# PM$_{10}$ SAMPLER ERRORS DUE TO THE INTERACTION OF PARTICLE SIZE AND SAMPLER PERFORMANCE CHARACTERISTICS

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## Abstract

Agricultural operations across the United States are encountering difficulties in complying with the current air pollution regulations for particulate matter (PM). The National Ambient Air Quality Standards (NAAQS) for PM in terms of PM$_{10}$, are ambient air concentration limits set by EPA that should not be exceeded. Further, EPA and State Air Pollution Regulatory Agencies (SAPRA's) utilize the NAAQS to regulate criteria pollutants emitted by industries by applying the ambient air concentration limits as a property line concentration limits. The primary NAAQS are health-based standards and an exceedance of the NAAQS implies that it is likely that there will be adverse health effects for the public. The current PM$_{10}$ primary 24-hour NAAQS is 150 micrograms per actual cubic meter (μg/acm). Prior to and since the inclusion of the PM$_{10}$ indicator into the PM regulation, numerous journal articles and technical references have been written to discuss the epidemiological effects of PM, trends of PM, regulation of PM, methods of determining PM$_{10}$, etc. A common trend among many of these publications is the use of samplers to collect information on PM. All to often, the sampler data are assumed to be an accurate measure of PM, when in fact issues such as; sampler uncertainties, environmental conditions, and material characteristics for which the sampler is measuring must be incorporated for accurate sampler measurements. The focus of this manuscript is on the errors associated with material characteristics or particle size distribution (PSD) of the material in the air that is being sampled, the assumptions associated with PSD's and sampler performance characteristics, and the interaction between these two characteristics. The common perception is that PM$_{10}$ measurement concentrations relate to true concentrations (also refereed to as virtual-cut concentrations) or PM with particle sizes less than 10 μm aerodynamic equivalent diameter (AED). However, these measurement concentrations are actually based on sampler measurements. PM$_{10}$ samplers bias the concentration measurements, since a portion of the PM less than 10 μm will not be collected on the filter and a portion of the PM greater than 10 μm will be collected on the filter. A common assumption made in the regulatory community to circumvent this problem is that the mass of particles less than 10 μm and captured by the pre-separator are equal to the mass of particles greater than 10μm and captured on the filter. This issue leads to a primary focus of this manuscript, that is, industries that emit PM with a mass median diameter (MMD) less than 10 μm are not regulated at the same level as agricultural operations, which typically emit PM with an MMD greater than 10 μm. This unequal regulation is primarily due to the interaction of the sampler performance and PSD characteristics. For example, if property line sampler concentration measurements from two industries are exactly the same and if 100% of industry A's PM is less than 10 μm and 38% of industry B's PM is less than 10 μm (true PM$_{10}$); then 100% industry A's PM can potentially reach the alveolar region of the lungs as compared to 38% of industry B's PM. Since the emphasis of the primary NAAQS is to protect public health; then in the previous example the two industries are not equally regulated. Therefore, in order to achieve equal regulation among differing industries, PM$_{10}$ measurements **MUST** be based on true concentration measurements.

## Introduction

The Federal Clean Air Act (FCAA) of 1960 and subsequent amendments established national goals for air quality and incorporated the use of standards for the control of pollutants in the environment. The 1970 FCAA Amendments (FCAAA) provided the authority to create the Environmental Protection Agency (EPA) and required the EPA to establish National Ambient Air Quality Standards (NAAQS). The NAAQS are composed of primary (based on protecting against adverse health effects of listed criteria pollutants among sensitive population groups) and secondary standards (based on protecting public welfare e.g., impacts on vegetation, crops, ecosystems, visibility, climate, man-made materials, etc). In 1971, EPA promulgated the primary and secondary NAAQS, as the maximum concentrations of selected pollutants (criteria pollutants) that, if exceeded, would lead to unacceptable air quality. The NAAQS for particulate matter (PM) was established and the indicator of PM was defined as total suspended particulate (TSP). The FCAAA of 1977 required EPA to review and revise the ambient air quality standards every five years to ensure that the standards met all criteria based on the latest scientific developments. In 1987 EPA modified the PM standard by replacing the TSP indicator with a new indicator that accounts for

particles with an aerodynamic equivalent diameter (AED) less than or equal to a nominal 10 μm ($PM_{10}$). (Cooper and Alley, 1994)

Prior to and since the inclusion of the $PM_{10}$ indicator into the PM regulation, numerous journal articles and technical references have been written to discuss the epidemiological effects of PM, trends of PM, regulation of PM, methods of determining $PM_{10}$, etc. A common trend among many of these publications is the use of samplers to collect information on PM. The data collected from the samplers are commonly used in statistical correlations and statistical comparisons to draw conclusions about PM emission concentrations. All to often, the sampler data are assumed to be an accurate measure of PM, when in fact issues such as; sampler uncertainties, environmental conditions (dry standard versus actual conditions), and material characteristics for which the sampler is measuring must be incorporated for accurate sampler measurements. The focus of this manuscript is on the material characteristics or particle size distribution (PSD) of the material in the air that is being sampled, the assumptions associated with PSD's and sampler performance characteristics, and the interaction between these two characteristics.

## Background

Health risks posed by inhaled particles are influenced by both the penetration and deposition of particles in the various regions of the respiratory tract and the biological responses to these deposited materials. The largest particles are deposited predominantly in the extrathoracic (head) region, with somewhat smaller particles deposited in the tracheobronchial region; still smaller particles can reach the deepest portion of the lung, the pulmonary region. Risks of adverse health effects associated with the deposition of typical ambient fine and coarse particles in the thoracic region (tracheobronchial and pulmonary deposition) are much greater than those associated with deposition in the extrathoracic region. Further, extrathoracic deposition of typical ambient PM is sufficiently low that particles depositing only in that region can safely be excluded from the indicator. Figure 1 shows the American Conference of Governmental Hygienists (ACGIH, 1997) sampling criteria for the inhalable, thoracic, and respirable fraction of PM. Note that virtually all respirable PM (PM that can penetrate into the alveolar region of the human lung) is less than 10 μm, whereas 50% of the 3.5 μm particles are respirable and can reach the alveolar region. (U.S. Environmental Protection Agency, 1996)

In 1987, the EPA staff recommended that a $PM_{10}$ indicator replace the TSP indicator for the PM standard. Based on the information in the literature, it was EPA's intent for the $PM_{10}$ sampler to mimic the thoracic fraction of PM, which is shown in Figure 1 (Hinds, 1982). The original acceptable concentration range proposed by the EPA Administrator, drawn from the 1984 staff analysis, was 150 to 250 μg/m³ $PM_{10}$ 24-hour average, with no more than one expected exceedance per year. The Administrator decided to set the final standard at the lower bound of the proposed range. The rationale behind this decision was that this standard would provided a substantial margin of safety below the levels at which there was a scientific consensus that PM caused premature mortality and aggravation of bronchitis, with a primary emphasis on children and the elderly (U. S. Environmental Protection Agency, 1996).

It should be emphasized that PM is the pollutant and TSP and $PM_{10}$ are indicators of the pollutant. Further, based on the indicator definitions, TSP represents a greater than or equal to indicator of PM than the $PM_{10}$ indicator. Although this comparison appears relatively trivial, several state air pollution regulatory agencies (SAPRA) currently utilize the TSP and $PM_{10}$ indicators and regulate these indicators at exactly the same level. The NAAQS for $PM_{10}$ is the concentration limit set by EPA that should not be exceeded (U. S. Environmental Protection Agency, 2000a). The regional or area consequences for multiple exceedances of the NAAQS are having an area designated as nonattainment with a corresponding reduction in the permit allowable emission rates for all sources of PM in the area. The source-specific consequence of an exceedance of the NAAQS at the property line is the SAPRA denying an operating permit. The current $PM_{10}$ primary 24-hour NAAQS is 150 micrograms per actual cubic meter (μg/acm) (U. S. Environmental Protection Agency, 2000a). The secondary NAAQS for $PM_{10}$ is set at the same level as the respective primary NAAQS.

## Particle Size Distributions

The distribution of particles with respect to size is perhaps the most important physical parameter governing their behavior. Aerosols containing only particles of a particular size are called monodisperse while those having a range or ranges of sizes are called polydisperse. Hinds (1982) indicated that most aerosols in the ambient air are polydisperse and that the lognormal distribution "is the most common distribution used for characterizing the particle sizes associated with the aerosol". The significance of using a lognormal distribution is that the PSD can be described in terms of the mass median diameter (MMD) and the geometric standard deviation (GSD). The lognormal mass density function is expressed as

$$f(d_p, MMD, GSD) = \frac{1}{d_p \ln GSD \sqrt{2\pi}} \exp\left[ \frac{-\left(\ln d_p - \ln MMD\right)^2}{2(\ln GSD)^2} \right] \tag{1}$$

For monodisperse particles GSD=1 and for polydisperse particles GSD>1. The fraction of the total number of particles $df$ having diameters between $d_p$ and $d_p + dd_p$ is

$$df = f(d_p, MMD, GSD) dd_p \tag{2}$$

where $dd_p$ is a differential interval of particle size. The area under the density distribution curve is always

$$\int_0^\infty f(d_p, MMD, GSD) dd_p = 1.0 \tag{3}$$

The area under the density function may be estimated for particle sizes ranging from zero to infinity, as in equation 3, between given sizes $a$ and $b$, or it may be the small interval $dd_p$. The area under the density function curve between two sizes $a$ and $b$ equals the fraction of particles whose diameters fall within this interval, which can be expressed as

$$f_{ab}(a, b, MMD, GSD) = \int_a^b f(d_p, MMD, GSD) dd_p \tag{4}$$

The size distribution can also be presented as a cumulative distribution function, $F(a, MMD, GSD)$,

$$F(a, MMD, GSD) = \int_0^a f(d_p, MMD, GSD) dd_p \tag{5}$$

where $F(a, MMD, GSD)$ is the fraction of the particles having diameters less than $a$. The fraction of particles having diameters between sizes $a$ and $b$, $f_{ab}(a, b, MMD, GSD)$, can be determined directly by subtracting the cumulative fraction for size $a$ from that for size $b$.

$$f_{ab}(a, b, MMD, GSD) = F(b, MMD, GSD) - F(a, MMD, GSD) \tag{6}$$

The concentration of particles having diameters between sizes $a$ and $b$, $C_{ab}(a, b, MMD, GSD)$, can be expressed as

$$C_{ab}(a, b, MMD, GSD) = C_T(F(b, MMD, GSD) - F(a, MMD, GSD)) \tag{7}$$

where $C_T$ is the total concentration of PM in the ambient air.

For a lognormal distribution, the mode < median < mean. A lognormal density distribution defined by a MMD of 20 μm and a GSD of 3.0 is shown in Figure 2 to illustrate the differences between the mode, median, and mean of a lognormal distribution. Three important characteristics of lognormal distributions are: (1) the mode shifts to the left as the GSD increases, (2) the median is not affected by the increase in GSD, and (3) the larger the GSD the more closely the lognormal distribution is to a uniform distribution.

**Sampler Performance Characteristics**
A sampler's performance is generally described by either a cumulative collection or penetration efficiency curve. The "sharpness of cut" of the sampler pre-separator or the "sharpness of the slope" of the sampler penetration efficiency curve significantly impacts the accuracy of sampler measurements. Three terms are often used to describe the sharpness of the penetration curve and are frequently and inappropriately interchanged. These terms are ideal, true, and sampler cut. An ideal cut corresponds to the penetration data provided in 40CFR53 (U. S. Environmental Protection Agency, 2000b). A true cut can be described as a step function; in other words, all the particles less than or equal to the size of interest are captured on the filter and all particles greater than the particle size of interest are captured by the pre-separator. A sampler cut refers to the actual penetration curve associated with a particular sampler. A sampler cut is defined by a sampler's performance characteristics and based on these characteristics, a portion of the PM less than the size of interest will not be collected on the filter and a portion of the PM greater than the size of interest will be collected on the filter. A common perception is that $PM_{10}$ measurement concentrations are true concentrations and that the concentrations relate to PM with particle sizes less than 10 μm or true $PM_{10}$; however, these measurement concentrations are actually based on a sampler cut.

A sampler's pre-separator collection efficiency curve is most commonly represented by a lognormal distribution, characterized by a $d_{50}$ (also referred to as cut-point) and slope of the collection efficiency curve. The cut-point is the particle

size where 50% of the PM is captured by the pre-separator and 50% of the PM penetrates to the filter. The slope is the ratio of the particle sizes corresponding to cumulative collection efficiencies of 84.1% and 50% ($d_{84.1}/d_{50}$) or 50% and 15.9% ($d_{50}/d_{15.9}$). Collection efficiency curves are usually assumed as constant and independent of particle size; in other words, it is assumed that a significant loading of large particles does not affect the pre-separators collection efficiency for smaller particles. Therefore, concentration data used to generate a sampler's pre-separator collection efficiency curve is typically determined by conducting an array of tests over several monodisperse particle sizes using known ambient concentrations. The concentration data from each test is used to determine the collection efficiency, $\varepsilon_m$, associated with each particle size, using the following equation.

$$\varepsilon_m = \frac{C_{\mathrm{Pre-Separator}}}{C_{ambient}}$$
(8)

In equation 8, $C_{Pre-Separator}$ is the concentration of particles captured by the pre-separator and $C_{ambient}$ is the concentration of particles used for the test. A smooth lognormal curve is fit to the calculated pre-separator collection efficiencies and the sampler performance characteristics ($d_{50}$ and slope) are determined from the fitted curve. The lognormal density distribution function for collection efficiency is defined as

$$\varepsilon_m\left(d_p, d_{50}, slope\right) = \left[\frac{1}{d_p \ln(slope)\sqrt{2\pi}} \exp\left[\frac{-\left(\ln d_p - \ln d_{50}\right)^2}{2(\ln(slope))^2}\right]\right]$$
(9)

For a true cut the slope is equal to 1 and for all other samplers the slope is greater than 1. Mathematical derivations for determining the cumulative distribution function for the collection efficiency can be achieved in the same manner presented in the particle size distribution section of this manuscript. The cumulative distribution function for the collection efficiency, $\psi(a,d_{50},slope)$, is defined by

$$\psi_m(a, d_{50}, slope) = \int_0^a \varepsilon_m(d_p, d_{50}, slope) dd_p$$
(10)

where $\psi(a,d_{50},slope)$ gives the collection efficiency for particles having diameters less than $a$. The penetration efficiency, $P_m(a,d_{50},slope)$, is defined as

$$P_m(a, d_{50}, slope) = 1 - \psi_m(a, d_{50}, slope)$$
(11)

Substituting equations 9 and 10 into equation 11 yields

$$P_m\left(a, d_{50}, slope\right) = 1 - \int_0^a \left[\frac{1}{d_p \ln(slope)\sqrt{2\pi}} \exp\left[\frac{-\left(\ln d_p - \ln d_{50}\right)^2}{2(\ln(slope))^2}\right]\right] dd_p$$
(12)

where $P_m(a,d_{50},slope)$ is the sampler penetration efficiency for particles having diameters less than $a$. Since a true cut is defined by a step function, equation 12 can be simplified so that the true cut penetration efficiency can be defined as

$$P_t(d_p, d_{50}, slope) = \begin{cases} 1 & if\ d_p \leq d_{50} \\ 0 & if\ d_p > d_{50} \end{cases}$$
(13)

Now that the penetration function has been defined, the sampler performance characteristics for the $PM_{10}$ sampler need to be defined in terms of $d_{50}$ and slope. EPA essentially defines these parameters in 40CFR53 in the discussion of tests required for a candidate sampler to receive EPA approval. The $d_{50}$ for the $PM_{10}$ sampler is explicitly stated in the EPA standards as $10.0 \pm 0.5$ μm. No slope values for the sampler are listed in EPA's 40CFR53 or any other current EPA standard; however, penetration data is presented 40CFR53. Ideally, the penetration data could be fit to a cumulative lognormal distribution to determine the characteristic $d_{50}$ and slope for each of the samplers; however, it was found that no single cumulative lognormal curve adequately represented the EPA data sets in 40CFR53.

The $PM_{10}$ cumulative penetration data set produced a rough curve, which appeared to have a larger slope for the particle sizes less than 10 μm than the slope for the particle sizes greater than 10 μm. Hinds (1982) suggested that the slope associated PM

deposited in the thoracic region of the human respiratory system had a slope of $1.5 \pm 0.1$ and that this slope represented the slope of the cumulative lognormal collection efficiency curve associated with the $PM_{10}$ sampler. When comparing the nine curves produced by these sampler performance characteristics ($d_{50}$ equal to 9.5, 10.0, and 10.5 µm and slopes equal to 1.4, 1.5, and 1.6) to the penetration data presented in 40CFR53, it was found that a combination of the nine curves produced a fairly good estimate of EPA's penetration data. Therefore, for the remaining sections of this manuscript the $PM_{10}$ performance specifications will be assumed to be a $d_{50}$ of $10 \pm 0.5$ µm and a slope of $1.5 \pm 0.1$.

Figure 3 illustrates the boundary penetration efficiency curves for the $PM_{10}$ sampler, based the previously defined sampler performance characteristics. When comparing the boundary penetration efficiency curves in Figure 3, it is apparent that there is an acceptable range of penetration efficiencies for the $PM_{10}$ sampler. The acceptable range of penetration efficiencies for a particle size of 10 µm AED is 44 to 56%, whereas the acceptable range for a particle size of 20 µm AED is 1 to 9%. These ranges are considered to be one form of inherent errors associated with $PM_{10}$ samplers. Figure 4 graphically illustrates the differences between a $PM_{2.5}$ sampler-cut, $PM_{10}$ sampler-cut, TSP-cut, $PM_{2.5}$ true-cut, and a $PM_{10}$ true-cut in relationship to a PSD characterized by an MMD of 20 µm and a GSD of 2.0.

### Methods and Procedures

The issue of which sampler performance characteristics are correct is a valid concern; however, the most important question is "what is the intent of the PM regulations". It was previously established that the primary purpose of the regulations is to protect public health. It is quite clear in the literature that PM collected from a $PM_{10}$ sampler should mimic the fraction of PM that penetrates the thoracic region of the human respiratory system, which leads to the perception that the sampler must have a slope greater than 1 based on information presented in Figure 1. Another assumption made in the $PM_{10}$ regulation is that it pertains to a measure of particles with an AED less than or equal to a <u>nominal</u> 10 µm. The term nominal implies that the measured PM does not account for all mass associated with particles less than or equal to 10 µm and does include some of the mass associated with particles larger than 10 µm.

This issue of nominal values leads to a primary focus of this manuscript, that is, that industries that emit PM with an MMD less than 10 µm are not regulated at the same level as agricultural operations, which typically emit PM with an MMD greater than 10 µm. This unequal regulation is primarily due to the interaction of the sampler performance and PSD characteristics. A common assumption made in the regulatory community to circumvent this problem is that mass of particles less than 10 µm and captured by the pre-separator is <u>equal</u> to the mass of particles greater than 10 µm and captured on the filter. Figure 5 graphically illustrates this assumption. This assumption is only valid when the density function of the particle size distribution of the ambient air can be represented by a uniform distribution. Further, this assumption introduces a major source of error when the particle size density distribution function is represented by a lognormal distribution; as is the case in virtually all situations involving ambient air. In simplistic terms, if property line sampler concentration measurements from two industries are exactly the same and if 100% of industry A's PM is less than 10 µm and 38% of industry B's PM is less than 10 µm; then based on Figure 1 100% industry A's PM can potentially reach the alveolar region of the lungs as compared to 38% of industry B's PM. Since the emphasis of the primary NAAQS is to protect public health; then in the previous scenario the two industries are not equally regulated. Therefore, in order to achieve equal regulation among differing industries, $PM_{10}$ measurements **MUST** be based on true measurements. A more in-depth discussion of this issue will be addressed herein.

### Estimating Sampler and Virtual Cut Concentrations
Sampler and true concentrations can be theoretically estimated using PSD and sampler performance characteristics. Sampler concentrations, $C_m(MMD,GSD,d_{50},slope)$, can be estimated by

$$C_m\left(MMD,GSD,d_{50},slope\right) = C_a \int_0^\infty f(d_p,MMD,GSD)P_m(d_p,d_{50},slope)dd_p \qquad (14)$$

For true concentrations, the cumulative penetration efficiency distribution function is assumed to be equal to 1 for all particle sizes less than or equal to the size of interest and zero for all other particle sizes. Therefore, the true concentration, $C_t(MMD,GSD,d_{50})$, can be estimated by

$$C_t\left(MMD,GSD,d_{50}\right) = C_a \int_0^{d_{50}} f(d_p,MMD,GSD)dd_p \qquad (15)$$

## Relative Differences between Sampler and Virtual-Cut Concentrations

As previously stated, sampler and true concentrations do not always produce equal values.  An estimate of the differences, $E(x)$, between these two concentrations can be estimated by

$$E(x) = \frac{(Measured - True)}{True} = \left(\frac{Measured}{True}\right) - 1 \tag{16}$$

where *Measured* and *True* represent the estimated sampler and the true concentrations, respectively.  Substituting equations 14 and 15 into equation 16 and canceling like terms, yields

$$E(MMD, GSD, d_{50}, slope) + 1 = \left[\frac{\int_0^\infty f(d_p, MMD, GSD)P_m(d_p, d_{50}, slope)dd_p}{\int_0^{d_{50}} f(d_p, MMD, GSD)dd_p}\right] \tag{17}$$

Throughout the remaining sections of this manuscript, $E(MMD, GSD, d_{50}, slope)+1$ will be referred to as the ratio of the sampler to true concentration.

## Results

Mathcad 2000 was used to evaluate equation 17 for various PSD and sampler performance characteristics in order to obtain a general concept of how the interaction of these characteristics impacts the concentration ratio.  The PSD characteristics included in the evaluation were MMD's of 5 and 10 µm with a GSD of 1.5 and MMD's of 15 and 20 µm with a GSD of 2.0.  The sampler performance characteristics included the nine combinations of $d_{50}$ and slope for the $PM_{10}$ sampler as described previously.  Table 1 lists the results of this evaluation.  In addition, Table 1 contains estimates for property line concentrations, under the assumption that the current regulated limit is based on a sampler concentration, and the regulation should be based on a true concentration.  In other words the NAAQS are based on sampler concentrations; however the NAAQS should be based on true concentrations so that all industries are equally regulated.  The mathematical definition for this assumption is

$$C_{Acceptable} = Ratio * C_{NAAQS} \tag{18}$$

where $C_{NAAQS}$ corresponds to the current concentrations associated with the NAAQS and $C_{acceptable}$ corresponds to the acceptable concentrations *if* the NAAQS were based on true concentrations.  The NAAQS for $PM_{10}$ is 150 µg/acm.  The following conclusions can be drawn from Table 1:  (1) the $PM_{10}$ sampler performance characteristics that define the range of acceptable concentrations are a $d_{50}$ of 9.5 µm with a slope of 1.4 and 1.6 and a $d_{50}$ of 10.5 µm with a slope of 1.4 and 1.6, (2) the ratios for $PM_{10}$ range from 89 to 139%, and (3) the ratio is equal to 100% only when the sampler $d_{50}$ is equal to the PSD's MMD.

To further describe how the interaction of the PSD and sampler characteristics affect the acceptable PM concentrations, a series of calculations were performed in Mathcad 2000 to generate a data file containing the solutions to equations 17 and 18 over a range of parameters.  These parameters included MMD values ranging from 1 to 40 µm (in increments of 1 µm), and GSD values ranging from 1.1 to 3.0 (in increments of 0.1).  To illustrate the results of this simulation, several graphs were created to demonstrate how each of the parameters affects the concentration ratio.

In Figure 6, the GSD is held constant at 2.0 for the four sets of $PM_{10}$ sampler performance characteristics, which define the acceptable concentrations for $PM_{10}$, and PSD MMDs ranging from 1 to 40 µm.  To aid in the interpretation of the graph, an average concentration ratio is defined as the average of the largest and smallest ratio associated with the range of ratios defined by the sampler performance characteristics for a particular MMD.  Conclusions that can be drawn from the information presented in this figure are: (1) the average ratio is less than 1 when MMD<$d_{50}$, (2) the average ratio is equal to 1 when MMD=$d_{50}$, (3) the average ratio is greater than 1 when MMD>$d_{50}$, and (4) the ratio range increases as the MMD increases.  In general terms, when the ratio is less than 1 the current method of regulating $PM_{10}$ underestimates the concentration of PM less than or equal to 10 µm AED and when the ratio is greater than 1 the current method overestimates the concentration of PM less than or equal to 10 µm AED.  For example, if a PSD were characterized by a MMD of 10 µm AED and a GSD of 2.0 then the acceptable range of $PM_{10}$ concentrations would be 143 to 158 µg/acm.  However, if a PSD

were characterized by a MMD of 20 μm AED and a GSD of 2.0 then the acceptable range of $PM_{10}$ concentrations would be 158 to 209 μg/acm.

The data presented in Figure 7 are based on the same assumptions as Figure 6, except the data are based on a GSD of 1.5. When comparing Figures 6 and 7, it is obvious that the ratios increase much more rapidly as the MMD increases when the GSD is 1.5 as compared to a GSD of 2.0. For example, if a PSD were characterized by a MMD of 10 μm AED and a GSD of 1.5 then the acceptable range of $PM_{10}$ concentrations would be 138 to 159 μg/acm. However, if a PSD were characterized by a MMD of 20 μm AED and a GSD of 1.5 then the acceptable range of $PM_{10}$ concentrations would be 272 to 515 μg/acm. Another conclusion that can be drawn from the data presented in Figure 7 is that the range of acceptable concentrations increases as the GSD increases.

Figure 8 is a generalized graph to illustrate how MMD's and GSD's affect the concentration ratios for a $PM_{10}$ sampler with a $d_{50}$ of 10.0 μm and a slope of 1.5. The general observation that should be made from this graph is that the concentration ratios decrease (ratio approaches 1.0) as the GSD increases.

Figure 9 further expands on how the concentration ratios are impacted by GSD. The data presented in Figure 9 are based on MMDs of 10 and 20 μm, sampler performance characteristics of $d_{50}$ = 9.5 μm with a slope of 1.4 and $d_{50}$ = 10.5 μm with a slope of 1.6, and variable GSD's ranging from 1.2 to 3.0. The general conclusions that should be drawn from this graph include: (1) when the MMD = d50 the range of concentration ratios is centered around 1.0 for all GSD's, (2) as the GSD increases the concentration ratio decreases and approaches 1.0, and (3) as the GSD decreases the concentration ratio increases and approaches infinity for an MMD of 20 μm AED.

## Summary and Conclusions

There are several errors associated with the current air pollution rules and regulations established by EPA, which should be minimized to assure an equal regulation of air pollutants between and within all industries. Potentially, one the most significant error is due to the interaction of the industry specific PSD and sampler performance characteristics. Currently, the regulation of PM is based on sampler measurements and NOT true concentrations. The significance here is that sampler concentrations do not account for all the mass associated with the particle diameters less than the size of interest and further, sampler concentrations include a portion of the mass associated with particle diameters greater than the size of interest. The alternative to this method bases the regulations on a true concentration, which would account for all the mass associated with the particle diameters less than the size of interest and would not include mass associated with particle diameters greater than the size of interest.

What is the impact of this error? The following example will demonstrate the impacts of this error. Assume:

- PSD associated with a coal-fired power plant is described by a MMD = 10 μm and a GSD = 1.5;
- PSD associated with a agricultural operation is described by a MMD = 20 μm and a GSD = 1.5;
- PM is currently regulated in terms of $PM_{10}$ sampler concentrations with a maximum property line concentrations limit of 150 μg/acm;
- $PM_{10}$ sampler performance characteristics are described by a $d_{50}$ = 10 ±0.5 μm and a slope of 1.5 ± 0.1.

Based on the current method of regulating PM, both the coal-fired power plant and the agricultural operation must not exceed the property line $PM_{10}$ concentrations of 150 μg/acm (based on sampler measurements), in order to maintain compliance with the PM regulations. This current method of regulation does NOT account for the errors associated with the sampler performance characteristics or errors associated with the interaction of the industry specific PSD and sampler performance characteristics. In order to adequately account for these errors, the maximum allowable compliance levels must be established based on the sampler performance characteristics that produce the largest concentration levels and the maximum allowable compliance levels must be based on true concentrations. In other words:

- the $PM_{10}$ sampler performance characteristics that should be used to estimate the maximum allowable compliance levels of $PM_{10}$ are a $d_{50}$ of 10.5 μm and a slope of 1.6; and
- the maximum allowable compliance levels should be based true concentrations (150 μg/acm for $PM_{10}$), meaning that if $PM_{10}$ concentrations are determined by the corresponding size specific samplers that the measured concentrations must be corrected to represent true concentrations;

Adjusting the maximum allowable compliance levels for these errors the following results are obtained:

- For the coal-fired power plant, a $PM_{10}$ sampler could measure concentrations as high as 159 μg/acm and still be in compliance with the regulations. This results in a 6% errors due to the sampler performance characteristics.
- For the agricultural operation, a $PM_{10}$ sampler could measure concentrations as high as 515 μg/acm and still be in compliance with the regulations. This results in a 243% errors due to the sampler performance characteristics and interactions of the PSD and sampler performance characteristics.

Further, based on this analysis, the agricultural operation is currently being regulated at a level, which is 3.2 times more stringent for $PM_{10}$ than that for a coal-fired power plant (under the previously stated assumptions).

The following are generalized conclusions drawn from the analysis in this manuscript:

- if $MMD < d_{50}$ then $C_{measured} < C_{virtual}$;
- if $MMD = d_{50}$ then $C_{measured} = C_{virtual}$;
- if $MMD > d_{50}$ then $C_{measured} > C_{virtual}$;
- as GSD increases the concentration ration of $C_{measured}$ to $C_{virtual}$ decreases; and
- as sampler slope decreases the concentration ration of $C_{measured}$ to $C_{virtual}$ decreases.

Results of the analysis presented in this manuscript show that not all industries are being equally regulated in terms of PM and that **ALL** industries should be concerned with the current site-specific regulations implemented by EPA and enforced by SAPRA's.

### Disclaimer

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### References

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Cooper, C. D. and F. C. Alley. 1994. *Air Pollution Control, A Design Approach.* Prospect Heights, IL. Waveland Press, Inc.

Hinds, W. C. 1982. Aerosol Technology – Properties, Behavior, and Measurement of Airborne Particles, 1st ed. New York, NY. John Wiley & Sons, Inc.

U. S. Environmental Protection Agency. 1996. Air quality criteria for particulate matter. Research Triangle Park, NC: Office of Health and Environmental Assessment, Environmental Criteria and Assessment Office; EPA report no. EPA-600/P-95/001aF. Available from: NTIS, Springfield, VA; PB96-168232.

U. S. Environmental Protection Agency. 2000a. 40CFR Part 50 National Ambient Air Quality Standards for Particulate Matter; Final Rule. Federal Register Vol. 65, No. 247.

U. S. Environmental Protection Agency. 2000b. 40CFR Part 53 National Ambient Air Quality Standards for Particulate Matter; Final Rule. Federal Register Vol. 65, No. 249.

Table 1. Percent differences between theoretical sampler true concentrations for various particle size and sampler performance characteristics.

| $PM_{10}$ sampler characteristics | Particle Size distribution (PSD) Characteristics | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | MMD = 5 $\mu$m GSD = 1.5 | | MMD = 10 $\mu$m GSD = 1.5 | | MMD = 15 $\mu$m GSD = 2.0 | | MMD = 20 $\mu$m GSD = 2.0 | |
| | Conc. ($\mu$g/m$^3$)[ς] | Ratio[γ] | Conc. ($\mu$g/m$^3$)[ς] | Ratio[γ] | Conc. ($\mu$g/m$^3$)[ς] | Ratio[γ] | Conc. ($\mu$g/m$^3$)[ς] | Ratio[γ] |
| $d_{50}$ = 9.5 $\mu$m; slope = 1.4 | 139.4 | 92.9% | *138.3* | 92.2% | *148.7* | 99.1% | *157.8* | 105.2% |
| $d_{50}$ = 9.5 $\mu$m; slope = 1.5 | 136.2 | 90.8% | 139.4 | 92.9% | 153.0 | 102.0% | 167.3 | 111.5% |
| $d_{50}$ = 9.5 $\mu$m; slope = 1.6 | *133.2* | 88.8% | 140.1 | 93.4% | 157.2 | 104.8% | 176.9 | 117.9% |
| $d_{50}$ = 10.0 $\mu$m; slope = 1.4 | 142.1 | 94.7% | 150.0 | 100.0% | 160.8 | 107.2% | 174.2 | 116.1% |
| $d_{50}$ = 10.0 $\mu$m; slope = 1.5 | 139.1 | 92.7% | 150.0 | 100.0% | 164.9 | 109.9% | 183.5 | 122.3% |
| $d_{50}$ = 10.0 $\mu$m; slope = 1.6 | 136.2 | 90.8% | 150.0 | 100.0% | 168.8 | 112.5% | 192.8 | 128.5% |
| $d_{50}$ = 10.5 $\mu$m; slope = 1.4 | *144.5* | 96.3% | *161.1* | 107.4% | 172.8 | 115.2% | 190.5 | 127.0% |
| $d_{50}$ = 10.5 $\mu$m; slope = 1.5 | 141.5 | 94.3% | 160.2 | 106.8% | 176.4 | 117.6% | 199.7 | 133.1% |
| $d_{50}$ = 10.5 $\mu$m; slope = 1.6 | 138.6 | 92.4% | 159.5 | 106.3% | *180.0* | 120.0% | *208.8* | 139.2% |

[ς] *Values are based on the assumption that true concentrations are the correct estimates of the corresponding PM.*

[γ] *Concentrations are based on the corresponding regulations and adjusted for the ratio. Property line concentrations for $PM_{10}$ are 150 $\mu$g/m3*
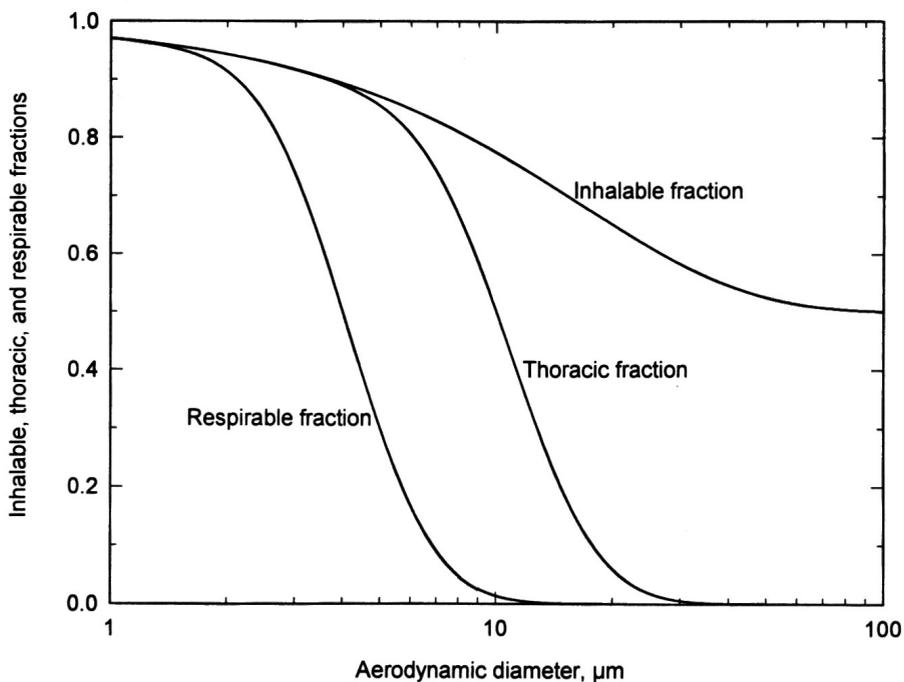


Figure 1. ACGIH sampling criteria for inhalable, thoracic, and respirable fraction of PM (ACGIH, 1997).
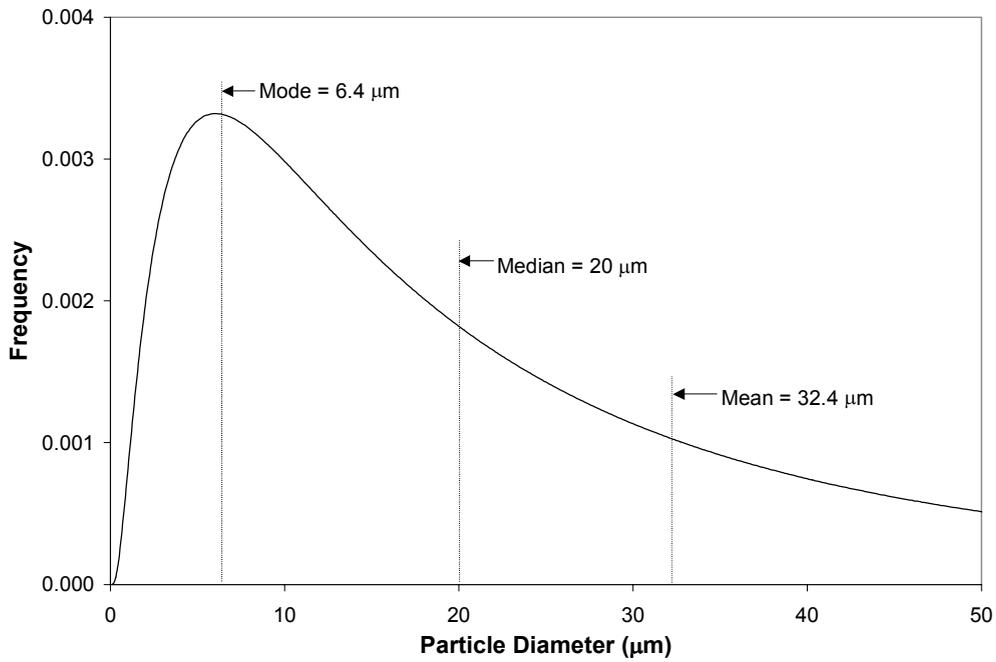
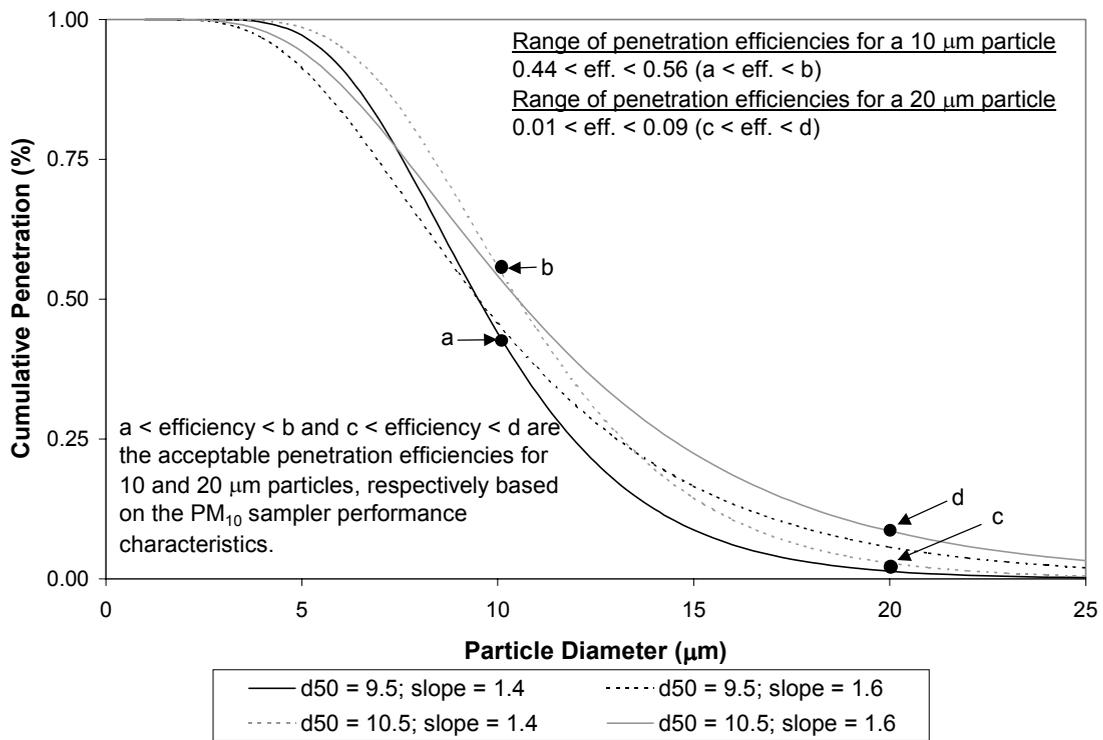Figure 2. Lognormal particle size distribution defined by a MMD of 20 μm and a GSD of 3.0.



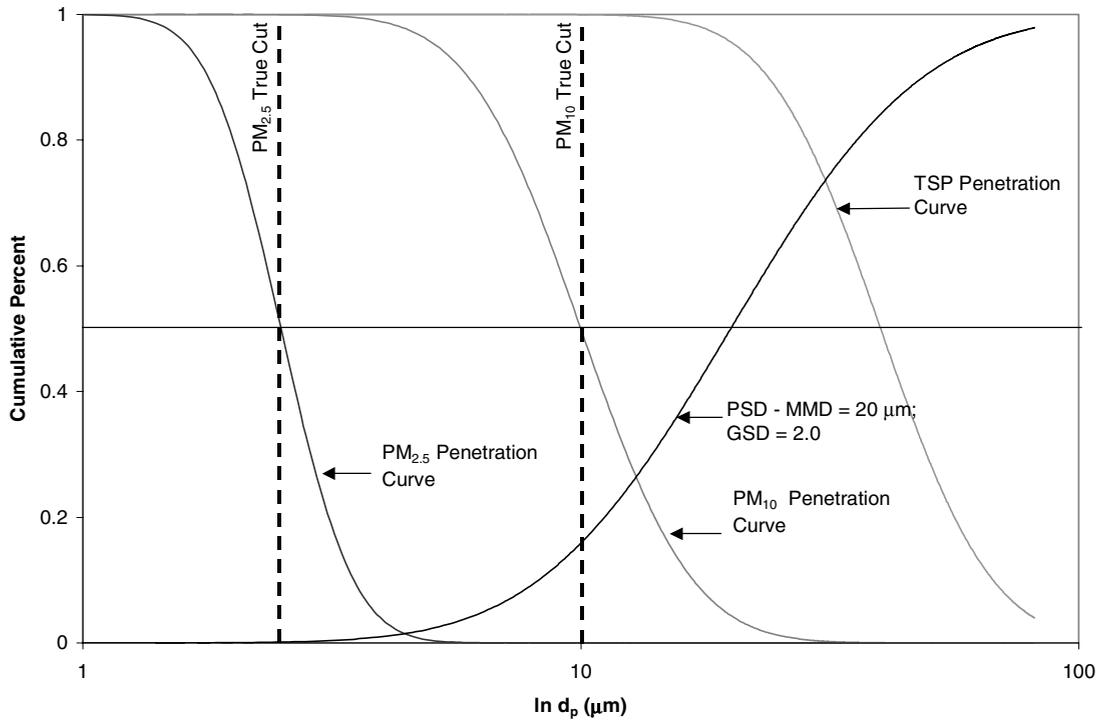Figure 3. PM$_{10}$ sampler penetration curves based on the defining performance characteristics.
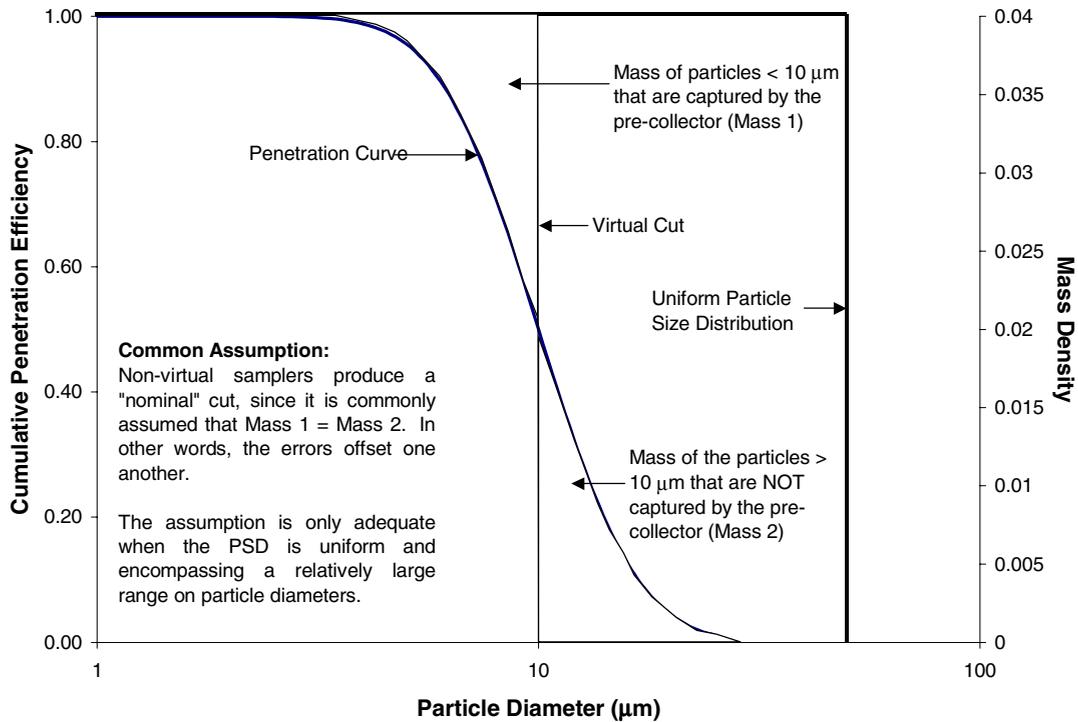
Figure 4. PM$_{2.5}$, PM$_{10}$, and TSP Penetration curves.
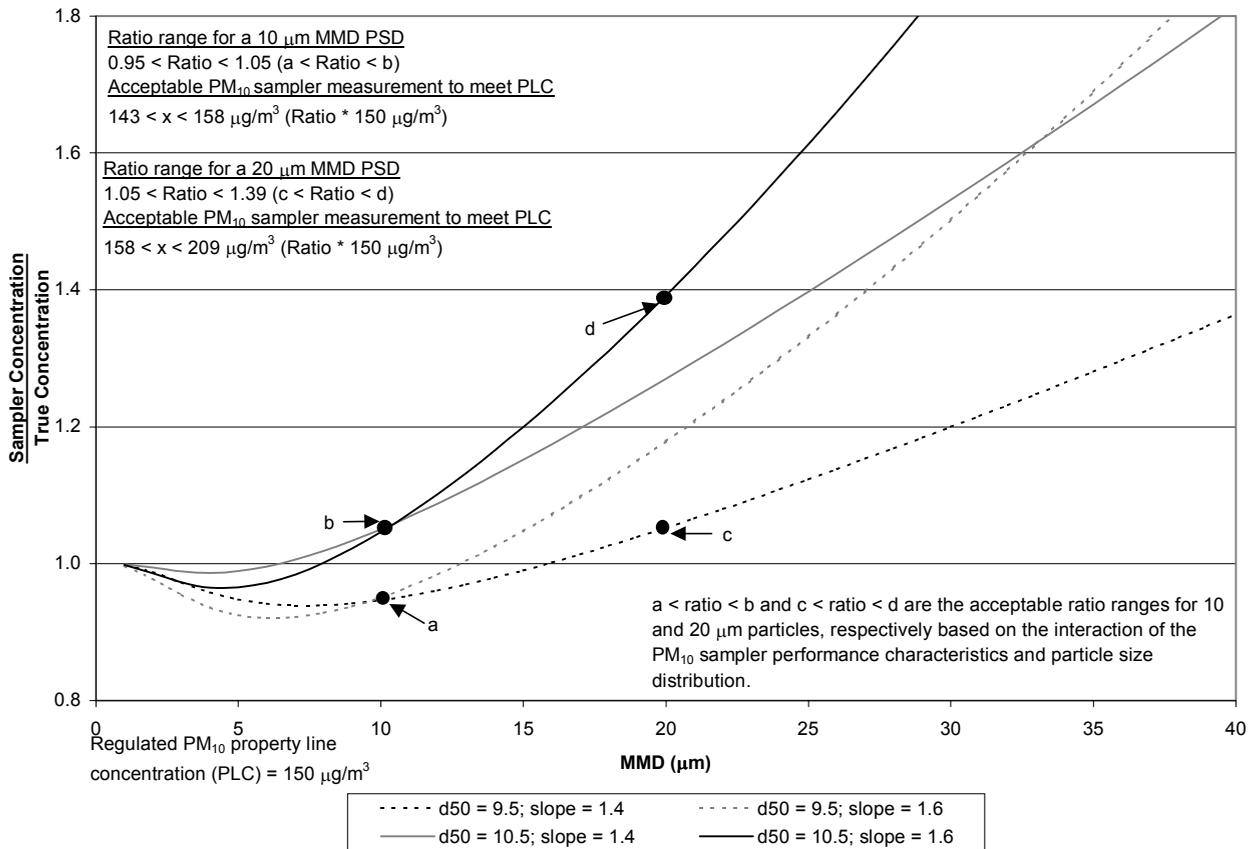


Figure 5. Sampler nominal cuts.

**Figure 6 (upper chart)**

1.8

Ratio range for a 10 μm MMD PSD
0.95 < Ratio < 1.05 (a < Ratio < b)
Acceptable PM₁₀ sampler measurement to meet PLC
143 < x < 158 μg/m³ (Ratio * 150 μg/m³)

Ratio range for a 20 μm MMD PSD
1.05 < Ratio < 1.39 (c < Ratio < d)
Acceptable PM₁₀ sampler measurement to meet PLC
158 < x < 209 μg/m³ (Ratio * 150 μg/m³)

1.6

1.4

d

Sampler Concentration / True Concentration

1.2

b

1.0

a

c

a < ratio < b and c < ratio < d are the acceptable ratio ranges for 10 and 20 μm particles, respectively based on the interaction of the PM₁₀ sampler performance characteristics and particle size distribution.

0.8

0       5       10      15      20      25      30      35      40

Regulated PM₁₀ property line concentration (PLC) = 150 μg/m³

MMD (μm)

- - - - d50 = 9.5; slope = 1.4      · · · · · d50 = 9.5; slope = 1.6
——— d50 = 10.5; slope = 1.4      ——— d50 = 10.5; slope = 1.6

Figure 6. Ratios of the theoretical PM₁₀ sampler concentrations to true PM₁₀ concentrations (PSD – GSD = 2.0).

**Figure 7 (lower chart)**

5.8

Ratio range for a 10 μm MMD PSD
0.92 < Ratio < 1.06 (a < Ratio < b)
Acceptable PM₁₀ sampler measurement to meet PLC
138 < x < 159 μg/m³ (Ratio * 150 μg/m³)

4.8

Ratio range for a 20 μm MMD PSD
1.81 < Ratio < 3.43 (c < Ratio < d)
Acceptable PM₁₀ sampler measurement to meet PLC
272 < x < 515 μg/m³ (Ratio * 150 μg/m³)

3.8

Sampler Concentration / True Concentration

d

2.8

1.8

c

a < ratio < b and c < ratio < d are the acceptable ratio ranges for 10 and 20 μm particles, respectively based on the interaction of the PM₁₀ sampler performance characteristics and particle size distribution.

b

a

0.8

0       5       10      15      20      25      30      35      40

Regulated PM₁₀ property line concentration (PLC) = 150 μg/m³

MMD (μm)

- - - - d50 = 9.5; slope = 1.4      · · · · · d50 = 9.5; slope = 1.6
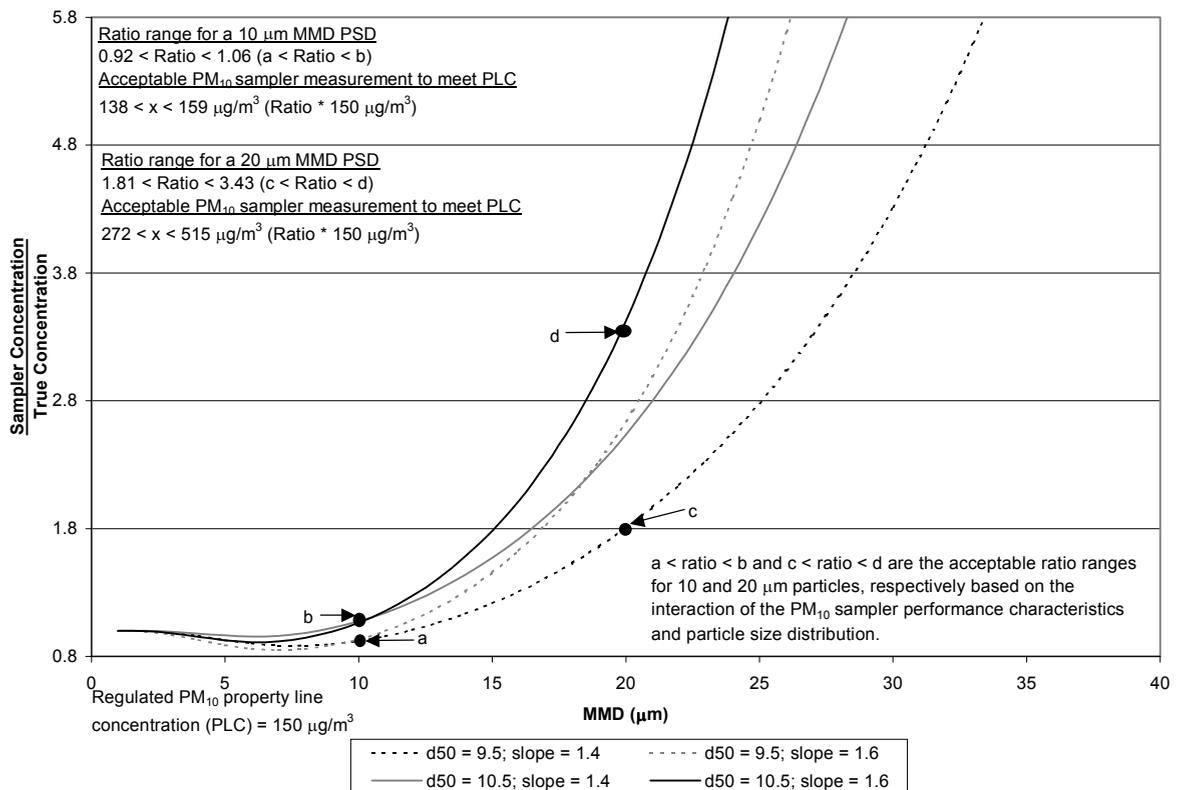——— d50 = 10.5; slope = 1.4      ——— d50 = 10.5; slope = 1.6

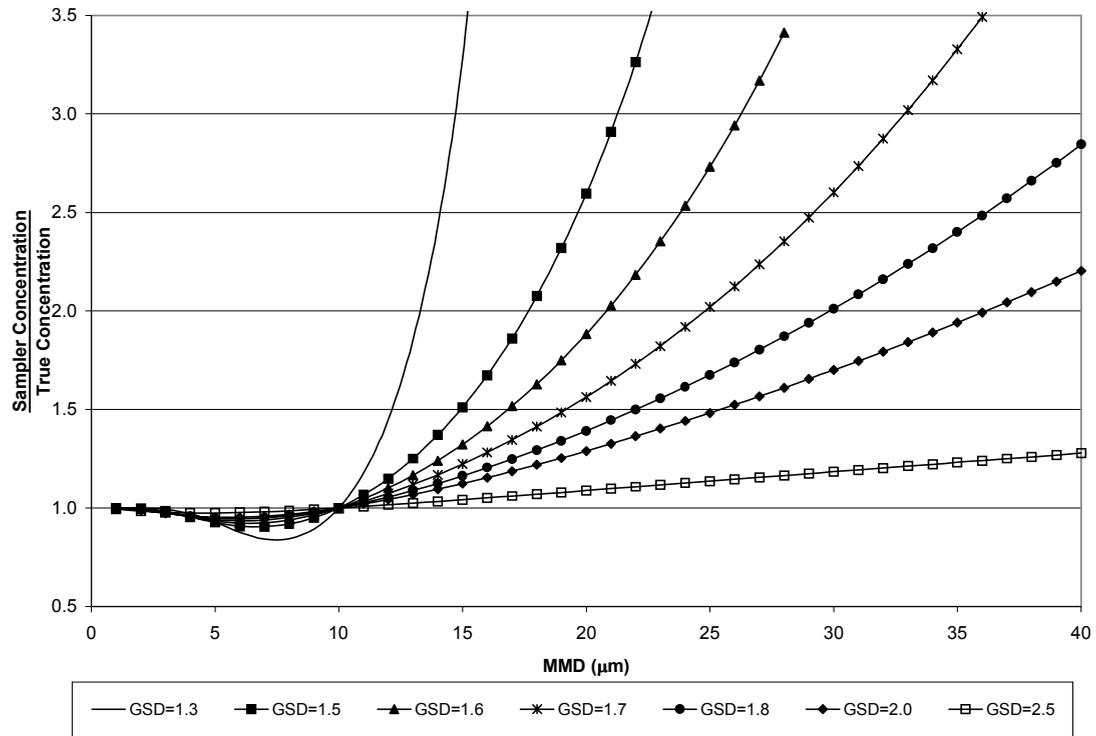Figure 7. Ratios of the theoretical PM₁₀ sampler concentrations to true PM₁₀ concentrations (PSD – GSD = 1.5).

Figure 8. Ratios of the theoretical $PM_{10}$ sampler concentrations to true $PM_{10}$ concentrations ($PM_{10}$ sampler characteristics; $d_{50} = 10$ µm and slope = 1.5).
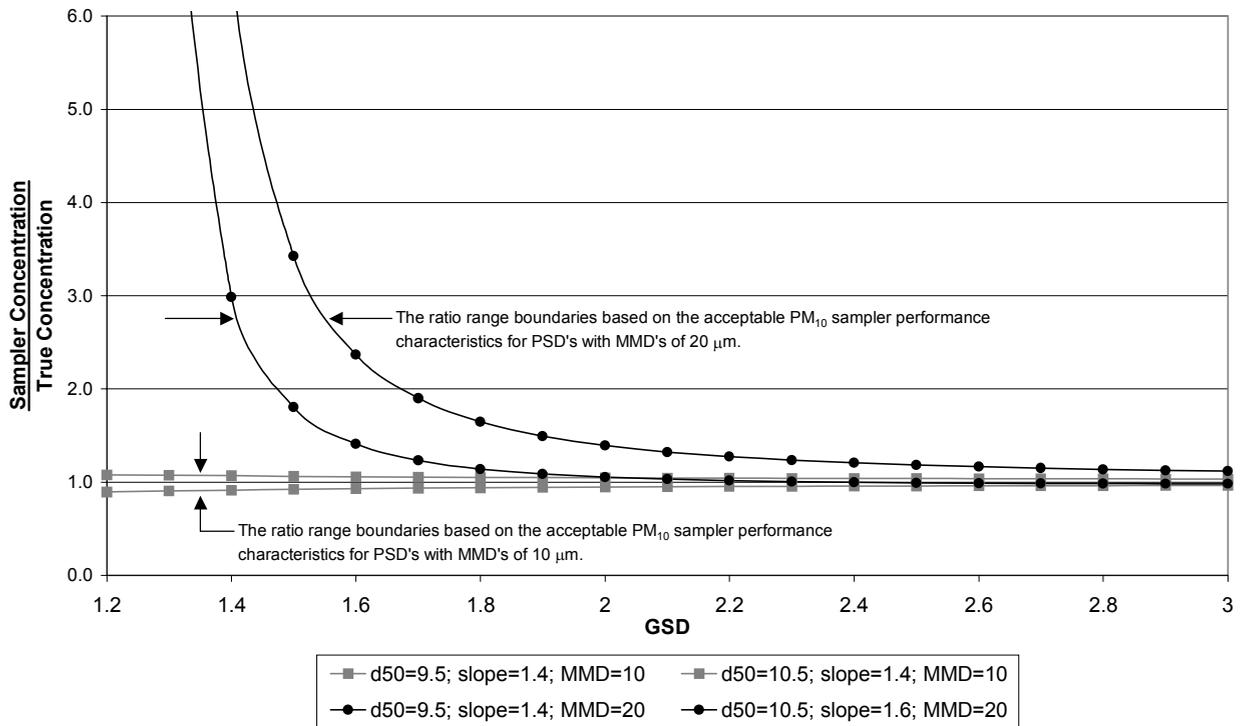


Figure 9. Ratios of the theoretical $PM_{10}$ sampler concentrations to true $PM_{10}$ concentrations for various GSD's.