

## ENGINEERING AND GINNING

### Mote Cleaner 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  $\text{PM}_{2.5}$  (particulate matter with nominal diameter less than or equal to 2.5  $\mu\text{m}$ ) and  $\text{PM}_{10}$  (particulate matter with nominal diameter less than or equal to 10  $\mu\text{m}$ ) emission factors did not exist for mote cleaner systems. The objective of this study was to characterize particulate emissions for mote cleaner systems from cotton gins across the cotton belt based on particle size distribution analysis of total particulate samples from EPA-approved stack sampling methods. Two gins with mote cleaner systems were sampled. The exhaust from one of the mote cleaner systems was combined with the module feeder dust system. The average PSD based  $\text{PM}_{2.5}$ ,  $\text{PM}_6$ , and  $\text{PM}_{10}$  emission factors for the mote cleaner system that was not combined with another cotton gin system were 0.0016 kg/227-kg bale (0.0036 lb/500-lb bale), 0.018 kg/bale (0.040 lb/bale), and 0.033 kg/bale (0.074 lb/bale), respectively. The PSD was characterized by an average MMD of 17.1  $\mu\text{m}$  AED. The ratio of  $\text{PM}_{2.5}$  to total

particulate was 1.53%,  $\text{PM}_6$  to total was 17.1%, and  $\text{PM}_{10}$  to total was 31.8%. The average PSD based  $\text{PM}_{2.5}$ ,  $\text{PM}_6$ , and  $\text{PM}_{10}$  emission factors for the mote cleaner system that was combined with module feeder dust system were 0.00092 kg/227-kg bale (0.0020 lb/500-lb bale), 0.011 kg/bale (0.024 lb/bale), and 0.022 kg/bale (0.048 lb/bale), respectively. The PSD was characterized by an average MMD of 26.7  $\mu\text{m}$  AED. The ratio of  $\text{PM}_{2.5}$  to total particulate was 0.85%,  $\text{PM}_6$  to total was 9.9%, and  $\text{PM}_{10}$  to total was 20.0%.

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).

AP-42 was developed by the EPA 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,

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PM<sub>10</sub> (PM with a particle diameter less than or equal to a nominal 10- $\mu$ m AED), and PM<sub>2.5</sub>. 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) 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 sam-

pling 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 mote cleaner 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 declined 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 $\mu$ m	Emission Factor kg/bale	% < 6.0 $\mu$ m	Emission Factor kg/bale	% < 10 $\mu$ 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.

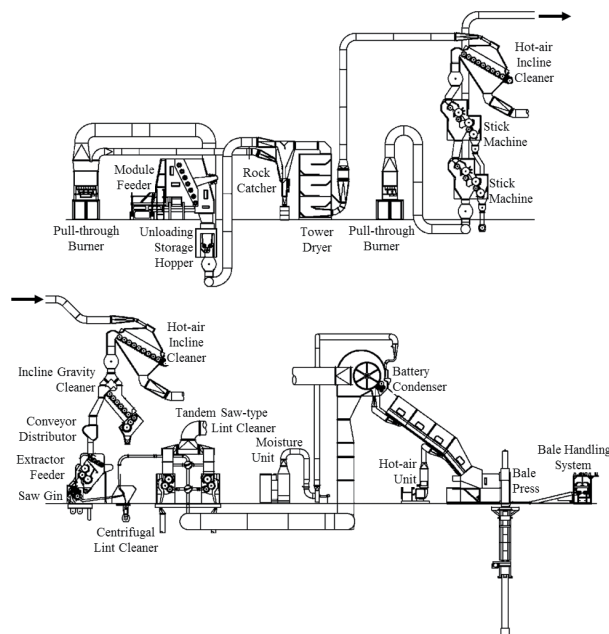


Figure 1. Typical modern cotton gin layout (Courtesy Lummus Corporation, Savannah, GA).

Material captured by cyclones that handle airstreams laden with greater amounts of lint (battery condenser, lint cleaning, and mote system cyclones), referred to as motes, has considerable value, especially when further cleaned in a device similar to a seed cotton cleaning machine; the mote cleaner. In mote cleaner systems (Fig. 2) the material is pneumatically conveyed from the trash exit of the cyclones to a screened separator where the motes are separated from the conveying airstream and dropped into the mote cleaner. The airstream from the screened separator continues through a centrifugal fan to one or more particulate abatement cyclones. A branch of the pneumatic system between the separator and fan is often utilized to pick up, by suction, the mote trash from the mote cleaner trash exit. The material handled by the mote cleaner system cyclones typically includes small leaf trash, soil, and some lint fibers (Fig. 3).

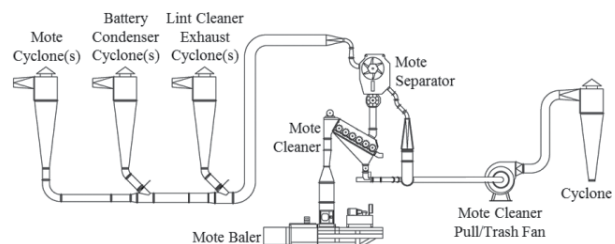


Figure 2. Typical cotton gin mote cleaner system layout (Courtesy Lummus Corporation, Savannah, GA).



Figure 3. Photograph of typical trash captured by the mote cleaner 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).

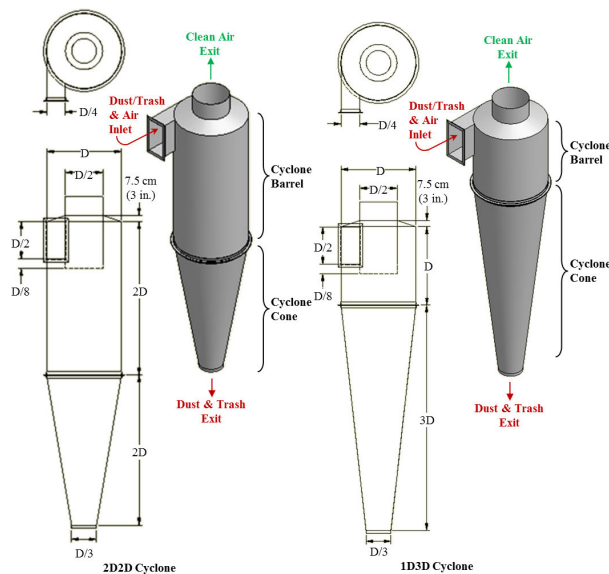


Figure 4. 2D2D and 1D3D cyclone schematics.

**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). Currently there are no total particulate,  $PM_{10}$  or  $PM_{2.5}$  emission factor data listed in the EPA AP-42 for cotton gin mote cleaner systems. The mote cleaner system would be similar to the combination of the mote fan and mote trash fan listed in AP-42 (EPA, 1996a, b). The AP-42 average  $PM_{10}$  emission factor for the mote fan was 0.060 kg (0.13 lb) per 217-kg (480-lb) bale with a range of 0.023 to 0.14 kg (0.050-0.30 lb) per bale. This average and range were based on six tests conducted in one geographical location. The AP-42  $PM_{10}$  emission factor for the mote trash fan was 0.0095 kg (0.021 lb) per bale with a range of 0.0021 to 0.018 kg (0.0046-0.040 lb) per bale and was based on three tests from one geographical region. The AP-42 total particulate emission factor for the mote fan was 0.13 kg (0.28 lb) per bale with a range of 0.045 to 0.47 kg (0.099-1.0 lb) per bale. This average and range were based on nine tests conducted in one geographical location. The AP-42 total particulate emission factor for the mote trash fan was 0.035 kg (0.077 lb) per bale with a range

of 0.025-0.051 kg (0.055 to 0.11 lb) per bale and was based on three tests. The EPA  $PM_{10}$  and total particulate emission factor quality ratings for both the mote fan and mote trash fan were D, which is the second lowest possible rating (EPA, 1996a).

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 mote cleaner systems evolved out of the Buser et al. (2012) project plan. Whitelock et al. (2015) reported on one study that used EPA Method 17 (CFR, 1978) to measure total particulate emission factors for the mote cleaner systems. The test average total particulate emission factor for a stand-alone mote cleaner system was 0.105 kg (0.232 lb) per 227 kg (500-lb) equivalent bale with a range of 0.089 to 0.121 kg (0.196-0.266 lb) per bale. The test average total particulate emission factor for a mote cleaner system combined with a module feeder dust system was 0.109 kg (0.239 lb) per 227-kg (500-lb) equivalent bale with a range of 0.100 to 0.117 kg (0.221-0.259 lb) per bale. Whitelock et al. (2014) reported on a second study that used EPA Method 201A (CFR, 2010) with only the  $PM_{10}$  sizing cyclone to measure mote cleaner system  $PM_{10}$  and total particulate emission factors. The stand-alone mote cleaner test average  $PM_{10}$  and total particulate emission factors were 0.050 kg/227-kg bale (0.109 lb/500-lb bale) and 0.090 kg/bale (0.199 lb/bale), respectively. The mote cleaner system combined with a module feeder dust system test average  $PM_{10}$  and total particulate emission factors were 0.071 kg/227-kg bale (0.157 lb/500-lb bale) and 0.109 kg/bale (0.241 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  $PM_{2.5}$  and total stand-alone mote cleaner emission factor was 0.0036 kg/227-kg bale (0.0079 lb/500-lb bale) and 0.065 kg/bale (0.14lb/bale), respectively. No stand-alone mote cleaner  $PM_{10}$  emission factor was reported because the  $PM_{10}$  cut size criteria was not met. The  $PM_{2.5}$  average mote cleaner system combined with a module feeder dust system emission factors was 0.022 kg/bale (0.050 lb/bale). No average mote cleaner system combined with a module feeder dust system  $PM_{10}$  or total emission factors were calculated.

Particulate 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 (Hughs and Wakelyn, 1997). Buser and Whitelock (2007) reported cotton ginning emission concentrations based on EPA-approved PM<sub>2.5</sub>, PM<sub>10</sub>, and total particulate stack sampling methods and PSD analyses of the total particulate samples coupled with the total particulate concentrations to calculate PM<sub>2.5</sub> and PM<sub>10</sub> concentrations. The mass median diameter (MMD) of the PM in the samples ranged from 6 to 8  $\mu\text{m}$ . 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 mote cleaner systems. The secondary objective was to develop PM<sub>2.5</sub> and PM<sub>10</sub> emission factors for cotton gin mote cleaner 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). Two of the seven gins had mote cleaner systems. The mote cleaner systems sampled were typical for the industry. At gin G, the motes were pneumatically conveyed from the trash exit of the lint handling cyclones (mote, lint cleaning, and battery condenser systems) to the mote cleaner. At the mote cleaner, the motes were separated from the conveying airstream by a screened separator and dropped into the cleaner.

The airstream from the screened separator continued through a centrifugal fan to a cyclone. The mote trash was picked up from the trash exit of the mote cleaner and combined with the exhaust airstream from the screened separator before the fan. The mote cleaner system at gin F was essentially the same, except a conveying airstream from a system that captured dust generated at the module feeder (module feeder dust system) was combined with the exhaust airstream before the fan. The addition of the module feeder dust system could significantly influence the particulate matter test results for the gin F mote cleaner system; therefore, no system averages were calculated. Whitelock et al. (2015) provided system flow diagrams for the mote cleaner systems that were tested.

The mote cleaner systems sampled at both gins F and G utilized single 1D3D cyclones to control emissions. The mote cleaner cyclone design for both systems included a 2D2D inlet and standard cone. The cyclone configurations outlined above, if properly designed and maintained, are recommended for controlling cotton gin emissions (Whitelock et al., 2009). Whitelock et al. (2015) provided detailed descriptions of the abatement cyclones that were tested.

**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 two gins with mote cleaner 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 Whitelock et al. (2015). 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.

**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 ± 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 µg readability and 0.9 µg 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 µg, the sample was reweighed. Gravimetric procedures for the acetone wash tubs were the same as those used for filters.

**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 µm. For this project, the LS230 fluid module was used with a 5% lithium chloride/methanol suspension fluid mixture. Approximately 10-L batches of the suspension fluid were prepared and stored in a self-contained, recirculating, filtration system equipped with 0.2 µm 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 five 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 g/cm<sup>3</sup>,  $\rho_p$  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 g/cm<sup>3</sup> (M. Buser, unpublished data, 2013). This earlier study used a helium displacement AccuPyc 1330 Pyconometer (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-µm 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 (Whitelock 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 mote cleaner systems were typical for the industry. The average ginning rate for the gin F mote cleaner system combined with the module feeder dust system was 47.0 bales/h and ranged from 44.9 to 49.5 bales/h (based on 227-kg [500-lb] equivalent bales). The average ginning rate for the gin G mote cleaner system was 32.7 bales/h and ranged from 30.5 to 34.0 bales/h. The 1D3D cyclone at gin F was operated with inlet velocities within design criteria,  $16.3 \pm 2$  m/s (3200 ± 400 fpm), but the cyclone at gin G was operated outside the design range due to limitations in available

system adjustments. 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. The stack gas temperatures ranged from 35.6 to 36.4°C (96-98°F) and 25 to 31°C (77-88°F) for gins F and G, respectively. The stack moisture content ranged from 0.7 to 1.3% and 1.3 to 2.1% for gins F and G, respectively. The individual systems and cyclone design variations were discussed by Whitelock et al. (2015). No system averages were calculated because the gin F mote cleaner system was combined with a module feeder dust system that could significantly affect the mote cleaner system emissions.

## RESULTS

The PSD characteristics and mass of the PM captured on the filters are shown in Table 2. The mass of the PM captured on the filter accounted for 88 to 99% of the total PM (filter and wash) collected from the individual test runs. The gin F test average MMD for particulate on the filters was 26.6 μm AED. The gin G test average MMD for particulate on the filters was 16.3 μm AED. The test averages are based on averaging PSDs and not averaging individual test results. The test average mass fraction of PM<sub>2.5</sub>, PM<sub>6</sub>, and PM<sub>10</sub> on the gin F filters was 0.82, 9.8, and 20.0%, respectively. The test average mass fraction of PM<sub>2.5</sub>, PM<sub>6</sub>, and PM<sub>10</sub> on the gin G filters was 1.56, 17.7, and 32.9%, respectively. Filter PM PSDs for the two gins are shown in Fig. 5. In general, the PSD curves for the PM captured on the filters for gins had similar shapes. The shift to the right illustrates the larger MMD of the gin F distribution, while the PSD for gin G exhibits characteristics of a smaller MMD.

Table 2. EPA Method 17 filter particle size distribution data for the mote cleaner system.

Gin	Test Run	Mass Median Diameter μm AED	PM <sub>2.5</sub> %	PM <sub>6</sub> %	PM <sub>10</sub> %	Sample Mass mg
F <sup>y</sup>	1	26.0	0.78	9.8	20.3	196.1
	2	28.4	0.78	9.3	18.9	196.6
	3	25.5	0.91	10.4	20.9	227.0
	Test Average (n = 3) <sup>z</sup>	26.6	0.82	9.8	20.0	
G	1	17.0	1.50	16.9	31.7	111.5
	2	16.6	1.47	16.8	31.8	82.8
	3	15.4	1.70	19.3	35.2	110.2
	Test Average (n = 3) <sup>z</sup>	16.3	1.56	17.7	32.9	

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

<sup>y</sup> Mote cleaner system exhaust was combined with a module feeder dust system exhaust

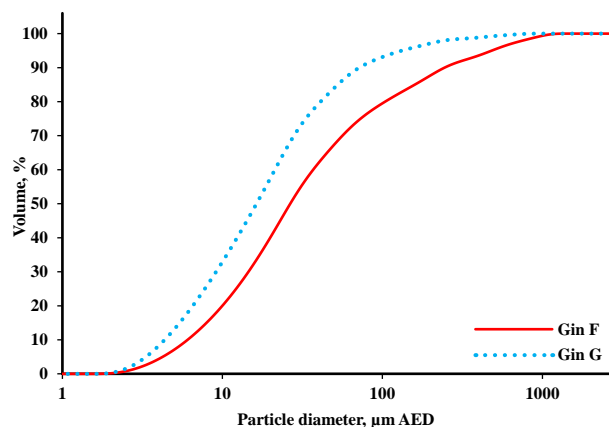


Figure 5. Gin average cumulative particle size distributions for the PM captured on a EPA-Method 17 filter from the mote cleaner systems.

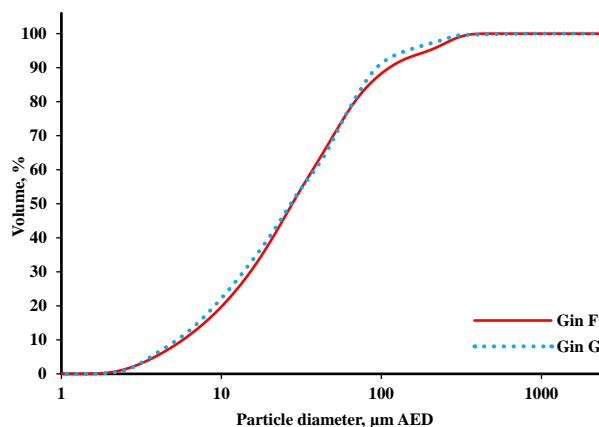


Figure 6. Gin average cumulative particle size distributions for the PM captured in the EPA-Method 17 sampler nozzle wash from the mote cleaner systems.

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 1 to 12% of the total PM (filter and wash) collected from the individual test runs. The gin F test average wash MMD was 27.8 μm AED. The gin G test average wash MMD was 27.1 μm AED. The test average wash mass fraction of PM<sub>2.5</sub>, PM<sub>6</sub>, and PM<sub>10</sub> for gin F was 1.40, 10.6, and 19.8%, respectively. The test average wash mass fraction of PM<sub>2.5</sub>, PM<sub>6</sub>, and PM<sub>10</sub> for gin G was 1.11, 11.9, and 22.2%, respectively. PSDs for the PM captured in the nozzle for the two gins are shown in Fig. 6. In general, the PSD curves for the PM captured in the washes had similar shapes and nearly overlay one another resulting in nearly identical PSD characteristic values.

The combined PSD characteristics for the PM captured on the filter and PM captured in the wash are shown in Table 4. The gin F test average combined filter and wash PSD MMD was 26.7 μm AED. There were no particles less than 1.0 μm in diameter. The combined filter and wash PM<sub>2.5</sub>, PM<sub>6</sub>, and PM<sub>10</sub> mass fractions for gin F were 0.85, 9.9, and 20.0, respectively. The gin G test average combined filter and wash PSD MMD was 17.1 μm. The combined filter and wash PM<sub>2.5</sub>, PM<sub>6</sub>, and PM<sub>10</sub> mass fractions for gin G were 1.53, 17.1, and 31.8, respectively. Combined PM PSDs for the two gins 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 3. EPA Method 17 nozzle wash particle size distribution data for the mote cleaner system.

Gin	Test Run	Mass Median Diameter μm AED	PM <sub>2.5</sub> %	PM <sub>6</sub> %	PM <sub>10</sub> %	Sample Mass mg
F <sup>y</sup>	1	30.3	1.41	10.0	18.6	13.64
	2	30.7	1.63	10.8	19.2	10.88
	3	23.7	1.16	11.2	21.4	2.12
	Test Average (n = 3) <sup>z</sup>	27.8	1.40	10.6	19.8	
G	1	45.6	1.22	7.9	14.1	15.18
	2	16.1	0.61	16.3	32.0	1.97
	3	31.4	1.52	11.6	20.5	10.30
	Test Average (n = 3) <sup>z</sup>	27.1	1.11	11.9	22.2	

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

<sup>y</sup> Mote cleaner system exhaust was combined with a module feeder dust system exhaust

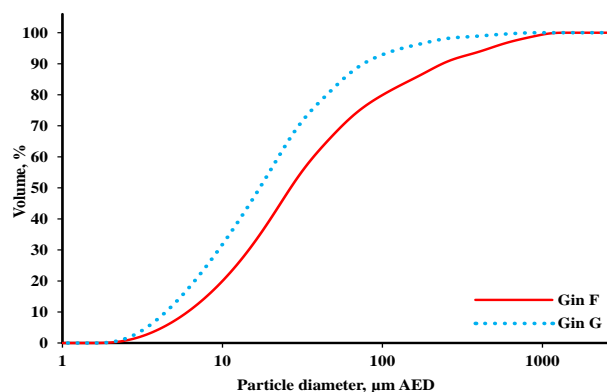


**Table 4. EPA Method 17 combined filter and wash particle size distribution data for the mote cleaner system.**

Gin	Test Run	Mass Median Diameter $\mu\text{m AED}$	PM <sub>2.5</sub> %	PM <sub>6</sub> %	PM <sub>10</sub> %
F <sup>y</sup>	1	26.2	0.82	9.9	20.2
	2	28.5	0.82	9.4	18.9
	3	25.5	0.91	10.4	20.9
	<b>Test Average (n = 3)<sup>z</sup></b>	<b>26.7</b>	<b>0.85</b>	<b>9.9</b>	<b>20.0</b>
G	1	18.6	1.47	15.8	29.6
	2	16.6	1.45	16.8	31.8
	3	16.2	1.68	18.7	34.0
	<b>Test Average (n = 3)<sup>z</sup></b>	<b>17.1</b>	<b>1.53</b>	<b>17.1</b>	<b>31.8</b>

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

<sup>y</sup> Mote cleaner system exhaust was combined with a module feeder dust system exhaust



**Figure 7. Gin average cumulative particle size distributions for the EPA-Method 17 combined filter and wash samples from the mote cleaner systems.**

The PSD-based emission factors for the mote cleaner systems are shown in Table 5. The test average PM<sub>2.5</sub> emission factors for gin F and G were 0.00092 kg/227-kg bale (0.0020 lb/500-lb bale) and 0.0016 kg/bale (0.0036 lb/bale), respectively. The gin F and G mote cleaner system test average PM<sub>6</sub> emission factors were 0.011 kg/bale (0.024 lb/bale) and 0.018 kg/bale (0.040 lb/bale), respectively. The mote cleaner test average PM<sub>10</sub> emission factor for gin F was 0.022 kg/bale (0.048 lb/bale) and gin G was 0.033 kg/bale (0.074 lb/bale). The gin F 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 were 0.85, 9.9, and 20.0%, respectively. The gin G 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 1.53, 17.1, and 31.8%, respectively.

The gin F (combined mote cleaner and module feeder dust system) PSD-based mote cleaner system PM<sub>2.5</sub> emission factor was approximately 4% of the PM<sub>2.5</sub> emission factor reported by Whitelock et al. (2013) and measured using EPA Method 201A, 0.022 kg (0.050 lb) per 227-kg (500-lb) bale, while the gin G (stand-alone mote cleaner system) PSD-based PM<sub>2.5</sub> emission

factor was about 45% of the emission factor reported by Whitelock et al. (2013), 0.0036 kg per bale (0.0079 lb/bale). The mote cleaner system PM<sub>10</sub> emission factor determined for gin F was about 32% of the combined EPA AP-42 published values for the mote fan and mote trash fan (EPA, 1996a, 1996b), which would be similar to the mote cleaner system. The PM<sub>10</sub> mote cleaner emission factor determined for gin G was about 49% of the combined EPA AP-42 mote fan and mote trash fan values. Also, the PSD-based PM<sub>10</sub> test average emission factors for gins F and G were 30 and 67% of the Method 201A (PM<sub>10</sub> sizing cyclone only) PM<sub>10</sub> emission factor reported by Whitelock et al. (2014), 0.071 kg (0.157 lb) per bale and 0.050 kg (0.109 lb) per bale, respectively. 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  $\mu\text{m}$  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.

**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 mote cleaner system.**

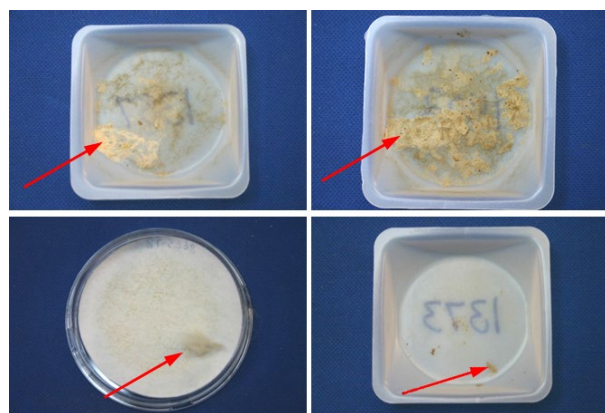
Gin	Test Run	Total <sup>z</sup>		PM <sub>2.5</sub> <sup>x</sup>		PM <sub>6</sub> <sup>x</sup>		PM <sub>10</sub> <sup>x</sup>	
		kg/bale <sup>y</sup>	lb/bale <sup>y</sup>	kg/bale <sup>y</sup>	lb/bale <sup>y</sup>	kg/bale <sup>y</sup>	lb/bale <sup>y</sup>	kg/bale <sup>y</sup>	lb/bale <sup>y</sup>
F <sup>w</sup>	1	0.100	0.221	0.00082	0.0018	0.010	0.022	0.020	0.045
	2	0.108	0.237	0.00089	0.0020	0.010	0.022	0.020	0.045
	3	0.117	0.259	0.0011	0.0024	0.012	0.027	0.025	0.054
	Test Average (n = 3)	0.109	0.239	0.00092	0.0020	0.011	0.024	0.022	0.048
G	1	0.121	0.266	0.0018	0.0039	0.019	0.042	0.036	0.079
	2	0.089	0.196	0.0013	0.0028	0.015	0.033	0.028	0.062
	3	0.106	0.234	0.0018	0.0039	0.020	0.044	0.036	0.080
	Test Average (n = 3)	0.105	0.232	0.0016	0.0036	0.018	0.040	0.033	0.074

<sup>z</sup> Taken from Whitelock et al. (2015)

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

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

<sup>w</sup> Mote cleaner system exhaust was combined with a module feeder dust system exhaust



**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.**

### 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. Two selected cotton gins had mote cleaner systems. The exhaust from one of the mote cleaner systems was combined with the module feeder dust system. Both systems were equipped with 1D3D cyclones for emissions control. The ginning rate of the two gins averaged 32.7 and 47.0 bales/h during testing for the stand-alone mote cleaner system and mote cleaner and module feeder dust system, respectively.

The average PSD-based PM<sub>2.5</sub>, PM<sub>6</sub>, and PM<sub>10</sub> emission factors for the stand-alone mote cleaner system at gin G (3 total test runs) were 0.0016 kg/227-kg bale (0.0036 lb/500-lb bale), 0.018 kg/bale (0.040 lb/bale), and 0.033 kg/bale (0.074 lb/bale), respectively. The PSD was characterized by an average MMD of 17.1 μm AED. The ratio of PM<sub>2.5</sub> to total particulate was 1.53%, PM<sub>6</sub> to total particulate was 17.1%, and PM<sub>10</sub> to total particulate was 31.8%. The average PSD-based PM<sub>2.5</sub>, PM<sub>6</sub>, and PM<sub>10</sub> emission factors for the mote cleaner system combined with the module feeder dust system at gin F (3 total test runs) were 0.00092 kg/227-kg bale (0.0020 lb/500-lb bale), 0.011 kg/bale (0.024 lb/bale), and 0.022 kg/bale (0.048 lb/bale), respectively. The PSDs were characterized by an average MMD of 26.7 μm AED. Also for the combined system, the ratio of PM<sub>2.5</sub> to total particulate was 0.85%, PM<sub>6</sub> to total particulate was 9.9%, and PM<sub>10</sub> to total particulate was 20.0%. PSD-based system average mote cleaner system PM<sub>2.5</sub> and PM<sub>10</sub> emission factors were 45% and 67% of those measured for the overall cotton gin sampling project utilizing EPA-approved methods. Currently there are no mote cleaner system emission factors published EPA AP-42.

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