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Evaluation of the validity of the inhalable and "total" dust concentration ratio

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EVALUATION OF THE VALIDITY OF THE INHALABLE AND "TOTAL" DUST CONCENTRATION RATIO

by

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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 for the thesis requirement for the Master of Science degree in Occupational and Environmental health at the May 2013 graduation.

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To my family, friends, and loved ones; thank you for all the support.

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ABSTRACT

Industrial hygienists can compare “total” dust concentrations to higher inhalable concentrations using a value called the performance ratio. A commonly used performance ratio of 2.5 is used for dusts found in the workplace, after results from multiple studies were compiled. The objective of this study was to evaluate the “total” and inhalable dust performance ratio over a range of conditions to investigate whether the commonly used value of 2.5 varies between: (1) dust type (2) IOM and Button inhalable samplers and (3) distance from the dust source.

Dust concentrations were generated in a still air chamber using three dust types; sawdust, flour, and glass microbeads. The IOM, Button, and CFC samplers were used to measure concentrations at four locations increasing in distance from the source. Linear regressions in the form of [Inhalable mg m^{-3}] = S x [“Total” mg m^{-3}] were used to calculate the appropriate performance ratio, S. The intercept of this regression was forced through the origin. Linear regression was also used to examine whether the effect of distance on S was significant and a distance factor (β_1) was calculated.

The calculated performance ratios, S, differed between sawdust, flour, and glass microbeads, and were 1.62, 2.82, and 2.97 respectively when comparing IOM concentration to CFC concentration. Performance ratios computed for the Button sampler for sawdust, flour, and glass microbreads were 0.82, 1.04, and 0.57 respectively. Performance ratios were significantly different ($p=0.049$) between the two inhalable sampler types. The IOM/CFC performance ratio for all three dusts averaged 2.47 (SD=0.74), whereas the Button/CFC performance ratio for the three dusts averaged 0.81 (SD=0.24). Only the IOM/CFC performance ratio had a statistically significant distance factor at $\alpha=0.05$.

The authors caution against using a single performance ratio of 2.5 for all dusts due to the large variance involved with dust sampler and dust type. Distance from the

source did not significantly affect the performance ratios computed under laboratory conditions. Industrial hygienists are advised to perform side by side sampling with inhalable and “total” dust samplers to create specific performance ratios appropriate for tasks found in the workplace.

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CHAPTER I

LITERATURE REVIEW

Background

Personal samplers are used by industrial hygienists to estimate worker exposures to occupational inhalation hazards. When the hazard is dust, the traditional sampler used is a 37-mm cassette. Recent developments and improvements in the understanding of how particles behave in the environment and in the respiratory system have led to the development and use of newer dust samplers called inhalable samplers, which better represent the aspiration of particles into the human body. Inhalable samplers collect aerosols at different efficiencies compared to the old samplers, and direct comparison is not valid. However, an industrial hygienist may wish to compare historical 37-mm cassette data to new inhalable data to make sure standards are still being met in the workplace. Researchers have examined ways to compare exposures from 37-mm cassettes to those measured by inhalable samplers. The purpose of this chapter is to review the current literature on size-selective sampling and to present shortcomings and improvements needed to improve ways to translate historical dust exposure data into estimates of inhalable dust exposures.

As knowledge has increased about the behavior of aerosols in the respiratory system, there has been an increased push to create representative samplers. Researchers wanted to characterize the entry efficiency of aerosols into the nose and mouth so that samplers that represent the sampling efficiency of the human head can be developed to better represent exposures to aerosols. The efficiency of the human head at aspirating particles is defined as inhalability (Soderholm, 1989). A report by the International Organization for Standardization (ISO) recommended sampling efficiencies at various particle sizes to represent the penetration of particles into the human lung (Harper and Demange, 2007). These sampling efficiencies have been adopted by the American Conference of Governmental Industrial Hygienists (ACGIH), and since 1998, 81 recommended exposure limits for inhalable airborne aerosols have been provided (ACGIH, 2012). The equation for the inhalable fraction, IF, is expressed as:

$$IF = 0.5(1+ \exp(-0.06\ d_a))$$

where d_a is the aerodynamic diameter in µm and air velocity is less than 4 m s^{-1}. This inhalable fraction provides aspiration efficiency by particle size. Efficiencies range from 100% for 1-µm particles to roughly 50% for particles 50 µm through 100 µm (Soderholm, 1989). Numerous personal samplers have been developed to sample airborne aerosol at similar sampling efficiencies given by this equation.

The inhalable convention is only one of three size-selective sampling parameters, and it represents the widest range of particle sizes. The respirable fraction aims to characterize any particle that penetrates into the alveolar region in the lungs. This respirable fraction is important, as certain particles are toxic in the alveolar region of the lungs. The respirable fraction has a 50% sampling efficiency of 4 µm, with a maximum sampling size of 10 µm. The thoracic fraction defines the size of particles that penetrate through the head airways and are available to deposit in the tracheobronchial region of the lungs. The thoracic fraction has a 50% sampling efficiency of 10 µm with an upper size limit of 30 µm (Soderholm, 1989).

Total Dust Sampling

The most common method for personal exposure sampling for airborne aerosols in the workplace involved the use of a 37-mm, closed-face cassette (CFC). The cassette is made of polystyrene and holds a filter. By measuring the gravimetric weight of aerosol collected on the filter and knowing the amount of air pulled through the cassette, the concentration of aerosol in the air can be calculated. NIOSH method 0500 is the preferred method for sampling dust with a CFC (NIOSH, 2003).

Sampling cassettes can be operated either closed-face or open-face. The closed-face cassette (CFC) is made of two or three plastic pieces. There is a 4-mm wide, 6-mm long inlet where air and any aerosol enter, and pass through a 37-mm filter. The CFC is worn on the lapel of the worker, and should be oriented approximately 45° below the horizontal. The CFC is preferred by practicing industrial hygienists and regulating agencies because the small opening prevents workers from affecting the sample (Buchan, Soderholm, & Tillery, 1986). Open-face cassettes involve removing the top piece of the three piece cassette, leaving a 33-mm opening for air and any aerosol to enter. Beaulieu, Fidino, Arlington, and Buchan (1980) discovered that the CFC underestimated a worker's exposure to airborne aerosol when compared to the open-face cassette. The mean ratio of open-face to closed-face aerosol concentrations in a field study was 1.3.

The CFC was not specifically built to sample for the inhalable criterion (Harper and Demange, 2007). The sampling efficiency of CFCs decrease as particle size increases. CFCs also have lower sampling efficiencies than inhalable samplers at all wind speeds and orientations (Li, Lundgren, & Rovell-Rixx, 2000). The CFC typically only collects 26 to 35% of what a mannequin inhales during inhalability tests, regardless of wind speed or orientation (Sleeth & Vincent, 2012). Hence, the fraction of dust collected by the CFC is considered "total dust," but it represents less than 100% aspiration that is achieved by a breathing person in the same environment.

Since the weight of the filter alone is used to calculate gravimetric weight, there is concern that the true amount of aerosol collected will not be represented because of particle loss on the interior walls of the sampler (Brisson & Archuleta, 2009). NIOSH method 0500 does not specify using an interior wipe to include the mass collected on the interior walls, though Chapter O of the NIOSH Manual of Analytical Methods (2003) does suggest including wall deposits on the CFC in all samples. OSHA considers any particle that enters the cassette to be part of the total sample (OSHA, 2003). Studies have shown that if these internal wall losses are included in the gravimetric weight, the CFC more closely matches the inhalability criterion (Demange, Görner, Elcabache, & Wrobel, 2002). CFC measurements where the internal wall losses were included matched IOM sampler measurements more closely than CFC measurements made without measuring the internal wall losses in the same study.

IOM Inhalable Sampler

With the development of the inhalable sampling criteria, researchers began to develop samplers that collect dust at efficiencies matching this criterion so that occupational exposures could better reflect the true dust concentrations inhaled by workers. The most widely used sampler in the United States is the Institute of Occupational Medicine (IOM) personal sampler, developed by Mark and Vincent (1986). The basis for development of the IOM sampler was to design a sampler that represents the amount of aerosol that a worker breathes into their nose and/or mouth (Mark & Vincent, 1986). There are two main components to the IOM sampler: the filter cassette and the sampler housing. The sampler housing is made up of two pieces, which screw together to the filter cassette. The interior filter cassette has a 15-mm opening, and at the opposite side has a 25-mm filter held to the cassette with a mesh screen behind. Dust on both the filter and internal cassette are analyzed to provide information on everything that entered the sampler. The cassette is then placed inside the sampler housing, and a 37-mm wide cover is placed over the cassette, only allowing the 15 mm opening to be exposed to the environment. The opening can also be covered to prevent aerosol from entering the sampler when not in use. The IOM sampler is connected to a personal sampling pump that is operated at a flow rate of 2 l min^{-1} (Mark and Vincent, 1986).

The sampling efficiency of the IOM was compared to the inhalable criterion over various wind speeds, orientations, and flow rates. When performing at wind speeds of 0.5 m s^{-1} and 4.0 m s^{-1}, the IOM sampler was found to sample adequately compared to the inhalable convention when facing the source (Kenny, et al., 1997). The IOM oversampled compared to the inhalable particulate matter curve, but not enough to cause concern at 0.5 m s^{-1}. Sampling efficiency at 4.0 m s^{-1} was found to decrease as particle size increased until particle size was larger than 80 µm. Efficiencies at these larger particle sizes were found to be above 60% (Kenny, et al., 1997). Research has shown that the wind speeds may be much lower in workplaces than the testing conditions of the inhalable samplers, around 0.2 m s^{-1} (Baldwin & Maynard, 1997). The IOM sampler was tested at these lower wind speeds to determine if the sampler still met the sampling criteria. Sampling efficiency was found to decrease as particle size increases in low wind conditions, which is to be expected. In higher wind speed wind tunnel experiments, sampling efficiency slightly increased. The IOM sampler was determined acceptable for use in low wind speeds less than 0.2 m s^{-1} (Kenny, Aitken, Baldwin, Beaumont, & Maynard, 1999).

For a sampler to match the inhalable particulate matter curve, the sampler must follow the IF when averaged over all orientations relative to the oncoming wind. The IOM has been tested under multiple orientations in order to determine whether it does indeed follow the inhalability standard at all orientations. A study found that the IOM sampler oversampled when facing the wind, but under sampled when at orientations of 90° and 180°. When facing the wind, efficiency increased above 100% as particle size increased from 0 to 60 µm (Li et al., 2000).

The effect of sampling flow rate on the collection efficiency of the IOM was also investigated. The sampler was tested at 10.6 L min^{-1} along with the standard 2.0 L min^{-1} at wind speeds of both 0.56 and 2.22 m s^{-1}. The IOM sampler was found to behave similar when sampling at 10.6 L min^{-1}, compared to the standard sampling flow rate of 2.0 L min^{-1}, though sampling efficiency was approximately 20% less when particle sizes were larger than 80 µm (Zhou and Cheng, 2009).

Weighing imprecision is a concern of the IOM sampler because of the fact that the entire filter cassette, which can be made of plastic or stainless steel, is weighed as a unit along with the filter. Humidity can cause large weighing imprecisions due to moisture absorbing to the plastic cassette. Keeping the cassettes in humidity controlled weighing room for seven days before and after use is recommended in order to keep weight fluctuation to ± 0.05 mg. To fully equilibrate the cassette to the weighing environment, 15-20 days of equilibration may be needed (Liden and Bergman, 2001). The results of the same study found that the oils on human hands add a statistically significant amount of weight to the filter cassette.

Button Inhalable Sampler

The Button sampler was developed to minimize the effects of wind direction and velocity on sampling efficiency. This inhalable sampler was developed to allow smooth flow over a front, mesh surface in high wind speeds. The Button sampler has a curved porous surface with multiple 381 μm diameter openings, with an overall porosity of 21%. This porous surface allows particles to enter the sampler in a manner that follows the inhalable fraction. The sampler is connected to a personal sampling pump that operates at a flow rate of 4 l min^{-1} to impart a significant pressure drop to allow uniform deposition across the internal 25-mm filter (Aizenberg, Grinshpun, Willeke, Smith, & Baron, 2000).

Wind speed and orientation were found to have no effect on the sampling efficiency of the Button sampler in a laboratory setting. Orientations ranging from 0° to 180° had no effect on the efficiency, nor did wind speeds of 0.5 m s^{-1} and 2.0 m s^{-1} (Aizenberg et al., 2000). The Button sampler was also found to have the highest precision when compared to other inhalable samplers, including the IOM sampler, by having the smallest coefficient of variation between repeat samples at 0°, 90°, and 180° (Aizenberg et al., 2000). These tests led researchers to believe that the Button sampler would be useful a personal inhalable sampler.

Witschger, Grinshpun, Fauvel, and Basso (2004) found that while the IOM sampler oversampled aerosol concentration at all particle sizes, the sampling efficiency of the Button sampler decreased as particle size increased in calm air. The Button sampled at 99% efficiency at a particle size of 7 μm and an efficiency of 59% at 76 μm. While the smaller holes in the screen can prevent large particles from entering the sampler and skewing results, these small holes can also be the cause of other problems. Reynolds, et al. (2009) found that when sampling agricultural dust from a poultry-producing environment, the holes of the Button sampler were clogged by large feather particles. This caused the sampling efficiency of the sampler to decrease to the point of being comparable to the CFC. Another large discrepancy of the Button sampler involves the sampling of liquid particles. Koehler, Anthony, Van Dyke, and Volckens (2012) found that the sampling efficiency dropped to less than 20% when droplets larger than 30 μm were introduced to the sampler. This was due to the droplets depositing on the screen and not entering through the pores to the filter. When 100 μm liquid droplets were used, seven times as much mass was deposited on the screen than was deposited on the filter (Koehler et al., 2012).

Although not as widely used as the IOM sampler, the Button sampler has been shown in studies to be a viable option for personal inhalable monitoring. The sampling efficiency was found to be only slightly lower than the IOM sampler in calm air and in moving air. The sampler performance underestimated relative to the inhalable criterion at particle sizes larger than 25 μm, which was hypothesized to be due to the spherical glass test particles being trapped on the porous screen (Görner, Simon, Wrobel, Kauffer, & Witschger, 2010). This finding is important as it identifies a limitation of the Button sampler.

Comparisons of Inhalable to "Total" Dust Samplers

With the emergence of new inhalable samplers and exposure limits based on inhalable criterion, there is a need to determine how inhalable measurements compare to historical "total" dust measurements. Industrial hygienists can use these comparisons to determine if control methods are effective at reducing exposures below inhalable limits, or epidemiologists can use these comparisons to relate epidemiological data collected using "total" dust sampling to inhalable sampling concentrations. Laboratory and field studies have sought to quantify the difference in sampled concentrations between the two methods of aerosol sampling. In a laboratory study by Görner et al. (2010) the sampling efficiencies of six different aerosol samplers were compared to the ISO inhalable convention using polydisperse glass microsphere test aerosol. The CFC performed the worst of the six samplers, sampling well under the inhalable convention, while the IOM sampler performed the best, sampling slightly more than the inhalable convention. The Button sampler sampled about 10% below the inhalable particulate matter curve. The IOM sampler was the only sampler to oversample compared to the standard. Another laboratory study by Mark, Lyons, Upton, and Kenny (1994) found that the IOM sampler had the closest sampling efficiency to the inhalable criterion using fused alumina test dust, but it did have much larger variability compared to other inhalable samplers tested. The 37-mm CFC had a sampling efficiency much lower than the inhalable criterion, as predicted. The walls of the cassettes were not wiped to account for particle losses.

Many other studies have compared sampling efficiencies of inhalable samplers to total dust samplers in the field. The goal of these studies was to calculate ratios and performance ratios, S, in order to relate the amount of dust collected with the inhalable and total dust samplers. The ratio is most commonly computed by performing a linear regression with the equation being:

$$E_{IPM} = S*E_{CFC}$$

where E_{IPM} is the exposure collected by the inhalable sampler and E_{CFC} is the exposure collected by the CFC, and the origin is forced through zero (Tsai, Vincent, Wahl, & Maldonado, 1996). The performance ratios calculated in various studies for the IOM sampler and CFC is summarized in Table 1. The results from these studies demonstrate the wide range of performance ratios found in the field. Harper and Muller (2002) reported a range of 1.19 to 19 for wood dust. Other studies have computed S factors for comparing inhalable concentration to “total dust” concentration for industries including bakeries, welding, metal mining, and woodworking.

Werner, Spear, and Vincent (1996) summarized these findings from 1980 to 1996 and reported that performance ratios demonstrate that concentrations collected by an IOM sampler (or other inhalable samplers) are higher than concentrations collected by the CFC. Werner et al. were motivated to compile these results was to generate universal performance ratios between CFC to IOM sampler measurement for a wide variety of processes and materials. These universal performance ratios can allow industrial hygienists and other occupational health specialists to compare historical to new data and to compare data collected to assess compliance with “total” dust standards to data inhalable dust exposure limits. Werner et al. recommends performance ratios (S) for the four categories of dusts, mists, hot processes, welding, and smoke.

The recommended S factor for dust is 2.5, 2.0 for mist, 1.5 for hot processes, and 1.0 for welding and smoke (Werner et al., 1996). These factors were determined from both worker exposure studies and laboratory studies. The size distribution of the airborne particles was the main factor for differences in the performance ratio by type of substance. Dusts generated mechanically contained particles much larger in size than what were found in smoke. The performance ratio was much higher for dusts than hot processes and smoke because dusts are made up of larger sized particles, where the collection efficiency differences between the CFC and the inhalable samplers were more pronounced. If most particles are larger than 50 µm, inhalable samplers will collect more particles than the CFC and thus will yield a higher concentration. Another study comparing the sampling efficiency of the IOM sampler to the open-face cassette reported a performance ratio of 2.0 for all dusts, and recommended that inhalable exposure limits be set two times higher than “total” aerosol exposure limits (Liden, Melin, Lidblom, Lindberg, & Noren, 2000).

These universal performance ratios are not appropriate for all situations. Harper and Muller (2002) do not recommend using the 2.5 performance ratio for dust when the dust of interest is wood dust. The average ratio of IOM sampler concentration to CFC concentration was 3.35, with a range up to 19. This wide range was attributed to particles larger than 100 µm being present in the wood dust, and oversampling of the IOM sampler due to the large opening of the sampler. Simple correction factors have been computed to scale these performance ratios more accurately relative to the size distribution of the dust being sampled. If the size distribution of the aerosol can be quantified a bias ratio can be computed which will allow the size distribution to be accounted for in these calculations (O’Shaughnessy et al., 2007). However, measuring a full size distribution of a dust may not be possible in the field as there is no field deployable equipment currently available to quantify size distributions larger than the approximately 30 µm. Partial size distributions may only be possible if particles in the dust are larger than 30 µm. For example, the Marple Personal Cascade Impactor (Thermo Fisher Scientific Inc., Waltham, MA.), a small personal impactor that could be deployed on a worker in the field has an upper cut point of 21 μm. While most dusts with mass median diameters less than 20 μm will be sized appropriately, this may not be possible for all inhalable dusts.

Objectives

The review of the current literature has shown that knowledge of the behavior of inhalable samplers is increasing, yet important questions still remain. Collection efficiencies of inhalable samplers are higher than "total" dust samplers when the aerosols contain a significant amount of larger size particle. Using a single S factor to apply to an entire category of aerosol may not be valid. Sampler comparison studies have been performed to compare inhalable dust exposures from "total" dust exposures, but uniform application is likely unwarranted. These performance ratios, S, are not equal to 1, and they vary due to differences in particle size.

The aims of this study will try to answer some of the gaps in understanding of the performance of inhalable samplers as they relate to "total" dust samplers. First, we evaluate whether the performance ratios between the Button sampler and the CFC equal to the performance ratios created by comparing the IOM sampler to the CFC. We also examine whether these two inhalable samplers (Button and IOM) collect similar concentrations that compare equally to the concentration collected by the CFC. Second, we examine factors specific to test dusts to evaluate performance ratios by dust material. Werner et al. (1996) recommend a performance ratio of 2.5 for all dusts, and we test whether this is a valid assumption. Finally, if the performance ratios vary by particle size, we examine whether the variability of the performance ratio is a predictable function of distance from the dust source. From these evaluations, we will provide specific recommendations to practicing industrial hygienists on how to relate historical "total" dust exposure data to new inhalable dust exposure limits.

Table 1 - Compiled performance ratios for inhalable vs. CFC concentrations from various processes, collected from the literature.

Process	Exposure	S_{range}	Author
Nickel Alloy	Nickel	1.70 – 2.18	Tsai, 1996
Lead Smelting	Lead	1.39 – 2.14	Spear, 1997
Lead Smelting	Cadmium	1.29 – 2.12	Spear, 1997
Hog Confinement	Agricultural Dust	1.02 – 1.10	Predicala, 2010
Hog Confinement	Agricultural Dust	0.80 – 3.20	Reynolds, 2009
Lumber mill	Wood Dust	1.83 – 2.22	Kauffer, 2010
Lumber mill	Wood Dust	1.19 - 19	Harper, 2002

CHAPTER II

PERFORMANCE RATIO ANALYSIS

Introduction

Inhalation exposure presents a major route for the industrial hygienist to control workplace exposures to hazardous substances. Personal samplers are designed to estimate the personal exposure of workers to aerosols and the sampling efficiency of these samplers has been researched extensively. Traditionally, personal aerosol sampling in the United States has been performed with a 37-mm closed face cassette (CFC). This sampler consists of two or three plastic filter holder pieces, with a 4-mm opening through which air and contaminants enter the cassette, resulting in particle deposition on a filter behind the opening (Mark, 1990). The mass of the aerosol collected by the CFC, combined with the volume of sampled air, is used to compute the “total” dust concentration and is the basis for regulatory compliance. The sampling efficiency of the CFC is near 100% for particles sized close to 1 µm, but efficiency drops to near 30% for particles 20 µm and greater (Kenny et al., 1999) In a wind tunnel study comparing the sampling efficiency of a CFC to the aspiration efficiency of a breathing mannequin, the CFC sampled only 26 to 35% of what the mannequin did. The CFC sampling efficiency does not accurately represent the efficiency of a human being (Sleeth and Vincent, 2012)

Since the 1970’s, as knowledge of aerosol behavior in the environment and within the respiratory system increased, efforts to collect a representative sample of aerosols that actually enters the respiratory system have been underway since 1978 (Ogden and Birkett, 1978). The inhalable fraction was defined to represent the amount of aerosol that enters the mouth and nose of an inhaling person, providing a biologically relevant representation of what a human would inhale (Soderholm, 1989). The equation for Inhalable Particulate Matter is given in the following equation:

(1)

where d_a is the aerodynamic diameter, in µm, and air velocity is less than 4 m s^{-1}. The inhalable particulate matter equation has a close to 100% sampling efficiency at particle sizes near 1 µm and a 50% sampling efficiency at a particle size of 100 µm. This standard has been accepted by ISO, CEN, and ACGIH. Dusts with health effects associated with all regions of the respiratory system have ACGIH TLVs that require exposure assessment using samplers that meet this inhalable particulate matter criterion (ACGIH, 2012). This coarser inhalable fraction is increasingly being used by professionals to better estimate worker exposure (Sleeth and Vincent, 2012).

Two commonly used personal inhalable samplers are the IOM sampler and the Button sampler. The IOM personal inhalable sampler (SKC Inc., Eighty Four, PA) is designed to sample aerosols with the same efficiency as the inhalable fraction (Mark and Vincent, 1986). The IOM sampler consists of a two-piece sampling cassette which holds a 25 mm filter, and a sampler housing. The IOM sampler has been found to oversample at particle sizes close to 100 µm when wind speeds are between 0.5 m s^{-1} and 4.0 m s^{-1}(Kenny et al., 1997) but under sample at larger particle sizes in wind speeds of 0.2 m s^{-1} (Kenny et al., 1999). Despite these limitations, the IOM sampler is the most commonly used inhalable sampler in the U.S. The Button sampler, developed in 1995 (Grinshpun, Willeke, Kalatoor, & Baron, 1995), is another inhalable sampler available for use (SKC Inc., Eighty Four, PA). The Button has a curved mesh inlet screen with pores of 381 µm, through which particles enter and deposit onto a 25 mm filter behind the screen. The Button sampler was created to minimize wind speed and direction sensitivity associated with other dust samplers (Aizenberg et al., 2000). Unfortunately, the Button sampler has been shown to have reduced efficiency when sampling liquid particles (Koehler et al., 2012), and large particles can clog the pores of the mesh screen causing the sampler to be more comparable to the CFC (Reynolds et al., 2009).

Even though inhalable samplers have been developed to provide improved estimates of inhaled dust concentration, the CFC remains the most commonly used sampler to measure exposures to “total” dust. The CFC has been in use for much longer than the newer inhalable samplers because it is disposable, familiar to practitioners, and is the reference sampler for regulatory exposure limits in the United States. However, the CFC aspirates particles with a much lower efficiency compared to the inhalable particulate matter curve for particles larger than 20 µm (Görner et al., 2010). Therefore, the mass collected by the CFC is generally less than inhalable samplers, especially if the size distribution of the aerosol being sampled includes particles larger than 20 µm.

Researchers have investigated performance ratios (S) to relate inhalable dust to total dust measured by CFCs using regression and weighted least squares analyses of collocated samplers. A study by Tsai et al. (1996) found that the IOM collected more dust than the CFC by a factor of two. A compilation of many field and laboratory sampler performance studies sought to establish a universal set of performance ratios that professionals could use to compare historical results to newer inhalable results. Werner et al. (1996) recommended an S factor of 2.5 for all dusts and coarse particles, meaning that an inhalable sampler collected a concentration 2.5 times higher than the CFC. However, this universal performance ratio has not been recommended for use by all researchers. A study comparing total to inhalable sampler mass concentrations in a wood processing plant yielded a mean S factor of 3.35 but ranged as high as 19 (Harper and Muller, 2002). The most common performance factor studies relate concentrations between an IOM sampler and a CFC. Fewer studies have investigated performance factors for the Button sampler.

Because of the variability in performance ratios within an aerosol category (e.g., “dust”) and within one process type (e.g., wood cutting), additional factors not previously studied may provide information about why these performance ratios are so varied. One factor that may be associated with the variability found in these performance ratios is distance of the sampler to the dust source. Large particles in the size range found in occupational dusts settle out of the air much faster than smaller particles. For example, a 100 µm particle has a settling velocity of 0.249 m s^{-1} compared to 3.48E-5 m s^{-1} for a 1 µm particle. In the very slow moving wind velocities found in the workplace, these larger particles will settle closer to the dust source as they will be in the air for less time than smaller particles. Hence, larger performance ratios may be identified when the samplers, or the worker wearing the samplers, are closer to dust sources where large particles may have not yet settled.

The objective of this study was to compare the sampler performances of inhalable and “total” dust samplers from a bulk-product dispensing unit in a still air chamber. There were three specific aims to this study. The first was to quantify the variability in performance ratios (“S factors”) based on dust types. The second aim was to calculate the variability in performance ratios based on inhalable sampler type. The final aim of this study was to quantify the impact of distance from a dust source on performance ratios. Finally, we provide recommendations to industrial hygiene practitioners to determine how to best relate inhalable to CFC “total” dust exposure data.

Methods

Experimental Setup

All experimental tests were conducted inside of a large, still air chamber (3.14 m long x 1.90 m wide x 2.08 m high). The chamber prevented wind from entering and kept the wind speed to a minimum, much like in most occupational settings (Baldwin and Maynard, 1998). Figure 1 displays the experimental setup apparatus. A gravity fed dust generation system was used to represent a common process that workers may encounter, such as a bag feeding operation. To generate airborne dust, the bottom opening of a 30 gallon induction feeder (Ace Roto-Mold, Hospers, IA) was placed at a height of 1.0 m above the ground. In order to control the flow of the dust substances from the induction feeder, a blast gate (McMaster-Carr, Elmhurst, IL) was attached to the bottom. Also, in order to prevent the dust substances from sticking inside of the feeder due to their moisture content, a paint stirrer (Kobalt, N. Wilkesboro, NC) was attached to a drill (Black and Decker, New Britain, CT) and mounted inside of the feeder. The drill was operated at 2500 rpm for each test. The drill was not used for the glass microbead trials. The blast gate was adjusted so that each test took five minutes to empty the contents of the induction feeder onto the floor.

Three different dust sources were dispensed from the feeder: sawdust (bulk material from radial saw collection system, multiple wood types), flour (Gold Medal All Purpose, Minneapolis, MN), and glass microbeads (Grade 2530, Potters Industries, Malvern, PA). These bulk materials were chosen because they contain a significant amount of particles in the inhalable size range. The dust materials in this study have been used in the literature before (Werner et al., 1996). The bulk dust materials were sieved to create appropriate size distributions. The mass median diameter (MMD) of the bulk sawdust was 297 µm (GSD = 3.01), the MMD of the bulk flour was 83.3 µm (GSD=1.22), and the MMD of the glass microbeads was 51 µm (GSD=1.18). Glass microbeads were chosen to provide a dust type that would differ in moisture content than the sawdust and flour.

Aerosol Samplers

Three aerosol samplers were used in this study, two inhalable samplers (IOM, Button) and one total dust sampler (37-mm closed face cassette). To sample dust concentrations within the chamber, four stands were placed inside of the chamber, on center, at four distances from the dust generating device (Figure 1). Samplers positioned on the stands at 1.5 m above the ground to simulate worker height. At each position, three samplers were positioned within 6 cm of each other, oriented as recommended by the manufacturer/literature, as indicated below.

The IOM inhalable aerosol samplers with plastic cassettes (SKC Inc., Eight Four, PA) were used. Each IOM cassette was loaded with a 25 mm PVC filter, and transportation caps sealed the units when not in use. The IOM samplers and filter media (25 mm PVC, pore size 5.0 µm; SKC Inc., Eighty Four, PA) were placed in a temperature and humidity controlled room for seven days prior to obtaining pre-weights and seven days after use prior to obtaining post-weights to minimize weight fluctuations, as recommended by Liden et al. (2001). The IOM cassettes were only handled with gloves in order to prevent unwanted weight gain to the cassette (Liden et al., 2001). The IOMs were connected to personal sampling pumps that were operated at a flow rate of 2 L min^{-1} and were oriented with the inlet facing the feeder.

Button samplers (SKC Inc., Eighty Four, PA) were also loaded with 25 mm PVC filters. Filters were handled in the same manner as with the IOM filter media. The sampling pump connected to the Button sampler was operated at a flow rate of 4 L min^{-1}, as prescribed by the manufacturer, and was hung vertically with the inlet facing the feeder. The third sampler used was the three-piece 37-mm closed face cassette (CFC). The CFC housed a 37 mm PVC filter (pore size 5.0 µm; SKC Inc., Eighty Four, PA) and a cellulose back-up pad.

The IOM and Button samplers were hung vertically, with the openings directly facing the source. The CFC samplers were hung with the opening facing approximately 45° below the horizontal, facing the feeder. The openings of each sampler were lined up in order to make sure each sampler was located at the same distance relative to the dust generating device. One IOM, Button, and CFC sampler were positioned on stands at 0.31, 0.91, 1.52, and 2.13 m from the dust feeder, resulting in a total of 12 samplers per trial. The position of the samplers (left, center, right) at each of these distances was randomly selected for each trial.

Sampling and Analytical Procedures

Every sampler was connected to and operated with a personal sampling pump (SKC Aircheck, Model #224-XR). Personal sampling pumps were pre- and post-calibrated to the required flow rate using a Defender DryCal (BIOS Int., Butler, NJ) on each sampling day. If pre- and post-calibration flow rates differed by 5%, they were not considered acceptable for analysis and the entire event was rerun. Sampling began as the materials began flowing through the induction feeder, continued through the five-minute period of material flow, and continued for an additional five minutes after the feeder was emptied. This sampling period was determined to provide sufficient mass deposition (1.0 – 1.5 mg) on all filter types without overloading (2.0 mg) the filters, according to NIOSH Method 0500 (NIOSH, 2003). Over all tests, the mean temperature and relative humidity in the chamber were 81°F (SD=4.16°F) and 30.6% (SD=13.2%), respectively.

All filters and filter-cassettes were weighed three times before and after sampling using a microbalance (SN M49950, Mettler Toledo, Columbus, OH.) with a limit of detection of 0.04 mg. Gravimetric weights were determined by subtracting the average pre-weight from the average post-weight. Dust concentration was calculated by dividing the weight gain by the product of flow rate and sample duration. All filters were stored and allowed to equilibrate in a humidity and temperature controlled room where they were also weighed. Over the duration of this study, the mean temperature inside the weighing room was 71.6°F (SD=3.3) and mean relative humidity was 26.6% (SD=8.8).

Data Analysis

Eight trials were performed for each of the three test materials (24 trials in total). Twelve samples were collected in each, leading to a total of 288 samples collected. Concentration data were tested for normality using a Shapiro-Wilk test and descriptive statistics were generated (Table 2). Linear regressions, forcing the intercept through the origin (Tsai, 1996), were performed comparing inhalable samplers to the CFC, with the slope providing the between-sampler performance ratios. A two sample t-test was performed to assess whether significant differences in performance ratios computed were present between the IOM sampler and Button sampler.

A linear regression model was used to investigate the effects of distance on these slope factors, as follows:

(2)

where [Sampler 1] is the concentration of the inhalable sampler, [Sampler 2] is the concentration of the “total” dust sampler, and β_1 is a “distance factor.” This “distance factor”, β_1, was evaluated for significance to assess whether distance contributed to change in the performance ratio (S). Non-parametric tests were also used to examine whether distance from the source impacted estimates of sampler performance ratios: Tukey’s test for multiple comparisons was performed for each dust type to assess differences in the average concentration collected by all three samplers at each of the four sampling locations. Data analysis was performed using Microsoft Excel and SAS v.9.3 (SAS Institute, Cary, NC). A significance level of 0.05 was used for all statistical tests.

Results

Descriptive statistics for data collected by each sampler type are provided in Table 2. Figures 2 and 3 illustrate the concentration measures from the flour dust trials, where data paired by position and test are plotted for the eight tests. (Appendix C contains data comparisons for additional materials and samplers.) As shown in Figure 2, the IOM sampler collected more dust than the CFC, as evidenced by the linear regression above the 1:1 line in the graphs with a slope of 2.8. Figure 3 illustrates that the Button sampler collected nearly the same concentrations as the CFC, with a slope equal to 1.04. The performance ratio of the Button/CFC was at or near 1.0 for all three dusts. Table 3 summarizes the performance ratio (S) for each of the three dust materials. For all material types, the IOM/CFC was larger than the Button/CFC. The R^2 values ranged from 0.88 to 0.38 for the simple linear regressions. The R^2 value for the IOM/CFC linear regression for sawdust had an R^2 value of 0.85. While the Button/CFC relationship was strong for sawdust (0.82), the variability in data for the glass bead sampler performance tests was less explained by the model (R^2=0.38). A two sample t-test comparing the performance ratios collected for the IOM/CFC comparison to the Button/CFC comparison showed a significant difference between the two inhalable samplers for all dust types (p=0.049)

Table 4 presents the results of the linear regression model (equation 2) investigating the whether the distance from the source is a significant contributor to the estimated performance factor (S). The performance ratio (S) and the distance factor, β_1, are provided, along with estimates of statistical significance for each term and the R^2 value for each regression. Distance provided significant improvement to the estimate of the relationship between an inhalable sampler and the CFC for sawdust only. The β_1 value for the Button to IOM sampler relationship approached significance, with a p value = 0.055. In all other tests, β_1 did not significantly differ from 0 in providing an estimate to the relationship between samplers. The performance ratios calculated using the distance model were similar except for the IOM-to-CFC and Button-to-CFC comparisons for glass microbeads. No single R^2 value for the distance model was computed to be over 0.12, demonstrating a poor fit to the model. At best, the distance model only accounted for 12% of the variation in the predicted outcome of sampler concentration.

Results from the Tukey's multiple comparison tests are located in Table 5 through 7. The objective of these tests was to compare the average concentration collected by all three samplers across the four different sampling locations. These tests identified that for sawdust, a difference in average concentration collected by all samplers was significant between the closest (0.30 m) and the farthest (2.1 m) sampling positions. Flour was the only dust that had no significant differences in average concentration collected by all samplers as the distance from the source increased.

Discussion

In this study we observed that the performance ratio, S, of commonly available dust samplers varied according to dust type. The performance ratios computed in this study were not consistent with the recommended 2.5 for all dust types by Werner (1996). Over three dust types studied here, the IOM/CFC performance ratios ranged from 1.6 for sawdust to 3.0 for glass microbeads, although the 95% confidence intervals for the two dust substances did overlap. These ratios were highly variable in the comparison of inhalable concentrations to "total" dust concentrations. The performance ratio computed for the glass microbeads was 1.8 times larger than the performance ratio for sawdust, for the IOM/CFC comparison. The use of the conventional S of 2.5 to convert "total" dust measurements to estimates of inhalable dust would lead to an underestimate of concentration for the glass microbeads and flour, as the two inhalable concentrations were shown to be 2.8 and 3.0 times higher than "total" concentration. The use of the 2.5 ratio would also lead to an overestimate of inhalable sawdust concentration, which was only 1.8 times larger than "total" concentration.

Different dust materials were chosen for this experiment in order to test the difference in S factors over a variety of size ranges. These S factors can be found in Table 3. It was presumed that airborne dusts that contain larger more large particles in its size distribution would have a higher IOM/CFC performance ratio compared to aerosols with smaller particles, because the CFC is known to under sample larger particles relative to the IPM criterion. In this study, the sawdust had the lower IOM/CFC performance ratio, while flour and glass microbeads had higher ratios. This implies that the sawdust had smaller particles relative to the other two test dusts. Previous literature suggests wood dust would have the largest sized particles of the three test materials.

The dust generation method used in this study involved dispensing dust directly on to the ground. It is possible that the largest particles of the sawdust remained on the floor after being dispensed, and energy of these particles projected the smaller particles into the air throughout the chamber. This would lead to only the much smaller sawdust particles being suspended in the air, and thus resulting in a lower IOM/CFC performance ratio.

The bulk flour contained smaller sized particles than the bulk sawdust, but the IOM/CFC ratio for flour was higher than the ratio for sawdust. Unlike the largest sawdust particles that were unlikely to become airborne, the largest flour particles were small enough to become airborne, leading to a higher performance ratio for flour over sawdust. The glass microbeads had the lowest collected concentrations, but the highest performance ratio. This is due to the mass median diameter of the glass beads being 51 μm, which is in the size range where the sampling efficiencies of the IOM sampler and CFC differ greatly. The CFC does not collect particles at this size as efficiently as the IOM sampler, meaning most of the concentration present in the air was not sampled by the CFC. The wood dust samples had much higher variability than the glass microbead samples for the IOM sampler (SD=38.4 and SD=6.82) also. Side-by-side comparisons of inhalable concentration and "total" concentration should be performed by professionals for each dust type or aerosol exposure found in the workplace in order to account for this variability.

We also observed that the performance ratio varies by inhalable sampler type (Table 3). The IOM/CFC performance ratio over all dust types was found to be significantly different than the Button/CFC performance ratio (p=0.049). The Button sampler had a performance ratio of approximately 1.0 or less when compared to the CFC, whereas the IOM sampler had a performance ratio ranging from 1.6 to 3.0 when compared to the CFC. Furthermore, the 95% confidence intervals for the IOM/CFC performance ratios did not overlap the confidence intervals for the Button/CFC performance ratios for any of the three dust substances. The performance of the two inhalable samplers was not equal in this study, and the use of an equal performance ratio is not appropriate. We attribute this finding to the differences in design of the two inhalable samplers, mainly the one large opening of the IOM sampler compared to multiple openings on the Button sampler. Reynolds, et al. (2009), also found the Button sampler to perform more closely to the CFC, due to particles becoming lodged in the small mesh openings and thus decreasing airflow through the filter. Concentrations collected by the Button sampler ranged from a factor of 0.57 to 0.80 times the concentration collected by the IOM sampler. The front mesh screens of the Button samplers were often covered in the dust material after a trial, thus large sized wood and flour particles may have blocked the openings of the Button sampler in this experiment, and stuck to the front mesh screen causing a decrease in sampling efficiency.

Another factor leading to the decreased sampling efficiency of the Button sampler may have been the moisture content of the dust materials. Koehler et al. (2012) discussed decreased sampling efficiencies of the Button sampler with completely liquid materials, but no research has been found on the performance of the sampler with dusts of high moisture content. The moisture in the sawdust and flour may have caused the dust to cling to the front of the mesh screen instead of enter the sampler. The glass beads did not have high moisture content, but the Button sampler only sampled 11% of the concentration sampled by the IOM sampler. These particles may have been more likely to bounce off of the mesh screen of the Button sampler and fall away from the sampler, whereas there was no surface for the glass microbeads to bounce off of on the IOM sampler. The Button sampler did not exhibit the performance characteristics of an inhalable sampler collected much lower concentrations than the IOM sampler. The limitations in the performance of the Button sampler, especially when sampling sticky, or high moisture content, dusts needs to be considered by the industrial hygienist when choosing an inhalable sampler.

The effect of distance from the source performance ratios between “total” and inhalable dust was observed to have little influence. The results of the regression model demonstrate that distance most likely has no significant effect on these performance ratios within 3 m from the dust generating device. The only test in which distance from the feeder was significant was for sawdust at 0.3 compared to 2.1 m from where materials were dropped. In examining sampler performance ratios by distance (Table 4), only the sawdust IOM/CFC ratio had a statistically significant distance term at $\alpha = 0.05$. This is consistent with the theory that larger particles will settle closer to the source. The low R^2 value of the significant finding, the IOM to CFC comparison for sawdust, demonstrates that an unknown variable may have been contributing to the variability found in the model. An investigation into the flow patterns inside the chamber did not reveal any inconsistencies which may have affected the movement of the dust. Four of the nine computed distance factors were negative, which indicate that the Inhalable to CFC ratio decreased with increased distance from the source, as expected. As distance from the source increased and the larger particles settle out of the air, sampling efficiencies for the smaller particles still left in the air will be similar for the inhalable and “total” dust samplers. Thus a decrease in S as distance increases was expected.

The R^2 values for the simple linear regression model were much higher than for the distance model regression, indicating a much better model fit. The distance models computed only were able to explain between 5-10% of the variability in the predicted concentration values. The simple linear regression model is more appropriate to use when computing an S factor to compare inhalable concentrations to “total” dust concentrations.

While distance was not found to have a significant difference on performance ratios, actual measured concentrations were significantly different at further distances from the source, as shown in Tables 5. For sawdust, the average concentration at 0.30 m from the dust source for all samplers was different than the average dust concentrations at 1.5 and 2.1 m from the source. More information is needed about the size distribution of the dust at each location in the chamber to determine if this was due to the large particles settling closer to the dust source or dilution of concentration from the source. Optical sizing of the particles collected on filters at each sampling location would accomplish this task.

Specific recommendations for industrial hygienists are provided after analyzing the data and results from this study. Under this scenario, the data showed that distance from the source plays no significant role in converting total dust concentrations to inhalable dust concentrations. This information can be of use to the occupational health professional. Industrial hygienists who use a CFC to sample for airborne aerosol exposure do not need to include distance from the source when converting to inhalable concentrations, within 2 meters of the dust source. While the size distribution of the particles inside this 2-meter radius may change, the difference was not substantial enough to affect sampler performance under these conditions. This data also confirmed what other studies have shown, namely that the IOM to CFC performance ratios are much more variable than the generally applied 2.5 (Werner, 1996). There were large 95% confidence intervals for each dust substance, and the confidence intervals for flour and glass microbeads bound the 2.5 value. While one performance ratio is needed for all distances within 2 meters, it is advised not to use a constant S for every dust type or inhalable sampler. Side-by side comparisons of IOM sampler concentration to CFC concentration should be performed to determine an appropriate performance ratio for each specific task. In this experiment an IOM to CFC performance ratio for dispensed sawdust was computed to be 1.6, whereas Kauffer (2002) computed performance ratios for wood dust ranging from 1.83 to 2.22. Due to the high variability in performance ratios computed for each dust type, performance ratios for each specific task will provide much more appropriate estimations of inhalable aerosol exposure to workers. These direct comparisons will ultimately allow the industrial hygienist to better understand historical exposures to inhalable dusts from the classic “total” dust measures from

CFC samplers, providing better estimates of exposures and decisions to focus efforts on worker's health protection.

Professionals should also consider the moisture content of the dust being sampled, when comparing historical to current exposures for a certain process. If the materials used in the process have changed over time, differences in moisture content of the dusts created may cause performance ratios to vary. The moisture content of the dust presents a challenge for the Button sampler, and can significantly decrease the sampling efficiency of the sampler. Industrial hygienists should use caution when selecting a Button sampler due to this decrease in sampling efficiency. These collection efficiency problems have not been observed in the IOM sampler.

While the results of this study demonstrate the large variability around the 2.5 performance ratio, there are situations where the use of 2.5 is appropriate. The simple linear regression results provided S values not equal to 2.5, but the performance ratios bound that value. The commonly used 2.5 performance ratio is within the range of results found, and can be useful as a starting point for industrial hygienists. When time is limited and side by side sampling cannot be performed, 2.5 will provide a rough estimate of inhalable concentration of aerosol in the workplace. Epidemiologists will also find the 2.5 value appropriate for use in long term studies using historical "total" dust data. This performance ratio will allow the epidemiologists to relate health effects found under "total" dust concentrations to inhalable dust concentration levels.

There were limitations in this study that may have prevented the finding of significant results. The dust generating device was created to simulate a process that may be found in the workplace, but the between-trial variability in the concentration of dust created was fairly high, which can be seen by the differences in concentration found in Figures 2 and 3. Variability in concentration measurements may have reduced our ability to identify significant differences from zero for distance factors. Precautions were taken to ensure uniformity, but the method needs more refinement. The use of the drill to dispense dust from the induction feeder may be the source of this variability. Due to moisture content of the dust materials used, the drill was used to prevent the materials from sticking to the sides of the induction feeder. The drill was not used for the glass microbead trials, which also produced the lowest concentrations of the three dusts. The use of the drill may have increased concentration inside the chamber due to increased dispensing speed.

The plots in Figures 2 and 3 display that measured dust concentrations in these experiments varied over an order of magnitude for a given dust type. Average concentration for sawdust 72.8 mg m^{-3} which is much higher than any exposure concentrations reported in the literature, including 40 mg m^{-3} (Harper, 2002). The study examined field exposures though, not concentrations created by dispensing wood dust as was done in this study. In certain trials, large amounts of dust were dispensed very quickly, leading to large concentrations of aerosol in the air, whereas other times the dust may have been dispensed much more consistently over the five minutes. A consistent stream of dust was not able to be dispensed through the entire five minutes using this method, but the feeder was emptied in the five minutes the drill was used. These dispensing speeds were most likely also slower than found in industry.

Due to the variability and large range of performance ratios calculated for different dust types and for different samplers, the use of a single performance to compare all inhalable and "total" dust concentrations may provide inaccurate concentrations under these laboratory conditions. Side-by-side sampler comparisons should be made to relate historical total dust exposures to current inhalable measurements. Separate performance ratios for each substance within a given worksite and production process needs to be determined to account for the wide variability found in this study.

Conclusion

The objective of this study was to compare sampler performance between inhalable and "total" dust personal samplers. Two inhalable samplers and one "total" dust sampler were used to collect airborne aerosols for three dust types in a still air chamber; sawdust, flour, and glass microbeads. The concentrations collected by these samplers were used in two separate regression analyses in order to compare the results from the inhalable samplers to the “total” dust sampler, and to create performance ratios that will predict the amount of inhalable aerosol present based off of the “total” dust sample. The calculated performance ratios were found to differ between dust types, and were not similar to the most commonly used performance ratio of 2.5 for all dust types in this laboratory setting. Performance ratios were also found to differ between the two inhalable sampler types used in this study; the IOM and the Button samplers. Unexpectedly, the Button sampler performed similarly to the CFC sampler, with performance ratios to be near 1.0, whereas the IOM sampler collected much more dust than the CFC and had computed performance ratios higher than 1.0. One additional objective of this study was to quantify the effects of distance on the computed performance ratios, using a regression model and an added “distance factor.” Only one sampler for one dust type, the IOM sampler and sawdust, displayed a significant relationship between performance ratio and distance. The distance factor computed was negative which demonstrated that the performance ratio decreased as distance from the dust source increased, due to larger particles settling out of the air closer to the source. Distance was not found to be significantly related to performance ratio for any other sampler or dust type.

We strongly suggest that industrial hygienists use caution when converting “total” dust concentrations to inhalable concentrations using the 2.5 performance ratio most commonly used. The variability found in this performance ratio over dust type and sampler type may lead to significant over- or under-estimations of worker exposure to dusts in the workplace. If performance ratios are necessary, we suggest performing side by side sampling of inhalable and “total” samplers for each process in order to compute appropriate performance ratios. Distance of the worker does not need to be taken into account when computing this ratio if the worker is within 2 meters. Inhalable aerosol sampling is recommended over “total” aerosol sampling in order to better estimate a worker’s personal exposure, which will in turn allow the industrial hygienist to better protect that worker’s health.

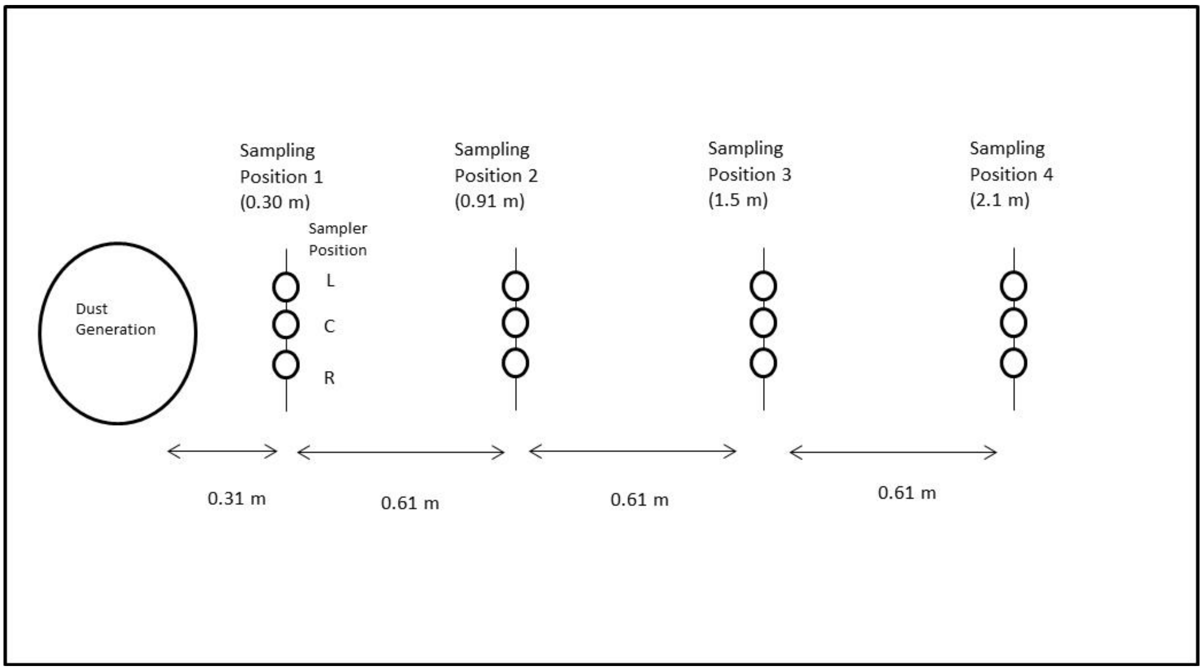

Figure 1 – Overhead view of experimental apparatus.

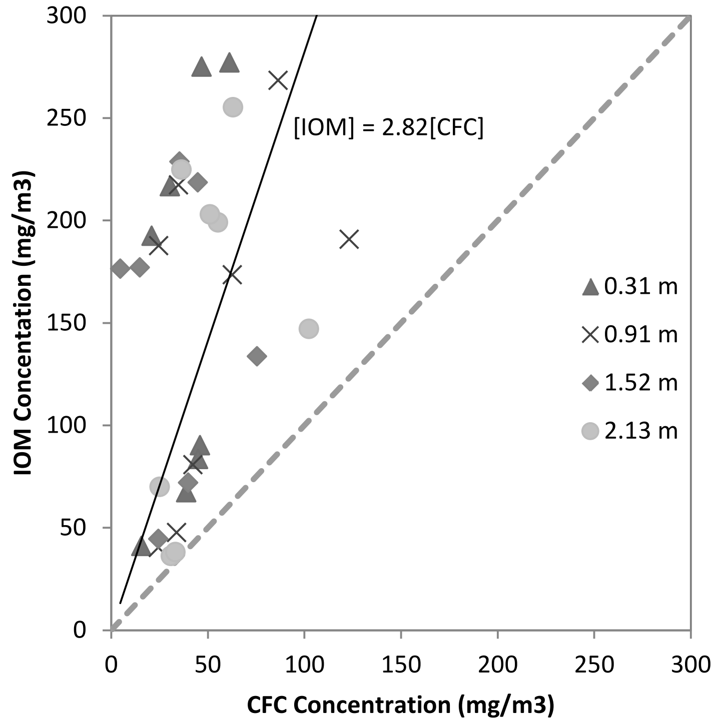

Figure 2 - IOM and CFC concentrations collected for flour trials.

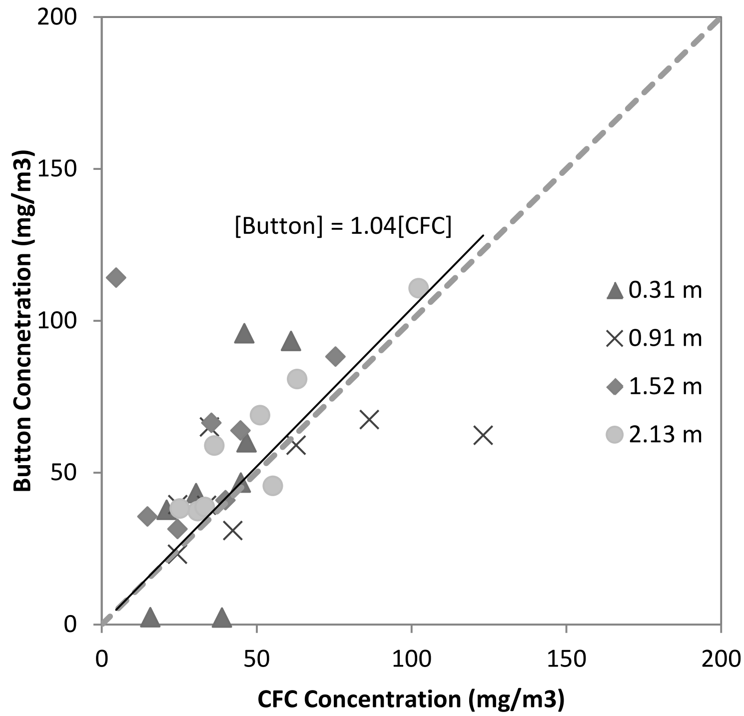

Figure 3 - Button and CFC concentrations collected for flour trials.

Table 2 – Mean concentrations and standard deviations for all sampler types, dust types, and sampling locations.

	Mean Aerosol Concentration (SD), mg m^{-3}				
Distance	All	0.30 m	0.91 m	1.5 m	2.1 m
Sawdust					
IOM	72.8 (38.4)	102 (51.4)	90.1 (30.6)	49.2 (17.4)	52.3 (17.9)
Button	36.9 (19.0)	47.3 (24.6)	32.5 (18.0)	31.2 (13.5)	34.8 (18.0)
CFC	43.4 (17.7)	51.0 (24.0)	49.1 (15.7)	37.6 (12.2)	34.5 (12.5)
Flour					
IOM	151 (81.2)	155 (96.0)	151 (84.1)	150 (70.5)	147 (87.6)
Button	54.4 (27.4)	47.7 (35.4)	48.3 (17.1)	62.9 (30.3)	59.9 (26.0)
CFC	44.4 (25.6)	38.1 (15.0)	54.1 (35.0)	34.2 (23.1)	49.7 (25.0)
Glass Beads					
IOM	12.6 (6.82)	16.9 (9.46)	11.5 (5.04)	11.1 (5.19)	11.0 (5.99)
Button	1.86 (1.07)	2.97 (1.30)	1.61 (0.78)	1.54 (0.65)	1.30 (0.65)
CFC	2.29 (1.93)	2.94 (2.65)	2.51 (2.19)	2.30 (1.33)	1.42 (1.25)

Table 3 - Simple linear regression results for concentration data for all dust types and sampler comparisons.

Dust Substance	S	95% CI	R^2
Sawdust			
IOM/CFC	1.62	(1.37, 1.87)	0.85
Button/CFC	0.82	(0.71, 0.93)	0.88
Button/IOM	0.46	(0.38, 0.54)	0.81
Flour			
IOM/CFC	2.82	(2.15, 3.49)	0.71
Button/CFC	1.04	(0.98, 1.10)	0.77
Button/IOM	0.32	(0.11, 0.53)	0.81
Glass Microbeads			
IOM/CFC	2.97	(1.59, 4.35)	0.38
Button/CFC	0.57	(0.41, 0.73)	0.64
Button/IOM	0.11	(0.08, 0.14)	0.62

Table 4 - Linear regression results using distance model for all dust types and sampler types.

Dust Type	S	95% CI	β_1	p	R^2
Sawdust					
IOM/CFC	2.17	(1.69, 2.65)	-0.34	0.05	0.12
Button/CFC	0.87	(0.61, 1.13)	0.011	0.91	0.0004
Button/IOM	0.38	(0.15, 0.61)	0.159	0.055	0.11
Flour					
IOM/CFC	4.56	(-0.46, 9.58)	0.282	0.87	0.0009
Button/CFC	1.26	(-1.89, 4.41)	0.61	0.59	0.01
Button/IOM	0.29	(0.09, 0.49)	0.13	0.085	0.099
Glass					
IOM/CFC	30.4	(2.64, 58.5)	-9.19	0.36	0.03
Button/CFC	3.59	(0.67, 6.51)	-1.14	0.27	0.04
Button/IOM	0.24	(0.12, 0.36)	-0.037	0.38	0.025

Table 5 - Results from Tukey's Test for Multiple Comparisons for sawdust mean concentration collected by all inhalable samplers, at the four different sampling locations.

Distance from Source	0.30 m	0.91 m	1.5 m	2.1 m
0.30 m	---	0.4944	0.0043	0.0120
0.91 m	---	---	0.1591	0.2972
1.5 m	---	---	---	0.9855
2.1 m	---	---	---	---

Table 6 -Results from Tukey's test for multiple comparisons for flour mean concentration collected by all inhalable samplers, at the four different sampling locations.

Distance from Source	0.30 m	0.91 m	1.5 m	2.1 m
0.30 m	---	0.9997	0.9963	0.9998
0.91 m	---	---	0.9898	0.9982
1.5 m	---	---	---	0.9989
2.1 m	---	---	---	---

Table 7 - Results from Tukey's Test for Multiple Comparisons for glass beads mean concentration collected by all inhalable samplers, at the four different sampling locations.

Distance from Source	0.30 m	0.91 m	1.5 m	2.1 m
0.30 m	---	0.1905	0.1433	0.1149
0.91 m	---	---	0.9989	0.9943
1.5 m	---	---	---	0.9996
2.1 m	---	---	---	---

CHAPTER III

CONCLUSIONS

This study assessed the validity of comparing inhalable dust concentrations to “total” dust concentrations using a performance ratio under laboratory conditions. This ratio allows professionals to convert “total” dust concentrations to inhalable dust concentrations. The performance ratio was compared over three dust types and two different inhalable dust samplers, and the effects of distance on the performance ratio were investigated as well. Four sampling stations were set up inside of a calm air chamber, at distances of 0.30, 0.91, 1.5, and 2.1 m from a dust source. An IOM sampler, Button sampler, and a 37-mm closed-face cassette (CFC) were attached 1.5 m from the floor at each of the four sampling locations, and dust concentrations were collected for eight trials of each of the three dust types.

Evidence in Chapter II suggests that the use of a single performance ratio for all dust types is not valid, as performance ratio varied between sawdust, flour, and glass microbeads. When only comparing IOM concentration to CFC concentration, a performance ratio of 1.62 was calculated for sawdust, 2.82 for flour, and 2.97 for glass microbeads. These three performance ratios varied greatly, and zero of the three performance ratios were equal to the most widely used ratio of 2.5.

IOM to CFC performance ratios ranged from 1.62 to 2.97, whereas Button to CFC performance ratios were near 1.0. This suggests that the Button sampler behaved more similar to the CFC than the inhalable IOM sampler. This finding was attributed to the high moisture content of the dusts causing the dust to cling to the mesh screen of the Button sampler instead of going through the pores and on to the filter.

Finally, the effects of distance from the dust source were investigated in this study. Distance was not found to be statistically significant from zero for any dust type or sampler type, with the exception of the IOM sampling sawdust. Dust concentration did not change significantly enough throughout the sampling chamber to cause a decrease in performance ratio as distance from the source increased.

The large amount of variability in the dust concentrations created inside of the chamber between trials is a main limitation in this study. The standard deviation of concentration created inside the chamber ranged from 96 to 0.65 mg m^{-3} for different sampler types and dust types. A more constant method of dispersing the dust into the air in the chamber may have decreased this variability. The high variability in these concentrations may have led to the lack of statistically significant findings, specifically in the use of the distance model.

Future research into the effects of distance from the source on performance ratios are warranted as this, to our knowledge, is the lonely study to investigate the effects of distance. Previous studies have either taken place in the field, where a worker’s distance from the source does not remain constant, or a laboratory where sampling only occurs at one distance from the dust source. A low velocity wind tunnel study with a constant dust generating method may decrease variability in concentrations created, which would either validate the findings of this study or find significant differences in performance ratio as distance increases from the source. Sampling at distances greater than two meters from the dust source would also be helpful. A greater understanding of how to calculate and use these performance ratios is needed because “total” dust sampling is still a commonly used method of determining a worker’s exposure to airborne aerosol, and this method has been shown to underestimate the true exposure. The inhalable fraction more accurately represents the amount of aerosol that enters a human’s nose and mouth while breathing and inhalable aerosol sampling can give professionals a better picture of worker exposure.

Recommendations for the use of performance ratios by professionals are made in this study. Industrial hygienists are advised to use caution when applying a performance ratio of 2.5 to convert “total” aerosol concentrations into inhalable aerosol concentrations. This conversion may be necessary to compute historical inhalable exposures from “total” measurements, in order to provide better estimates of exposure for future decisions on protecting worker health.

Industrial hygienists are encouraged to create personal, task specific performance ratios for their own facilities and environments, in order to more accurately assess worker exposure. Side-by-side exposure sampling with an IOM and a CFC placed on workers are recommended to compute specific performance ratios for each task in order to examine the relationship between traditional CFC samplers and more physiologically relevant inhalable dust samplers. Due to the high variability in performance ratio between dust types, the design of task-specific performance ratios to estimate inhalable concentration from "total" concentration will prevent professionals from underestimating or overestimating a worker's aerosol exposure by using an inaccurate metric to convert "total" dust concentration to inhalable dust concentration. Professionals are also advised to use caution in selecting an inhalable sampler with regards to the moisture content of the dust sampled. A final recommendation to professionals is to only use these performance ratios if inhalable sampling is not a viable option.

The variability in S found in this study demonstrates the uncertainty in using a single performance ratio. The ultimate goal of the industrial hygienist is to protect worker health, in order to prevent workplace injury and illness. The use of these performance ratios can lead to an underestimate of a worker's aerosol exposure which could potentially have negative consequences. Industrial hygienists should perform inhalable aerosol sampling when possible, as it more accurately represents the biological does of aerosol inhaled by the worker. Despite the limitations, the results found in this study are important and can provide important information to both professionals and researchers.

Many lessons were learned throughout this process that would improve this study if completed again. First, I gained familiarity with personal aerosol samplers and the process of collecting concentration and exposure data that will be used throughout the rest of my career as an industrial hygienist. By going through the entire process from collecting aerosol, obtaining gravimetric weight, and to calculating concentration, I gained an understanding of all the steps that go into obtaining accurate data. For example, the relative humidity level of the balance room did not remain constant throughout the summer, which led to different gravimetric weights measured for filters on two different days. A trial was performed where a set of filters with sawdust were weighed over seven days to determine how long weight stabilization took. It was determined that filters maintained a stable weight after seven days inside the balance room, and all filters used in this study were allowed seven days to stabilize. All laboratories used in my professional career will need to assure that samples are kept at constant temperatures and humidity levels due to this project.

Another lesson learned in this study was to position the collocated samplers within 6 cm of each other when sampling side by side at each of the four sampling locations. The first round of sampling for sawdust was conducted with the three samplers used in this study being placed around 0.3 m away from one another. With the samplers this far apart, the concentration of dust in the air at the location of the IOM may not have been the same as the location of the Button or CFC. This discrepancy would defeat the purpose of this study, as concentrations collected by the different samplers could not be compared. Originally starting out with the samplers collocated much closer to one another would have saved a lot of time in the completion of this project.

One piece of data that is missing in this study is the measured size distributions of the airborne dusts used. The bulk materials were sieved to create size distributions, but these may not have been representative of the particles that became airborne. This information would help provide a better picture of particle behavior inside of the chamber.

The information from this study that made the largest impression on me, and will always be considered as an industrial hygienist, is the knowledge gained on the topic of inhalable versus “total” dust sampling. As an industrial hygienist it will be my job to protect workers’ health, and I feel that measuring airborne aerosol exposure with inhalable samplers instead of “total” dust samplers will allow me to better achieve this objective. The inhalable criterion is scientifically based on human aspiration, and takes into account much larger particles that are not sampled by a CFC. I will always choose inhalable aerosol sampling when possible. I will also use performance ratios to convert “total” dust concentrations to inhalable concentrations with caution, because I have seen first-hand through this project the variability involved with these ratios. The commonly used performance ratio of 2.5 can provide a starting point estimation of inhalable concentration for many dusts found in the workplace, but when time and funds allow I plan to create my own performance ratios.

APPENDIX A. RAW COLLECTED DATA

This appendix lists the data that went into calculating the concentrations used in the analysis for this study. Gravimetric weight, sampling pump flow rate, time sampled, and calculated concentration are included in the following tables.

Table A1 - Raw data collected for sawdust trials with IOM.

Filter	Run #	Position	Time (seconds)	Time (minutes)	Flow Rate (L min^{-1})	Air Volume (L)	Air Volume (m^3)	Weight (mg)	Concentration (mg m^{-3})
IOM-25	7	1	623	10.4	1.9946	20.7	0.0207	1.810	87.4
IOM-26	7	2	623	10.4	2.0960	21.8	0.0218	3.000	138
IOM-27	7	3	623	10.4	2.0091	20.9	0.0209	1.347	64.6
IOM-28	7	4	623	10.4	2.0156	20.9	0.0209	1.366	65.3
IOM-29	8	1	615	10.3	1.9946	20.4	0.0204	1.601	78.3
IOM-30	8	2	615	10.3	2.0960	21.5	0.0215	1.983	92.3
IOM-31	8	3	615	10.3	2.0091	20.6	0.0206	1.763	85.6
IOM-32	8	4	615	10.3	2.0156	20.7	0.0207	1.728	83.7
IOM-33	9	1	629	10.5	1.9946	20.9	0.0209	1.881	90.0
IOM-34	9	2	629	10.5	2.0960	22.0	0.0220	2.203	100
IOM-35	9	3	629	10.5	2.0091	21.1	0.0211	0.695	33.0
IOM-36	9	4	629	10.5	2.0156	21.1	0.0211	1.111	52.6
IOM-37	10	1	621	10.4	2.0434	21.1	0.0211	0.988	46.7
IOM-38	10	2	621	10.4	2.0802	21.5	0.0215	1.048	48.7
IOM-39	10	3	621	10.4	2.0306	21.0	0.0210	0.983	46.8
IOM-40	10	4	621	10.4	2.0351	21.1	0.0211	1.157	54.9
IOM-61	13	1	674	11.2	1.9995	22.5	0.0225	4.723	210
IOM-62	13	2	674	11.2	2.0642	23.2	0.0232	2.674	115
IOM-63	13	3	674	11.2	2.0396	22.9	0.0229	0.900	39.3
IOM-64	13	4	674	11.2	2.0364	22.9	0.0229	1.294	56.6
IOM-65	14	1	651	10.9	1.9995	21.7	0.0217	1.276	58.8
IOM-66	14	2	651	10.9	2.0642	22.4	0.0224	1.877	83.8
IOM-67	14	3	651	10.9	2.0396	22.1	0.0221	0.921	41.6
IOM-68	14	4	651	10.9	2.0364	22.1	0.0221	0.923	41.8
IOM-69	15	1	662	11.0	1.9995	22.1	0.0221	2.879	131
IOM-70	15	2	662	11.0	2.0642	22.8	0.0228	1.194	52.4
IOM-71	15	3	662	11.0	2.0396	22.5	0.0225	0.882	39.2
IOM-72	15	4	662	11.0	2.0364	22.5	0.0225	0.538	23.9
IOM-73	16	1	658	11.0	1.9995	21.9	0.0219	2.493	114
IOM-74	16	2	658	11.0	2.0642	22.6	0.0226	1.571	69.4
IOM-75	16	3	658	11.0	2.0396	22.4	0.0224	0.971	43.4
IOM-76	16	4	658	11.0	2.0364	22.3	0.0223	0.897	40.2

Table A2 - Raw data collected for sawdust trials using Button.

Filter	Run #	Position	Time (seconds)	Time (minutes)	Flow Rate (L min^{-1})	Air Volume (L)	Air Volume (m^3)	Weight (mg)	Concentration (mg m^{-3})
BU-25	7	1	623	10.4	4.0437	42.0	0.0420	1.536	36.6
BU-26	7	2	623	10.4	4.0601	42.2	0.0422	0.190	4.5
BU-27	7	3	623	10.4	4.0328	41.9	0.0419	0.989	23.6
BU-28	7	4	623	10.4	4.0229	41.8	0.0418	2.077	49.7
BU-29	8	1	615	10.3	4.0437	41.4	0.0414	1.247	30.1
BU-30	8	2	615	10.3	4.0601	41.6	0.0416	1.696	40.8
BU-31	8	3	615	10.3	4.0328	41.3	0.0413	1.210	29.3
BU-32	8	4	615	10.3	4.0229	41.2	0.0412	1.235	29.9
BU-33	9	1	629	10.5	4.0437	42.4	0.0424	2.433	57.4
BU-34	9	2	629	10.5	4.0601	42.6	0.0426	2.435	57.2
BU-35	9	3	629	10.5	4.0328	42.3	0.0423	2.075	49.1
BU-36	9	4	629	10.5	4.0229	42.2	0.0422	2.252	53.4
BU-37	10	1	621	10.4	4.0529	41.9	0.0419	1.015	24.2
BU-38	10	2	621	10.4	4.0460	41.9	0.0419	1.192	28.5
BU-39	10	3	621	10.4	4.0313	41.7	0.0417	1.329	31.8
BU-40	10	4	621	10.4	4.0097	41.5	0.0415	1.535	37.0
BU-49	13	1	674	11.2	4.0574	45.6	0.0456	4.533	99.5
BU-50	13	2	674	11.2	4.0057	45.0	0.0450	2.304	51.2
BU-51	13	3	674	11.2	4.0189	45.1	0.0451	2.337	51.8
BU-52	13	4	674	11.2	4.0131	45.1	0.0451	2.602	57.7
BU-53	14	1	651	10.9	4.0574	44.0	0.0440	1.189	27.0
BU-54	14	2	651	10.9	4.0057	43.5	0.0435	1.264	29.1
BU-55	14	3	651	10.9	4.0189	43.6	0.0436	1.411	32.4
BU-56	14	4	651	10.9	4.0131	43.5	0.0435	0.569	13.1
BU-57	15	1	662	11.0	4.0574	44.8	0.0448	2.221	49.6
BU-58	15	2	662	11.0	4.0057	44.2	0.0442	0.720	16.3
BU-59	15	3	662	11.0	4.0189	44.3	0.0443	0.762	17.2
BU-60	15	4	662	11.0	4.0131	44.3	0.0443	1.219	27.5
BU-61	16	1	658	11.0	4.0574	44.5	0.0445	2.400	53.9
BU-62	16	2	658	11.0	4.0057	43.9	0.0439	2.012	45.8
BU-63	16	3	658	11.0	4.0189	44.1	0.0441	0.648	14.7
BU-64	16	4	658	11.0	4.0131	44.0	0.0440	0.446	10.1

Table A3 - Raw data collected for sawdust trials using CFC.

Filter	Run #	Position	Time (seconds)	Time (minutes)	Flow Rate (L min^{-1})	Air Volume (L)	Air Volume (m^3)	Weight (mg)	Concentration (mg m^{-3})
CFC-25	7	1	623	10.4	2.0676	21.5	0.0215	0.624	29.1
CFC-26	7	2	623	10.4	1.9823	20.6	0.0206	0.828	40.2
CFC-27	7	3	623	10.4	1.9939	20.7	0.0207	0.778	37.6
CFC-28	7	4	623	10.4	2.0297	21.1	0.0211	0.899	42.7
CFC-29	8	1	615	10.3	2.0676	21.2	0.0212	0.827	39.0
CFC-30	8	2	615	10.3	1.9823	20.3	0.0203	0.840	41.3
CFC-31	8	3	615	10.3	1.9939	20.4	0.0204	0.771	37.7
CFC-32	8	4	615	10.3	2.0297	20.8	0.0208	0.672	32.3
CFC-33	9	1	629	10.5	2.0676	21.7	0.0217	0.748	34.5
CFC-34	9	2	629	10.5	1.9823	20.8	0.0208	1.173	56.4
CFC-35	9	3	629	10.5	1.9939	20.9	0.0209	1.098	52.5
CFC-36	9	4	629	10.5	2.0297	21.3	0.0213	1.210	56.9
CFC-37	10	1	621	10.4	2.0861	21.6	0.0216	0.472	21.9
CFC-38	10	2	621	10.4	2.0143	20.8	0.0208	0.465	22.3
CFC-39	10	3	621	10.4	2.0017	20.7	0.0207	0.637	30.8
CFC-40	10	4	621	10.4	2.0447	21.2	0.0212	0.566	26.7
CFC-49	13	1	674	11.2	2.0614	23.2	0.0232	2.010	86.8
CFC-50	13	2	674	11.2	2.0151	22.6	0.0226	1.659	73.3
CFC-51	13	3	674	11.2	1.9966	22.4	0.0224	1.297	57.8
CFC-52	13	4	674	11.2	2.0111	22.6	0.0226	1.020	45.1
CFC-53	14	1	651	10.9	2.0614	22.4	0.0224	1.674	74.8
CFC-54	14	2	651	10.9	2.0151	21.9	0.0219	1.276	58.3
CFC-55	14	3	651	10.9	1.9966	21.7	0.0217	0.766	35.3
CFC-56	14	4	651	10.9	2.0111	21.8	0.0218	0.532	24.4
CFC-57	15	1	662	11.0	2.0614	22.7	0.0227	1.125	49.4
CFC-58	15	2	662	11.0	2.0151	22.2	0.0222	1.143	51.4
CFC-59	15	3	662	11.0	1.9966	22.0	0.0220	0.595	27.0
CFC-60	15	4	662	11.0	2.0111	22.2	0.0222	0.455	20.5
CFC-61	16	1	658	11.0	2.0614	22.6	0.0226	1.629	72.0
CFC-62	16	2	658	11.0	2.0151	22.1	0.0221	1.370	62.0
CFC-63	16	3	658	11.0	1.9966	21.9	0.0219	0.477	21.8
CFC-64	16	4	658	11.0	2.0111	22.1	0.0221	0.597	27.1

Table A4 - Raw data collected for flour trials with IOM.

Filter	Run #	Position	Time (seconds)	Time (minutes)	Flow Rate (L min^{-1})	Air Volume (L)	Air Volume (m^3)	Weight (mg)	Concentration (mg m^{-3})
IOM-01	1	1	681	11.4	2.0004	22.7	0.0227	0.931	41.0
IOM-02	1	2	681	11.4	2.0197	22.9	0.0229	0.925	40.4
IOM-03	1	3	681	11.4	2.0443	23.2	0.0232	1.034	44.6
IOM-04	1	4	681	11.4	2.0458	23.2	0.0232	0.840	36.2
IOM-05	2	1	643	10.7	2.0004	21.4	0.0214	1.443	67.3
IOM-06	2	2	643	10.7	2.0197	21.6	0.0216	1.030	47.6
IOM-08	2	4	643	10.7	2.0458	21.9	0.0219	4.363	199
IOM-09	3	1	645	10.8	2.0004	21.5	0.0215	1.939	90.2
IOM-10	3	2	645	10.8	2.0197	21.7	0.0217	4.142	191
IOM-11	3	3	645	10.8	2.0443	22.0	0.0220	3.877	176
IOM-12	3	4	645	10.8	2.0458	22.0	0.0220	3.234	147
IOM-13	4	1	632	10.5	2.0004	21.1	0.0211	1.760	83.5
IOM-14	4	2	632	10.5	2.0197	21.3	0.0213	1.716	80.7
IOM-15	4	3	632	10.5	2.0443	21.5	0.0215	1.550	72.0
IOM-16	4	4	632	10.5	2.0458	21.5	0.0215	0.821	38.1
IOM-17	5	1	639	10.7	2.0004	21.3	0.0213	4.614	217
IOM-18	5	2	639	10.7	2.0197	21.5	0.0215	4.675	217
IOM-19	5	3	639	10.7	2.0443	21.8	0.0218	4.758	219
IOM-20	5	4	639	10.7	2.0458	21.8	0.0218	4.898	225
IOM-21	6	1	624	10.4	2.0004	20.8	0.0208	5.765	277
IOM-22	6	2	624	10.4	2.0197	21.0	0.0210	5.638	268
IOM-23	6	3	624	10.4	2.0443	21.3	0.0213	2.841	134
IOM-24	6	4	624	10.4	2.0458	21.3	0.0213	5.430	255
IOM-25	7	1	648	10.8	2.0004	21.6	0.0216	5.941	275
IOM-26	7	2	648	10.8	2.0197	21.8	0.0218	3.784	173
IOM-27	7	3	648	10.8	2.0443	22.1	0.0221	5.048	229
IOM-28	7	4	648	10.8	2.0458	22.1	0.0221	4.482	203
IOM-29	8	1	652	10.9	2.0004	21.7	0.0217	4.184	192
IOM-30	8	2	652	10.9	2.0197	21.9	0.0219	4.116	188
IOM-31	8	3	652	10.9	2.0443	22.2	0.0222	3.934	177
IOM-32	8	4	652	10.9	2.0458	22.2	0.0222	1.555	69.9

Table A5 - Raw data collected for flour trials with Button.

Filter	Run #	Position	Time (seconds)	Time (minutes)	Flow Rate (L min^{-1})	Air Volume (L)	Air Volume (m^3)	Weight (mg)	Concentration (mg m^{-3})
BU-01	1	1	681	11.4	4.0050	45.5	0.0455	0.108	2.38
BU-02	1	2	681	11.4	3.9976	45.4	0.0454	1.046	23.1
BU-03	1	3	681	11.4	4.0023	45.4	0.0454	1.428	31.4
BU-04	1	4	681	11.4	4.0124	45.5	0.0455	1.700	37.3
BU-05	2	1	643	10.7	4.0050	42.9	0.0429	0.097	2.27
BU-06	2	2	643	10.7	3.9976	42.8	0.0428	1.677	39.1
BU-08	2	4	643	10.7	4.0124	43.0	0.0430	1.962	45.6
BU-09	3	1	645	10.8	4.0050	43.1	0.0431	4.127	95.9
BU-10	3	2	645	10.8	3.9976	43.0	0.0430	2.677	62.3
BU-11	3	3	645	10.8	4.0023	43.0	0.0430	4.908	114
BU-12	3	4	645	10.8	4.0124	43.1	0.0431	4.773	111
BU-13	4	1	632	10.5	4.0050	42.2	0.0422	1.970	46.7
BU-14	4	2	632	10.5	3.9976	42.1	0.0421	1.298	30.8
BU-15	4	3	632	10.5	4.0023	42.2	0.0422	1.721	40.8
BU-16	4	4	632	10.5	4.0124	42.3	0.0423	1.634	38.7
BU-17	5	1	639	10.7	4.0050	42.7	0.0427	1.841	43.2
BU-18	5	2	639	10.7	3.9976	42.6	0.0426	2.764	64.9
BU-19	5	3	639	10.7	4.0023	42.6	0.0426	2.722	63.9
BU-20	5	4	639	10.7	4.0124	42.7	0.0427	2.513	58.8
BU-21	6	1	624	10.4	4.0050	41.7	0.0417	3.888	93.3
BU-22	6	2	624	10.4	3.9976	41.6	0.0416	2.804	67.4
BU-23	6	3	624	10.4	4.0023	41.6	0.0416	3.669	88.1
BU-24	6	4	624	10.4	4.0124	41.7	0.0417	3.371	80.8
BU-25	7	1	648	10.8	4.0050	43.3	0.0433	2.592	59.9
BU-26	7	2	648	10.8	3.9976	43.2	0.0432	2.547	59.0
BU-27	7	3	648	10.8	4.0023	43.2	0.0432	2.865	66.3
BU-28	7	4	648	10.8	4.0124	43.3	0.0433	2.984	68.9
BU-29	8	1	652	10.9	4.0050	43.5	0.0435	1.641	37.7
BU-30	8	2	652	10.9	3.9976	43.4	0.0434	1.713	39.4
BU-31	8	3	652	10.9	4.0023	43.5	0.0435	1.546	35.5
BU-32	8	4	652	10.9	4.0124	43.6	0.0436	1.663	38.1

Table A6 - Raw data collected for flour trials with CFC.

Filter	Run #	Position	Time (seconds)	Time (minutes)	Flow Rate (L min^{-1})	Air Volume (L)	Air Volume (m^3)	Weight (mg)	Concentration (mg m^{-3})
CFC-01	1	1	681	11.4	2.0004	22.7	0.0227	0.358	15.8
CFC-02	1	2	681	11.4	2.0197	22.9	0.0229	0.562	24.5
CFC-03	1	3	681	11.4	2.0443	23.2	0.0232	0.569	24.5
CFC-04	1	4	681	11.4	2.0458	23.2	0.0232	0.719	31.0
CFC-05	2	1	643	10.7	2.0004	21.4	0.0214	0.833	38.9
CFC-06	2	2	643	10.7	2.0197	21.6	0.0216	0.733	33.9
CFC-08	2	4	643	10.7	2.0458	21.9	0.0219	1.212	55.3
CFC-09	3	1	645	10.8	2.0004	21.5	0.0215	0.990	46.1
CFC-10	3	2	645	10.8	2.0197	21.7	0.0217	2.674	123
CFC-11	3	3	645	10.8	2.0443	22.0	0.0220	0.102	4.66
CFC-12	3	4	645	10.8	2.0458	22.0	0.0220	2.250	102
CFC-13	4	1	632	10.5	2.0004	21.1	0.0211	0.947	44.9
CFC-14	4	2	632	10.5	2.0197	21.3	0.0213	0.902	42.4
CFC-15	4	3	632	10.5	2.0443	21.5	0.0215	0.860	39.9
CFC-16	4	4	632	10.5	2.0458	21.5	0.0215	0.716	33.2
CFC-17	5	1	639	10.7	2.0004	21.3	0.0213	0.649	30.5
CFC-18	5	2	639	10.7	2.0197	21.5	0.0215	0.749	34.8
CFC-19	5	3	639	10.7	2.0443	21.8	0.0218	0.975	44.8
CFC-20	5	4	639	10.7	2.0458	21.8	0.0218	0.792	36.3
CFC-21	6	1	624	10.4	2.0004	20.8	0.0208	1.273	61.2
CFC-22	6	2	624	10.4	2.0197	21.0	0.0210	1.816	86.4
CFC-23	6	3	624	10.4	2.0443	21.3	0.0213	1.605	75.5
CFC-24	6	4	624	10.4	2.0458	21.3	0.0213	1.344	63.2
CFC-25	7	1	648	10.8	2.0004	21.6	0.0216	1.012	46.8
CFC-26	7	2	648	10.8	2.0197	21.8	0.0218	1.369	62.8
CFC-27	7	3	648	10.8	2.0443	22.1	0.0221	0.783	35.5
CFC-28	7	4	648	10.8	2.0458	22.1	0.0221	1.130	51.2
CFC-29	8	1	652	10.9	2.0004	21.7	0.0217	0.455	20.9
CFC-30	8	2	652	10.9	2.0197	21.9	0.0219	0.540	24.6
CFC-31	8	3	652	10.9	2.0443	22.2	0.0222	0.328	14.8
CFC-32	8	4	652	10.9	2.0458	22.2	0.0222	0.560	25.2

Table A7 - Raw data collected for glass microbead trials with IOM.

Filter	Run #	Position	Time (seconds)	Time (minutes)	Flow Rate (L min^{-1})	Air Volume (L)	Air Volume (m^3)	Weight (mg)	Concentration (mg m^{-3})
IOM-1	1	1	632	10.5	2.0140	21.2	0.0212	0.169	7.95
IOM-2	1	2	632	10.5	2.0422	21.5	0.0215	0.150	6.97
IOM-3	1	3	632	10.5	2.0321	21.4	0.0214	0.132	6.18
IOM-4	1	4	632	10.5	2.0774	21.9	0.0219	0.116	5.32
IOM-5	2	1	627	10.5	2.0140	21.0	0.0210	0.191	9.08
IOM-6	2	2	627	10.5	2.0422	21.3	0.0213	0.190	8.89
IOM-7	2	3	627	10.5	2.0321	21.2	0.0212	0.140	6.61
IOM-8	2	4	627	10.5	2.0774	21.7	0.0217	0.082	3.78
IOM-9	3	1	639	10.7	2.0140	21.4	0.0214	0.574	26.8
IOM-10	3	2	639	10.7	2.0422	21.7	0.0217	0.128	5.90
IOM-11	3	3	639	10.7	2.0321	21.6	0.0216	0.183	8.44
IOM-12	3	4	639	10.7	2.0774	22.1	0.0221	0.190	8.60
IOM-13	4	1	626	10.4	2.0140	21.0	0.0210	0.135	6.44
IOM-14	4	2	626	10.4	2.0422	21.3	0.0213	0.173	8.10
IOM-15	4	3	626	10.4	2.0321	21.2	0.0212	0.294	13.9
IOM-16	4	4	626	10.4	2.0774	21.7	0.0217	0.160	7.37
IOM-17	5	1	641	10.7	2.0140	21.5	0.0215	0.512	23.8
IOM-18	5	2	641	10.7	2.0422	21.8	0.0218	0.374	17.2
IOM-19	5	3	641	10.7	2.0321	21.7	0.0217	0.462	21.3
IOM-20	5	4	641	10.7	2.0774	22.2	0.0222	0.458	20.7
IOM-21	6	1	629	10.5	2.0058	21.0	0.0210	0.310	14.8
IOM-22	6	2	629	10.5	2.0540	21.5	0.0215	0.410	19.0
IOM-23	6	3	629	10.5	2.0757	21.8	0.0218	0.191	8.78
IOM-24	6	4	629	10.5	2.0022	21.0	0.0210	0.374	17.8
IOM-25	7	1	622	10.4	2.0058	20.8	0.0208	0.662	31.8
IOM-26	7	2	622	10.4	2.0540	21.3	0.0213	0.334	15.7
IOM-27	7	3	622	10.4	2.0757	21.5	0.0215	0.320	14.9
IOM-28	7	4	622	10.4	2.0022	20.8	0.0208	0.286	13.8
IOM-29	8	1	643	10.7	2.0058	21.5	0.0215	0.318	14.8
IOM-30	8	2	643	10.7	2.0540	22.0	0.0220	0.226	10.3
IOM-31	8	3	643	10.7	2.0757	22.2	0.0222	0.193	8.69
IOM-32	8	4	643	10.7	2.0022	21.5	0.0215	0.224	10.5

Table A8 - Raw data collected for glass microbeads trials with Button.

Filter	Run #	Position	Time (seconds)	Time (minutes)	Flow Rate (L min^{-1})	Air Volume (L)	Air Volume (m^3)	Weight (mg)	Concentration (mg m^{-3})
BU-01	1	1	632	10.5	4.0585	42.7	0.0427	0.0470	1.10
BU-02	1	2	632	10.5	4.0580	42.7	0.0427	0.0793	1.86
BU-03	1	3	632	10.5	4.0637	42.8	0.0428	0.0503	1.18
BU-04	1	4	632	10.5	3.9992	42.1	0.0421	0.0233	0.554
BU-05	2	1	627	10.5	4.0585	42.4	0.0424	0.197	4.65
BU-06	2	2	627	10.5	4.0580	42.4	0.0424	0.145	3.43
BU-07	2	3	627	10.5	4.0637	42.5	0.0425	0.110	2.58
BU-08	2	4	627	10.5	3.9992	41.8	0.0418	0.104	2.49
BU-09	3	1	639	10.7	4.0585	43.2	0.0432	0.141	3.25
BU-10	3	2	639	10.7	4.0580	43.2	0.0432	0.0557	1.29
BU-11	3	3	639	10.7	4.0637	43.3	0.0433	0.0810	1.87
BU-12	3	4	639	10.7	3.9992	42.6	0.0426	0.0470	1.10
BU-13	4	1	626	10.4	4.0585	42.3	0.0423	0.177	4.19
BU-14	4	2	626	10.4	4.0580	42.3	0.0423	0.0580	1.37
BU-15	4	3	626	10.4	4.0637	42.4	0.0424	0.0783	1.85
BU-16	4	4	626	10.4	3.9992	41.7	0.0417	0.0623	1.49
BU-17	5	1	641	10.7	4.0585	43.4	0.0434	0.119	2.74
BU-18	5	2	641	10.7	4.0580	43.4	0.0434	0.0633	1.46
BU-19	5	3	641	10.7	4.0637	43.4	0.0434	0.0833	1.92
BU-20	5	4	641	10.7	3.9992	42.7	0.0427	0.0393	0.921
BU-21	6	1	629	10.5	4.0575	42.5	0.0425	0.0693	1.63
BU-22	6	2	629	10.5	4.0433	42.4	0.0424	0.0387	0.912
BU-23	6	3	629	10.5	4.0305	42.3	0.0423	0.0313	0.742
BU-24	6	4	629	10.5	4.0136	42.1	0.0421	0.0813	1.93
BU-25	7	1	622	10.4	4.0575	42.1	0.0421	0.0867	2.06
BU-26	7	2	622	10.4	4.0433	41.9	0.0419	0.0587	1.40
BU-27	7	3	622	10.4	4.0305	41.8	0.0418	0.0647	1.55
BU-28	7	4	622	10.4	4.0136	41.6	0.0416	0.0310	0.745
BU-29	8	1	643	10.7	4.0575	43.5	0.0435	0.178	4.10
BU-30	8	2	643	10.7	4.0433	43.3	0.0433	0.0530	1.22
BU-31	8	3	643	10.7	4.0305	43.2	0.0432	0.0277	0.641
BU-32	8	4	643	10.7	4.0136	43.0	0.0430	0.0500	1.16

Table A9 - Raw data collected for glass microbeads trials with CFC.

Filter	Run #	Position	Time (seconds)	Time (minutes)	Flow Rate (L min^{-1})	Air Volume (L)	Air Volume (m^3)	Weight (mg)	Concentration (mg m^{-3})
CFC-01	1	1	632	10.5	2.0378	21.5	0.0215	0.0987	4.60
CFC-02	1	2	632	10.5	2.0154	21.2	0.0212	0.0470	2.21
CFC-03	1	3	632	10.5	2.0250	21.3	0.0213	0.0403	1.89
CFC-04	1	4	632	10.5	2.0463	21.6	0.0216	0.007	0.309
CFC-05	2	1	627	10.5	2.0378	21.3	0.0213	0.180	8.47
CFC-06	2	2	627	10.5	2.0154	21.1	0.0211	0.136	6.47
CFC-07	2	3	627	10.5	2.0250	21.2	0.0212	0.0653	3.09
CFC-08	2	4	627	10.5	2.0463	21.4	0.0214	0.0137	0.639
CFC-09	3	1	639	10.7	2.0378	21.7	0.0217	0.0157	0.722
CFC-10	3	2	639	10.7	2.0154	21.5	0.0215	0.0287	1.34
CFC-11	3	3	639	10.7	2.0250	21.6	0.0216	0.0440	2.04
CFC-12	3	4	639	10.7	2.0463	21.8	0.0218	0.0743	3.41
CFC-13	4	1	626	10.4	2.0378	21.3	0.0213	0.0353	1.66
CFC-14	4	2	626	10.4	2.0154	21.0	0.0210	0.0980	4.66
CFC-15	4	3	626	10.4	2.0250	21.1	0.0211	0.110	5.21
CFC-16	4	4	626	10.4	2.0463	21.4	0.0214	0.0517	2.42
CFC-17	5	1	641	10.7	2.0378	21.8	0.0218	0.0030	0.138
CFC-18	5	2	641	10.7	2.0154	21.5	0.0215	0.0027	0.124
CFC-19	5	3	641	10.7	2.0250	21.6	0.0216	0.0400	1.85
CFC-20	5	4	641	10.7	2.0463	21.9	0.0219	0.0260	1.19
CFC-21	6	1	629	10.5	2.0249	21.2	0.0212	0.0620	2.92
CFC-22	6	2	629	10.5	2.0202	21.2	0.0212	0.0730	3.45
CFC-23	6	3	629	10.5	2.0174	21.1	0.0211	0.0437	2.06
CFC-24	6	4	629	10.5	2.0388	21.4	0.0214	0.0580	2.71
CFC-25	7	1	622	10.4	2.0249	21.0	0.0210	0.0387	1.84
CFC-26	7	2	622	10.4	2.0202	20.9	0.0209	0.0213	1.02
CFC-27	7	3	622	10.4	2.0174	20.9	0.0209	0.0273	1.31
CFC-28	7	4	622	10.4	2.0388	21.1	0.0211	0.0100	0.473
CFC-29	8	1	643	10.7	2.0249	21.7	0.0217	0.0693	3.20
CFC-30	8	2	643	10.7	2.0202	21.6	0.0216	0.0170	0.785
CFC-31	8	3	643	10.7	2.0174	21.6	0.0216	0.0203	0.940
CFC-32	8	4	643	10.7	2.0388	21.8	0.0218	0.0040	0.183

Table A10 - Filter blanks for all dust types and lab blank.

Filter	Dust Type	Gravimetric Weight (mg)
LB	N/A	0.004
IOM 67	Sawdust	0.012
BU 65	Sawdust	0.006
CFC 65	Sawdust	0.009
IOM 33	Flour	0.014
BU 33	Flour	0.007
CFC 33	Flour	0.010
IOM 33	Glass beads	0.009
BU 33	Glass beads	0.007
CFC 33	Glass beads	0.015

APPENDIX B. DISTRIBUTION ANALYSIS

The normality of the data used in this study was analyzed using SAS (Version 9.3, SAS Institute Inc., Cary, NC, USA). The data were tested for normality with a Shapiro-Wilk test. Results with a $p < 0.05$ were interpreted as not being normally distributed.

Table B1 - Results of Shapiro-Wilk test for normality.

	0.30 m	0.91 m	1.5 m	2.1 m
Sawdust				
IOM	0.2089	0.8734	0.0316	0.9525
Button	0.1027	0.8377	0.4016	0.5274
CFC	0.4209	0.8945	0.5340	0.3667
Flour				
IOM	0.1704	0.3272	0.4445	0.2052
Button	0.0067	0.2345	0.4550	0.1279
CFC	0.7645	0.0742	0.8254	0.1313
Glass Microbeads				
IOM	0.3517	0.2269	0.1133	0.6487
Button	0.6557	0.0046	0.6444	0.5472
CFC	0.2245	0.3910	0.0481	0.1461

APPENDIX C. SIMPLE LINEAR REGRESSION ANALYSIS RESULTS

Graphs plotting the concentration collected for two personal samplers for each dust type are located below. Graphs were created using Microsoft Excel.

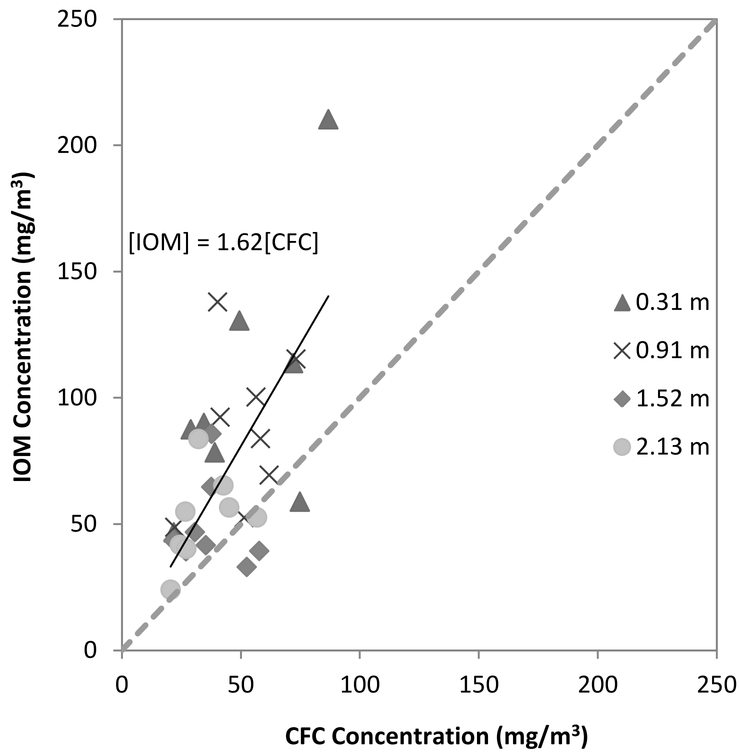

Figure C1 - IOM and CFC concentration data collected for sawdust trials.

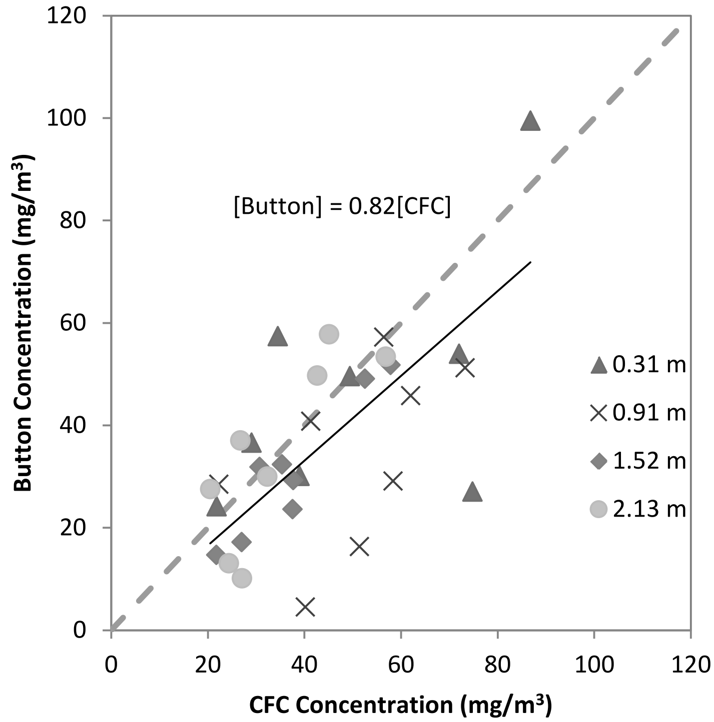

Figure C2 - Button and CFC concentration data collected for sawdust trials.

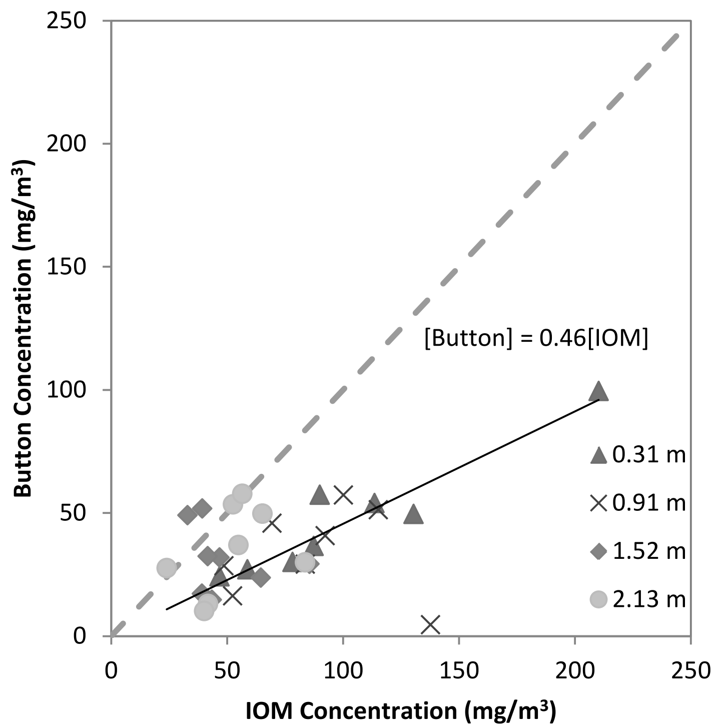

Figure C3 - Button and IOM concentration data collected for sawdust trials.

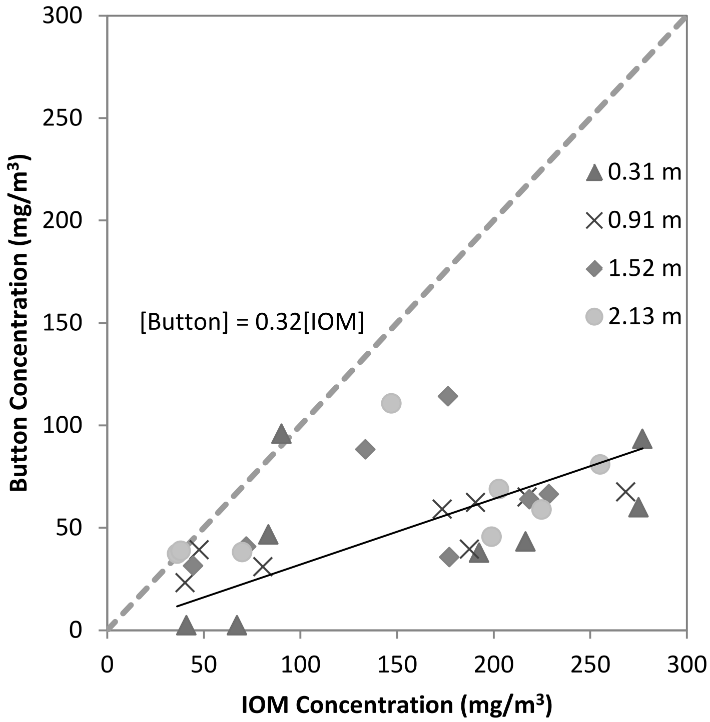

Figure C4 - Button and IOM concentration data collected for flour trials.

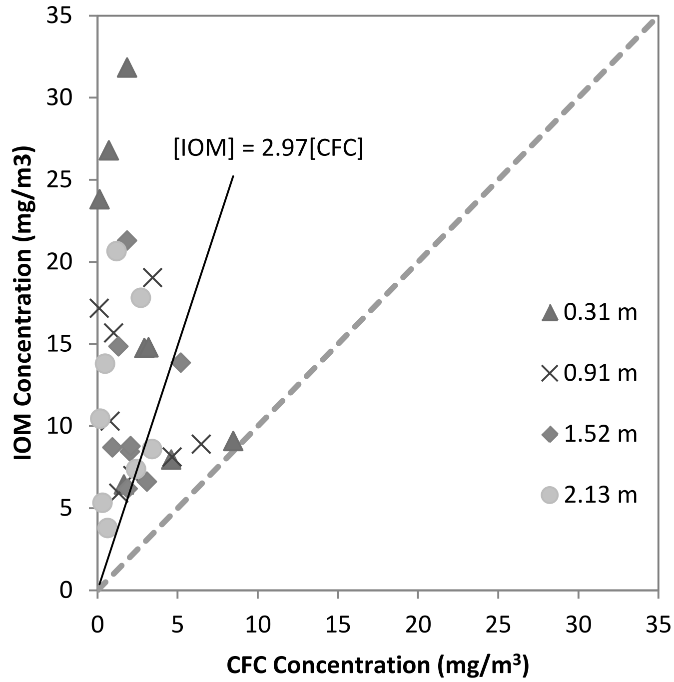

Figure C5 - IOM and CFC concentration data collected for glass microbead trials.

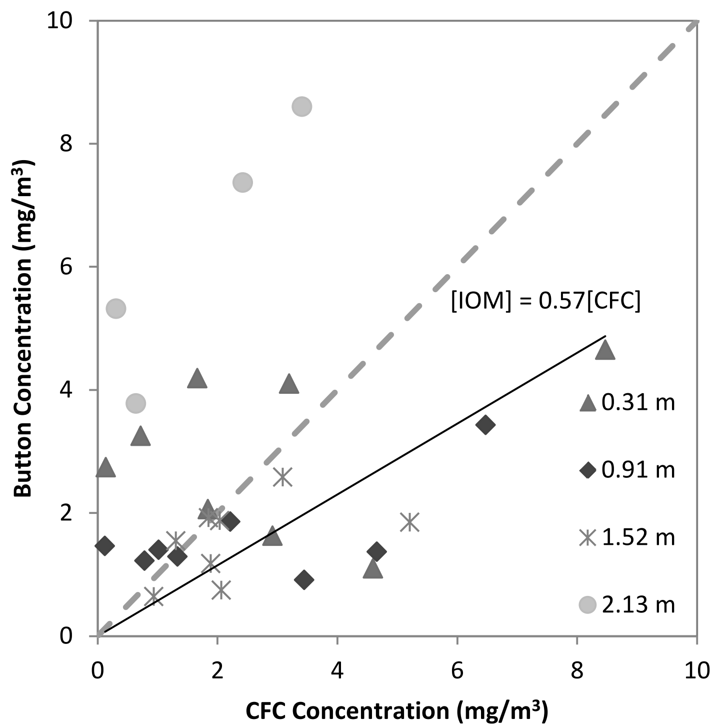

Figure C6 - Button and CFC concentration data collected for glass microbead trials.

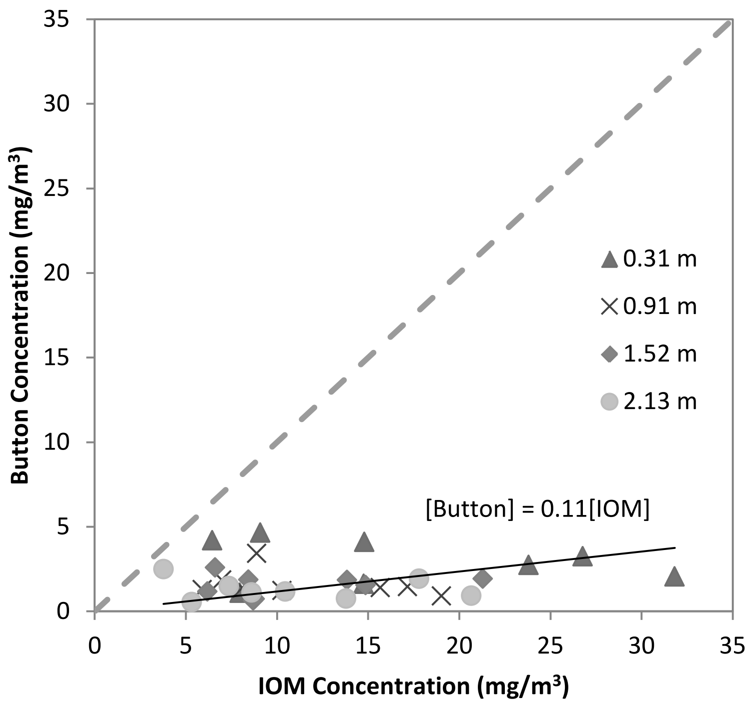

Figure C7 - Button and IOM concentration data collected for glass microbead trials.

APPENDIX D. DISTANCE MODEL REGRESSION RESULTS

The results of the linear distance model regression to assess the effects of distance from the source on performance ratios are included in this appendix. Linear regressions were run using SAS (Version 9.3, SAS Institute Inc., Cary, NC, USA). SAS readouts are given below, along with code used.

Number of Observations Read	32
Number of Observations Used	32

Analysis of Variance					
Source	**DF**	**Sum of Squares**	**Mean Square**	**F Value**	**Pr > F**
Model	1	1.75094	1.75094	4.15	0.0506
Error	30	12.65993	0.42200		
Corrected Total	31	14.41087			

Root MSE	0.64961	**R-Square**	0.1215
Dependent Mean	1.75307	**Adj R-Sq**	0.0922
Coeff Var	37.05582		

Parameter Estimates						
Variable	**Label**	**DF**	**Parameter Estimate**	**Standard Error**	**t Value**	**Pr > |t|**
Intercept	Intercept	1	2.17151	0.23534	9.23	<.0001
Meters	Meters	1	-0.34321	0.16849	-2.04	0.0506

Figure D1 - Distance model linear regression results for IOM/CFC comparison for sawdust.

Number of Observations Read	32
Number of Observations Used	32

Analysis of Variance					
Source	**DF**	**Sum of Squares**	**Mean Square**	**F Value**	**Pr > F**
Model	1	0.00168	0.00168	0.01	0.9089
Error	30	3.77493	0.12583		
Corrected Total	31	3.77661			

Root MSE	0.35473	**R-Square**	0.0004
Dependent Mean	0.87937	**Adj R-Sq**	-0.0329
Coeff Var	40.33861		

Parameter Estimates						
Variable	**Label**	**DF**	**Parameter Estimate**	**Standard Error**	**t Value**	**Pr > |t|**
Intercept	Intercept	1	0.86642	0.12851	6.74	<.0001
Meters	Meters	1	0.01062	0.09201	0.12	0.9089

Figure D2 - Distance model linear regression results for Button/CFC comparison for sawdust.

Number of Observations Read	32
Number of Observations Used	32

Analysis of Variance					
Source	**DF**	**Sum of Squares**	**Mean Square**	**F Value**	**Pr > F**
Model	1	0.37601	0.37601	4.00	0.0546
Error	30	2.82061	0.09402		
Corrected Total	31	3.19663			

Root MSE	0.30663	**R-Square**	0.1176
Dependent Mean	0.57596	**Adj R-Sq**	0.0882
Coeff Var	53.23786		

Parameter Estimates						
Variable	**Label**	**DF**	**Parameter Estimate**	**Standard Error**	**t Value**	**Pr > |t|**
Intercept	Intercept	1	0.38205	0.11109	3.44	0.0017
Meters	Meters	1	0.15905	0.07953	2.00	0.0546

Figure D3 - Distance model linear regression results for Button/IOM comparison for sawdust.

Number of Observations Read	31
Number of Observations Used	31

Analysis of Variance					
Source	**DF**	**Sum of Squares**	**Mean Square**	**F Value**	**Pr > F**
Model	1	1.17112	1.17112	0.03	0.8744
Error	29	1335.61781	46.05579		
Corrected Total	30	1336.78893			

Root MSE	6.78644	**R-Square**	0.0009
Dependent Mean	4.90320	**Adj R-Sq**	-0.0336
Coeff Var	138.40845		

Parameter Estimates						
Variable	**Label**	**DF**	**Parameter Estimate**	**Standard Error**	**t Value**	**Pr > |t|**
Intercept	Intercept	1	4.56264	2.45900	1.86	0.0737
Meters	Meters	1	0.28160	1.76593	0.16	0.8744

Figure D4 - Distance model linear regression results for IOM/CFC comparison for flour.

Number of Observations Read	31
Number of Observations Used	31

Analysis of Variance					
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	5.35532	5.35532	0.30	0.5911
Error	29	526.10410	18.14152		
Corrected Total	30	531.45943			

Root MSE	4.25929	R-Square	0.0101
Dependent Mean	1.98614	Adj R-Sq	-0.0241
Coeff Var	214.44997		

Parameter Estimates						
Variable	Label	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	Intercept	1	1.25789	1.54331	0.82	0.4217
Meters	Meters	1	0.60218	1.10833	0.54	0.5911

Figure D5 - Distance model linear regression results for Button/CFC comparison for flour.

Number of Observations Read	31
Number of Observations Used	31

Analysis of Variance					
Source	**DF**	**Sum of Squares**	**Mean Square**	**F Value**	**Pr > F**
Model	1	0.23276	0.23276	3.18	0.0852
Error	29	2.12515	0.07328		
Corrected Total	30	2.35792			

Root MSE	0.27070	**R-Square**	0.0987
Dependent Mean	0.44252	**Adj R-Sq**	0.0676
Coeff Var	61.17344		

Parameter Estimates						
Variable	**Label**	**DF**	**Parameter Estimate**	**Standard Error**	**t Value**	**Pr > |t|**
Intercept	Intercept	1	0.29069	0.09809	2.96	0.0060
Meters	Meters	1	0.12554	0.07044	1.78	0.0852

Figure D6 - Distance model linear regression results for Button/IOM comparison for flour.

Number of Observations Read	32
Number of Observations Used	32

Analysis of Variance					
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	1256.19797	1256.19797	0.87	0.3588
Error	30	43393	1446.44032		
Corrected Total	31	44649			

Root MSE	38.03210	R-Square	0.0281
Dependent Mean	19.18958	Adj R-Sq	-0.0043
Coeff Var	198.19136		

Parameter Estimates						
Variable	Label	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	Intercept	1	30.39761	13.77844	2.21	0.0352
Meters	Meters	1	-9.19293	9.86451	-0.93	0.3588

Figure D7 - Distance model linear regression results for IOM/CFC comparison for glass microbeads.

Number of Observations Read	32
Number of Observations Used	32

Analysis of Variance					
Source	**DF**	**Sum of Squares**	**Mean Square**	**F Value**	**Pr > F**
Model	1	19.32079	19.32079	1.24	0.2738
Error	30	466.39907	15.54664		
Corrected Total	31	485.71987			

Root MSE	3.94292	**R-Square**	0.0398
Dependent Mean	2.19818	**Adj R-Sq**	0.0078
Coeff Var	179.37202		

Parameter Estimates						
Variable	**Label**	**DF**	**Parameter Estimate**	**Standard Error**	**t Value**	**Pr > |t|**
Intercept	Intercept	1	3.58817	1.42846	2.51	0.0176
Meters	Meters	1	-1.14009	1.02269	-1.11	0.2738

Figure D8 - Distance model linear regression results for Button/CFC comparison for glass microbeads.

Number of Observations Read	32
Number of Observations Used	32

Analysis of Variance					
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	0.02084	0.02084	0.78	0.3835
Error	30	0.79947	0.02665		
Corrected Total	31	0.82031			

Root MSE	0.16325	R-Square	0.0254
Dependent Mean	0.18975	Adj R-Sq	-0.0071
Coeff Var	86.03135		

Parameter Estimates						
Variable	Label	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	Intercept	1	0.23540	0.05914	3.98	0.0004
Meters	Meters	1	-0.03744	0.04234	-0.88	0.3835

Figure D9 - Distance model linear regression results for Button/IOM comparison for glass microbeads.

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