

**ENGINEERING APPROACHES TO ADDRESS ERRORS IN MEASURED AND
PREDICTED PARTICULATE MATTER CONCENTRATIONS**

A Thesis

by

JOHN DAVID WANJURA

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE

May 2005

Major Subject: Biological and Agricultural Engineering

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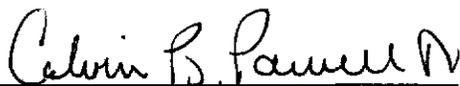
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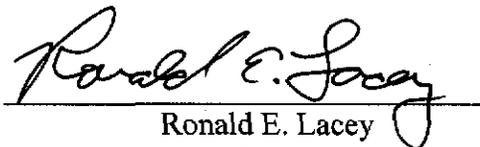
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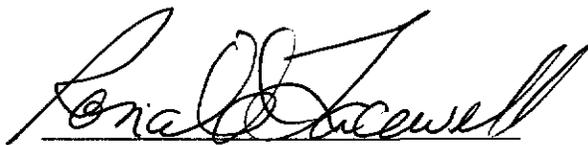
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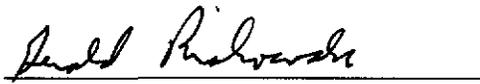
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ABSTRACT

Engineering Approaches to Address Errors in Measured and Predicted Particulate Matter Concentrations. (May 2005)

John David Wanjura,

B.S.; B.S., Texas A&M University

Chair of Advisory Committee: Dr. Calvin B. Parnell, Jr.

Some of the air pollution regulations in the United States are based on an application of the National Ambient Air Quality Standards at the property line. Agricultural operations such as cotton gins, feed mills, and cattle feed yards may be inappropriately regulated by such regulations if the current methods of measuring and predicting the concentrations of regulated pollutants are used. The regulated particulate matter pollutants are those with aerodynamic equivalent diameters less than or equal to a nominal 10 and 2.5 micrometers (PM_{10} and $PM_{2.5}$) respectively.

The current Federal Reference Method PM_{10} and $PM_{2.5}$ samplers exhibit over-sampling errors when sampling dusts with particle size distributions similar to those of agricultural sources. These errors are due to the interaction of the performance characteristics of the sampler with the particle size distribution of the dust being sampled. The results of this work demonstrate the development of a new sampler that may be used to accurately sample total suspended particulate (TSP) concentrations. The particle size distribution of TSP samples can be obtained and used to more accurately determine PM_{10} and $PM_{2.5}$ concentrations. The results of this work indicate that accurate

measures of TSP can be taken on a low volume basis. This work also shows that the low volume samplers provide advantages in maintaining more consistent sampling flow rates, and more robust measurements of TSP concentrations in high dust concentrations.

The EPA approved dispersion model most commonly used to estimate concentrations downwind from a stationary source is the Industrial Source Complex Short Term version 3 (ISCST3). ISCST3 is known to over-predict downwind concentrations from low level point sources. The results of this research show that the magnitude of these errors could be as much as 250%. A new approach to correcting these errors using the power law with P values as a function of stability class and downwind distance is demonstrated. Correcting the results of ISCST3 using this new approach results in an average estimated concentration reduction factor of 2.3.

ACKNOWLEDGMENTS

Throughout the course of my time as a graduate student, I have often wondered if I would ever get the chance to write this page and what I would say. Well I made it and here it is...

I would like to thank God for providing me with every opportunity, challenge, grace, and blessing each day of my life. I owe God everything for his blessings and it truly amazes me how He continues to bless me each day.

To my mother and father I would like to say thank you and I love you both very much. Mom, your constant love and care for all of your children and grandchildren influences us in ways too many to number. Dad, you have been a constant source of inspiration for me. Your subtle yet steady push for me to do my best has helped me greatly. I would like to thank both of you from the bottom of my heart.

To Vic, Eric, Amy, and Christine...thank you. Although we have been separated by a few miles these last few years, our frequent talks have helped me keep everything in perspective.

To Sarah, Sophia, Ben, Amalia, Hugh, and who knows...You all are a constant source of joy and inspiration to me. I love you all very much and I look forward to the future and watching each one of you grow.

To Dr. and Mrs. Parnell...Thank you both for your help and encouragement throughout this entire process. Mrs. Parnell, thank you for the wonderful meals I was fortunate enough to be able to participate in. Dr. Parnell, Thank you, Thank you, Thank you! Your great inspiration has driven me to become a better engineer and given me the

tools to succeed in my professional career. Our sometimes long talks between “you, me, and the gatepost” have given me insight to things that will forever influence the way that I perceive and handle situations. Your confidence assures all, your style motivates all, and your wisdom inspires all.

To the “Crew” I would like to say thanks and it has been fun. Bonz, Barry, Clay, Craig, Brad, Mike, Amber, Ling, Amy, Lee, Sergio, Ryan, “Tree”, Jackie, Shay, Jing, Mark, Nathaniel, Cale, Shane, Clint, Atilla, “Stanley”, Toni, Scott, Lee, and Brock it has been a great experience working with you all. I wish you all the best of luck.

To my girlfriend, Karen. The late nights spent up in the lab have been hard to handle at times, but you have always been a great source of support and care. I look forward to the future! I love you and thank you for your love and support.

To Drs. Shaw, Lacey, Lacewell, Mukhtar, Capareda, and Riskowski, thank you all for your help and support. I have learned a great deal from you and I am eternally grateful.

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CHAPTER I

INTRODUCTION

The Federal Clean Air Act (FCAA) provides the legislative authority to the Environmental Protection Agency (EPA) to regulate air quality in the United States. The EPA delegates authority to the states to implement and enforce air quality standards. The EPA requires states to submit state implementation plans (SIP) detailing the actions that the states will take to ensure that federal air quality standards will be met. The federal standards that the states are required to comply with are the national ambient air quality standards (NAAQS). NAAQS are listed for six criteria pollutants including particulate matter. The NAAQS for particulate matter was established in 1971 as a maximum ambient concentration limit for total suspended particulate (TSP). In 1987 the indicator for the particulate matter NAAQS was changed from TSP to PM₁₀ (Federal Register, 1987). PM₁₀ is defined as all particles with an aerodynamic equivalent diameter (AED) less than or equal to 10 micrometers (μm). The NAAQS for PM was further amended in 1997 to include a standard for particulate matter having AED less than or equal to 2.5μm (Federal Register, 1997). Primary standards to protect public health and secondary standards to protect public well-being are established for each criteria pollutant (Cooper and Alley, 2002). States may implement and enforce air quality regulations that are more stringent than the national standards.

This thesis follows the style and format of the *Transactions of the ASAE*.

In the 1977 amendments to the Federal Clean Air Act (FCAA), Congress instituted the new source review (NSR) permitting program for stationary sources emitting regulated pollutants. The NSR permit is known as the “construction permit” in many states. Under NSR, new and existing sources are required to obtain a permit before construction (of a new facility) or modification (to an existing facility) may begin. The purpose of an NSR permit is to ensure that the construction or modification of an air pollution source will not preclude the state’s ability to maintain or improve air quality levels. During the NSR permitting process, sources are required to demonstrate that the emission of pollutants will not detrimentally influence the air quality in that region.

States have employed numerous methods by which sources can demonstrate compliance with permit requirements (Parnell et al., 2002; Wanjura et al., 2005). Among the methods used are ambient sampling near a source with federal reference method (FRM) ambient samplers and dispersion modeling. The results of these methods are used to show compliance with property line concentration limits.

Some states have implemented the NAAQS as property line concentration limits. The current primary NAAQS for PM_{10} is 150 micrograms per actual cubic meter ($\mu\text{g}/\text{am}^3$)(24-hour average). The secondary NAAQS for PM_{10} is the same as the primary standard. The proposed primary NAAQS for $PM_{2.5}$ is $65\mu\text{g}/\text{am}^3$ (24-hour average) with the secondary standard set at the same limit.

There exist problems with the current methods used to demonstrate compliance with property line concentration limits. FRM ambient PM_{10} and $PM_{2.5}$ samplers are

known to over-sample¹ when exposed to PM with mass median diameters (MMD) and geometric standard deviations (GSD) in excess of the cut point (d_{50}) and slope of the sampler. The EPA approved dispersion model, Industrial Source Complex Short Term version 3 (ISCST3), is known to over estimate downwind concentrations from low-level point sources by a factor ranging from 2 to 10 (Beychok, 1994).

These problems significantly impact the agricultural industry because of the defining characteristics of agricultural sources. Cotton gins, feed mills, and grain elevators are common agricultural low-level point sources. Most agricultural sources and many other anthropogenic sources of organic dusts emit particulate matter with relatively large and broad particle size distributions. Redwine and Lacey (2001) state that the typical particle size distribution of dust emitted from agricultural sources is characterized by a lognormal distribution with MMD ranging from 15 to 25 μm (AED) and GSD ranging from 1.5 to 2.0.

Typically, the performance characteristics of an ambient air sampler are defined by the d_{50} and slope of the sampler's lognormal fractional efficiency curve (FEC). The d_{50} and slope of the fractional efficiency curve (FEC) of the FRM PM₁₀ sampler are $10 \pm 0.5 \mu\text{m}$ and 1.5 ± 0.1 respectively (CFR, 1999b). The d_{50} of the FRM PM_{2.5} sampler is defined by EPA as $2.5 \pm 0.2 \mu\text{m}$ with no slope specifically stated (Buser, 2004). Further work by Peters and Vanderpool (1996) indicate that the slope of the WINS Impactor is 1.3 ± 0.03 . Buser et al. (2001) indicate that an FRM PM₁₀ sampler sampling a dust with

¹ Over-sampling refers to the condition under which the FRM sampler measures a higher concentration of PM₁₀ or PM_{2.5} than the true concentration.

MMD = 20 μ m and GSD = 2.0 could over state the concentration by 343% with the sampler operating as designed. An FRM PM_{2.5} sampler sampling the same dust could be in error by a factor of 181.

ISCST3 is the Gaussian dispersion model most commonly used by state air pollution regulatory agencies (SAPRA) to estimate downwind concentrations from stationary sources. The Pasquill-Gifford plume spread parameter estimates (σ_y and σ_z) are used to estimate the spread of the plume at distances downwind from the source. It has been the subject of much scientific debate as to the time frame associated with the concentration data used to develop the Pasquill-Gifford plume spread parameters. The concentration time dependence is a result of the change in wind speed and direction over some time period. Over shorter periods there are expected to be fewer changes in wind speed and wind direction resulting in higher concentrations at points directly downwind from the source. However, over longer periods there is a higher probability of wind speed and wind direction shifts resulting in lower concentrations at points directly downwind of the source. The data presented by Pasquill (1960) used to develop the Pasquill-Gifford plume spread parameters (σ_y and σ_z) is taken from experiments with durations ranging from four to thirty minutes. Beychok (1994) states that most of the scientific community agrees that the time frame used by Pasquill (1960) was in the range of ten to fifteen minutes. If the Pasquill-Gifford σ_y and σ_z are taken to be from ten-minute average data, the implication is that the Gaussian dispersion equation will return ten-minute average concentrations. The assumption was made by the developers of ISCST3 that the concentrations returned by the Gaussian equation are one-hour average

concentrations. Beychok (1994) goes further to say that assuming the Gaussian dispersion equation yields one-hour average concentrations rather than ten-minute average concentrations could result in an over-prediction error of 250%.

The goals of this research were to identify the errors associated with the concentration measurement and prediction methods used by air pollution regulators and to develop and demonstrate innovative engineering approaches for correcting the aforementioned errors. Specifically the objectives of this research were:

1. Develop a new ambient TSP sampler with improved operating characteristics over those observed with the use of the FRM high volume TSP sampler.
2. Identify and demonstrate unique methods for correcting the concentration time averaging errors associated with ISCST3.
3. Identify errors in the current emission factors used for permitting cotton gins and demonstrate the effect that more accurate emission factors would have on the estimated concentrations.
4. Demonstrate the relative effects of the errors encountered with ambient sampling and dispersion modeling of agricultural low level point sources.

The focus of the research presented is on cotton ginning but is applicable to all agricultural operations required to comply with air quality regulations.

This thesis is presented for consideration as a compilation of three manuscripts prepared to address the subject matter outlined above. The first objective of this work is specifically addressed by manuscript number one. The second and third objectives are

addressed by the second manuscript. The third manuscript specifically addresses objective four. Appendix A discusses the publication status of the three manuscripts used in this thesis.

CHAPTER II

THE DESIGN AND EVALUATION OF A LOW VOLUME TOTAL SUSPENDED PARTICULATE SAMPLER*

OVERVIEW

The regulation of particulate matter (PM) emitted by agricultural sources (cotton gins, feed mills, concentrated animal feeding operations (CAFOs)) is based upon downwind concentrations of particulate matter less than 10 and 2.5 micrometers (μm) (PM_{10} and $\text{PM}_{2.5}$) aerodynamic equivalent diameter (AED). Both PM_{10} and $\text{PM}_{2.5}$ samplers operate by pre-separating PM larger than the size of interest (10 and 2.5 μm) prior to capturing the PM on the filter. It has been shown that Federal Reference Method (FRM) PM_{10} and $\text{PM}_{2.5}$ samplers have concentration measurement errors (Buser et al, 2001, 2002b) when sampling PM in ambient air having mass median diameters (MMD) larger than the size of interest. It has also been demonstrated that most PM from agricultural sources typically have particle size distributions with MMDs larger than 10 μm (AED) (Redwine and Lacey, 2001). The PM_{10} concentration measurement error can be as much as 343% for ambient PM with an MMD=20 μm . These errors are a consequence of the PM_{10} pre-separator allowing a larger mass of PM greater than 10 μm

* Reprinted with permission from The Design and Evaluation of a Low Volume Total Suspended Particulate Sampler by J.D. Wanjura, C.B. Parnell, Jr., B.W. Shaw, and R.E. Lacey, 2005. *Transactions of the ASAE*. 2005 by The American Society of Agricultural Engineers (Submitted).

to penetrate to the filter than the mass of PM less than 10 μm captured by the pre-separator. The mass of the particles greater than 10 μm that are allowed to penetrate to the filter, introduce a substantial error in the calculated concentration of PM_{10} . Pargmann et al (2001) reported that sampling PM larger than 2.5 μm (AED) resulted in a shift in the cut-point of the pre-separator. If this is true for all PM_{10} and $\text{PM}_{2.5}$ samplers, the resulting errors in measurements of ambient concentrations could be even larger than those reported by Buser.

One solution to this problem is to measure the concentration of total suspended particulate matter (TSP) and calculate the concentration of PM_{10} by determining the mass fraction of PM less than size of interest from the particle size distribution (PSD). The “standard” high volume (TSP) sampler operates at a volume rate-of-flow in excess of 1.13 m^3/min (40 ft^3/min) (CFR, 1987b). Most of the current PM_{10} and $\text{PM}_{2.5}$ samplers operate at one cubic meter per hour (cmh). (1 cmh = 0.589 cfm.) McFarland (1983) reported that TSP samplers have a “cut-point” of a nominal 45 μm (AED). EPA specifies the engineering design parameters for TSP samplers in 40CFR Part 50 (1987b). This paper reports the engineering design and evaluation of a low volume (0.589 cfm) TSP sampler (TSP_{LV}). The results suggest that the new TSP_{LV} may be more robust and more accurate than the “standard” high volume (TSP) sampler.

INTRODUCTION

Prior to 1987, the United States Environmental Protection Agency (EPA) regulated particulate matter (PM) emission sources based upon a measure of the total suspended particulate (TSP) (Hughes and Wakelyn, 1997). In 1987, the EPA began

regulating PM pollution sources based on the 24-hour property line concentration of PM_{10} (52 *Federal Register* 24854, 1987). PM_{10} concentration as defined by EPA 40CFR Part 50 (1999a) is the concentration of PM with an aerodynamic diameter (AED) of less than or equal to a nominal $10\mu m$. The National Ambient Air Quality Standard (NAAQS) mandates that public exposure to the 24-hour ambient concentration of PM_{10} should be no more than $150\ \mu g/m^3$ (CFR, 1999a). Some states have viewed the NAAQS as a property line concentration limit not-to-be exceeded.

The EPA Federal Reference Method (FRM) PM_{10} sampler defined in 40CFR Part 53, is designed to have a nominal cut point of $10 \pm 0.5\mu m$ with a slope of $1.5 \pm .1$ (Buser et al., 2001). Agricultural dusts typically have particle size distributions (PSD) characterized by a MMD between 15 and $20\mu m$ with a GSD ranging from 1.5 to 2.5. It has been shown that a FRM sampler sampling in ambient conditions with MMD equal to $20\mu m$ could over-sample by as much as 181 to 343% (Buser et al., 2001).

It is becoming more common practice to measure concentrations of PM_{10} and $PM_{2.5}$ on a low volume basis. Low volume sampling is sampling ambient air at a flow rate of 1 cubic meter per hour. The EPA approved Tapered Element Oscillation Microbalance (TEOM) sampler is a low volume sampler. When the TEOM is equipped with the proper pre-separator, it is used to measure concentrations of PM_{10} or $PM_{2.5}$. However, all PM_{10} or $PM_{2.5}$ concentration measurement instruments equipped with FRM pre-separators will be in error when sampling PM with an MMD larger than 10 and $2.5\ \mu m$, respectively (Buser et al., 2001).

The TSP sampler designated as the FRM instrument by the EPA (CFR, 1987b) operates at a flow rate ranging from 1.1 to 1.7 m³/min (39 to 60 ft³/min). The filter media used with the FRM TSP sampler measures 20.3 x 25.4 cm giving a total filter area of 515.6 cm². When sampling in high concentrations, the FRM TSP samplers experience difficulties in trying to maintain a constant flow rate over the duration of the test (Price and Lacey, 2003). This is primarily because of the increased pressure drop across the filter media as the mass of particulate matter increases on the filter. These changes in flow rate introduce errors in the calculation of the total air volume pulled through the filter during the test and subsequently introduce errors in the concentration measurement.

The EPA specifies the design and operation criteria for the high volume (39 to 60 ft³/min) TSP sampler in 40 CFR Part 50, App. B (CFR, 1987b). As defined, the TSP pre-separator has a gabled hood that should overhang the filter housing “somewhat” so as to form an inlet gap that is approximately equal on all sides. This inlet gap is to be designed so as to provide a particle capture air velocity between 20 and 35 cm/sec. This capture air velocity provides the nominal cut-point for the TSP sampler. According to McFarland and Ortiz (1983), the TSP pre-separator has a cut-point of approximately 45µm with a slope of 1.5.

LOW VOLUME TSP SAMPLER DESIGN

Currently, there are no EPA design guidelines for a low volume TSP sampler. The low volume TSP pre-separator (TSP_{LV}) designed by the Center for Agricultural Air Quality Engineering and Science (CAAQES) at Texas A&M University was based upon

the applicable guidelines for a high volume TSP sampler in 40 CFR Part 50, Appendix B (CFR, 1987b).

The critical design point maintained from the high volume method was the capture air inlet area. The capture air inlet area is critical to the performance of the sampler because the capture air velocity is a direct function of this area. The capture air inlet area shown in figure 1 is the area between the inside bottom diameter of the cone and the outer diameter of the hood base. Equation 1 was used to calculate the minimum and maximum capture air inlet area for the range of capture air velocities (20 to 35 cm/sec) given in 40 CFR Part 50 (CFR, 1987b). The air sampling flow rate used in the design of the low volume TSP sampler was 16.7 liters per minute (16.7 lpm = 0.59 ft³/min = 1 m³/hr).

$$CAIA = \frac{ASFR}{CAV} * 1.667 \quad (1)$$

where

CAIA = capture air inlet area (m²),

ASFR = air sampling flow rate (m³/min),

CAV = capture air velocity (cm/s), and

1.667 = conversion factor.

Once the maximum and minimum values for the CAIA were established using

the maximum and minimum CAV values of 35 and 20 cm/s respectively, a dimension convenient for manufacture was chosen within the limits for the CAIA. The CAIA value chosen was 2.01 in² (1297 mm²). The TSP_{LV} hood base (shown in figure 1) was designed to attach directly to the 47mm filter holder manufactured by F and J Specialty Products, Inc (FJ-34P, F&J Specialty Products, Inc., Ocala, FL). The height of the base was chosen so that disassembly of the pre-separator from the filter holder would be trouble free. With the diameter of the outer edge of the hood base known, equation 2 was used to calculate the inner base diameter of the TSP_{LV} hood/cone.

$$D_2 = \sqrt{D_1^2 + \frac{CAIA_a * 4 * 10^6}{\pi}} \quad (2)$$

where

D_2 = Inner hood/cone diameter (mm),

D_1 = Hood base outer edge diameter (mm),

$CAIA_a$ = Chosen CAIA dimension within range calculated above (m²),

and

10^6 = Conversion Factor (m² to mm²).

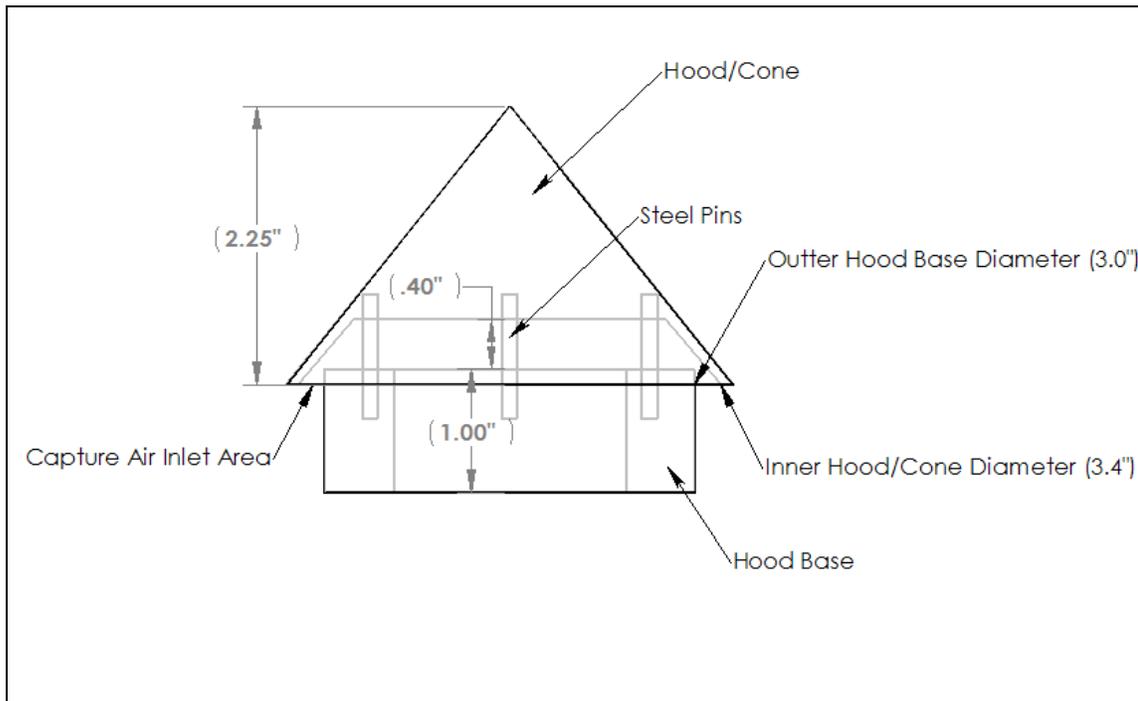


Figure 1. Illustration of the side view of the low volume pre-separator used with the low volume TSP sampler.

With the inner hood/cone diameter established, the wall thickness of the hood/cone was chosen and added to the inner radius of the hood/cone to determine the outer radius. The angle of the cone vertex is not overly critical, but was chosen arbitrarily at 80 degrees. The bottom edge of the hood/cone overhangs the top surface of the hood base 3.3 mm (0.13 in) as per the guidelines for the high volume TSP sampler (CFR, 1987b). Appendix B shows detailed drawings of the low volume TSP sampler.

TESTING PROTOCOL

The TSP_{LV} samplers fitted with pre-separators were evaluated in a controlled particulate concentration chamber located in the CAAQES Processing Lab at Texas A&M University. The design and general operating parameters of the chamber were described by Pargmann et al (2001). Seven samplers were placed in the chamber during the tests to measure particulate matter concentrations and to collect PM samples for particle size distribution analysis. Among the seven samplers were two low volume TSP samplers, two low volume PM₁₀ samplers, and three high volume TSP samplers. The arrangement of the low volume samplers in the chamber was not considered to be significant as the PM concentration throughout the cube body of the chamber was assumed to be uniform. It should be noted that the two low volume PM₁₀ inlets and one of the high volume TSP samplers (HT2) were used to collect data for another study. No data from these samplers (PM10_{LV} #1, PM10_{LV} #2, and HT2) is used in this manuscript. Figures 2 and 3 show the arrangement of the samplers in the chamber.

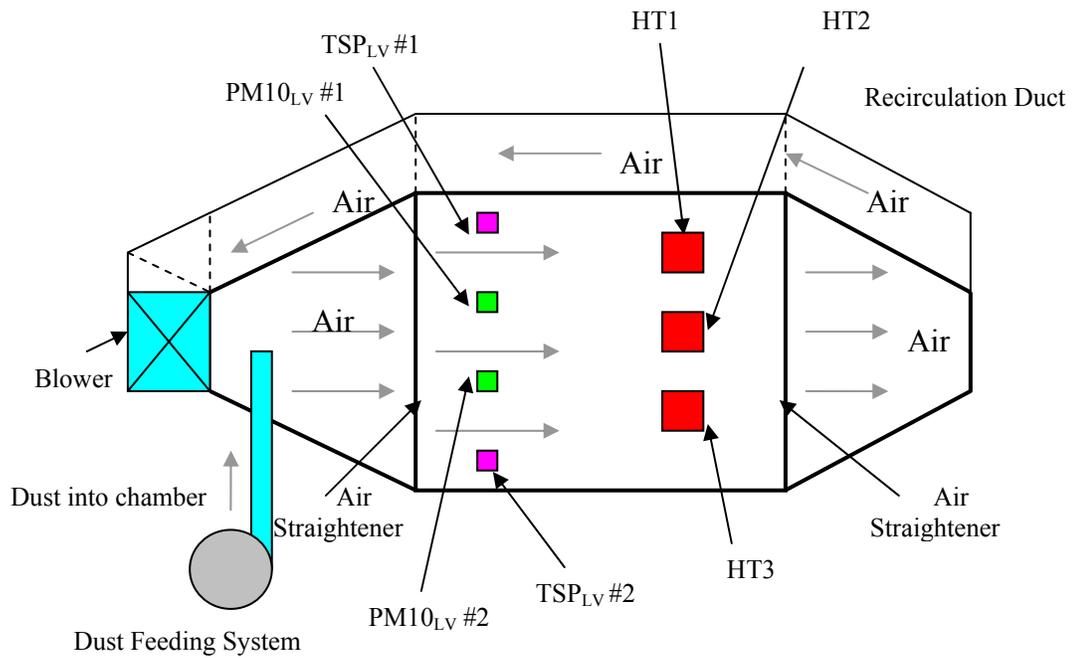


Figure 2. Schematic of the test chamber and relative location of the samplers. The two low volume TSP and two low volume PM₁₀ samplers are TSP_{LV}#1, TSP_{LV}#2, PM10_{LV}#1, and PM10_{LV}#2 respectively. The three high volume samplers are HT1, HT2, and HT3.

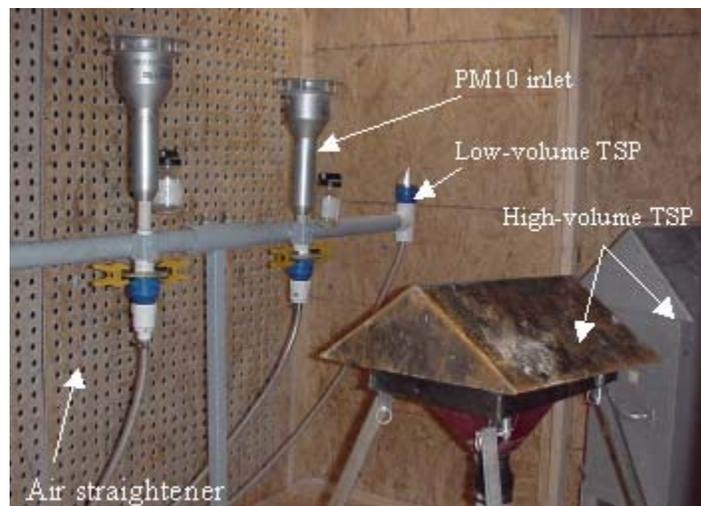


Figure 3. Sampler setup inside the testing chamber showing low volume TSP and PM₁₀ samplers with two high volume TSP samplers.

The following are additional details of the sampling protocol:

- Each test was one hour in duration.
- The dust was fed into the chamber once the air circulation rate of 128 m³/min was established. The feeding rate of the dust into the chamber was not held constant for each test because the dust feeding rate was not an experimental variable.
- Three polydisperse dusts were used in the experiments to evaluate the performance of the low volume TSP samplers over a wide range of particle sizes. Polydisperse dusts were used to evaluate the performance of the low volume samplers because they are more typical of the aerosols that the samplers may be exposed to under field conditions. Hinds (1999) indicates that most aerosols are polydisperse rather than monodisperse. The dusts used in the tests were:
 - corn starch (MMD 18.6 μm, GSD 1.4)²
 - fly ash (MMD 13.0, GSD 2.4)²
 - aluminum oxide (MMD 9.03, GSD 1.4)².

The MMD and GSD values of the

- A factorial experimental design with a block on dust type was used to measure 1) particulate matter concentrations and 2) the particle size distribution of the dusts. The data for this study was collected using four

² Dust particle size distributions were obtained from the Coulter Multisizer3 (Beckman – Coulter, Coulter Multisizer III, Miami, FL).

samplers, TSP_{LV}#1, TSP_{LV}#2, HT1, and HT3. Five replications with each dust (corn starch, fly ash, and aluminum oxide) were conducted yielding 15 tests. The 47mm Teflon filters used on the low volume TSP samplers were used with the glass fiber filters (203 x 254 mm) from the HT3 sampler for the concentration analysis and again with the poly-web filters (203 x 254 mm) from the HT1 sampler for the PSD analysis.

- The filters were conditioned in an environmental chamber for 24 hours before being weighed prior to the tests and another 24-hours before being weighed after the tests. The conditions of the air in the environmental chamber were held constant at 25°C and 47% relative humidity as specified by EPA. The filters were weighed using a high-precision analytical balance (AG245, Mettler Toledo, Greifensee Switzerland) (range: 0-41g, accuracy: ±0.01mg) in the environmental chamber. Appendix C describes the filter weighing process for the unloaded and loaded filters.
- The test chamber was cleaned after all replications of one dust were completed before a new dust was used. During cleaning, the dust deposited onto the surfaces of the chamber was removed by a manual vacuum cleaner and the surfaces wiped clean with a moist cloth. The interior and exterior surfaces of the samplers (high and low volume TSP) were cleaned at the same time.

- After each replication, the filters were collected from the samplers and placed into protective containers. (Technicians used latex gloves and small tongs to prevent any contamination of the filter media.)
- Each of the low volume samplers used a 0.09 kW (1/8 hp) diaphragm pump (Thomas 917CA18, Thomas Pumps and Compressors, Sheboygan, WI) to provide the 1 m³/hr airflow rate.
- The high volume TSP samplers were operated at the required airflow rate of 1.42 m³/min (50 cfm) using a centrifugal fan.
- A sharp edge orifice plate was used to monitor the airflow rates through both the high and low volume samplers. Appendix D describes the calibration procedure for the sharp edged orifice meters.
- The pressure drop across the sharp edge orifices was monitored using a differential pressure transducer (Omega, PX274, Omega Engineering Inc., Stamford, CT) and with a magnehelic gage for a visual check. Appendix E describes the calibration of the pressure transducers. Equation 3 was used to determine the flow rate of air corresponding to a measured pressure drop across the sharp edged orifice.

$$Q = 3.478 * K * D_o^2 * \sqrt{\frac{\Delta P}{\rho_a}} \quad (3)$$

where,

Q = air flow rate through the orifice meter (m³/s),

K = flow coefficient (dimensionless),

D_o = orifice diameter (m),

ΔP = pressure drop cross the orifice (mm H₂O), and

ρ_a = air density (kg/m³).

The density of air was calculated using equation 4.

$$\rho_a = \frac{P_b - P_{wv}}{0.0028 * (t_{db} + 273)} + \frac{P_{wv}}{0.0046 * (t_{db} + 273)} \quad (4)$$

where,

P_b = Barometric pressure, (atm),

P_{wv} = Water vapor pressure, (atm), and

t_{db} = Dry bulb temperature, (°C).

- The filter number, beginning and end time, and magnehelic gage pressure was recorded in a log sheet for each test.
- A data logger (HOBO H8 RH/Temp/2x External, Onset Computer Corp, Pocasset, MA) recorded the voltage output of the pressure transducer at 12-second intervals. This output voltage was later converted to a differential pressure using a pressure transducer specific calibration equation (Appendix E). Figure 4 illustrates the general setup of the TSP samplers used in this study. Both the inlets and the flow control devices are specific to the airflow rate of the sampler. The low volume TSP samplers used the inlet shown in figure1 and a needle valve to control the flow of air. The high volume FRM TSP samplers used an inlet designed according to EPA specifications for the high volume TSP sampler and a variable transformer (Dayton E165942,

Dayton Electric Manufacturing Co., Niles, IL) to control the speed of the centrifugal fan.

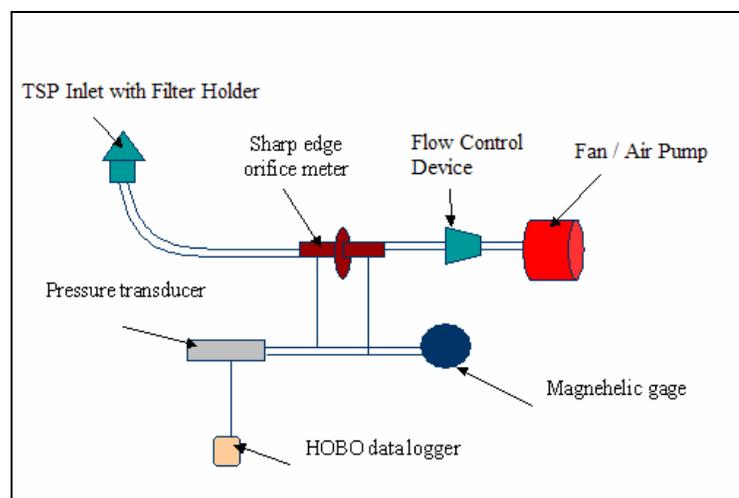


Figure 4. The general sampler setup for the low and high volume TSP samplers used in this study.

CONCENTRATION AND PSD CALCULATION

One-hour concentrations were calculated using the 12-second flow rates and the weight differentials from each of the filters. The 12-second pressure drop readings were used to calculate a volume flow for the 12-second intervals. The sum of these flow volumes was used in the concentration calculation. Equation 5 was used to calculate the one-hour concentrations.

$$C_{1Hr} = \frac{\Delta M}{V_{air}} \quad (5)$$

where:

$$C_{1Hr} = \text{one hour concentration (mg/m}^3\text{)},$$

ΔM = mass of PM on the filters (mg), and

V_{air} = total volume of air sampled (m^3).

Particle size distributions were obtained from the polytetrafluoroethylene (PTFE) (47mm diameter - 2 μm pore size Zefluor Membrane Filters, Pall Corp., East Hills, NY) and poly web (20.3 cm x 25.4 cm polyweb filter media) filters using the Coulter Multisizer3 (Beckman – Coulter, Coulter Multisizer III, Miami, FL) according to the method described by Buser (2004). The equivalent spherical diameters (ESD) measured by the Coulter Counter were converted to aerodynamic equivalent diameter (AED) using equation 6.

$$AED = ESD * \sqrt{\frac{\rho_p}{\rho_w \chi}} \quad (6)$$

where:

AED = particle aerodynamic equivalent diameter (μm),

ESD = particle equivalent spherical diameter (μm),

ρ_p = particle density (g/cm^3),

ρ_w = density of water ($1 \text{ g}/\text{cm}^3$), and

χ = particle shape factor.

The particle densities of the three dusts were measured using a pycnometer (Micromeritics, AccuPyc 1330 Pycnometer, Norcross, GA). The procedure used to determine the particle density of the dusts is described in appendix F. The particle densities for cornstarch, fly ash, and aluminum oxide were $1.5 \text{ g}/\text{cm}^3$, $2.7 \text{ g}/\text{cm}^3$, and $3.9 \text{ g}/\text{cm}^3$ respectively. The shape factor used for each dust was assumed to be 1.0.

RESULTS AND DISCUSSION

The concentration results (table 1) show no significant difference ($\alpha = 0.05$) in concentration measurements between the low volume TSP samplers. The t-test was used to test the null hypothesis that there was no difference in the concentration measurements made by high and low volume TSP samplers for any of the three dusts.

Table 1. Concentration measurement results for two low volume (1 m³/hr) and one high volume (85 m³/hr) TSP sampler. The samplers were exposed to three dusts (corn starch, fly ash, aluminum oxide) under various (uncontrolled) loading conditions. The concentration means with the same superscript letter are not significantly different at $\alpha = 0.05$.

Dust Type	Sampler	Number of Samples	Mean Concentration (mg/m ³)	Std. Deviation (mg/m ³)	Std. Error	95% Confidence Interval for Mean		P - Value
						Lower Bound	Upper Bound	
Cornstarch	TSP _{LV} #1	5	37.1 ^a	9.8	4.4	24.9	49.2	0.787
	TSP _{LV} #2	5	38.5 ^a	9.9	4.4	26.2	50.8	
	HT3	5	41.4 ^a	10	4.5	28.9	53.8	
Fly Ash	TSP _{LV} #1	5	51.2 ^b	12.5	5.6	35.7	66.7	0.281
	TSP _{LV} #2	5	52.0 ^b	13.5	6	35.3	68.8	
	HT3	5	40.5 ^b	9.9	4.4	28.3	52.8	
Aluminum Oxide	TSP _{LV} #1	5	26.0 ^c	5.9	2.6	18.7	33.3	0.037
	TSP _{LV} #2	5	28.8 ^c	6.2	2.8	21.1	36.5	
	HT3	5	18.7 ^d	4.4	2	13.2	24.2	

The results (table 1) also indicate that there was no significant difference ($\alpha = 0.05$) between the measured concentrations by the low volume TSP samplers and the high volume TSP sampler for the corn starch ($P = 0.787$) and fly ash ($P = 0.281$) tests. A significant difference in the concentrations measured by the low volume and high volume TSP samplers was observed at the $\alpha = 0.05$ level for the aluminum oxide tests ($P = 0.037$).

The significant difference in the measurements from the aluminum oxide tests is partially attributable to the large variation in flow rate of the high volume TSP sampler as compared to the low volume samplers. Figure 5 shows the sampler flow rate coefficient of variation (SFRCV) from TSP_{LV}#1, TSP_{LV}#2, and HT3 for the 15 tests. The SFRCV is found by dividing the flow rate standard deviation of a particular sampler by the mean flow rate for that sampler for that test. The corn starch, fly ash, and aluminum oxide tests correspond to test numbers 1 through 5, 6 through 10, and 11 through 15 respectively. There is no SFRCV for HT3 on test 1 because of a pressure transducer failure. In this case, the average pressure drop over the test was obtained from the log sheet data and used to calculate the total air volume for the test.

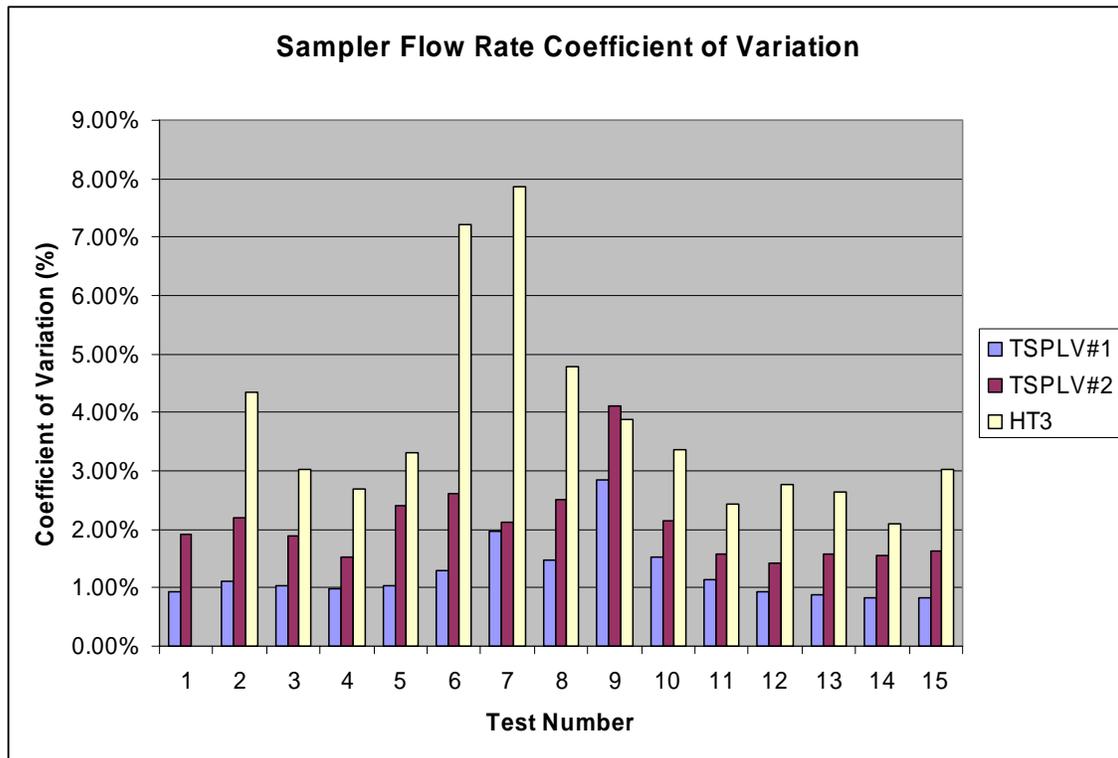


Figure 5. SFRCV for two low volume TSP samplers and one high volume TSP sampler. The dusts used in tests 1 – 5, 6 - 10, and 11 - 15 were corn starch, fly ash, and aluminum oxide respectively.

A correlation test was conducted to determine if there was a relationship between the measured concentration and the SFRCV. The concentration measurements from both of the low volume TSP samplers produced positive correlation coefficients when correlated with the corresponding SFRCV. The correlation coefficients for TSP_{LV}#1 and TSP_{LV}#2 were 0.695 and 0.57 respectively and were both significant at the $\alpha = 0.05$ level. The correlation coefficient for the concentration measurements from HT3 and the corresponding SFRCV was 0.452 and was not significant at the $\alpha = 0.05$ level.

The data from the data loggers show that the flow rate of the TSP_{LV} pre-separators was held relatively constant over the entire time of each test, while the flow rates of the high volume TSP samplers were reduced as the mass of PM on the filter increased (See Appendix G). As a consequence, the speeds of the centrifugal fans operating the high volume samplers were increased during the tests to maintain the required flow rate.

Three factors may have contributed to these results:

- The PM mass loading rate of the low volume sampler filters was significantly lower because of the decreased airflow rate per unit area ($9.6 \text{ m}^3/\text{m}^2/\text{min}$ for the low volume TSP versus $27.4 \text{ m}^3/\text{m}^2/\text{min}$ for the high volume TSP). The airflow rate per unit of filter area is known as the penetration velocity of the air passing through the filter. (Assuming a constant PM concentration in the ambient air being sampled, the loading on a 20.3 x 25.4 cm high volume TSP sampler filter is 286% higher than the loading on a low volume TSP 47mm diameter filter.)
- The lower penetration velocity of the low volume TSP samplers ($9.6 \text{ m}^3/\text{m}^2/\text{min}$) relative to the high volume TSP samplers ($27.4 \text{ m}^3/\text{m}^2/\text{min}$) resulted

in a lower pressure drop across the captured PM (on the filter) and the filter allowing the sampler to operate in high concentrations for longer periods of time.

- The diaphragm pumps used with the low volume TSP samplers do not exhibit as large a decrease in flow rate with an increase in static pressure as compared to the centrifugal fans used with the high volume TSP samplers. This result is due to the inherent characteristics of the diaphragm pump (positive displacement type pump) and the centrifugal fan (non-positive displacement type pump).

A particle size distribution was determined from each low volume TSP sampler filter and also from the high volume TSP sampler (HT1) filter. An analysis of variance test (ANOVA) on the average MMD and GSD from the high and low volume TSP samplers for each test was conducted. Tukey's Studentized Range post hoc procedure (HSD) ($\alpha = 0.05$) shows that there is no significant difference in the performance of the low volume TSP samplers and the high volume TSP sampler for any of the dusts. Tukey's procedure was used to control the experiment-wise error rate and give a more accurate comparison of the mean values of the MMD and GSD over the five replications for each dust. Table 2 shows the average MMD and GSD data for the two low volume TSP samplers and for the high volume TSP sampler.

Table 2. Average particle size distribution results for the low and high volume sampler tests. The data reported include average mass median aerodynamic equivalent diameters (MMD) in micrometers (μm) and geometric standard deviations (GSD) of the two low and one high volume samplers tested ($\text{TSP}_{\text{LV}\#1}$, $\text{TSP}_{\text{LV}\#2}$, and HT1, respectively). MMD's and GSD's with the same superscript letter are not significantly different using Tukey's Studentized Range ($\alpha = .05$).

Sampler	Corn Starch Average		Fly Ash Average		Alum. Oxide Average	
	MMD	GSD	MMD	GSD	MMD	GSD
$\text{TSP}_{\text{LV}\#1}$	14.1 ^a	1.7 ^b	12.0 ^c	2.1 ^d	9.6 ^e	2.0 ^f
$\text{TSP}_{\text{LV}\#2}$	13.9 ^a	1.6 ^b	11.8 ^c	2.0 ^d	9.6 ^e	1.9 ^f
HT1	14.5 ^a	1.7 ^b	13.0 ^c	2.0 ^d	10.3 ^e	2.0 ^f

A correlation test was conducted to determine if there was a relationship between the MMD values and the SFRCV and also between the GSD values and the SFRCV. None of the resulting correlation coefficients were significant ($\alpha = 0.05$) indicating no relationship between MMD or GSD and SFRCV.

SUMMARY AND CONCLUSIONS

The results of this study suggest the following:

- Accurate measurements of TSP can be made with a low volume ($1 \text{ m}^3/\text{h}$) sampler (TSP_{LV}) provided a properly designed TSP pre-separator is used.
- The concentration and PSD data from these series of tests suggest that the TSP_{LV} sampler had less variability than the high volume TSP samplers.
- The lower penetration velocity relative to the high volume TSP sampler avoids the significant increase in pressure drop across the filter during the sampling period because of increased mass loading rates. This factor allows for less variability of flow rate as well.
- The low volume systems are lightweight and require less energy to operate than the high volume systems lending themselves easily to field applications. The

overall system weight of the low volume TSP sampler is approximately 18.2 kg (40 lbs) whereas the high volume TSP system weighs approximately 25kg (55 lbs). The low volume systems will draw approximately 4 amps of electrical current compared to the 10 amps required by the high volume systems. The lower energy requirement allows for the use of smaller and lighter generators. A 480 watt generator is needed to operate one low volume TSP sampler where a 1200 watt generator is required to operate one high volume TSP sampler.

CHAPTER III
DISPERSION MODELING OF AGRICULTURAL LOW LEVEL
POINT SOURCES*

OVERVIEW

Cotton gins, feed mills, and grain elevators are examples of low-level point sources that are permitted based upon the predicted ambient concentrations from dispersion modeling. ISCST3, the current EPA approved dispersion model for low level point sources, uses an emission rate developed from the emission factors listed in AP42 to predict a 10-minute downwind concentration. This paper addresses the problems associated with the errors in the emission factors listed in AP-42 as well as those associated with the assumption by the developers of ISCST3 that a 10-minute concentration is equal to a 60-minute concentration.

The six Pasquill-Gifford stability classes, used by ISCST3, were developed from 10-minute average field data and can only be used to calculate 10-minute concentrations. In addition, the meteorological data (wind speed and direction) used in ISCST3 is a 10-minute average that is assumed to be a 60-minute average. These assumptions cause ISCST3 to over-predict downwind concentrations by approximately 2.5 times. Monte Carlo simulations and the power law model were used to develop P values (dependent

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upon stability class and down wind distance) that were used to give more accurate predictions of downwind concentrations.

INTRODUCTION

The operation of low-level point sources such as cotton gins, grain elevators, and feed mills is dependent upon obtaining an air permit from the state air pollution regulatory agency (SAPRA). The SAPRA permitting process uses either direct field sampling data taken from the facility or dispersion modeling results to determine whether the facility is in compliance with the ambient air quality standards. The National Ambient Air Quality Standards have been used to regulate property line concentrations by some state air pollution regulatory agencies (SAPRA). The primary NAAQS for PM₁₀ is 150 $\mu\text{g}/\text{m}^3$ (24-hour average). PM₁₀ is defined as particulate matter (PM) that has an aerodynamic equivalent diameter of 10 μm or less.

The current dispersion model approved by the US EPA for modeling low-level point sources is the Industrial Source Complex Short Term version 3 (ISCST3). ISCST3 is a Gaussian dispersion model that uses the Pasquill-Gifford horizontal and vertical plume spread parameters, σ_y and σ_z , respectively. The calculation of σ_y and σ_z is dependent upon atmospheric stability class and downwind distance (x). These dispersion parameters are used in the Gaussian dispersion equation along with emission rate, wind velocity, and effective emission height to calculate downwind concentrations. The concentrations predicted by the Gaussian model can be taken as 10-minute average concentrations (Stiggins et al., 2003). This is due to the fact that the Pasquill-Gifford stability classes were developed from 10 to 15 minute average data (Beychok, 1994).

ISCST3 calculates 24 10-minute average concentrations (not 24 60 minute averages) and takes their average to be a 24-hour average (Turner, 1994). The error associated with this method is that wind direction changes within the hour are not taken into account. By not taking these fluctuations into consideration, the modeled concentrations are significantly over-predicted (Beychok, 1994).

Stiggins et al. (2003) developed a method by which the over-prediction of downwind concentrations by ISCST3 can be corrected. This approach utilized Monte Carlo simulation (Crystal Ball, 2002) and published wind standard deviations (EPA, 2000) to determine a set of P values. The P values are used in the power law model (Cooper and Alley, 2002) to convert 10-minute concentrations (C_{10}) to 60-minute concentrations (C_{60}). Hino (1968) states that for averaging periods between 10 minutes and 5 hours, a P value of 0.5 is appropriate. The P values determined by the Stiggins method produces an individual P value for each of the six Pasquill-Gifford stability classes (Cooper and Alley, 2002). The Stiggins method did not take into account the effect of downwind distance (x) on the P value.

This research uses a modified version of the Stiggins method to demonstrate the over-prediction errors associated with ISCST3. Regression equations to determine a P value dependent upon stability class and down wind distance (x) were developed using simulation (Crystal Ball, 2002). These P values were used with the meteorological data published by Fritz (2002) and the Gaussian model to develop a more accurate estimate of 60-minute average concentrations.

The errors associated with ISCST3 are confounded when the emission rates used in the modeling process are flawed. This problem affects cotton gins in a two-fold manner. First, the emission factors published by EPA in 1996 AP-42 state that the PM₁₀ percentage of TSP is 39% (Buser, 2001). This figure corresponds to an average mass median diameter (MMD) of 12.6 with geometric standard deviation (GSD) of 2.0. Buser (2002a) suggests that a more accurate estimate of the average MMD and GSD of cotton gin dust is 18 μ m and 2.2, respectively. Taking the PM₁₀ percentage of TSP to be 39% instead of 23% overstates the PM₁₀ emissions from a cotton gin by a factor of 1.7.

Second, some SAPRAs estimate the collection efficiency of all cyclones on cotton gin exhausts to be 90%. Wang (2000) reported collection efficiencies for 1D2D and 1D3D cyclones to be in excess of 98%. The effect of this difference is seen in the mass of PM that penetrates the cyclone. A collection efficiency of 90% corresponds to a 10% penetration (penetration refers to the percent of the PM entering the cyclone that escapes the cyclone through the gas exit tube) where a 98% collection efficiency corresponds to a 2% penetration. This in effect suggests that the emission factors from cotton gin cyclones could be over-estimated by as much as 5 times.

These two scenarios were taken into account and ISCST3 models were developed to show the effect of assuming a new particle size distribution and new abatement system efficiencies. The models taking into account the errors in the emission factors from AP-42 indicate a significant difference in the predicted concentrations. The goal of this research was to demonstrate the effects of using 1) a more accurate PSD to describe the percentage of TSP that is PM₁₀ and 2) more accurate

cyclone efficiencies on the estimation of concentrations downwind of cotton gins through dispersion modeling.

METHODS

The Gaussian Dispersion Model

The Gaussian dispersion equation is used in ISCST3 to calculate 60-minute concentrations based upon the Pasquill-Gifford dispersion parameters σ_y and σ_z (EPA, 1995). To demonstrate this, a spreadsheet model was developed using the following equations to calculate values for the variables used in the Gaussian equation. The calculation of σ_y and σ_z is accomplished using equations 7 and 8 respectively (Turner, 1994).

$$\sigma_y = \frac{1000 * X * \tan(T)}{2.15} \quad (7)$$

$$\sigma_z = a * X^b \quad (8)$$

where

σ_y, σ_z = Pasquill-Gifford horizontal and vertical dispersion parameters (m),

X = distance down the centerline of the plume, see equation 9 (km),

T = one half of Pasquill's θ , dependent upon stability class (see Table 3) (degrees), and

a, b = constants dependent upon stability class and X (see Turner, 1994).

Table 3. Equations used to calculate T for use in the calculation of σ_y . Equations obtained from Turner (1994).

Stability Class	Equation for T
A (1)	$T = 24.167 - 2.5334 * \ln(X)$
B (2)	$T = 18.333 - 1.8096 * \ln(X)$
C (3)	$T = 12.5 - 1.0857 * \ln(X)$
D (4)	$T = 8.3333 - 0.72382 * \ln(X)$
E (5)	$T = 6.25 - 0.54287 * \ln(X)$
F (6)	$T = 4.1667 - 0.36191 * \ln(X)$

$$X = \frac{(x_{rec} - x_{source}) * \sin(\Theta) + (y_{rec} - y_{source}) * \cos(\Theta)}{1000} \quad (9)$$

$$Y = (x_{rec} - x_{source}) * \cos(\Theta) - (y_{rec} - y_{source}) * \sin(\Theta) \quad (10)$$

where

Y = horizontal distance from plume centerline (m),

x_{rec}, y_{rec} = Cartesian coordinate location of the receptor measuring the C_{10} value (m),

x_{source}, y_{source} = Cartesian coordinate location of the source (m), and

Θ = wind direction (degrees) North corresponds to 0 or 365 and increases in a clockwise rotation.

The Gaussian dispersion equation (equation 11) was used to calculate a C_{10} value. The Y component was calculated using equation 10.

$$C = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left(-\frac{1}{2} \frac{y^2}{\sigma_y^2}\right) \left\{ \exp\left(-\frac{1}{2} \frac{(z-H)^2}{\sigma_z^2}\right) + \exp\left(-\frac{1}{2} \frac{(z+H)^2}{\sigma_z^2}\right) \right\} \quad (11)$$

where

C = steady state concentration at a point (x,y,z) ($\mu\text{g}/\text{m}^3$),

Q = emission rate ($\mu\text{g}/\text{s}$),

u = average wind speed at stack height (m/s),

y = horizontal distance from plume centerline (m),

z = height of receptor with respect to ground (m), and

H = effective stack height ($H=h+\Delta h$, where h = physical stack height and Δh = plume rise)(m).

The emission rate used for this model was 2.85 g/s (1.2 lb/bale) which corresponded to the total PM_{10} emission rate for a 20 bale per hour cotton gin based upon 1996 AP-42 emission factors. The source, located at $x_{\text{source}} = 0$ and $y_{\text{source}} = 0$, had a stack height set arbitrarily at 8 meters to approximate the exit height of a cyclone. The same source parameters were input to ISCST3 using BreezeISC (Trinity Consultants, 2002) and the same meteorological data for each day were used to determine the location of the maximum 24-hour average concentration. A polar receptor grid with 36 radials and 10 rings spaced at 100-meter intervals was used to locate the maximum 24-hour average concentrations. Once this location was determined, the receptor grid was

removed and a single discrete receptor was placed in the location of the maximum 24-hour average concentration. The model was then repeated to obtain the 24 C_{60} values from that particular day using ISCST3. The receptor location used in the ISCST3 model was also used in the spreadsheet model to calculate concentrations.

The Power Law Model

The power law model is commonly used to determine concentrations for periods longer than 10 minutes (Cooper and Alley, 1994). The determination of longer time period averages is crucial to the permitting process for cotton gins because the average of 24 C_{10} values will grossly over estimate the true concentrations. The Hino model (1968) suggests that the ratio of a 24-hour average concentration based upon 10-minute concentrations to that of one based on 60-minute concentrations is 2.5:1.

The power law model (equation 12) converts C_{10} values to C_{60} values using an exponent value or “P” value (Cooper and Alley, 2002)

$$C_t = C_{10} * \left(\frac{10}{t}\right)^P \quad (12)$$

where

C_t = concentration from a time average of t minutes ($\mu\text{g}/\text{m}^3$),

t = time period (minutes), and

P = P value used to convert the 10-minute concentration to C_t .

The P value is a function of source, stability class, and downwind distance X. The standard deviation of the wind direction is greatest for stability class A and least for stability class F. As the wind direction varies away from directly at the receptor, the

measured concentration will decrease. Lower P values will result in less difference between the values of C_{10} and C_t (Stiggins, et al. 2002).

Solving equation 12 for P yields equation 13.

$$P = \frac{\ln\left(\frac{C_{60}}{C_{10}}\right)}{\ln\left(\frac{10}{60}\right)} \quad (13)$$

A second spreadsheet model was developed to apply Monte Carlo simulation to develop a set of P value equations. These equations were dependent upon stability class and downwind distance X. The spreadsheet calculated C_{10} concentrations that were based on an initial wind direction of 90 degrees, which was the direction of the wind blowing directly from the source to the receptor. The C_{10} value calculated using the initial wind direction was used as C_{10} in equation 13. The wind direction was simulated (Crystal Ball, 2002) based upon a normal distribution with the mean set at 90 degrees and the standard deviation corresponding to that published by the EPA (2000) depending upon stability class (see Table 4). For each of 5 distances ($X = 50, 100, 250, 500, 1000$ meters), six C_{10} values were calculated and their average used as the value for C_{60} in equation 13. The P value was then calculated using equation 13. This process was repeated 1600 times for each distance and stability class and the P values from each distance averaged to give a final P value.

Table 4. Standard deviations of horizontal wind direction variations by stability class reported by EPA (2000). It was assumed that wind direction variations were normally distributed.

Stability Class	Range of Standard Deviation of Horizontal Wind Direction Fluctuations (degrees)
1 (A)	> 22.5
2 (B)	17.5 – 22.5
3 (C)	12.5 – 17.5
4 (D)	7.5 – 12.5
5 (E)	3.8 – 7.5
6 (F)	< 3.8

Equations for P values dependent upon stability class and downwind distance (X) were obtained by fitting a regression line to the data points found for each stability class. A second order polynomial equation was used in each case and yielded an R² value in excess of .99. These new P value equations were then input to the original spreadsheet model and C₆₀ values were determined based upon the original C₁₀ values found by the Gaussian model.

Emission Factor Changes

The current emission factors from 1996 AP-42 for cotton gins are shown in Table 5 where the percentage of TSP that is PM₁₀ was assumed to be 39%. This assumption is incorrect. The true percentage of PM₁₀ demonstrated by Buser et al. (2002a) is better approximated by a lognormal particle size distribution (PSD) with MMD = 18 and GSD = 2.2. Assuming these PSD characteristics, the percentage of PM₁₀ was reduced from 39% to 23%. New emission factors based upon these new PSD characteristics were developed (see Table 6).

The efficiencies of cyclone abatement systems is assumed by most SAPRAs to be 90%. BBACT states that high efficiency cyclones (1D3D cyclones) are to be used on all centrifugal fan exhausts and at a minimum, covered condenser drums on all axial flow exhausts. Wang (2000) reported measured collection efficiencies for 1D2D and 1D3D cyclones in excess of 98%. Increasing the assumed collection efficiency of cyclones from 90 to 98% would decrease the emission rate by a factor of 5. A more conservative increase to 95% would decrease the emission rates by a factor of 2. A new set of emission factors based upon the more conservative estimate (95%) of the true collection efficiency of cyclones was developed and is reported in Table 7.

Table 5. 1996 AP-42 emission factors for cotton gins. The emission factors assume that PM₁₀ is 39% of TSP. CCD = covered condenser drum.

Process	Abatement Device	TSP kg/bale	TSP lb/bale	PM ₁₀ kg/bale	PM ₁₀ lb/bale
Unloading System	1D3D Cyclone	0.20	0.44	0.08	0.17
1st Stage Cleaner/Dryer	1D3D Cyclone	0.11	0.25	0.04	0.10
2nd Stage Cleaner/Dryer	1D3D Cyclone	0.06	0.14	0.02	0.05
Trash Fan	1D3D Cyclone	0.02	0.05	0.01	0.02
Master Trash Fan	1D3D Cyclone	0.10	0.23	0.04	0.09
Overflow Fan	1D3D Cyclone	0.05	0.11	0.02	0.04
Mote Fan	1D3D Cyclone	0.12	0.27	0.05	0.11
First Stage Lint Cleaner	CCD	0.50	1.10	0.19	0.43
Second Stage Lint Cleaner	CCD	0.09	0.20	0.04	0.08
Battery Condenser	CCD	0.12	0.26	0.05	0.10
	Total	1.38	3.05	0.54	1.19

Table 6. 1996 AP-42 emission factors (Table 5) based upon a new particle size distribution with a MMD = 18 and a GSD = 2.2. The mass fraction of TSP that is PM₁₀ is 22.8%. CCD = covered condenser drum.

Process	Abatement Device	TSP kg/bale	TSP lb/bale	PM ₁₀ kg/bale	PM ₁₀ lb/bale
Unloading System	1D3D Cyclone	0.20	0.44	0.05	0.10
1 st Stage Cleaner/Dryer	1D3D Cyclone	0.11	0.25	0.03	0.06
2 nd Stage Cleaner/Dryer	1D3D Cyclone	0.06	0.14	0.01	0.03
Trash Fan	1D3D Cyclone	0.02	0.05	0.01	0.01
Master Trash Fan	1D3D Cyclone	0.10	0.23	0.02	0.05
Overflow Fan	1D3D Cyclone	0.05	0.11	0.01	0.03
Mote Fan	1D3D Cyclone	0.12	0.27	0.03	0.06
First Stage Lint Cleaner	CCD	0.50	1.10	0.11	0.25
Second Stage Lint Cleaner	CCD	0.09	0.20	0.02	0.05
Battery Condenser	CCD	0.12	0.26	0.03	0.06
	Total	1.38	3.05	0.32	0.70

Table 7. 1996 AP-42 emission factors (Table 5) modified assuming 95% collection efficiency for all exhausts with cyclones as the abatement device. All covered condenser drums have been replaced with 1D2D cyclones. PM₁₀ is 39% of TSP.

Process	Abatement Device	TSP kg/bale	TSP lb/bale	PM ₁₀ kg/bale	PM ₁₀ lb/bale
Unloading System	1D3D Cyclone	0.10	0.22	0.04	0.09
1st Stage Cleaner/Dryer	1D3D Cyclone	0.06	0.13	0.02	0.05
2nd Stage Cleaner/Dryer	1D3D Cyclone	0.03	0.07	0.01	0.03
Trash Fan	1D3D Cyclone	0.01	0.03	0.00	0.01
Master Trash Fan	1D3D Cyclone	0.05	0.12	0.02	0.04
Overflow Fan	1D3D Cyclone	0.02	0.06	0.01	0.02
Mote Fan	1D3D Cyclone	0.06	0.14	0.02	0.05
First Stage Lint Cleaner	1D2D Cyclone	0.05	0.11	0.02	0.04
Second Stage Lint Cleaner	1D2D Cyclone	0.01	0.02	0.00	0.01
Battery Condenser	1D2D Cyclone	0.01	0.03	0.00	0.01
	Total	0.41	0.90	0.16	0.35

It should be noted that 1996 AP-42 only lists 8 process streams with a total TSP emission factor of 1.38 kg/bale (3.05 lb/bale). In this research, the 10 process streams used in 1988 AP-42 were also used. The total TSP emission rate from 1988 AP-42 was 1.013 kg/bale (2.24 lb/bale). The TSP emission factors from the ten process streams from 1988 AP-42 were multiplied by the ratio of the total 1996 AP-42 TSP emission factor to the total 1988 AP-42 TSP emission factor to get the modified 1996 AP-42 TSP emission factors used in this research.

To show the impacts of changing the emission rate on the dispersion modeling of low-level agricultural point sources, three different scenarios presented above were used to develop dispersion models in ISCST3. These scenarios were 1) the original gin layout using the 1996 AP-42 emission factors, 2) the same gin layout using the 1996 AP-42 emission factors corrected with a more accurate PM_{10} fraction of TSP (i.e. a new PSD where PM_{10} is 23% of TSP instead of 39%), and 3) the same gin layout with the 1996 AP-42 emission factors corrected by using more accurate cyclone collection efficiencies. Three different ginning rates were modeled for each scenario, 20, 30, and 40 bales per hour. The same model setup was used for each scenario. The gin plant was 30 meters wide by 60 meters long and 12 meters tall placed in the center of a 500 by 500 meter property line boundary. A 2000 meter by 2000-meter uniform Cartesian receptor grid was used with receptors placed 100 meters apart. The meteorological data used in the models was for the period from October 15 through January 15 of 1988 from a county in south Texas (Cameron county). Building Profile Input Program (BPIP) was used to calculate the downwash for these models. Building downwash tends to increase on-

property concentrations because of wind wake effects on the downwind side of a structure (Trinity Consultants, 2000).

RESULTS

The modified Stiggins method yielded a set of six equations (Table 8) that predicted P values as a function of stability class and down wind distance (X). These P value equations were then used to convert the C₁₀ values predicted by ISCST3 to C₆₀ values. The average over-prediction for the 10 days of meteorological data used was 230%. Table 9 lists the concentrations predicted by the spreadsheet model, ISCST3, and the corrected C₆₀ values with a corresponding C₁₀ to C₆₀ ratio.

Table 8. P value equations as a function of stability class and downwind distance X. The unit of X is meters.

Stability Class	P value as a function of x	R ²
A	$P = -1E-07x^2 + 0.0003x + 0.358$	0.992
B	$P = -1E-07x^2 + 0.0003x + 0.4112$	0.996
C	$P = -1E-07x^2 + 0.0003x + 0.4842$	0.996
D	$P = -1E-07x^2 + 0.0003x + 0.4908$	0.996
E	$P = -1E-07x^2 + 0.0002x + 0.3653$	0.995
F	$P = -6E-08x^2 + 0.0001x + 0.1517$	0.996

Table 9. Concentrations predicted by the Gaussian spreadsheet model (C_{10}), ISCST3 (C_{10}), and the corrected C_{60} values from the power law model.

	Spreadsheet C_{10}	ISCST3 C_{10}	Power Law C_{60}	Ratio of C_{10} to C_{60}
Day	mg/m ³	mg/m ³	mg/m ³	
1	559.8	558.7	243.9	2.29
2	323.2	323.2	147.7	2.19
3	625.1	625.0	255.6	2.44
4	405.1	405.2	166.2	2.44
5	385.8	385.8	188.0	2.05
6	312.0	312.0	142.0	2.20
7	491.1	491.1	196.4	2.50
8	421.3	421.3	193.0	2.18
9	579.9	579.8	251.4	2.31
10	497.4	497.3	209.5	2.37
			Average	2.30

The results of the highest 24 hour average modeled concentrations are shown in Table 10. The models with lowered overall emission factors showed lower predicted concentrations than the original gin models using 1996 AP-42 emission factors. The decrease in modeled concentrations is directly proportional to the decrease in emission rate.

Table 10. Maximum ISCST3 predicted 24 hour average concentrations for three gin scenarios based upon 1996 AP-42 emission factors and corrections thereof to reduce the emission factors. The increase in emission rate is directly proportional to the increase in gin throughput capacity.

Ginning Rate (bales/hr)	Gin Emission Factor Scenario		
	1996 AP-42 ($\mu\text{g}/\text{m}^3$)	New PSD ($\mu\text{g}/\text{m}^3$)	95% Cyclone Efficiency ($\mu\text{g}/\text{m}^3$)
20	258.4	138.9	71.1
30	366.9	211.8	105.3
40	488.8	282.5	140.2

CONCLUSIONS

The main intent of this paper was to demonstrate the impacts of known errors currently associated with dispersion modeling and emission factors for cotton gins. The Gaussian dispersion equation was used with the Pasquill-Gifford dispersion parameters σ_y and σ_z , as calculated by Turner (1994), to determine 10-minute average concentrations (C_{10}). The decision was made by the developers of ISCST3 to use these C_{10} values as 60-minute average concentrations. The results from this research show that this decision causes an over-prediction of downwind concentration by ISCST3 by an average factor of 2.3.

The over-estimate of concentration by ISCST3 directly impacts the operation of low level point sources such as cotton gins, feed mills, and grain elevators. Through this research it has been shown that a cotton gin, modeled by a SAPRA, could actually be in compliance with the NAAQS if the maximum 24-hour average PM_{10} concentration predicted by ISCST3 was $345\mu\text{g}/\text{m}^3$. The development of the equations for P values as a function of stability class and downwind distance (X) support the previous findings of Stiggins et al. (2003), that reducing ISCST3 predicted concentrations by a factor of 2 yields a more accurate yet still conservative estimate of true 24-hour average concentrations.

The errors associated with the emission factors used in the modeling process also have a great impact on predicted concentrations. Predicted concentrations vary directly with changes to the emission rate. Changing the characteristics of the PSD of typical gin dusts from $MMD = 12.6\mu\text{m}$ and $GSD = 2.0$ to $MMD = 18\mu\text{m}$ and $GSD = 2.2$, will

reduce the modeled concentrations by a factor of 1.7. Changing the collection efficiency value for high efficiency cyclones from 90% to a conservative 95% will reduce the predicted concentrations by a factor of 3.5.

CHAPTER IV
A SIMULATED APPROACH TO ESTIMATING PM₁₀ AND PM_{2.5}
CONCENTRATIONS DOWNWIND FROM COTTON GINS*

OVERVIEW

Cotton gins are required to obtain operating permits from state air pollution regulatory agencies (SAPRA), which regulate the amount of particulate matter that can be emitted. Industrial Source Complex Short Term version 3 (ISCST3) is the Gaussian dispersion model currently used by some SAPRAs to predict downwind concentrations used in the regulatory process in the absence of field sampling data. The maximum ambient concentrations for PM₁₀ and PM_{2.5} are set by the National Ambient Air Quality Standard (NAAQS) at 150 µg/m³ and 65 µg/m³ (24-hour average) respectively. Some SAPRAs use the NAAQS concentrations as property line concentrations for regulatory purposes. This paper reports the results of a unique approach to estimating downwind PM₁₀ and PM_{2.5} concentrations using Monte Carlo simulation, the Gaussian dispersion equation, the Power Law, and a particle size distribution that characterizes the dust typically emitted from cotton gin exhausts. These results were then compared to a ten-minute concentration (C₁₀) and the concentrations that would be measured by a FRM PM₁₀ and PM_{2.5} sampler. The total suspended particulate (TSP) emission rate, particle

* Reprinted with permission from A Simulated Approach to Estimating PM₁₀ and PM_{2.5} Concentrations Downwind from Cotton Gins by J.D. Wanjura, M.D. Buser, C.B. Parnell, Jr., B.W. Shaw, and R.E. Lacey, 2005. *Transactions of the ASAE*. 2005 by The American Society of Agricultural Engineers (Submitted)

size distributions, and sampler performance characteristics were assigned to triangular distributions to simulate the real world operation of the gin and sampling systems. The TSP emission factor given in AP-42 for cotton gins was used to derive the PM mass emission rate from a 40 bale per hour plant. The Gaussian equation was used to model the ambient TSP concentration downwind from the gin. The performance characteristics for the PM₁₀ and PM_{2.5} samplers were then used to predict what the measured concentration would be for two PSD conditions. The first PSD assumption was that the mass median diameter (MMD) and geometric standard deviation (GSD) were constant at 12 μ m and 2 and the second scenario assigned a triangular distribution to the MMD and GSD of {15, 20, 25} μ m and {1.8, 2.0, 2.2} respectively. The results show that the PM_{2.5} fraction of the dust emitted under either PSD condition was negligible when compared to the NAAQS for PM_{2.5} of 65 μ g/m³. The results also demonstrate that correcting for wind direction changes within the hour using the power law reduces the ambient concentration by a factor of 2.45.

INTRODUCTION

While the national ambient air quality standards (NAAQS) for criteria pollutants were originally intended for use as ambient concentration standards, some air pollution regulations for cotton ginning facilities are based upon compliance with the NAAQS as a 24-hour average property line concentrations (PLC). PM₁₀ is the criteria pollutant emitted by cotton gins requiring the facility to obtain an operating permit from the state air pollution regulatory agency (SAPRA). PM₁₀ is defined as the mass fraction of dust particles with aerodynamic equivalent diameter (AED) equal to or less than 10

micrometers (μm). $\text{PM}_{2.5}$ is defined as the mass fraction of dust particles with AED equal to or less than $2.5\mu\text{m}$. It should be noted that $\text{PM}_{2.5}$ is currently not regulated by the Environmental Protection Agency (EPA), but is listed as a criteria pollutant in the NAAQS.

Currently EPA is in the process of promulgating a new standard for PM, PM coarse (PM_c). PM_c is defined as the fraction of particles less than or equal to a nominal $10\mu\text{m}$ (AED) but greater than a nominal $2.5\mu\text{m}$ (AED). There is currently no approved FRM sampler to measure PM_c concentrations. One proposed method of measuring PM_c concentrations is to take both a PM_{10} and $\text{PM}_{2.5}$ concentration and subtract the $\text{PM}_{2.5}$ concentration from the PM_{10} concentration, the result being PM_c . Appendix H discusses the implications of this new standard for agricultural operations.

The two methods regulators have to obtain the PLCs of PM_{10} for regulatory purposes are dispersion modeling and field sampling. There are errors in the protocol for both of these processes. Buser et al. (2001) demonstrated mathematically the measurement errors encountered when using federal reference method (FRM) PM_{10} and $\text{PM}_{2.5}$ samplers to measure particulate matter (PM) concentrations from sources emitting dust with mass median diameter and geometric standard deviation in excess of $10\mu\text{m}$ and 1.5 respectively. The errors in the dispersion modeling process are a result of the assumption by the developers of the model that the concentrations calculated by the model are one hour concentrations, while in reality, they are approximately ten minute average concentrations (Stiggins et al. 2003). These errors result in measured and predicted PM concentrations downwind from agricultural low level point sources

(LLPS) (agricultural low level point sources include cotton gins, feed mills, and grain elevators) to be in excess of the true concentrations.

Industrial source complex short term version 3 (ISCST3) is the EPA approved dispersion model most commonly used to predict time averaged PM concentrations downwind from a LLPS. The concentration time dependence is a result of the change in wind speed and direction over some time period. Boubel et al. (1994) states: “If emission and meteorological conditions remained unchanged hour after hour, concentrations at various locations downwind would remain the same. However, since such conditions are ever-changing, concentrations vary with time.” Cooper and Alley (2002) state that “The longer the averaging time, the more likely many such shifts will occur. These random fluctuations help spread the plume over a larger downwind area.” ISCST3 uses the Pasquill-Gifford atmospheric stability parameter estimates to estimate the horizontal and vertical plume dispersion parameters (σ_y and σ_z respectively) used in the Gaussian dispersion equation. The values for σ_y and σ_z vary with atmospheric stability class and distance. The stability of the atmosphere has been divided into six classes, A through F, with A being the most unstable and F the most stable (Cooper and Alley, 2002). Pasquill (1960) discusses the plume spread characteristic results of several experiments with varying source emission durations ranging from three to thirty minutes. However, the time period associated with the Pasquill-Gifford σ_y and σ_z is the subject of much scientific debate. The following paragraph from Beychok (1996) summarizes the issue.

“A major problem with the Gaussian dispersion equation is defining what the calculated concentration C represents when using Pasquill’s dispersion coefficients. D.B Turner states that C represents a 3- to 15-minute average; an American Petroleum Institute dispersion modeling publication believes C represents a 10- to 30-minute average; S.R. Hanna and P.J. Drivas believe C is a 10-minute average; and others attribute averaging times from 5-minutes to 30-minutes. Most agree on a range of 10-minutes to 15-minutes. However, many Environmental Protection Agency computer models used to determine regulatory compliance assume that the Gaussian dispersion equation yields 60-minute average concentrations. Assuming that the Gaussian dispersion equation yields 60-minute values rather than 10-minute values constitutes a built-in over-prediction error that may be as large as 2.5.”

ISCST3 assumes the concentration from the Gaussian equation to be a one-hour average concentration (C_{60}) (Turner, 1994; EPA, 1995). This assumption ($C = C_{60}$) results in an overestimation of downwind concentrations from low level point sources. The assumption by the developers of ISCST3, in essence, state that the variation of the wind direction and wind velocity over a one-hour time period is the same as that for a short time period (approximately ten minutes) (EPA, 1995).

The research presented in this manuscript assumes that the time period associated with the horizontal and vertical plume spread parameters (Pasquill-Gifford σ_y and σ_z) is ten minutes.

Several sources have suggested that the relationship between short and long time averaged concentrations follows that of a “power law” model. Hino (1968) suggests that using a power law model with a P value of 0.5 is appropriate to use in converting short time average concentrations to longer time average concentrations ranging from ten minutes to five hours. Research by Stiggins et al. (2003) indicate that the P value can range from 0.172 to 0.607 depending upon stability class. Wanjura et al. (2003) present P values as a function of stability class and distance. Gifford (1960) states that the exponent used in the peak to mean equation can range from 0.2 to 0.7.

The performance characteristics of a federal reference method (FRM) ambient PM_{10} sampler are characterized by a lognormal distribution with a cut point (d_{50}) of $10 \pm 0.5 \mu m$ and slope of 1.5 ± 0.1 (Hinds, 1982). EPA defines the performance characteristics of the FRM $PM_{2.5}$ sampler as having a $d_{50} = 2.5 \pm 0.2 \mu m$ with no slope specifically stated. Work by Peters and Vanderpool (1996) suggests a slope of the fractional efficiency curve (FEC) for the WINS Impactor ($PM_{2.5}$ sampler) of 1.18. Further work by Buch (1999) indicates the performance characteristics of the WINS Impactor to have a slope of 1.3 ± 0.03 . The lognormal distributions defined for the PM_{10} and $PM_{2.5}$ samplers describe the FEC in which the samplers are expected to operate. The FEC gives the expected collection efficiency of the sampler for any given particle diameter or stated differently, it gives the percentage of particles in the PSD that should be prevented from penetrating to the filter. Buser et al. (2001) reported that inherent sampler errors exist for PM_{10} samplers when sampling in dusts with MMDs larger than $10 \mu m$ and also for $PM_{2.5}$ samplers when sampling in dusts with MMDs greater than

2.5 μm . Buser went further to report that the ratio of the measured PM₁₀ concentration by the sampler to the true PM₁₀ concentration for PM₁₀ samplers sampling a dust with MMD = 20 μm and GSD = 1.5 ranges from 1.81 with the sampler operating with $d_{50} = 9.5$ and slope = 1.4 to 3.43 with the sampler operating with $d_{50} = 10.5\mu\text{m}$ and slope = 1.6. The ratio of the measured concentrations to true concentrations for PM_{2.5} samplers sampling the same PSD range from 14.8 with the sampler operating at $d_{50} = 2.3\mu\text{m}$ and slope = 1.27 to 183 with the sampler operating with $d_{50} = 2.7\mu\text{m}$ and slope = 1.33.

The mass and PSD of the particulate matter penetrating the abatement systems of cotton gins varies depending upon the trash content of the cotton processed. The average PM₁₀ percentage of TSP reported by AP-42 is 39%, which corresponds to a PSD with a 12 μm MMD assuming a GSD of 2. Buser et al. (2002a) reported MMDs in excess of 15 μm for gin exhausts. Agricultural dusts typically have PSDs characterized by an MMD ranging from 15 to 25 μm with a GSD typically ranging from 1.5 to 2.0 (Redwine et. al., 2001). Over-sampling errors caused by MMDs larger than the sampler's cutpoint result in great inaccuracies in measuring downwind concentrations.

OBJECTIVES

The purpose of this manuscript is to demonstrate the inaccuracies of the tools available to air pollution regulators for predicting and measuring PM concentrations (dispersion modeling and ambient sampling) downwind from low level point sources, more specifically cotton gins. It is not the intent of this manuscript to suggest a new dispersion model for modeling low-level point sources. The assumptions made in this manuscript are:

- Gaussian dispersion modeling, when corrected for concentration time averaging errors, can be used to more accurately predict downwind TSP concentrations.
- The PSD of the dust emitted from the gin is the same as the PSD of the dust downwind of the gin.
- Mass fraction versus particle size distributions applied to TSP concentrations can be used to accurately determine PM₁₀ concentrations.
- The distribution of the MMD and GSD of the PSD of the dust emitted from a cotton gin can be described by the triangular distribution.
- The FRM PM₁₀ and PM_{2.5} sampler will operate within the design ranges for d_{50} and slope.
- The distribution of the slope and cut point (d_{50}) of the FEC for an FRM PM₁₀ and PM_{2.5} sampler can be described by the triangular distribution.

The following analysis uses Gaussian dispersion modeling to estimate the TSP concentration downwind from a cotton gin. The initial TSP concentration is adjusted using a simulated PSD to determine the PM₁₀ and PM_{2.5} concentrations that would be reported by ISCST3. The initial TSP concentration was corrected for the time averaging errors associated with assuming that a ten-minute concentration is a one-hour concentration using the power law ($p = 0.5$). Using this corrected TSP concentration with a simulated PSD and the simulated performance characteristics of the FRM PM₁₀ and PM_{2.5} sampler, the magnitude of the concentration that would be measured by the samplers is determined (these concentrations are termed “nominal measured”

concentrations). The true PM_{10} and $PM_{2.5}$ concentrations are obtained using the corrected TSP concentration with the simulated PSD. Finally, the modeled, true, and quasi-measured PM_{10} and $PM_{2.5}$ concentrations are compared to show the inaccuracies associated with the current concentration measurement and prediction methods.

METHODS

Two scenarios were developed to simulate the emission of particulate matter from a forty-bale per hour cotton gin. Scenario A was performed under the assumption that the PSD of the dust emitted from the gin was constant and had an $MMD = 12\mu m$ and $GSD = 2$. Scenario B assigned a triangular distributions to the MMD and GSD of the PSD of the dust emitted from the gin. The range of a random variable defined by a triangular distribution will be denoted by $\{A, C, B\}$. The triangular distribution is defined by equations 14 through 16:

$$\Theta = \frac{C - A}{B - A} \quad (14)$$

$$X = A + \sqrt{(B - A) * (C - A) * R} \quad \text{For } 0 \leq R \leq \Theta \quad (15)$$

$$X = B - \sqrt{(B - A) * (B - C) * (1 - R)} \quad \text{For } \Theta < R \leq 1 \quad (16)$$

where:

θ = constant ratio;

A = minimum value of the simulated variable,

B = maximum value of the simulated variable,

C = most likely value of the simulated variable,

X = simulated/random variable, and

R = random number.

Figure 6 shows a graphical representation of the triangular distribution.

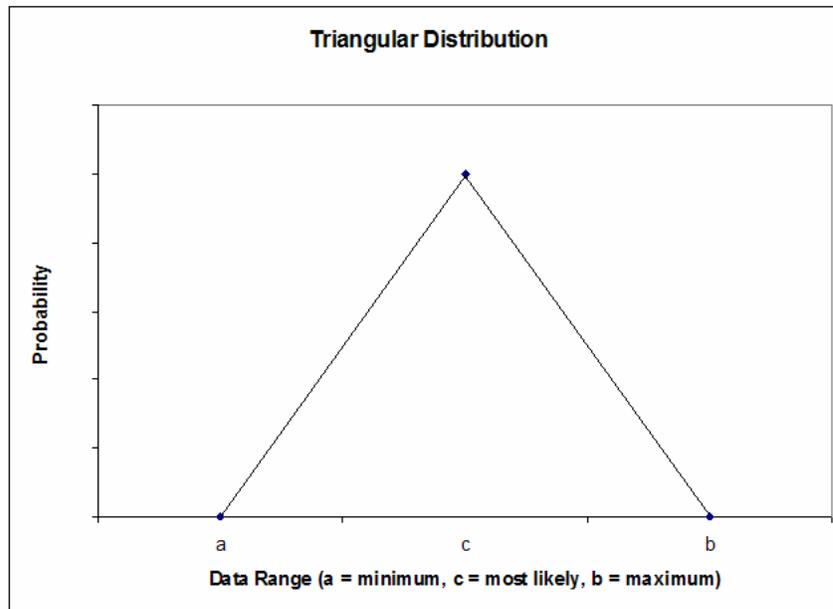


Figure 6. Graphical illustration of the triangular probability distribution showing the values of (a,c,b). A is the minimum value of the data range, c is the most likely value of the data range, and b is the maximum value of the data range.

The parameters of the MMD and GSD distributions were {15, 20, 25} μm and {1.8, 2.0, 2.2} respectively.

The TSP emission factor for the 40 bale per hour gin was defined by a triangular distribution {0.91, 1.39, 1.82} kg/bale. It was assumed that the emission factor would change based upon the trash content of the incoming seed cotton and so an emission factor range was assigned as ± 0.454 kg (± 1 lb) from the total 1996 AP-42 TSP (EPA,

1996) emission factor of 1.38 kg/bale (3.05 lbs/bale). Equation 17 was used to calculate the TSP emission rate for the gin.

$$ER_{TSP} = EF_{TSP} * GR * \frac{10^9}{3600} \quad (17)$$

where:

ER_{TSP} = TSP Emission Rate ($\mu\text{g/s}$),

EF_{TSP} = AP-42 TSP Emission Factor (kg/bale),

GR = Ginning Rate (bales/hour), and

$10^9/3600$ = unit conversion constants.

This TSP emission rate was then used as the emission rate in the Gaussian equation as shown in equation 18.

$$C_{10} = \frac{ER_{TSP}}{2\pi u \sigma_y \sigma_z} \exp\left(-\frac{1}{2} \frac{y^2}{\sigma_y^2}\right) \left\{ \exp\left(-\frac{1}{2} \frac{(z-H)^2}{\sigma_z^2}\right) + \exp\left(-\frac{1}{2} \frac{(z+H)^2}{\sigma_z^2}\right) \right\} \quad (18)$$

where:

C_{10} = ten minute average steady state concentration at a point (x, y, z) ($\mu\text{g/m}^3$),

u = average wind speed at stack height (m/s),

y = horizontal distance from plume centerline (m),

z = height of receptor with respect to ground (m),

H = effective stack height ($H=h+\Delta h$, where h = physical stack height and Δh = plume rise)(m), and

σ_y, σ_z = horizontal and vertical plume dispersion coefficients (m).

The values for σ_y and σ_z were calculated according to the procedure outlined in Turner (1994). Turner's method of approximating the Pasquill-Gifford plume spread

parameters (σ_y and σ_z) are used in ISCST3 to estimate the spread of the plume at different distances for the six atmospheric stability classes (A through F). Equations 19 through 21 are used by Turner (1994) to approximate the Pasquill-Gifford σ_y and σ_z .

$$\sigma_y = \frac{1000(X) \tan(T)}{2.15} \quad (19)$$

$$T = 8.3333 - 0.72382 \ln(X) \quad (20)$$

$$\sigma_z = aX^b \quad (21)$$

where:

X = downwind distance from source to receptor (km),

T = stability class dependent equation (degrees) (shown here for stability class D), and

a, b = stability class dependent constants.

The reader should note that the equation for T is stability class dependent and is shown here for stability class D only. The value of T represents one half of Pasquill's theta (Turner, 1994).

The downwind distances (X) used for both scenarios were 550 and 300 meters. These distances were chosen to demonstrate the effect of the particle size distribution on the required distance between the property-line and the emission point in order for the gin to be in compliance with the NAAQS at the property line.

The following assumptions were made for the model:

- Constant wind speed of 6 m/s,
- Stability class D,
- Average wind direction is directly from source to receptor ($y=0$),

- Concentrations calculated at ground level ($z=0$), and
- Effective stack height of 10 meters (typical cyclone height with rain cap preventing momentum plume rise).

These assumptions were made to simplify the execution of the model. Stability class D was chosen because it is the only stability class that can be used for both night time and day time conditions. According to the solar radiation/delta-T method (EPA, 2000), for stability class D to be used for daytime conditions, the wind speed must be greater than or equal to 6 m/s. There is no limit on the wind speed for stability class D at night. Thus the minimum daytime wind speed was assumed (6 m/s). The assumption of the average wind direction being directly from source to receptor and the decision to calculate the concentrations at ground level help to further simplify equation 18. The effective stack height of 10 meters was assumed to be the average height of the gas exit tube of a cyclone mounted on a commercially fabricated cyclone rack outside of a typical gin.

Equation 18 was evaluated at hourly intervals for ten days resulting in a total of 240 C_{10} concentrations for each scenario. The meteorological data and TSP emission rates used to calculate these C_{10} values were input to ISCST3 and the hourly concentrations over the ten days were calculated. The C_{10} concentration values and the hourly concentration values from ISCST3 matched one another exactly, confirming that what ISCST3 produces as hourly concentrations are, in fact, ten-minute concentrations. The particle size distributions for scenarios A and B were used with the modeled ten-minute average TSP concentrations downwind to calculate PM_{10} and $PM_{2.5}$.

concentrations that would result from ISCST3. These concentration values are known as the *ISCST3 Modeled Concentrations*.

The original TSP C_{10} values were then converted to C_{60} values using the power law model with P value of 0.5 as shown in equation 22.

$$C_{60} = C_{10} * \left(\frac{10}{60}\right)^{0.5} \quad (22)$$

where:

C_{60} = one hour TSP concentration ($\mu\text{g}/\text{m}^3$), and

10/60 = time ratio used to convert a 10 minute concentration to a 60 minute concentration.

The true PM_{10} and $\text{PM}_{2.5}$ concentrations were calculated using the TSP C_{60} values calculated using equation 9 and the lognormal distribution defined by $\text{MMD} = 12\mu\text{m}$ and $\text{GSD} = 2$ for scenario A and by $\text{MMD} = \{15, 20, 25\}\mu\text{m}$ and $\text{GSD} = \{1.8, 2.0, 2.2\}$ for scenario B. AP-42 (EPA, 1996) states that the PM_{10} emission factor for a cotton gin is 0.54 kg/bale (1.2 lbs/bale) and that the TSP emission factor is 1.38 kg/bale (3.05 lbs/bale). The ratio of these two emission factors implies that the percentage of a TSP concentration that is PM_{10} is 39%. The PM_{10} percentage of a lognormal particle size distribution characterized by an MMD of $12\mu\text{m}$ and GSD of 2.0 is 39%. The ranges used for the MMD and GSD for scenario B are taken from Redwine and Lacey (2001).

The lognormal mass density function is defined as:

$$f(d_p, \text{MMD}, \text{GSD}) = \frac{1}{d_p \ln(\text{GSD}) \sqrt{2\pi}} \exp\left[\frac{-(\ln(d_p) - \ln(\text{MMD}))^2}{2(\ln(\text{GSD}))^2}\right] \quad (23)$$

where:

d_p = particle diameter (μm), and

$f(d_p, \text{MMD}, \text{GSD})$ = mass fraction of particles having diameter d_p .

The mass fraction of particles less than a given size is found by integrating equation 23 from 0 to the particle diameter of interest, this is known as the lognormal cumulative distribution function. To find the concentration of a particular size range of particles in a TSP concentration, equation 24 was used.

$$C(x) = C_{60} * \int_0^x f(d_p, \text{MMD}, \text{GSD}) dd_p \quad (24)$$

where:

x = Particle size of interest (μm) (PM_{10} : $x = 10$, $\text{PM}_{2.5}$: $x = 2.5$), and

$C(x)$ = One hour concentration of particles equal to or less than $x \mu\text{m}$ (true PM_x concentration) ($\mu\text{g}/\text{m}^3$).

The d_{50} for the PM_{10} ambient air sampler in dust PSD scenarios A and B varied according to the triangular distribution {9.5, 10, 10.5} and the slope varied according to {1.4, 1.5, 1.6}. The d_{50} for the $\text{PM}_{2.5}$ sampler in both scenarios was constant at $2.5 \mu\text{m}$ with slope constant at 1.18. The lognormal density distribution function of the collection efficiency of a sampler is given by equation 25.

$$\eta(d_p, d_{50}, \text{slope}) = \frac{1}{d_p \ln(\text{slope}) \sqrt{2\pi}} \exp \left[\frac{-(\ln(d_p) - \ln(d_{50}))^2}{2(\ln(\text{slope}))^2} \right] \quad (25)$$

where:

$\eta(d_p, d_{50}, \text{slope})$ = collection efficiency of the sampler for particles of diameter d_p .

The cumulative distribution function of the collection efficiency curve is given by equation 26.

$$N(x, d_{50}, slope) = \int_0^x \eta(d_p, d_{50}, slope) \quad (26)$$

where:

$N(x, d_{50}, slope)$ = the cumulative collection efficiency of particles equal to or less than $x \mu\text{m}$ in diameter.

The collection efficiency $N(x, d_{50}, slope)$ is used in equation 27 to find the cumulative penetration efficiency.

$$P(x, d_{50}, slope) = 1 - N(x, d_{50}, slope) = 1 - \int_0^x \frac{1}{d_p \ln slope \sqrt{2\pi}} \exp\left[\frac{-(\ln d_p - \ln d_{50})^2}{2(\ln slope)^2}\right] \quad (27)$$

where:

$P(x, d_{50}, slope)$ = the cumulative penetration efficiency of particles less than $x \mu\text{m}$ in diameter.

The concentration measured by the sampler is given by equation 28.

$$M(MMD, GSD, d_{50}, slope) = C_{60} * \int_0^{\infty} f(d_p, MMD, GSD) * P(d_p, d_{50}, slope) dd_p \quad (28)$$

where:

$M(MMD, GSD, d_{50}, slope)$ = the measured concentration by the sampler using a one hour TSP concentration ($\mu\text{g}/\text{m}^3$).

Equation 28 was used in both scenario A and B to determine a “nominal measured” PM_{10} and $\text{PM}_{2.5}$ concentration. The term “nominal measured” is used

because the concentrations reported were not physically measured by a sampler in the field.

RESULTS

The results of the concentrations 300 and 550 meters downwind of the cotton gin in scenario A are shown in tables 11 and 12 respectively.

Table 11. Downwind 24-hour average concentration results from scenario A with constant PSD (MMD = 12, GSD = 2) at 300 meters downwind from a 40-bale/hour cotton gin.

Day	True Concentration ¹ (24-hour average)		ISCST3 Modeled Concentration ² (24-hour average)		Nominal Measured Concentration ³ (24-hour average)	
	PM ₁₀ μg/m ³	PM _{2.5} μg/m ³	PM ₁₀ μg/m ³	PM _{2.5} μg/m ³	PM ₁₀ μg/m ³	PM _{2.5} μg/m ³
1	336.2	10.0	823.4	24.6	347.1	11.8
2	342.2	10.2	838.3	25.0	352.3	12.0
3	334.3	10.0	818.9	24.4	347.4	11.7
4	340.7	10.2	834.6	24.9	351.6	11.9
5	340.2	10.1	833.4	24.9	352.3	11.9
6	339.0	10.1	830.4	24.8	348.1	11.9
7	336.5	10.0	824.3	24.6	349.0	11.8
8	351.2	10.5	860.4	25.7	365.0	12.3
9	356.8	10.6	873.9	26.1	370.7	12.5
10	346.9	10.3	849.7	25.3	360.9	12.1

1. Equations 18, 22, and 23 are used in the calculation of the True concentrations.
2. Equations 18, and 23 were used in the calculation of the ISCST3 Modeled concentrations.
3. Equations 18, 22, and 28 were used in the calculation of the Nominal Measured concentrations.

Table 12. Downwind 24-hour average concentration results from scenario A with constant PSD (MMD = 12, GSD = 2) at 550 meters downwind from a 40-bale/hour cotton gin.

Day	True Concentration ¹ (24-hour average)		ISCST3 Modeled Concentration ² (24-hour average)		Nominal Measured Concentration ³ (24-hour average)	
	PM ₁₀	PM _{2.5}	PM ₁₀	PM _{2.5}	PM ₁₀	PM _{2.5}
	µg/m ³	µg/m ³	µg/m ³	µg/m ³	µg/m ³	µg/m ³
1	146.0	4.4	357.7	10.7	150.8	5.1
2	148.6	4.4	364.1	10.9	153.0	5.2
3	145.2	4.3	355.7	10.6	150.9	5.1
4	148.0	4.4	362.5	10.8	152.7	5.2
5	147.8	4.4	362.0	10.8	153.0	5.2
6	147.2	4.4	360.7	10.8	151.2	5.2
7	146.2	4.4	358.0	10.7	151.6	5.1
8	152.6	4.5	373.7	11.1	158.5	5.3
9	155.0	4.6	379.6	11.3	161.0	5.4
10	150.7	4.5	369.0	11.0	156.7	5.3

1. Equations 18, 22, and 23 are used in the calculation of the True concentrations.
2. Equations 18, and 23 were used in the calculation of the ISCST3 Modeled concentrations.
3. Equations 18, 22, and 28 were used in the calculation of the Nominal Measured concentrations.

The results from scenario A show that the ratio of the true concentrations to the ISCST3 modeled concentrations is 2.45 for both the PM₁₀ and PM_{2.5} concentrations. The ratio of the nominal measured concentration to the true concentration is 1.04 and 1.17 for the PM₁₀ and PM_{2.5} concentrations respectively. The ratio of the quasi-measured concentration to the true concentration is known as the over-sampling rate. The all of the concentrations (true, ISCST3 modeled, and nominal measured) at the property line at 300 meters would cause the gin to exceed an air quality standard which applies the NAAQS for PM₁₀ (150 µg/m³ 24-hour average) at the property line. The true and quasi-measured PM₁₀ concentrations at 550 meters could be considered to be marginal when used to determine compliance with the NAAQS for PM₁₀. However, the

ISCST3 modeled concentrations still indicate an exceedance at the 550-meter property line. The PM_{2.5} concentrations at either 300 or 550 meters down wind were negligible compared to the NAAQS of 65 µg/m³ (24-hour average).

Tables 13 and 14 show the results of scenario B at 300 and 550 meters downwind from a 40-bale/hour cotton gin.

Table 13. Downwind 24-hour average concentration results from scenario B with simulated PSD (MMD = {15, 20, 25}, GSD = {1.8, 2.0, 2.2}) at 300 meters downwind from a 40-bale/hour cotton gin.

Day	True Concentration ¹ (24-hour average)		ISCST3 Modeled Concentration ² (24-hour average)		Nominal Measured Concentration ³ (24-hour average)	
	PM ₁₀ µg/m ³	PM _{2.5} µg/m ³	PM ₁₀ µg/m ³	PM _{2.5} µg/m ³	PM ₁₀ µg/m ³	PM _{2.5} µg/m ³
1	134.3	1.3	329.1	3.3	162.9	1.7
2	133.5	1.5	327.0	3.7	163.5	1.9
3	127.7	1.3	312.9	3.3	156.4	1.7
4	146.2	1.6	358.1	3.8	174.9	2.0
5	146.4	1.7	358.7	4.1	178.3	2.1
6	135.8	1.4	332.7	3.5	163.9	1.8
7	154.2	1.8	377.8	4.3	186.4	2.2
8	134.8	1.2	330.3	3.0	164.9	1.6
9	135.3	1.3	331.4	3.2	163.6	1.7
10	160.9	1.8	394.2	4.3	195.1	2.2

1. Equations 18, 22, and 23 are used in the calculation of the True concentrations.
2. Equations 18, and 23 were used in the calculation of the ISCST3 Modeled concentrations.
3. Equations 18, 22, and 28 were used in the calculation of the Nominal Measured concentrations.

Table 14. Downwind 24-hour average concentration results from scenario B with simulated PSD (MMD = (15, 20, 25), GSD = (1.8, 2.0, 2.2)) at 550 meters downwind from a 40-bale/hour cotton gin.

Day	True Concentration ¹ (24-hour average)		ISCST3 Modeled Concentration ² (24-hour average)		Nominal Measured Concentration ³ (24-hour average)	
	PM ₁₀ μg/m ³	PM _{2.5} μg/m ³	PM ₁₀ μg/m ³	PM _{2.5} μg/m ³	PM ₁₀ μg/m ³	PM _{2.5} μg/m ³
1	58.3	0.6	142.9	1.4	70.8	0.7
2	58.0	0.7	142.0	1.6	71.0	0.8
3	55.5	0.6	135.9	1.4	67.9	0.7
4	63.5	0.7	155.5	1.7	76.0	0.9
5	63.6	0.7	155.8	1.8	77.4	0.9
6	59.0	0.6	144.5	1.5	71.2	0.8
7	67.0	0.8	164.1	1.9	81.0	1.0
8	58.6	0.5	143.5	1.3	71.6	0.7
9	58.8	0.6	143.9	1.4	71.1	0.7
10	69.9	0.8	171.2	1.9	84.8	1.0

1. Equations 18, 22, and 23 are used in the calculation of the True concentrations.
2. Equations 18, and 23 were used in the calculation of the ISCST3 Modeled concentrations.
3. Equations 18, 22, and 28 were used in the calculation of the Nominal Measured concentrations.

The results for scenario B show similar differences between the true and ISCST3 modeled concentrations for both PM₁₀ and PM_{2.5} as those of scenario A. The ratio of the true to ISCST3 modeled concentrations was 2.45 for both the PM₁₀ and PM_{2.5} concentrations at both 300 and 550 meters down wind. The over-sampling rate increased for both the PM₁₀ and PM_{2.5} concentrations to 1.21 and 1.26 respectively. The increase in over-sampling rate was a consequence of the increase in the MMD and GSD

of the PSD of the dust sampled. Over the ten-day period, the average MMD was $19.8\mu\text{m}$ and the average GSD was 2.0. For both 300 and 550 meters downwind, the PM_{10} true concentrations indicate that the gin would be in compliance with the NAAQS of $150\ \mu\text{g}/\text{m}^3$ (24-hour average) at the property line. The ISCST3 modeled concentrations at either distance (300 or 550 meters) result in an exceedance of the NAAQS for PM_{10} . The quasi-measured PM_{10} concentrations at 300 meters were not in compliance with the NAAQS for PM_{10} . However, the quasi-measured PM_{10} concentrations at 550 meters were in compliance with the NAAQS for PM_{10} .

All of the $\text{PM}_{2.5}$ concentrations at either distance under scenario B were negligible when compared to the NAAQS for $\text{PM}_{2.5}$ of $65\ \mu\text{g}/\text{m}^3$ (24-hour average).

CONCLUSIONS

The following conclusions can be drawn from the results of this work.

- Using the power law (with $P = 0.5$) to correct for the concentration time averaging errors associated with concentrations predicted by ISCST3 results in more accurate downwind estimations of PM_{10} and $\text{PM}_{2.5}$ concentrations. On average, the concentrations from ISCST3 will be reduced by a factor of 2.45 using the power law with $P = 0.5$.
- The particle size distribution of the PM plays a significant role in accurately measuring downwind concentrations of PM_{10} and $\text{PM}_{2.5}$ when measuring concentrations with FRM samplers. PM_{10} concentration measurements of PM with MMDs close to $10\mu\text{m}$ will result in concentration measurements close to the true concentration of PM_{10} .

However, as the MMD of the dust increases over $10\mu\text{m}$, the over-sampling rate also increases.

- Assuming a typical PSD range as specified by Redwine and Lacey (2001), the $\text{PM}_{2.5}$ fraction of TSP concentrations from agricultural sources (such as cotton gins) are negligible when compared to regulatory limits (NAAQS for $\text{PM}_{2.5} = 65 \mu\text{g}/\text{m}^3$ 24-hour average).

CHAPTER V

CONCLUSIONS

The following conclusions can be drawn from the research presented here:

- Accurate TSP concentration measurements can be made with a low volume sampler given that a properly designed low volume TSP inlet head is used. The low volume TSP samplers are more robust in maintaining the required flow rate over the sampling test duration primarily due to the following reasons:
 - a. The air passing through the 47mm diameter filter has a face velocity 2.85 times less than that of the FRM high volume TSP sampler.
 - b. Under the same concentrations, the mass of collected PM on the high volume TSP sampler filters is 286% higher than that of the low volume TSP sampler filter resulting in a lower pressure drop across the low volume TSP sampler filter.
- The particle size distribution of the dust sampled downwind from a source has a significant impact on the accuracy of the concentration measurements when using FRM PM₁₀ and PM_{2.5} samplers.
- The concentration time averaging period assumption that the concentrations predicted by a Gaussian model using the Pasquill-Gifford atmospheric stability parameter estimates are one hour averages leads to the over-prediction of downwind concentrations by a factor of 2.5.

- The power law using stability class and downwind distance dependent P values provides a means by which to correct for the time averaging errors in the current dispersion model (ISCST3).

FUTURE WORK

The work presented here shows that there is much work to be done to improve the accuracy of concentration measurements and predictions downwind from agricultural LLPS. Some of the specific areas of interest are:

1. Determine the uncertainty associated with taking TSP measurements and performing PSD analyses to determine PM_{10} concentrations.
2. Develop new ways to accurately measure PM_{10} concentrations from agricultural PM sources given their inherent large PSD.
3. Develop a standard reference calibration material and procedure to determine the absolute accuracy of PM samplers.
4. Develop more accurate emission factors for cotton gins not only defining the mass emission rates but also characterizing the PSD of the emitted dust.
5. Determine more accurate collection efficiencies for cyclones used as the primary abatement system on cotton gins.
6. Develop new methods to correct the error of ISCST3 in using a ten-minute concentration as a one-hour concentration.

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APPENDIX A**PUBLICATION STATUS OF MANUSCRIPTS USED IN THIS THESIS**

The manuscript titled “The Design and Evaluation of a Low Volume Total Suspended Particulate Sampler” (CHAPTER II) has been submitted to the journal: *Transactions of the ASAE* and has been accepted for publication. Three reviewers made comments on the manuscript. All of the comments made by the reviewers have been addressed and a revised manuscript has been re-submitted for publication. The revised manuscript is included in Chapter II.

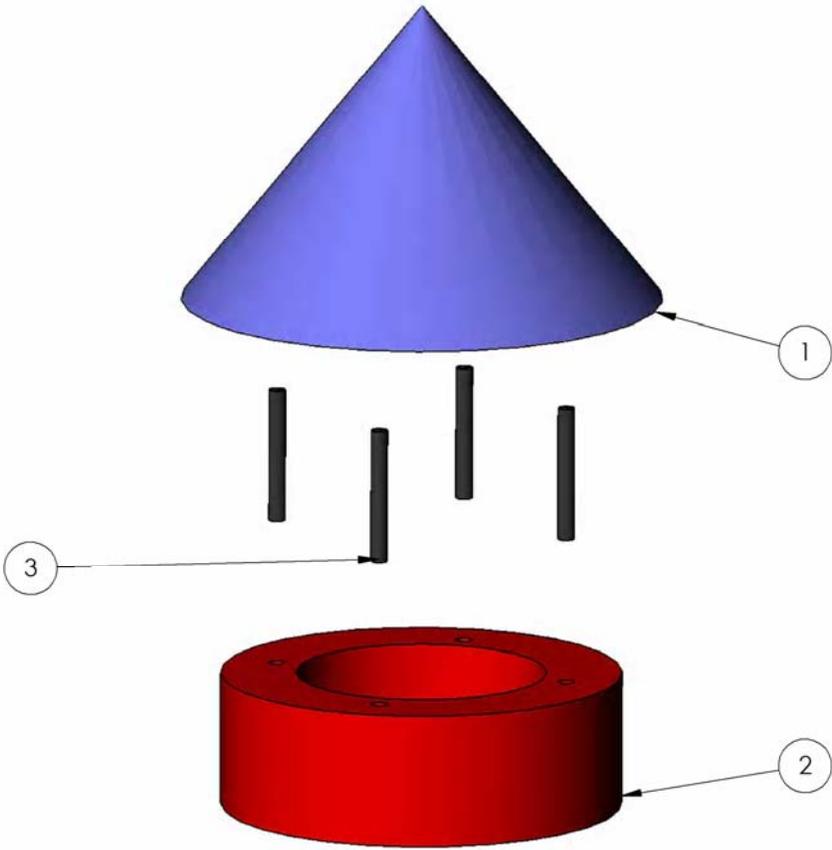
The manuscript titled “Dispersion Modeling of Agricultural Low Level Point Sources” (CHAPTER III) has been submitted to the journal: *Transactions of the ASAE* and has been accepted for publication. Three reviewers made comments on the manuscript. The comments made by the reviewers have not been addressed in the manuscript version included in Chapter III.

The manuscript titled “A Simulated Approach to Estimating PM₁₀ and PM_{2.5} Concentrations Downwind from Cotton Gins” (CHAPTER IV) has been submitted to the journal: *Transactions of the ASAE* and has been accepted for publication. Two reviewers commented on the manuscript. All of the comments made by the reviewers have been addressed and a revised manuscript has been re-submitted for publication. The revised manuscript is included in Chapter IV.

APPENDIX B

DETAILED DRAWINGS OF THE LOW VOLUME TSP SAMPLER

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Hood Cone		1
2	Hood Base		1
3	Spring Pin		4



DIMENSIONS ARE IN INCHES			NAME	DATE	
TOLERANCES:			DRAWN	JDW	08/02
FRACTIONAL ±			CHECKED		
ANGULAR: MACH ±1 BEND ±			ENG APPR.		
TWO PLACE DECIMAL ±			MFG APPR.		
THREE PLACE DECIMAL ±0.005			Q.A.		
MATERIAL			COMMENTS:		
NEXT ASSY	USED ON	FINISH	SIZE DWG. NO. A All Drawing Sheets REV.		
APPLICATION		DO NOT SCALE DRAWING	SCALE:1:2	WEIGHT:	SHEET 1 OF 5

Figure 7. Exploded view of the low volume TSP sampler.

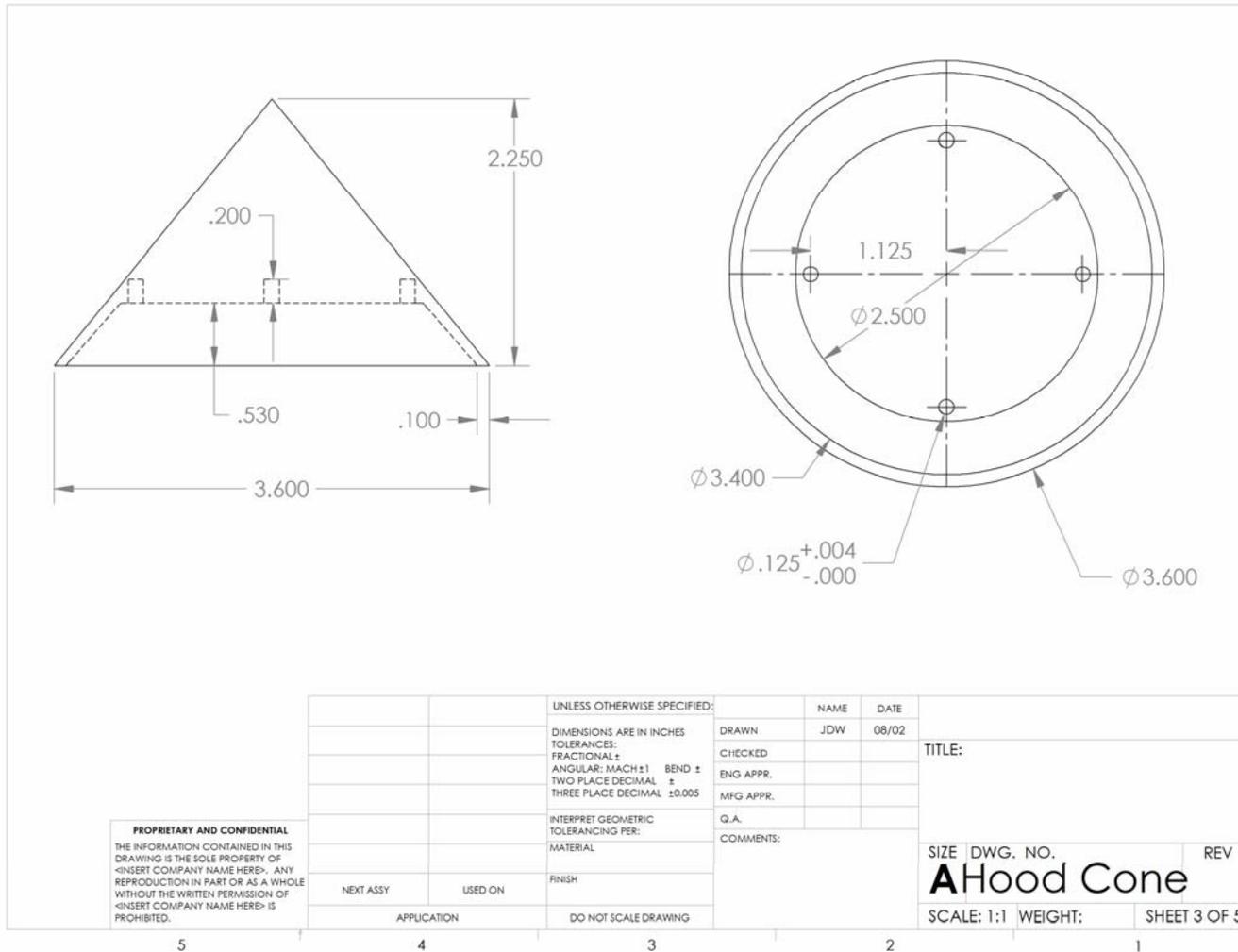


Figure 9. Detailed drawing of the hood cone section of the low volume TSP sampler.

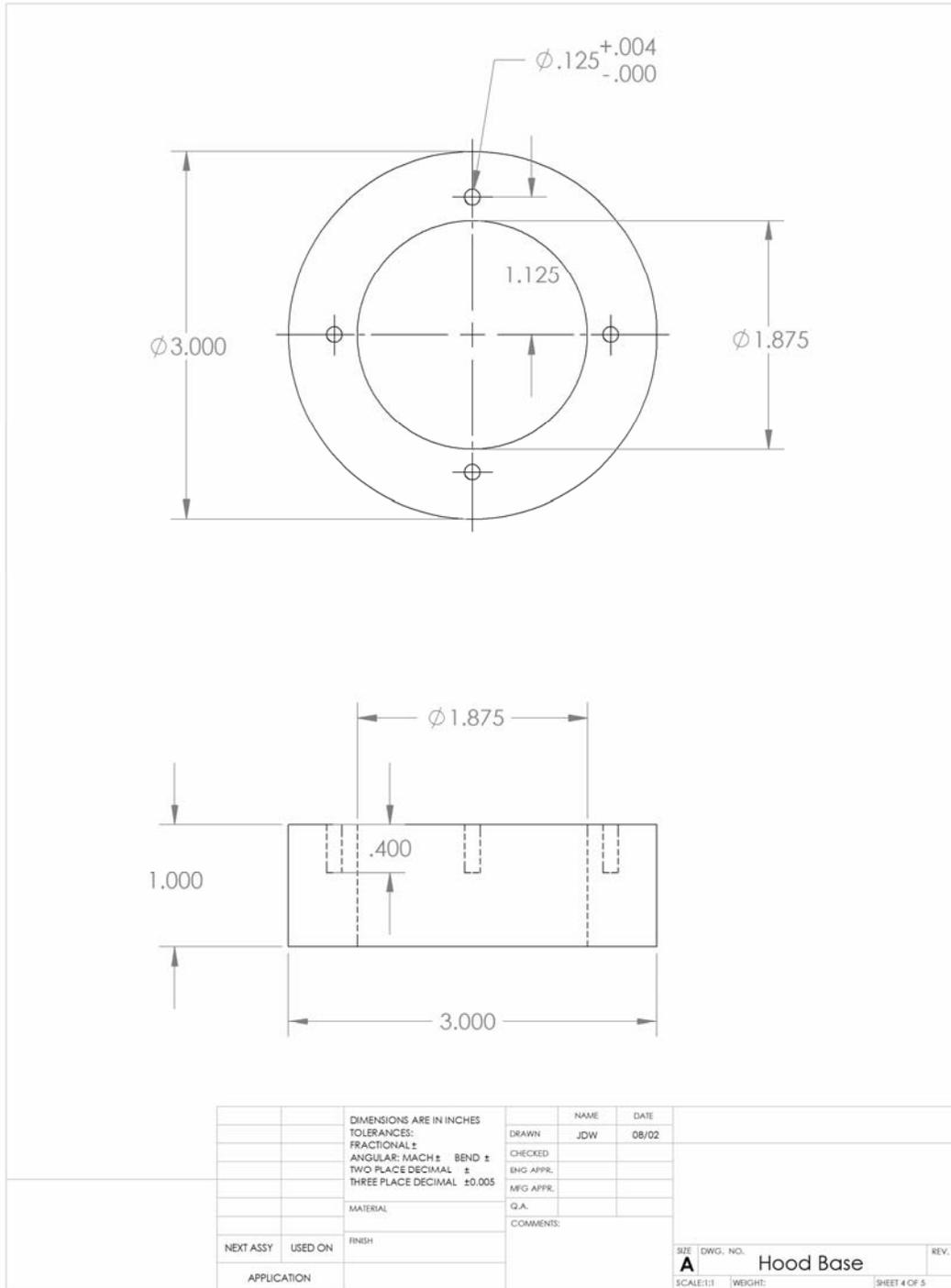


Figure 10. Detailed drawing of the hood base section of the low volume TSP sampler.

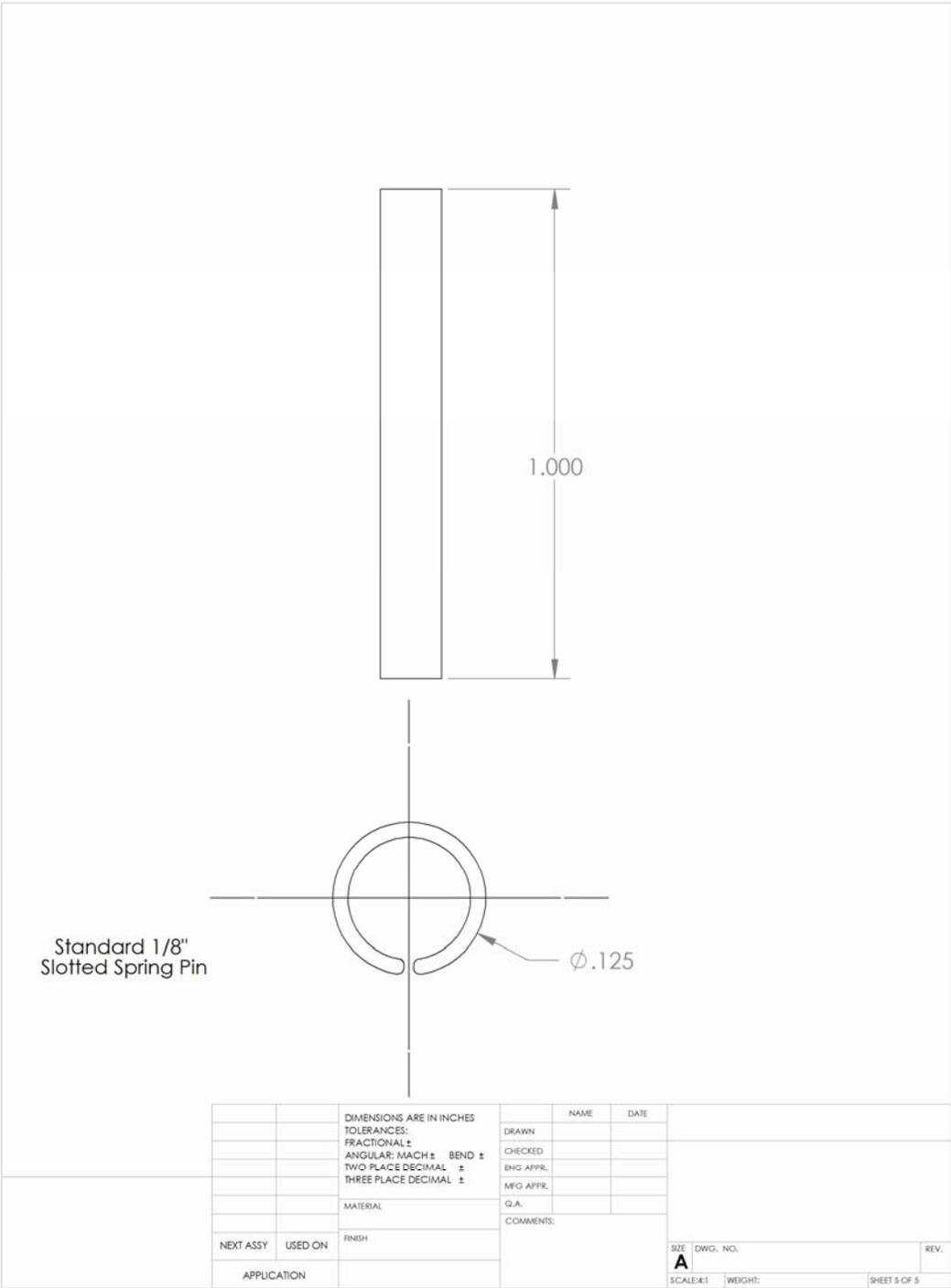


Figure 11. Detailed drawing of the standard 1/8 inch spring pin used in the low volume TSP sampler.

APPENDIX C
WEIGHING PROCEDURE FOR HIGH AND LOW VOLUME SAMPLER
FILTERS

The following procedure was used to weigh the filters used by the high and low volume TSP samplers. The procedures outlined below are presented in the operating instructions manual for the Mettler – Toledo AG245 balance (Mettler – Toledo, 1994).

Preparing the Filters:

Both new and loaded filters must be conditioned in an environmental chamber for 24 hours before weighing with the Mettler-Toledo AG245 balance. The conditions of the air in the chamber must be held at 25°C and 47% relative humidity.

Unloaded (New) low and high volume sampler filters should be numbered using a permanent marker before weighing.

Low Volume Filters:

- a. Write the filter number clearly on one side of the unloaded 47mm diameter filter.
- b. Place the newly numbered filter in a new 50mm diameter petri-dish. Do not number the petri-dish.
- c. Stack the petri-dishes loaded with numbered filters in order by filter number in stacks of 25.

High Volume Filters:

- a. Write the filter number clearly on one side of the unloaded 20.3 x 25.4 cm (8 x 10 inches) filter.
- b. Write the same number on a new anti-static bag.
- c. Fold the filter in half twice and place the folded filter into the anti-static bag.

- d. Stack the numbered anti-static bags loaded with filters in stacks of 25.

Calibrating the Scale:

Once the scale has been plugged into the electrical wall outlet for 30 minutes, press the <<On/Off>> button to turn the scale on. Calibrate the scale using the following steps.

- 1) Press and briefly hold (1-2 seconds) the <<1/10d / Cal>> button on the control panel to start the self-calibration routine.
- 2) The scale will perform the internal calibration routine. The routine is finished once the display message “cal done” appears. If the “abort” message appears during the calibration routine, press the <<C>> button to clear the scale control panel. Repeat step (1) until the calibration routine finishes successfully.
- 3) Tare the scale readout by pressing the <<O/T>> button.

Weighing a Batch of Filters:

- 1) Open the scale weight spreadsheet on the computer next to the scale table to record the weights into.
- 2) Enter the number of the filters that are to be weighed into the spreadsheet.
- 3) Open the balance tray door and place the filter holder apparatus with anti-static tray onto the balance pan.
- 4) Close the balance tray door.
- 5) Tare the scale by pressing the <<O/T>> button.

- 6) Press the <<1/10 d>> button on the scale control panel to add one decimal place to the readout number range.
- 7) Open the balance tray door and place either the anti-static bag containing the numbered filter (for high volume sampler filter weighing) or the 47mm numbered filter (for low volume sampler filter weighing) on the filter holder apparatus. For low volume sampler filter weighing, weigh only the numbered filter not the filter and petri-dish combined.
- 8) Once the “o” symbol disappears from the readout, press the <<menu>> button. A three second countdown will begin.
- 9) Once the countdown has finished, the stable weight will appear on the readout. Record this weight in the spreadsheet.
- 10) Open the balance tray door and remove the anti-static bag or the low volume filter.
- 11) Close the balance tray door.
- 12) Tare the scale by pressing the <<O/T>> button.
- 13) Repeat steps 7 – 12 for a total of 3 weights before weighing a different filter.
- 14) Perform the weighing procedure for all of the numbered filters.

Assuring the Quality of the Filter Weights

The standard deviation of the filter weights calculated by the spreadsheet should be less than approximately 0.00003 grams. If the standard deviation of the three weights is above this value, re-weigh the filter until the standard deviation of the three weights is

less than 0.00003 g. If the problem persists the scale may need to be recalibrated or allowed to “warm up” for about 10 minutes before weighing again.

Scale Technical Data

Model: Mettler-Toledo AG245

Readability: 0.01 mg

Max Capacity: 41 g

Repeatability: 0.02 mg

Linearity: 0.03 mg

References:

Mettler – Toledo AG. 1994. Operating instructions for Mettler – Toledo AG balances.

Greifensee, Switzerland: Mettler – Toledo AG.

APPENDIX D
SHARP EDGE ORIFICE METER CALIBRATION PROCEDURE

The following procedure was used to calibrate the orifice meters used with the low volume TSP samplers.

Equipment Used:

1. Aalborg GFM Mass Flow Meter (GFM373, 0-20 slpm)

Range: 0 – 20 slpm

Accuracy: $\pm 1.5\%$ Full Scale (F.S.)

2. Electrical transformer for mass flow meter

3. Fluke multimeter (867B Graphical Multimeter)

Accuracy: $\pm 0.025\%$ basic accuracy

4. Digital differential pressure gauge (Dwyer Series 475-1 Mark III digital manometer)

Range: 0 – 19.99 in W.C.

Accuracy: $\pm 0.5\%$ F.S. (15.6 – 25.6°C), $\pm 1.5\%$ F.S. (0 – 15.6 and 25.6 – 40°C)

5. Digital temperature, barometric pressure, and relative humidity sensor (Davis Perception II)

6. Needle valve

7. Compressed air source

8. 3 - 3 ft pieces of 3/8" diameter plastic tubing

9. 2 – 2 ft pieces of 1/8" diameter plastic tubing

10. 6 steel hose clamps

Setup:

1. Connect the needle valve to the compressed air source using one piece of the plastic tubing.
2. Connect the open end of the needle valve to the upstream port on the mass flow meter using a piece of the plastic tubing.
3. Connect the downstream port of the mass flow meter to the upstream port on the orifice meter.

**The upstream port of the orifice meter is on the side with the pressure tap furthest from the orifice plate.*

4. Plug the electrical transformer for the mass flow meter into the wall outlet and connect it to the mass flow meter.

**The mass flow meter must be plugged in for 15 minutes before taking flow measurements.*

5. Connect the RS-232 cable to the communication port on the mass flow meter and tighten the holding screws.
6. Connect the multimeter leads to the free ends of the two wires of the RS-232 cable. Turn on the multimeter and set it to read in the 1 volt range.
7. Connect the positive pressure port of the digital manometer to the upstream pressure tap on the orifice meter with a piece of the 1/8" diameter tubing. Connect the negative port to the downstream side with the other piece of 1/8" diameter tubing.

Procedure:

1. Record the barometric pressure, temperature, and relative humidity from the Davis Perception II instrument onto the log sheet.
2. With no air flowing through the system, record the voltage from multimeter on the log sheet. This is the “zero flow voltage”.
3. Turn on the differential pressure gauge and zero the readout by turning the small steel knob between the pressure ports. Set the readout units to be “in WC” by pressing the E/M button.
4. Turn the knob on the needle valve counter clockwise until the display on the multimeter reads $5.0 \pm .05$ volts.
5. Record the actual voltage and differential pressure on the log sheet.
6. Turn the knob on the needle valve clockwise until the voltage reading is approximately 0.1V less than the previous reading.
7. Record the actual voltage and differential pressure on the log sheet.
8. Repeat steps 6 and 7 until the multimeter reads approximately 2.5 volts.
9. Once all of the readings have been taken, convert the voltage readings to flow readings using equation 29.

$$Q = 4.0076(V) - 4.0076(V_z) \quad (29)$$

where:

Q = standard flow rate (standard liters per minute),

V = voltage reading (volts), and

V_z = zero flow voltage (volts).

The standard conditions of the air used by the mass flow meter are 21.1°C and 14.7 PSIA.

10. Calculate the K values for each flow/differential pressure point using equation 30.

$$K = \frac{Q}{169.2D_o^2 \sqrt{\frac{\Delta P}{\rho_a}}} \quad (30)$$

Where:

D_o = Orifice diameter (inches),

ΔP = differential pressure (in WC), and

ρ_a = density of standard air (0.075 lb/ft³), and

169.2 = unit conversion constant.

11. The average of all the K values determined above is the K value for the orifice meter.

APPENDIX E

DIFFERENTIAL PRESSURE TRANSDUCER CALIBRATION PROCEDURE

The following procedure was used to determine the differential pressure (in W.C.) vs. output current (ma) for the differential pressure transducers used with the low volume and high volume TSP samplers.

Equipment:

11. Differential pressure transducer (Omega PX274-30DI, Omega Engineering inc., Stamford, CT)

Accuracy: $\pm 1\%$ Full Scale (FS) (linearity, repeatability, and hysteresis)

Operating Temperature: -18 to 80°C ($0 - 175^{\circ}\text{F}$)

Media Compatibility: Clean dry air or inert gas

Environment: 10 to 90% RH non-condensing

Excitation: 12 to 40 Vdc

Output: 4 – 20 mA

Supply Current: 20 mA maximum

Load Impedance: 1.6 K ohms at 40 Vdc maximum

12. Electrical transformer for differential pressure transducer

13. Fluke multimeter (867B Graphical Multimeter)

Accuracy: $\pm 0.025\%$ basic accuracy

14. Digital differential pressure gauge (Dwyer Series 475-1 Mark III digital manometer)

Range: 0 – 19.99 in W.C.

Accuracy: $\pm 0.5\%$ F.S. ($15.6 - 25.6^{\circ}\text{C}$), $\pm 1.5\%$ F.S. ($0 - 15.6$ and $25.6 - 40^{\circ}\text{C}$)

15. Digital temperature, barometric pressure, and relative humidity sensor (Davis Perception II)
16. Air pressure generator (Beckman Air Comparison Pycnometer 93001, Beckman Instruments, inc., Irvine, CA)
17. 3 – 2ft pieces of 3/16” ID Tygon tubing
18. 1 - 3/16” OD plastic “T” connector for Tygon tubing
19. Wooden test stand

Procedure:

1. Mount the pressure transducer vertically on the test stand with the pressure taps pointing downward.
2. Remove the two screws from the front face of the pressure transducer and pull off the front cover.
3. Connect the pressure generator to the plastic “T” using one piece of the Tygon tubing.
4. Connect one end of the “T” connector to the “+” port of the differential pressure gauge.
5. Connect the open end of the “T” connector to the “+” port of the differential pressure transducer.
6. Locate the “+” and “-“ terminals on the differential pressure transducer.
7. Connect the “+” terminal on the pressure transducer to the “+” terminal on the power transformer. Connect the “-“ terminal on the pressure transducer to the “-“ terminal on the power transformer.

DO NOT PLUG THE TRANSFORMER INTO THE WALL AT THIS TIME!

8. Connect the multimeter in series with the pressure transducer and power transformer on the “-“ side as shown in figure 12.

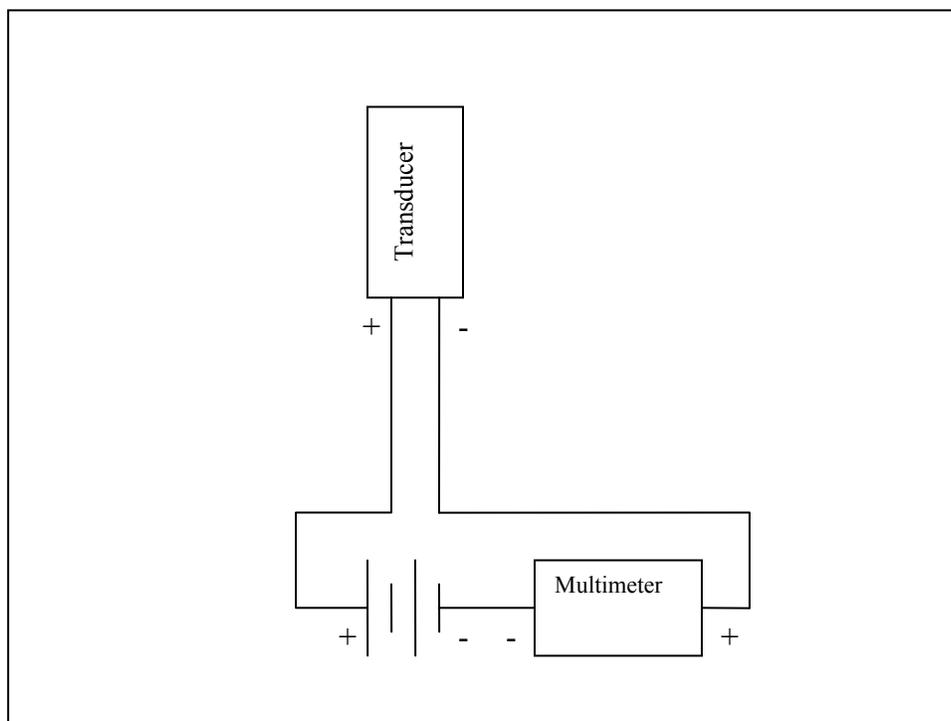


Figure 12. Wiring schematic for calibrating the differential pressure transducers used with the low and high volume TSP samplers.

9. Locate the jumper settings for the 0 – 7.5 in W.C. range in the users guide for the PX274 and make sure that the jumpers are set correctly on the differential pressure transducer.
10. Plug the power transformer into the wall electrical outlet.
11. With no pressure applied to the “+” side of the differential pressure transducer, adjust the zero trimmer to obtain the desired low pressure output. The low

pressure output should be as close to 4 mA as possible as read by the multimeter set to read in the mA range.

12. Record the low pressure reading from the differential pressure gauge (in W.C.) and the corresponding current output (mA) on the log sheet. Also record the temperature, relative humidity, and barometric pressure from the digital weather station.
13. Turn the knob on the pressure generator until the differential pressure gauge reads 0.5 in W.C. and record the corresponding current output from the differential pressure transducer.
14. Repeat step 13 over the operating range of 0 to 7.5 in W.C.
15. Once all of the differential pressure/output current data points have been taken, input them into a statistical software package (SPSS or SAS) and perform a linear regression analysis on the data. Obtain the linear regression equation coefficients and the coefficient of determination (R^2) from the statistical software output.

APPENDIX F

DUST PARTICLE DENSITY DETERMINATION PROCEDURE

The following procedure was used to determine the particle density of the three dusts used (corn starch, fly ash, and aluminum oxide). The procedures outlined here are presented in the AccuPyc 1330 Pycnometer Operator's Manual (Micromeritics, 2000).

Equipment:

1. AccuPyc 1330 Pycnometer (AccuPyc 1330 Pycnometer, Micromeritics

Instrument Corp., Norcross, GA)

Precision: Reproducibility typically to within $\pm 0.01\%$ of the nominal full-scale cell chamber volume. The nominal full scale cell chamber volume is the sample capacity. Reproducibility guaranteed to within $\pm 0.02\%$ of the nominal full-scale volume on clean, dry, thermally equilibrated samples.

Accuracy: Accurate to within $\pm 0.03\%$ of reading plus 0.03% of the nominal full scale cell chamber volume.

Sample Volume: 0.5 to 100 cm³

2. Mettler-Toledo AG245 balance

Readability: 0.01 mg

Max Capacity: 41 g

Repeatability: 0.02 mg

Linearity: 0.03 mg

3. Calibration Standards

Two – 23/32" diameter Tungsten Carbide calibration balls calibrated with master balls calibrated by the NIST Test No. 821 25B 592-97 (Precision Ball and Gauge Co., Alvadore, OR).

Calibration Procedure:

The pycnometer should be recalibrated anytime it is restarted. The following procedure should be followed to calibrate the pycnometer.

1. Check the calibration of the pycnometer by performing an analysis on the empty sample cup to see how close the average volume is to zero. If the volume returned is not within $\pm 0.05\%$ of full scale, recalibrate the pycnometer using the following procedure.

When recalibrating the pycnometer, you should set up the calibration parameters so that 10 purges and 10 runs are performed. Perform the procedures in step #8 below before beginning the calibration routine.

2. Place an empty cup in the cell chamber.
3. Replace the cell chamber cap.
4. Press [] + [·] to begin the calibration procedure.
5. The following messages will be displayed:

Volume of cal std: 1.0000 cm³

Enter the volume of the calibration standard used and press [ENTER].

[Enter] to start [Escape] to cancel

Press [ENTER] to begin the calibration procedure. The pycnometer will beep 3 times once the first phase of the calibration is complete.

Insert cal std [Enter] to start

Insert the calibration standard in the cup in the cell chamber. Use both calibration balls for calibrating the 10 cm³ pycnometer.

6. Replace the cell chamber cap and press [ENTER].
7. During each calibration and analysis procedure, the pycnometer automatically zeros the pressure transducer. This can be done manually by pressing [] + [0].
8. Entering the analysis and calibration parameters
 - a. Press [] + [2] to display and edit the analysis and calibration parameters
 - b. Press [CHOICE] until *Analysis Parameters* is displayed and press [ENTER].
 - c. Enter the number of purges to be performed (10) and press [ENTER].
 - d. Enter the purge fill pressure and press [ENTER]. The purge fill pressure should be 19.5 psig.
 - e. Enter the number of runs to be performed (10) and press [ENTER].
 - f. Enter the run fill pressure (19.5 psig) and press [ENTER].
 - g. Enter the Equilibration Rate (0.005 psig/min) and press [ENTER].
 - h. Enter no when asked "*Use run precision?*" and press [ENTER]
 - i. Enter the number "0.05" when asked "*Percent full scale?*" and press [ENTER]
 - j. Press [SAVE] to save the changes made and return to the display mode.

Performing an Analysis:

The cell chamber and cap must be kept clean at all times. Use a lint-free cloth to wipe particles from the surfaces before performing an analysis.

1. Check the helium tank pressure on the regulator to make sure that it is above 200 psig. Lower tank pressures may cause inadequate sample saturation.
2. Set the regulator pressure to 2 psig above the user defined fill pressure for purging and running (see step 8 above). This pressure should be about 21.5 psig.
 - a. Press [] + [1] to enter manual mode.
 - b. Press [8] (expand) and [9] (vent) to open the expansion and vent valves. When the valves are open, the indicators above the keys are turned on.
 - c. Press [7] (fill) to open the fill valve.
 - d. Set the regulator pressure control knob on the tank to the desired pressure (21.5 psig).
 - e. Press [7] (fill) to close the fill valve. Press [SAVE] to return to display mode.
3. Setting report options
 - a. Press [] + [2].
 - b. Press [CHOICE] until *Report Options* is displayed and press [ENTER].
 - c. Select density and press [ENTER].
 - d. Select Yes for *Request Sample ID?* This option allows the user to enter a sample identification number containing 1 to 20 numbers and dashes.
 - e. Press [ENTER].
 - f. For *Transmission Format*, select single column.
 - g. The *Report Destination* should be set to display. Press [ENTER].

h. Press [SAVE].

4. Preparing the sample.

- a. Keep the cap on the cell chamber except when actually inserting or removing a sample. If the chamber remains uncapped, temperature instability will occur which could affect analysis results.
- b. Weigh the empty sample cup and record the weight on the log sheet.
- c. Sieve a sample of the dust to be analyzed using a 100 micrometer screen mesh.
- d. Place a quantity of the sample in the sample cup. Use as large a quantity of sample as possible. Try to fill the cup at least two-thirds full. Pack powders and fluffy materials (if permissible) to obtain maximum sample weight in the cup.
- e. Dry the sieved sample in the sample cup according to the procedures outlined in the ASTM Designation: D 3173 – 00 (ASTM, 2000).
- f. Once the sample has been dried and allowed to cool to room temperature in a desiccator, weigh the sample cup containing the dried sample.
- g. Subtract the empty cup weight from the weight of the cup containing the dried sample to obtain the dried sample weight.
- h. Remove the cell chamber cap.
- i. Insert the sample cup with sample into the cell chamber.
- j. Replace the cell chamber cap.

5. Starting the Analysis

- a. To start the analysis press [] + [4].
 - b. Enter the sample ID and press [ENTER] when prompted.
 - c. Enter the dried sample weight when prompted for the sample weight and press [ENTER]. The sample weight should be entered in grams.
 - d. Press [ENTER] to begin the analysis.
6. Viewing the Analysis Results
- a. The pycnometer will beep three times when the analysis is complete.
Remove the sample from the test chamber and press [CHOICE] to cycle through the error messages.
 - b. Once all of the error messages have been displayed, the average density of the user defined number of runs is displayed on the display along with the deviation from the mean. Press [ENTER].
 - c. When the *Reload* prompt is displayed, you may begin another operation.

References

- Micromeritics Instrument Corp. 2000. AccuPyc 1330 Pycnometer Operator's Manual v3.xx. Norcross, GA: Micromeritics Instrument Corp.
- ASTM. 2000. ASTM D 3173 – 00. Standard test method for moisture in the analysis sample of coal and coke. West Conshohocken, PA: ASTM.

APPENDIX G

PLOTS OF THE PRESSURE TRANSDUCER CURRENT RECORDED BY THE

HOBO DATA LOGGERS FOR TWO LOW VOLUME AND TWO HIGH

VOLUME TSP SAMPLERS

Figures 13 through 16 show the current output from the differential pressure transducer as measured and logged by the HOBO data loggers for HT1, HT2, TSP_{LV}#1, and TSP_{LV}#2 for test 7 (fly ash dust). The current (mA) on the vertical axis is directly related to the pressure drop across the sharp edged orifice through a pressure transducer specific calibration equation. The pressure drop across the orifice is used to calculate the volume flow rate air passing through the filters.

The air flow rate for the high volume samplers (HT1, and HT2) decreased with time during the test. This was primarily due to the increase in pressure drop across the filter as the mass of PM on the filter increased. To correct for this, the speed of the fan was increased several times during the test.

The air flow rate for both low volume samplers (TSP_{LV}#1 and TSP_{LV}#2) was almost constant over the test period. The flow rate for both of the low volume samplers was not adjusted during the test.

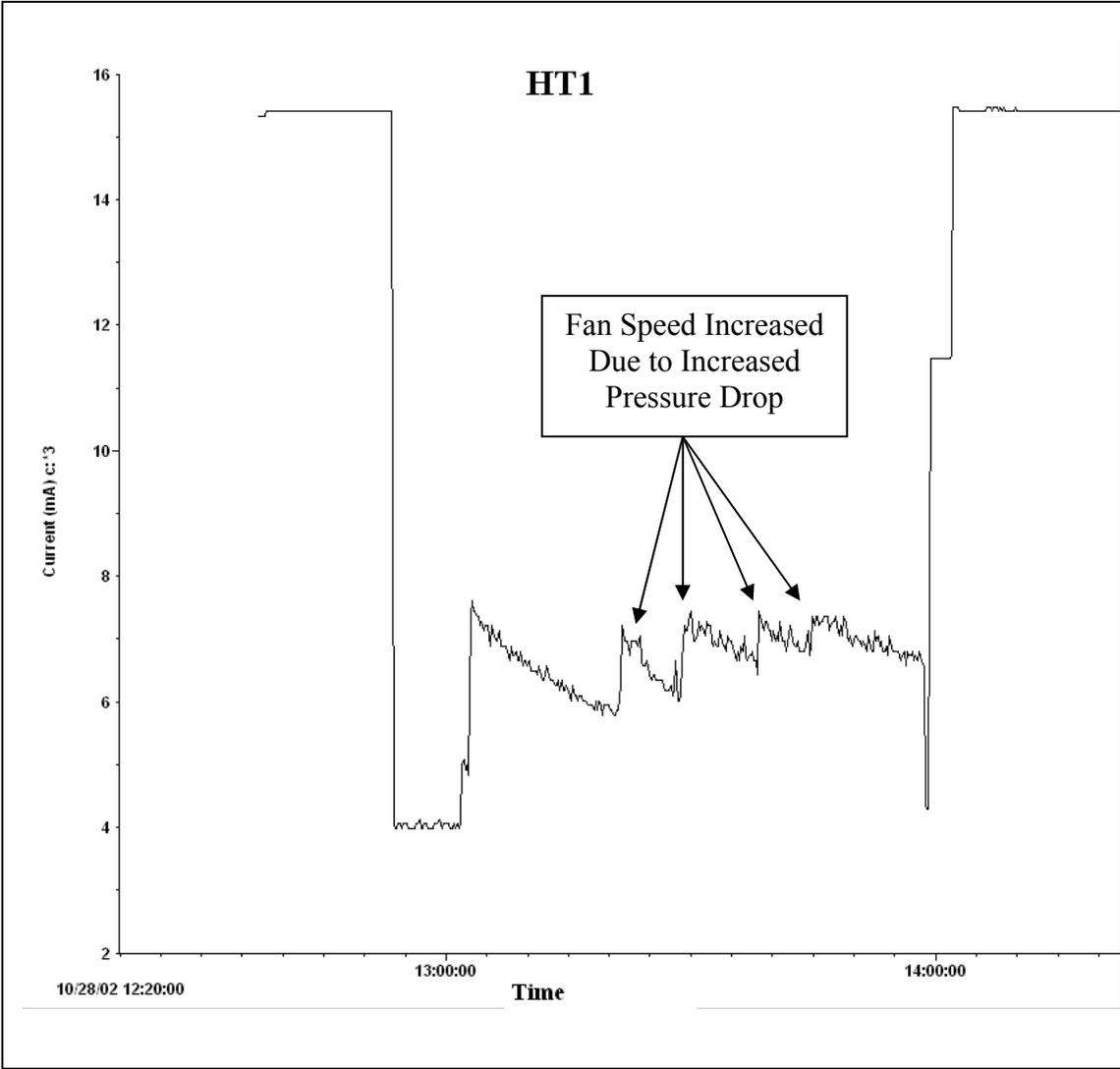


Figure 13. Differential pressure transducer current (mA) versus test time plot for HT1 during test #7. The dust sampled was fly ash.

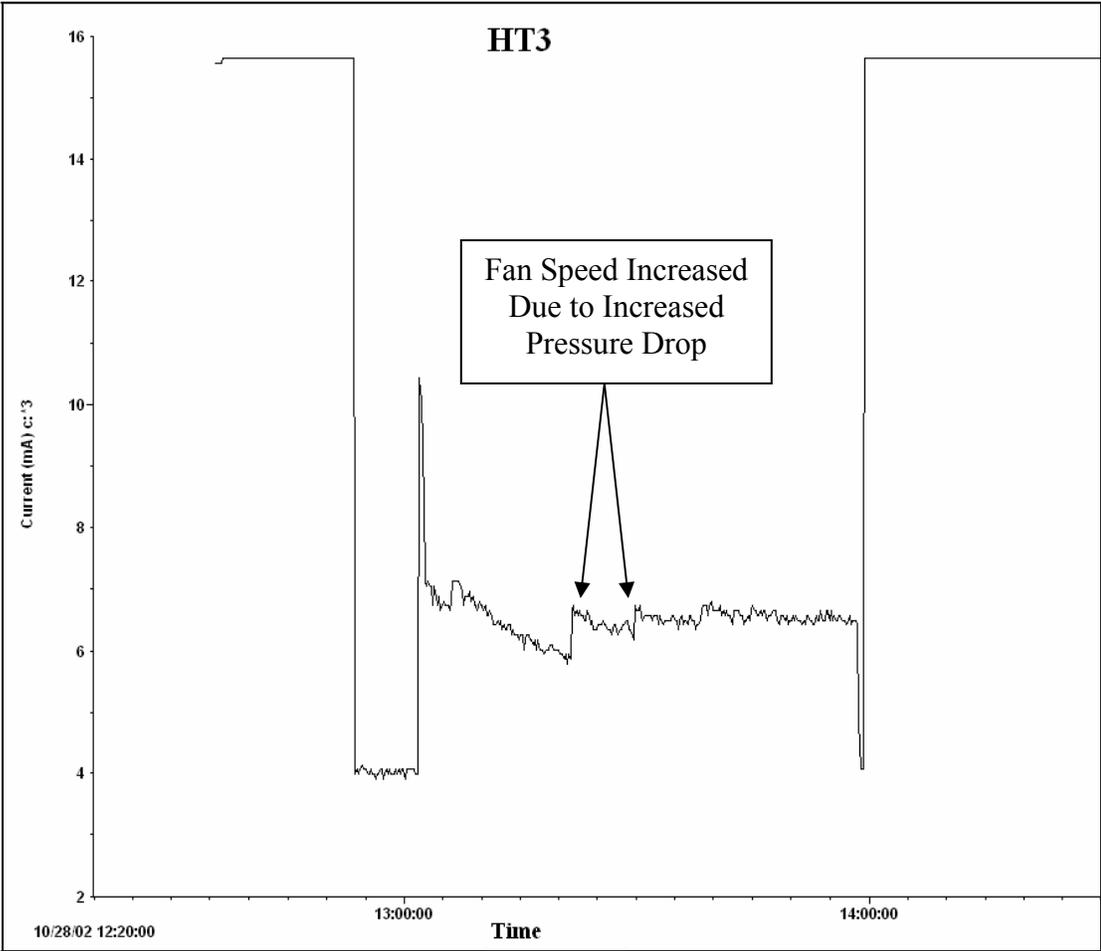


Figure 14. Differential pressure transducer current (mA) versus test time plot for HT3 during test #7. The dust sampled was fly ash.

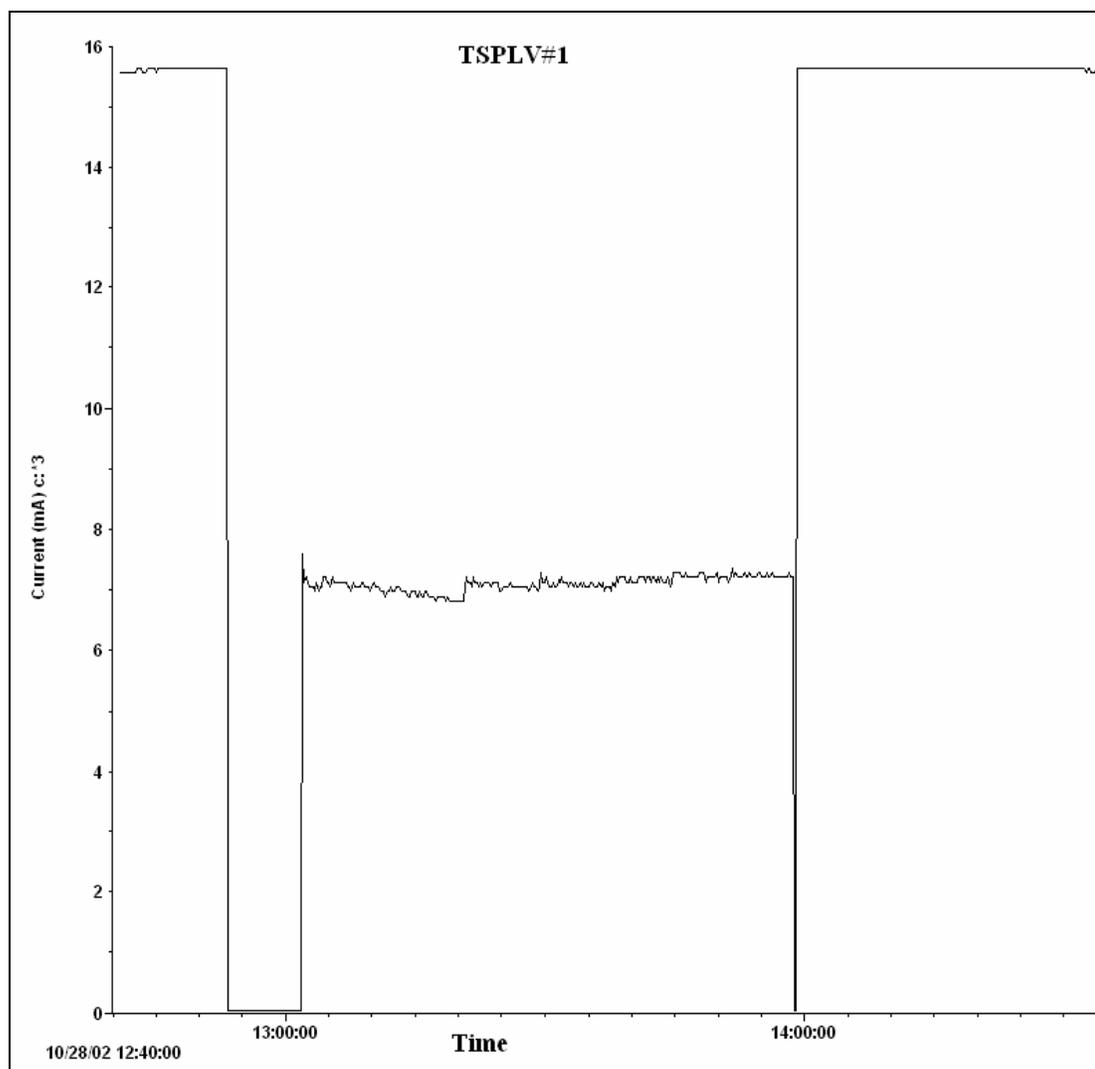


Figure 15. Differential pressure transducer current (mA) versus test time plot for TSP_{LV}#1 during test #7. The dust sampled was fly ash.

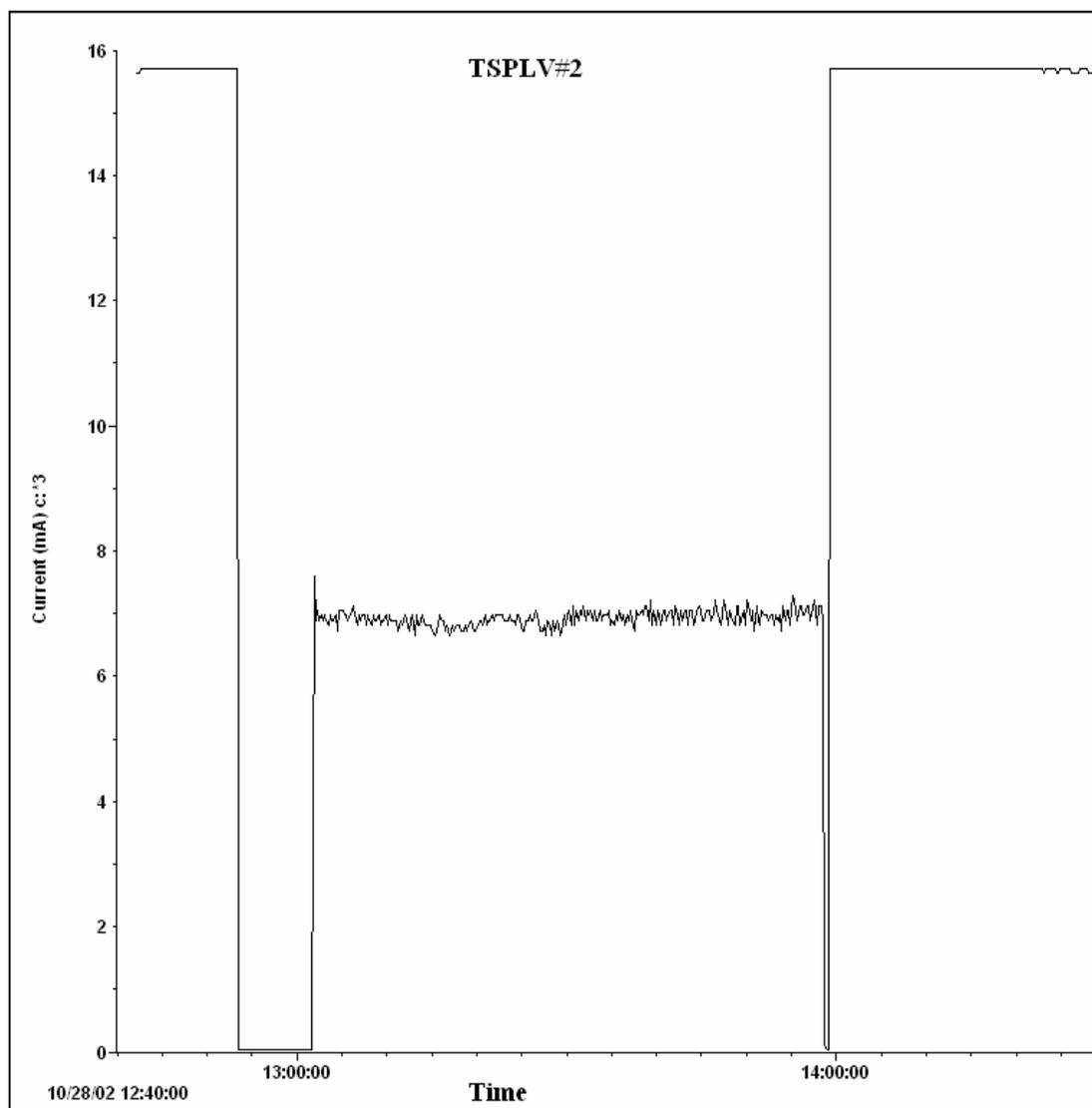


Figure 16. Differential pressure transducer current (mA) versus test time plot for TSP_{LV}#2 during test #7. The dust sampled was fly ash.

APPENDIX H
BASIS FOR REGULATING AGRICULTURAL OPERATIONS BASED ON PM
COARSE (PM_C)

EPA is currently in the process of promulgating a new national ambient air quality standard (NAAQS) for particulate matter (PM) known as PM coarse (PM_C) (EPA, 1996). PM_C is intended to regulate the thoracic coarse fraction of particles less than $10\mu\text{m}$ aerodynamic equivalent diameter (AED) but greater than $2.5\mu\text{m}$ AED. Currently, there are two size specific indicators for the PM NAAQS including PM_{10} and $PM_{2.5}$. The current primary and secondary PM_{10} NAAQS is $150\mu\text{g}/\text{m}^3$ on a 24-hour average basis. The current primary and secondary $PM_{2.5}$ NAAQS is $65\mu\text{g}/\text{m}^3$ on a 24-hour average basis. Annual average primary and secondary NAAQS for PM_{10} and $PM_{2.5}$ have also been established at 50 and $15\mu\text{g}/\text{m}^3$ respectively. One approach to establishing the PM_C NAAQS is to take the difference in the two 24-hour average standards (for PM_{10} and $PM_{2.5}$) and set the PM_C NAAQS at $85\mu\text{g}/\text{m}^3$. However, in an effort to make the new standard more restrictive than the existing standards, a proposed concentration limit for PM_C under consideration is $75\mu\text{g}/\text{m}^3$.

The regulation indicator for PM has evolved over the years from a total suspended particulate (TSP) basis in 1971 to a particulate matter $\leq 10\mu\text{m}$ AED (PM_{10}) basis in 1987 (Federal Register, 1987) and most recently in 1997 to a particulate matter $\leq 2.5\mu\text{m}$ AED ($PM_{2.5}$) basis (Federal Register, 1997). The original PM standards were established to help protect against adverse health effects from inhalable particles which penetrate to the lower (thoracic) regions of the human respiratory system (Federal Register, 1987). The standard based on $PM_{2.5}$ was established as a result of epidemiological studies showing a relationship between serious health effects and PM concentrations (EPA, 2001). The epidemiological studies focused primarily on the

concentrations of two size ranges of PM including PM fine ($PM_{2.5}$) and PM coarse (PM_C).

The proposed implementation of the PM_C standard is to be in addition to the existing PM_{10} and $PM_{2.5}$ standards. In other words, state air pollution regulatory agencies (SAPRA) will have to show compliance with all three federal PM standards (PM_{10} , PM_C , and $PM_{2.5}$) if the PM_C standard is implemented. This could prove to be a quite daunting task for SAPRAs with regions in which ambient PM concentrations are close to the federal concentration limits for PM_{10} or $PM_{2.5}$.

Some states have used the NAAQS as a property line concentration limit not to be exceeded. The implementation of the new PM_C standard as a property line concentration limit will have detrimental effects on agricultural operations because of the relatively large particle size distributions (PSD) characterizing the dust that they emit.

To demonstrate the difficulty for both SAPRAs and agricultural operations to comply with the PM_C NAAQS as either an ambient concentration limit or as a property line concentration limit, the following four scenarios were developed. The concentrations reported are in terms of true PM_{10} , $PM_{2.5}$ and PM_C as obtained from the PSD of a TSP sample taken in each setting.

1. The true PM_{10} concentration measured in an urban environment is $150\mu\text{g}/\text{m}^3$.

The EPA (EPA, 1996) characterizes the PSD of urban dust as having a mass median diameter (MMD) and geometric standard deviation (GSD) of $5.7\mu\text{m}$ and 2.25 respectively.

2. The true PM_{10} concentration at the downwind property line of a cotton gin is $150\mu\text{g}/\text{m}^3$. The PSD of the dust is characterized as indicated by AP-42 with PM_{10} being 39% of TSP. This PSD is also defined by a MMD and GSD of $12.2\mu\text{m}$ and 2.0 respectively.
3. The true PM_{10} concentration at the downwind property line of a cotton gin is $150\mu\text{g}/\text{m}^3$. The PSD of the dust is characterized as indicated by Buser et al. (2002) with MMD and GSD of $18\mu\text{m}$ and 2.2 respectively.
4. The true PM_{10} concentration at the downwind property line of a cattle feedyard is $150\mu\text{g}/\text{m}^3$. The PSD of the dust is characterized as indicated by Capareda et al. (2004) with MMD and GSD of $17\mu\text{m}$ and 2.0.

Table 15 shows the concentration results of the four scenarios. None of the four scenarios meet the PM_C regulation on a 24-hour average basis. However, the PM_{10} and $PM_{2.5}$ standards are met under the four different scenarios.

Table 15. Four different particle size distribution scenarios (one urban and three agricultural) showing compliance with PM_{10} and $PM_{2.5}$ NAAQS (150 and $65\mu\text{g}/\text{m}^3$ respectively) while not meeting the proposed NAAQS for PM_C ($75\mu\text{g}/\text{m}^3$).

	#1	#2	#3	#4
	Urban PSD	1996 AP42 Cotton Gin PSD	Measured Cotton Gin PSD	Measured Feedyard PSD
MMD (μm)	5.7	12.2	18	17
GSD	2.25	2	2.2	2
TSP ($\mu\text{g}/\text{m}^3$)	198	387	658	676
PM_{10} ($\mu\text{g}/\text{m}^3$)	150	150	150	150
$PM_{2.5}$ ($\mu\text{g}/\text{m}^3$)	31	4	4	2
PM_C ($\mu\text{g}/\text{m}^3$)	119	146	146	148

The imposition of the PM_C standard will effectively regulate PM_{10} and $PM_{2.5}$ on a much more restrictive basis than the current NAAQS for PM_{10} and $PM_{2.5}$. Table 16 shows the maximum PM_{10} and $PM_{2.5}$ concentrations that can be measured under the four different scenarios presented if the PM_C concentration is held constant at $75\mu\text{g}/\text{m}^3$.

Table 16. Maximum PM_{10} and $PM_{2.5}$ concentrations, for four different scenarios (one urban and three agricultural), that can be measured while maintaining compliance with the proposed PM_C standard of $75\mu\text{g}/\text{m}^3$.

	#1 Urban PSD	#2 1996 AP42 Cotton Gin PSD	#3 Measured Cotton Gin PSD	#4 Measured Feedyard PSD
MMD (μm)	5.7	12.2	18	17
GSD	2.25	2	2.2	2
TSP ($\mu\text{g}/\text{m}^3$)	125	199	338	342
PM_{10} ($\mu\text{g}/\text{m}^3$)	94	77	77	76
$PM_{2.5}$ ($\mu\text{g}/\text{m}^3$)	19	2	2	1
PM_C ($\mu\text{g}/\text{m}^3$)	75	75	75	75

Enforcing a PM_C standard of $75\mu\text{g}/\text{m}^3$ effectively reduces the PM_{10} standard to 94 and $77\mu\text{g}/\text{m}^3$ for the urban and agricultural scenarios respectively. Similarly, the $PM_{2.5}$ standard is effectively reduced to 19 and $2\mu\text{g}/\text{m}^3$ for the urban and agricultural scenarios respectively. These results are a consequence of the PSD of the dust measured from each source.

Ambient concentration or property line concentration regulations based on true concentration measurements of PM_{10} and $PM_{2.5}$ from either urban or agricultural (rural) sources can not meet the proposed standard for PM_C if the PM_{10} concentrations

measured are $150\mu\text{g}/\text{m}^3$. There is no scientific basis for regulating the coarse fraction of particles (PM_C) based on the difference in the existing standards for PM_{10} and $\text{PM}_{2.5}$. Regulating PM_C based on the difference in the existing standards ($\text{PM}_{10} - \text{PM}_{2.5} = \text{PM}_C$) effectively reduces the established standards for PM_{10} and $\text{PM}_{2.5}$. Applying the PM_C standard as a property line concentration limit will force many agricultural operations to comply with unattainable property line concentration limits. These overly-stringent property line concentration limits will impose undue financial burden on these sources as they are required to implement more efficient and costly control equipment. The increased financial burden could potentially drive many of these operations out of business.

The original PM_{10} standard (24-hour average concentration $\leq 150\mu\text{g}/\text{m}^3$) was implemented to protect the public from the adverse health effects associated with inhalable particles penetrating to the thoracic region of the human respiratory system. The “thoracic fraction” of particles is considered to be the coarse fraction of inhalable particles (EPA, 2003). The respirable fraction of particles is considered to be the fine fraction of inhalable particles. Respirable particles are a subset of the thoracic fraction of inhalable particles but have a much higher probability of reaching the thoracic portions of the human respiratory system. Respirable particles are defined by EPA to be the fine fraction of inhalable particles having an upper 50% cut point of $2.5\mu\text{m}$ (EPA, 2003). The EPA recognized the need to regulate the coarse and fine mode particles separately (Miller et al., 1979). PM_C is considered to be a better indicator of the coarse fraction of inhalable particles and does not include $\text{PM}_{2.5}$ (EPA, 2003).

A problem is encountered when trying to establish a common regulatory standard for all regions in the US based on fine ($PM_{2.5}$) and coarse (PM_C) particles. Particulate matter particle size distributions change by location within the US because of geography, industrial influence, etc. Consequently, the coarse and fine fractions of PM change with location as well. Establishing a PM_C standard to regulate the same size fraction of particles as the PM_{10} standard was intended to regulate has scientific merit. However, establishing such a regulation based on the difference in the current PM_{10} and $PM_{2.5}$ standard has no scientific merit. Thus, a more appropriate regulatory limit for PM_C should be set at or very near to $150\mu\text{g}/\text{m}^3$ on a 24-hour average basis.

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