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# Evaluation of shaker dust collector for use in a swine farrowing barn

Russell Sawvel  
*University of Iowa*

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EVALUATION OF SHAKER DUST COLLECTOR FOR USE  
IN A SWINE FARROWING BARN

by  
Russell Sawvel

A thesis submitted in partial fulfillment  
of the requirements for the Master of  
Science degree in Occupational and Environmental Health  
in the Graduate College of  
The University of Iowa

August 2014

Thesis Supervisor: Associate Professor Thomas M. Peters

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Graduate College  
The University of Iowa  
Iowa City, Iowa

CERTIFICATE OF APPROVAL

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MASTER'S THESIS

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This is to certify that the Master's thesis of

Russell Sawvel

has been approved by the Examining Committee  
for the thesis requirement for the Master of Science  
degree in Occupational and Environmental Health at the August 2014  
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To my beloved late Mother.

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## ABSTRACT

A shaker dust collector was evaluated to 1. determine filter capacity in terms of mass loading, pressure drop, airflow, and runtime; 2. determine particle collection efficiency by size prior to and following repeated loadings.

A shaker dust collector was setup in the laboratory to take in contaminated air, collect dust, and exhaust treated air. For each loading test, Arizona road dust (~1 to 200  $\mu\text{m}$ ) was introduced into the airstream entering the dust collector at an emission rate and duration to simulate 3-months in a swine barn in winter. Filter pressure drop and exhaust velocity pressure were measured throughout loading. Filter collection efficiency was tested using polydisperse solid glass microspheres (~1 to 10  $\mu\text{m}$ ) and measured with an aerodynamic particle sizer at the startup and end of loadings. Cleaning cycles were run between loading tests.

Overall efficiency was 44% for new filter, and ranged from 27% for 1- $\mu\text{m}$  particles, increasing to 96% for 10- $\mu\text{m}$  particles. Collection efficiency for loaded filter was 99% overall, and 99% over the range of 1 to 10- $\mu\text{m}$  particles. Following cleaning, overall efficiency was 91%, and 91% for 1- $\mu\text{m}$  particles, increasing to 99% for 10- $\mu\text{m}$  particles.

Exhaust airflow decreased linearly with pressure drop ( $R^2=0.99$ ) for all three loading tests. At startup, system airflows were approximately  $1,700 \text{ m}^3 \text{ hr}^{-1}$  and at shutdown, system airflows were approximately  $1,200 \text{ m}^3 \text{ hr}^{-1}$ . Significant recovery of filter pressure drop was observed following primary cleanings ( $p<0.001$ ).

The shaker dust collector has adequate capacity to treat swine barn air continuously over a 3-month period at a dust concentration of  $1 \text{ mg m}^{-3}$ . High collection

efficiency (>99%) of particles ( $d_p$  1-10  $\mu\text{m}$ ) was achieved after an initial loading period of approximately 2 days. High collection efficiency (90-99%) was also achieved after cleaning. The engineering control system is recommended for further testing to improve indoor air quality inside a Midwestern farrowing barn during winter.

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## CHAPTER I

### LITERATURE REVIEW

#### Overview

The U.S. pork industry has been growing and changing substantially due to the prevalence of animal feeding operations and technological advances in livestock production. The density of livestock in swine facilities has been increasing since the 1960s due to increased herd size, decreased number of sites, and increased swine inventory (USDA 2008). High livestock density operations are facilitated by the use of large, enclosed facilities that are referred to as concentrated animal feeding operations (CAFOs). CAFO buildings in the Midwest have typical capacities of 1,000-2,400 head (Jacobson 2011).

CAFO workers are exposed to a variety of airborne contaminants including particulate matter, bioaerosols, ammonia, hydrogen sulfide, carbon dioxide, carbon monoxide, and trace gases (Merchant et al. 2002). Although designs of contemporary CAFO buildings include mechanical ventilation and heating, control of hazardous dusts and gases is not addressed (Aland and Banhazi 2013).

This thesis explored the application of engineering controls to reduce simulated airborne dust concentrations in swine farrowing facilities. Control devices used in other industrial applications were considered, and a dust collector system was selected to be evaluated.

#### Review of Literature

##### Dust and Gas Concentrations

Airborne particulate matter in swine CAFO buildings is generated from feed dust, livestock dander, hair, and dried manure (Donham 1986c). Swine CAFO dusts are high in

organic content (Heber et al. 1988b). CAFO dust largely consists of primary coarse particles,  $d_p > 1 \mu\text{m}$  (Cambra et al. 2011).

Particle size distributions have been measured in nursery, farrowing, and finishing buildings and are available in the literature. The particle size distribution of CAFO dust is lognormal (Maghirang et al. 1997). In a study by Maghirang et al. (1997) the dust mass distribution in 13 nursery barns had an overall mass median diameter of  $13 \mu\text{m}$  and geometric standard deviation (GSD) of 3 and was measured with an Andersen eight stage cascade impactor. Donham et al. (1986b) sampled areas for dust inside nine swine farrowing buildings and reported a mass median diameter of  $9 \mu\text{m}$  (geometric standard deviation not stated) and used an Andersen eight stage cascade impactor. A study of 11 finishing buildings by Heber et al. (1988b) reported a mass median diameter of  $4.21 \mu\text{m}$  and geometric standard deviation of 1.61 and was measured using a resistive pulse particle analyzer. The respirable fraction in 21 swine buildings in Iowa was approximately 8% of total dust mass concentration and was measured with a 37-mm closed face cassette and 10-mm cyclone (Donham et al. 1986a).

A range of airborne dust concentrations have been recognized inside swine CAFOs. Average total mass concentrations of 21 swine buildings in Iowa (nursery, farrowing, finishing) reported by Donham et al. (1986b) ranged from 3 to  $15 \text{ mg m}^{-3}$  (GSD ranged from 1.4-1.6) Heber et al. (1988a) summarized data from gestation, nursery, farrowing, and finishing buildings where average total dust concentrations ranged from 0.8 to  $15 \text{ mg m}^{-3}$ . Reeve et al. (2013) reported daily mean respirable dust concentrations in a farrowing room ranging from approximately 0.3 to  $0.5 \text{ mg m}^{-3}$  (standard deviation 0.12-0.19, based on continuous photometer readings).

Gaseous compounds inside swine CAFOs have several sources: generation by biological activity in the manure pit, animal respiration, and combustion gases from the building heating system. Ammonia and hydrogen sulfide are among gases generated in CAFO manure pits by biological decomposition of animal waste or the biochemical

reduction of aqueous compounds by anaerobic microorganisms. Livestock respiration produces carbon dioxide gas. Carbon dioxide and carbon monoxide gases are produced by open flame natural gas heaters which are common in livestock barns. An Illinois study by Hoff et al. (2005) reported annual (fall 2002 - spring 2004) average daily concentrations of gases in a 2400-sow farrowing room: ammonia ( $5.5 \pm 2.3$  ppm), hydrogen sulfide ( $0.28 \pm 0.15$  ppm), and carbon dioxide ( $1320 \pm 480$  ppm). Reeve et al. (2013) reported mean winter concentrations in a 14-sow Iowa farrowing room: ammonia ( $3.9 \pm 0.8$  ppm), hydrogen sulfide ( $0.11 \pm 0.05$  ppm), carbon dioxide ( $2920 \pm 120$  ppm), and carbon monoxide ( $1.2 \pm 0.5$  ppm).

In the Upper Midwest U.S., CAFO dust concentrations are seasonally higher in winter when ventilation rates are low compared to in summer when ventilation rates are higher (Takai et al. 1998, O'Shaughnessy et al. 2002). In swine finishing operations Duchaine et al. (2000) found elevated concentrations of ammonia, carbon dioxide, and dust in winter relative to summer. In cold climates, low ventilation rates are used to conserve heat (Donham 1977). Ventilation rates have been shown to be a dominant factor affecting dust concentrations (Peters et al. 2012, Zhu et al. 2000). The development of potentially hazardous contaminant concentrations under low ventilation conditions in winter months is of interest because CAFO workers perform a majority of their work tasks indoors.

Ventilation systems are an integral component to any enclosed swine CAFO building. General ventilation controls, with recirculation to conserve heat, may be more practical than other control hierarchy options (e.g., personal respirator).

Other factors that influence contaminant concentrations include daily feeding patterns, temperature, and worker tasks. Inhalable and respirable dust concentrations were expected to be higher in daytime coinciding with livestock activity as opposed to inactive night hours (Takai et al. 1998). Daily variation in temperature affects ammonia concentrations. High indoor temperatures are associated with elevated ammonia

concentrations and ammonia emissions per animal unit were directly proportional to indoor temperatures (Ni et al. 2000). Worker tasks such as hog loading and power washing can aerosolize particles resulting in high concentrations of particulates (O'Shaughnessy et al. 2012).

### Respiratory Health Hazards and Disease

Respiratory health hazards and disease related to agriculture have been evident throughout history and were recognized by Olaus Magnus in 1555 (Radon et al. 2001). Occupational diseases identified among agricultural workers in the twentieth century include asthma, bronchitis, and pneumonia (Fawcitt 1938). On the order of 100 cases of "Farmers Lung" were cited in literature prior to 1957 (Staines 1961); however, these cases predate CAFOs.

Swine CAFO workers have a high prevalence of respiratory symptoms (Takai et al. 1998). These respiratory symptoms include: cough, sputum, chronic bronchitis, nasal complaints (Holness et al. 1987); airway inflammation, obstructive lung disease (Pedersen 1996); acute respiratory distress syndrome, pulmonary edema, acute bronchitis, occupational asthma, organic dust toxic syndrome (Merchant et al. 2002); sinusitis, and rhinitis (Rylander et al. 1994).

CAFO workers are at risk of acute and chronic respiratory diseases that have been associated with exposure to indoor dusts and gases from CAFO emissions (Bowman et al. 2000). Accumulation and high concentrations of pollutants are potentially hazardous to human health (Merchant et al. 2002, Donham 1995). A study of European livestock operations by Radon et al. (2001) concluded that a swine worker's risk of developing adverse health effects increases with the number of hours per day spent in a swine building (duration of work ranged from 0.15 to 10 hours per day).

### Regulatory Standards, Recommended Limits, and Guidelines

In the U.S., regulatory standards that apply to worker exposure in CAFOs are defined by the Occupational Safety and Health Administration (OSHA). OSHA regulates farm production facilities that have more than 10 employees (29 CFR 1928). OSHA established permissible exposure limits (PELs) that are health based limits designed to protect workers; PELs are “regulatory limits on the amount or concentration of a substance in the air” (OSHA Table Z-1, 2006). PEL-TWAs are eight-hour time-weighted average exposure limits. TWAs applicable to CAFOs include: ammonia (50 ppm), carbon monoxide (50 ppm), carbon dioxide (5,000 ppm), and particulates not otherwise regulated (15 mg m<sup>-3</sup> total dust and 5 mg m<sup>-3</sup> respirable fraction) (OSHA Table Z-1, 2006). Ceiling values are exposure limits that are not to be exceeded at any time. The PEL ceiling for hydrogen sulfide is 20 ppm.

The National Institute of Occupational and Safety and Health (NIOSH) develops recommended exposure limits (RELs). REL-TWAs relevant to swine CAFO include: ammonia (25 ppm), carbon monoxide (35 ppm), and carbon dioxide (5,000 ppm) (NIOSH 2003). A limit for particles not otherwise regulated has not been established. Short-term exposure limits (STEL) are 15-minute TWAs that should not be exceeded at any time. The REL STEL for ammonia is 35 ppm and the STEL for carbon dioxide is 30,000 ppm. The REL ceiling value for hydrogen sulfide is 10 ppm.

Guidelines used for industrial hygiene practice that are based on observed health effects are developed by the American Council of Government Industrial Hygienists (ACGIH). ACGIH recommended threshold values, or TLVs, are in reference to airborne concentrations of compounds below which adverse health effects are not expected. TLVs relevant to CAFOs include: ammonia (25 ppm), hydrogen sulfide (1 ppm), carbon monoxide (25 ppm), carbon dioxide (5,000 ppm), and respirable particulates (3 mg m<sup>-3</sup>) (ACGIH 2013).

Recommendations for agricultural health limits are suggested in the literature. Donham and Cumro (1999) identified a significant dose-response relationship between exposure and decreased baseline pulmonary function that was observed over a shift in swine workers. Threshold concentrations were identified as  $2.4 \text{ mg m}^{-3}$  for total dust and  $0.23 \text{ mg m}^{-3}$  for respirable dust. Additional suggested exposure limits for swine confinement workers include ammonia (7 ppm) and carbon dioxide (1500 ppm) (Donham et al. 1989). The recommended limits are lower than ACGIH TLVs.

Guidelines based on human comfort are developed by the American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE). ASHRAE recommended indoor air quality based recommended limits include: carbon monoxide (9 ppm) and carbon dioxide (700 ppm in excess of the ambient outdoor concentration). Typical values of outdoor carbon dioxide concentrations range from 300 ppm to 500 ppm (ASHRAE 1999).

#### Current Control Practices

Numerous strategies have been considered to reduce contaminant concentrations in swine CAFOs. Practices identified by the Pew Commission on Industrial Farm Animal Production include use of covered feeders, using extra fat or oil in feed, sprinkling of vegetable oil, power washing surfaces, using plastic coated flooring, and using vented heaters (PCIFAP 2008). The Commission recommended that health hazards in swine CAFOs should be addressed by a) using management procedures that decrease generation of dust and gases, b) using ventilation to reduce contaminants, and c) use of individual respirator personal protection equipment (PCIFAP 2008). More generally, the hierarchy of control methods to prevent exposure to occupational hazards are: elimination and substitution, engineering controls, administrative controls, and personal protective equipment (NOISH 2010).

Elimination and substitution have been considered to reduce contaminant concentrations in swine CAFOs. Feed modification can reduce feed dust concentrations. In a study by Takai and Pedersen (2000), in an 11 m x 11 m swine finishing room in Denmark, liquid feed was substituted for dry feed. Total dust was reduced by 27% but reduction of respirable dust was inconclusive. Feed amendments, or adding 5% fat, can reduce inhalable dust levels on the order of 50% (Pedersen et al. 2000). Feed modification does not address contaminant emissions from other sources.

Outdoor or nonintegrated manure storage has been recommended as a new building design criterion by Jacobson (2011). Nonintegrated manure storage eliminates indoor manure emissions in CAFO buildings (ammonia, carbon dioxide, hydrogen sulfide, methane); however, it does not address feed or dander source emissions. Construction of nonintegrated facilities increases CAFO capital cost (Jacobson 2011).

Dilution ventilation is practiced as a temperature control method in most swine CAFOs, however, ventilation rates are typically reduced during cold weather months to conserve heat (Donham et al. 1977). Operation of manure pit fans can significantly reduce airborne contaminant concentrations but dust control may be insufficient to control exposure (Reeve et al. 2013). Another type of ventilation control, purge ventilation, involves a brief period of elevated ventilation to temporarily reduce dust concentrations. However, dust concentrations can rapidly rebound following a purge event (Takai and Pedersen 2000, Robertson 1989). Filtration of contaminants from general exhaust and the incorporation of a recirculation loop of treated air is a logical and practical option that has been explored to reduce indoor concentrations while controlling heating energy costs. Dry filtration can remove 50% to 60% of dust, by mass, from recirculated air in livestock buildings (Pearson and Sharples 1995).

Application of vegetable oil spray has been recognized as a promising treatment to reduce dust concentrations. Total dust concentrations were reduced by 58% - 82% following one month of daily vegetable oil treatments inside a 700-swine CAFO finishing

building in the Mid-Atlantic region (Rule et al. 2005). In a review of literature, Rule et al. (2005) identified spraying of vegetable oil as the most effective dust control method that has been tested in swine CAFOs. Nonnenmann et al. (2004) studied sprinkling of canola oil in a 71-swine finishing room in Iowa resulted in total dust reduction of 56% (from  $1.35 \text{ mg m}^{-3}$  to  $0.65 \text{ mg m}^{-3}$ ) over 13 weeks. Application of oil droplets greater than 150- $\mu\text{m}$  diameter were recommended to prevent inhalation and health hazards (Pedersen et al. 2000). A disadvantage to oil application was the accumulation of residue on surfaces demand for more stringent housekeeping.

Richardson et al. (2003) used an electrostatic charge device to remove dust in a poultry-broiler building. The study was based on a poultry environment rather than a swine environment. The experimental setup included two environmentally controlled rooms (9 m x 7 m) and treatment resulted in an average reduction of 61% over 27 weeks (from  $3.75 \text{ mg m}^{-3}$  to  $1.45 \text{ mg m}^{-3}$  based on direct reading instrument measurements). A detailed investigation of electrostatic precipitators and swine CAFO dust was not found in the literature.

Biofiltration of waste air from a 22-swine finishing barn in Germany was evaluated by Martens et al. (2001) as a method to control odors in exhausted air. The biofilter treated airstream was discharged to atmosphere and was not recirculated inside buildings. Data were collected from five biofilters on five days over two months. Reductions were observed in levels of bacteria, volatile organic compounds, and odors. However, the treatment was not effective at removing ammonia, fungi, or endotoxin.

Personal protective equipment is considered last in the controls hierarchy (NIOSH 2010). A 1993 study of approximately 300 subjects by Zejda et al. reported that 30% of swine CAFO workers used disposable respirators. A 2002 survey of more than 2,400 farmers by Carpenter et al. the use of dust respirators was described as “rare”.

Numerous strategies have been considered to reduce airborne contaminant concentrations in swine CAFOs. An individual strategy or array of complement strategies

that can be applied to existing CAFOs is desirable. Elements of such a solution may reside in control strategies that are in place in other industries. A control technology that has been used in general exhaust ventilation to clean industrial air is the shaker dust collector.

### Control Strategies in Other Industries

Air pollution control devices found in industries other than agriculture may provide cost-effective performance to remove particles inside swine CAFOs. Several treatment alternatives that are commercially available for the control of airborne particulates are: shaker dust collector, cyclone, electrostatic precipitator, and wet scrubber. Although widely used in industrial applications, these technologies have yet to be applied to commercial swine CAFO buildings.

Shaker dust collectors use a fan to draw exhaust air through a fabric filtration medium. Particles in the airstream are collected by impaction and interception on the fabric itself or on a residue layer atop the fabric. Particle collection efficiencies are commonly greater than 95% for sizes greater than 0.1  $\mu\text{m}$  (Table I-1). Common industrial applications include: bin ventilation, buffing, grinding, mixing, packaging, polishing, sanding, and sawing (UAS Inc, 2013). Operation can be described by preloading time, duty cycle (time for airflow to decrease to a set limit), dust collection capacity (mass of dust accumulated over the duty cycle), filter collection efficiency, pressure drop, airflow, and cleaning cycle. Advantages of shaker dust collectors are high removal efficiency, relatively low pressure drop, and reusable filter. High dust concentrations in a swine barn are compatible with shaker dust collector loading. A possible disadvantage is reduced collection efficiency under moist conditions (Cooper and Alley 1986) that are expected in swine rooms that have manure pits.

Centrifugal collectors, or cyclone devices, use centrifugal force to separate particles from an airstream. A fan driven airstream enters the cylindrical cyclone body

tangentially, travels around the cylinder wall, and exit through the central axis. Particles separate from the airstream at the cylinder wall and are collected in a hopper at base of the device. Typical removal efficiencies are greater than 90% for particles larger than 10  $\mu\text{m}$  (Table I-1). Cyclone industrial applications include collection of coarse particles in woodworking or machining, and recovery of powdered paint (Donaldson Co. 2012). Cyclones can be compatible with high concentrations of large dust particulates found in swine barns. While cyclones collect coarse particles, the collection efficiency for smaller particles, 1- $\mu\text{m}$  to 10- $\mu\text{m}$ , may be too low to use the cyclone as a standalone device. The cyclone may be best suited as a precleaner to remove particles larger than 10- $\mu\text{m}$ . By removing dust from the airstream a precleaner device would extend the life of devices that follow in the cleaning process.

Electrostatic precipitators electrically charge airstream particles that are subsequently collected on grounded plates. The exhaust airstream is driven by a fan. Collection efficiencies are above 95% for particle diameters larger than 0.1  $\mu\text{m}$  (Table I-1). Industrial applications include coal-fired power plants, cement kilns, and heating ventilation/air conditioning systems (Burgess, Ellenbecker, and Treitman 2004). Disadvantages of electrostatic precipitators are high capital cost, high operation cost, and large area requirements. Electrostatic precipitator use has been explored in livestock agriculture (Richardson et al. 2003) and is expected to reduce dust concentrations. However, performance specific to swine barns has yet to be investigated and no detailed research has been found for electrostatic dust collectors in livestock application (Pearson and Sharples 1995).

Wet scrubbers remove particles from airstreams via contact with liquid. Particulate removal efficiency is high, greater than 95% for particle sizes greater than 2  $\mu\text{m}$  (Table I-1). However, these systems inherently produce high humidity exhaust airstreams, and their operation requires management and disposal of liquid waste. Industrial applications include incineration, steel furnaces, foundries, and asphalt plants

(Burgess, Ellenbecker, Treitman 2004). Wet scrubbers can remove over 80% of dust mass from room recirculated air in livestock applications (Pearson and Sharples 1995).

### Shortcomings of Literature

Airborne contaminants at concentrations exceeding industry guidelines to prevent adverse respiratory health effects are common inside swine confinement buildings. Indoor dust concentrations are of particular concern during cold weather conditions when ventilation rates are low. Additional control strategies are necessary to reduce dust concentrations below recommended agricultural threshold levels. Research and development addressing hazardous indoor air quality and reduction of contaminant concentrations within CAFOs are being pursued (Rule et al. 2005). A treatment strategy is needed that improves indoor air quality, is cost effective, and is simple to operate and maintain. A dust collector control system for swine CAFOs may be a solution to reduce dust concentrations below recommended exposure concentrations for workers.

### Objectives

The efficacy of a shaker dust collector for use in a swine farrowing barn was investigated in this study. Performance requirements for a viable control strategy include high airflow, high collection efficiency, low pressure drop, and treatment capacity for high dust loading. The specific aims were to:

1. Determine filter capacity in terms of mass loading, pressure drop, airflow, and run time.
2. Determine particle collection efficiency by size prior to and following repeated loadings.
3. Determine the effect of filter preloading on startup lead-time.
4. Determine the minimum number of cleaning cycles required to reclaim filter pressure drop.

To achieve these aims, laboratory testing of the shaker dust collector included an initial loading and two additional loadings to mimic three winter seasons in a swine barn. Accelerated filter loading was scaled at a ratio of one laboratory day equal to 20 days in a swine barn. Loadings occurred at a constant emission rate. Filter pressure drop and system exhaust velocity pressure were monitored. Collection efficiency was assessed at startup and conclusion of loadings. Cleaning cycles were evaluated between loadings.

Table I-1. Airborne particulate control systems.

Control Device	Pro	Con
Shaker Dust Collector	<p><math>\eta=90-99\%</math> for <math>d_p=1-10 \mu\text{m}^a</math>  <math>\Delta p=125-1000 \text{ Pa}^a</math></p> <p>High collection efficiency,<sup>c</sup>  <math>\eta&gt;95\%</math>, <math>d_p&gt;0.1 \mu\text{m}</math></p> <p>Low pressure drop,  <math>\Delta p&lt;1500 \text{ Pa}^d</math></p> <p>Filter cloth is reusable<sup>a</sup></p>	Low collection efficiency in moist environments <sup>b</sup>
Centrifugal Collector, Cyclone	<p>High collection efficiency<sup>c</sup> <math>\eta&gt;90\%</math>  for <math>d_p&gt;10\mu\text{m}^d</math></p> <p>Low pressure drop,  <math>\Delta p=500-1500 \text{ Pa}^c</math></p> <p>Low capital cost,  simple system</p> <p>Cyclone device is reusable</p>	Low collection efficiency for $d_p<10 \mu\text{m}$
Electrostatic Precipitator	<p>High removal efficiency, <math>\eta&gt;95\%</math>  for <math>d_p&gt;0.1 \mu\text{m}^c</math></p> <p>Low pressure drop,  <math>\Delta p=125-250 \text{ Pa}^c</math></p>	High capital cost and operating cost, large footprint <sup>c</sup>
Wet Scrubber	<p>High removal efficiency, <math>&gt;95\%</math> for  <math>d_p&gt;2\mu\text{m}^c</math></p> <p>Low pressure drop,  <math>\Delta p=500-1500 \text{ Pa}^c</math></p>	High capital cost and operating cost, complex system <sup>c</sup>

Notes.  $\eta$ : collection efficiency,  $\Delta p$ : pressure drop,  $d_p$ : aerodynamic particle diameter, <sup>a</sup> Source: this study, <sup>b</sup> Cooper and Alley (1986), <sup>c</sup> Burgess, Ellenbecker, and Treitman (2004), <sup>d</sup> Donaldson Co. (2012)

## CHAPTER II

### SHAKER DUST COLLECTOR EVALUATION

#### Introduction

Since the 1960s, U.S. swine producers have increasingly implemented the use of concentrated animal feeding operations (CAFOs) with increased herd sizes at fewer sites (USDA 2008). High density livestock operations are facilitated by the installation of large enclosed CAFO buildings at swine production sites. Swine CAFO buildings accumulate indoor air contaminants including particulate matter, bioaerosols, ammonia, hydrogen sulfide, carbon dioxide, carbon monoxide, and trace gases (Merchant et al. 2002). Swine CAFO workers have a high prevalence of respiratory symptoms (Takai and Pedersen 1998). In the Upper Midwest U.S., CAFO dust concentrations are seasonally higher in winter when ventilation rates are low compared to in summer when ventilation rates are higher (Takai et al. 1998, O'Shaughnessy et al. 2002). Ventilation rates have been shown to be a dominant factor affecting dust concentrations (Peters et al. 2012, Zhu et al. 2000).

Contaminant control methods are necessary to reduce dust concentrations below recommended threshold levels. Research and development of technology addressing hazardous indoor air quality and the reduction of contaminant concentrations within CAFOs are being pursued (Rule et al. 2005): feed modification, nonintegrated manure pit, ventilation, oil spray, electrostatic device, and biofiltration. Feed modification, or use of liquid feed or fat amended feed, can reduce feed dust concentrations (Takai and Pedersen 2000). However, feed modification does not address contaminant emissions from other sources. Outdoor or nonintegrated manure storage has been recommended as a new building design criterion by Jacobson (2011). Nonintegrated manure storage eliminates indoor manure emissions in CAFO buildings; however, it does not address feed or dander source emissions. Dilution ventilation is a practiced as a temperature

control method in most swine CAFOs, however, ventilation rates are typically reduced during cold weather months to conserve heat (Donham et al. 1977).

Spraying of vegetable oil has been found to be an effective way to lower dust concentrations in swine CAFOs (Rule et al. 2005). Nonnenmann et al. (2004) studied sprinkling of canola oil in a 71-swine finishing room in Iowa resulted in total dust reduction of 56% (from  $1.35 \text{ mg m}^{-3}$  to  $0.65 \text{ mg m}^{-3}$ ) over 13 weeks. A disadvantage to oil application is that the accumulation of residue on surfaces demands more stringent housekeeping. Richardson et al. (2003) used an electrostatic charge device to remove dust in a poultry-broiler building. Treatment resulted in an average reduction of 61% over 27 weeks (from  $3.75 \text{ mg m}^{-3}$  to  $1.45 \text{ mg m}^{-3}$  based on direct reading instrument measurements). Biofiltration of waste air from a 22-swine finishing barn in Germany was evaluated by Martens et al. (2001) as a method to control odors. Reductions were observed in levels of bacteria, volatile organic compounds, and odors. However, the treatment was not effective at removing ammonia, fungi, or endotoxin.

Several commercially available treatment alternatives used in other industries to control dust are: shaker dust collector, cyclone, electrostatic precipitator, and wet scrubber. Although widely used in industrial applications, these technologies have yet to be applied to commercial swine CAFO buildings. The shaker dust collector has higher collection efficiency than the cyclone for particles  $<10 \mu\text{m}$  and lower capital cost than an electrostatic precipitator or wet scrubber. Common industrial applications for the shaker dust collector are: bin ventilation, buffing, grinding, mixing, packaging, polishing, sanding, and sawing (UAS Inc, 2013). Advantages of the shaker dust collector over other air cleaners are high removal efficiency, low pressure drop, and a reusable filter. Particle collection efficiencies are commonly greater than 95%. The high dust concentrations found in swine CAFOs are compatible with shaker dust collector loading. A limitation of dry filtration is the inability to remove gaseous compounds.

Filtration of contaminants from general exhaust and the incorporation of a recirculation loop of treated air is a logical and practical option that has been explored to reduce indoor concentrations while controlling heating energy costs (Pearson and Sharples 1995). Dry filtration can remove 50% to 60% of dust, by mass, from recirculated air in livestock buildings (Pearson and Sharples 1995). The efficacy of dust collectors applied to swine barns has yet to be investigated in detail.

In this work, we selected the shaker dust collector for further evaluation because of potentially high collection efficiency of particulates at low pressure drop, simplicity of operation, and low capital cost. The purpose of repeated testing in the laboratory was to enumerate values of collection efficiency and pressure drop using a standard test dust with consistent particle size distribution, constant emission rate, and controlled temperature and relative humidity. Repeated filter cleaning was tested to determine the number of cleanings required to reclaim pressure drop and minimize mechanical wear of the fabric. Laboratory evaluation provided a performance baseline that can be used for comparison between different filter fabrics and to other control devices. A baseline evaluation should not be performed under field conditions because of lack of test repeatability, uncontrolled temperature and relative humidity, variable particle size distribution, and influences of unknown field factors.

## Methods

### Experimental Setup

A commercial off-the-shelf  $1700\text{-m}^3 \text{ hr}^{-1}$  (1000-CFM) shaker dust collector (SDC, Model 140, United Air Specialists Inc., Cincinnati, OH) and exhaust ventilation system was assembled as shown in Figure I-1. SDC cabinet dimensions were 0.8 m x 0.7 m x 1.2 m. The radial flow fan motor power was 2.2-kilowatts. All tests were conducted with a 14-pocket, polyester sateen filter (SDC-140, 9-ounce cloth with  $13\text{-m}^2$  surface area). Separated particulate matter accumulated in a storage drum beneath the unit. The

collector drum also accumulated dislodged dust from SDC cleanings. Airflow first entered the SDC and traveled around a baffle plate, which separated large particles from the airstream. Airflow and suspended particulate matter then passed through fabric filter media (subject to collection efficiency). Filtered, exhaust air was vented to the atmosphere.

The duct system was assembled of 254-mm (10-inch) diameter, circular, galvanized steel ducting with clamp-together connections (NORDFAB USA, Thomasville, NC). The inlet duct length was approximately 3 m (longitudinal distance of 12 duct diameters) and the exhaust duct length was 7.6 m. Airflow was controlled by a blast gate positioned at the inlet of the system.

SDC filter pressure drop (Pa) and exhaust duct velocity ( $\text{m s}^{-1}$ ) were measured with electronic pressure transmitters (Model 616-2, Dwyer Instruments, Michigan City, IN). Velocity pressure of the exhaust was measured using a Pitot tube that was installed 8 duct diameters downstream of the SDC outlet (Figure I-1). The Pitot tube ports were connected to the pressure transmitter using small diameter plastic tubing. Pressure transmitter signals were recorded using an electronic data logger (Arduino, Adafruit Industries, New York, NY). Measurements were logged once every second.

All tests were conducted indoors where room temperatures ranged from 22-26°C, relative humidity ranged from 45-62%, and atmospheric pressure ranged from 737-745 mm Hg.

### Loading

Coarse Arizona road dust (ARD,  $d_p < 1$  to 200  $\mu\text{m}$ , A4 Coarse Test Dust, Powder Technology Inc., Burnsville, MN) was used to simulate swine barn dust. ARD was selected because ARD is a standard test dust, the size distribution includes inhalable particles, it is commercially available, and loading was repeatable. ARD was dispensed one-half duct diameters downstream from the inlet, at  $0.6 \text{ g min}^{-1}$ , with an auger-type dry

material feeder (Model 53190, Accurate, Whitewater, WI) as per standard operating procedure (Appendix A). The lowest dispensary setting of the material feeder was used. ARD became entrained in the airflow prior to entering the SDC.

Three loading tests were administered to simulate operation in a swine barn over a three-month period at a concentration of  $1 \text{ mg m}^{-3}$ . This simulated dust concentration was near the lower limit of swine barn dust concentrations ( $0.8\text{-}15 \text{ mg m}^{-3}$ ) summarized in a review by Heber et al. (1988a). Each test was stopped when the filter pressure drop reached the manufacturer's recommended maximum of 1000 Pa. Continuous runtimes for each test were 7.1, 5.6, and 5.0 days at constant emission rate. The initial loading test duration was longer than subsequent tests because it included preloading of the filter. The cumulative 18-day laboratory run loaded approximately 14 kg and was equivalent to a simulated loading of more than 350 days. The mass loading for 1 day in the laboratory, based on emission rate, is given in Equation 1. The simulated mass loading for 1 day in a swine barn is given in Equation 2. The ratio of laboratory loading to simulated loading was 20 (i.e.,  $0.8 \text{ kg d}^{-1}/0.04 \text{ kg d}^{-1}$ ).

$$\begin{aligned} \text{Daily Mass, Lab} &= ER \times \Delta t & (1) \\ &= 0.6 \frac{g}{min} \times \frac{kg}{10^3 g} \times 1440 \frac{min}{d} \approx 0.8 \frac{kg}{d} \end{aligned}$$

Where: ER = emission rate

$\Delta t$  = time, days

$$\begin{aligned} \text{Daily Mass, Simulated} &= QC\Delta t & (2) \\ &= 1700 \frac{m^3}{hr} \times 1 \frac{mg}{m^3} \times \frac{kg}{10^6 mg} \times 24 \frac{hr}{d} \approx 0.04 \frac{kg}{d} \end{aligned}$$

Where: Q = exhaust airflow of a control device

C = dust concentration of a swine farrowing barn

$\Delta t$  = time, days

Airflow can be estimated as a function of pressure drop. The coefficient of determination ( $R^2$ ) was calculated for each loading test in Microsoft Excel (Version 14,

Microsoft Corp., Redmond, WA). A change in unit pressure drop (Pa) explained 99% of the variability in a change in unit airflow ( $\text{m}^3 \text{hr}^{-1}$ ).

### Collection Efficiency

The collection efficiency of fabric filters is characteristically greater than 90% (Burgess, Ellenbecker, and Treitman 2004). Collection efficiency by particle size of the SDC was measured at startup of the first loading, at end of first loading, at the startup of second loading, and at the end of second loading as per the standard operating procedure provided in Appendix A.

Polydisperse solid glass microspheres (3.3  $\mu\text{m}$  CMD, 1.7 GSD; 5000A, Potters Industries, Valley Forge, PA) were used as the challenge aerosol. The density of the material was constant ( $2.5 \text{ g cm}^{-3}$ ). Glass microspheres were compatible with the operation of the aerodynamic particle counter; ARD can form a buildup inside measurement devices that can interfere with particle counting. The challenge aerosol was generated using the same auger-type dry material feeder used in loading (Model 53190, Accurate, Whitewater, WI). Dry feed was dispensed into a Venturi valve (Model JD-90M, Vaccon, Medway, MA) and the aerosolized challenge dust was introduced at the duct system inlet. Challenge aerosol was sampled isokinetically in the inlet and exhaust ducts using gooseneck nozzles (Model 401SS, Clean Air Engineering, Palatine, IL) at a sample airflow of  $4.4 \text{ L min}^{-1}$ . Isokinetic sampling was necessary to avoid undersampling or oversampling from the duct airstream.

Particle count by size was measured with an aerodynamic particle sizer (APS, Model 3321, TSI, Shoreview, MN). The APS measured concentrations in one of two locations: inlet duct or exhaust duct. Tubing length from either gooseneck nozzle to the APS inlet was identical. The operation in the inlet duct is denoted as “WO” and the operation in the exhaust duct is denoted as “W.” The APS was operated for three consecutive samples each with (W) and without (WO) filtration. The operation occurred

in the following sequence: WO-W-WO-W-WO-W-WO. The APS sample airflow was 4.4 L min<sup>-1</sup> and the sample time was 60 seconds per measurement. The sample airflow was decreased from the default 5 L min<sup>-1</sup> to meet isokinetic requirements. Particle density was 2500 kg m<sup>-3</sup> and Stokes correction was applied to the aerodynamic diameter. Three measurements of SDC collection efficiency by particle aerodynamic diameter were calculated for each performance test for the SDC. For a particular aerodynamic particle diameter, collection efficiency was calculated as shown below in Equation 3.

$$CE = \frac{1}{3} \left[ \left( 1 - \frac{W_i}{\frac{WO_j + WO_{j+1}}{2}} \right) + \left( 1 - \frac{W_{i+1}}{\frac{WO_{j+1} + WO_{j+2}}{2}} \right) + \left( 1 - \frac{W_{i+2}}{\frac{WO_{j+2} + WO_{j+3}}{2}} \right) \right] 100\% \quad (3)$$

where: CE = percent collection efficiency

$W_i, W_{i+1}, W_{i+2}$  = measurements with filter

$WO_j, WO_{j+1}, WO_{j+2}, WO_{j+3}$  = measurements without filter

The overall collection efficiency was calculated as the arithmetic mean of collection efficiencies (CE, Equation 3) over the range of particle diameters.

#### Quality Factor

Quality factor is a parameter that can be used to compare or rank different types of air pollution control devices. It is a function of collection efficiency and pressure drop. Quality factor was assessed at startup of the first loading, end of first loading, startup of second loading, and end of second loading. Quality factor was calculated using Equation 4.

$$q_F = \frac{-\ln(1-CE_{overall})}{\Delta p} \quad (4)$$

where:  $q_F$  = quality factor

$CE_{overall}$  = overall collection efficiency

$\Delta p$  = pressure drop

## Cleaning

The SDC was cleaned following each loading test using the standard feature reciprocating shaker arm mechanism that dislodged dust cake from the filter media. The time of the cleaning cycle was 35 seconds (manufacturer default). Cleaning was repeated three times following each loading for a total of nine cleanings. The filter pressure drop was measured at the end of each loading and following each filter cleaning to investigate pressure drop recovery. The change in pressure drop between cleaning cycles were compared using two-sample t-tests for equal variances. For all analysis a p-value <0.05 was considered significant. Statistical analyses were performed in Minitab (Version 16.1, Minitab, Inc., State College PA).

## Results

### Loading

A summary of loading tests is provided in Table II-1. The pressure drop and airflow during these loading tests are depicted in Figure II-2. Raw data is provided in Appendix B. The initial pressure drop for the clean filter was 120 Pa. The pressure drop gradually increased to 950 Pa at conclusion of the first loading that represented 140 swine barn days. Following cleaning, the pressure drop reduced to 350 Pa. Over the course of the second loading (110 swine barn days), the pressure drop across the SDC filter reached 970 Pa. Following the second cleaning, the pressure drop was reduced to 370 Pa. Over the duration of the third loading (100 swine barn days), the pressure drop climbed to 1000 Pa.

In all three tests, the startup system airflow was approximately  $1700 \text{ m}^3 \text{ hr}^{-1}$ . Airflow decreased linearly as pressure drop increased (Figure II-3). At shutdown, the system airflow rate was approximately  $1200 \text{ m}^3 \text{ hr}^{-1}$ . Average velocity in the exhaust duct decreased from approximately  $9.6 \text{ m s}^{-1}$  at startup to  $6.6 \text{ m s}^{-1}$  at shutdown. Airflow through a filter fabric characteristically decreases with an increase in pressure drop.

Airflow reduced by approximately 30% over the course of loadings. The total mass of ARD dispensed was 5.6 kg for Test 1, 4.5 kg for Test 2, and 4.0 kg for Test 3.

### Collection efficiency

As shown in Figure II-4, filter collection efficiency at startup before the first loading was 27% for 1- $\mu\text{m}$  particles, increasing steadily to 96% for 10- $\mu\text{m}$  particles, with an overall collection efficiency of 44%. At the end of the first loading, collection efficiency ranged from 98-99%, for  $d_p$  1-10  $\mu\text{m}$ , and 99% for overall collection efficiency. At startup of the second loading, collection efficiency was 90% for 1- $\mu\text{m}$  particles and increased to 99% for 10- $\mu\text{m}$  particles. Overall collection efficiency was 91%. At the conclusion of the second loading, collection efficiency for particle sizes between 1-10  $\mu\text{m}$  was 99%, and the overall efficiency was 99% (Table II- 2). Raw data is found in Appendix A.

### Quality Factor

Filter quality data is tabulated in Table II- 2. The filter quality factor ranged from 0.005 – 0.009  $\text{Pa}^{-1}$ . The quality factors were slightly less than literature values. In a collection of studies by Dennis and Wilder (1975) a quality factor of 0.01  $\text{Pa}^{-1}$  was typical for cotton fabric bags filtering fly ash.

### Cleaning

Cleaning tests are summarized in Table II- 3 and depicted in Figure II-2. The effect of serial, repeated cleanings was examined to determine the recovery of pressure drop as a result of the cleaning operation and delineate the beneficial number of cleanings. The average pressure drop recovery for the first cleaning was 550 Pa. The average pressure drop recovery for the second cleaning was 25 Pa and the average pressure drop recovery for the third cleaning was 2.5 Pa. The pressure drop recovery for the first cleaning was statistically significant ( $p < 0.001$ ). The pressure drop recovery for

subsequent cleaning was not statistically significant ( $p=0.06$ ). Statistical test output is provided in Appendix C.

### Discussion

After an initial loading period the collection efficiency of the SDC was high and may be effective to control indoor dust concentrations in a swine barn. Initial, overall collection efficiency was low for the new filter, 44%. As loading proceeded, collection efficiency improved for the preloaded filter, and the overall collection efficiency was greater than 99%. Approximately 2-laboratory days or 40-simulated days of preloading were required to obtain high collection efficiency. “Just cleaned” collection efficiency remained high, 90% overall, and improved to greater than 99% with continued loading.

Filter collection efficiency relied on the ability of the fabric to develop and maintain a dust cake. New filter collection efficiency was characteristically lower than the preloaded filter with residual dust. New filter media consisted of woven cloth fibers with open spaces. The loaded filter became coated with a layer of buildup, or dust cake, that was beneficial to particle capture and substantially increased collection efficiency. Collection efficiency trends in this work agree with the conclusions of Dennis and Wilder (1975) for cotton fabrics and fly ash.

Collection efficiency by size, 90-99% for particles 1-10  $\mu\text{m}$ , and a normalized filter pressure drop of 9800  $\text{Pa m s}^{-1}$  (0.2 in. w.g.  $\text{ft}^{-1} \text{min}^{-1}$  at 7  $\text{ft min}^{-1}$ ) in this study were consistent with findings by Dennis (1974) for industrial fabric filter systems and fly ash filtration: particle collection efficiency by size ranged from 85-99.5% and a normalized pressure drop of 9800  $\text{Pa m s}^{-1}$  (0.2 in. w.g.  $\text{ft}^{-1} \text{min}^{-1}$  at 3  $\text{ft min}^{-1}$ ). Billings et al. (1954) reported that preloaded fabric dust collectors typically collect greater than 99% of dust particles for particles <1-50  $\mu\text{m}$  and the pressure drop ranges from 250-2500 Pa (1-10 in. w.g.).

In this work a single cleaning cycle was found to be sufficient to recover filter pressure drop. The first cleaning yielded an average pressure drop reduction of 550 Pa. The second cleaning yielded a reduction of 25 Pa, which was a statistically significant change ( $p < 0.001$ ). However, there is no practical significance to a second cleaning with such small yield. The third cleaning did not significantly reduce pressure drop ( $p = 0.06$ ) and was deemed unnecessary. Cleaning via mechanical shaking imparts stress and strain to the filter media and excessive wear shortens filter life. Determination of an appropriate cleaning schedule can prolong the life of the shaker's mechanical components. Single-cycle cleanings are typical in many industrial applications where shaker cleaning is performed at a predetermined pressure drop and varies by application. In an EPA report by Dennis and Wilder (1975) the upper limit of individual shakes in a single cleaning cycle was found to be approximately 200 (i.e., 20 s at 10 Hz). Their filters were cleaned for two 20-second cycles. Dust was removed in decreasingly smaller increments that decayed exponentially.

#### Limitations

The primary limitation of the shaker dust collector is its specificity to dust collection. Gaseous compounds pass through the dust collector with airflow. Exploration of other control technology to remove contaminants such as ammonia would be appropriate where concentrations pose a hazard. Physical differences, especially high humidity conditions in swine barns, may result in increased collection efficiency than what was observed in the study (Billings and Wilder 1970). Aerosol characteristics of the test dust were consistent between tests in source emission, particle size distribution, inorganic content, temperature, relative humidity, and chemical composition. Actual swine barn dust has variable source emissions, size distribution, organic content, temperature, and relative humidity.

In this study, dust cake accumulation occurred under a constant emission rate. Field loading conditions are subject to variability in dust concentration, ventilation rate, livestock inventory, feeding events, and activity in the barn. Under field conditions preloading-startup and loading to reach target collection efficiency may require more or less lead time. Depending on the pressure drop of swine barn dust cake additional cleanings may be required to maintain a desired airflow.

Laboratory loading tests that simulated preloading period and three winter seasons were conducted continuously. Loading ceased only to conduct cleaning and collection efficiency tests. Time between loading tests was on the order of hours. In field application loading is expected to be continuous for three months followed by inactivity for nine months. Potential effects on startup and collection efficiency following long dormant periods are unknown.

This study investigated one type of filter fabric that was supplied by default with the air cleaner. Other commercially available filters should be evaluated and filter quality should be used as a benchmark to quantitatively compare media performance. Filter life span is another issue to be addressed in the field. In the field filter material will be exposed to corrosive compounds such as ammonia. Weathering and premature deterioration of the filter should be investigated.

### Conclusion

The SDC was capable of processing a mass of dust equivalent to 3-months of loading in a swine barn (Table II- 4). Based on a laboratory preload time of 2 days and a scaling factor of 20, a 40-day field preloading time was estimated to provide the opportunity for dust cake formation. In the laboratory approximately 4 kg of dust were loaded over a period of 5 days representing a field simulated time of 100 days (roughly one 3-month winter season) with an exhaust airflow of 1,700-1,200 m<sup>3</sup> hr<sup>-1</sup> and dust concentration of 1 mg m<sup>-3</sup>. Following preloading the SDC achieved greater than 99%

collection efficiency for particles 1-10  $\mu\text{m}$ . The filter pressure drop in the laboratory was within the typical range of operation (370-1,000 Pa) for a fabric filter type collectors and is estimated to undergo similar airflow resistance in the field. A single cleaning cycle was estimated to be required approximately every 100 days and corresponds to a period of once per winter season.

Table II- 1. Summary of loading tests.

<b>Loading</b>	<b>Mass Loading</b>	<b>Increase in Pressure Drop, Pa</b>	<b>Change in Airflow Q, m<sup>3</sup> hr<sup>-1</sup></b>
<b>1<sup>st</sup></b>	Runtime=7.1 d Mass=5.7 kg ARD	830	-520
<b>2<sup>nd</sup></b>	Runtime=5.6 d Mass=4.5 kg ARD	620	-490
<b>3<sup>rd</sup></b>	Runtime=5.0 d Mass=4.0 kg ARD	630	-490

Table II- 2. Summary of collection efficiency and quality factor.

<b>Test Condition</b>	<b>Pressure Drop <math>\Delta p</math>, Pa</b>	<b>Collection Efficiency <math>d_p</math> 1-10 <math>\mu\text{m}</math></b>	<b>Collection Efficiency Overall, <math>\eta</math>, %</b>	<b>Quality Factor <math>q_F</math>, Pa<sup>-1</sup></b>
Startup of 1 <sup>st</sup> Loading (see Figure II-4A)	120	27-96	44	0.005
End of 1 <sup>st</sup> Loading (see Figure II-4B)	950	98-99	99	0.005
Startup of 2 <sup>nd</sup> Loading (see Figure II-4C)	350	90-99	91	0.007
End of 2 <sup>nd</sup> Loading (see Figure II-4D)	970	99	99	0.005

Table II- 3. Summary of cleaning tests.

Test Condition	Pressure Drop, $\Delta p$ , Pa	
	Mean	Standard Deviation
Startup 1 <sup>st</sup> load	120	9.5
End 1 <sup>st</sup> load	941	15
Clean 1A	326	11
Clean 1B	316	12
Clean 1C	314	11
Startup 2 <sup>nd</sup> load	344	9.5
End 2 <sup>nd</sup> load	964	13
Clean 2A	423	11
Clean 2B	388	8.7
Clean 2C	376	9.7
Startup 3 <sup>rd</sup> load	996	16
End 3 <sup>rd</sup> load	500	11
Clean 3A	471	12
Clean 3B	466	10
Clean 3C	120	9.5

Notes: Pressure drop data were recorded per second, one minute averages were reported.  
A, B, C represent sequential cleaning cycles.

Table II- 4. Dust collector parameters.

<b>Parameter</b>	<b>Laboratory Value</b>	<b>Extrapolated Field Estimate</b>
Preload time	2 d	40 d
Duty cycle	5 d	100 d
Dust collection capacity (within duty cycle)	~4 kg	~4 kg
Overall Collection efficiency (preloaded condition)	91-99%	91-99%
Pressure drop (within duty cycle)	370-1000 Pa	370-1000 Pa
No. of cleanings (per duty cycle)	1	1

Note: Estimates are based on emission rate= $0.6 \text{ g min}^{-1}$ , airflow= $1700 \text{ m}^3 \text{ min}^{-1}$  and field site dust concentration= $1 \text{ mg m}^{-3}$ .

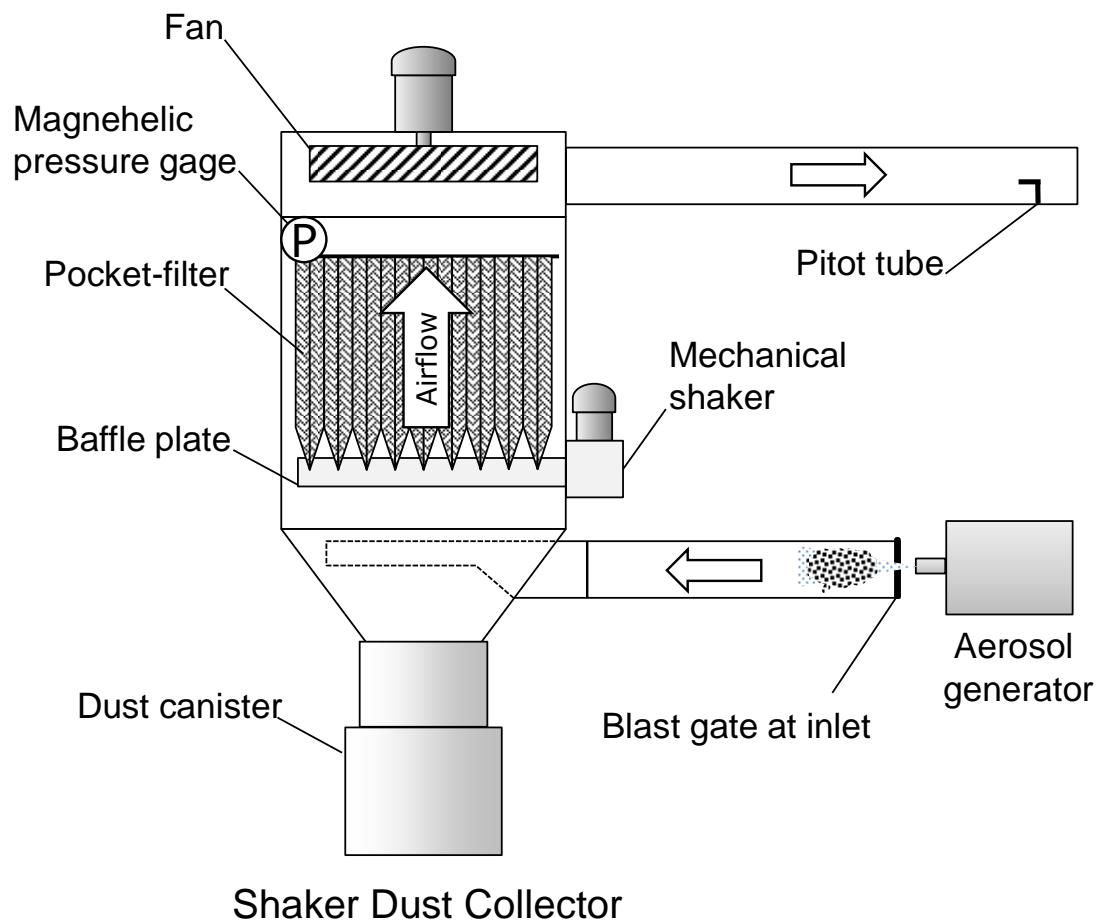


Figure II-1. Schematic of shaker dust collector system.

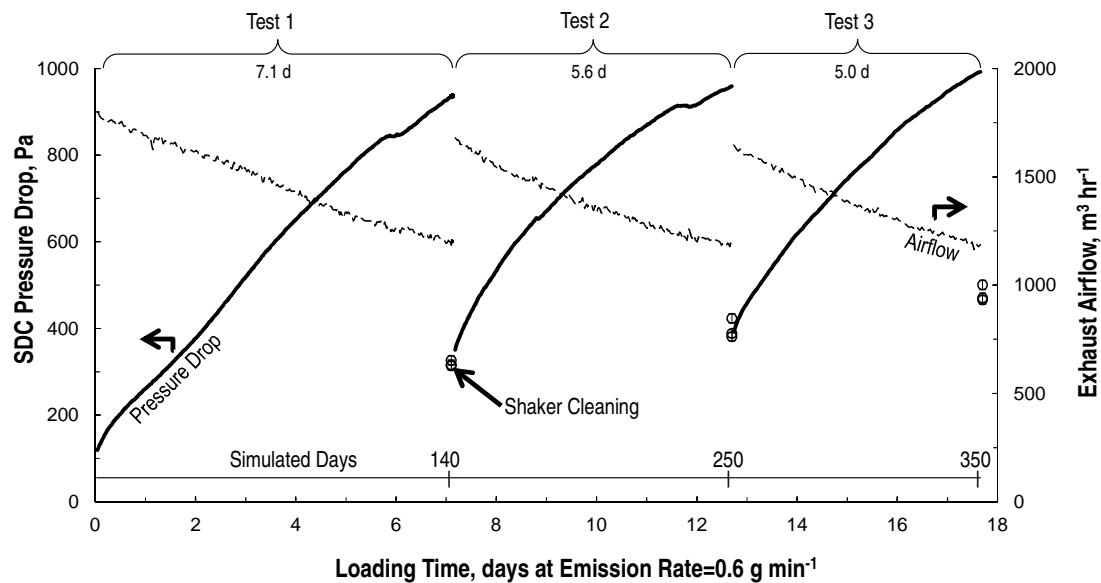


Figure II-2. Filter pressure drop and air flow observed during loading. Airflow was calculated from measured velocity pressure. Pressure drop and airflow lines are represented by hourly averages.

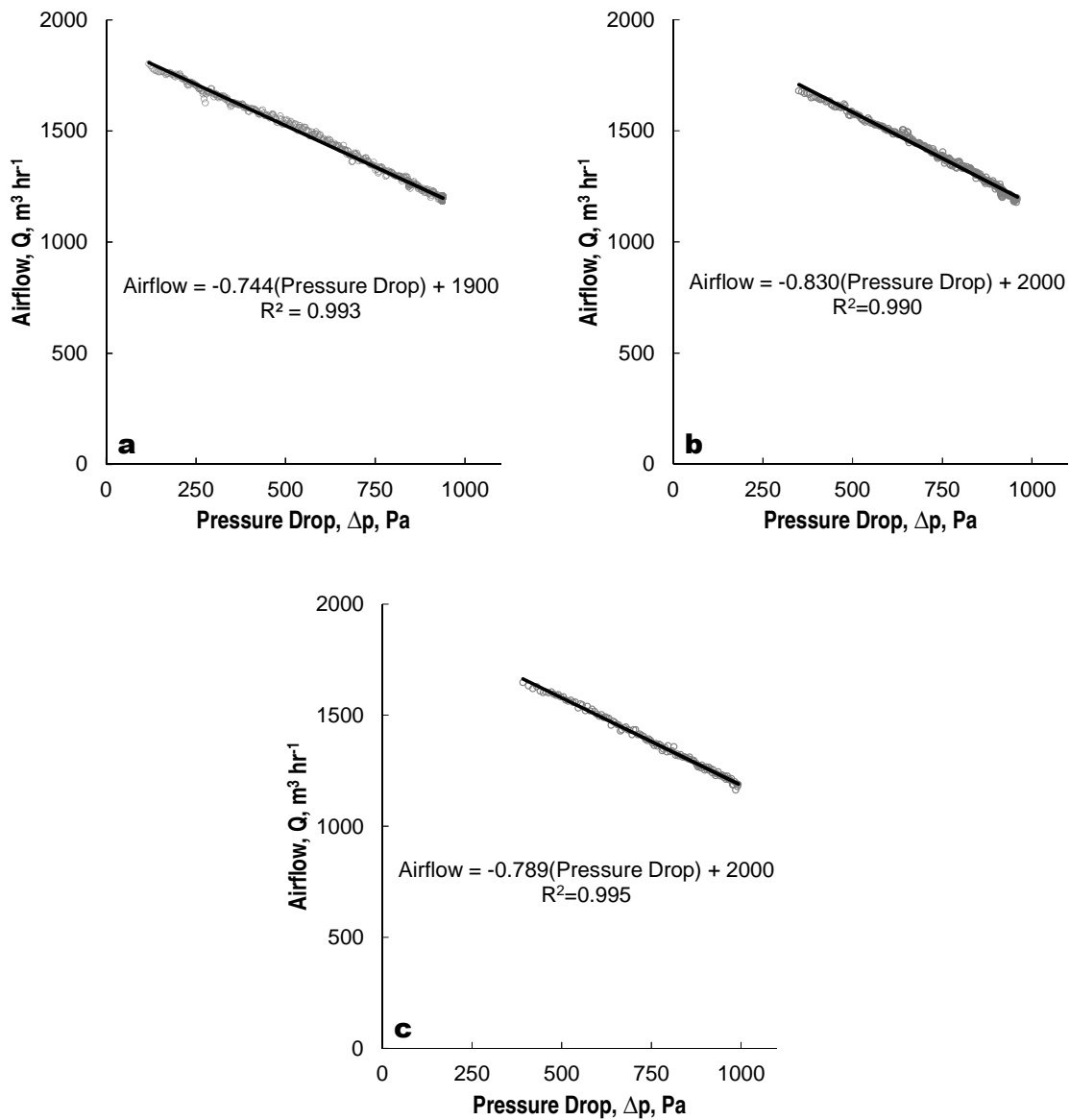


Figure II-3. Linear regression of airflow vs. pressure drop for (a) the first loading, (b) second loading, (c) and third loading.

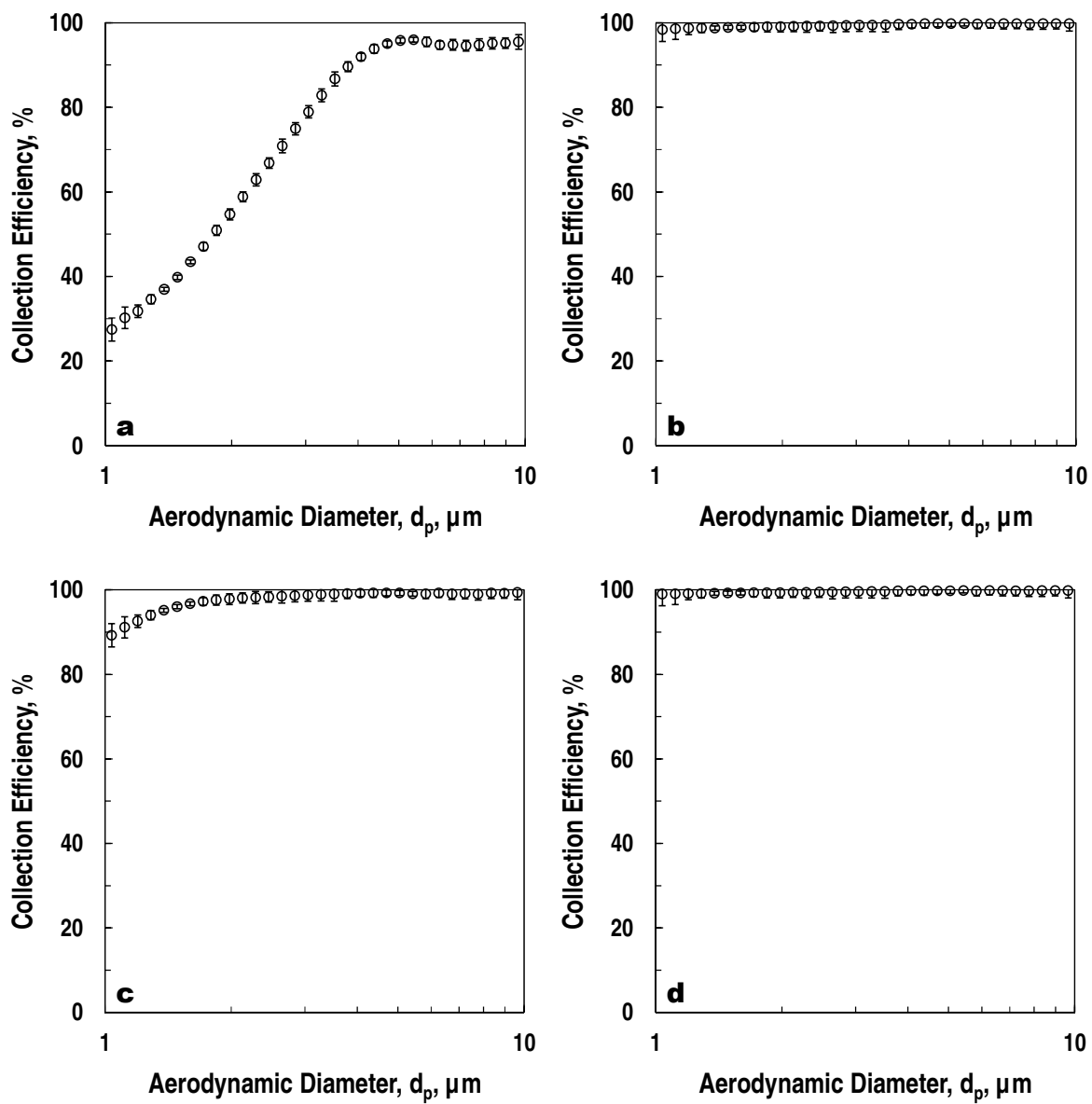


Figure II-4. Collection efficiency by particle size for startup of first loading (a), end of first loading (b), startup of second loading (c), and end of second loading (d).

## CHAPTER III

### CONCLUSIONS

The loading parameters and collection efficiency of a shaker dust collector were evaluated using a standard test dust. SDC pressure drop and exhaust duct velocity pressure were measured per second at constant dust emission rate for three loadings over a total of 18 days. Cleanings were performed between loadings. Challenge aerosol concentrations were measured at startup and end of first loading, and at startup and end of second loading. Collection efficiency by size was calculated for particles 1-10  $\mu\text{m}$ . Preloading was required to achieve high collection efficiency. The number of cleanings required to reach stable residual pressure was determined. The relationship between pressure drop and airflow was found to be a linear. Laboratory data that mimicked three winter seasons was used to estimate field performance in a swine farrowing barn.

Results in Chapter II support the conclusion that SDC collection efficiency is high and pressure drop and airflow operate within ranges that might provide effective control of indoor dust concentrations in a swine barn ( $1 \text{ mg m}^{-3}$ ). High removal efficiencies were achieved following loading periods (99% overall). The accumulation of dust cake was necessary to achieve high collection efficiency and SDC collection efficiency prior to any loading was low. Cleaning and removal of dust cake after loadings reduced overall collection efficiency from 99% to 91%. A single cleaning cycle between loadings was effective to remove excessive dust layers on the filter, recover filter pressure drop, and regain airflow capacity. Airflow decreased linearly as with respect to pressure drop increase. In all three tests, startup system airflow was approximately  $1700 \text{ m}^3 \text{ hr}^{-1}$ . At shutdown, system airflow rate reduced to  $1200 \text{ m}^3 \text{ hr}^{-1}$ . The three loading tests simulated the expected lifetime of a pocket filter. Three test loadings generated a total mass of approximately 14 kg. The mass of loaded dust simulated continuous operation in a swine barn equivalent to a 40-day preloading and three 90-day winter seasons.

This study investigated one type of polyester filter fabric that was supplied by default with the shaker dust collector. Other commercially available filters should be evaluated and filter quality should be used as a benchmark to quantitatively compare media performance. Filter life span is another issue to be addressed. In the field filter material will be exposed to corrosive gaseous compounds such as ammonia and traces of hydrogen sulfide. Wintertime startup of preloaded filters is also in question. The projected filter life was three winter seasons. Actual performance will likely vary due to environmental conditions and more frequent filter replacement may be needed. Effects of storage, weathering and possible premature deterioration of the filter should be investigated. High relative humidity atmospheres found in swine barns may be another important factor for filter material selection. The high organic content of swine barn dust in addition to high relative humidity may produce a “sticky dust” with characteristics unlike the mineralized Arizona test dust. Actual removal efficiency, pressure drop, airflow, and frequency of cleanings deserve further field evaluation.

Future research is needed for field-based testing of the SDC and ventilation system to confirm laboratory-based estimates and affirm efficacy of the SDC under variable loading and environmental conditions in a swine farrowing barn. An estimated 50,000 swine CAFO workers and 200,000 - 500,000 livestock CAFO workers spend the majority of their working days indoors. The use of personal protective equipment can be effective to protect against hazardous dust concentrations but the consistent use of personal respirators among CAFO workers has not been observed. PPE is the lowest option in the control hierarchy. Elimination of dust emissions by practices such as feed substitution using liquid or fat-amended mixtures have been studied but do not consider other emission sources such as dander and manure that continue to be an issue. The use of engineering controls have been of interest and practices such as oil spray application have been promising but not without incurred challenges. Ventilation engineering controls are a logical solution to dust control. This work, as a preliminary investigation of

the dust collector, is a complement to other work including field contaminant characterization, ventilation modeling, and simulation modeling with cost analysis. Ultimately, successful implementation of controls will require education and adoption by stakeholders, agricultural business leaders, and livestock growers.

The actual startup time required to reach high collection efficiency (90%) would substantiate preloading requirements beyond the estimate provided by this study. More frequent concentration measurements would be needed to determine the change in efficiency over time. Frequent measurements with the collection efficiency method used in this work are impractical. A direct reading instrument could be used to quickly trend changes in efficiency and determine the appropriate time to conduct collection efficiency tests.

Arizona test dust contains crystalline silica that is hazardous to respiratory health. An N-95 personal respirator was used when handling the test dust, loading the auger feeder, changing the filter, and while cleaning equipment. The auger feeder itself was fitted with a plastic enclosure to prevent unintentional release into the laboratory. All air handled by the shaker dust collector system was vented to atmosphere and was not recirculated indoors.

The next phase of research to complement this work would include field deployment of a shaker dust collector and recirculation ventilation system in a swine barn. An intervention study could allow for comparison of dust concentrations of an uncontrolled work environment (without control device) to that of a controlled work environment (with a dust collector system).

A study parallel to this work would be the application of other air pollution control devices. An investigation of a cyclone device would be of interest because of its low capital and operating costs, operational simplicity, and high removal efficiency for certain size particles. Two configuration options for particle collection include a standalone cyclone system and a pre-cleaner cyclone system. The use of a cyclone as a

pre-cleaner system may be beneficial to prolonging the equipment life of other control devices in a system. For example the addition of a cyclone device located upstream of a shaker dust collector may reduce the dust loading burden and extend filter life.

## APPENDIX A: STANDARD OPERATING PROCEDURES

**Peters Laboratory**  
The University of Iowa

**Standard Operating Procedure**

**SOP1005.01**

## SOP1005.01

# Swine Barn Air Pollution Control (APC) System Shaker Dust Collector (SDC) *System Operation SOP*

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Effective Date:

Edited By:

Russ Sawvel on 5/1/13

Approved By:

Supersedes Document/Version No:

N/A

### 1. Purpose and Applicability

This document outlines a procedure to operate the Swine Barn APC system in the laboratory

### 2. Safety and Operating Precautions

- All electrical, mechanical, and rotating machinery are potentially hazardous
- Possible hazards include: energized mechanical equipment and moving parts (i.e. fan blades, shaker arm), electrical devices, active air streams
- Air stream discharge: to atmosphere (never into the room)
- Personal protective equipment (for filter maintenance): Goggles, gloves, lab coat, respirator

### 3. Equipment and Materials

List of supplies needed to carry out procedure

Table 1. Air Pollution Control System ..... 2  
Includes air pollution control system, aerosol generation, and sampling equipment

Table 2. APC Sampling: Airflow & nozzle size ..... 3

**Table 1. Air Pollution Control System**

Equipment	Description
Shaker Dust Collector (SDC) <i>Filters dust and contaminants</i>	United Air Specialists, Inc. Model 140. SN 60065736 Three filter types: 9 oz. Polyester Sateen
Pressure gage <i>To monitor pressure drop across bag-filter</i>	Dwyer Series 475 Mark III Digital Manometer, Series 475-0-FM Range: 0-10" W.C.  Magnehelic
Pressure data logging <i>Tracks system operation</i>	Dwyer pressure transmitter Dwyer DW-USB-4 data logger or equivalent
Inlet duct <i>Transports contaminated air to SDC</i>	10-inch diameter, galvanized steel, Nordfab Quick Fit clamp joints
Inlet blast gate <i>Controls air flow rate</i>	Set Adjust airflow to 500 or 1000 CFM
Exhaust duct <i>Returns filtered air to a barn room</i>	10-inch diameter, galvanized steel, Nordfab Quick Fit clamp joints
Exhaust blast gate <i>Isolates system when fan is off</i>	100% open for operation Closed when system is not in use
Pitot tube <i>Used to monitor velocity pressure</i>	Mounted vertical insertion from top of duct
Arizona Test Dust <i>Loading dust</i>	ISO 12103-1, A4 Coarse Test Dust, 11686C Powder Technology Inc, Burnsville MN
Auger Feeder <i>Feeds loading dust Generates steady test aerosol in the laboratory</i>	Accurate Dry Material Feeder, Model 53190 Whitewater, WI
Solid Glass Microspheres <i>Challenge aerosol</i>	Potters Industries 5000A Solid Glass Microspheres (A-Series Technical Quality Glass Spheres) Lot # 080536476K

Dust Filter Assembly

**Aerosol Generation**

Aerosol Generator  
*Generates challenge aerosol for efficiency test*

Accurate Dry Material Feeder, Model 53190  
Whitewater, WI

Compressed air supply and preconditioning assembly

Consists of oil trap, shutoff valve, pressure regulator, desiccator, HEPA filter

*Conditions compress air prior to entering the fluidized aerosol generator*

Aerodynamic Particle Sizer

Measures particle number concentration and size distribution in the exhaust duct

TSI, Model 3321, SN: 70450237

**Monitoring or Sampling**

Isokinetic Nozzle  
*Gooseneck type*

Matches in-duct velocity to sampling port velocity to prevent under-sampling and over-sampling

CleanAir Engineering (Palatine, IL)

1/8" Model 0401SS, 3/16" Model 0402SS

DustTrak

Direct reading instrument

*Used to monitor filter loading (trending but no quantification)*

TSI (Shoreview, MN)

DustTrak II, Model 8532, SN 8532114301, SN 8532114402

Dilution filter

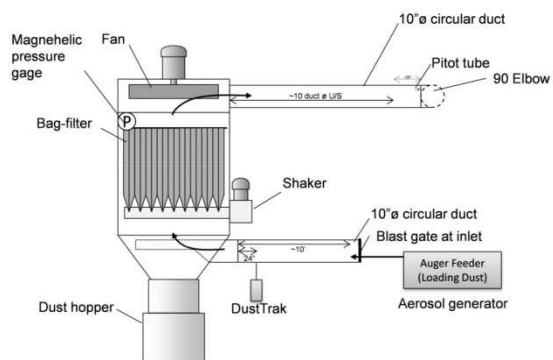
Whatman HEPA-CAP in-line filter, Model#90406B

Used to prevent overloading of DustTrak monitor

Hole diameter=0.040"

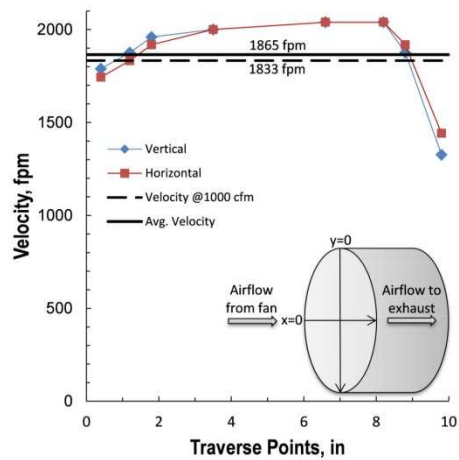
**Table 2. APC Sampling: Airflow rate & nozzle size**

Scenario	System Airflow & Duct Diameter	Instrument & Sample Airflow	Sample Nozzle Diameter	Sampling Condition
A	Q = 500 CFM	APS	<b>0.1875" (3/16")</b>	Isokinetic
Low Flow	D = 10"	5.0 LPM		$\frac{v_{\text{sample}}}{v_{\text{duct}}} = 1.007$
W/ APS		(No modifications)		
B	Q = 1000 CFM	APS	<b>0.125" (1/8")</b>	Isokinetic
High Flow	D = 10"	4.411 LPM		$\frac{v_{\text{sample}}}{v_{\text{duct}}} = 1.000$
W/ APS		(Modify sheath flow)		



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Figure 1. Pilot Scale APC System – Dust Loading



Airflow: Velocity traverse was performed to determine gate setting at design airflow  
Blast gate should be marked for 1000 cfm and 500 cfm as determined by velocity traverse

#### 4. References

Other SOPs this procedure depends upon: None  
Other SOPs that are dependent on this procedure: SOP1010.01

#### 5. Definitions

Acronyms and definitions used by procedure are listed below.

LIST OF ACRONYMS:

<b>Acronym</b>	<b>Full Term</b>
SOP	Standard operating procedure
CFM	Cubic feet per minute
SDC	Shaker Dust Collector
LPM	Liters per minute
APS	Aerodynamic Particle Sizer
W/	with
W/O	without

## 6. Procedure

### *Outline:*

#### **Loading test**

##### **Step 1 Prepare for Test Run**

- 1.1 Check electrical
- 1.2 Set airflow path & install appurtenances
- 1.3 Check Bag-filter

##### **Step 2 Test Run**

- 2.1 Verify electrical, power on, start fan
- 2.2 Setup equipment to monitor filter pressure drop, velocity pressure. Use DustTrak to monitor in situ concentration.
- 3.0 Mass loading
- 4.0 Bag-filter cleaning

##### **Step 3 System shutdown**

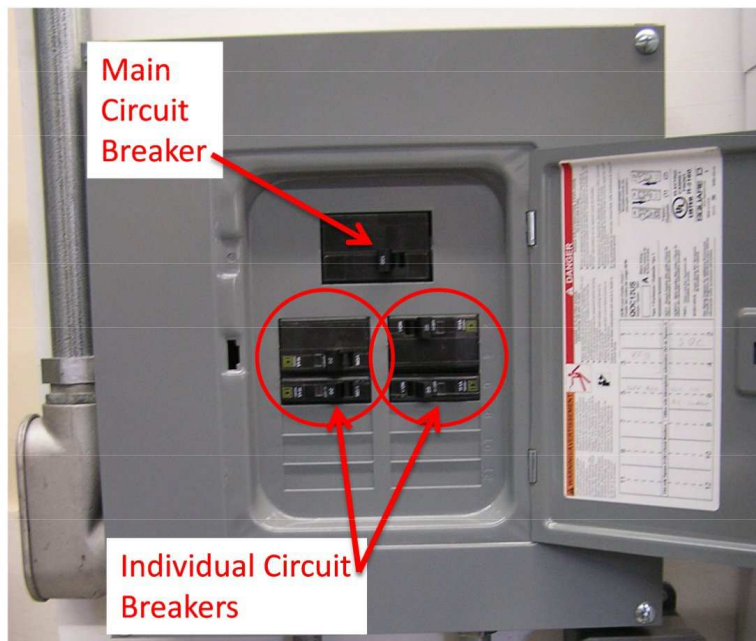
Shutdown and de-energize

##### **Step 4 Data**

Velocity pressure log  
Filter pressure drop log  
Concentrations from DustTrak

#### **1. Preparing for Experimental Run (Verify De-energized System)**

- 1.1. Verify system is OFF and de-energized
  - 1.1.1. Verify that no one else is operating equipment
  - 1.1.2. Visually inspect the general area to ensure everyone is physically clear of the equipment.
  - 1.1.3. Verify individual power breakers are set to OFF (see photo below)
  - 1.1.4. Verify main power breaker is set to OFF

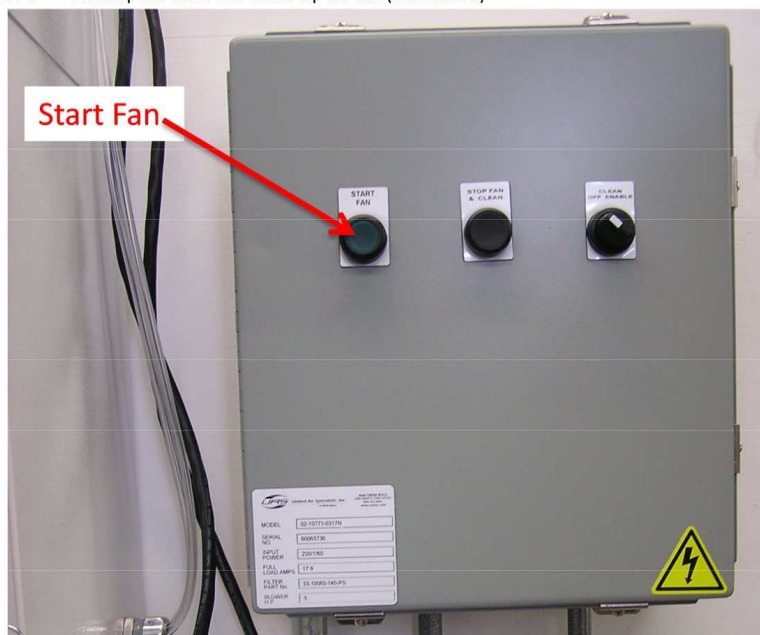


Switch number	Description
1,3	VFD power for makeup-air fan (if installed)
2,4	Shaker Dust Collector
5	Powerstrip located below breaker box
6	Outlet located inside the white box



1.1.5. Verify power is OFF by attempting to start equipment

- 1.1.5.1. Attempt to start the SDC fan by pressing “start fan” button-switch (see photo below)
- 1.1.5.2. Attempt to start the make-up air fan (if installed)



- 1.1.6. After verification set all operation controls to OFF position
- 1.1.7. Disconnection shall be performed after and only after power OFF verification
  - 1.1.7.1. Disconnect (unplug) the SDC fan electrical adaptor
  - 1.1.7.2. Disconnect (unplug) the SDC shaker-arm electrical adaptor
  - 1.1.7.3. Disconnect (unplug) the make-up air fan electrical adaptor (if installed)



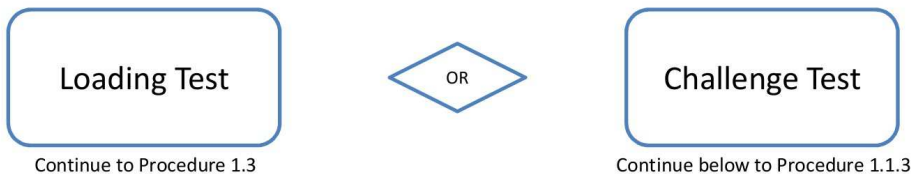
1.2. Set physical airflow path

1.2.1. Set exhaust gate to 100% OPEN when system is ON (gate should be CLOSED when system is OFF)



1.2.2. Set intake gate to control airflow (set at 500 or 1000 CFM mark)





1.2.3. For CHALLENGE DUST ONLY Install isokinetic nozzle for APS (see Figure 1 ). Select size from Table 3



Internal view of isokinetic nozzle in a duct (duct is assembled this is just an illustration)



Use markings to ensure proper alignment

1.2.4. The nozzle will slide in and needs to be secured with tape or a strap.

1.2.5. Carefully align the nozzle so it is perpendicular to duct airflow. Mark the alignment of the nozzle for repeat installations.

### 1.3. Bag-filter

*Note: This section assumes that a filter from a previous run is still installed in the cabinet and was not removed (as is often the case).*

1.3.1. Removal of old filter. Release SDC cabinet door levers

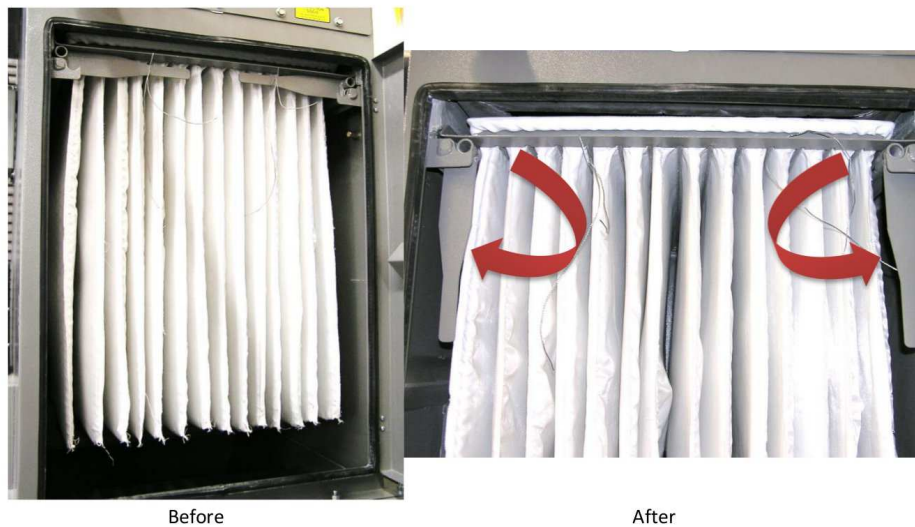


1.3.2. Open SDC cabinet door

1.3.2.1. Note for laboratory installation: Never enter the cabinet.

1.3.2.2. Note for field installation only: Never enter the cabinet. If entry becomes necessary to remove debris then measure concentrations of ammonia and hydrogen sulfide prior to entering or servicing the dust collector filter chamber. Verify levels are safe for confined space entry.

1.3.3. Remove camlock restraint cables and unlock camlocks



1.3.4. Remove bag-filter tray from cabinet (slides out, very easy with 2 people). Test run will be either with desired bag-filter or without any bag-filter.

W/ Bag-filter

OR

W/O Bag-filter

Continue to Procedure 1.4 below.

\*Used for loading and efficiency test

Close and secure door.

Continue to Procedure 2.1.

\*Used for collection efficiency test

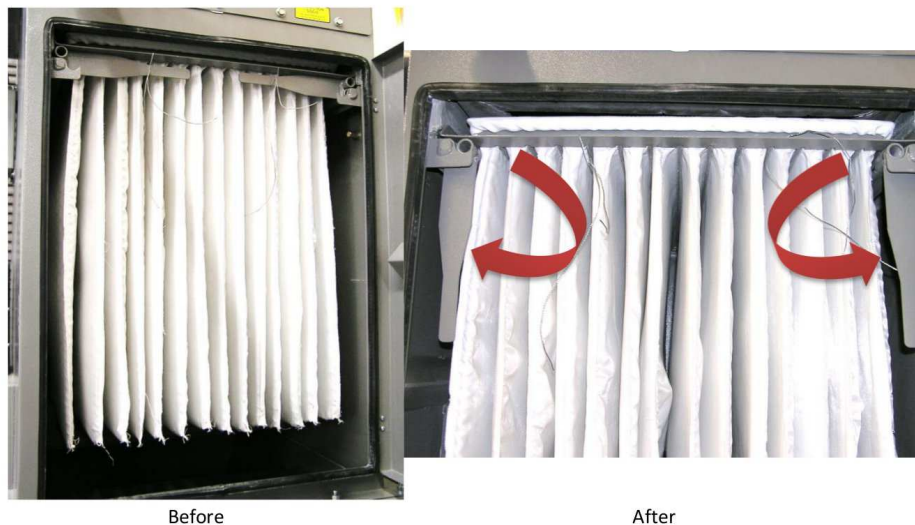
1.3.5. Bag-filter setup and installation (loading tray)

1.3.6. Set and support bag-filter tray assembly onto scaffolding (see photo below)

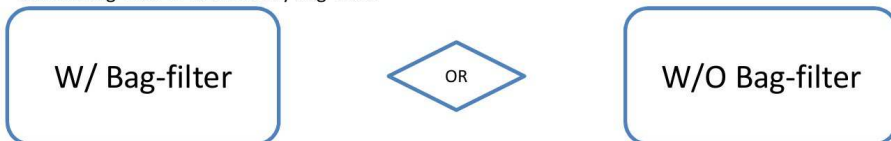
1.3.7. Remove wire frame inserts and old bag-filter (simply lift each sock out of frame)

1.3.8. Install new bag-filter into tray/rack (stuff each sock through spacer & pull lip over edges)

1.3.9. Install wire frame inserts into each sock (simply slide in)



1.3.4. Remove bag-filter tray from cabinet (slides out, very easy with 2 people). Test run will be either with desired bag-filter or without any bag-filter.



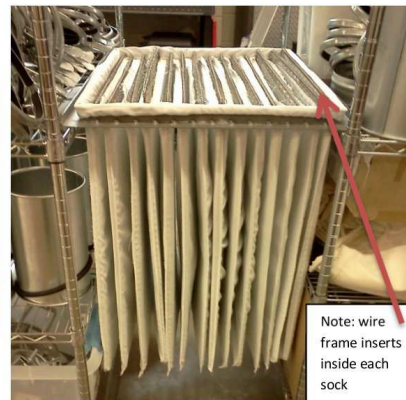
Continue to Procedure 1.4 below.  
\*Used for loading and efficiency test

Close and secure door.  
Continue to Procedure 2.1.  
\*Used for collection efficiency test

- 1.3.5. Bag-filter setup and installation (loading tray)
- 1.3.6. Set and support bag-filter tray assembly onto scaffolding (see photo below)
- 1.3.7. Remove wire frame inserts and old bag-filter (simply lift each sock out of frame)
- 1.3.8. Install new bag-filter into tray/rack (stuff each sock through spacer & pull lip over edges)
- 1.3.9. Install wire frame inserts into each sock (simply slide in)



Bag-filter selection



Bag-filter tray

Note: wire  
frame inserts  
inside each  
sock

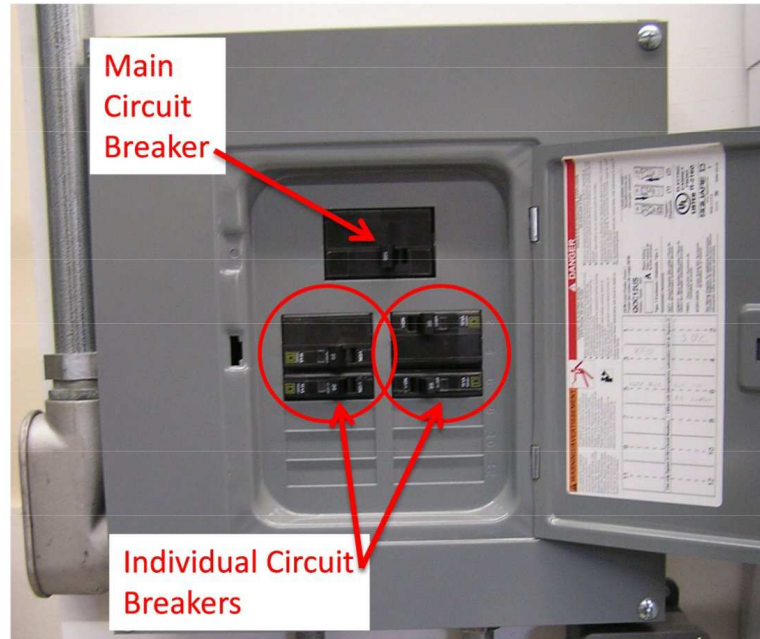
- 1.3.10. Bag-filter tray reinstallation
- 1.3.11. Slide filter tray back into the cabinet (simply push in, very easy with 2 people)
- 1.3.12. Set camlocks to seal position
- 1.3.13. Restrain camlocks in place (use wire ties)
- 1.3.14. Close the door and secure door levers

## 2. SDC System – “Run one test”

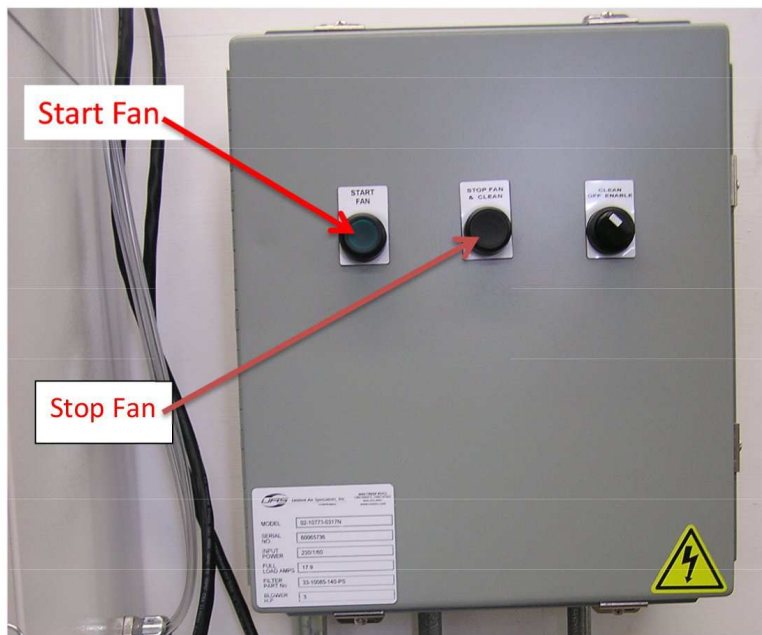
- 2.1. IMPORTANT — Power: Proceed if and only if system was **de-energized** per Procedure 1.1.  
If you are not sure go back to Procedure 1.1.
  - 2.1.1. Plug in SDC electrical adaptors. There are two plugs: one for fan, one for shaker.



- 2.1.2. For field installation: Plug in make-up air fan adaptor (if installed)
- 2.1.3. Restore main power and set breaker to ON
- 2.1.4. Restore individual power circuits and set breakers to ON



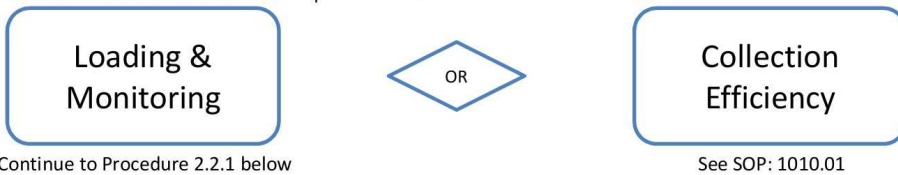
2.1.5. Set the shaker dust collector (SDC) controls to ON (starts airflow)



2.1.6. For field installation: Set the make-up air fan controls to ON (if installed)

2.2. Setup equipment (monitoring or sampling and peripheral devices)

As noted in References this SOP is coupled to 1005.01

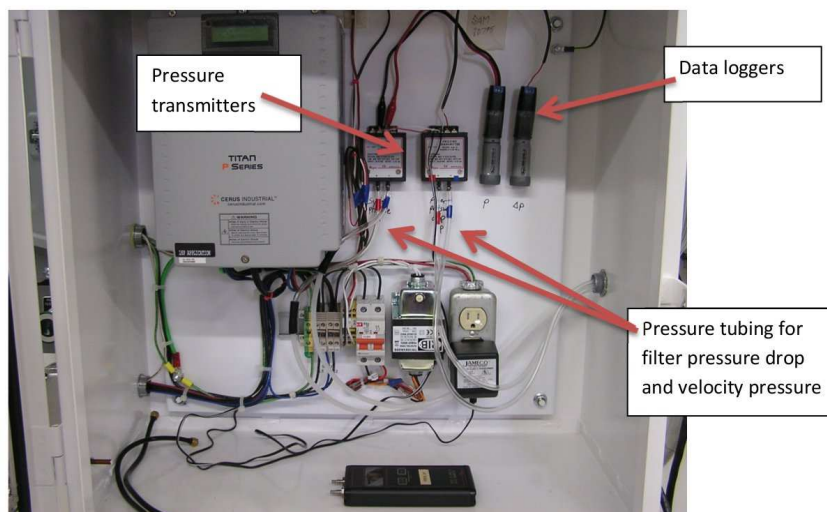


2.2.1. Monitor pressures

- 2.2.1.1. Read filter pressure drop from the magnehelic gage mounted on the side of the APC unit. Use digital manometer to read filter pressure drop and velocity pressure in the duct. Pressure hose connections are in the white cabinet. Record readings in your lab book.
- 2.2.1.2. Install pressure transmitter data loggers
- 2.2.1.3. Connect pressure tubing to pressure transmitters



Magnehelic  
gage is  
mounted on  
the APC unit



Pressure  
transmitters

Data loggers

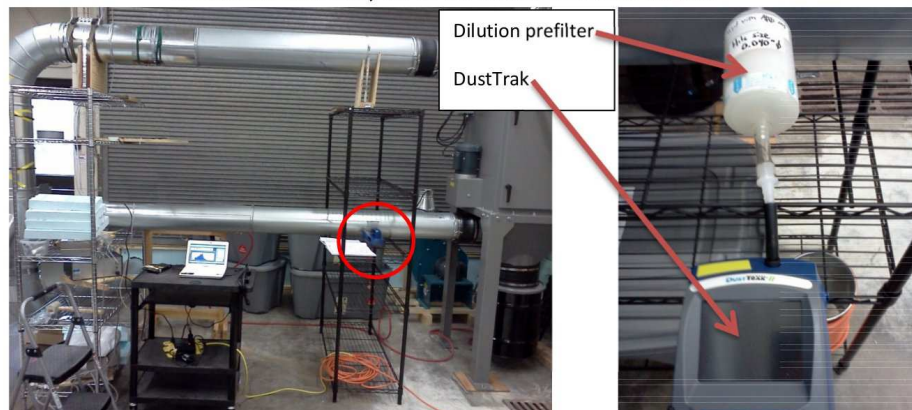
Pressure tubing for  
filter pressure drop  
and velocity pressure

### 2.2.2. DustTrak

- 2.2.2.1. Set DustTrak configuration (see Procedure 5)
- 2.2.2.2. Tap START on the main screen to begin a run
- 2.2.2.3. Install into duct as shown. Unfiltered particles will foul the instrument. Definitely use a prefilter: Modified Whatman HEPA-CAP 90406B with 0.040" diameter hole drilled through

center (dilution filter). DustTrak is not installed for monitoring/trending concentrations and not for the purpose of isokinetic sampling.

2.2.2.4. Use for the first two minutes of loading. Then stop the instrument. Use for another two minutes mid-run. Finally use for the last two minutes of the test.



### 3. Loading Test

#### 3.1. Aerosol generation (dust loading) – Auger feeder

- 3.1.1. This section assumes the auger hopper is clean or was previously loaded with ARD test dust (if not first clean the hopper and auger)
- 3.1.2. Set feed control to OFF
- 3.1.3. Verify that 3/4" diameter auger is installed
- 3.1.4. Weigh desired quantity of test dust in a bucket (weigh the bucket before and after adding dust)
- 3.1.5. Fill hopper with desired quantity of test dust (ARD). Test dust quantity = 2 kg max
- 3.1.6. Initial feed rate should be 000 (Note: the auger is active at "000" as opposed to being off)
- 3.1.7. Position feeder as shown below, centered, 5" away from inlet



- 3.1.8. Power on auger feeder. Start timer and increase feed rate to 100.
- 3.1.9. Load until pressure drop across bag-filter is 4" W.C. Remember to watch the timer and record critical times. Aerosol should disperse while being captured at the inlet like in the photo below. Loading time is a function of mass added.



- 3.1.10. Pressure drop across filter: record digital manometer pressure gage reading (pressure drop across SDC filter), magnehelic gage, and pitot tube velocity pressure before ending each test run

#### **4. Filter-bag cleaning**

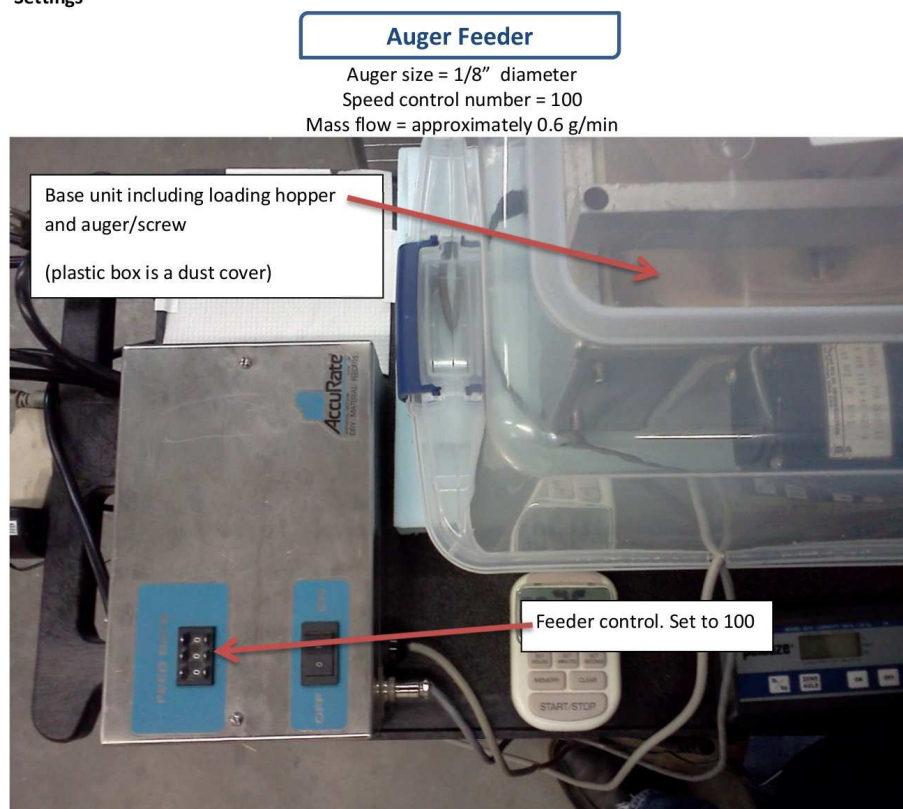
- 4.1. Following mass loading: record pressure drop and velocity pressure prior to stopping airflow by pressing stop fan on the control panel. Ensure the cleaning control knob is set to enable.
- 4.2. The shake will begin about 1-minute after pressing STOP. The shake will last for 35 sec.
- 4.3. After a shake cycle restart the airflow for a short time and press STOP to evoke the next shake down.
- 4.4. Repeat shaker-cleaning until residual pressure = 1.5" or stop after 2 repeats. Record pressure drop and velocity pressure following each cleaning.

#### **5. SDC System - Shutdown**

- 5.1.
- 5.2. Shut down the equipment in an orderly fashion.
- 5.3. Power off the shaker dust collector by pressing the STOP button on the control panel.
- 5.4. Power off the make-up air fan by pressing the STOP button (if equipped)
- 5.5. Individually power off all peripheral devices except for DustTrak.
- 5.6. Set individual breakers to OFF position
- 5.7. Set the main power breaker switch to OFF
- 5.8. Verify the disconnect by attempting to start equipment
  - 5.8.1. Attempt to start the SDC.
  - 5.8.2. Attempt to start the make-up air fan (IF EQUIPPED)
- 5.9. After verification set operation controls to OFF

- 5.10. Unplug the SDC electrical adapter
- 5.11. Unplug the make-up air electrical adaptor (if equipped)
- 5.12. Remove DustTrak from duct (record the time when this occurred)
- 5.13. Let DustTrak run in ambient room air for several minutes.
- 5.14. Install zero filter onto DustTrak and verify readings are zero
- 5.15. Tap STOP on the DustTrak main screen to end the session. Data needs to be retrieved from the instrument. Go to Post processing in Procedure 6

## 6. Settings

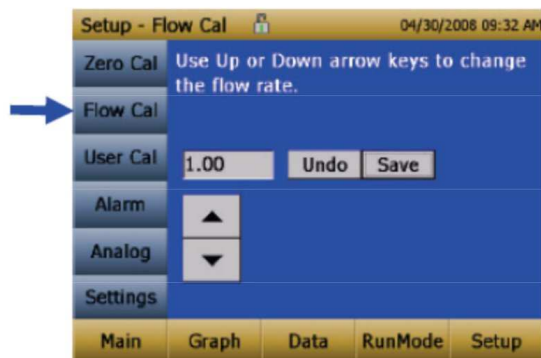




Main Screen

Power on the DustTrak. Then navigate thru menus and settings

1. From the main menu tap SETUP → SETTINGS → DATE TIME → CURRENT DATE (tap to set to date)
2. From the main menu tap SETUP → SETTINGS → DATE TIME → CURRENT TIME (tap to set to time)
3. Main Menu → RunMode → MANUAL → Test Length → 8 hours → Save
4. Main Menu → RunMode → MANUAL → Log Interval → 15 sec → Save
5. Main Menu → RunMode → MANUAL → Time Constant → 15 sec → Save
6. Install zero filter onto inlet
7. Set sample flow rate per Table 3. Adjust pump using up & down arrows (below). Use a flow calibrator to measure airflow rate.



**Flow Cal** is run if the user wants to change the flow set point.  
The flow set point is factory set to 3 L/min total flow (or 1.00)

8. Tap Setup → zero cal → start, then wait 60 sec and Remove zero filter when prompted
9. Go to Main screen, tap start and run with zero filter on for approximately 1-minute to verify 0.000 mg/m<sup>3</sup>. Then remove zero filter (and begin to read ambient background concentrations)

#### 7. Post processing – Data files - Software

7.1. TrakPro

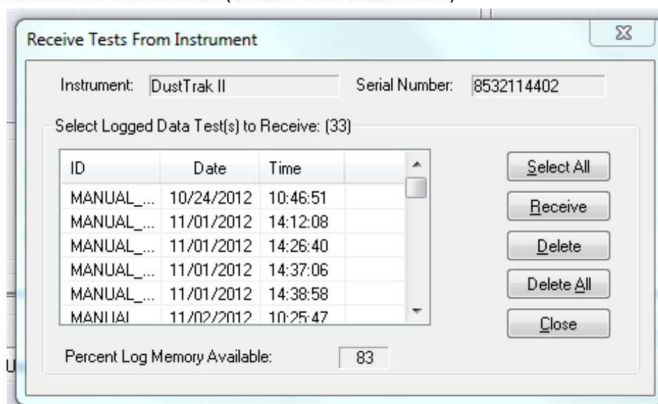


7.1.1. Connect DustTrak USB cable to destination computer

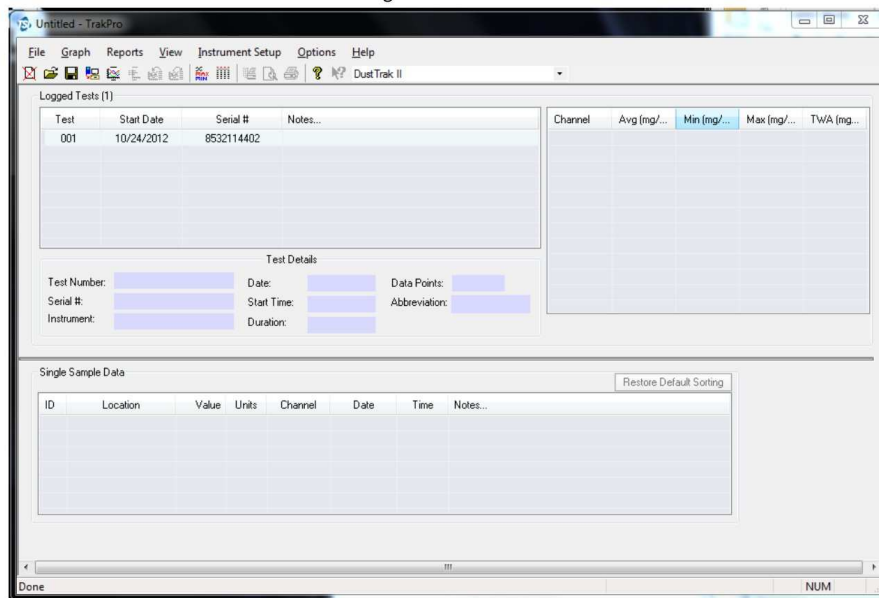
7.1.2. Open TrakPro software

7.1.3. Go to FILE → RECEIVE (wait a few secs)

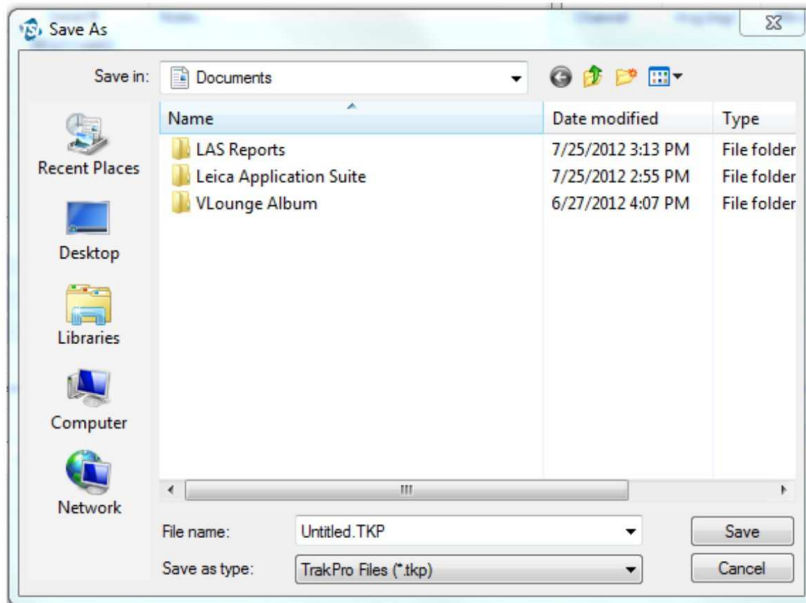
7.1.4. Then select data from list (click file then click receive)



7.1.5. After data downloads close the receive dialogue. Test data is now native in TrakPro.

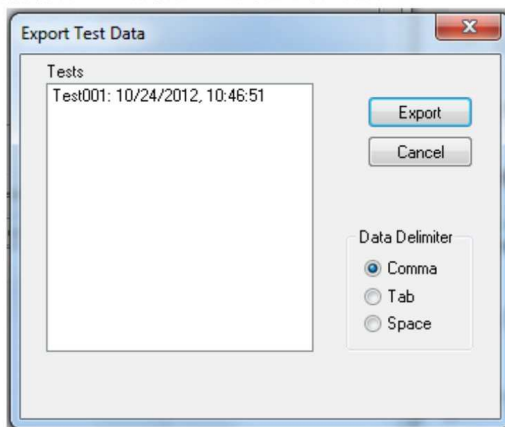


7.1.6. Save the data file to the "Swine Kirky" folder. recommended filename is YYYYMMDDThmm.tkp

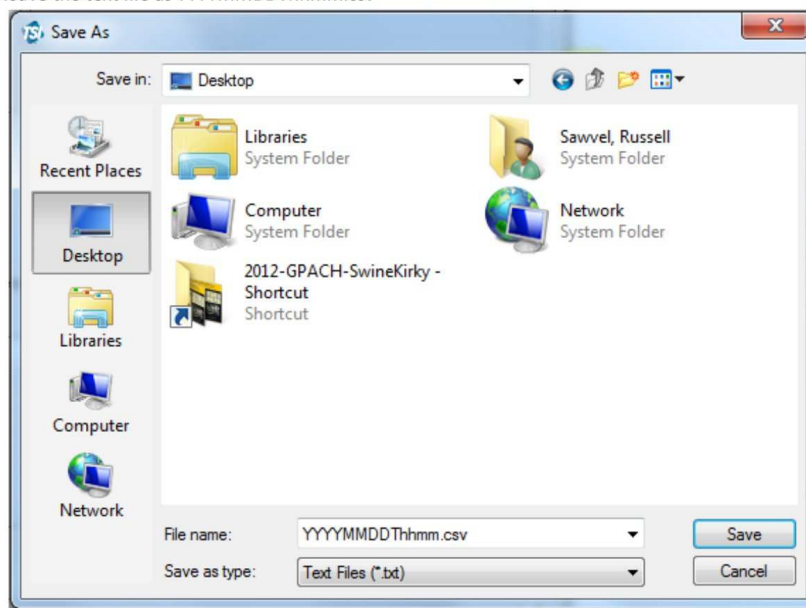


7.1.7. Next, export the data file just saved (tkp) to Excel importable format

7.1.8. Go to FILE → EXPORT → EXPORT TEST DATA



7.1.9. Save the text file as YYYYMMDDThhmm.csv



7.1.10. The CSV can be easily imported into Excel. Exit TRAKPRO & disconnect DUSTTRAK.

7.1.11. Excel: Open csv file in excel and save as native format xlsx with desired name in desired location

## 8. SDC System – Emergency Shutdown

kill switches

## 9. Notes for Maintenance

- 9.1. In the case of maintenance consult the equipment manufacturer's written recommendations and guidelines.
- 9.2. There should be no entry to the APC cabinet (never enter the cabinet). However, if the field installation were to be entered: measure concentrations of ammonia and hydrogen sulfide prior to entering or servicing the dust collector filter chamber. Verify levels are safe for confined space entry.
- 9.3. Where service will be performed block and restrain the dust shaker arm to prevent motion.
- 9.4. Where service will be performed block and restrain the fan to prevent motion.

## SOP 0000-QC Quality Control Document

### Title of Standard Operating Procedure

---

Operator: \_\_\_\_\_

Date: \_\_\_\_\_

Batch ID: \_\_\_\_\_

Section/Step	Result	Batch No.	Initials

Comments: \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_

Operator Signature: \_\_\_\_\_

Date: \_\_\_\_\_

Supervisor Signature: \_\_\_\_\_

Date: \_\_\_\_\_

**Accepted**

**Rejected**

# SOP1010.01

## Swine Barn APC: Shaker Dust Collector

### *Collection Efficiency SOP*

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Effective Date:

Edited By:

Russ Sawvel on 5/1/13

Approved By:

Supersedes Document/Version No: N/A

#### **1. Purpose and Applicability**

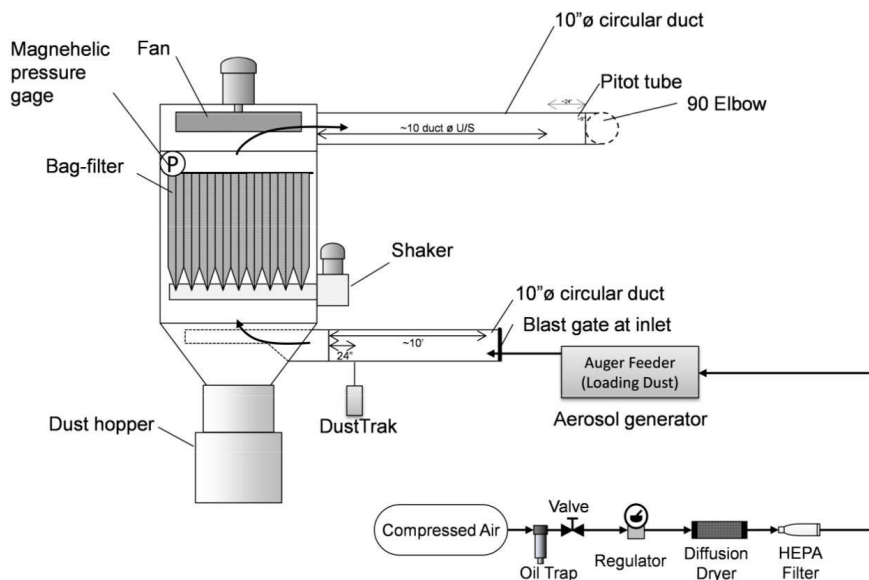
- ∞ This document outlines a procedure to collect aerosol samples within the Swine Barn APC system (laboratory build) using an Aerodynamic Particle Sizer.
- ∞ Data collected will be used for characterizing the performance of a shaker dust collector unit under laboratory conditions

#### **2. Safety and Operating Precautions**

- ∞ Safety and operating precautions are included in SOP1005.01

#### **3. Equipment and Materials**

- ∞ List of supplies needed to carry out procedure are included in SOP1005.01



NTS

Figure 1. Pilot Scale APC System – Challenge Aerosol

∞ Software for APS



**4. References**

Other SOPs this procedure depends upon: SOP1005.01

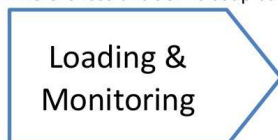
Other SOPs that are dependent on this procedure: None

**5. Definitions**

Acronyms and definitions used by procedure are included in SOP1005.01

## 6. Procedure

As noted in References this SOP is coupled to 1005.01



From SOP: 1005.01



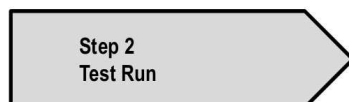
This SOP: 1010.01  
Continue below

### *Outline:*

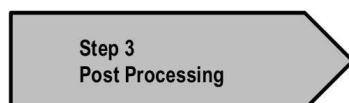
#### Efficiency test



1.1 & 1.3 Test particle generation system  
1.2 Particle measurement system  
Check the reference system



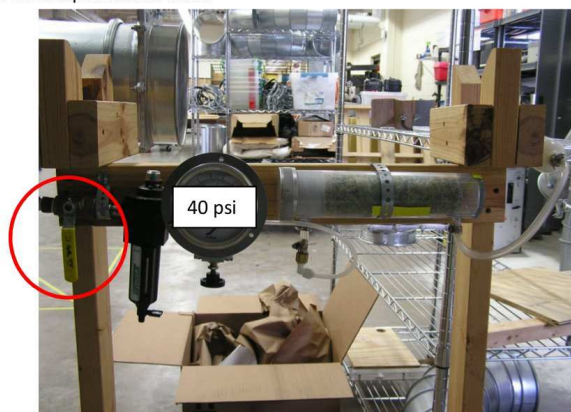
1.3 Particle monitoring



2.0 Data

1. Determine collection efficiency
  - 1.1. Aerosol generation – fluidized bed generator
    - 1.1.1. This section assumes the fluidized bed is clean or was previously loaded with glass microspheres (if not first clean the fluidized bed)
    - 1.1.2. Fill reservoir with desired quantity of test particles, Potters Industries 5000A Solid Glass Microspheres (see setup photo)
    - 1.1.3. Setup the unit on a shelf beneath the intake duct and connect to the inlet tap

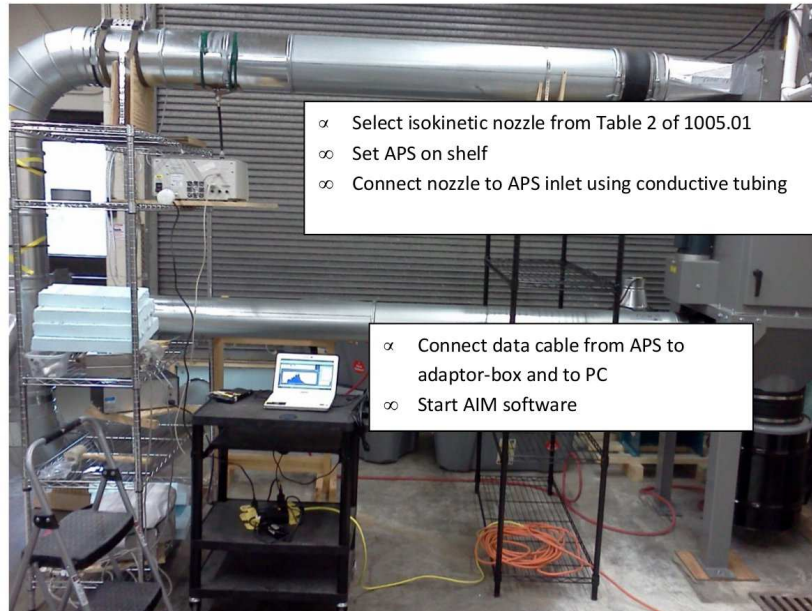
- 1.1.4. Verify that compressed air pressure regulator is set at 40 psi
- 1.1.5. Connect compressed air to fluidized bed generator (plastic hose connects to push-on)
- 1.1.6. Slowly turn on compressed air valve



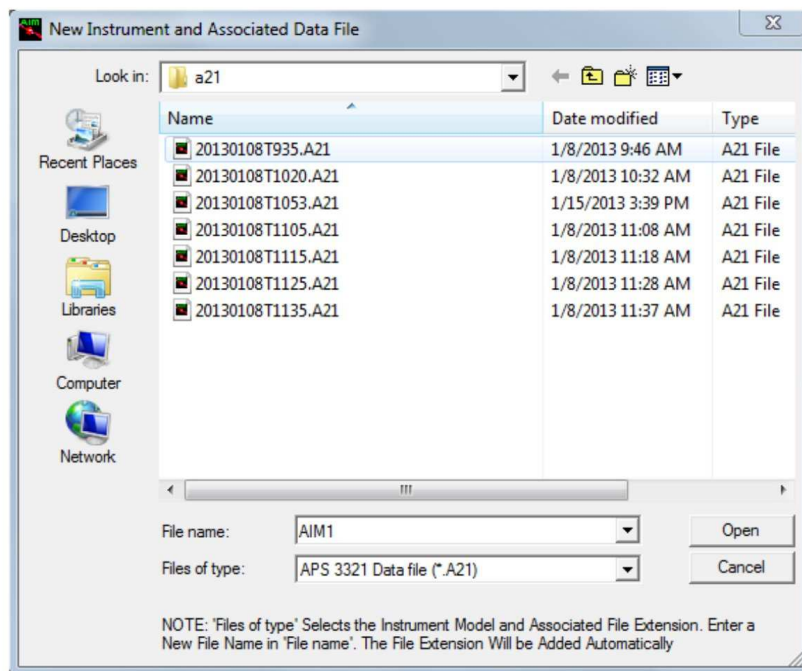
- 1.1.7. Start fluidized bed generator. Settings are included in Section 3
- 1.1.8. Allow aerosol generation to stabilize. Lead time is several minutes (usually 10-15)
- 1.1.9. Intake duct concentrations can be monitored using DustTrak

## 1.2. Aerodynamic Particle Sizer

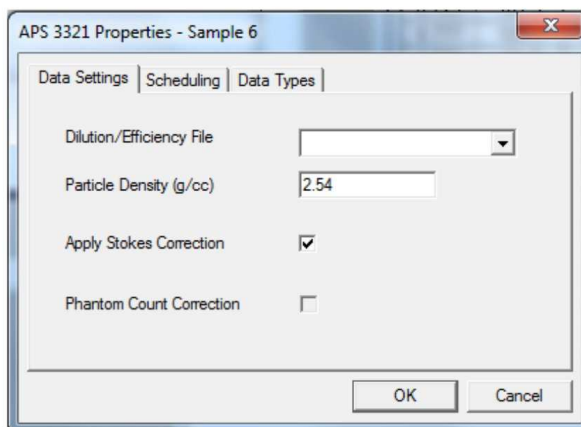
- 1.2.1. Setup APS beneath the exhaust duct. Connect to isokinetic nozzle using conductive tubing
- 1.2.2. Set Samsung notebook PC in proximity of the APS



- 1.2.3. Connect data cable
- 1.2.4. Power on APS and the PC
- 1.2.5. Start APS/AIM on the PC
- 1.2.6. Go to File → new → filename.a21



- 1.2.7. Go to Run → properties → data settings
- 1.2.7.1. Set particle density 2.54 g/cc
- 1.2.7.2. Check box to apply Stokes correction

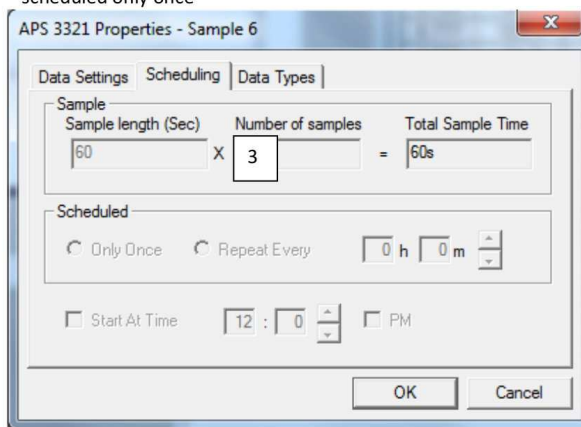


1.2.8. Go to Run → properties → scheduling

1.2.8.1. sample time = 60 sec

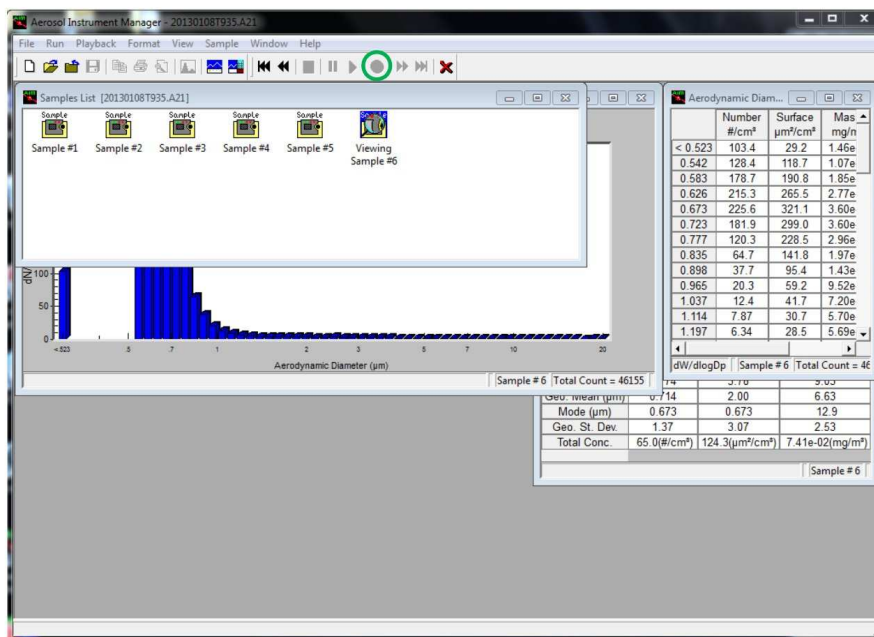
1.2.8.2. number of samples = 3

1.2.8.3. scheduled only once



1.2.9. Go to Run → properties → scheduling

1.2.10. Click green circle icon/button to begin sampling



1.3. Following the sampling events (3 repetitions with or without a filter) return to SOP 1005.01

Collection  
Efficiency

From SOP: 1010.01

Loading &  
Monitoring

Continue to Procedure  
6-4.1 through 6-4.8

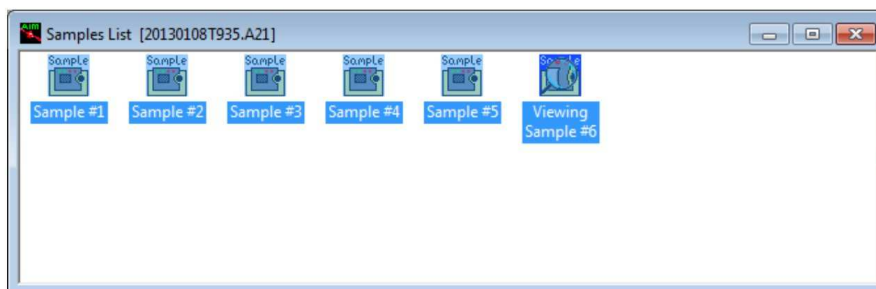
1.4. Airflow measurement: Velocity traverse was performed to determine gate setting (and associated airflow)

1.5. Verify APS calibration using PSL standard spheres

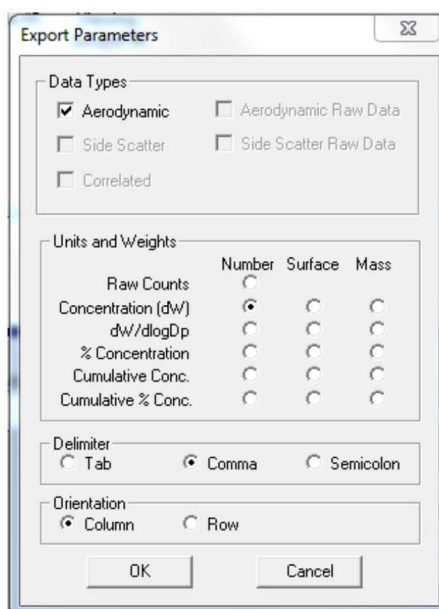
## 2. Post Processing

2.1.1. AIM's \*.a21 files save automatically so no need to re-save an \*.a21 file

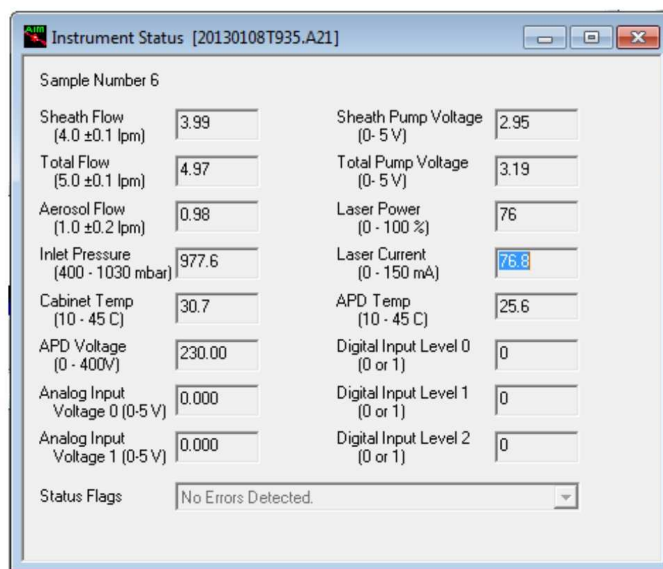
2.1.2. Need to export data to Excel. Click in "white space" of Samples List. Select all samples using control+A on keyboard. If selection was done correctly all files will be highlighted.



- 2.1.3. Go to File → export
- 2.1.3.1. concentration + number (or conc + mass)
  - 2.1.3.2. delimiter comma
  - 2.1.3.3. orientation column



- 2.1.4. Recommended export filename YYYYMMDDThmm.csv to import into Excel (date and time stamp match record in your lab notebook)
- 2.2. Check APS flows before and after test run. Go to View → instrument status
- 2.2.1. Total flow = 4.4 LPM



Sample Number 6	
Sheath Flow (4.0 ±0.1 lpm)	3.99
Total Flow (5.0 ±0.1 lpm)	4.97
Aerosol Flow (1.0 ±0.2 lpm)	0.98
Inlet Pressure (400 - 1030 mbar)	977.6
Cabinet Temp (10 - 45 C)	30.7
APD Voltage (0 - 400V)	230.00
Analog Input Voltage 0 (0-5 V)	0.000
Analog Input Voltage 1 (0-5 V)	0.000
Sheath Pump Voltage (0- 5 V)	2.95
Total Pump Voltage (0- 5 V)	3.19
Laser Power (0 - 100 %)	76
Laser Current (0 - 150 mA)	76.8
APD Temp (10 - 45 C)	25.6
Digital Input Level 0 (0 or 1)	0
Digital Input Level 1 (0 or 1)	0
Digital Input Level 2 (0 or 1)	0
Status Flags	No Errors Detected.

Excel Calculations

Test sequence:

- Aerosol generation inactive

Background test of ambient airflow

- Aerosol generation active

Repetition #1: without filter, with filter

Repetition #2: without filter, with filter

Repetition #3: without filter, with filter

Migrate and organize APS number concentration data from CSV file to commented excel spreadsheet (example format below)

Test number  
(1,2 or3)

	A	B	C	D	E	F	G	H	I		
1	Trial #1, poly filter, without filter W/O					Trial #1, poly filter, with filter W/					
2	Sample File C:\data\swinekirky\20130108T1020.A21					Sample File M:\GENERA~1\102PET~1\Research					
3	Sample Time 60					Sample Time 60					
4	Density 2.54					Density 2.54					
5	Stokes Co on					Stokes Co on					
6	Lower Char 0.486968					Lower Char 0.486968					
7	Upper Char 17.7828					Upper Char 17.7828					
8	Sample # 1			2		3			Sample # 1		
9	Date	1/8/2013	1/8/2013	1/8/2013	Date	1/8/2013	1/8/2013	1/8/2013			
10	Start Time	10:28:25	10:29:25	10:30:25	Start Time	10:52:56	10:53:56	10:54:56			
11	Aerodyna dN	dN	dN	dN	Aerodyna dN	dN	dN	dN			
12	<0.523	34.9293	34.0813	35.1363	<0.523	31.3804	31.1544	31.1934			
13	0.542	6.27298	6.20323	6.18307	0.542	5.7256	5.64257	5.78139			
14	0.583	6.63078	6.68766	6.61798	0.583	5.97818	5.93568	5.95744			
15	0.626	5.97141	6.11108	5.94616	0.626	5.2545	5.36004	5.36323			
16	0.673	4.90904	5.07258	4.92908	0.673	4.21984	4.32329	4.24848			
17	0.723	3.62559	3.8155	3.77622	0.723	2.96167	3.07264	3.08192			
18	0.777	2.93887	2.97829	3.1544	0.777	2.2877	2.30494	2.34124			
19	0.835	2.64745	2.61282	2.77305	0.835	1.96798	1.92027	2.02734			
20	0.898	2.81103	2.85416	2.93822	0.898	1.93302	1.87187	2.06191			
21	0.965	2.90924	2.9971	3.11942	0.965	2.03434	1.92414	2.02922			
22	1.037	3.17627	3.24258	3.45761	1.037	2.18952	2.15303	2.18092			

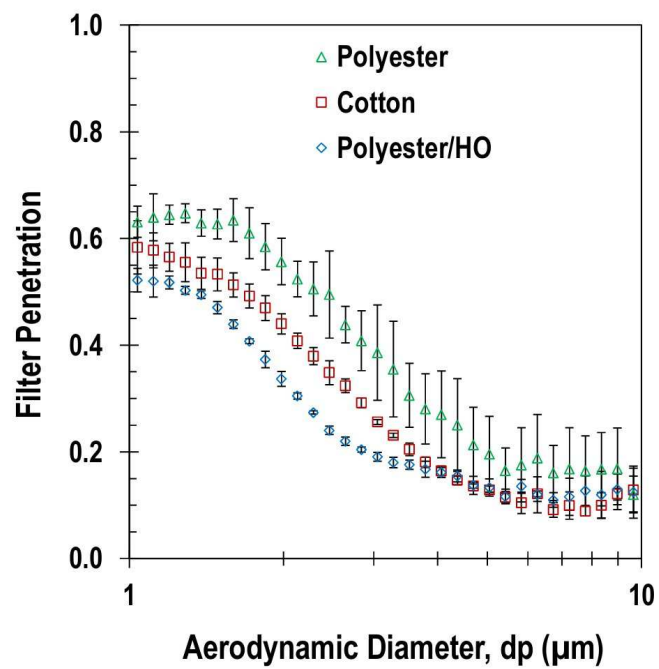
Repetition number  
(1,2 or 3)

Calculate average number concentration of three repetitions and standard deviation

Test number	A	B	C	D	E
1	TRIAL #1		poly		
2	Aerodynamic Diameter	Without Filter	Without Filter	With Filter	With Filter
3	um	#/cm3	#/cm3	#/cm3	#/cm3
4		mean	stdev	mean	stdev
5	0.542	6.21976	0.047179	5.71652	0.069854
6	0.583	6.645473	0.037091	5.9571	0.021252
7	0.626	6.00955	0.088829	5.325923	0.061875
8	0.673	4.970233	0.089199	4.26387	0.053415
9	0.723	3.739103	0.100248	3.038743	0.066909
10	0.777	3.023853	0.114762	2.311293	0.02733
11	0.835	2.677773	0.084309	1.971863	0.053641
12	0.898	2.867803	0.064683	1.9556	0.097011
13	0.965	3.008587	0.10556	1.9959	0.062199
14	1.037	3.292153	0.147075	2.17449	0.019076

Calculate average penetration of three repetitions:  $P = N_{out}/N_{in} = (\text{with filter})/(\text{without filter})$   
 Penetration as a percentage is  $P * 100\%$ . Three average penetrations were calculated from three repetitions each (for each bin diameter). Average penetration is the average of three tests ("p 1,2,3 below").

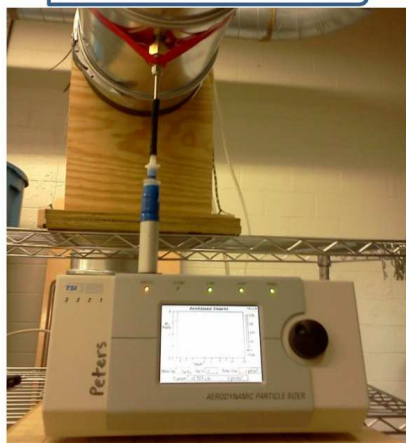
Test number	A	B	C	D	E	F	G	H
1								
2								
3	d1	p1	d2	p2	d3	p3	p 1,2,3	p stdev
4	um	fraction	um	fraction	um	fraction		
5	0.542	0.91909	0.542	0.768441	0.542	0.876997	0.854845	0.07773
6	0.583	0.896415	0.583	0.835481	0.583	0.876704	0.869533	0.031093
7	0.626	0.886243	0.626	0.927055	0.626	0.861854	0.891717	0.032943
8	0.673	0.857881	0.673	0.972426	0.673	0.846564	0.89229	0.06963
9	0.723	0.812693	0.723	0.98314	0.723	0.797519	0.864451	0.103067
10	0.777	0.764354	0.777	0.887222	0.777	0.745818	0.799131	0.07685
11	0.835	0.736382	0.835	0.757836	0.835	0.67378	0.722666	0.043674
12	0.898	0.681916	0.898	0.652596	0.898	0.644484	0.659665	0.019692
13	0.965	0.663401	0.965	0.627831	0.965	0.629551	0.640261	0.020058
14	1.037	0.660507	1.037	0.602243	1.037	0.630769	0.631173	0.029134



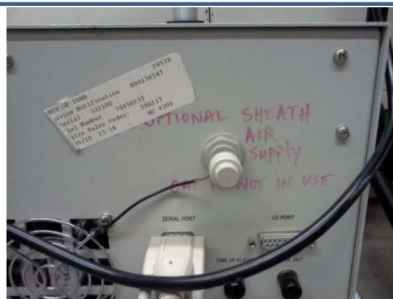
3. Settings

As per 1005.01 §6

Aerodynamic Particle Sizer



Aerodynamic Particle Sizer with Modified Sheath Airflow



Total flow rate: 4.4LPM

## SOP 0000-QC Quality Control Document

### Title of Standard Operating Procedure

---

Operator: \_\_\_\_\_

Date: \_\_\_\_\_

Batch ID: \_\_\_\_\_

Section/Step	Result	Batch No.	Initials

Comments: \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_

Operator Signature: \_\_\_\_\_

Date: \_\_\_\_\_

Supervisor Signature: \_\_\_\_\_

Date: \_\_\_\_\_

**Accepted**

**Rejected**

## APPENDIX B: RAW DATA

Table B- 1. Velocity pressure and airflow hourly data for loading test 1.

Time Hours	Pressure Drop inches w.g.	Airflow CFM	Time Hours	Pressure Drop inches w.g.	Airflow CFM
1	0.50	1054	37	1.30	972
2	0.54	1043	38	1.32	972
3	0.58	1039	39	1.34	968
4	0.62	1039	40	1.36	964
5	0.65	1037	41	1.38	954
6	0.68	1034	42	1.40	950
7	0.71	1037	43	1.42	957
8	0.74	1032	44	1.44	956
9	0.76	1028	45	1.46	953
10	0.78	1033	46	1.48	953
11	0.81	1027	47	1.50	951
12	0.83	1033	48	1.52	954
13	0.85	1020	49	1.55	944
14	0.87	1021	50	1.57	946
15	0.89	1018	51	1.59	934
16	0.91	1005	52	1.61	941
17	0.93	1005	53	1.64	941
18	0.94	1012	54	1.66	939
19	0.96	1009	55	1.68	936
20	0.98	1008	56	1.71	927
21	1.00	1003	57	1.73	927
22	1.02	1001	58	1.75	938
23	1.04	994	59	1.78	922
24	1.06	994	60	1.80	925
25	1.08	988	61	1.83	917
26	1.09	985	62	1.86	925
27	1.11	956	63	1.87	925
28	1.13	987	64	1.90	913
29	1.15	985	65	1.92	904
30	1.17	986	66	1.95	922
31	1.18	994	67	1.98	901
32	1.21	972	68	2.00	902
33	1.22	981	69	2.02	912
34	1.24	979	70	2.05	901
35	1.26	970	71	2.07	908
36	1.28	975	72	2.10	896

Table B-1 continued.

Time Hours	Pressure Drop inches w.g.	Airflow CFM	Time Hours	Pressure Drop inches w.g.	Airflow CFM
73	2.12	901	109	2.87	804
74	2.14	883	110	2.89	809
75	2.17	897	111	2.91	811
76	2.19	888	112	2.93	803
77	2.22	892	113	2.95	796
78	2.24	884	114	2.97	793
79	2.27	882	115	2.99	790
80	2.29	868	116	3.00	790
81	2.31	874	117	3.03	787
82	2.33	875	118	3.05	771
83	2.35	880	119	3.06	785
84	2.38	866	120	3.08	782
85	2.40	872	121	3.09	784
86	2.42	858	122	3.11	779
87	2.44	859	123	3.13	762
88	2.46	854	124	3.15	775
89	2.48	856	125	3.17	772
90	2.50	859	126	3.19	774
91	2.53	846	127	3.21	769
92	2.55	846	128	3.22	765
93	2.57	846	129	3.24	763
94	2.59	843	130	3.26	762
95	2.61	843	131	3.27	762
96	2.62	835	132	3.28	763
97	2.64	835	133	3.30	755
98	2.67	833	134	3.32	755
99	2.68	829	135	3.33	760
100	2.70	830	136	3.35	763
101	2.72	819	137	3.36	752
102	2.74	816	138	3.37	760
103	2.76	802	139	3.39	742
104	2.78	821	140	3.39	749
105	2.80	821	141	3.39	734
106	2.82	817	142	3.39	736
107	2.83	809	143	3.39	740
108	2.85	806	144	3.41	743

Table B-1 continued.

Time Hours	Pressure Drop inches w.g.	Airflow CFM
145	3.40	740
146	3.41	739
147	3.42	740
148	3.43	742
149	3.45	749
150	3.47	738
151	3.47	740
152	3.49	732
153	3.50	734
154	3.52	729
155	3.54	724
156	3.56	725
157	3.57	720
158	3.59	728
159	3.61	716
160	3.62	726
161	3.63	706
162	3.64	718
163	3.66	723
164	3.67	718
165	3.69	712
166	3.70	714
167	3.72	707
168	3.73	703
169	3.75	707

Table B- 2. Velocity pressure and airflow daily data for loading test 1.

Time Days	Pressure Drop inches w.g.		Airflow CFM	
	Average	Std Dev.	Average	Std Dev.
1	0.95	0.067	1008	9.32
2	1.41	0.071	959	8.58
3	1.96	0.086	911	9.47
4	2.51	0.073	852	9.97
5	2.97	0.067	794	11.72
6	3.36	0.033	750	9.31
7	3.65	0.050	716	7.33

Table B- 3. Velocity pressure and airflow hourly data for loading test 2.

Time Hours	Pressure Drop inches w.g.	Airflow CFM	Time Hours	Pressure Drop inches w.g.	Airflow CFM
1	1.47	981	37	2.65	865
2	1.52	979	38	2.67	856
3	1.57	971	39	2.69	854
4	1.63	966	40	2.71	852
5	1.67	966	41	2.75	851
6	1.73	960	42	2.77	847
7	1.77	951	43	2.80	843
8	1.82	945	44	2.82	840
9	1.86	945	45	2.84	833
10	1.90	945	46	2.86	837
11	1.93	949	47	2.88	828
12	1.97	924	48	2.90	823
13	2.00	934	49	2.92	829
14	2.03	925	50	2.94	822
15	2.06	924	51	2.97	815
16	2.09	923	52	2.99	810
17	2.12	911	53	3.01	814
18	2.15	905	54	3.02	826
19	2.18	916	55	3.05	803
20	2.21	903	56	3.06	801
21	2.24	902	57	3.08	809
22	2.27	898	58	3.09	807
23	2.31	896	59	3.11	791
24	2.35	893	60	3.12	795
25	2.38	887	61	3.15	798
26	2.40	884	62	3.16	785
27	2.42	883	63	3.18	795
28	2.45	880	64	3.20	799
29	2.48	879	65	3.21	797
30	2.50	874	66	3.24	782
31	2.53	873	67	3.25	789
32	2.55	873	68	3.27	782
33	2.58	885	69	3.29	786
34	2.60	874	70	3.31	780
35	2.63	865	71	3.32	784
36	2.63	858	72	3.34	778

Table B-3 continued.

Time Hours	Pressure Drop inches w.g.	Airflow CFM	Time Hours	Pressure Drop inches w.g.	Airflow CFM
73	3.36	771	109	3.76	711
74	3.37	774	110	3.77	714
75	3.39	765	111	3.78	710
76	3.40	769	112	3.79	709
77	3.42	766	113	3.80	707
78	3.44	767	114	3.81	697
79	3.45	756	115	3.82	699
80	3.47	758	116	3.82	699
81	3.48	750	117	3.83	703
82	3.50	743	118	3.84	693
83	3.51	749	119	3.85	701
84	3.53	751			
85	3.54	743			
86	3.56	746			
87	3.58	750			
88	3.59	738			
89	3.61	728			
90	3.62	741			
91	3.63	737			
92	3.64	728			
93	3.65	728			
94	3.66	730			
95	3.67	725			
96	3.67	730			
97	3.67	723			
98	3.67	719			
99	3.67	710			
100	3.66	731			
101	3.66	715			
102	3.67	713			
103	3.68	705			
104	3.69	725			
105	3.71	717			
106	3.73	715			
107	3.74	715			
108	3.75	714			

Table B- 4. Velocity pressure and airflow daily data for loading test 2.

Time Days	Pressure Drop inches w.g. Average	Pressure Drop inches w.g. Std Dev.	Airflow CFM Average	Airflow CFM Std Dev.
1	2.19	0.105	908	11.51
2	2.79	0.072	843	9.88
3	3.25	0.059	787	7.07
4	3.62	0.038	735	7.50
5	3.80	0.030	705	6.55

Table B- 5. Velocity pressure and airflow hourly data for loading test 3.

Time Hours	Pressure Drop inches w.g.	Airflow CFM	Time Hours	Pressure Drop inches w.g.	Airflow CFM
1	1.58	969	37	2.60	863
2	1.64	960	38	2.63	857
3	1.69	952	39	2.65	855
4	1.73	958	40	2.67	840
5	1.77	946	41	2.68	843
6	1.80	942	42	2.71	849
7	1.83	943	43	2.73	851
8	1.86	942	44	2.75	843
9	1.89	944	45	2.77	842
10	1.92	938	46	2.80	830
11	1.95	935	47	2.82	844
12	1.97	937	48	2.84	844
13	2.00	930	49	2.86	830
14	2.03	931	50	2.89	832
15	2.05	922	51	2.91	829
16	2.08	920	52	2.93	826
17	2.11	922	53	2.95	819
18	2.14	916	54	2.97	814
19	2.16	917	55	2.99	819
20	2.20	901	56	3.01	815
21	2.22	912	57	3.02	809
22	2.24	909	58	3.04	802
23	2.27	894	59	3.06	807
24	2.30	906	60	3.08	800
25	2.33	894	61	3.10	805
26	2.35	898	62	3.11	803
27	2.38	891	63	3.14	788
28	2.40	885	64	3.15	792
29	2.43	880	65	3.17	796
30	2.45	884	66	3.19	785
31	2.48	876	67	3.20	801
32	2.50	878	68	3.22	786
33	2.52	875	69	3.25	788
34	2.54	874	70	3.27	799
35	2.56	856	71	3.29	776
36	2.58	866	72	3.30	779

Table B-5 continued.

Time Hours	Pressure Drop inches w.g.	Airflow CFM	Time Hours	Pressure Drop inches w.g.	Airflow CFM
73	3.32	774	109	3.87	714
74	3.34	778	110	3.88	712
75	3.37	771	111	3.90	710
76	3.38	772	112	3.91	714
77	3.40	769	113	3.92	698
78	3.43	766	114	3.93	698
79	3.44	771	115	3.95	706
80	3.45	764	116	3.96	684
81	3.48	762	117	3.97	700
82	3.49	762	118	3.98	693
83	3.51	755	119	3.99	699
84	3.53	749			
85	3.54	745			
86	3.55	747			
87	3.57	743			
88	3.58	750			
89	3.60	744			
90	3.61	737			
91	3.62	745			
92	3.64	738			
93	3.66	744			
94	3.66	736			
95	3.68	740			
96	3.70	729			
97	3.70	738			
98	3.72	729			
99	3.73	722			
100	3.75	727			
101	3.76	732			
102	3.79	721			
103	3.80	722			
104	3.81	723			
105	3.82	717			
106	3.84	721			
107	3.85	712			
108	3.87	721			

Table B- 6. Velocity pressure and airflow daily data for loading test 3.

Time Days	Pressure Drop inches w.g. Average	Pressure Drop inches w.g. Std Dev.	Airflow CFM Average	Airflow CFM Std Dev.
1	1.98	0.209	931	19.5
2	2.59	0.154	863	19.7
3	3.09	0.132	804	16.4
4	3.52	0.112	754	14.4
5	3.85	0.091	714	13.6

Table B- 7. Collection efficiency by size, startup of first loading

TEST #	dp um	avg inlet #/cc	exhaust #/cc	collect eff %
TEST #1	0.542	2.097032	1.91143	8.9
	0.583	3.017285	2.68449	11.0
	0.626	4.43872	3.804817	14.3
	0.673	6.945563	5.78973	16.6
	0.723	10.55207	8.500673	19.4
	0.777	15.02642	11.83667	21.2
	0.835	19.12985	14.7174	23.1
	0.898	23.20282	17.41987	24.9
	0.965	25.29453	18.54407	26.7
	1.037	27.7773	19.64717	29.3
	1.114	29.36442	20.09377	31.6
	1.197	29.20512	19.69383	32.6
	1.286	28.46493	18.45653	35.2
	1.382	27.13408	17.16513	36.7
	1.486	25.60642	15.53977	39.3
	1.596	23.70512	13.53743	42.9
	1.715	21.92547	11.84457	46.0
	1.843	20.1988	10.19423	49.5
	1.981	18.72033	8.76218	53.2
	2.129	17.75633	7.55418	57.5
	2.288	16.34303	6.341633	61.2
	2.458	14.90063	5.157183	65.4
	2.642	13.76927	4.25931	69.1
	2.839	12.1387	3.214723	73.5
	3.051	10.17624	2.29613	77.4
	3.278	8.351282	1.56442	81.3
	3.523	7.493188	1.125117	85.0
	3.786	6.46269	0.74518	88.5
	4.068	4.871275	0.436869	91.0
	4.371	3.786045	0.27297	92.8
	4.698	3.027122	0.171427	94.3
	5.048	2.754908	0.134607	95.1
	5.425	2.63158	0.120144	95.4
	5.829	2.215068	0.121467	94.5
	6.264	1.996938	0.124938	93.7
	6.732	1.891093	0.121239	93.6
	7.234	1.564705	0.106768	93.2
	7.774	1.460553	0.094484	93.5

Table B-7 continued.

TEST #	dp um	avg inlet #/cc	exhaust #/cc	collect eff %
TEST #1	8.354	1.308537	0.081731	93.8
	8.977	1.120993	0.06947	93.8
	9.647	0.940793	0.060779	93.5
	10.37	0.831516	0.047586	94.3
	11.14	0.743384	0.03393	95.4
	11.97	0.553976	0.025083	95.5
	12.86	0.441916	0.020853	95.3
	13.82	0.361289	0.017417	95.2
	14.86	0.281805	0.015758	94.4
	15.96	0.201012	0.0099	95.1
	17.15	0.099916	0.004484	95.5
TEST #2	0.542	2.102435	1.853023	11.86299
	0.583	3.005772	2.608513	13.21652
	0.626	4.402147	3.648833	17.11241
	0.673	6.932118	5.621247	18.91012
	0.723	10.53275	8.41889	20.0694
	0.777	14.92748	11.73437	21.39086
	0.835	18.99167	14.54853	23.39517
	0.898	22.96175	17.21373	25.03301
	0.965	25.00313	18.32477	26.71012
	1.037	27.44813	19.56423	28.7229
	1.114	29.13105	19.89483	31.70575
	1.197	28.70912	19.31733	32.71359
	1.286	27.84222	18.01717	35.28832
	1.382	26.4788	16.56707	37.43271
	1.486	25.03538	14.9384	40.33085
	1.596	23.25408	13.06813	43.80284
	1.715	21.47327	11.23197	47.69326
	1.843	19.73173	9.53432	51.68027
	1.981	18.37815	8.17872	55.49759
	2.129	17.46685	7.050813	59.63317
2.288	16.00872	5.824813	63.61474	
2.458	14.66322	4.778307	67.41297	
2.642	13.52148	3.8735	71.353	
2.839	11.86685	2.97816	74.90353	

Table B-7 continued.

TEST #	dp um	avg inlet #/cc	exhaust #/cc	collect eff %
TEST #2	3.051	10.07897	2.116703	78.99882
	3.278	8.231528	1.40176	82.97084
	3.523	7.420437	0.974752	86.86396
	3.786	6.366652	0.666406	89.53287
	4.068	4.76755	0.377393	92.08412
	4.371	3.71604	0.226213	93.91253
	4.698	3.014868	0.149713	95.03418
	5.048	2.755818	0.110533	95.98912
	5.425	2.561552	0.104117	95.93541
	5.829	2.199258	0.104525	95.24727
	6.264	2.041302	0.108517	94.68395
	6.732	1.858355	0.098655	94.69129
	7.234	1.56078	0.078512	94.96969
	7.774	1.462652	0.078393	94.64034
	8.354	1.289468	0.061834	95.20471
	8.977	1.125258	0.049317	95.61728
	9.647	0.958234	0.038076	96.02639
	10.37	0.825671	0.031881	96.13884
	11.14	0.734857	0.027745	96.22449
	11.97	0.55847	0.018822	96.62981
12.86	0.430667	0.01811	95.79497	
13.82	0.361735	0.012137	96.6447	
14.86	0.28149	0.007401	97.37075	
15.96	0.202868	0.005039	97.5161	
17.15	0.096407	0.002924	96.96663	
TEST #3	0.542	2.10819	1.878843	10.87884
	0.583	3.002975	2.69999	10.08949
	0.626	4.347765	3.84693	11.51937
	0.673	6.872123	5.93909	13.57707
	0.723	10.48592	8.929067	14.84706
	0.777	14.89327	12.3435	17.12026
	0.835	18.92085	15.54273	17.85394
	0.898	22.82238	18.5035	18.92389
	0.965	24.94622	19.62503	21.33062
1.037	27.53222	20.85243	24.2617	

Table B-7 continued.

TEST #	dp um	avg inlet #/cc	exhaust #/cc	collect eff %
TEST #3	1.114	29.16373	21.21093	27.26949
	1.197	28.75772	20.10413	30.09134
	1.286	27.74983	18.4972	33.34302
	1.382	26.29665	16.68083	36.5667
	1.486	24.85247	14.9907	39.68124
	1.596	23.12225	13.03163	43.64029
	1.715	21.28318	11.17597	47.48921
	1.843	19.57353	9.489337	51.51955
	1.981	18.22312	8.145407	55.30179
	2.129	17.43803	7.07633	59.42014
	2.288	15.95005	5.78557	63.72695
	2.458	14.61235	4.731877	67.61728
	2.642	13.51048	3.757223	72.19031
	2.839	11.81023	2.788873	76.38596
	3.051	10.01386	1.970293	80.32433
	3.278	8.291318	1.302207	84.29434
	3.523	7.542515	0.882631	88.29792
	3.786	6.27765	0.576376	90.8186
	4.068	4.664587	0.338053	92.75277
	4.371	3.73246	0.194343	94.79317
	4.698	3.0399	0.129093	95.75338
	5.048	2.781783	0.102893	96.30117
	5.425	2.519335	0.086432	96.56927
	5.829	2.199957	0.072819	96.68998
	6.264	2.061775	0.087588	95.7518
	6.732	1.882668	0.073994	96.06975
	7.234	1.572407	0.069702	95.56718
	7.774	1.49257	0.055991	96.24867
	8.354	1.296212	0.045887	96.45994
	8.977	1.118023	0.043128	96.14251
	9.647	0.983454	0.030358	96.91318
	10.37	0.826368	0.025935	96.8616
	11.14	0.732159	0.027938	96.18418
	11.97	0.569758	0.015303	97.31416
	12.86	0.428637	0.010491	97.55257
	13.82	0.354495	0.008016	97.73879
	14.86	0.272191	0.006093	97.76168
	15.96	0.199143	0.00413	97.92629
	17.15	0.094359	0.001365	98.55371

Table B- 8. Collection efficiency by size, end of first loading.

TEST #	dp	avg inlet	exhaust	collect eff
	um	#/cc	#/cc	%
TEST #1	0.542	3.796893	0.144919	96.18323
	0.583	5.298685	0.199361	96.23754
	0.626	7.090713	0.254601	96.40937
	0.673	9.669258	0.325714	96.63145
	0.723	12.91645	0.388425	96.99279
	0.777	17.26173	0.463206	97.31657
	0.835	21.75877	0.507973	97.66543
	0.898	26.49035	0.57298	97.83702
	0.965	29.1345	0.547573	98.12053
	1.037	31.6868	0.543534	98.28467
	1.114	33.29287	0.502932	98.48937
	1.197	33.36865	0.46459	98.60771
	1.286	32.38248	0.430383	98.67094
	1.382	30.84857	0.405744	98.68472
	1.486	29.60532	0.359751	98.78484
	1.596	27.52668	0.307009	98.88469
	1.715	25.50858	0.268341	98.94804
	1.843	23.91012	0.248302	98.96152
	1.981	22.167	0.221106	99.00254
	2.129	21.09135	0.181945	99.13735
	2.288	19.37665	0.159307	99.17784
	2.458	17.31377	0.131319	99.24153
	2.642	16.07687	0.112741	99.29874
	2.839	14.67873	0.099282	99.32363
	3.051	12.63905	0.078234	99.38102
	3.278	10.43663	0.060171	99.42346
	3.523	8.940843	0.043929	99.50867
	3.786	7.847232	0.029902	99.61895
	4.068	6.283982	0.02118	99.66295
	4.371	4.967563	0.013105	99.73619
	4.698	4.043723	0.011175	99.72364
	5.048	3.476778	0.008339	99.76015
	5.425	3.510927	0.005102	99.85468
	5.829	2.872495	0.010176	99.64575
	6.264	2.613843	0.005921	99.77349
	6.732	2.414087	0.006653	99.7244
	7.234	2.145133	0.003342	99.8442
	7.774	1.912577	0.005059	99.73548
	8.354	1.844443	0.002241	99.8785
	8.977	1.555412	0.003097	99.80087

Table B-8 continued.

TEST #	dp um	avg inlet #/cc	exhaust #/cc	collect eff %
TEST #1	9.647	1.34883	0.003094	99.77063
	10.37	1.157678	0.002473	99.78635
	11.14	1.05232	0.000884	99.91597
	11.97	0.807375	0.001047	99.87036
	12.86	0.627074	0.000814	99.87016
	13.82	0.519593	0.001331	99.74374
	14.86	0.408993	0.000548	99.86591
	15.96	0.280098	0.000336	99.88007
	17.15	0.128672	0.000195	99.84848
TEST #2	0.542	3.631022	0.147818	95.92902
	0.583	5.084685	0.184895	96.36369
	0.626	6.818603	0.227504	96.66348
	0.673	9.234348	0.284319	96.92107
	0.723	12.36737	0.360775	97.08285
	0.777	16.6036	0.42562	97.43658
	0.835	20.9811	0.463821	97.78934
	0.898	25.62605	0.496135	98.06394
	0.965	28.01445	0.49104	98.24719
	1.037	30.4791	0.510228	98.32598
	1.114	31.95837	0.47495	98.51385
	1.197	32.02768	0.420858	98.68595
	1.286	31.11422	0.396317	98.72625
	1.382	29.58862	0.371493	98.74447
	1.486	28.50163	0.308893	98.91623
	1.596	26.54767	0.292964	98.89646
	1.715	24.79248	0.261032	98.94713
	1.843	23.27933	0.221774	99.04734
	1.981	21.6544	0.203828	99.05872
	2.129	20.76233	0.17681	99.14841
	2.288	19.0877	0.147955	99.22487
	2.458	17.0912	0.132886	99.22249
	2.642	15.97278	0.115309	99.27809
	2.839	14.85458	0.093149	99.37293
	3.051	12.87997	0.078227	99.39265
	3.278	10.63608	0.065503	99.38414
	3.523	9.253228	0.045383	99.50954
3.786	8.211022	0.028861	99.64851	
4.068	6.50135	0.022767	99.64981	

Table B-8 continued.

TEST #	dp	avg inlet	exhaust	collect eff
	um	#/cc	#/cc	%
TEST #2	4.371	5.138227	0.013041	99.74619
	4.698	4.243345	0.006976	99.83561
	5.048	3.647922	0.010507	99.71197
	5.425	3.6907	0.005674	99.84626
	5.829	3.033375	0.003881	99.87205
	6.264	2.821328	0.005734	99.79675
	6.732	2.575793	0.001952	99.92423
	7.234	2.305958	0.00524	99.77274
	7.774	2.08051	0.005721	99.72504
	8.354	1.974817	0.004602	99.76695
	8.977	1.661888	0.003374	99.797
	9.647	1.450928	0.002703	99.81372
	10.37	1.235202	0.001198	99.90303
	11.14	1.099253	0.000687	99.93752
	11.97	0.83456	0.001011	99.87892
	12.86	0.640091	0.001714	99.73216
	13.82	0.51764	0.001204	99.76731
14.86	0.411868	0.000206	99.9499	
15.96	0.28395	0	100	
17.15	0.126723	0	100	
TEST #3	0.542	3.577342	0.130863	96.34188
	0.583	5.02355	0.165562	96.70428
	0.626	6.677683	0.209269	96.86614
	0.673	9.057385	0.254178	97.19369
	0.723	12.14997	0.298202	97.54566
	0.777	16.42408	0.363724	97.78542
	0.835	20.85845	0.40987	98.03499
	0.898	25.41488	0.446069	98.24485
	0.965	27.8947	0.430148	98.45796
	1.037	30.28483	0.459149	98.4839
	1.114	31.77643	0.425485	98.661
	1.197	31.88855	0.399364	98.74763
	1.286	30.9969	0.362968	98.82902
	1.382	29.56463	0.341119	98.84619
	1.486	28.30458	0.303328	98.92834
1.596	26.42625	0.283983	98.92538	
1.715	24.64162	0.242384	99.01636	
1.843	23.22627	0.211218	99.09061	

Table B-8 continued.

TEST #	dp	avg inlet	exhaust	collect eff
	um	#/cc	#/cc	%
TEST #3	1.981	21.73733	0.190876	99.1219
	2.129	20.94823	0.176053	99.15958
	2.288	19.23603	0.155698	99.19059
	2.458	17.22532	0.123626	99.2823
	2.642	16.08395	0.106821	99.33586
	2.839	14.97222	0.089993	99.39893
	3.051	13.08387	0.071637	99.45248
	3.278	10.77483	0.053392	99.50447
	3.523	9.323537	0.047901	99.48623
	3.786	8.307645	0.037972	99.54292
	4.068	6.586847	0.022962	99.65139
	4.371	5.179638	0.012549	99.75772
	4.698	4.285245	0.015153	99.64639
	5.048	3.728488	0.008612	99.76903
	5.425	3.674445	0.010163	99.7234
	5.829	3.085893	0.009755	99.68388
	6.264	2.833803	0.00623	99.78016
	6.732	2.693323	0.006054	99.77524
	7.234	2.388575	0.0041	99.82835
	7.774	2.179963	0.006573	99.69848
	8.354	2.076718	0.004371	99.78951
	8.977	1.736582	0.00365	99.78982
	9.647	1.502305	0.002937	99.80448
	10.37	1.30148	0.002584	99.80149
	11.14	1.14371	0.0024	99.79018
	11.97	0.896926	0.000902	99.89941
	12.86	0.687481	0.001018	99.85191
	13.82	0.552305	0.00085	99.84602
	14.86	0.437696	0.001167	99.73328
	15.96	0.303069	0.000336	99.88916
	17.15	0.137933	0.000195	99.85866

Table B- 9. Collection efficiency by size, startup of second loading.

TEST #	dp	avg inlet	exhaust	collect eff
	um	#/cc	#/cc	%
TEST #1	0.542	3.949725	1.14208	71.08457
	0.583	5.451987	1.48704	72.7248
	0.626	7.200712	1.85541	74.23296
	0.673	9.841162	2.25912	77.04417
	0.723	13.17818	2.640287	79.96471
	0.777	17.62755	3.147587	82.14394
	0.835	22.40775	3.54565	84.17668
	0.898	27.44682	3.820863	86.07903
	0.965	30.35458	3.683997	87.86346
	1.037	33.3555	3.538933	89.39026
	1.114	35.1821	3.099217	91.19093
	1.197	35.35625	2.557037	92.76779
	1.286	34.59913	2.024977	94.14732
	1.382	32.98092	1.584747	95.19496
	1.486	31.30192	1.25017	96.00609
	1.596	29.02857	0.976502	96.63606
	1.715	26.70018	0.746876	97.20273
	1.843	24.88525	0.607763	97.55774
	1.981	23.00202	0.519104	97.74322
	2.129	21.43462	0.411242	98.08141
	2.288	19.48018	0.351643	98.19487
	2.458	17.42813	0.307833	98.2337
	2.642	15.9584	0.245777	98.45989
	2.839	14.37837	0.202953	98.58849
	3.051	12.2104	0.156269	98.7202
	3.278	10.01134	0.112685	98.87443
	3.523	8.535318	0.088321	98.96523
	3.786	7.336897	0.066595	99.09232
	4.068	5.721333	0.045721	99.20087
	4.371	4.408288	0.03469	99.21307
	4.698	3.498813	0.027755	99.20673
	5.048	2.931595	0.020266	99.30871
	5.425	2.541458	0.024801	99.02415
	5.829	2.109757	0.019708	99.06586
	6.264	1.805588	0.014988	99.1699
	6.732	1.59533	0.018274	98.85455
	7.234	1.422282	0.013376	99.05955
	7.774	1.26996	0.014851	98.83062
	8.354	1.197435	0.008622	99.27996
	8.977	1.048846	0.010121	99.03504
	9.647	0.941087	0.008577	99.08856

Table B-9 continued.

TEST #	dp	avg inlet	exhaust	collect eff
	um	#/cc	#/cc	%
TEST #1	11.14	0.753384	0.006027	99.19999
	11.97	0.592648	0.003844	99.35145
	12.86	0.460695	0.00419	99.09047
	13.82	0.368067	0.001712	99.53474
	14.86	0.28309	0.00171	99.39578
	15.96	0.203568	0.000988	99.51474
	17.15	0.094749	0	100
TEST #2	0.542	3.82743	1.06761	72.10635
	0.583	5.250523	1.430043	72.76379
	0.626	6.878077	1.74449	74.63695
	0.673	9.232162	2.098563	77.26899
	0.723	12.19003	2.510347	79.40656
	0.777	16.18743	2.954027	81.75111
	0.835	20.38042	3.32105	83.7047
	0.898	24.74675	3.571737	85.56685
	0.965	27.17565	3.451303	87.30002
	1.037	29.58602	3.197223	89.19346
	1.114	30.88488	2.749657	91.09708
	1.197	30.7267	2.31063	92.48006
	1.286	29.95685	1.822287	93.91696
	1.382	28.56552	1.40029	95.09797
	1.486	26.98327	1.09894	95.92733
	1.596	25.07042	0.849075	96.61324
	1.715	23.21148	0.670672	97.1106
	1.843	21.60683	0.543631	97.48399
	1.981	20.1042	0.437432	97.82418
	2.129	18.91572	0.360406	98.09467
	2.288	17.15768	0.313526	98.17268
	2.458	15.38507	0.256956	98.32983
	2.642	14.19057	0.222116	98.43477
	2.839	12.98567	0.179104	98.62076
	3.051	11.1597	0.139971	98.74575
	3.278	9.021857	0.105401	98.83172
	3.523	7.672457	0.077923	98.98438
	3.786	6.590848	0.061465	99.06743
	4.068	4.991933	0.04416	99.11538
	4.371	3.702852	0.027462	99.25835
4.698	2.872282	0.022572	99.21414	
5.048	2.371183	0.020339	99.14223	
5.425	2.121033	0.021994	98.96304	
5.829	1.784282	0.021564	98.79147	

Table B-9 continued.

TEST #	dp	avg inlet	exhaust	collect eff
	um	#/cc	#/cc	%
TEST #2	6.264	1.636443	0.013521	99.17373
	6.732	1.50881	0.014104	99.06523
	7.234	1.3929	0.013482	99.0321
	7.774	1.299202	0.013146	98.98816
	8.354	1.221242	0.009198	99.24682
	8.977	1.057896	0.009037	99.1458
	9.647	0.949485	0.003625	99.61823
	10.37	0.82228	0.003448	99.58064
	11.14	0.749437	0.004464	99.40429
	11.97	0.596519	0.003375	99.43428
	12.86	0.460292	0.0015	99.67413
	13.82	0.373753	0.001762	99.52844
	14.86	0.291009	0.001091	99.62494
	15.96	0.207342	0.001818	99.12317
	17.15	0.096309	0.00117	98.78542
TEST #3	0.542	3.815093	0.967656	74.63612
	0.583	5.168768	1.270533	75.41903
	0.626	6.744368	1.575583	76.63853
	0.673	8.963155	1.945223	78.29756
	0.723	11.75923	2.313537	80.32579
	0.777	15.51907	2.752533	82.26354
	0.835	19.35933	3.128257	83.84109
	0.898	23.49902	3.407393	85.49985
	0.965	25.58045	3.223523	87.39849
	1.037	27.83257	3.020027	89.14931
	1.114	28.98472	2.587387	91.07327
	1.197	28.7229	2.165993	92.459
	1.286	27.9951	1.684573	93.98261
	1.382	26.6141	1.30746	95.08734
	1.486	25.20928	0.983245	96.09967
	1.596	23.49767	0.736119	96.86727
	1.715	21.91885	0.57608	97.37176
	1.843	20.4455	0.466176	97.71991
	1.981	19.0256	0.408714	97.85177
	2.129	18.09992	0.347031	98.08269
2.288	16.43507	0.29495	98.20536	
2.458	14.8594	0.239467	98.38845	
2.642	13.74387	0.199038	98.5518	
2.839	12.58132	0.173987	98.6171	
3.051	10.91768	0.131243	98.79788	
3.278	8.934863	0.096064	98.92484	

Table B-9 continued.

TEST #	dp	avg inlet	exhaust	collect eff
	um	#/cc	#/cc	%
TEST #3	3.523	7.680605	0.075658	99.01494
	3.786	6.700855	0.058084	99.13318
	4.068	5.173213	0.038237	99.26087
	4.371	3.994515	0.027309	99.31634
	4.698	3.240837	0.019289	99.4048
	5.048	2.769037	0.020759	99.25031
	5.425	2.57211	0.020806	99.19108
	5.829	2.132408	0.015857	99.25637
	6.264	1.938738	0.013587	99.29918
	6.732	1.781942	0.016571	99.07007
	7.234	1.59139	0.012065	99.24187
	7.774	1.468152	0.014524	99.01074
	8.354	1.368828	0.009781	99.28546
	8.977	1.187898	0.006951	99.41488
	9.647	1.025495	0.006515	99.3647
	10.37	0.879651	0.004214	99.52098
	11.14	0.789535	0.005156	99.34701
	11.97	0.641174	0.005666	99.11624
	12.86	0.477433	0.002733	99.42766
	13.82	0.38478	0.002182	99.43294
	14.86	0.298296	0.001852	99.37927
	15.96	0.213428	0.001008	99.5278
	17.15	0.099039	0.000585	99.40945

Table B- 10. Collection efficiency by size, end of second loading.

TEST #	dp	avg inlet	exhaust	collect eff
	um	#/cc	#/cc	%
TEST #1	0.542	2.89994	0.053787	98.14523
	0.583	4.084598	0.077062	98.11336
	0.626	5.65198	0.098901	98.25016
	0.673	8.207617	0.142261	98.26672
	0.723	11.84238	0.190087	98.39486
	0.777	16.76042	0.242482	98.55324
	0.835	21.81573	0.278919	98.72148
	0.898	26.88253	0.321294	98.80482
	0.965	29.60142	0.330804	98.88247
	1.037	32.34065	0.323908	98.99845
	1.114	34.09183	0.335879	99.01478
	1.197	34.08972	0.294005	99.13755
	1.286	33.19317	0.30033	99.09521
	1.382	31.59457	0.258029	99.18331
	1.486	30.18023	0.243942	99.19172
	1.596	27.83937	0.206429	99.2585
	1.715	25.94065	0.181017	99.30219
	1.843	24.19385	0.166636	99.31125
	1.981	22.48958	0.156112	99.30585
	2.129	21.31222	0.129122	99.39414
	2.288	19.35737	0.110262	99.43039
	2.458	17.23838	0.105071	99.39048
	2.642	15.86682	0.088693	99.44101
	2.839	14.35188	0.066437	99.53709
	3.051	12.23538	0.053753	99.56068
	3.278	9.916852	0.045405	99.54214
	3.523	8.407247	0.033373	99.60305
	3.786	7.26628	0.020687	99.7153
	4.068	5.701458	0.015554	99.72719
	4.371	4.415942	0.011358	99.7428
	4.698	3.5568	0.007212	99.79723
	5.048	3.056078	0.007192	99.76467
	5.425	2.970375	0.004728	99.84084
	5.829	2.394108	0.00684	99.71432
	6.264	2.163542	0.006111	99.71752
	6.732	1.962498	0.002829	99.85586
	7.234	1.741295	0.003759	99.78413
	7.774	1.5805	0.003445	99.78203
	8.354	1.49149	0.00345	99.76868
	8.977	1.266647	0.002899	99.77111
	9.647	1.068678	0.000922	99.91372

Table B-10 continued.

TEST #	dp	avg inlet	exhaust	collect eff
	um	#/cc	#/cc	%
TEST #1	10.37	0.901678	0.001453	99.83887
	11.14	0.781066	0.000687	99.91206
	11.97	0.564642	0.000577	99.89773
	12.86	0.43405	0.000579	99.86671
	13.82	0.346209	0.0009	99.7399
	14.86	0.259681	0.000548	99.78881
	15.96	0.181159	0.000198	99.89094
	17.15	0.080712	0	100
TEST #2	0.542	2.739735	0.049905	98.17846
	0.583	3.858717	0.058874	98.47426
	0.626	5.339755	0.082204	98.46052
	0.673	7.858393	0.123038	98.43431
	0.723	11.49542	0.165834	98.55739
	0.777	16.28277	0.199475	98.77493
	0.835	21.29923	0.24845	98.83353
	0.898	26.29498	0.284879	98.9166
	0.965	29.10653	0.294936	98.9867
	1.037	31.777	0.295272	99.0708
	1.114	33.50942	0.282442	99.15713
	1.197	33.52102	0.264484	99.21099
	1.286	32.52847	0.241414	99.25784
	1.382	31.11033	0.220734	99.29048
	1.486	29.6311	0.208877	99.29508
	1.596	27.45347	0.185114	99.32572
	1.715	25.48063	0.16483	99.35312
	1.843	23.75993	0.149252	99.37183
	1.981	22.13605	0.133587	99.39652
	2.129	21.03093	0.12165	99.42157
	2.288	19.08632	0.09944	99.479
	2.458	17.00675	0.082532	99.51471
	2.642	15.67592	0.070619	99.54951
	2.839	14.22488	0.063401	99.55429
	3.051	12.1027	0.052674	99.56478
	3.278	9.820645	0.0404	99.58862
	3.523	8.334528	0.027083	99.67505
	3.786	7.211197	0.017477	99.75764
	4.068	5.508892	0.014604	99.7349
	4.371	4.184272	0.011217	99.73192
4.698	3.367848	0.00838	99.75116	
5.048	2.918297	0.006137	99.78972	
5.425	2.770043	0.004933	99.82192	

Table B-10 continued.

TEST #	dp	avg inlet	exhaust	collect eff
	um	#/cc	#/cc	%
TEST #2	5.829	2.328412	0.007519	99.67708
	6.264	2.114117	0.004469	99.78861
	6.732	1.975553	0.003451	99.82531
	7.234	1.739928	0.003448	99.80182
	7.774	1.607823	0.003535	99.78011
	8.354	1.484413	0.003798	99.74412
	8.977	1.24063	0.002133	99.8281
	9.647	1.07813	0.002172	99.79857
	10.37	0.900498	0.001286	99.85715
	11.14	0.767932	0.00103	99.86584
	11.97	0.573403	0.001029	99.82061
	12.86	0.439722	0.000911	99.79286
	13.82	0.35735	0.000431	99.87939
	14.86	0.264755	0	100
	15.96	0.186228	0.000138	99.9257
17.15	0.085489	0.000195	99.77195	
TEST #3	0.542	2.773663	0.058042	97.90739
	0.583	3.90059	0.078598	97.98497
	0.626	5.382225	0.106721	98.01715
	0.673	7.98657	0.153733	98.0751
	0.723	11.7171	0.203753	98.26106
	0.777	16.54683	0.25622	98.45155
	0.835	21.51913	0.307102	98.57289
	0.898	26.38733	0.361186	98.63122
	0.965	29.09927	0.35907	98.76605
	1.037	31.69348	0.349566	98.89704
	1.114	33.448	0.346907	98.96285
	1.197	33.21958	0.321759	99.03142
	1.286	32.11175	0.291917	99.09093
	1.382	30.76292	0.270609	99.12034
	1.486	29.28295	0.249577	99.1477
	1.596	27.16007	0.210679	99.2243
	1.715	25.28385	0.191573	99.24231
	1.843	23.63902	0.173198	99.26732
	1.981	21.94803	0.157511	99.28235
	2.129	20.92395	0.13603	99.34988
2.288	18.9594	0.120282	99.36558	
2.458	16.9715	0.104803	99.38248	
2.642	15.60052	0.088377	99.4335	
2.839	14.13525	0.072603	99.48637	
3.051	12.06612	0.053697	99.55498	

Table B-10 continued.

TEST #	dp	avg inlet	exhaust	collect eff
	um	#/cc	#/cc	%
TEST #3	3.278	9.760662	0.042361	99.566
	3.523	8.372292	0.033168	99.60383
	3.786	7.308918	0.021976	99.69933
	4.068	5.554337	0.013	99.76595
	4.371	4.238973	0.010863	99.74374
	4.698	3.374422	0.009896	99.70673
	5.048	2.979172	0.009089	99.69491
	5.425	2.790823	0.006141	99.77996
	5.829	2.35537	0.006568	99.72113
	6.264	2.147728	0.003165	99.85266
	6.732	1.984368	0.004486	99.77392
	7.234	1.720887	0.004449	99.7415
	7.774	1.62052	0.003726	99.77005
	8.354	1.472028	0.001206	99.91808
	8.977	1.222417	0.002065	99.83108
	9.647	1.056828	0.002063	99.80484
	10.37	0.890038	0.001708	99.8081
	11.14	0.760751	0.000588	99.92269
	11.97	0.582553	0.000668	99.88539
	12.86	0.435088	0.001372	99.68476
	13.82	0.34959	0.001243	99.64445
	14.86	0.250029	0.000619	99.75243
	15.96	0.176518	0.000138	99.92161
	17.15	0.086561	0.000195	99.77477

## APPENDIX C: CLEANING TEST ANALYSIS

Table C- 1. Cleaning test analysis.

Test Condition	Pressure Drop $\Delta p$ , in. w.g.		Change	Change in Pressure Drop $\Delta[\Delta p]$ , in. w.g.		F-test	T-test
	Measurement	Difference		Mean	Standard Deviation	p	p
Load #1	3.78						
		2.47	Loaded-				
			A	2.2	0.24		
1A	1.31					0.091	<0.001
		0.04	A-B	0.10	0.05		
1B	1.27					0.069	0.062
		0.01	B-C	0.02	0.01		
1C	1.26						
Load #2	3.87						
		2.17					
2A	1.70						
		0.14					
2B	1.56						
		0.03					
2C	1.53						
Load #3	4.00						
		1.99					
3A	2.01						
		0.12					
3B	1.89						
		0.02					
3C	1.87						

Note: A, B, C represent sequential cleaning cycles

## REFERENCES

- ACGIH (2013). *2013 TLVs and BEIs Based on the Documentation of the Threshold Limit Values for Chemical Substances and Physical Agents & Biological Exposure Indices*. Cincinnati, Ohio: American Conference of Governmental Industrial Hygienists
- American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE). (1999). *ASHRAE Standard 62-1999: Ventilation for Acceptable Indoor Air Quality*. Atlanta, GA: ASHRAE
- Aland, A. and Banhazi, T. (2013). *Livestock Housing: Modern Management to Ensure Optimal Health and Welfare of Farm*. Wageningen Academic
- Billings, C., Dennis, R., Silverman, L. (1954). Performance of Three Types of Fabric Dust Collectors, *Air Repair*, 4(3):131-136
- Billings, C. and Wilder, J. (1970). *Handbook of Fabric Filter Technology Volume 1 Fabric Filter Systems Study*. U.S. Department of Commerce report number APTD-0690, U.S. Department of Health, Education, and Welfare, PHS Consumer Protection and Environmental Health Service, Washington D.C.
- Bowman, A., Mueller, K., Smith, M. (2000). Increased Animal Waste Production from Concentrated Animal Feeding Operations: Potential Implications for Public and Environmental Health. The Nebraska Center for Rural Health Research Occasional Paper Series. Number 2.
- Burgess, W., Ellenbecker, M., Treitman, R. (2004). *Ventilation for Control of the Work Environment*. John Wiley & Sons Inc., Hoboken, New Jersey
- Cambra-López, M., Torres, A., Aarnink, A., Ogink, N. (2011). Source analysis of fine and coarse particulate matter from livestock houses. *Atmospheric Environment* 45: 694-707
- Carpenter, S. W., Barbara, L. C., Gunderson, P. D., Stueland, D.T. (2002). Assessment of Personal Protective Equipment Use Among Midwestern Farmers. *American Journal of Industrial Medicine*. 42:236-247
- Cooper, C., Alley, F. (1986). *Air pollution control a design approach*. Waveland Press. Prospect Height, IL
- Dennis, R. (1974). Collection Efficiency as a Function of Particle Size, Shape and Density: Theory and Experience. *Journal of the Air Pollution Control Association*, 24(12):1156-1163
- Dennis, R. and Wilder, J. (1975). *Fabric Filter Cleaning Studies*. EPA publication EPA-650/2-75-009, National Technical Information Service, Springfield VA

- Donaldson Company Inc (2012). Donaldson Torit Cyclone Dust Collectors.  
<http://www2.donaldson.com/torit/en-us/Product%20Literature/productbrochures/cyclone.pdf>
- Donham, K., Rubino, M., Thedell, T., Kammermeyer, J. (1977). Potential Health Hazards to Agricultural Workers in Swine Confinement Buildings. *J. Occupational Medicine*. 19(6):383-387
- Donham, K., Scallon, L., Popendorf, W., Larsson, L. (1986a). Characterization of Dusts Collected from Swine Confinement Buildings. *American Journal of Industrial Medicine*. 10:294-2
- Donham, K., Scallon, L., Popendorf, W., Treuhaft, M. Roberst, R. (1986b). Characterization of Dusts Collected from Swine Confinement Buildings. *American Industrial Hygiene Association Journal*. 47(7):404-410
- Donham, K. (1986c). Hazardous Agents in Agricultural Dusts and Methods of Evaluation. *American Journal of Industrial Medicine*. 10:205-220
- Donham, K., Hagland, P., Peterson, Y., Rylander, R., Belin, L. (1989). Environmental and health studies of farm workers in Swedish swine confinement buildings. *British Journal of Industrial Medicine*. 46:31-37
- Donham, K., Reynolds, S., Whitten, P., Merchant, J., Burmeister, L., Popendorf, W. (1995). Respiratory dysfunction in swine production facility workers: Dose-response relationships of environmental exposures and pulmonary function. *Am. J. Ind. Med.* 27:405-418
- Donham, K., Cumro, D. (1999). Setting maximum dust exposure levels for people and animals in livestock facilities. In *Dust Control in Animal Production Facilities*, Aarhus (Denmark), 30 May-2 Jun 1999. DJF.
- Duchaine, C., Grimarda, Y., Cormierb, Y. (2000). Influence of Building Maintenance, Environmental Factors, and Seasons on Airborne Contaminants of Swine Confinement Buildings. *J. American Industrial Hygiene Association*, 61-1:56-63
- Fawcitt, R., (1938). Occupational Diseases of the Lungs in Agricultural Workers. *British Journal of Radiology*, 11:378-392
- Heber, A. J., Stroik, M., Nelsson J.L., Nichols, D.A. (1988a). Influence of environmental factors on concentrations and inorganic content of aerial dust in swine finishing buildings. *Transactions of the ASAE*. 31(3):875-881

- Heber, A.J., Stroik, M., Faubion, J.M., Willard, L.H. (1988b). Size distribution and identification of aerial dust particles in swine finishing buildings. *Transactions of the ASAE* 31:882-887
- Hoff, S.J, Zelle, B.C., Huebner, M.A., Gralapp, A.K., Bundy, D.S., Jacobson, L.D., Heber, A.J., Ni, J., Koziel, J.A., Sweeten, J.M., Zhang, Y., Beasley, D.B.: NH<sub>3</sub>, H<sub>2</sub>S, CO<sub>2</sub>, PM, and odor animal emission data from the six-state (APECAB) project: Swine deep-pit finishing buildings in Iowa, Paper 05-A-648, presented at the 2005 Annual Convention and Exhibition of the Air & Waste Management Association, Minneapolis, MN, June 21–24, 2005
- Holness, D., O’Blenis, E., Sass, A., et al. (1987). Respiratory Effects and Dust Exposures in Hog Confinement Farming. *American Journal of Industrial Medicine*, 11:571-580
- Jacobson, L. (2011). Reducing the Environmental Footprint of Pig Finishing Barns. National Pork Board Pork Checkoff Report #09-055
- Martens, W., Marintec, M., Zapirain, R., Stark, M., Hartung, E., Palmgren, U. (2001). Reduction of microbial odour and ammonia emissions from a pig facility by biofilters. *J. Hyg. Environ. Health*, 203:335-345
- Maghirang, R.G., Puma, M.C., Liu, Y., Clark, P. (1997). Dust Concentrations and Particle Size Distribution in an Enclosed Swine Nursery. *Transactions of the ASAE*. 40(3):749-754
- Merchant, J., Ross, R., Thorne, P. (2002). Iowa Concentrated Animal Feeding Operations Air Quality Study, Iowa State University and The University of Iowa Study Group, The University of Iowa Environmental Health Sciences Research Center, pp. 1-221
- Ni, J., Heber, A., Lim, T., Diehl, C., Duggirala, R., Haymore, B., Sutton, A. (2000). Ammonia Emission from a Large Mechanically-Ventilated Swine Building during Warm Weather. *Journal of Environmental Quality*. 29:751-758
- NIOSH (2010) CDC Engineering Controls - NIOSH Workplace Safety and Health Topic <http://www.cdc.gov/niosh/topics/engcontrols/>
- Nonnenmann, M. W., Donham, K. J., Rautiainen, R. H., O’Shaughnessy, P. T., Burmeister, L. F., Reynolds, S. J. (2004). Vegetable oil sprinkling as a dust reduction method in swine confinement. *J. Agric. Saf. Health*, 10:7-15
- OSHA Table Z-1 (2006). Air Contaminants. 29 CFR 1910.1000. [https:// www.osha.gov/dsg/annotated-pels/tablez-1.html](https://www.osha.gov/dsg/annotated-pels/tablez-1.html)
- O’Shaughnessy, P.T., Achutan, C., Karsten, A.W. (2002). Temporal Variation of Indoor Air Quality in an Enclosed Swine Confinement Building. *Journal of Agricultural Safety and Health*. 8(4): 349–364

- O'Shaughnessy, P., Peters, T., Donham, K., Taylor, C., Altmaier, R., Kelly, K. (2012). Assessment of Swine Worker Exposures to Dust and Endotoxin during Hog Load-Out and Power Washing. *Ann. Occup. Hyg.* 56(7), 843-851
- Pearson, C., Sharples, T. (1995). Airborne Dust Concentrations in Livestock Buildings and the Effect of Feed. *J. Agric. Engng. Res.*, 60:145-154
- Pedersen, B., Iversen, M., Bundgaard, B., Larsen, R. (1996). Pig farmers have signs of bronchial inflammation and increased numbers of lymphocytes and neutrophils in BAL fluid. *Eur Respir J.*, 9:524-530
- Pedersen, S., Nonnenmann, M. W., Rautiainen, R. H., Demmers, T. G., Banhazi, T., Lyngbye, M. (2000). Dust in pig buildings. *J. Agric. Saf. Health*, 6:261-274
- Peters, T., Anthony, R., Taylor, C., et al. (2012). Distribution of Particle and Gas Concentrations in Swine Gestation Confined Animal Feeding Operations. *Ann. Occup. Hyg.*, 56(9):1080-1090
- Pew Commission on Industrial Farm Animal Production, PCIFAP (2008). Occupational and Community Public Health Impacts of Industrial Farm Animal Production. Accessed June 22, 2012 at [www.ncifap.org/reports](http://www.ncifap.org/reports) and [www.ncifap.org/\\_images/PH\\_FINAL.pdf](http://www.ncifap.org/_images/PH_FINAL.pdf)
- Radon, K., Danuser, B., Iversen, M., Jorres, R., Monso, E., Opravil, U., Weber, C., Donham, K., Nowak, D. (2001). Respiratory Symptoms in European Animal Farmers. *Eur. Respir. J.*, 17:747-754
- Reeve, K.A., Peters, T.M., Anthony, T.R. (2013). Wintertime Factors Affecting Contaminant Distribution in a Swine Farrowing Room. *Journal of Occupational and Environmental Hygiene*, 10:287-296
- Richardson, L. J.; Hofacre, C. L.; Mitchell, B. W.; Wilson, J. L. (2003). Effect of electrostatic space charge on reduction of airborne transmission of Salmonella and other bacteria in broiler breeders in production and their progeny. *Avian Dis.*, 47:1352-1361
- Robertson, J. (1989). Effect of purge ventilation on the concentration of airborne dust in pig buildings. In *Land and Water Use*, 1495-1499
- Rule, A.M., Chapin, A.R., McCarthy, K.E., Schwab, K.J., Buckley, T.J. (2005). Assessment of an Aerosol Treatment To Improve Air Quality in a Swine Concentrated Animal Feeding Operation. *Environ. Sci. Technol.* 39(24):9649-9655
- Rylander, R., Essle, N., Donham K. (1990). Bronchial hyper-reactivity among pig and dairy farmers. *Am. J. Ind. Med.*, 17:66-69

- Staines, F., Forman, J. (1961) A Survey of Farmer's Lung. *J. Coll. Gen. Pract.*, 4:351
- Takai, H., Pedersen, S., Johnsen, J., Metz, J., Groot Koerkamp, P., Uenk, G., Short, J. (1998). Concentrations and emissions of airborne dust in livestock buildings in Northern Europe. *Journal of Agricultural Engineering Research*. 70(1):59-78
- Takai, H., Pedersen, S. (2000) A comparison study of different dust control methods in pig buildings. *Appl. Eng. Agric.*, 16:269-277
- UAS Inc (2013). Self-contained Shaker Dust Collectors.  
<http://www.uasinc.com/SDC.aspx>
- USDA (2008). Swine 2006 Part IV: Changes in the U.S. Pork Industry, 1990-2006. USDA-APHIS-VS, CEAH. Fort Collins, CO. #N520.1108  
[http://www.aphis.usda.gov/animal\\_health/nahms/swine/index.shtml](http://www.aphis.usda.gov/animal_health/nahms/swine/index.shtml)
- Zejda JE, Hurst TS, Barber EM, et al. (1993). Respiratory health status in swine producers using respiratory protective devices. *Am J Ind Med*. 23:743-750
- Zhu, J., Jacobson, L., Schmidt, D., Nicolai, R. (2000). Daily variations in odor and gas emissions from animal facilities. *Applied Engineering in Agriculture*. 16(2):153-158