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A STUDY OF THE RESPONSE OF TWO AEROSOL PHOTOMETERS WHEN ASSESSING ORGANIC AND INORGANIC DUST CONCENTRATIONS RELATIVE TO STANDARD GRAVIMETRIC METHODS

by

Jeremy Michael Slagley

A thesis submitted in partial fulfillment
of the requirements for the Master of
Science degree in Preventive Medicine and Environmental Health
(Industrial Hygiene) in the Graduate College of
The University of Iowa

May 2000

Thesis supervisor: Assistant Professor Patrick T. O'Shaughnessy

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CERTIFICATE OF APPROVAL

MASTER'S THESIS

This is to certify that the Master's thesis of

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has been approved by the Examining Committee
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To the mother of us all, the Blessed Virgin Mary. May we all follow the example of her Immaculate Heart in our journey to see her beloved son.

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ABSTRACT

The purpose of this project was to determine the utility of direct reading aerosol photometers for organic dust environments. The study compared the response of two photometers to organic vs. inorganic dust. The results could be explained by the photometer theory to determine the most important aspects of photometric dust exposure assessment in agriculture.

The MiniRAM and the HAM were exposed to organic corn grain dust for 16 trials over a range of concentrations. The experiments were repeated using inorganic Arizona Road Dust. Gravimetric total and respirable dust samples were taken, along with personal cascade impactor data. Least squares regression provided models for using photometric readings to predict gravimetric measurements. Using the HAM to predict total dust, the response was not different between the two dusts ($p=0.7834$). For all others (HAM for Respirable, MiniRAM for total and respirable), there was a significant difference in photometer response ($p=0.0001$, 0.0042, and 0.0001, respectively).

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CHAPTER I
INTRODUCTION

The potential health impact of organic dust exposure is staggering. The potentially exposed population of agricultural workers in the United States alone is more than five million. Greater than 80% of the populations of developing nations are also involved in agriculture and are likely exposed to organic dusts as well (Kline et al. 1998). Agricultural workers represent the single largest work group in the world, including planting, growing, harvesting, transporting, and storing crops; tending and feeding animals; and processing agricultural raw materials at grain facilities, livestock-processing facilities, etc. Airborne organic dust exposure is one of the ubiquitous hazards of the agricultural community (Jacobs 1994b). For a wide range of agricultural practices and related fields, organic dust exposure presents a risk for development of such illnesses as Organic Dust Toxic Syndrome (ODTS), hypersensitivity pneumonitis (farmer's lung), and chronic bronchitis (Zejda et al. 1993). Ramazzini noted the hazards of exposure to agricultural dusts in his classic work, *De Morbis Artificum* (Ramazzini 1713). In order to understand the hazards of organic dusts, as well as the inherent difficulties in organic dust exposure assessment, it is essential to understand the characteristics of organic dusts.

Organic Dust Characteristics

It must be understood that agricultural dusts in general contain both inorganic and organic components. However, most of the inorganic dusts in agriculture are little more

than nuisance dusts, save asbestos and silica as seen in parts of Eastern Europe. The biologically active component of agricultural dusts is the organic fraction. Organic dusts are derived from such diverse sources as animal dander and hair; feathers; urine and feces; insect parts; mites; and bits of plants, pollens, bacteria, endotoxins, fungal spores, and mycotoxins (Donham 1986a). However, in a different time, organic dust was barely worthy of note. Landis noted in 1919 that:

> Whether organic dust is of itself injurious is debatable. Certainly up to the present the evidence in favor of its causing chronic pathological changes in any way comparable to those produced by inorganic dust is not forthcoming...we can dismiss at once the question of injury to the respiratory tract as the result of the inhalation of organic material. (Landis 1919)

Organic and inorganic dusts differ considerably. Organics tend to be larger in diameter, more hygroscopic, more frequently charged, and extremely irregular in size and shape compared with inorganics. One of the widespread organic dusts of interest is grain dust. The actual grain dust to which workers are exposed is a mixture of approximately 25% to 40% organic and 60% to 75% inorganic materials (Yoshida et al. 1980). The NIOSH criteria document for grain dust combined several studies to determine this general percent composition of grain dust, as well as lists of components derived from various studies (Brown 1988). Grain dust components are similar to other agricultural dusts. Components include pieces of grains and seeds of the type depending on the crops involved in the task. At a farm predominantly growing corn and wheat, one would expect to find those grain pieces in the dust. In a terminal grain elevator that serves a large area and may take different crops, one might find a whole host of different grain particles.

Since Iowa is the number one corn- and soybean-producing state in the U.S., corn and soybean grain dusts are of special interest. Grain dust contains many different materials including animal hair, feathers, and excreta as well as insect parts (Becklake 1980). Microorganisms play an important role in grain dust diseases such as bronchitis and organic dust toxic syndrome (Von Essen et al. 1997). The type of microorganisms present varies widely depending on growing conditions, season, geography, water content, temperature, grain type, and storage practices. Some organisms take up residence with the grain in the field, while others invade during storage (Brown 1988). Fungi such as *Cladosporium, Alternaria,* and *Ustilago* abound in the dust in the field. Stored grain exhibits higher concentrations of *Aspergillus and Penicillium.* Along with these microorganisms come the associated mycotoxins, endotoxins, and glucans (do Pico 1994).

Organic dust exposure levels in agriculture can be exceedingly high. Any time grain is moved, there is significant dust created. Farant (1989) estimates 1 –2 kilograms of dust is produced per ton of grain. Although the main emission mechanism is grain striking a surface, such as during unloading or loading grain, Wallace cited EPA studies that consistently showed the highest average emissions at all size elevators occurred during cleaning operations (Wallace 1992). Total dust levels at grain elevators in the 1970's ranged from 0.04 to 781 milligrams per cubic meter (mg/m^3). These decreased to 0.59 to 9.73 mg/m^3 by 1985 (do Pico 1994). The main factors affecting dust concentrations in general around the elevator are ventilation systems; housekeeping; humidity; and amount, age, cleanliness, and manipulation of the grain (Brown 1988).

The two main factors affecting dust emissions at the specific loading/unloading operations are local wind currents and the amount of dust generated by the striking of the grain.

A more recent and relevant estimate of exposure levels revealed a high concentration during such operations as silo uncapping of 10 to 20 mg/m^3, with 10^6 to 10^9 microbes/m^3 microbial content, and 10^3 to 10^5 endotoxin units (EU)/m^3 endotoxin content. More typical daily exposures were estimated at 2 to 9 mg/m^3 dust, 10^3 to 10^5 microbes/m^3, and 50 to 900 EU/m^3 endotoxin count (Von Essen et al. 1997). Given this wide range of constituents and the high level of exposures found in agriculture, the following adverse health effects of organic dust exposure are not surprising.

Health Effects

Grain dust specifically began to receive some necessary attention at the International Symposium on Grain Dust and Health in Saskatoon, Canada, in 1977 as published by Dosman and Cotton. Further attention was focused at the International Workshop on the Health Effects of Organic Dusts in the Farm Environment in Skokloster, Sweden, in 1985, as published by Rylander, Donham, and Peterson in the American Journal of Industrial Medicine (1986). The term "Organic Dust Toxic Syndrome" was coined to describe the specific toxic syndrome that can develop from acute high-level exposures to organic dusts. The workshop differentiated this syndrome from the less common hypersensitivity pneumonitis or "farmer's lung," which is an allergic illness (Donham et al. 1986b).

Respiratory diseases associated with organic dusts include the above ODTS and hypersensitivity pneumonitis, as well as chronic bronchitis, asthma, and rhinitis (Von Essen et al. 1997). Corn dust in particular has been shown to cause acute inflammation in the lower respiratory tract (Deetz et al. 1997). Epidemiological studies have associated dust exposures with these illnesses and other symptoms in millers, bakers, and other food manufacturers (Smith et al. 1999; Deacon et al. 1988). Manfreda et al. (1989) performed an epidemiological study investigating chronic respiratory disorders among a rural community. By comparing 1892 subjects grouped by farming status ("farmer," "used to farm," and "never farmed"), they looked at the association of illness with grain dust exposure. No significant difference was found between the chronic illness rates of the groups. Any rural person in the study was just as likely to be symptomatic, regardless of dust exposure, although smoking status was clearly associated with symptoms.

Grain-dust exposures have also been studied in Canadian dock workers (Dimich-Ward et al. 1995a&b), and grain-processing and animal feed industries (Post et al. 1998). Four different populations were studied in a pooled Canadian-Dutch grain dust study. A strange negative exposure response relationship was found which might be explained by a strong healthy worker effect (Peelen et al. 1996). All relevant epidemiological studies linking grain dust to health effects were reviewed by Fonn et al. (1994). An earlier review of epidemiological data studied the impact of grain dust on respiratory health and reported populations at risk, processes to handle grain, composition of grain dust, syndromes caused by grain dust, and current permissible concentrations (Chan-Yueng et al. 1992).

Of all the various components of grain dust, ranging from insect parts to grain to silica, one of the most important constituents for disease relation seems to be endotoxins. One study compared postal workers to grain workers and found that regardless of total dust concentrations, higher endotoxin concentrations were significantly associated with decreased airflow and increased bronchial reactivity (Schwartz et al. 1995). Given the range of adverse health effects and the large exposed population, it is of interest to accurately assess exposures to organic dusts.

Exposure Assessment

Useful organic dust exposure assessment includes both accurate measurement of the dust and comparison to science-based exposure limits.

Exposure Limits

Other countries have promulgated exposure limits for specific organic dusts (Jacobs 1994a). Exposure limits in the U.S. are promulgated by the Occupational Safety and Health Administration (OSHA), with recommendations from the National Institute for Occupational Safety and Health (NIOSH). OSHA's current Permissible Exposure Limit (PEL) for inhalable grain dust (oat, wheat, and barley) is 10 mg/m^3. Inhalable dust is the total dust with a cut-point of 100μm set for dusts that are hazardous when deposited anywhere in the respiratory tract. The cut-point is defined as the particle diameter where the collection method attains 50% collection efficiency. Particles smaller than the cut-point are collected more efficiently (>50% of the mass of the smaller particles is collected). Particles larger than the cut-point are collected with less efficiency.

The current NIOSH Recommended Exposure Limit (REL), which is not enforceable under law, is 4 mg/m^3 for inhalable grain dust (oat, wheat, and barley). The American Conference of Governmental Industrial Hygienists (ACGIH) is a group of professionals that recommend exposure limits that are not enforceable by law, but that are widely accepted and used in industry. The current ACGIH inhalable grain dust (oat, wheat, and barley) Threshold Limit Value (TLV) is 4 mg/m^3. These limits are set to prevent the critical effects of irritation, bronchitis, and pulmonary function deficit (ACGIH 1999; NIOSH 1997).

Prior to the establishment of the grain dust limit, hygienists would fall back to the nuisance dust limit, now referred to as "Particulates (insoluble) not otherwise classified (PNOC)" (Jacobs 1994a), also referred to as "Particulates not otherwise regulated (PNOR)" (NIOSH 1997). The current OSHA PEL for PNOR is 15 mg/m^3 total dust (analogous to inhalable dust), and 5 mg/m^3 respirable dust. NIOSH conducted a limited evaluation of the literature in 1988 and concluded that the documentation cited by OSHA was inadequate to support the PNOR PEL (NIOSH 1997). The 1999 PNOC limits from ACGIH, 10 mg/m^3 inhalable and 3 mg/m^3 respirable, were set to prevent adverse lung effects. Respirable dust is that fraction of the total dust with cut-point of 4μm that is hazardous when deposited in the gas exchange regions of the lungs. The PNOC limits are applicable only when the particulate in question contains no asbestos and less than 1% crystalline silica (ACGIH 1999).

There is also a proposed limit added in 1999 under consideration for inhalable flour dust of 0.5 mg/m^3. The flour dust proposal also notes its sensitizing capability. The

flour dust TLV was proposed to prevent the critical adverse effects of asthma, pulmonary function detriment, and bronchitis.

Also, grain dust may contain 8-18% silica (Brown 1988), with corresponding TLVs ranging between 0.1 and 10 mg/m^3, depending on the specific silica type. The OSHA PELs for silica depend on the percent silicon dioxide (SiO_2) in the specific dust collected and are calculated for total and respirable dust after collection and analysis. The NIOSH REL for total amorphous silica is 6 mg/m^3, and for respirable crystalline silica, 0.05 mg/m^3. The silica TLVs were set to control critical health effects ranging from pulmonary fibrosis and irritation, to pneumoconiosis and recurrent fever (ACGIH 1999). The crystalline silica REL adds the potential for lung cancer found in animal studies (NIOSH 1997).

There have also been proposals in the literature for specific organic dust limits. For swine production workers, recommendations were 2.5 mg/m^3 for total dust and 0.23 mg/m^3 for respirable dust. For poultry workers, recommendations were 2.4 mg/m^3 for total dust and 0.16 mg/m^3 for respirable dust (Donham et al. 1995; Reynolds et al. 1996; Donham et al. 2000). Awareness of all these limits is necessary to understand what field applications may be desired.

Measurement

From the beginning of the industrial hygiene profession, aerosol measurement was recognized as an important asset for assessment and control of workplace hazards. Henry Smyth (1919) reviewed available dust measurement techniques in the third issue of the Journal of Industrial Hygiene. He described the wide variety of methods available,

many involving settling onto syrup or vaseline-coated plates. He noted that all were flawed, but admired "Palmer's Apparatus." Palmer's Apparatus drew air through water for later analysis, the start of what is recognized as the standard gravimetric technique. Interestingly, Smyth also noted that Coleman devised a system to photograph particles in a beam of light and count the particles.

The most widely-accepted measurement technique is gravimetric. Both total and respirable dust techniques (NIOSH methods 0500 and 0600) are commonly used in organic dust assessment (Jacobs 1994a). The total dust method involves pulling a known volume of dusty air across a pre-weighed filter. The additional weight of the accumulated dust can then be interpreted in terms of mg/m^3. The respirable measurement technique uses a cyclone to precondition the incoming dust by removing larger particles. The cut-point particle diameter can be shifted based on flow rate through the system.

Real-time exposure assessment in agricultural settings can prove problematic. Traditional gravimetric techniques are the accepted standard but take expertise and time that limit the number of organic dust task characterizations that can be made. Photometric direct reading instruments have long been used for task exposure assessment as well as long-term aerosol monitoring. A useful scattered-light photometer named the "Owl" was developed during World War II for measuring particles from 0.1 to 2 μm. Several optical measurement techniques as well as other available techniques including multi-stage impactors were widespread by the mid 1970's (Cadle 1975). Most photometers are calibrated for the inorganic test standard dust, Arizona Road Dust (ARD).

Given the physical theory of light scattering by particles, the flux of light scattered by a single particle is given by $P_\lambda(d_p,\lambda,m)$, meaning that it depends on the individual particle diameter, d_p, the wavelength of the light, λ, and the refractive index of the particle, m. Integrating across the probability density function of the particle size distribution, $f(d_p)$, and multiplying by the number concentration (#/volume) of particles in the sensing volume of a photometer, c_n, will give the resultant flux of light collected by the detector of the photometer for the given particle cloud (Gebhart 1993):

$$R = c_n \int f(d_p) P_\lambda(d_p,\lambda,m) \mathrm{d}d_p. \qquad (1)$$

However, in order to correlate the flux of light for a number concentration of particles to a mass concentration of particles (mass/volume), the particle properties of density, refractive index, and size distribution must be fixed. Further, the relation of the instrument response to particle size must be such that the particle volume is predicted (roughly d_p^3).

However, from the photometer response of Equation (1), one sees that the only useful linear response will be where $R = c_n$ x *some constant*. $R = c_n$ x *constant* will only happen when the flux of scattered light $P_\lambda(d_p,\lambda,m)$ is a function of the volume of the particle. For a specific situation of scattering, $P_{\lambda s}(d_p,\lambda,m)$ can be defined:

$$P_{\lambda s}(d_p,\lambda,m) = P_\lambda(d_p,\lambda,m) / \rho_p (\pi/6) d_p^3. \qquad (2)$$

The flux of light scattered per unit mass concentration of aerosol is given in Equation (1). However, for the given situation where refractive index (m) and wavelength (λ) are fixed, the instrument varies relative to particle size. An example of such a fixed situation is given in Figure 1. for the HAM photometer and ARD dust. For micrometer size particles, where $d_p \geq 2$ μm, light scattering is a surface effect and the flux, $P_{\lambda s}$, decreases proportionally to d_p^{-1}. For particles with $d_p \leq 0.3$ μm, the specific scattering function increases proportional to d_p^3. For particles with $d_p \approx \lambda$ (HAM λ = 0.815 μm), there is a maximum for the function (Gebhart 1993). So that for particles between about 0.3 μm and 2 μm, flux is proportional to d_p^3, or volume. Therefore, knowing the density of the particles, one can correlate flux to mass within the sensing volume and compute mass concentration in mg/m^3.

Therefore, photometer accuracy is a function of how the measured dust differs in size distribution and density compared with that of the dust originally used to calibrate the instrument by the factory. Furthermore, as shown in Figure 1, dusts with a large mass median aerodynamic diameter (MMAD) will indicate a much lower response than those with MMAD's near 1 μm for the same concentration level.

Schaller and Nicholson (1980) addressed the importance of particle size determination as well as concentration measurement for grain dust assessment. Particle size determines what areas of the lungs with which the aerosol will interact. Yoshida and Maybank's (1980) description of grain dust characteristics illustrated some of the problems with photometric measurement of grain dust. They reported that diameters of individual particles could reach a maximum range from 60 to 110 μm, well beyond the

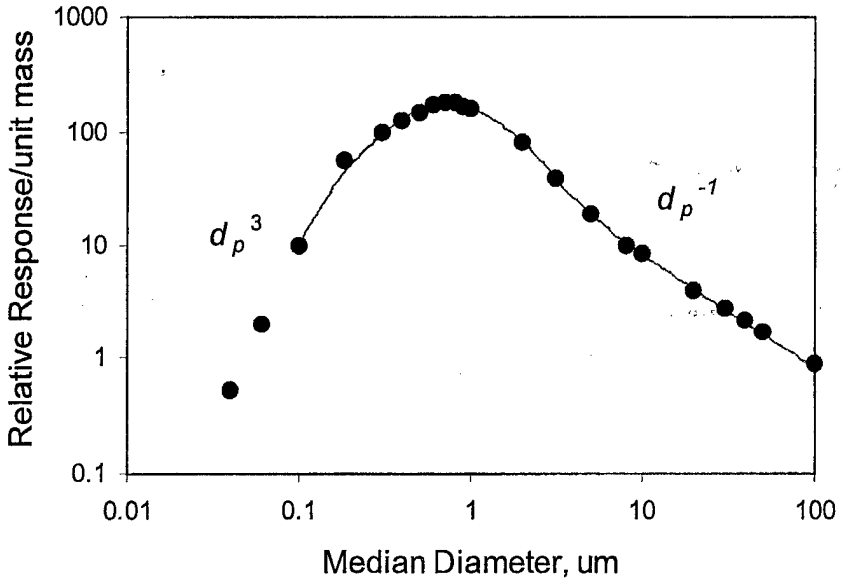


Figure 1. HAM Response Relative to Gravimetric as a Function of Particle Median Diameter

preferential measurement range of most commercially available photometers. However, MMAD's for grain elevator dusts ranged from 3-8.5 μm.

Martin et al. (1985) tested a light attenuation system for grain dust measurement. Light attenuation involves measuring the amount of light passing through a transparent medium before and after being loaded with dust. Rajendran and Stockham (1985) evaluated several existing instruments for grain dust measurement and noted the light-scattering ORNL probe was worthy of further development. Vinzents (1996) developed an interesting passive dust monitor using a technique where dust attaches to a sticky tape which is then quantified by light extinction. This method has not yet been made commercially available.

The Real-time Aerosol Monitor (RAM-1, MIE Inc, Bedford, Mass.), developed for the Bureau of Mines, was tested by Page and Jankowski (1984). They correlated the RAM-1 to respirable dust measurements of coal dust with a MMAD of 8.5 μm at different positions along the longwall shearer face in a coal mine. The average ratio of RAM-1/Respirable dust was 0.53 for the intake area and 0.75 at the midpoint of the longwall shearer face. They noted how it is generally accepted that the RAM-1 response was highly dependent on the particle size distribution.

Glinsman and Rosenthal (1985) reported the inverse of this ratio (gravimetric/photometer) when they evaluated an aerosol photometer (P-5H Digital Dust Indicator®, Sibata) for monitoring welding fume levels in a shipyard. They noted that the photometer seemed unreliable for their purposes due to the nature of the welding fumes, but was good at noting peak levels. Welding fumes typically vary in refractive index and

particle size enough that the theoretical difference between maximum and minimum ratios could be up to a factor of 30. The researchers actually found a difference in experimental maximum to minimum ratios of 31. Since the ratios varied so much for the same fumes, determining accurate gravimetric results with the photometer was difficult.

Smith et al. (1987) evaluated the response of several light-scattering photometers using coal dust. They noted that the ATI-722, RAM-S, and PCAM-TX were all highly dependent on particle size because of the change in light scattering for different particle sizes. Cheng et al. (1988) also evaluated the RAM-S, but specifically for inhalation studies. They noted that it was useful for monitoring so long as its readings were correlated with gravimetric analysis. Similarly, Armbruster (1987) noted that two photometers predicting respirable dust were so dependent on particle size distribution that no general conversion factor could be given.

Recently, Middendorf et al. (1999) evaluated the MiniRAM model PDM-3 in different configurations for monitoring coal dust. They also performed a field calibration for gravimetric total and respirable coal dust. They reported very specific but somewhat complicated calibration equations for the MiniRAM using the SAS Covariance Analysis of Linear Structural Equations (CALIS) procedure (SAS Institute, Knoxville, Tenn.), which expresses relations among several variables. The researchers stated that usual least squares regression analysis was inappropriate for this type of model because both the independent (gravimetric dust measurement) and dependent (photometric dust measurement) variables are measured with some associated error. They used the SAS CALIS procedure to account for variability in both the predictor and the predicted

variables. However, the assumption that the gravimetric method can be considered without error has been made when applying this method of analysis (least squares regression) in publications for some time. (Glinsman et al. 1985; Page et al. 1984; Smith et al. 1987).

Taylor (1996) evaluated MiniRAM and gravimetric response in swine confinement buildings in 1996. The study revealed a high correlation between MiniRAM and total dust (r=0.903), but recommended further study, especially focused on respirable dust where photometers respond better. Overall there has been limited research in photometric measurement of organic dusts.

Exposure Chambers

As dust exposure assessment research took form and development advanced over the years, dust exposure chambers were developed early on to assess toxicology in laboratory animals. Deichmann (1944) developed a "Dust Shaker" to create controlled dust concentrations for study during World War II.

The Symposium on Aerosol Generation and Exposure Facilities in Honolulu in 1979 brought together the international community interested in this type of exposure experimentation (Willeke 1980). Recent exposure chamber ideas include the Heitbrink et al. (1992) free-falling powder experiments. The investigators found that the trap door to release the powder had too great an impact on the particle size distribution of the resultant aerosol.

Controlling the concentration inside the exposure chamber is key to assessments as Deichmann noted. Davis and Irwin (1982) used a light extinction (opacity monitor)

feedback device to achieve stable concentrations of several organic dusts, including ARD. Hirano (1987) used a photoionization detector (PID) to regulate sulfuric acid mist concentrations in an animal exposure chamber.

O'Shaughnessy and Hemenway (1994) developed a computer-regulated, dry-dust exposure system. They used a Handheld Aerosol Monitor (HAM) photometer feeding to a computer that controlled a dust-cake scraper (Wright Dust Feed, BGI Inc., Waltham, Mass.) dust-generation system in order to maintain a constant aerosol concentration in an exposure chamber.

Although most of the aerosol exposure systems do not deal with organic dust exposures, Volckens et al. (1998) did use an acoustical dust generation system to generate inspirable grain dust from oats.

Objectives

The following chapter summarizes a study undertaken to compare the response of two light-scattering photometers to organic versus inorganic dusts, as compared with gravimetric measurements. The project was executed for the purpose of determining the utility of photometers for agricultural applications in general while considering the inherent differences in the two types of dust and attempting to control for, or describe, the differences.

The first objective of the study was to determine whetehr the photometers responded differently to the two dust types. The second objective was to determine calibration equations for organic dust measurement for the photometers.

CHAPTER II

PHOTOMETER COMPARISON

Project Overview

Agriculture is the single leading field of employment for the world's population (Kline et al. 1998). One of the ubiquitous hazards in agriculture is airborne agricultural dust (Jacobs 1994a). Agricultural dust is made up of inorganic and organic components. The organic component has sources as diverse as animal hair and dander, feces, insect parts, plant pieces and pollen, grain pieces, fungal spores, mycotoxins, bacteria, and endotoxins (Donham 1986a). Occupational exposure via inhalation to organic dusts has been associated with illness such as Organic Dust Toxic Syndrome (ODTS), chronic bronchitis, asthma, a non-allergic asthma-like condition, mucous membrane irritation, and hypersensitivity pneumonitis (HP) (Zejda et al. 1993; Von Essen et al. 1997; Smith et al. 1999; Deacon et al. 1988, Dimich-Ward et al. 1995a&b; Post et al. 1988; Schwartz et al. 1995). Total organic dust exposures of 10 to 20 mg/m^3 have been found during silo uncapping, and 2 to 9 mg/m^3 during normal operations (Von Essen et al. 1997). Most organic dust monitoring was done with the standard gravimetric techniques of total and respirable dust measurement (Jacobs 1994a).

Photometers have long been used for aerosol monitoring of airborne dust in industry (Cadle 1975). They have typically been used for coal and inorganic dusts such as silica, welding fumes, nickel sulfate hexahydrate, nickel oxide, nickel subsulfide, and

azodicarbonamide (Page et al. 1984; Glinsman et al. 1985; Smith et al. 1987; Cheng et al. 1988; Armbruster 1987; Middendorf et al. 1999). The benefits of real-time monitoring with photometers may be desirable in the agricultural health community (Taylor 1996), but due to the differences in inorganic versus organic dusts (photometers are calibrated using the inorganic standard Arizona Road Dust - ARD), photometers should be validated on organic dusts before use (Schaller et al. 1980; Yoshida et al. 1980).

Photometer response between different aerosols is a function of the refractive index, m, particle size, d_p, and the particle density, ρ_p (Gebhart 1993). The particle size for most aerosols is polydisperse, meaning it is made up of a distribution of particle sizes. This distribution is described by the mass median aerodynamic diameter (MMAD) and the geometric standard deviation (GSD). Organic dusts are typically larger in diameter and more hygroscopic than inorganic dusts. The differences between organic dusts and inorganic dusts would suggest that there is a substantial difference in how photometers would predict the gravimetric concentrations of the two dusts. Many researchers have developed correction factors for specific dusts. Page et al. (1984) used Photometer/Gravimetric while Glinsman et al. (1985) used Gravimetric/Photometer. The current study used the correction factor of Photometer/Gravimetric.

The purpose of this project was to examine the accuracy of two different photometers when measuring a standardized organic corn grain dust (CGD) versus the inorganic test standard ARD, compared with side-by-side gravimetric sampling methods. Additionally, an algorithm was sought to increase the accuracy of the photometers for

the CGD. The experiment was designed to control as many factors as possible, with consideration of field applicability of the potential results.

Materials and Methods

The two photometers selected for the study, the Handheld Aerosol Monitor (HAM) model 1060 (PPM Inc., Knoxville, Tenn.) and the Miniature Real-time Aerosol Monitor (MiniRAM) model PDM-3 (MIE Inc., Bedford, Mass.) were both factory calibrated by the manufacturers using ARD. The mathematical relationships between photometer response and gravimetric measurements are based on the ARD-gravimetric associations and programmed into the integrated circuitry of each instrument.

Chamber Set-up and Trial Procedures

The photometers were placed (over-and-under) on a wire stand in a dynamic dust chamber along with gravimetric samplers (Figure 2). There were two closed-face 37-millimeter total dust samplers (SKC, Eighty-four, Penn.) with 0.8 μm Metricel® membrane filters (Gelman Sciences, Ann Arbor, Mich.) and two aluminum cyclone 37-mm respirable dust samplers (SKC, Eighty-four, Penn.). The gravimetric sampling trains were supplied with negative pressure from two high-volume sampling pumps (Emerson, St. Louis, MO) through plastic tubing containing critical orifices. This system provided constant flow rates for the sampling. The total dust sampling was conducted at 2.0 liters per minute (lpm), and the respirable dust sampling was conducted at 2.5 lpm, as prescribed by the National Institute of Occupational Safety and Health's (NIOSH) analytical methods 0500 and 0600, respectively (Clere et al. 1994; Bartley 1994).

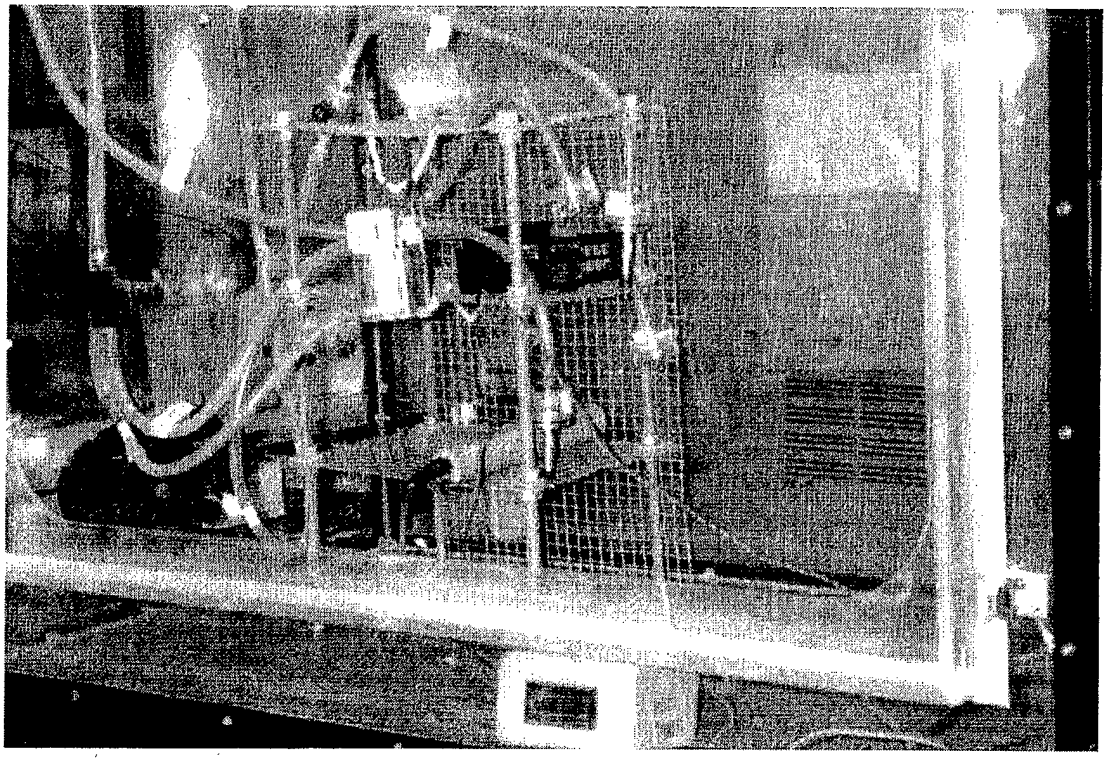


Figure 2. Exposure Chamber

Sample flow rates were determined using a primary standard Gilibrator bubble meter (Gilian Instrument Corp., West Caldwell, N.J.) pre- and post-trial. The MMAD was determined by an eight-stage personal cascade impactor (Andersen, Smyrna, GA) operated at 2.0 lpm also via critical orifice.

A 0.6 m^3 chamber constructed of plexiglass with a side air inlet and top exhaust was used for this research. A flow rate of 136 lpm was maintained through the chamber for all trials. Dust was delivered to the inlet air stream via a Wright Dust Feed (BGI Inc., Waltham, Mass.). A fan in the back right top corner of the chamber aided in mixing of the aerosol. Generator output rate was theoretically determined by mathematical formula, considering air flow through the chamber, total volume of the chamber, dust packing density, and dust feed settings of rotations per minute (rpm). These settings were then verified by trials at different dust feed rpm. The gravimetric data and photometer data were then used to estimate dust feed rpm settings for achieving four different concentration levels, 0-2.5, 5, 10, and 20 mg/m^3 for both dust types. There were four trials at each concentration level. The order of the concentration levels was determined by a random number generator. Trial duration was dictated by chamber concentration and maximum loading specifications for the gravimetric analysis.

The HAM was cleaned with 1, 1, 1, 2 tetrafluoroethane (Super Friendly Air'it™, Control Co., Houston, TX), zeroed with clean air passed through a high efficiency particulate air (HEPA) filter, and calibrated before each use with a sensing element inserted into the view-volume of the photometer that gave a constant reading. Readings before and after correction was recorded.

The MiniRAM was also cleaned with 1, 1, 1, 2 tetrafluoroethane. If it would not zero, the detection chamber was carefully washed and rinsed with deionized water, dried, and the instrument re-zeroed. The MiniRAM was then verified against its standard sensing element check source. If the response deviated more than 10% from the expected reading, the instrument was recalibrated and re-zeroed, then rechecked.

Photometer real-time output was sent to an analog-to-digital converter and recorded in a personal computer. This method of microcomputer control of exposure chambers was developed by O'Shaughnessy et al. (1994). Samples were taken every second for the HAM and every five seconds for the MiniRAM over the duration of the trial and stored in a data file. A spreadsheet was then used to compute the time-weighted average concentrations recorded by each photometer. This average was used for comparison with gravimetric samples taken over the same time period. Initially this comparison was made by computing the ratio of Photometric (HAM or MiniRAM)/Gravimetric (total or respirable dust). Typical photometer output data for organic and inorganic trials show the minimal response difference between the photometers (Figure 3).

For the specific instruments used, the following parameters in Table 1 are important for data analysis (PPM Inc. 1983; MIE Inc. 1984). The three factors that will affect how a photometer predicts dust concentration are refractive index, m, particle size, d_p, and the particle density, ρ_p. Particle size for distributions of particles is given as MMAD. Table 2 below gives the relative values of the two dusts used in this experiment (MIE Inc. 1984; McCrone et al. 1973). In order to best analyze the differences in how

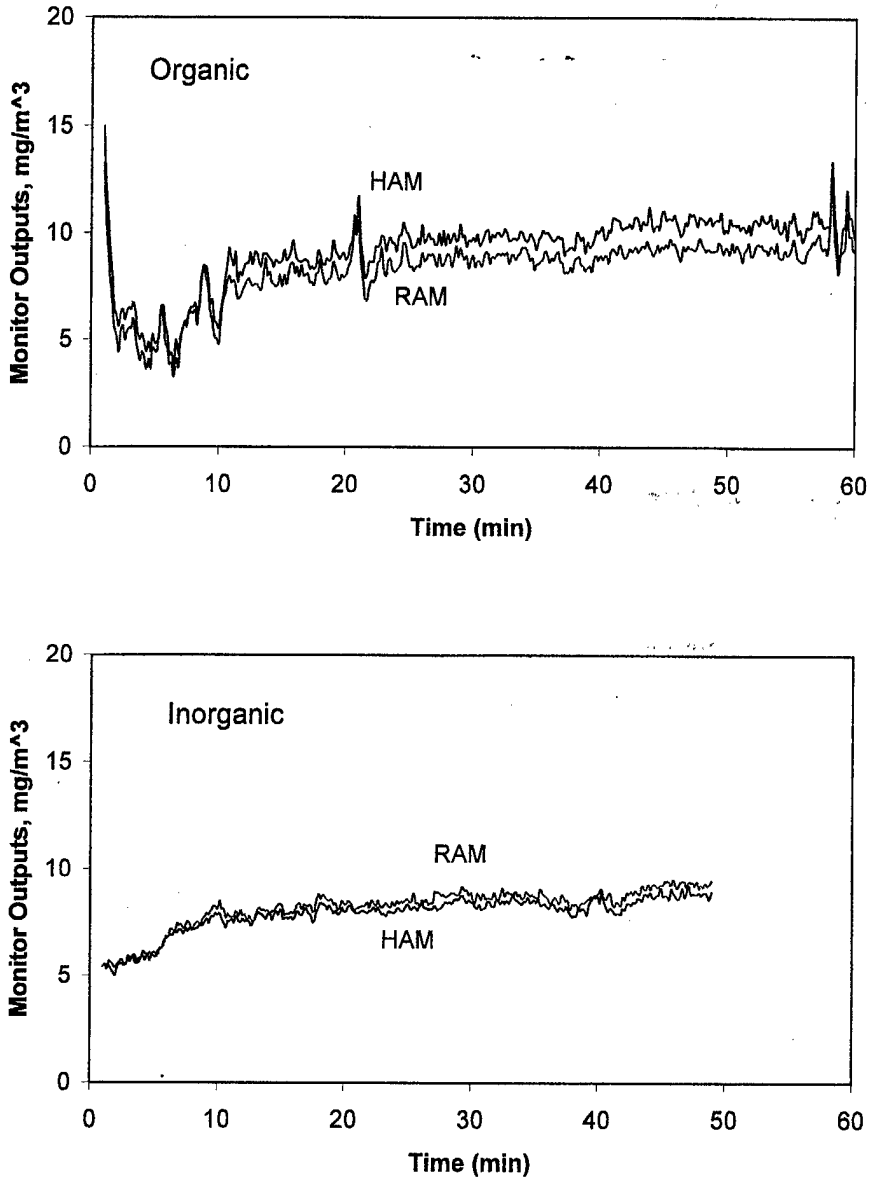


Figure 3. Typical Real-time Photometer Response for the Two Dust Types

Table 1. Photometer Specifications

Parameter	HAM, model 1060	MiniRAM, model PDM-3
Source light wavelength, λ	0.815 μm	0.880 μm
Calibration dust	ARD fine test dust with adjusted density factor	ARD fine test dust
Calibration density, ρ_p	1.5 g/cc	2.6 g/cc
Calibration MMAD	0.3 – 1.6 μm	2.0 μm
Refractive index, m	1.5-j0	1.5-0i
Angle of scatter, θ	5 - 15°	45 - 90°
Estimated accuracy to unknown dusts	± 25% for particles 0.3-2.0 μm	± 28% for particles 0.25-2.5 μm
Preferential weighting d_p range	0.5 – 10 μm	0.1 – 10 μm

Table 2. Experimental Dust Physical Characteristics

Characteristic	ARD (inorganic)	CGD (organic)
Density (ρ_p)	2.65 g/cc	1.4 g/cc
Particle size distribution	Mean MMAD = 8.02 μm Mean GSD = 2.90	Mean MMAD = 11.19 μm Mean GSD = 2.76
Refractive index (m)	1.5	1.53

the instruments respond to organic versus inorganic dust (the main point of the experiment), one can use the information in Table 2 to predict how each instrument would respond differently given each characteristic.

Since the refractive indices of the two dusts were approximately equal, there should be little difference in how the instruments respond given this variable. The important differences lie in the different densities and particle size distributions. The apparent best method to analyze dust response difference was to look at each instrument separately.

Experimental Dusts

Four sets of CGD trials were performed at four levels of dust concentration. The trials were performed in random order (via random number generator) of concentration levels, 5, 10, 2.5, then 20 mg/m^3. Four trials in each concentration group were performed. A final set of four trials was performed by first running the CGD through a cyclone before entering the chamber to achieve a lower MMAD and concentration near 5 mg/m^3.

The CGD was sieved through a number 10 sieve, then 1 g was ground to increase uniformity in a ball mill (Retsch, Haan, Germany) for 10 minutes. The resulting dust was then run through a 40 mesh sieve mounted on a dental shaker. The final product was loaded into the Wright Dust Feed with rod and hammer. All CGD trials were completed before starting the next dust.

Next, after the chamber and all components were meticulously cleaned, trials with titanium dioxide were begun as the inorganic dust source. The titanium dioxide was

troublesome to use and very sticky, so International Standards Organization (ISO) medium and fine test dust, ARD, was procured (Powder Technology Inc., Burnsville, Minn.) as the inorganic dust. The medium dust was chosen to better match the particle size distribution of the CGD. The fine dust was used for the final four alternate MMAD trials. The inorganic trials were performed in random order of concentrations 2.5, 10, 20, then 5 mg/m^3. The four alternate MMAD trials had an average concentration of 21.29 mg/m^3, which would be classified in the 20 mg/m^3 range. The ARD was loaded into the dust feed in the same manner, via rod and hammer.

Conduct of Trials

Each trial consisted of two photometers, two total dust and two respirable dust gravimetric samplers, and a personal cascade impactor. The impactor was used to characterize the particle size distribution for each trial.

Before each trial, the air and dust supply and exhaust were turned on and allowed to stabilize. Air supply flow of the Wright Dust Feed, exhaust flow of the chamber, pressure reading within the chamber, and temperature and humidity were recorded before activating the photometer logging and gravimetric sampling pumps. All samplers were manually activated outside the chamber simultaneously and the corresponding time of photometer recording noted.

After each trial, the gravimetric samplers were turned off at the same time and the photometer log time noted to limit photometer data to the actual on-time of the pumps. The chamber air and dust supply was then turned off and the exhaust was allowed to keep running to remove a majority of the dust. After some time for dust clearing, the

researcher donned an N-95 respirator (model 8210, Minnesota Mining and Manufacturing, St. Paul, Minn.) and opened the chamber to remove the gravimetric samplers very carefully. The samples were then taken to the adjoining weigh room to equilibrate for 24 hours before weighing.

The photometers were then cleaned and the chamber bottom vacuumed to remove the settled dust. Dust adhering to the walls of the chamber was left until dust types were changed in order to minimize dust loss to the sides of the chamber on each run.

Weigh Room Procedures

The weigh room was located in the adjacent laboratory with the same air supply system as the chamber. This minimized differences in filter conditions between sample chamber and weigh room. Before each trial, all sample cassettes and cyclones were meticulously cleaned. The membrane filters were pre-weighed on a Mettler microbalance (MT 5, Mettler Instruments Corp., Hightstown, N.J.). Three field blanks and three laboratory blanks were used to correct filter weights for the membrane filters. Field blanks were subject to field conditions (i.e. being taken to the next room). Laboratory blanks stayed in the weigh room unsealed but covered. The cascade impactor stainless steel substrates (SEC-290-SS, Andersen, Smyrna, GA) were cleaned with acetone, dried, and sprayed as prescribed with silicone spray (316 Silicone Release Spray, Dow Corning Corp., Midland, MI) to aid in particle adhesion. There were two stainless steel substrate blanks prepared identically, as well as three 35-mm backup filter blanks (SEF-290-P5, Andersen, Smyrna, GA) to correct the weights of the substrates and final stage backup filter, respectively. All filters and plates were statically grounded

using a 500 microCurie (μCi) Polonium-210 source (Staticmaster® 2U500, NRD Inc., Grand Island, N.Y.).

Quality control in the lab was done as required in the NIOSH methods. At least 10% of each type of substrate was reweighed to verify scale precision. Weigh room temperature and humidity were recorded. Each type of substrate was weighed in one concurrent session to minimize laboratory error. All weighing was performed by the same technician to minimize individual interpretation error.

During data interpretation, blank corrections were averaged for each type of substrate and subtracted from readings. Limits of detection (LOD) were determined by the mean of the blank corrections plus three standard deviations (Dietrich 1997). Any gravimetric dust weights below the LOD were thrown out. If insufficient data remained for a particular trial, the entire trial was thrown out and repeated.

Randomization Procedures

In order to curtail systemic bias in the experiments, the order of concentration level trials was randomized. Further, the placement of the samplers on the wire stand shelves within the chamber was also randomized in order to reduce bias. Before the experiments commenced, a trial was conducted with six total dust gravimetric samplers; two placed side-by-side on each of the three upper shelves of the stand. The difference between the average total dust measurements (5.13, 5.83, and 6.19 mg/m^3 for shelves 1, 2, and 3, respectively) at the three different shelves was not statistically significant ($p=0.210$). In order to confirm particle distribution, an Aerosol Particle Sizer (model 3310, TSI, St. Paul, Minn.) was used during the trial to count particles and determine size

distributions at the different shelf locations. There was no significant difference in particle size distribution or particle count between the shelves ($p=0.757$ and $p=0.964$, respectively). The average mass median diameter (MMD) readings for the shelves in order were 8.73, 8.94, and 8.09 μm. The mean particle counts for the shelves in order were 33619, 35618, and 29816 particles.

Even with the chamber characterization satisfactory for complete mixing, the placement on the shelves was still randomized because of the apparent trend for higher gravimetric readings on successively lower shelves. Also, instrument placement was restricted to the second and third shelves, since they had the closest readings.

Results

All data were carefully compiled in concentration groups. Tables 3 and 4 contain a summary of the data for all concentration levels with a simple ratio, photometer reading (either HAM or MiniRAM) divided by gravimetric concentration (either Total or Respirable dust), given to compare gravimetric and photometric results.

The variance of all the MiniRAM/Total ratios was 0.01 versus 0.17 for the HAM/Total ratios. The variances of the two ratios were not equal ($p<0.0001$). The means of all organic and inorganic HAM/Total ratios were not significantly different ($p=0.8488$), with 0.67±0.37 (mean±standard deviation) for organic and 0.64±0.47 for inorganic. The means of all organic and inorganic MiniRAM/Total ratios were also not significantly different ($p=0.1738$), with 0.42±0.09 for organic and 0.47±0.11 for inorganic. There is not a significant difference in how the instruments relate to

gravimetric measurements between the organic and inorganic dust types, but the significantly lower variances for the MiniRAM ratios reveal its higher precision.

Table 3. Total Dust Measurement Data (mg/m^3±std. dev.) Relative to Photometer Measurement

ORGANIC DUST				INORGANIC DUST		
Target Level	HAM[1]	Total Dust[2]	Ratio	HAM[1]	Total Dust[2]	Ratio
2.5	0.79±0.09	0.68±0.19	1.21±0.32	0.98±0.19	1.12±0.58	1.17±0.78
5	2.06±0.20	3.51±0.50	0.60±0.09	2.01±0.11	3.94±0.24	0.51±0.01
10	4.10±0.61	9.35±1.52	0.44±0.01	3.69±0.64	8.07±1.51	0.46±0.01
20	9.79±0.47	23.67±2.02	0.42±0.04	8.11±0.77	19.94±1.16	0.41±0.02
Target Level	MiniRAM[3]	Total Dust[2]	Ratio	MiniRAM[3]	Total Dust[2]	Ratio
2.5	0.30±0.13	0.68±0.19	0.43±0.18	0.58±0.33	1.12±0.58	0.55±0.21
5	1.57±0.24	3.51±0.50	0.45±0.07	1.80±0.13	3.94±0.24	0.46±0.01
10	3.93±0.73	9.35±1.52	0.42±0.02	3.67±0.76	8.07±1.51	0.45±0.02
20	8.92±0.43	23.67±2.02	0.38±0.03	8.30±0.65	19.94±1.16	0.42±0.01

[1] Handheld Aerosol Monitor
[2] Measured gravimetrically
[3] Miniature Real-time Aerosol Monitor

The variance of all the MiniRAM/Respirable ratios was 0.58 versus 4.24 for the HAM/Respirable ratios. The variances of the two ratios were not equal ($p<0.0001$). The means of all organic and inorganic HAM/Respirable ratios were significantly different ($p=0.0001$), with 4.12±1.74 for organic and 2.46±2.07 for inorganic. The means of all organic and inorganic MiniRAM/Respirable ratios were also significantly different ($p=0.0198$), with 2.75±0.74 for organic and 1.77±0.35 for inorganic. This reveals the significant difference in how both instruments relate to gravimetric respirable

measurements between the organic and inorganic dust types. The significantly lower variance for the MiniRAM ratio reveals its higher precision.

Table 4. Respirable Dust Measurement Data (mg/m^3±std. dev.) Relative to Photometer Measurement

ORGANIC DUST				INORGANIC DUST		
Target Level	HAM[1]	Respirable Dust[2]	Ratio	HAM[1]	Respirable Dust[2]	Ratio
2.5	0.79±0.09	0.12±0.04	6.77±1.38	0.98±0.19	0.30±0.16	4.64±3.59
5	2.06±0.20	0.56±0.07	3.70±0.40	2.01±0.11	1.12±0.09	1.81±0.17
10	4.10±0.61	1.44±0.25	2.87±0.24	3.69±0.64	2.15±0.48	1.73±0.14
20	9.79±0.47	3.12±0.29	3.16±0.28	8.11±0.77	4.91±0.46	1.65±0.07
Target Level	MiniRAM[3]	Respirable Dust[2]	Ratio	MiniRAM[3]	Respirable Dust[2]	Ratio
2.5	0.30±0.13	0.12±0.04	2.61±1.59	0.58±0.33	0.30±0.16	2.04±0.66
5	1.57±0.24	0.56±0.07	2.79±0.26	1.80±0.13	1.12±0.09	1.62±0.19
10	3.93±0.73	1.44±0.25	2.74±0.23	3.67±0.76	2.15±0.48	1.71±0.11
20	8.92±0.43	3.12±0.29	2.88±0.21	8.30±0.65	4.91±0.46	1.69±0.07

[1] Handheld Aerosol Monitor
[2] Measured gravimetrically
[3] Miniature Real-time Aerosol Monitor

Statistical Analysis

The data were assumed to be independent based on the fact that each trial was performed separately, there was only one person performing the trials, the chamber was vacuumed in between trials, and the order of trials was randomized. The only variables that may have hampered independence were temperature and humidity during the trials. Temperature and humidity in the laboratory were controlled, however, and should not have had an effect on independence.

The statistical software package SAS (SAS Institute, Knoxville, Tenn.) was used to determine any significant interactions in the data variables of dust-type, MMAD, gravimetric measurement, and photometer reading. The only significant interaction found was the type of dust (organic or inorganic) multiplied by the gravimetric measurement. The SAS general linear models procedure, proc GLM, was used with the variables of dust type, gravimetric measurement, and the interaction term of dust-type multiplied by gravimetric measurement. The general equation for the least squares regression model became:

$$I = \beta_0 + \beta_1(T) + \beta_2 (G) + \beta_3(T*G) + E \qquad (3)$$

where:

I = instrument response (HAM or MiniRAM), mg/m^3

T = dichotomous type of dust where organic = 0 and inorganic = 1

G = gravimetric measurement (Total or Respirable), mg/m^3

T*G = interaction term of T multiplied by G which will be 0 for organic

β_0 = intercept estimate

β_{1-3} = parameter estimates

E = error.

The resultant models described the error in the data well with high adjusted R^2. The R^2 was adjusted because there were three predictor variables in the model which always increase R^2, and may lead to false conclusions about the appropriateness of

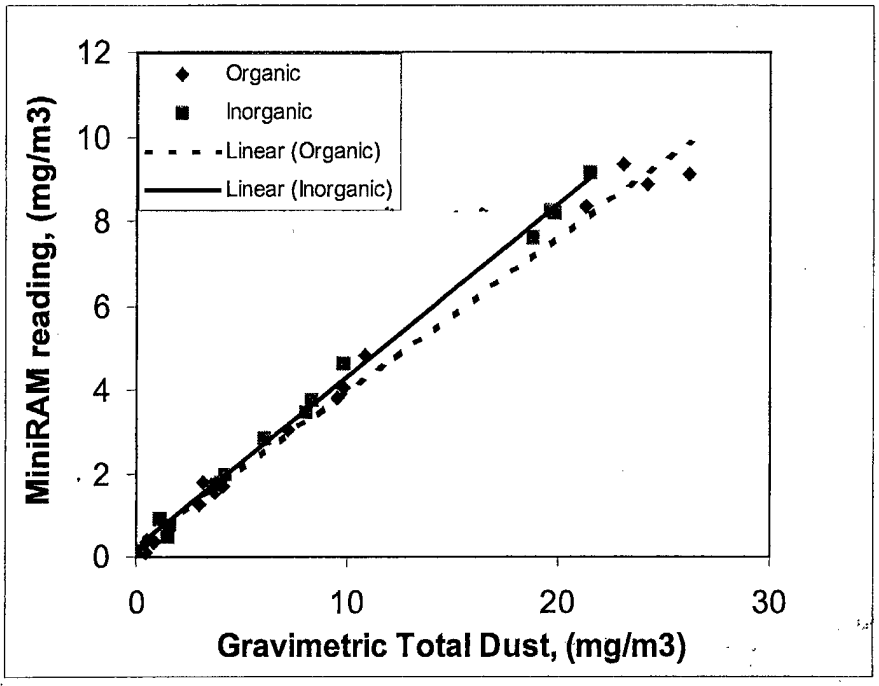
models. All interaction terms except for the HAM / Gravimetric total dust regression were significant as shown in Table 5:

Table 5. Significance of Interaction Terms and Adjusted R^2 of Regression Models

Instrument	Total dust		Respirable dust	
	p-value	Adj. R^2	p-value	Adj. R^2
MiniRAM	0.0042	0.9916	0.0001	0.9907
HAM	0.7834	0.9898	0.0001	0.9841

Scatter plots were generated to visually display differences in regression line slopes for each of the four situations. The scatter plots for MiniRAM vs. Total dust (Figure 4a), MiniRAM vs. Respirable dust (Figure 4b), and HAM vs. Respirable dust (Figure 5b) had significantly different regression line slopes between organic and inorganic dusts ($p=0.0001$, $p=0.0042$, and $p=0.0001$, respectively). The scatter plot for HAM vs. Total dust (Figure 5a) did not have a significant difference between regression line slopes for the two dusts ($p=0.7834$).

Given the model which adjusts for dust type and includes interaction between dust type and gravimetric measurement, the MiniRAM and HAM both correlated well to total dust measurements with Pearson correlation coefficients of $r=0.9937$ and $r=0.9953$, respectively. The MiniRAM and HAM correlated with respirable dust concentrations resulted in Pearson correlation coefficients of $r=0.9252$ and $r=0.8881$, respectively.



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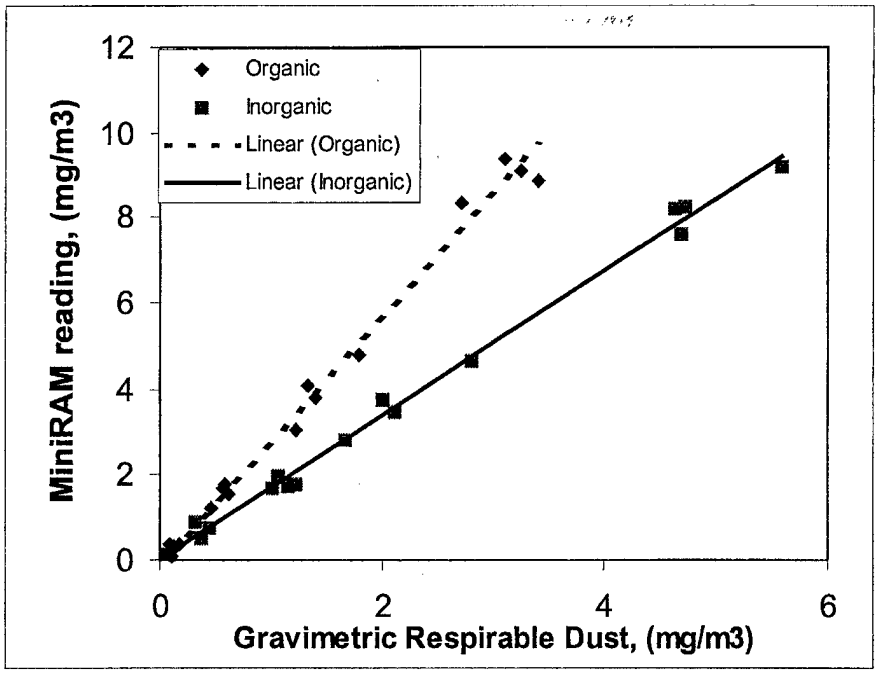

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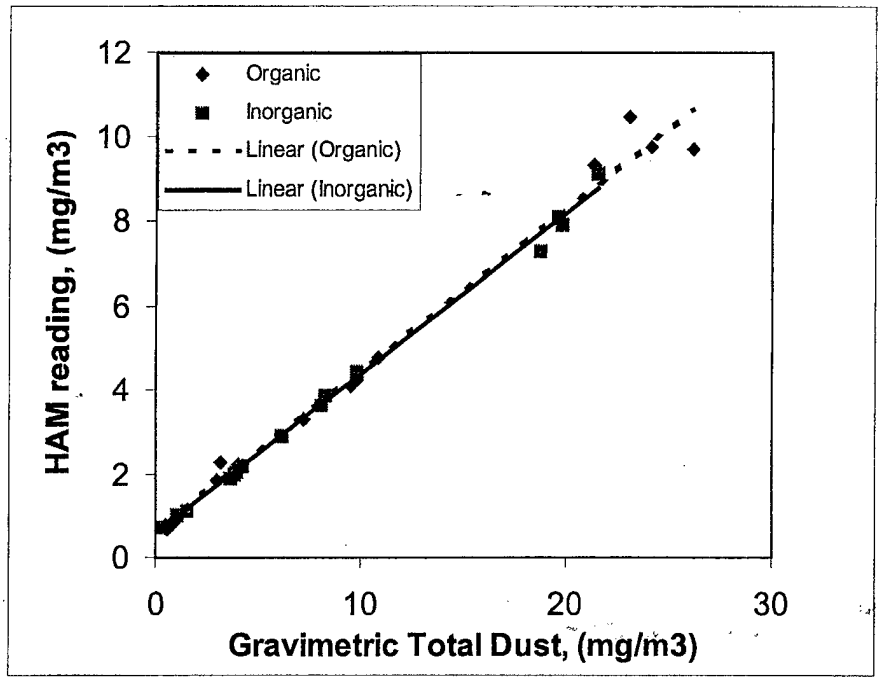
Figure 4. MiniRAM Response Plot and Regression Relative to Total Dust (a) and Respirable Dust (b)



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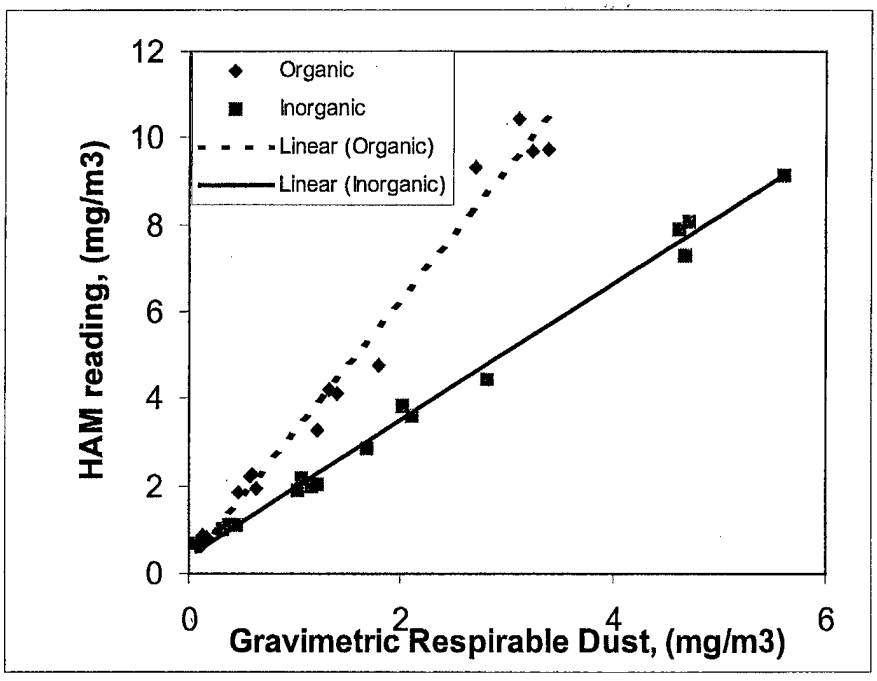

b

Figure 5. HAM Response Plot and Regression Relative to Total Dust (a) and Respirable Dust (b)

There is a difference in how the instruments respond to the two types of dust in every case except the HAM-to-total dust relationship. Algebraic reversal of the regression equations resulted in calibration equations for predicting gravimetric measurements given photometric readings. The resultant equations for predicting gravimetric dust measurements given instrument readings are given in Table 6:

Table 6. Regression Equations for Predicting Gravimetric Measurements

Situation	Equation
Total Organic Dust given HAM readings	Y = -1.54 + 2.56(HAM)
Total Inorganic Dust given HAM	Y = -1.45 + 2.63(HAM)
Total Organic Dust given MiniRAM readings	Y = -0.65 + 2.70(MiniRAM)
Total Inorganic Dust given MiniRAM	Y = -0.49 + 2.44(MiniRAM)
Respirable Organic Dust given HAM readings	Y = -0.10 + 0.34(HAM)
Respirable Inorganic Dust given HAM	Y = -0.25 + 0.64(HAM)
Respirable Organic Dust given MiniRAM	Y = 0.02 + 0.35(MiniRAM)
Respirable Inorganic Dust given MiniRAM	Y = -0.02 + 0.60(MiniRAM)

Given these regression equations for predicting gravimetric concentrations, the following table presents just the slope coefficients. For purposes of this discussion, the

slopes of the regression lines will be referred to as correction factors. The four intercepts of the regression equations for gravimetric respirable dust were not significantly different from zero. Therefore the slopes for the gravimetric respirable dust equations are more readily comparable., The gravimetric total dust regression equations all had significant intercepts. The comparison of slopes alone is a simplifying method. The full regression equations are required to best predict gravimetric measurements given photometric readings. These factors are useful for interpreting instrument response between the two types of dust, and are given in Tables 7 and 8.

Table 7. Correction Factors for Prediction (Gravimetric/MiniRAM)

MiniRAM	Inorganic	Organic
Gravimetric Total Dust	2.44	2.70
Gravimetric Respirable Dust	0.60	0.35

Table 8. Correction Factors for Prediction (Gravimetric/HAM)

HAM	Inorganic	Organic
Gravimetric Total Dust	2.63	2.56
Gravimetric Respirable Dust	0.64	0.34

These data show that, for each photometer, the correction factor to multiply photometer reading by to get gravimetric estimates for respirable inorganic dust was

roughly twice that for respirable organic dust. This means that the photometers overestimate organic respirable dust more than inorganic respirable dust given the factory calibrations. Interestingly, the correction factors for total dust for the MiniRAM are higher for organic than for inorganic dust but reversed for the HAM. The slopes were only slightly different, making generalizations about the difference between the dusts difficult.

Power and Sample Size

All statistical interpretations and tests were performed with probability for type I error of $\alpha = 0.05$ and probability of type II error of $\beta = 0.20$. Also, each observation, although done in the same chamber, was assumed to be independent. There was only one experimenter performing all the tests and weighing. The only problem that may have arisen would have been from temperature and humidity in the laboratory. The laboratory was temperature and humidity controlled. The dust samples were kept sealed. Open dust in the dust scraper cylinder was kept in a dessicant chamber. Given these parameters, the sample size required to detect a difference in means between inorganic and organic dust readings at least as large as the common standard deviation in a two group t-test was determined to be an n of 16 for each dust type for each of the four situations. The sample size was 16 (4 trials of 4 different concentrations each), therefore, the sample size was adequate for the power (80%) specified.

Discussion

Because of the differences in factory density settings between the two photometers, discussion of the instruments response to organic versus inorganic dusts must be done according to each instrument separately.

MiniRAM

The MiniRAM preferentially weights particles in the 0.1 to 10 μm size range. The factory calibration density is ρ_{cal} = 2.6 g/cc. Based on this alone, the MiniRAM should do a better job predicting inorganic dust concentrations than organic dust concentrations because many inorganic dusts have a density near 2.6 g/cc. It is beneficial to analyze the instrument performance specifically by gravimetric measurement type.

MiniRAM Total Dust Prediction

For both dusts, the total gravimetric measurement would be expected to be much larger than the photometer response because the total dust measurement would account for all the particles in the distribution up to 100 μm as compared to the photometer accounting for only a fraction of the distribution below 10 μm. The expected correction factor, or slope of the MiniRAM regression analysis would be:

$$\text{slope} = \text{gravimetric/instrument} > 1. \quad (4)$$

However, since dust size distributions vary, and both of the dusts in the experiment had distributions with significant portions above 10 μm, one cannot use the instruments to predict total dust given the correction factor unless the particle size

distributions are similar. The MiniRAM read similar portions of the particle distributions for the two dusts. As for the density, the correction factor should be smaller for organic, since the photometer would overestimate mass with ρ_{cal} = 2.6 g/cc versus $\rho_{organic}$ = 1.4 g/cc.

Using the simplifying assumption that the photometers respond at 100% for all particles sized 1 to 10 μm, the expected photometer correction factor can be estimated by Equation (5)

$$CF = \frac{\left(\frac{\rho_{dust}}{\rho_{cal}}\right)}{(\% \leq 10\mu m)}. \qquad (5)$$

Taking both density and particle size distribution into account, one would expect the organic correction factor to be overestimated by roughly 2 times because of density, but underestimated by approximately 0.45 (the fraction of the particles below 10 μm, taken from Figure 6). Likewise, the inorganic correction factor should be very well predicted in terms of density, but underestimated by approximately 0.58 by the particle size distribution (Figure 6). A simple rough estimation for organic would be 1.17, and for inorganic 1.72.

As seen in Table 7, the total dust correction factors were both greater than 1 as expected with organic correction factor = 2.70 and inorganic correction factor = 2.44. The discrepancy between expected and observed correction factors can be attributed to the larger proportion of inorganic particles than organic particles not only less than 10

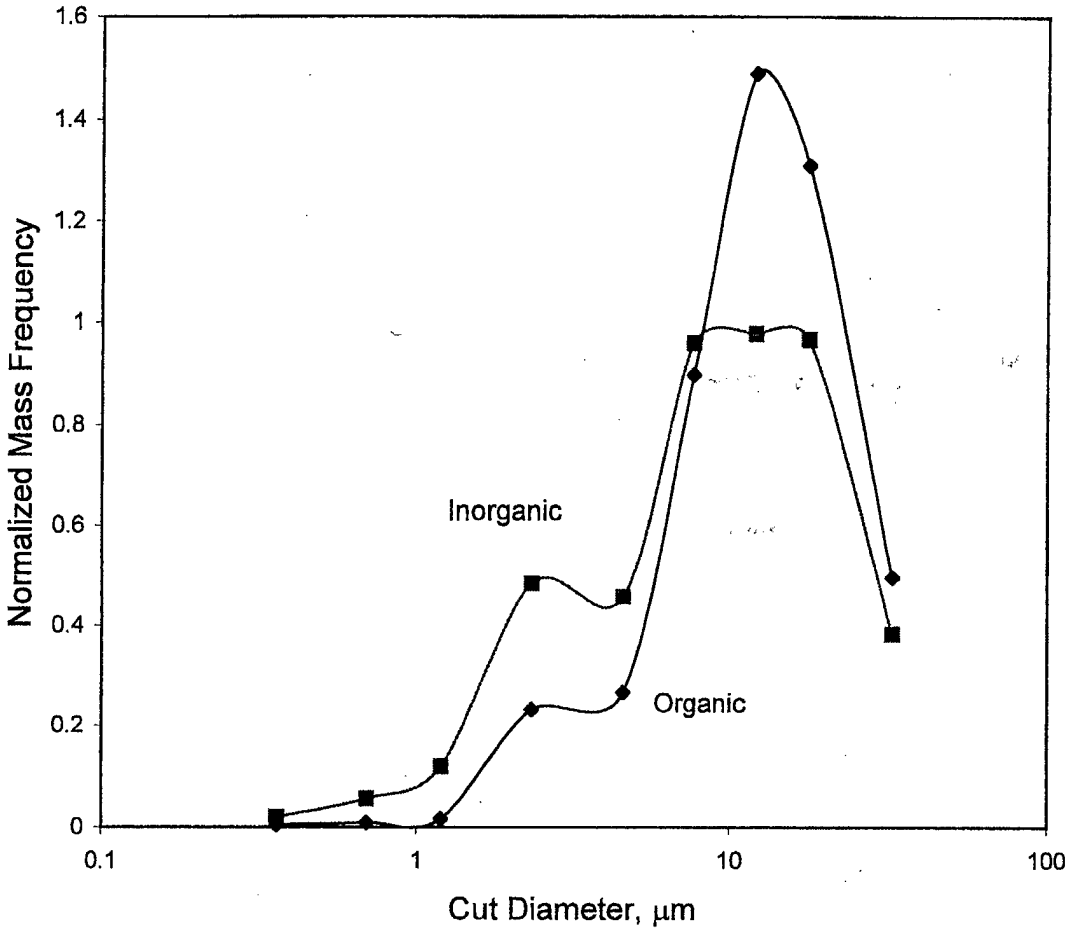

Figure 6. Cumulative Percent Size Distribution for the Two Experimental Dusts

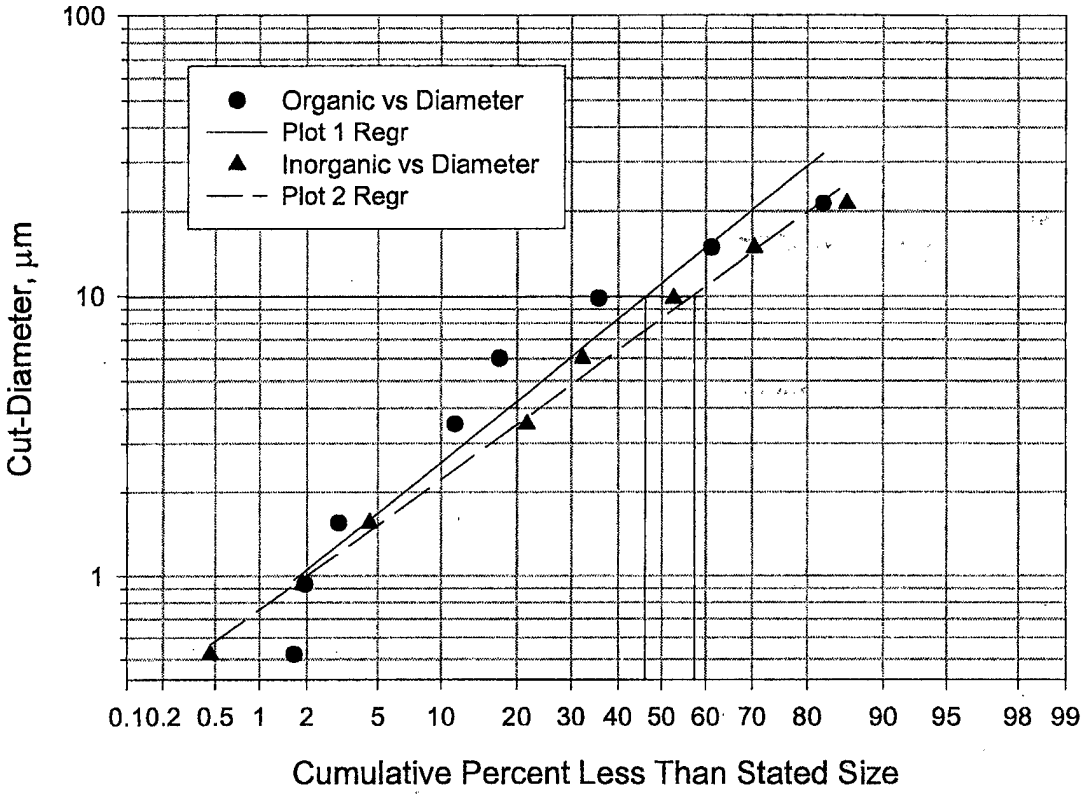

Figure 7. Particle Size Distributions for the Two Experimental Dusts

μm, but also less than 2.5 μm, where the photometers have a higher relative response. This would allow the inorganic correction factor to be closer to 1 than the organic correction factor. The organic dust had very little of its mass less than 2.5 μm (Figure 7) where the photometers respond best, even with 45% organic dust mass less than 10 μm (Figure 6). Thus the observed correction factor for gravimetric organic total dust was higher than expected.

Overall, caution should be exercised for total dust estimations unless the particle size distributions are known. If the size distributions are known, one can correct given the instrument response curve in Figure 1. Since the grain dust TLV of 4 mg/m^3 is total dust, and most grain dusts are relatively large when compared to the best response range of photometers, caution should be exercised in using the photometers for comparison to the current TLV.

MiniRAM Respirable Dust Prediction

For both dusts, the respirable gravimetric measurement should be smaller than the photometer response based on size distribution, since the photometer will still count particles between the respirable cut point of 4 μm and the photometer upper limit of 10 μm. There should be very little respirable-sized organic dust to measure gravimetrically. There should be much more inorganic dust to measure, but there is still a large portion to measure photometrically that will not fall into the respirable range. One would expect, based on particle size distribution alone, the correction factor for both to be:

$$\text{slope} = \Downarrow \text{gravimetric} / \Uparrow \text{photometric} < 1. \qquad (6)$$

The photometer should read at least all the particles captured on the respirable filter. Also, since $\rho_{cal} = \rho_{inorganic}$, one would expect the inorganic correction factor to be closer to 1, and the organic correction factor smaller than the inorganic. Based on density ratios alone, one would expect correction factors to be estimated well by Equation (7)

$$CF = \left(\frac{\rho_{dust}}{\rho_{cal}} \right). \quad (7)$$

The expected correction factors using Equation (7) were 1.00 for inorganic and 0.53 for organic. The observed correction factors from Table 7 were 0.60 for inorganic and 0.35 for organic. The photometrically counted particles above the gravimetric respirable dust cut-point of 4 μm made the correction factors smaller than expected based on density alone.

HAM

The HAM preferentially weights particles in the 0.5 to 10 μm size range. The calibration density is $\rho_{cal} = 1.5$ g/cc. Based on this alone, the HAM should do a better job predicting organic dust concentrations than inorganic dust concentrations. Again, it is beneficial to analyze the instrument performance specifically by gravimetric measurement type.

HAM Total Dust Prediction

Using the same simplifying assumption as for the MiniRAM that the photometers respond at 100% for all particles sized 1 to 10 μm, the expected photometer correction factor can be estimated by Equation (5). The simple rough estimation for organic would be 2.07, and for inorganic 3.05.

For the same reasons as the MiniRAM, the total gravimetric measurement for both dusts would be expected to be much larger than the photometer response because the total dust measurement would account for all the particles in the distribution up to 100 μm as compared to the photometer accounting for only the fraction of the distribution below 10 μm. The expected correction factor, or slope of the HAM regression, would be the same as in Equation (4), with slope > 1. However, since dust size distributions vary, and both of the dusts in the experiment had distributions with substantial portions above 10 μm, one cannot use the instruments to predict total dust given the correction factor unless the particle size distributions are similar. The HAM read similar portions of the particle distributions for the two dusts. Given density alone, the correction factor should be closer to 1 for organic, since the photometer would underestimate inorganic mass with $\rho_{cal} = 1.5$ g/cc versus $\rho_{inorganic} = 2.65$ g/cc. The HAM should do a better job predicting organic dust concentrations since the calibration dust was of a similar density compared to the organic dust in the experiment.

As given in Table 8, the total dust correction factors were both greater than 1 as expected by size distribution alone, with organic correction factor = 2.56 and inorganic correction factor = 2.63. The observed organic correction factor was larger than expected

due to the particle size distribution being larger than the optimum response range. The inorganic correction factor was smaller than expected due to the internal correction of the HAM. PPM Inc. provided a sample of ARD calibration dust which was aerosolized and characterized with a personal cascade impactor. The MMAD of the calibration dust was 6.2 μm. It was determined that the HAM uses internal correction based on its response curve (Figure 1) to bring its reading of this size dust to 100% relative response. This correction made the observed inorganic correction factor smaller than expected. It had less effect on the organic correction factor because the organic dust had less percent mass at the 6.2 μm size as shown in Figure 7.

HAM Respirable Dust Prediction

The respirable gravimetric measurement for both dusts should be smaller than the photometer response based on size distribution, since the photometer will still count particles between the respirable cut point of 4 μm and the photometer upper limit of 10 μm. There should have been very little respirable-sized organic dust to measure gravimetrically, based on the particle size distribution charts (Figure 7). There should have been much more inorganic dust to measure, but there is still a large portion to measure photometrically that will not fall into the respirable range. One would expect the correction factor for both to be slope < 1, as given in Equation 6, based on particle size distribution alone. The HAM should read at least all the particles captured on the respirable filter. Considering particle density alone ($\rho_{cal} \cong \rho_{organic}$), one would expect the organic correction factor to be closer to 1, but the inorganic correction factor to be larger than the organic. Based on density ratios alone, one would expect for the HAM 0.93 for

organic and 1.77 for inorganic based on Equation (7). The observed correction factors from Table 8 were 0.34 for organic and 0.64 for inorganic.

However, since the organic particle size distribution has much less percent mass at the smaller particle sizes compared to the inorganic particle size distribution (Figure 7), there just were not many organic particles in the respirable range to measure gravimetrically compared to the organic particles measured photometrically. Plus, the underestimation of density for the inorganic dust would cause the correction factor for inorganic to be larger than organic. As was observed with HAM, respirable dust correction factor for organic was 0.34 vs. 0.64 for inorganic. The difference in observed and expected correction factors can also be explained by the internal correction for larger dust response in the HAM.

Precision

Since the essential function of the regression was to create calibration equations, the associated standard deviation for each regression equation had to be estimated based on a photometer reading. The standard deviation of a given reading would then depend upon the magnitude of the reading as shown in the estimation of the sample variance (s_m^2) of the photometer measure (C_m) (Watson et al. 1995):

$$s_{m^2} = \left(\frac{s_{\alpha}^2}{\alpha^2}\right) \times (C_m - b)^2 + s_{b^2} \qquad (8)$$

where:

s_{α}^2 = Sample variance of the slope or span for the instrument

α^2 = Slope or span for the instrument squared

b = Intercept of the regression equation

s_b^2 = Sample variance of the intercept.

The precision of the instruments is worse at low magnitudes, where the intercept of the regression equations is larger in comparison with the actual photometer reading. The manufacturers of both photometers claim to be accurate within ± 25% for particles within a size range of 0.3 to 2.0 μm. The precision equation for calibrating direct-reading instruments (8) resulted in a variance for the photometer measurement. Coefficients of variation (relative standard deviation) were computed for each situation for organic dust detecting. For organic dust prediction, the Total/HAM, Total/MiniRAM, and Respirable/MiniRAM coefficients of variation were within ± 25% of the reading at concentration readings above 2.5 mg/m^3. The Respirable/HAM coefficient of variation was not within ± 25% until the HAM reading was above 3.5 mg/m^3. This shows that the precision at the low levels, which may be most important when comparing to the standard, was relatively poor. The corresponding minimum gravimetric organic dust levels where the photometer precision reaches ± 25% are shown in Table 9:

The photometer reading alone may be misleading as shown in Table 9. The MiniRAM requires a higher gravimetric total dust concentration to be within ± 25% than the HAM. And although the HAM would appear to need much more respirable dust to be reliable, the actual gravimetric dust concentration for the two photometers to measure respirable dust precisely is not extremely different.

Table 9. Minimum Organic Dust Gravimetric Levels for ± 25% Precision

Prediction Situation	Minimum Photometer Reading for ± 25% (mg/m^3)	Corresponding Gravimetric Concentration (mg/m^3)
Total/HAM	2.5 mg/m^3	4.86 mg/m^3
Total/MiniRAM	2.5 mg/m^3	6.10 mg/m^3
Respirable/MiniRAM	2.5 mg/m^3	0.90 mg/m^3
Respirable/HAM	3.5 mg/m^3	1.09 mg/m^3

Summary

Except for the HAM response to total dust, the instruments responded differently to organic versus inorganic dusts, with the significance levels given in Table 4. The different responses were explained by two of the three main factors of photometer response (particle density and size distribution). Photometers should be field-calibrated to the specific type of dust being measured. However, they can certainly be used for organic dusts, even with the differing dust properties, because the response was linear over the range of concentrations. Specifically, they can be used for corn grain dust with the correction factors listed in Tables 7 and 8. Total dust estimations were more troublesome due to the particle size distributions. The respirable dust estimations were more reliable and useful.

When comparing to the ACGIH TLV for grain dust, which is a total dust measurement, total dust estimates can be made from the particle size distributions and

percent mass in the respirable range. However, that would be at least as cumbersome as just taking total dust gravimetric samples. Field-calibrating the instruments would be useful for large-scale agricultural operations, like swine confinements, where long-term monitoring was desirable. Once a calibration equation is determined, the photometer readings can be used repeatedly for that specific dust and task. Another use for photometers would be qualitative comparisons, like before and after the implementation of controls.

The precision of the photometers may prevent utility in the swine and poultry industries, where the proposed standards are far below the concentrations where the instruments are within ± 25%. If the task was "dusty" visually, and the worker complained of respiratory distress, the concentration level would likely exceed the proposed limits, and could be easily confirmed with a photometer.

In summary, photometers can be useful instruments for long-term task characterization where particle size distribution measurement is also warranted. They can also be used qualitatively to evaluate efficacy of controls.

CHAPTER III

CONCLUSION

The results of the experiment showed that photometers predict organic and inorganic gravimetric dust measurements differently, except the HAM for total dust. The HAM predicted smaller gravimetric inorganic respirable dust concentrations than gravimetric organic respirable dust concentrations ($p<0.0001$). The MiniRAM also predicted smaller gravimetric inorganic respirable dust than gravimetric inorganic respirable dust concentrations ($p<0.0001$). The MiniRAM predicted the two total dusts differently ($p=0.0042$). The HAM predicted total organic and inorganic dust similarly ($p=0.7834$).

However, since particle size distribution plays such an important role in total dust prediction, and organic dusts typically have MMAD's larger than the preferential sensing range of the photometers, instruments should be field-calibrated to the dust of interest in order to accurately predict gravimetric total dust measurements. This makes the instruments less useful for total dust prediction using the reported calibration equations. Field calibration or, at the least, knowledge of the particle size distribution of the dust of interest would be required beforehand to compare to this experiment in order to use the calibration equations. Since many organic particles have densities similar to that of the grain dust in this experiment (McCrone et al. 1973), the calibration equations could be

used in varied organic dust settings to predict gravimetric dust concentrations with some accuracy, if the particle size distributions were known.

The fact that the current TLV for grain dust is in terms of total dust may limit the field applicability of photometric respirable dust prediction. However, the information is still useful to estimate exposure, for comparison crudely to the total grain dust TLV, and to evaluate the efficacy of engineering controls. Also, since the proposed limits for swine and poultry dusts are below the range where the photometers were within ± 25%, the utility in those industries may be limited.

This experiment was designed to match particle size distributions between the two types of dust to lessen the effects of size distribution and help focus on the other differences between the two dusts. There were 16 trials with each dust, then an additional 4 trials with each dust having a smaller particle size distribution. The MMAD's of the 4 dusts are listed below in Table 10:

Table 10. Average MMAD for the Four Dust Types

Dust Type	Average MMAD (μm)
Organic	11.19 μm
Inorganic (ARD medium test dust)	8.02 μm
Organic – reduced MMAD (cyclone)	7.02 μm
Inorganic (ARD fine test dust)	6.55 μm

The ARD medium test dust was chosen in an attempt to best match the MMAD of the raw CGD. As shown in Table 10, the ARD fine test dust and the reduced CGD had the closest MMAD's. Future experiments might be better designed to correct for different particle size distributions between the inorganic and organic dusts by using these two dusts and sufficient replications. More informatively, future experiments might be performed on a set of similar grain dusts with different particle size distributions only.

The photometers themselves were easy to use and had a linear response. They could prove quite useful in agricultural industrial hygiene. Direct reading instruments allow a health professional to do quick assessments of dust exposures at various tasks. Given the isolation of individual farms and workers, as well as the low number of agricultural industrial hygienists who serve large geographic areas, these instruments could help assess exposures at more locations. Also, with a slightly larger capital investment than gravimetric sampling equipment, these simple instruments could be used with less training by health professionals already in the rural areas.

In summary, the photometers predict gravimetric organic and inorganic dust concentrations differently except for the HAM predicting gravimetric total dust. The differences in gravimetric dust prediction were best explained by the difference between the density of the dust and the calibration density of the photometers, as well as particle size distribution.

REFERENCES

American Conference of Governmental Industrial Hygienists: *Threshold Limit Values for Chemical Substances and Physical Agents.* Cincinnati, OH: ACGIH, 1999.

Armbruster, L.: A New Generation of Light-Scattering Instruments for Respirable Dust Measurement. *Annals of Occupational Hygiene.* 31(2):181-193 (1987).

Bartley, D. L.: Particulates Not Otherwise Regulated, Respirable: Method 0600. In *NIOSH Manual of Analytical Methods, 4th Ed.* Cincinnati, OH: NIOSH. 1994.

Becklake, M. R.: Grain Dust and Health: State of the Art. In *Occupational Pulmonary Disease, Focus on Grain Dust and Health*, edited by J. A. Dosman and D. J. Cotton. New York: Academic Press. 1980. pp. 189-200.

Brown, M. A.: *NIOH and NIOSH Basis for an Occupational Health Standard: Grain Dust: Health Hazards of Storing, Handling, and Shipping Grain.* Cincinnati, OH: National Institute for Occupational Safety and Health, 1988.

Cadle, R. D.: *The Measurement of Airborne Particles.* New York: John Wiley & Sons, 1975.

Chan-Yeung, M., D. A. Enarson, and S. M. Kennedy: The Impact of Grain Dust on Respiratory Health. *Am. Rev. Respir. Dis.* 145: 476-487 (1992).

Cheng, Y. S., E. B. Barr, J. M. Benson, E. G. Damon, M. A. Medinsky, C. H. Hobbs, and T. J. Goehl: Evaluation of a Real-Time Aerosol Monitor (RAM-S) for Inhalation Studies. *Fundamental and Applied Toxicology.* 10:321-328 (1988).

Clere, J., and F. Hearl: Particulates Not Otherwise Regulated, Total: Method 0500. In *NIOSH Manual of Analytical Methods, 4th Ed.* Cincinnati, OH: NIOSH. 1994.

Davis, J. W., and V. C. Irwin: A Dry Dust Generator System for Animal Exposures at Controlled Concentrations. *Am. Ind. Hyg. Assoc. J.* 43(9):704-711 (1982).

Deacon, S. P., and G. M. Paddle: Respiratory Symptoms and Ventilatory Performance in Workers Exposed to Grain and Grain based Food Dusts. *Occupational Medicine.* 48(4): 227-230 (1988).

Deetz, D. C., P. J. Jagielo, T. J. Quinn, P. S. Thorne, S. A. Bleuer, and D. A. Schwartz: The Kinetics of Grain Dust-Induced Inflammation of the Lower Respiratory Tract. *American Journal of Respiratory and Critical Care Medicine.* 155(1): 254-259 (1997).

Deichmann, W. B.: A Dust Shaker: An Apparatus Designed for the Production of Controlled Dust Concentrations in the Air Breathed by Experimental Animals. *The Journal of Industrial Hygiene and Toxicology.* 26(10): 334-335 (1944).

Dietrich, D. F.: Sampling of Gases and Vapors. In *The Occupational Environment – Its Evaluation and Control,* edited by S. R. DiNardi. Fairfax, VA: AIHA Press. 1997. pp. 210-227.

Dimich-Ward, H. D., S. M. Kennedy, M. A. Dittrick, and M. Chan-Yeung: Time Trends in the Respiratory Health of Recently Hired Grain Elevator Workers. In *Agricultural Health and Safety: Workplace, Environment, Sustainability,* edited by H. H. McDuffie, J. A. Dosman, K. M. Semchuk, S. A. Olenchock, and A. Senthilselvan. Boca Raton, FL: Lewis Publishers. 1995. pp. 19-22.

Dimich-Ward, H. D., S. M. Kennedy, M. A. Dittrick, A. DyBuncio, and M. Chan-Yeung: Evaluation of the Respiratory Health of Dock Workers Who Load Grain Cargoes in British Columbia. *Occupational and Environmental Medicine.* 52(4): 273-278 (1995).

Donham, K. J.: Hazardous Agents in Agricultural Dusts and Methods of Evaluation. *American Journal of Industrial Medicine.* 10(3): 205-220 (1986a).

Donham, K. J., D. Cumro, S. J. Reynolds, and J. A. Merchant: Dose-Response Relationships Between Occupational Aerosol Exposures and Cross-Shift Declines of Lung Function in Poultry Workers: Recommendations for Exposure Limits. *Journal of Occupational and Environmental Medicine.* 42(3): 260-269 (2000).

Donham, K. J., S. J. Reynolds, P. Whitten, J. A. Merchant, L. Burmeister, and W. J. Popendorf: Respiratory Dysfunction in Swine Production Facility Workers: Dose-Response Relationships of Environmental Exposures and Pulmonary Function. *American Journal of Industrial Medicine.* 27:405-418 (1995).

Donham, K. J., and R. Rylander: Epilogue: Health Effects of Organic Dusts in the Farm Environment. *American Journal of Industrial Medicine.* 10(3): 339-340 (1986b).

DoPico, G. A.: Grain Dust. In *Organic Dusts, Exposure, Effects, and Prevention* edited by R. Rylander and R. R. Jacobs. Boca Raton, FL: CRC Press. 1994. pp. 193-218.

Farant, J. P.: Assessment of Dust Nature and Levels in the Grain Industry. In *Principles of Health and Safety in Agriculture,* edited by J. A. Dosman and D. W. Cockcroft. Boca Raton, FL: CRC Press. 1989. pp. 178-181.

Fonn, S., and M. R. Becklake: Documentation of Ill-Health Effects of Occupational Exposure to Grain Dust through Sequential, Coherent Epidemiologic Investigation. *Scandinavian Journal of Work, Environment and Health.* 20(1), 13-21 (1994).

Gebhart, J.: Optical Direct-reading Techniques: Light Intensity Systems. In *Aerosol Measurement: Principles, Techniques, and Applications*, edited by K. Willeke and P. A. Baron. New York: Van Nostrand Reinhold. 1993. pp. 313-344.

Glinsmann, P. W., and F. S. Rosenthal: Evaluation of an Aerosol Photometer for Monitoring Welding Fume Levels in a Shipyard. *Am. Ind. Hyg. Assoc. J.* 46(7):391-5 (1985).

Heitbrink, W. A., P. A. Baron, and K. Willeke: An Investigation of Dust Generation by Free Falling Powders. *Am. Ind. Hyg. Assoc. J.* 53(10): 617-24. (1992).

Hirano, S.: Automatic Control of Aerosol Concentrations in Exposure Chambers. *Am. Ind. Hyg. Assoc. J.* 48(12):972-976 (1987).

Jacobs, R. R.: Exposure Assessment. In *Organic Dusts: Exposure, Effects, and Prevention*, edited by R. Rylander and R. R. Jacobs. Boca Raton, FL: Lewis Publishers. 1994a. pp. 43-59.

Jacobs, R. R.: Risk Environments. In *Organic Dusts: Exposure, Effects, and Prevention*, edited by R. Rylander and R. R. Jacobs. Boca Raton, FL: Lewis Publishers. 1994b. pp. 3-15.

Kline, J. N., and D. A. Schwartz: Agricultural Dust-Induced Lung Disease. In *Environmental and Occupational Medicine, 3rd Ed.*, edited by W. N. Rom. Philadelphia, Penn.: Lippincott-Raven Publishers. 1998. pp. 565-571.

Landis, H. R. M.: The Pathological and Clinical Manifestations Following the Inhalation of Dust. *The Journal of Industrial Hygiene.* 1(3): 117-139 (1919).

Manfreda, J., M. Cheang, and C. P. W. Warren: Chronic Respiratory Disorders Related to Farming and Exposure to Grain Dust in a Rural Adult Community. *American Journal of Industrial Medicine.* 15(1): 7-19 (1989).

Martin, C. R., D. F. Aldis, and R. S. Lee: *In Situ* Measurement of Grain Dust Particle Size Distribution and Concentration. *Transactions of the American Society of Agricultural Engineers.* 28(4) 1319-1327 (1985).

McCrone, W. C., and J. G. Delly: The Particle Atlas, 2nd Ed. Volume IV. Ann Arbor, MI: Ann Arbor Science Publishers, Inc., 1973.

Middendorf, P. J., A. H. Lehocky, and P. L. Williams: Evaluation and Field Calibration of the Miniram PDM-3 Aerosol Monitor for Measuring Respirable and Total Coal Dust. *Am. Ind. Hyg. Assoc. J.* 60:502-511 (1999).

MIE Inc.: *MiniRAM Personal Monitor Model PDM-3 Operations Manual.* Bedford, MA: MIE Inc., 1984.

NIOSH: *Pocket Guide to Chemical Hazards*. Cincinnati, OH: NIOSH Publications, 1997.

O'Shaughnessy, P. T. and D. R. Hemenway: Computer Automation of a Dry-Dust Generating System. *Inhalation Toxicology*. 6:95-113 (1994).

Page, S. J., and R. A. Jankowski. Correlations Between Measurements with RAM-1 and Gravimetric Samplers on Longwall Shearer Faces. *Am. Ind. Hyg. Assoc. J.* 45(9):610-616 (1984).

Peelen, S. J. M., D. Heederik, H. D. Dimich-Ward, M. Chan-Yeung, and S. M. Kennedy: Comparison of Dust Related Respiratory Effects in Dutch and Canadian Grain Handling Industries: A Pooled Analysis. *Occupational and Environmental Medicine.* 53(8): 559-566 (1996).

Post, W., D. Heederik, and R. Houba: Decline in Lung Function Related to Exposure and Selection Processes Among Workers in the Grain Processing and Animal Feed Industry. *Occupational and Environmental Medicine.* 55(5): 349-355 (1998).

PPM, Inc.: *Operating Instructions for Handheld Aerosol Monitor Model 1010/1060.* Knoxville, TN: PPM Inc., 1983.

Rajendran, N. and J. D. Stockham: Grain Dust Measurement Techniques-An Evaluation. *Transactions of the American Society of Agricultural Engineers*. 28(6) 2030-2036 (1985).

Ramazzini, B.: *De Morbis Artificum* (1713). Trans. By W. C. Wright, U. of Chicago Press, 1940.

Reynolds, S. J., K. J. Donham, P. Whitten, J. A. Merchant, L. F. Burmeister, and W. J. Popendorf: Longitudinal Evaluation of Dose-Response Relationships for Environmental Exposures and Pulmonary Function in Swine Production Workers. *American Journal of Industrial Medicine*. 29: 33-40 (1996).

Schaller, R. E., and R. M. Nicholson: The Nature, Behavior, and Characterization of Grain Dust. In *Occupational Pulmonary Disease: Focus on Grain Dust and Health*, edited by J. A. Dosman and D. J. Cotton. New York: Academic Press. 1980. pp. 513-525.

Schwartz, D. A., P. S. Thorne, S. J. Yagla, L. F. Burmeister, S. A. Olenchock, J. L. Watt, and T. J. Quinn: The Role of Endotoxin in Grain Dust-induced Lung Disease. *Am. J. Respir. Crit. Care Med.* 152: 603-608 (1995).

Smith, J. P., P. A. Baron, and D. J. Murdock. Response Characteristics of Scattered Light Aerosol Sensors Used for Control Monitoring. *Am. Ind. Hyg. Assoc. J.* 48(3):219-29 (1987).

Smith, T.A., and J. Patton: Health Surveillance in Milling, Baking and Other Food Manufacturing Operations: Five Years' Experience. *Occupational Medicine.* 49(3): 147-153 (1999).

Smyth, H. F.: A Critical Review of Methods for the Study of Dust Content in Air. *The Journal of Industrial Hygiene.* 1(3): 140-149 (1919).

Taylor, C.: *A Comparison of Light Scattering Photometers and Gravimetric Methods in the Presence of Agricultural Organic Dusts.* Master's thesis, University of Iowa, 1996.

Vinzents, P. S.: A Passive Personal Dust Monitor. *Ann. Occup. Hyg.* 40(3): 261-280 (1996).

Volckens, J., P. T. O'Shaughnessy, and D. R. Hemenway: An Aerosol Generation System for the Production of Respirable Grain Dust. *Applied Occupational and Environmental Hygiene.* 13(2): 122-126 (1998).

Von Essen, S. G., and K. J. Donham: Respiratory Diseases Related to Work in Agriculture. In *Safety and Health in Agriculture, Forestry, and Fisheries*, edited by R. L. Langley, R. L. McLymore, Sr., W. J. Meggs, and G. T. Roberson. Rockville, MD: Government Institutes. 1997. pp. 353-384.

Wallace, D.: Grain Handling and Processing. In *Air Pollution Engineering Manual*, edited by A. J. Buonicore and W. T. Davis. New York: Van Nostrand Reinhold. 1992. pp. 517-528.

Watson, J. G., P. J. Lioy, and P. K. Mueller: The Measurement Process: Precision, Accuracy, and Validity. In *Air Sampling Instruments for Evaluation of Atmospheric Contaminants, 8th Ed.*, edited by B. S. Cohen and S. V. Hering. Cincinnati, OH: ACGIH. 1995. pp. 187-193.

Willeke, K, ed.: *Generation of Aerosols and Facilities for Exposure Experiments*. Ann Arbor, MI: Ann Arbor Science Publishers, Inc. 1980.

Willeke, K. and P. A. Baron, eds.: *Aerosol Measurement: Principles, Techniques, and Applications*. New York: Van Nostrand Reinhold. 1993.

Yoshida, K., and J. Maybank: Physical and Environmental Characteristics of Grain Dust. In *Occupational Pulmonary Disease: Focus on Grain Dust and Health*, edited by J. A. Dosman and D. J. Cotton. New York: Academic Press. 1980. pp. 441-461.

Zejda, J. E., H. H. McDuffie, and J. A. Dosman: Respiratory Effects of Exposure to Grain Dust. *Seminars in Respiratory Medicine*. 14(1) 20-30 (1993).