

## ENGINEERING AND GINNING

### First Stage Seed-Cotton Cleaning System Particulate Emission Factors for Cotton Gins: Particle Size Distribution Characteristics

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#### ABSTRACT

This report is part of a project to characterize cotton gin emissions from the standpoint of total particulate stack sampling and particle size analyses. In 2006 and again in 2013, the United States (U.S.) Environmental Protection Agency (EPA) published a more stringent National Ambient Air Quality Standard for particulate matter with nominal diameter less than or equal to 2.5  $\mu\text{m}$  ( $\text{PM}_{2.5}$ ). This created an urgent need to collect additional cotton gin emissions data to address current regulatory issues, because EPA AP-42 cotton gin  $\text{PM}_{2.5}$  emission factors were limited. In addition, current EPA AP-42 emission factor quality ratings for cotton gin  $\text{PM}_{10}$  (particulate matter with nominal diameter less than or equal to 10  $\mu\text{m}$ ) data are questionable, being extremely low. The objective of this study was to characterize particulate emissions for 1<sup>st</sup> stage seed-cotton cleaning systems from cotton gins across the cotton belt based on particle size distribution analysis of total particulate samples from EPA-approved stack sampling methods. Average measured  $\text{PM}_{2.5}$ ,  $\text{PM}_6$ , and  $\text{PM}_{10}$  emission factors based on the mass and particle size analyses of EPA Method 17 total particulate filter and wash samples from seven gins (18 total test runs) were 0.0045 kg/227-kg bale (0.010 lb/500-lb bale), 0.042 kg/bale (0.092 lb/bale), and 0.072 kg/bale (0.159 lb/bale), respectively. The 1<sup>st</sup> stage seed-cotton cleaning system particle size distributions were characterized by an average

mass median diameter of 10.7  $\mu\text{m}$  (aerodynamic equivalent diameter). Based on system average emission factors, the ratio of  $\text{PM}_{2.5}$  to total particulate was 2.99%,  $\text{PM}_6$  to total particulate was 27.5%, and  $\text{PM}_{10}$  to total particulate was 47.5%.

In 2006 and again in 2013, the United States (U.S.) Environmental Protection Agency (EPA) published a more stringent standard for particulate matter (PM) with a particle diameter less than or equal to a nominal 2.5- $\mu\text{m}$  ( $\text{PM}_{2.5}$ ) aerodynamic equivalent diameter (AED) (CFR, 2013). The cotton industry's primary concern with this standard was the limited cotton gin  $\text{PM}_{2.5}$  emissions data published in the literature and in EPA's AP-42, Compilation of Air Pollutant Emission Factors (EPA, 1996b). AP-42 was first circulated in 1972 and the last complete document revision was in 1995. Since 1995, only updates and supplements have been added. AP-42 contains air pollutant emission factors for more than 200 industrial sources of air pollution along with information on the processes conducted at these sources.

An emission factor is a relationship between a process and the amount of air pollution emitted by that process into the atmosphere (EPA, 1996b). Emission factors are usually defined as the weight of pollutant emitted per unit weight, volume, distance, or duration of the activity producing the pollutant (e.g., kilograms of particulate emitted per cotton bale ginned). These relationships have been established from source test data, modeling, material balance studies, and engineering estimates and are usually averages of all data that have been gathered for a particular process (EPA, 1996a).

EPA's AP-42 was developed to include emission factors for all criteria pollutants and additional pollutants beyond the scope of the National Ambient Air Quality Standards (NAAQS), including total PM,  $\text{PM}_{10}$  (PM with a particle diameter less than or equal to a nominal 10- $\mu\text{m}$  AED), and  $\text{PM}_{2.5}$ . Current AP-42 cotton gin emission factors are located in section 9.7 (EPA, 1996b). Further, Appendix B.1 of AP-42 contains particle size distribution (PSD)

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data and emission factors based on these PSDs (EPA, 1996c). The only PM<sub>2.5</sub> emission factors in the current AP-42 were listed in Appendix B.1 and were based on PSDs. The 1996 AP-42 version only contained cotton ginning PSD data for the battery condenser and combined lint cleaning systems. The information for the battery condenser system equipped with cyclones was based on two tests and the PSD data was determined using a UW Mark 3 Impactor. The information for the combined lint cleaning system equipped with cyclones was based on four tests. The total particulate concentration data was determined using EPA Method 5 and the PSD data was determined by using a Coulter Counter to process the Method 5 samples (Hughes et al., 1982). Hughes et al. (1982) did not specifically state whether the PSD results were based on both the Method 5 wash and filter samples, wash only, or filter only. Table 1 provides examples of the types of data that were provided in EPA's AP-42 Appendix B.1.

Emission factors from EPA AP-42 developed prior to 2013 were assigned ratings to assess the quality of the data being referenced. The ratings ranged from A (excellent) to E (poor). The PSD data quality rating in the 1996 AP-42 for both the battery condenser and combined lint cleaning systems was E (EPA, 1996c).

Cotton ginners' associations across the U.S. cotton belt, including the National, Texas, Southern, Southeastern, and California associations, agreed that there was an urgent need to collect additional PSD data on PM being emitted from cotton ginning system exhausts. Working with cotton ginning associations across the country, state and federal regulatory agencies, Oklahoma State University, and USDA-Agricultural Research Service (ARS) researchers developed a proposal and sampling plan that was initiated in 2008 to address this need. Buser et al. (2012) provided the details of this sampling plan. This article is part of a series that details cotton gin emission factors developed from coupling total particulate stack sampling concentrations and particle size analyses. Each manuscript in the series

addresses a specific cotton ginning system. The systems covered in the series include: unloading, 1<sup>st</sup> stage seed-cotton cleaning, 2<sup>nd</sup> stage seed-cotton cleaning, 3<sup>rd</sup> stage seed-cotton cleaning, overflow, 1<sup>st</sup> stage lint cleaning, 2<sup>nd</sup> stage lint cleaning, combined lint cleaning, cyclone robber, 1<sup>st</sup> stage mote, 2<sup>nd</sup> stage mote, combined mote, mote cyclone robber, mote cleaner, mote trash, battery condenser, and master trash. This manuscript reports on the characterization of PM<sub>2.5</sub> and PM<sub>10</sub> emissions from 1<sup>st</sup> stage seed-cotton cleaning systems.

**Cotton Ginning.** Seed cotton is a perishable commodity that has no real value until the fiber and seed are separated (Wakelyn et al., 2005). Cotton must be processed or ginned at the cotton gin to separate the fiber and seed, producing 227-kg (500-lb) bales of marketable cotton fiber. Cotton ginning is considered an agricultural process and an extension of the harvest by several federal and state agencies (Wakelyn et al., 2005). Although the main function of the cotton gin is to remove the lint fiber from the seed, many other processes occur during ginning, such as cleaning, drying, and packaging the lint. Pneumatic conveying systems are the primary method of material handling in a cotton gin. As material reaches a processing point, the conveying air is separated and emitted outside the gin through a pollution control device. The amount of PM emitted by a system varies with the process and the composition of the material being processed.

Cotton ginning is a seasonal industry with the ginning season lasting from 75 to 120 days, depending on the crop size and condition. Although the general trend for U.S. cotton production has remained constant at about 17 million bales per year during the last 20 years, production from year to year often varies greatly for various reasons, including climate and market pressure. The number of active gins in the U.S. has not remained constant, but has steadily declining from 1,018 in 2000 to 682 in 2011 (NASS, 2001, 2012). Consequently, the average cotton gin production capacity across the U.S. cotton belt has increased to an approximate average of 25 bales per hour (Valco et al., 2003, 2006, 2009, 2012).

**Table 1. EPA AP-42 Appendix B.1 particle size distribution data for the battery condenser and combined lint cleaning systems equipped with cyclones on the system exhausts.**

System	% < 2.5 $\mu\text{m}$	Emission Factor kg/bale	% < 6.0 $\mu\text{m}$	Emission Factor kg/bale	% < 10 $\mu\text{m}$	Emission Factor kg/bale
Lint cleaner	1	Not Reported	20	Not Reported	54	Not Reported
Battery condenser	8	0.007	33	0.028	62	0.053

Typical cotton gin processing systems include: unloading, dryers, seed-cotton cleaners, gin stands, overflow, lint cleaners, battery condenser, bale packaging, and trash handling (Fig. 1); however, the number and type of machines and processes can vary. Each of these systems serves a unique function with the ultimate goal of ginning the cotton to produce a marketable product. Raw seed cotton harvested from the field is compacted into large units called “modules” for delivery to the gin. The unloading system removes seed cotton either mechanically or pneumatically from the module feeding system and conveys the seed cotton to the cleaning systems. Seed-cotton cleaning systems assist in drying the seed cotton and removing foreign matter prior to ginning. Ginning systems also remove foreign matter and separate the cotton fiber from seed. Lint cleaning systems further clean the cotton lint after ginning. The battery condenser and packaging systems combine lint from the lint cleaning systems and compress the lint into dense bales for efficient transport. Gin systems produce by-products or trash, such as rocks, soil, sticks, hulls, leaf material, and short or tangled immature fiber (motes), as a result of processing the seed cotton or lint. These streams of by-products must be removed from the machinery and handled by trash collection systems. These trash systems typically further process the by-products (e.g., mote cleaners) and/or consolidate the trash from the gin systems into a hopper or pile for subsequent removal.

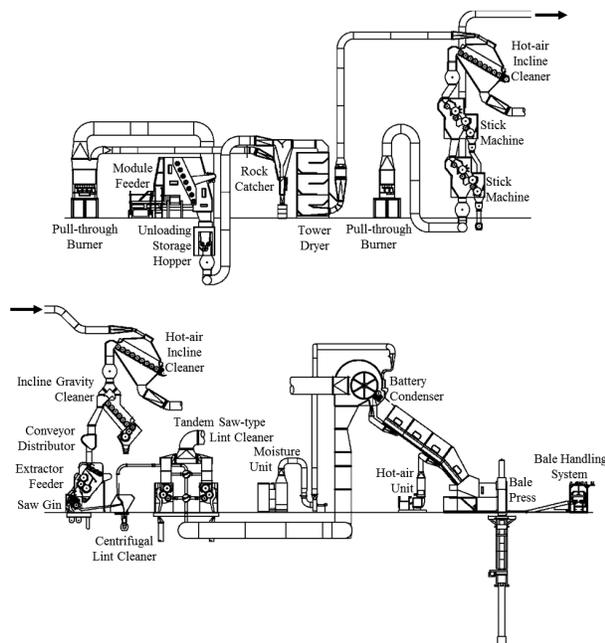


Figure 1. Typical modern cotton gin layout (Courtesy Lummus Corporation, Savannah, GA).

The seed cotton is cleaned and dried in the seed-cotton cleaning systems. In the typical 1<sup>st</sup> stage seed-cotton cleaning system (Fig. 2), seed cotton is pneumatically conveyed with heated air from either the feed control or module feeder through a dryer to the seed-cotton cleaning machinery. The seed cotton is pulled directly into the seed-cotton cleaning machinery and separated from the conveying airstream by the cleaning mechanism (called a hot-air cleaner) or separated from the conveying air via a screened separator and dropped into the cleaning machinery. Seed-cotton cleaning machinery includes cylinder cleaners or extractors. Each stage often employs two cleaners in series. This system removes foreign matter that includes rocks, soil, sticks, hulls, and leaf material. The air stream from the 1<sup>st</sup> stage seed-cotton cleaning system continues through a centrifugal fan to an abatement system; generally one or more cyclones. This cleaning system might use air heated up to 117°C (350°F) at the seed cotton and air mixing point to accomplish drying during transport (ASABE, 2007). Based on system configuration, the air stream temperature at the abatement device could range from ambient to about 50% of the mixing-point temperature. The material handled by the abatement system is typically the same as that removed by the seed-cotton cleaning machinery (rocks, soil, sticks, hulls, and leaf material) and lint extracted with the trash (Fig. 3).

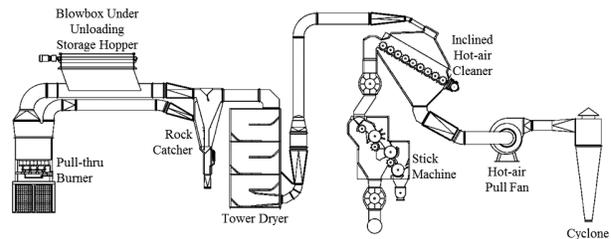


Figure 2. Typical cotton gin 1<sup>st</sup> stage seed-cotton cleaning system layout (Courtesy Lummus Corporation, Savannah, GA).



Figure 3. Photograph of typical trash captured by the 1<sup>st</sup> stage seed-cotton cleaning system cyclones.

**Cyclones.** Cyclones are the most common PM abatement devices used at cotton gins. Standard cyclone designs used at cotton ginning facilities are the 2D2D and 1D3D (Whitelock et al., 2009). The first D in the designation indicates the length of the cyclone barrel relative to the cyclone barrel diameter. The second D indicates the length of the cyclone cone relative to the cyclone barrel diameter. A standard 2D2D cyclone (Fig. 4) has an inlet height of  $D/2$  and width of  $D/4$  and design inlet velocity of  $15.2 \pm 2$  m/s ( $3000 \pm 400$  fpm). The standard 1D3D cyclone (Fig. 4) has the same inlet dimensions as either the 2D2D or the original 1D3D inlet with height of  $D$  and width  $D/8$ . Also, it has a design inlet velocity of  $16.3 \pm 2$  m/s ( $3200 \pm 400$  fpm).

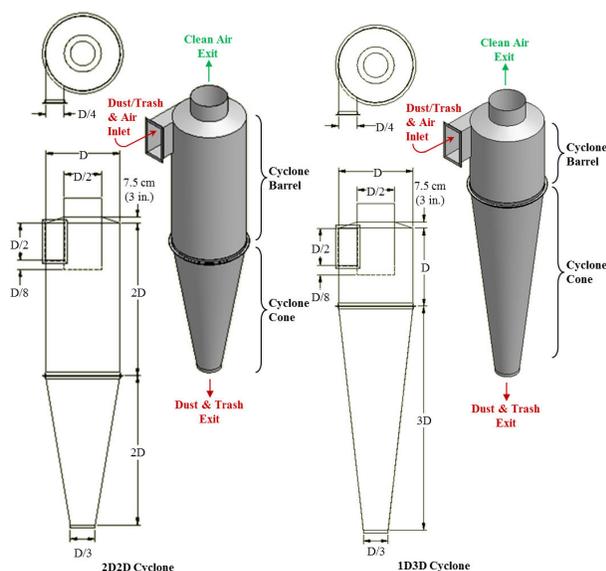


Figure 4. 2D2D and 1D3D cyclone schematics.

**Cotton Gin Emission Factors.** EPA emission factors for cotton gins are published in EPA's Compilation of Air Pollution Emission Factors, AP-42 (EPA, 1996b). The AP-42 average total particulate emission factor for the No. 1 dryer and cleaner, which is an equivalent system to the 1<sup>st</sup> stage seed-cotton cleaning system, was 0.17 kg (0.36 lb) per 217-kg (480-lb) equivalent bale with a range of 0.11 to 0.25 kg (0.24 to 0.54 lb) per bale. This average and range were based on seven tests conducted in one geographical location. The EPA emission factor quality rating was D, which is the second lowest possible rating (EPA, 1996b). The AP-42 average  $PM_{10}$  emission factor for the No. 1 dryer and cleaner was 0.055 kg (0.12 lb) per 217-kg (480-lb) equivalent bale with a range of 0.039 to 0.096 kg (0.088-0.21 lb) per bale (EPA, 1996a, b). This average and range were based on five

tests conducted in one geographical location and also had a D quality rating. Currently there are no  $PM_{2.5}$  emission factor data listed in the AP-42 for cotton gin 1<sup>st</sup> stage seed-cotton cleaning systems.

Buser et al. (2012) discussed the plan of a large-scale project focused on developing cotton gin PM emission factors. Part of this project was focused on developing PM emission factors based on EPA-approved methodologies. Three studies focused on 1<sup>st</sup> stage seed-cotton cleaning systems evolved out of the Buser et al. (2012) project plan. Boykin et al. (2015) reported on one study that used EPA Method 17 (CFR, 1978) to measure total particulate emission factors for the 1<sup>st</sup> stage seed-cotton cleaning systems. The system average total particulate emission factor was 0.152 kg (0.334 lb) per 227-kg (500-lb) equivalent bale with a range of 0.093 to 0.203 kg (0.206-0.447 lb) per bale. Buser et al. (2014) reported on a second study that used EPA Method 201A (CFR, 2010) with only the  $PM_{10}$  sizing cyclone to measure 1<sup>st</sup> stage seed-cotton cleaning system  $PM_{10}$  and total particulate emission factors. The system average  $PM_{10}$  and total particulate emission factors were 0.097 kg/227-kg bale (0.215 lb/500-lb bale) and 0.144 kg/bale (0.317 lb/bale), respectively. In the third study, reported by Whitelock et al. (2013), EPA Method 201A with both the  $PM_{10}$  and  $PM_{2.5}$  sizing cyclones was used to measure  $PM_{2.5}$ ,  $PM_{10}$ , and total particulate emission factors. The average measured  $PM_{2.5}$  emission factor was 0.0083 kg/227-kg bale (0.018 lb/500-lb bale). The  $PM_{10}$  and total particulate average emission factors were 0.074 kg/bale (0.162 lb/bale) and 0.101 kg/bale (0.222 lb/bale), respectively.

Particle size distribution analyses have been utilized in conjunction with total particulate sampling methods to calculate PM emissions concentration and factors for agricultural operations for more than 40 years (Wesley et al., 1972). Some examples include: cattle feedlot operations (Sweeten et al., 1998), poultry production facilities (Lacey et al., 2003), nut harvesting operations (Faulkner et al., 2009), grain handling (Boac et al., 2009), swine finishing (Barber et al., 1991), and cotton ginning (Hughes and Wakelyn, 1997). Buser and Whitelock (2007) reported cotton ginning emission concentrations based on EPA-approved  $PM_{2.5}$ ,  $PM_{10}$ , and total particulate stack sampling methods and PSD analyses of the total particulate samples coupled with the total particulate concentrations to calculate  $PM_{2.5}$  and  $PM_{10}$  concentrations. The mass median diameter (MMD) of the PM in the samples ranged from 6 to 8  $\mu$ m. The study results

indicated that the PSD and EPA sampler-based PM<sub>10</sub> concentrations were in good agreement, whereas the PM<sub>2.5</sub> EPA sampler concentrations ranged from 5.8 to 13.3 times the PSD-based concentrations.

The primary objective of this study was to develop PSD characteristics for the PM emitted from cotton gin 1<sup>st</sup> stage seed-cotton cleaning systems. The secondary objective was to develop PM<sub>2.5</sub> and PM<sub>10</sub> emission factors for cotton gin 1<sup>st</sup> stage seed-cotton cleaning systems equipped with cyclones on the system exhausts based on particle size distribution analysis of total particulate samples from EPA-approved stack sampling methods.

## METHODS

Seven cotton gins were sampled across the cotton belt for the overall cotton gin sampling project described by Buser et al. (2012). Key factors for selecting specific cotton gins included: 1) facility location (geographically diverse), 2) production capacity (industry representative), 3) processing systems (typical for industry), and 4) particulate abatement technologies (properly designed and maintained 1D3D cyclones). All seven gins had 1<sup>st</sup> stage seed-cotton cleaning systems. The 1<sup>st</sup> stage seed-cotton cleaning systems sampled were typical for the industry. Gins B, E, and G had similar 1<sup>st</sup> stage seed-cotton cleaning systems. The seed-cotton material was pneumatically conveyed from the module feeder to a series of seed-cotton cleaners. The material was separated from the air stream by the first cleaner. The air then passed through a fan and exhausted through one or more cyclones. The gin A system used a feed control unit to regulate the flow of seed cotton. The material was conveyed pneumatically from the feed control unit through a dryer then the material stream was split. The air was separated from each stream by the first set of parallel cleaners. The two air streams then merged and passed through a fan and exhausted through one or more cyclones. The 1<sup>st</sup> stage seed-cotton cleaning systems at gins D and F were similar to the systems at gins B, E, and G except the material stream was split into two parallel systems after the feed control or module feeder. The 1<sup>st</sup> stage seed-cotton cleaning system for gin C was similar to the system at gin F except there were separate feed control units for the parallel systems. Boykin et al. (2015) provided system flow diagrams for the 1<sup>st</sup> stage seed-cotton cleaning systems that were tested.

All 1<sup>st</sup> stage seed-cotton cleaning systems sampled utilized 1D3D cyclones to control emissions (Fig. 4), but there were some cyclone design variations among the gins. All the gins, except gin E, split the system exhaust flow between two cyclones in a dual configuration (side by side as opposed to one behind another). The system air stream for gin E was exhausted through a single cyclone. Inlets on all the 1<sup>st</sup> stage seed-cotton cleaning cyclones were 2D2D type, except gin C that had inverted 1D3D inlets. Expansion chambers were present on 1<sup>st</sup> stage seed-cotton cleaning cyclones at all gins, except gins E and F, which had standard cones. All of the cyclone variations outlined above, if properly designed and maintained, are recommended for controlling cotton gin emissions (Whitelock et al., 2009). The cyclones at gin F had angle-iron welded inside and down the length of the cone. This is occasionally done by cyclone manufacturers for systems with high particulate loading, especially sand, to encourage material to exit the cyclone more quickly and reduce cone wear; this is not a recommended practice. Boykin et al. (2015) provided detailed descriptions of the abatement cyclones that were tested for the 1<sup>st</sup> stage seed-cotton cleaning systems.

**Method 17 Stack Sampling.** The samples utilized for the PSD analyses and gravimetric sample data used in developing the PSD characteristics and PSD-based emission factors were obtained from EPA Method 17 stack testing (CFR, 1978) that was conducted at the seven gins with 1<sup>st</sup> stage seed-cotton cleaning systems as part of the overall cotton gin sampling project described by Buser et al. (2012). The Method 17 sampling methods and the procedures for retrieving the filter and conducting acetone wash of the sampler nozzle are described in the EPA Method 17 documentation (CFR, 1978). Further details of the project specific sampling methods, procedures, and results of the EPA Method 17 stack testing were reported by Boykin et al. (2015).

**Laboratory Analysis.** All laboratory analyses were conducted at the USDA-ARS Air Quality Lab (AQL) in Lubbock, TX. All filters were conditioned in an environmental chamber ( $21 \pm 2^\circ\text{C}$  [ $70 \pm 3.6^\circ\text{F}$ ];  $35 \pm 5\%$  RH) for 48 h prior to gravimetric analyses. Filters were weighed in the environmental chamber on a Mettler MX-5 microbalance (Mettler-Toledo Inc., Columbus, OH; 1  $\mu\text{g}$  readability and 0.9  $\mu\text{g}$  repeatability) after being passed through an anti-static device. The MX-5 microbalance was leveled on a marble table and housed inside an acrylic box

to minimize the effects of air currents and vibrations. To reduce recording errors, weights were digitally transferred from the microbalance directly to a spreadsheet. Technicians wore latex gloves and a particulate respirator mask to avoid contaminating the filter or sample. AQL procedures required that each sample be weighed three times. If the standard deviation of the weights for a given sample exceeded 10  $\mu\text{g}$ , the sample was reweighed. Gravimetric procedures for the acetone wash tubs were the same as those used for filters.

In addition to gravimetric analyses, each sample was visually inspected for unusual characteristics, such as cotton lint content or extraneous material. Digital pictures were taken of all filters and washes for documentation purposes. After the laboratory analyses were completed all stack sampling, cotton gin production, and laboratory data were merged.

**Particle Size Analysis.** A Beckman Coulter LS230 laser diffraction system (Beckman Coulter Inc., Miami, FL) with software version 3.29 was used to perform the particle size analyses on the filter and wash samples. The instrument sizes particles with diameters ranging from 0.4 to 2000  $\mu\text{m}$ . For this project, the LS230 fluid module was used with a 5% lithium chloride/methanol suspension fluid. Approximately 10-L batches of the suspension fluid were prepared and stored in a self-contained, recirculating, system equipped with 0.2  $\mu\text{m}$  filters to keep the fluid well mixed and free of larger particles. Prior to each test run a background particle check was performed on the fluid to help minimize particulate contamination from non-sample sources. The process of analyzing the samples included the following steps:

1. pour approximately 40 mL of clean suspension fluid into a clean 100-mL beaker;
2. transfer a particulate sample to the 100-mL beaker with clean suspension fluid,
  - a. for 47-mm filter media, remove the filter from the Petri dish with tweezers and place the filter in the 100-mL beaker with the suspension fluid,
  - b. for the wash samples contained in a sample tub, use a small amount of the suspension fluid and a sterile foam swab to transfer the sample from the tub to the 100-mL beaker;
3. place the 100-mL beaker in an ultrasonic bath for 5 min to disperse the PM sample in the fluid;
4. using a sterile pipette, gradually introduce the PM and suspension fluid mixture into clean suspension fluid that is being monitored by the LS230 until an obscuration level of 10% is reached;
5. activate the LS230 system to measure the diffraction patterns and calculate the PSD;
6. repeat step 5 a total of three times and average the results; and
7. drain and flush/clean the LS230 system.

Optical models for calculating laser diffraction-based PSDs require input of a refractive index for the suspension fluid and real and imaginary refractive indices for the sample. A refractive index of 1.326 for methanol was used for the suspension fluid (Beckman Coulter, 2011). Hughs et al. (1997) showed that particulate from cyclone exhausts was about 34% ash or fine soil particulate with the balance made up of water and organic material (e.g., cellulose, lignin, protein). Real and imaginary refractive index values for common soil constituents—quartz, clay minerals, silica, and feldspars—are 1.56 and 0.01, respectively (Buurman et al., 2001). These indices were used in the optical model used in calculating the PSD for the cyclone particulate samples. Wang-Li et al. (2013) and Buser (2004) provided additional details on the PSD methodology.

The LS230 PSD results are in the form of particle volume versus equivalent spherical diameter. The PSD results were converted to particle volume versus AED using the following equation:

$$d_a = d_p \left( \frac{\rho_p}{\kappa \rho_w} \right)^{1/2}$$

where  $\rho_w$  is the density of water with a value of 1  $\text{g}/\text{cm}^3$ ,  $\rho_p$  is the particle density, and  $\kappa$  is the dynamic shape factor. The dynamic shape factor was determined to be 1.4 based on Hinds (1982) factors for quartz and sand dust. The particle density, assumed to be constant for the Method 17 filter and wash samples evaluated in this study, was determined in an earlier study to be 2.65  $\text{g}/\text{cm}^3$  (M. Buser, unpublished data, 2013). This earlier study used a helium displacement AccuPyc 1330 Pycnometer (Micromeritics, Norcross, GA) to determine the particle density of cotton gin waste that passed through a No. 200 sieve (particles that pass through a 74- $\mu\text{m}$  sieve opening). The study was based on three random samples collected at 43 different cotton gins.

Results obtained from each average adjusted PSD included: MMD, mass fraction of PM with diameter less than or equal to 10 μm (PM<sub>10</sub>), mass fraction of PM with diameter less than or equal to 6 μm (PM<sub>6</sub>), and mass fraction of PM with diameter less than or equal to 2.5 μm (PM<sub>2.5</sub>). This information was coupled with the corresponding Method 17 sample mass to calculate the PM<sub>10</sub>, PM<sub>6</sub>, and PM<sub>2.5</sub> emission factors using the following equation:

$$EF_i = EF_{tot} \left( \left( \frac{M_F}{M_F + M_W} \right) w_{Fi} + \left( \frac{M_W}{M_F + M_W} \right) w_{Wi} \right)$$

where  $EF_i$  = emission factor for particle in the size range  $i$ ;

$EF_{tot}$  = total particulate emission factor obtained from total particulate tests (Boykin et al., 2015);

$M_F$  = total mass of particulate on filter;

$M_W$  = total mass of particulate in nozzle wash;

$w_{Fi}$  = mass fraction of particles on the filter in the size range  $i$ ; and

$w_{Wi}$  = mass fraction of particles in the nozzle wash in the size range  $i$ .

The 1<sup>st</sup> stage seed-cotton cleaning systems sampled were typical for the industry. The system average ginning rate was 31.8 bales/h and the test average ginning rate at each gin ranged from 20.1 to 49.8 bales/h (based on 227-kg [500-lb] equivalent bales). The capacity of gins sampled was representative of the industry average, approximately 25 bales/h. The 1D3D cyclones were all operated with inlet velocities within design criteria,  $16.3 \pm 2$  m/s ( $3200 \pm 400$  fpm), except the test runs at gin C and two runs at gin E that were outside the design range due to limitations in available system adjustments. The first run at gin F was omitted from the test average because of ginning issues; extremely low ginning rate. There are criteria specified in EPA Method 17 for test runs to be valid for total particulate measurements (CFR, 1978). Isokinetic sampling must fall within EPA-defined range of  $100 \pm 10\%$ . All tests met the isokinetic criteria, except run one for gin B and C; these runs were removed from the emissions test averages. The stack gas temperatures ranged from 20 to 75°C (67-166°F) and moisture content ranged from 0.3 to 4.6%. The individual systems and cyclone design variations were discussed by Boykin et al. (2015).

## RESULTS

The PSD characteristics and mass of the PM captured on the filters are shown in Table 2. The variability of PSD characteristics from test to test for a given gin was minor compared to the gin-to-gin variability. The mass of the PM captured on the filter accounted for 68 to 97% of the total PM (filter and wash) collected from the individual test runs. The system average MMD for particulate on the filters was 9.7 μm AED. Test averages ranged from 7.2 to 14.0 μm AED. The test and system averages are based on averaging PSDs and not averaging individual test results. The mass fraction of PM<sub>2.5</sub>, PM<sub>6</sub>, and PM<sub>10</sub> ranged from 1.03 to 5.21%, 20.4 to 41.1%, and 37.6 to 64.4%, respectively. Filter PM PSDs for the seven gins and the system average are shown in Fig. 5. In general, the PSD characteristics for the PM captured on the filters for the gins were consistent. The PSDs for gins E, F, and G show a shift to the right illustrating the effect of a larger proportion of particles larger than 10 μm than the other gins.

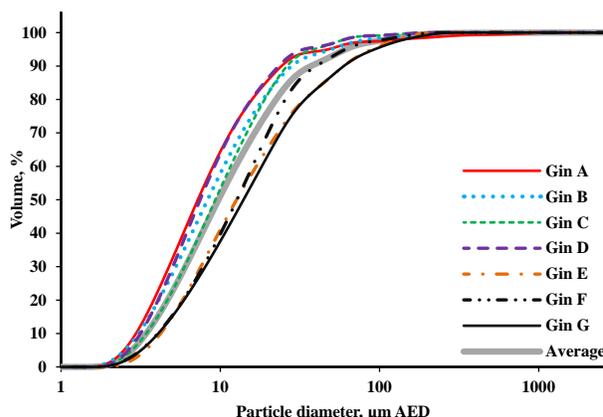


Figure 5. Gin average cumulative particle size distributions for the PM captured on a EPA-Method 17 filter from the 1<sup>st</sup> stage seed-cotton cleaning systems.

The PSD characteristics and mass of the PM captured in the washes are shown in Table 3. The mass of the PM captured in the sampler nozzle and retrieved in the wash accounted for 3 to 32% of the total PM (filter and wash) collected from the individual test runs. The system average MMD was 19.8 μm AED. Test average MMDs ranged from 10.4 to 39.4 μm AED. The mass fraction of PM<sub>2.5</sub>, PM<sub>6</sub>, and PM<sub>10</sub> ranged from 0.89 to 6.04%, 8.3 to 29.6%, and 15.9 to 48.5%, respectively. PSDs for the PM captured in the nozzle for the seven gins and the system average are shown in Fig. 6. In general, the PSDs for the PM captured in the nozzle had larger MMDs (illustrated by the wider

spread and shift to the right of the curves) with greater between test variability than the PM captured on the filter. The PSDs for gins A, E, and F show a shift to the right, again illustrating the effect of a larger proportion of particles larger than 10 μm than the other gins.

The combined PSD characteristics for the PM captured on the filter and PM captured in the wash are shown in Table 4. The 1<sup>st</sup> stage seed-cotton cleaning system average combined filter and wash PSD MMD was 10.7 μm AED (7.9 to 14.5 μm test

average range). Less than 0.01% of the particles had a diameter of 1 μm or smaller. The combined filter and wash PM<sub>2.5</sub>, PM<sub>6</sub>, and PM<sub>10</sub> mass fractions ranged from 1.01 to 5.01%, 18.6 to 36.7%, and 35.4 to 60.4%, respectively. Combined PM PSDs for the seven gins and the system average are shown in Fig. 7. These combined PSDs are more consistent with the filter PSDs than the wash PSDs. This was expected because the majority of the PM mass was captured on the filter as compared to the nozzle wash.

**Table 2. EPA Method 17 filter particle size distribution data for the 1<sup>st</sup> stage seed-cotton cleaning system.**

Gin	Test Run	Mass Median Diameter μm AED	PM <sub>2.5</sub> %	PM <sub>6</sub> %	PM <sub>10</sub> %	Sample Total mg
A	1	7.8	5.30	38.2	61.2	152.79
	2	7.0	5.07	41.9	66.3	181.52
	3	6.9	5.24	43.1	65.6	102.46
Test Average (n = 3) <sup>x</sup>		7.2	5.21	41.1	64.4	
B	1 <sup>z</sup>	6.7	6.37	44.6	67.2	113.35
	2	8.8	4.59	34.0	55.3	81.07
	3	7.9	5.31	37.3	60.3	45.87
Test Average (n = 2) <sup>x</sup>		8.3	4.95	35.6	57.8	
C	1 <sup>z</sup>	8.5	4.37	34.0	57.9	33.03
	2	8.7	3.62	32.4	56.4	28.11
	3	10.0	2.77	28.0	50.1	26.91
Test Average (n = 2) <sup>x</sup>		9.3	3.20	30.2	53.2	
D	1	7.5	3.64	38.8	63.3	44.64
	2	7.3	3.86	39.5	65.1	83.66
	3	7.6	4.04	38.2	62.7	73.67
Test Average (n = 3) <sup>x</sup>		7.5	3.85	38.8	63.7	
E	1	12.2	1.05	21.8	42.1	146.27
	2	12.7	1.04	21.4	41.1	112.96
	3	13.1	0.99	20.6	39.9	104.83
Test Average (n = 3) <sup>x</sup>		12.7	1.03	21.3	41.0	
F	1 <sup>y</sup>	11.2	1.92	22.6	44.6	14.90
	2	12.7	2.03	21.3	40.0	95.57
	3	12.8	1.81	20.5	39.4	74.39
Test Average (n = 2) <sup>x</sup>		12.7	1.92	20.9	39.7	
G	1	14.2	1.93	20.3	37.1	84.69
	2	13.0	1.86	21.8	40.0	115.17
	3	14.9	1.66	19.2	35.6	96.10
Test Average (n = 3) <sup>x</sup>		14.0	1.82	20.4	37.6	
System Average (n = 7) <sup>x</sup>		9.7	3.14	29.8	51.1	

<sup>z</sup> Test run omitted from test averages because isokinetic sampling rate (100 ± 10%) was not met

<sup>y</sup> Test run omitted from test averages because of ginning issues

<sup>x</sup> Based on averaged particle size distributions

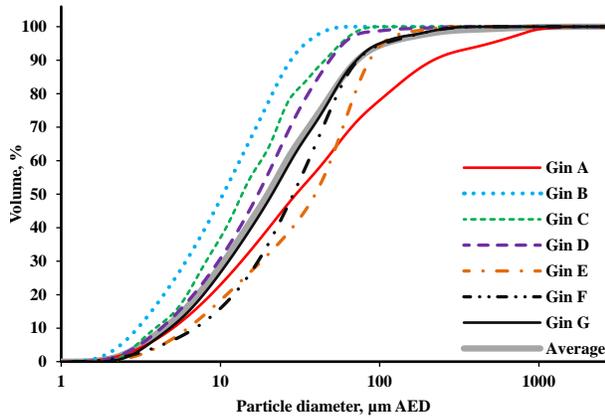


Figure 6. Gin average cumulative particle size distributions for the PM captured in the EPA-Method 17 sampler nozzle wash from the 1<sup>st</sup> stage seed-cotton cleaning systems.

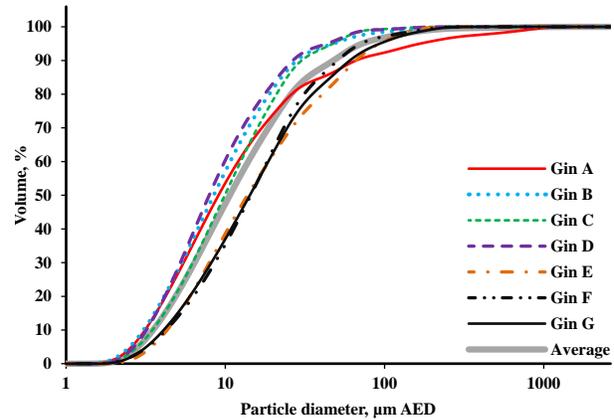


Figure 7. Gin average cumulative particle size distributions for the EPA-Method 17 combined filter and wash samples from the 1<sup>st</sup> stage seed-cotton cleaning systems.

Table 3. EPA Method 17 nozzle wash particle size distribution data for the 1<sup>st</sup> stage seed-cotton cleaning system.

Gin	Test Run	Mass Median Diameter µm AED	PM <sub>2.5</sub> %	PM <sub>6</sub> %	PM <sub>10</sub> %	Sample Total mg
A	1	42.0	1.75	10.4	18.7	31.64
	2	23.7	2.27	14.1	25.6	73.64
	3	27.6	2.68	14.2	24.6	48.28
Test Average (n = 3) <sup>x</sup>		29.8	2.23	12.9	23.0	
B	1 <sup>z</sup>	24.5	4.09	17.5	29.4	38.36
	2	13.6	4.47	22.2	38.3	7.14
	3	8.2	7.60	36.9	58.6	2.59
Test Average (n = 2) <sup>x</sup>		10.4	6.04	29.6	48.5	
C	1 <sup>z</sup>	31.8	5.68	15.9	24.9	14.60
	2	10.6	2.11	23.5	47.3	2.49
	3	20.9	2.19	14.7	26.7	7.35
Test Average (n = 2) <sup>x</sup>		13.7	2.15	19.1	37.0	
D	1	21.1	3.02	14.7	25.3	9.06
	2	15.8	2.38	18.5	33.6	5.14
	3	15.4	2.17	18.1	33.5	4.50
Test Average (n = 3) <sup>x</sup>		17.2	2.52	17.1	30.8	
E	1	36.7	0.93	9.1	18.1	13.97
	2	39.9	0.87	10.0	19.3	16.52
	3	41.5	0.86	9.1	17.4	12.41
Test Average (n = 3) <sup>x</sup>		39.4	0.89	9.4	18.3	
F	1 <sup>y</sup>	16.0	1.05	14.3	30.1	1.85
	2	29.5	1.45	8.0	15.5	16.30
	3	27.9	1.57	8.5	16.4	20.85
Test Average (n = 2) <sup>x</sup>		28.7	1.51	8.3	15.9	
G	1	23.7	1.47	13.0	24.2	6.39
	2	16.8	0.78	16.9	32.3	3.45
	3	23.6	1.23	12.1	23.3	4.61
Test Average (n = 3) <sup>x</sup>		21.1	1.16	14.0	26.6	
System Average (n = 7) <sup>x</sup>		19.8	2.36	15.8	28.6	

<sup>z</sup> Test run omitted from test averages because isokinetic sampling rate (100 ± 10%) was not met

<sup>y</sup> Test run omitted from test averages because of ginning issues

<sup>x</sup> Based on averaged particle size distributions

**Table 4. EPA Method 17 combined filter and wash particle size distribution data for the 1<sup>st</sup> stage seed-cotton cleaning system.**

Gin	Test Run	Mass Median Diameter µm AED	PM <sub>2.5</sub> %	PM <sub>6</sub> %	PM <sub>10</sub> %
A	1	9.1	4.69	33.4	53.9
	2	8.9	4.26	33.9	54.6
	3	9.3	4.42	33.8	52.4
	Test Average (n = 3) <sup>x</sup>	9.1	4.46	33.7	53.6
B	1 <sup>z</sup>	8.1	5.79	37.8	57.7
	2	9.1	4.58	33.0	53.9
	3	7.9	5.43	37.2	60.3
	Test Average (n = 2) <sup>x</sup>	8.5	5.01	35.1	57.1
C	1 <sup>z</sup>	10.6	4.77	28.4	47.8
	2	8.9	3.50	31.6	55.6
	3	11.3	2.65	25.2	45.1
	Test Average (n = 2) <sup>x</sup>	9.9	3.07	28.4	50.4
D	1	8.5	3.53	34.7	56.9
	2	7.5	3.78	38.3	63.3
	3	7.8	3.93	37.1	61.0
	Test Average (n = 3) <sup>x</sup>	7.9	3.75	36.7	60.4
E	1	13.1	1.04	20.7	40.0
	2	14.0	1.02	19.9	38.3
	3	14.3	0.98	19.3	37.5
	Test Average (n = 3) <sup>x</sup>	13.8	1.01	20.0	38.6
F	1 <sup>y</sup>	11.6	1.82	21.7	43.0
	2	14.1	1.95	19.4	36.5
	3	14.8	1.76	17.9	34.4
	Test Average (n = 2) <sup>x</sup>	14.5	1.85	18.6	35.4
G	1	14.6	1.90	19.8	36.2
	2	13.1	1.83	21.7	39.8
	3	15.2	1.64	18.9	35.1
	Test Average (n = 3) <sup>x</sup>	14.3	1.79	20.1	37.0
System Average (n = 7) <sup>x</sup>		10.7	2.99	27.5	47.5

<sup>z</sup> Test run omitted from test averages because isokinetic sampling rate (100 ± 10%) was not met

<sup>y</sup> Test run omitted from test averages because of ginning issues

<sup>x</sup> Based on averaged particle size distributions

The PSD-based emission factors for the 1<sup>st</sup> stage seed-cotton cleaning systems are shown in Table 5. The system average PM<sub>2.5</sub> emission factor was 0.0045 kg/227-kg bale (0.010 lb/500-lb bale). PM<sub>2.5</sub> emission factors ranged from 0.0016 to 0.0177 kg (0.0034-0.0390 lb) per bale. The 1<sup>st</sup> stage seed-cotton cleaning system average PM<sub>6</sub> emission factor was 0.042 kg/bale (0.092 lb/bale). The PM<sub>6</sub> emission factors ranged from 0.020 to 0.115 kg/bale (0.044-0.255 lb/bale). The 1<sup>st</sup> stage seed-cotton cleaning system average PM<sub>10</sub> emission factor was 0.072 kg/bale (0.159 lb/bale) and ranged from 0.037 to 0.176 kg (0.082-0.389 lb) per bale. The ratios of PM<sub>2.5</sub> to total particulate, PM<sub>6</sub> to total particulate, and PM<sub>10</sub> to total particulate, based on the system averages, were 2.99, 27.5, and 47.5%, respectively.

The PSD-based 1<sup>st</sup> stage seed-cotton cleaning system PM<sub>2.5</sub> emission factor was approximately 55% of the PM<sub>2.5</sub> emission factor reported by Whitelock et al. (2013) and measured using EPA Method 201A, 0.0083 kg (0.018 lb) per 227-kg (500-lb) bale. The PSD-based 1<sup>st</sup> stage seed-cotton cleaning system PM<sub>10</sub> emission factor was 1.3 times the EPA AP-42 published value for the No. 1 dryer and cleaner, 0.055 kg (0.12 lb) per bale (EPA, 1996a). Also, the PSD-based system PM<sub>10</sub> emission factor was 74% of the Method 201A (PM<sub>10</sub> sizing cyclone only) PM<sub>10</sub> emission factor reported by Buser et al. (2014), 0.097 kg (0.215 lb) per bale. The PSD-based PM<sub>10</sub> emission factor was 98% of the Method 201A (PM<sub>10</sub> and PM<sub>2.5</sub> sizing cyclones) PM<sub>10</sub> emission factor reported by Whitelock et al. (2013),

0.074 kg (0.162 lb) per bale. The differences among the methods could be attributed to several sources. First, due to constraints in the EPA methods, the three studies utilizing Method 17 for total particulate sampling and PSD analyses, Method 201A for PM<sub>10</sub> sampling, and Method 201A for PM<sub>2.5</sub> and PM<sub>10</sub> sampling could not be conducted simultaneously. Combined with the fact that emissions from cotton ginning can vary with the condition of incoming cotton, PM concentrations measured among the three studies could have varied. Second, for reasons described by Buser (2007a, b, c) and documented by Buser and Whitelock (2007), some larger particles could penetrate the Method 201A sampler PM<sub>10</sub> or PM<sub>2.5</sub> sizing cyclones and collect on the filter. Finally, cotton fibers have a cross-sectional diameter much larger than 10 μm and are difficult to scrub out of air streams. These fibers could cycle in the sizing cyclones and pass through to deposit on the filters. This behavior was observed during some of the Method 201A testing where cotton fibers were found

in Method 201A sampler washes and on filters (Fig. 8). Currently there are no EPA-approved guidelines to adjust Method 201A PM<sub>10</sub> or PM<sub>2.5</sub> concentration measurements to account for these fibers.

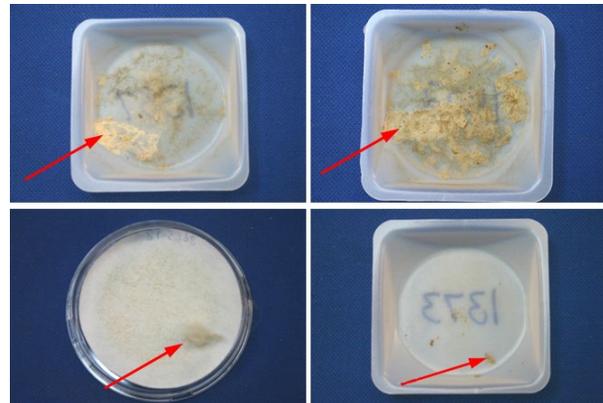


Figure 8. Example EPA Method 201A filter and sampler head acetone washes with lint (indicated by arrows) in the washes and on the filter. Clockwise from top left: > 10 μm wash, 10 to 2.5 μm wash, ≤ 2.5 μm wash, and filter.

Table 5. EPA Method 17 total particulate and particle size distribution-based PM<sub>2.5</sub>, PM<sub>6</sub>, and PM<sub>10</sub> emission factor data for the 1<sup>st</sup> stage seed-cotton cleaning system.

Gin	Test Run	Total <sup>w</sup>		PM <sub>2.5</sub> <sup>v</sup>		PM <sub>6</sub> <sup>v</sup>		PM <sub>10</sub> <sup>v</sup>	
		kg/bale <sup>z</sup>	lb/bale <sup>z</sup>	kg/bale <sup>z</sup>	lb/bale <sup>z</sup>	kg/bale <sup>z</sup>	lb/bale <sup>z</sup>	kg/bale <sup>z</sup>	lb/bale <sup>z</sup>
A	1	0.148	0.327	0.0070	0.015	0.050	0.109	0.080	0.176
	2	0.192	0.423	0.0082	0.018	0.065	0.143	0.105	0.231
	3	0.112	0.247	0.0049	0.011	0.038	0.083	0.059	0.129
B	1 <sup>y</sup>	0.306	0.674	0.0177	0.039	0.115	0.255	0.176	0.389
	2	0.186	0.411	0.0085	0.019	0.062	0.136	0.101	0.222
	3	0.219	0.484	0.0119	0.026	0.082	0.180	0.132	0.291
C	1 <sup>y</sup>	0.132	0.292	0.0063	0.014	0.038	0.083	0.063	0.139
	2	0.094	0.207	0.0033	0.0072	0.030	0.065	0.052	0.115
	3	0.093	0.205	0.0025	0.0054	0.023	0.052	0.042	0.093
D	1	0.069	0.152	0.0024	0.0054	0.024	0.053	0.039	0.087
	2	0.126	0.278	0.0048	0.011	0.048	0.107	0.080	0.176
	3	0.103	0.228	0.0041	0.0089	0.038	0.084	0.063	0.139
E	1	0.243	0.536	0.0025	0.0056	0.050	0.111	0.097	0.215
	2	0.204	0.450	0.0021	0.0046	0.041	0.090	0.078	0.172
	3	0.159	0.351	0.0016	0.0034	0.031	0.068	0.060	0.132
F	1 <sup>x</sup>	0.396	0.874	0.0072	0.016	0.086	0.190	0.171	0.376
	2	0.199	0.439	0.0039	0.0085	0.039	0.085	0.073	0.160
	3	0.161	0.354	0.0028	0.0062	0.029	0.063	0.055	0.122
G	1	0.143	0.316	0.0027	0.0060	0.028	0.062	0.052	0.115
	2	0.147	0.325	0.0027	0.0059	0.032	0.070	0.059	0.129
	3	0.107	0.235	0.0018	0.0039	0.020	0.044	0.037	0.082
System	Average	0.152	0.334	0.0045	0.010	0.042	0.092	0.072	0.159

<sup>z</sup> 227-kg (500-lb) equivalent bales

<sup>y</sup> Test run omitted from test averages because isokinetic sampling rate (100 ± 10%) was not met

<sup>x</sup> Test run omitted from test averages because of ginning issues

<sup>w</sup> Taken from Boykin et al. (2015)

<sup>v</sup> Factors are the product of the corresponding PM percentage from Table 4 and the total particulate emission factor.

## SUMMARY

Cotton gins across the U.S. cotton belt were sampled using EPA-approved methods to fill the data gap that exists for PM<sub>2.5</sub> cotton gin emissions data and to collect additional data to improve the EPA AP-42 total and PM<sub>10</sub> emission factor quality ratings for cotton gins. Samples were further analyzed to characterize the PSD of the particulate measured. Seven selected cotton gins had 1<sup>st</sup> stage seed-cotton cleaning systems that used pneumatic conveyance and had exhaust airstreams that were not combined with another system. All tested systems were similar in design and typical of the ginning industry and were equipped with 1D3D cyclones for emissions control. In terms of capacity, the seven gins were typical of the industry, averaging 31.8 bales/h during testing. The average PSD-based 1<sup>st</sup> stage seed-cotton cleaning system PM<sub>2.5</sub>, PM<sub>6</sub>, and PM<sub>10</sub> emission factors from the seven gins tested (18 total test runs) were 0.0045 kg/227-kg bale (0.010 lb/500-lb bale), 0.042 kg/bale (0.092 lb/bale), and 0.072 kg/bale (0.159 lb/bale), respectively. The PSDs were characterized by an average MMD of 10.7  $\mu$ m AED. Based on system average emission factors, the ratio of PM<sub>2.5</sub> to total particulate was 2.99%, PM<sub>6</sub> to total particulate was 27.5%, and PM<sub>10</sub> to total particulate was 47.5%. PSD-based system average PM<sub>2.5</sub> and PM<sub>10</sub> emission factors were 55% and 74% of those measured for the overall cotton gin sampling project utilizing EPA-approved methods. The PSD-based PM<sub>10</sub> emission factor was 1.3 times that currently published in EPA AP-42.

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