and a total concentration of 100 µg/m^3.

Range µm	dj µm	nj fraction	mj µg/m^3	mj µg/m^3	nj*mj µg/m^3	PM2.5 µg/m^3
0--.5	0.25	0.00	0.00	0.00	0.00	0.00
.5--1	0.75	0.00	0.00	0.04	0.00	0.04
1--1.5	1.25	0.00	0.00	0.27	0.00	0.27
1.5--2	1.75	0.06	0.01	0.71	0.04	0.67
2--2.5	2.25	0.26	0.02	1.27	0.33	0.95
2.5--3	2.75	0.53	0.04	1.86	0.98	0.88
3--3.5	3.25	0.75	0.07	2.39	1.79	0.60
3.5--4	3.75	0.88	0.09	2.83	2.50	0.33
4--4.5	4.25	0.95	0.13	3.17	3.01	0.16
≥4.5	4.75	0.98	0.16	87.46	85.64	1.83
			0.84	100	94.27	5.73
					Mass less than 2.5 µm =	2.29

Table 12. Engineering analysis of the performance of an IMPROVE sampler with the fractional efficiency curve defined by d_{50} = 3.8 µm and slope =1.63 for a lognormal PSD distribution (MMD= 10, σ_g = 2) and a total concentration of 100 µg/m^3.

Range µm	dj µm	nj fraction	mj µg/m^3	mj µg/m^3	nj*mj µg/m^3	PM2.5 µg/m^3
0--.5	0.25	0.00	0.00	0.00	0.00	0.00
.5--1	0.75	0.00	0.00	0.04	0.00	0.04
1--1.5	1.25	0.01	0.00	0.27	0.00	0.26
1.5--2	1.75	0.06	0.01	0.71	0.04	0.67
2--2.5	2.25	0.14	0.02	1.27	0.18	1.09
2.5--3	2.75	0.25	0.04	1.86	0.47	1.39
3--3.5	3.25	0.37	0.07	2.39	0.89	1.49
3.5--4	3.75	0.49	0.09	2.83	1.38	1.45
4--4.5	4.25	0.59	0.13	3.17	1.87	1.30
≥4.5	4.75	0.68	0.16	87.46	59.15	28.32
			0.84	100	63.99	36.01
					Mass less than 2.5 µm =	2.29

Table 13. Summary of PM_{10} sampler performance characteristics for PM having a uniform distribution from 0 to 20 µm {uniform (0,20)} with a concentration of 100 µg/m^3. The concentration of PM less than 10 µm was 50 µg/m^3. (See Tables 1-3)

Pre-Separator Characteristics		Sampler Performance		
d50 µm	slope	Conc. µg/m^3	Error 1 %	Error 2 %
10.0	1.5	53.4	+6.8	0
9.5	1.4	50.0	0	-6.8
10.5	1.6	56.3	+12.6	+5.4

Note: Error 1 = percent difference from concentration less than 10 µm. Error 2 = percent difference from concentration measured at ideal operating conditions (d_{50} = 1.5 µm and slope = 1.5).

Table 14. Summary of FRM PM_{10} sampler performance characteristics for PM having a lognormal distribution (MMD = 25 µm , σ_g = 2.0) and a concentration of 100 µg/m^3. The concentration of PM less than 10 µm is 9.28 µg/m^3. (See Tables 4-6.)

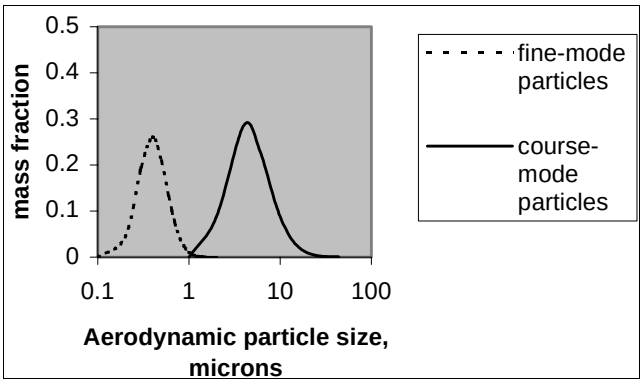
Pre-Separator Characteristics		Sampler Performance		
d50 µm	slope	Conc. µg/m^3	Error 1 %	Error 2 %
10.0	1.5	15.85	+71	0
9.5	1.4	11.59	25	-27
10.5	1.6	20.41	+120	29

Table 15. Summary of three $PM_{2.5}$ sampler performance characteristics for PM having a uniform distribution from 0 to 5 µm {uniform (0,5)} with a concentration of 100 µg/m^3. The concentration of PM less than 2.5 µm is 50 µg/m^3. (See Tables 7-9)

Pre-Separator Characteristics		Sampler Performance	
d50 µm	slope	Conc. µg/m^3	Error 1 %
2.5	1.18	50.7	+1.4
2.7	1.32	56.0	+12.0
3.8	1.63	74.1	+49.4

Table 16. Summary of three $PM_{2.5}$ sampler performance characteristics for PM having a lognormal distribution (MMD = 10 µm , σ_g = 2.0) and a concentration of 100 µg/m^3. The concentration of PM less than 2.5µm was 2.29 µg/m^3. (See Tables 10-12.)

Pre-Separator Characteristics		Sampler Performance	
d50 µm	slope	Conc. µg/m^3	Error 1 %
2.5	1.18	2.63	+14.8
2.7	1.32	5.73	+150
3.8	1.63	36.0	+1,472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0.4
0.3
0.2
0.1
0
mass fraction
0.1
1
10
100
Aerodynamic particle size, microns
fine-mode particles
course-mode particles