A COMPARISON OF U.S. COAL MINE RESPIRABLE DUST CALIBRATION PROCEDURES AND THE IMPACT ON MEASURED FLOW RATES

by

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Abstract

Particulate matter (PM) is a common occupational and ambient exposure concern. Some examples of occupational sources of PM include; stone crushing, burning wood, grinding, cutting, drilling, and emissions from cars, trucks, buses, and factories. Respirable pm, also commonly called respirable dust, is of particular concern because it is small enough to reach the gas-exchange region of the lungs. There are several methods used to assess occupational and ambient exposures to respirable pm. The most common of these methods is to use a cyclone sampler to collect PM onto a filter, which is then analyzed gravimetrically. Accurate assessment and measurement of PM exposure requires accurate pump-calibration procedures.

This study evaluates the coal mine respirable dust sampling calibration methods published by the U.S. Mine Safety and Health Administration (MSHA) to determine if there are significant differences in flow rates achieved with the various methods. A Dorr Oliver cyclone attached to a 37 mm PVC filter was connected to an MSA Escort Elf pump. Three trials were conducted in which two of MSHA's calibration methods (Jar and Tape Method) were compared. Calibration flow rates were measured using a Gilibrator calibration device.

A one-way analysis of variance (ANOVA) with a 95% confidence interval was performed on combined data from all three trials to determine if there were differences or correlations between the flow rates of the calibration methods. The flow rates of all three trials ($n = 240$) were compared against the five calibration types that were performed in each trial (jar, duct, electrical, clay, and masking tape). When comparing flow rate and calibration type, a significant difference was found ($p = 0.000$). A Tukey comparison of the data also showed that some of the types of tape had significantly different flow rates.

Keywords: Calibration techniques, Dorr Oliver, Cyclone, Respirable Coal Dust

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Abbreviations

ACGIH	American Conference of Governmental Industrial Hygienists
ANOVA	Analysis of Variance
BMRC	British Medical Research Council
BMRE	British Mining Research Establishment
COPD	Chronic Obstructive Pulmonary Disease
CWP	Coal Workers Pneumoconiosis
IR	Informational Report
LPM	Liters per Minute
MSA	Mine Safety Appliance Company
MSHA	Mine Safety and Health Administration
NIOSH	National Institute for Occupational Safety and Health
NIST	National Institute of Standards and Technology
OSHA	Occupational Safety and Health Administration
OTM	OSHA Technical Manual
PEL	Permissible Exposure Limit
PM	Particulate Matter
PMF	Progressive Massive Fibrosis
PVC	Polyvinyl Chloride
ROS	Reactive Oxygen Species
TLV	Threshold Limit Value
USAEC	United States Atomic Energy Commission

1. Introduction

Coal mines are well-known sources of crystalline silica containing particulate matter (PM) which, if inhaled, can result in Chronic Obstructivev Pulmonary Disease (COPD) (Centers for Disease Control and Prevention, CDC, 2012), the leading cause of morbidity and mortality in the U.S (CDC, 2012). It is estimated that15% of COPD is caused by occupational exposures from industries such as coal mining and construction. Exposure to PM in coal mining operations could include inhalation of coal PM when overburden or topsoil is removed. In addition to COPD, exposures to silica could cause silicosis, lung cancer, pulmonary tuberculosis, and other airway diseases (Schins & Borm, 1999).

Industrial Hygienists are primarily concerned with respirable PM because it is small enough to reach the gas-exchange region of the lungs. The Mine Safety and Health Administration (MSHA) set Permisible Exposure Limits (PELs) in order to provide the maximum concentrations of contaminant a worker can be exposed to without adverse health effects. The MSHA PEL for coal mine respirable PM is 2.0 milligrams of respirable dust per cubic meter of air (mg/m^3) (NIOSH Pocket Guide to Chemical Hazards, 2011). In coal mines, respirable PM is sampled using a cyclone (a device that seperates respirable PM from larger PM). A sampling pump is used to draw a predetermined amount of PM-laden air through the cyclone onto a filter, which is then analyzed gravimetrically.

Gravimetric analysis is a process in which the initial weight of a filter is obtained, PM-laden air is drawn through the filter with a specific volume, and the filter is then weighed post sampling to determine the mass captured (Anna, 2011). The volume is determined by the duration of the sampling session and the flow rate of the pump, which is determined by calibration. Calibration is a measurement that assesses the volume of air that is pumped though the cyclone and the PM filter (World Health Organization WHO/SDE/OEH/99.14, 1999). If sampling pumps are not calibrated correctly, gravimetric mass concentrations may be erroneous.

1.1. Purpose of the Study

The primary objective of this study was to evaluate two of the coal mine respirable dust sampling calibration methods published by MSHA to determine if there are significant differences in flow rates achieved with the various methods. Respirable PM sampling procedures for the United States coal mining industry are published by MSHA in Informational Report (IR) 1240 (Tomb & Parobeck, 1999). There are two approved calibration techniques within IR 1240. These calibration techniques include:

1. Placing a Dorr Oliver Cyclone in a calibration jar, which is placed between the sampling pump and the calibrator. This method is referred to herein as the Jar Method.
2. Sealing the inlet of the Dorr Oliver Cyclone with tape or modeling clay, removing the grit pot, and connecting the calibrator outlet. This method is referred to herein as the Tape Method.

Calibration technique variability within the U.S. coal mining industry may result in significantly different flow rates. Accurate flow rates are crucial for calculating precise gravimetric mass concentrations upon which worker exposures are based.

1.2. Research Question

The following research question was developed in order to evaluate the accuracy of MSHA Coal's Tape Method verses the accuracy of the Jar Method.

- Will measured flow rates from the Jar Method and the Tape Method for cyclone calibration be significantly different?

1.3. Hypothesis

The hypothesis developed to address the research question is characterized below:

Ha: There will be a significant difference ($p \leq 0.05$) in measured flow rates obtained with the MSHA Coal Tape Method vs. the standard Jar Method.

Ho: There will not be a significant difference ($p > 0.05$) in measured flow rates obtained with the MSHA Coal Tape Method vs. the standard Jar Method.

2. Background

The calibration and sampling equipment required for respirable dust sampling have changed with advances in technology. The procedures for calibration however, have not changed to reflect the use of new equipment. There are several differences between OSHA and different branches within MSHA in both the equipment and procedures used for calibration of sampling pumps. In this section, respirable PM sampling techniques including flow rates, cutpoints, and aerodynamic diameter are characterized. In addition the history of MSHA and OSHA calibration procedures and equipment are outlined in this section.

2.1. History of MSHA Coal Mining Respirable PM Calibration and Maintenance Techniques

In 1977, the Federal Mine Safety and Health Act established that respirable coal mine dust must be measured with a device approved by the Secretary of Labor and Human Services. The Act also specifies that the approved sampling devices are calibrated at a flow rate of 2.0 liters per minute (USDOL, 1999). The IR provides calibration and maintenance procedures using equipment that are approved under the Mine Safety and Health Act.

Historically in the coal mining industry, there have been three different versions of the IR. These include IR 1073, IR 1121, and IR 1240 (US DOL, 1999; Tomb & Parobeck, 1999). The latest IR update, 1240, allowed for the use of fast-response calibrators that contain a volumetric tube in addition to the already approved sampling equipment included in IR 1121 (US DOL, 1999). This revision considered the use of additional primary calibrators. However, no changes were made to the calibration methods.

2.2. Classification of PM (deposition, sampling efficiencies, equipment, and techniques)

Particulate matter is a common occupational and ambient exposure concern. Some examples of occupational sources of PM include; stone crushing, burning wood, grinding, cutting, drilling, and emissions from cars, trucks, buses, and factories (National Library of Medicine, 2012; WHO, 1999). There are several different methods used to assess occupational and ambient exposures to PM. The most common of these methods is to use a cyclone sampler to collect PM onto a filter, which is then analyzed gravimetrically.

Aerodynamic diameter is defined as the diameter of a sphere with a unit of density that will settle in calm air at the same rate as the particle in question. The aerodynamic diameter of PM influences where particle deposition is most likely to occur in the respiratory tract (Environmental Protection Agency, 1983). Therefore, ambient and occupational exposure standards commonly consider PM in specific size fractions. PM air sampling methods are performed to assess compliance with exposure limits, which typically apply size fractioning techniques. For example, in the ambient environment, PM is sampled in the coarse, fine and ultrafine size ranges (National Library of Medicine, 2012; United States USEPA, 2012). Coarse PM are particles that could deposit along the airways, fine PM can be inhaled deep into the lung, and ultrafine particles can have widespread deposition within the respiratory tract (United States Environmental Protection Agency, 2012).

In the occupational environment, PM is most commonly divided into inhalable, thoracic, and respirable size fractions. Inhalable particulate fraction is the portion of dust that can be breathed into the nose or mouth, while thoracic particulate fraction is the portion of dust that can penetrate the airway of the lung, and respirable particulate fraction is the fraction of dust that can penetrate into the gas-exchange region of the lungs (WHO, 1999). Figure 1 below depicts the deposition of inhalable, thoracic, and respirable particles in the human airway.

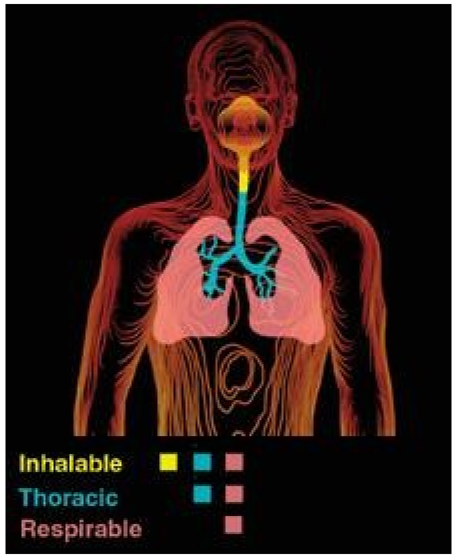

Figure 1: Deposition of Inhalable, Thoracic, and Respirable Particles in the Human Airway (SKC, n.d.).

Industrial Hygienists are primarily concerned with respirable PM because it is small enough to reach the gas-exchange region of the lungs. Sampling for respirable PM is most commonly performed by drawing air through a cyclone, which is designed to separate larger PM from respirable PM. A cyclone is a sampling device that draws air through the inlet at a specified flow rate. A rapid circulation of air is generated, which allows for respirable PM to collect on a filter while larger particles drop into the grit pot. Figure 2 illustrates the components of the Dorr Oliver Cyclone, which is the required cyclone for MSHA respirable PM sampling.

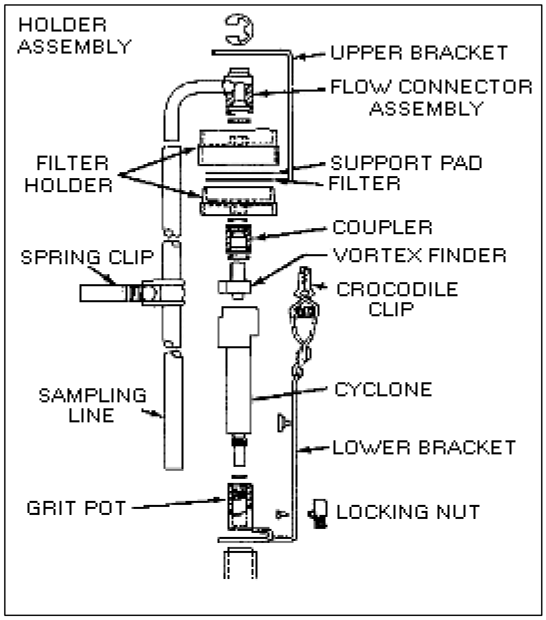

Figure 2: Illustration of a Dorr Oliver Cyclone (OSHA, 1996)

Air is pulled through the cyclone with a personal sampling pump at a flow rate that is determined by the type of cyclone used as well as the cutpoint that is required. A cutpoint is used to define sampling of respirable, thoracic, and inhalable particles that are representative of the human lung. The cutpoint is the diameter of a particle that has a 50% chance of being collected by the device when sampling or deposited in the lung when inhaled and 50% chance of being passed through. The occupational 50% cutpoint for inhalable PM is 100µm, thoracic PM is 10µm, and respirable PM is 4µm (SKC Inc., 2011; USEPA, 1983). As particles decrease in size, their collection/sampling efficiency increases.

Typically, for respirable PM sampling, a 50% (median) cutpoint of 4.0 µm is required and a flow rate of 1.7 liters per minute (lpm) is used. However, MSHA coal uses a 50% cutpoint of 3.5 µm. Therefore, when sampling for respirable PM in a coal mine, a flow rate of 2.0 liters per minute (lpm) is needed to achieve 50% efficiency when sampling with a Dorr Oliver Cyclone (USEPA, 1983).

2.3. MSHA Coal Calibration Techniques and Equipment

In order to ensure an accurate flow rate, calibration of the pump along with the sampling train should be performed with a primary standard both pre- and post-sampling. Calibration is a measurement that assesses the volume of air that is pumped though the cyclone and the PM filter (WHO, 1999). The gravimetric PM mass concentration, commonly expressed as milligrams or micrograms of PM per cubic meter of air (mg/m^3 or $\mu g/m^3$), is calculated by dividing the gravimetric sample mass by the volume of air through the filter. The volume of air is calculated by multiplying the flow rate, in lpm, by the sample time in minutes.

The latest calibration procedures that are required for compliance respirable PM sampling in coal mines are found in IR 1240, Calibration and Maintenance Procedures for Coal Mine Respirable Dust Samplers (Tomb & Parobeck, 1999).

2.3.1. MSHA Coal Calibration Procedures

In IR 1240, two methods of calibration are described. The first method, the Tape Method, includes removing the grit pot from the bottom of the cyclone, connecting the calibrator outlet to the bottom of the cyclone, and sealing the cyclone inlet with “tape or modeling clay” (Tomb & Parobeck, 1999). It is important to note that the type of tape or clay that should be used is not specified in IR 1240.

When performing respirable PM sampling with a Dorr Oliver Cyclone, air enters through the cyclone inlet as depicted in Figure 3. Calibration using the Tape Method seals the inlet of the cyclone thereby changing the intended inlet of air and air flow through the sampler as illustrated in Figure 4. A personal breathing zone pump draws air through the inlet and past the filter

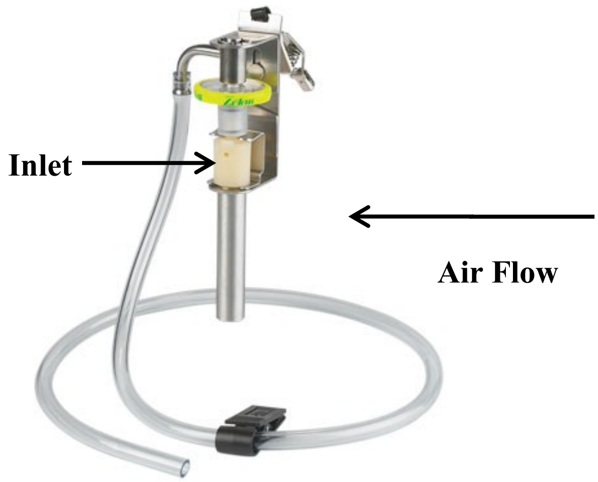

Figure 3: Inlet and Air Flow in the Dorr Oliver Cyclone

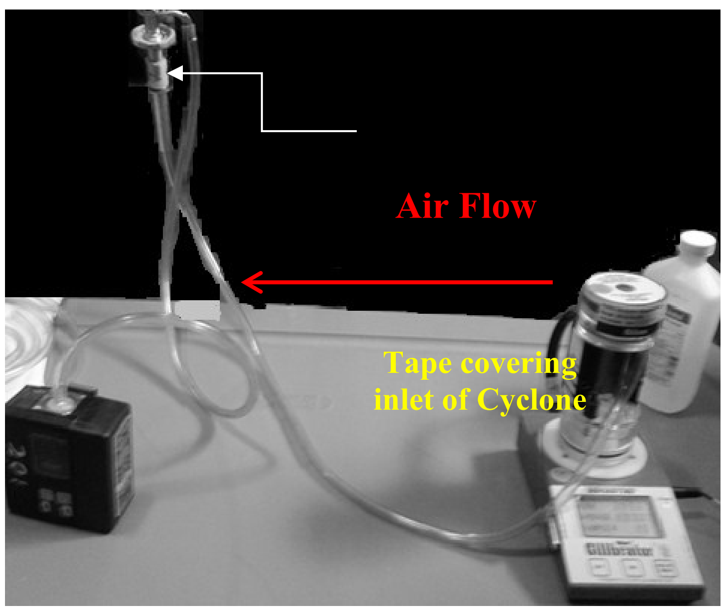

Figure 4: MSHA Coal Tape Method

The second method included in IR 1240, the Jar Method, involves sealing the cyclone in an airtight container. IR 1240 identifies the Jar Method as an alternate but preferred method of calibration because it eliminates the need to seal the cyclone inlet or remove the grit pot (Tomb & Parobeck, 1999). In the Jar Method, the cyclone is sealed inside of a calibration jar. Tubing is connected from the inlet of the calibration jar to the calibrator and then from the outlet of the cyclone to the outlet of the calibration jar, which is connected to the sampling pump (SKC, n.d.).

Figure 5Figure 5 illustrates the flow of air through the Jar Method calibration train. This method more closely imitates sampling conditions because it utilizes the cyclone inlet and intended flow through the cyclone.

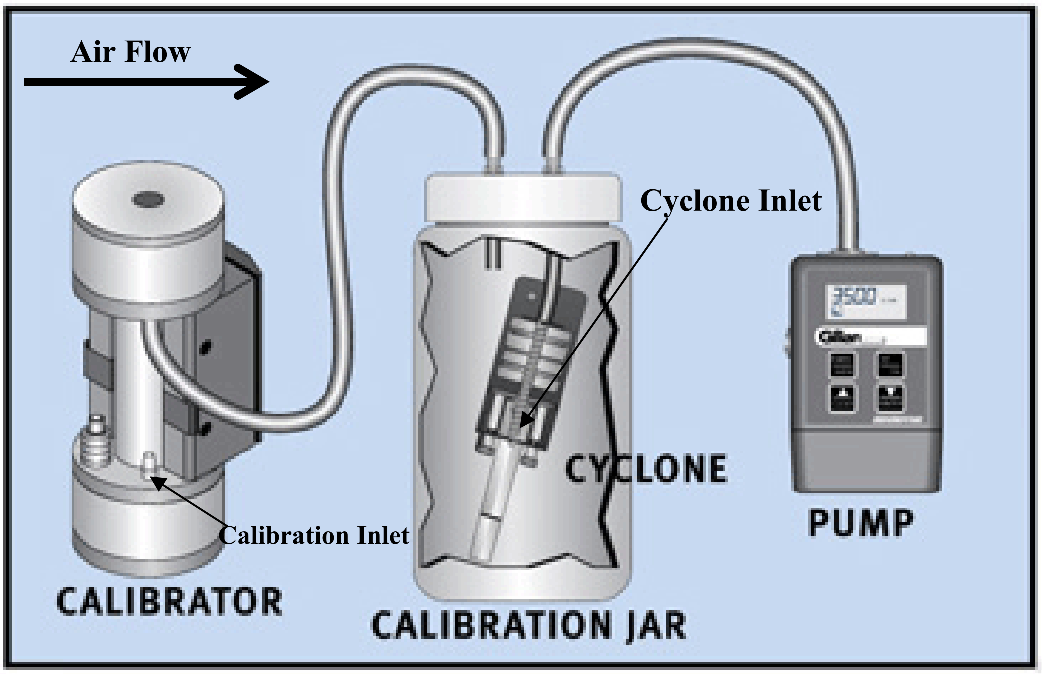

Figure 5: MSHA Coal Jar Method (Environmental Monitoring Systems, N.D.)

2.3.2. MSHA Coal Calibrators

Primary flow calibrators that are MSHA-approved for coal mine respirable PM sampling include: a Wet-test meter with a 3.0 liter capacity, an SKC model 302 film flow meter that has a 1.0 liter capacity, or any other fast-response flow measurement device that measures volume and is traceable to the National Institute of Standards and Technology (NIST) (Tomb & Parobeck, 1999). Electronic soap bubble film meters such as the Gilian Gilibrator® and dry calibration primary flow meters such as the DryCal® DC-Lite are examples of calibration devices that are traceable to NIST.

2.3.3. MSHA Coal Pumps

MSHA pumps that are approved for coal mines include: MSA Model G Monitaire, MSA Flow-Lite, the MSA Flow-Lite Et, and the MSA Escort Elf® (Tomb & Parobeck, 1999). The Model G, Flow-Lite, and MSA Flow-Lite Et are no longer commercially available, but may still be used at mine sites. The Escort Elf® is the only approved option left when purchasing a new pump for respirable PM sampling. Contrary to the commonly used flow rate of 1.7 liters per minute (OSHA Technical Manual, 2008), MSHA requires the Escort ELF® pump to be set at a flow rate of 2.0 liters per minute based on a cutpoint of 3.5 μm (Tomb & Parobeck, 1999).

2.3.4. MSHA Coal Cyclone Samplers

The only sampler approved for respirable dust sampling in a coal mine is the nylon Dorr Oliver cyclone sampler model 456243. A 37 mm diameter polyvinyl chloride (PVC) filter with a five micron pore size in a cassette that is manufactured by Mine Safety Appliance Company (MSA) is specified for use with the Dorr Oliver cyclone for coal mine respirable PM sampling (MSHA, 2006)

2.4. OSHA and MSHA Metal/Nonmetal Equipment and Techniques

For comparison purposes, calibration equipment and techniques within other branches of MSHA, Metal/Nonmetal, and OSHA are summarized.

2.4.1. MSHA Calibration Procedures Metal/Nonmetal

Calibration procedures for respirable dust samplers in metal/nonmetal mines are found in PH06-IV-I (1) Metal/Nonmetal Health Inspection Procedures Handbook (United States Department of Labor, 2006).

The only method used in the Metal/Nonmetal handbook for cyclones is the previously discussed Jar Method. The difference in the method is the addition of a Mason jar as an approved calibration jar (MSHA, 2006).

2.4.2. MSHA Metal/Nonmetal Calibrators

Primary flow Calibrators that are MSHA approved for Metal/Nonmetal respirable PM sampling include: the use of a glass burette soap bubble film method and an electronic soap bubble film instrument. The Gilian Gilibrator® and the Mini-Buck Wet Bubble Calibrator® are examples of electronic soap bubble film meters that are approved under MSHA for Metal/Nonmetal sampling (United States Department of Labor, 2006).

2.4.3. MSHA Metal/Nonmetal Pumps

MSHA approved pumps in Metal/Nonmetal mines include: SKC Model 224-44XR and the Gilian Model HFS 513A-U (United States Department of Labor, 2006). The pumps are specified to be set at a flow rate of 1.7 lpm for use with a Dorr Oliver Cyclone.

2.4.4. MSHA Metal/Nonmetal Cyclone Samplers

The only sampler that is approved for metal/ nonmetal dust sampling is a 10mm nylon Dorr Oliver cyclone sampler. A 37mm preweighted PVC filter with a five micron pore size in a cassette that is manufactured by MSA is specified to be used with a Dorr Oliver Cyclone for metal/nonmetal mine respirable PM sampling (MSHA, 2006).

2.5. OSHA Calibration Procedures

Calibration procedures for respirable dust samplers for OSHA are found in the OSHA Technical Manual (OTM) (OSHA Technical Manual, 2008).

There are two methods of calibration in the OTM; the first method, the Jarless Method, includes setting the pump at 1.7 lpm using a bubble burette or an electronic bubble meter. A "T" connector is used to connect the pump inlet to a water manometer and then to the outlet of the cyclone. An adjustable load is used and two to five inches of pressure on the gauge should be obtained as shown in Figure 6.

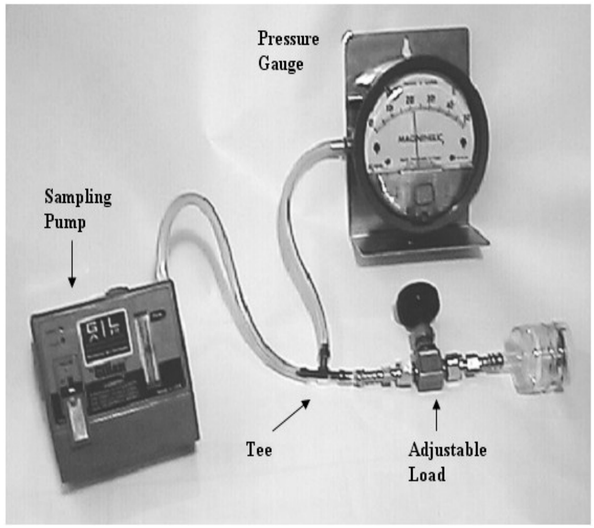

Figure 6: OSHA Jarless Method, adjustable load (OSHA Technical Manual, 2008)

The load is slowly increased until the gauge indicates between 25 and 35 inches of water and then the cyclone is put in place of the adjustable load as depicted in Figure 7.

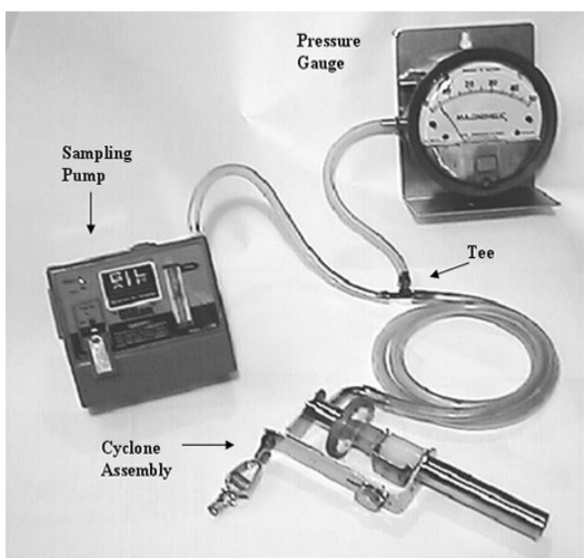

Figure 7: OSHA Jarless Method, cyclone (OSHA Technical Manual, 2008)

The pump is then checked to make sure it remained at 1.7 lpm using a calibrator. The second method uses electronic flow calibrators such as DryCals to calibrate the cyclones. The Jar Method is then used in a similar manner as previously described. The OTM also includes the use of a leak test kit to check for leaks within the calibration train and calibration with a light load, a 37mm five micron filter, and a heavy load, created by slightly pinching the tubing, both pre and post sampling (OSHA Technical Manual, 2008).

2.5.1. OSHA Calibrators

The calibrators that are approved for OSHA respirable dust sampling include: a bubble burette, Gilian Gilibrator®, and a Bios DryCal® DC-Lite. The OSHA Technical Manual states that the DC-Lite is not to be used with the MSA Escort ELF® pumps because operation of the pump is affected by the DC-Lite (OSHA Technical Manual, 2008).

2.5.2. OSHA Pumps

The pumps that are OSHA approved include any pumps that consist of a diaphragm or piston pump and are driven by a battery-powered electric motor. The pump must also be able to control the air volume with a rotameter, a stroke counter, or a micro pressure sensor. The sampling pump should operate continuously for at least eight hours between charges (Mody & Jakhete, 1987).

2.5.3. OSHA Cyclone Samplers

The sampler that is approved for OSHA respirable dust compliance sampling is any cyclone that separates respirable from non-respirable sized particles. The cyclone must contain a vortex finder, cyclone body, and a grit pot (Mody & Jakhete, 1987).

3. Toxicology

Acute and chronic effects and PM deposition and clearance mechanisms associated with inhalation of respirable coal dust will be discussed in section 3. Occupational exposure limits set forth by MSHA and OSHA along with discrepancies between them will also be examined.

3.1. Coal Mine Respirable PM Toxicity

Coal dust is black to dark brown in color and can be created from crushing, grinding, or pulverizing coal. (Occupational Safety and Health Administration, 1996). There are four different types of coal; Lignite, Subbituminous, Bituminous, and Anthracite. Coal is ranked from lowest to highest based on their heating value. Lignite has the lowest rank with a heating value of 8300 British Thermal Units (BTU) and a carbon content of 60-70%. Anthracite has the highest heating rank and has a carbon content of over 87%. The most abundant type of coal is Bituminous, which accounts for 50% of the coal produced in the U.S (King, n.d.). The primary route of exposure is inhalation. Inhalation of mineral dusts such as asbestos, silica, and coal dust is the leading cause of occupational lung diseases in the world. Coal mining can include inhalation of coal dust which could include silica. The higher ranked coal, such as Bituminous and Anthracite, usually contain more silica particles than the dust of a lower rank (Government of Alberta, 2010). In humans, overexposure to coal dust can cause diseases including emphysema, chronic bronchitis, coal workers pneumoconiosis (CWP), also known as black lung, progressive massive fibrosis (PMF), and lung function loss (OSHA, 1996 ; Schins & Borm, 1999). Animal studies have shown that coal dust is a tumorigenic agent that has produced adrenal cortex tumors in rats exposed to high doses of coal (OSHA, 1996). Exposures to silica could produce silicosis, lung cancer, pulmonary tuberculosis, and other airway diseases (Schins & Borm, 1999).

3.2. Acute and Chronic Effects of Coal Dust

Acute effects of coal dust inhalation include coughing, wheezing, and shortness of breath. Chronic inhalation of coal dust can result in symptoms of bronchitis and emphysema (OSHA, 1996). Bronchitis symptoms can include wheezing, chest discomfort and coughing. A large amount of mucus may be produced with the coughing (U.S. Department of Health and Human Services, n.d.). Emphysema symptoms can include shortness of breath, grey or blue fingernails, and tachycardia, a heart rate that exceeds the normal rate (Mayo Clinic, n.d.). Exposure to Silica can cause silicosis, which reduces the lung's ability to extract oxygen from the air. Inhalation of silica can produce several symptoms including shortness of breath, loss of appetite, blue-tinged skin or lips, chest pain, and death (MSHA, n.d).

3.3. PM Deposition and Clearance

There are several similarities in biological responses between coal dust and other mineral dust when comparing in vitro and in vivo research (Schins & Borm, 1999). Animal research has shown that the number of alveolar macrophages increases in the lungs when the lungs are chronically exposed to mineral particles (Schins & Borm, 1999 ; Kuhn, Stanley, el-Ayouby, & Demers, 1990). Phagocytosis results in an increased activation state of the macrophage, which can cause the release of bioactive lipids, oxidants, cytokines, growth factors, proteases and antiproteases. Particle overload can happen quickly as the macrophage phagocytosis represents the slow-phase of particle clearance, which can cause damage to the alveolar epithelium (Kuhn, Stanley, el-Ayouby, & Demers, 1990).

3.4. Mechanisms

When PM is inhaled it can either be exhaled or deposited in the airway depending on the physiological characteristics of the particle. The World Health Organization (WHO, 1999) lists the five deposition mechanisms of PM as sedimentation, inertial impaction, diffusion, interception, and electrostatic deposition. Aerodynamic diameter is the primary factor in sedimentation and impaction and is the most important mechanisms when inhalation of PM occurs. When particles are inhaled into the nose or mouth, mucous-covered cilia can move the particle upwards towards the epiglottis where it is swallowed or otherwise eliminated. Nasal passages are more efficient in filtering out PM than the oral passages. Therefore, people who breathe most of the time through the mouth might have more particles reach the lung. Bronchiole movement such as coughing and sneezing is also an effective mechanism in removing particles. When particles reach the alveolar region, particles can be engulfed by macrophage cells or phagocytes. The engulfed particles can then travel to the ciliated epithelium and be removed, enter into the lymphatic system, or remain in the lungs. Other clearance mechanisms include particles dissolving and removed via the blood stream or being cleared upward by the mucociliary escalator (Klaassen, 2008). Particles that contain silica, such as dust from a coal mine, could impair phagocytosis or kill the macrophage cells and might stay in the lung for very long periods of time (WHO, 1999).

Mechanisms of mineral dust in the respiratory tract have been studied using in vitro studies, epidemiological studies, and animal inhalation studies. Coal dust studies primarily consist of epidemiological studies and many interactions have been described. There are two major pathways in which the mechanisms of coal dust toxicity can be divided (Schins & Borm, 1999).

The first pathway involves the production of reactive oxygen species (ROS) and the related antioxidant protection. ROS in the lung can damage cell membranes by lipid peroxidation process, protein oxidation, or damage to the DNA of target cells. DNA damage can cause cell death or tissue proliferation or destruction. The second pathway involves expression and release of growth factors and cytokines. Cytokines are produced by almost all nucleated cells and as such are involved in several biological events such as inflammation, metabolism cell growth, differentiation, morphogenesis, fibrogenesis, and homeostasis. Both of the pathways are based on macrophage activation and lung inflammation, which are crucial in the respiratory effects observed when a worker is chronically exposed to mineral dusts (Schins & Borm, 1999).

3.5. Occupational Exposure Limits

Respirable dust standards listed in MSHA regulation 30 CFR § 70.100 state that the MSHA respirable dust standard is 2.0 milligrams of respirable dust per cubic meter of air (mg/m^3) if it contains less than 5% silica. The OSHA permissible exposure limit (PEL) for coal dust with less than 5% silica is 2.4 mg/m^3. The American Conference of Governmental Industrial Hygienists (ACGIH) lists the TLV for coal dust as 0.4 mg/m^3 for bituminous coal and 0.9 mg/m^3 for anthracite coal (ACGIH, 2012). The National Institute for Occupational Safety and Health (NIOSH) does not currently have a recommended exposure limit for coal dust. If the silica content is 5% or greater than the exposure limits are recalculated by using the formula: 10 $mg/m^3 \div \%Silica + 2$ (Tomb & Parobeck, 1999).

3.6. Calibration Discrepancies between OSHA and MSHA

A comparison of various calibration techniques and inter-agency differences as described above are shown in Table 1.

Table 1: A Comparison of Approved Calibration Equipment and Procedures among Agencies
***Flow Rates if using a 10mm Nylon Dorr Oliver Cyclone**

Agency	Cyclone	Flow Rates (lpm)	Pumps	Calibration Methods
MSHA Coal	10mm nylon Dorr Oliver Cyclone	2.0*	MSA Escort ELF®	Jar Method Tape Method
MSHA Metal/Nonmetal	10 mm nylon Dorr Oliver Cyclone	1.7*	SKC model 224-44XR Gilian Model HFS-513A-U(3)	Jar Method
OSHA	Any cyclone that separates respirable and non respirable PM and contains a vortex finder, cyclone body, and grit pot.	1.7*	Any pump with 8hr. Battery life, diaphragm or piston pump, and a battery powered electric motor	Jar Method Jarless Method

An analysis of these various techniques revealed several discrepancies and commonalities. MSHA Coal's Tape Method is unique to coal mining. This method requires removing the grit pot from the bottom of the cyclone and connecting the outlet of the calibrator to the bottom of the cyclone. Tape or modeling clay is then used to seal the inlet of the cyclone. The Jar Method is commonly cited among the three regulatory categories evaluated. However, there are some slight variations in the Jar Method techniques. In metal/nonmetal mines, calibration with the Jar Method may be performed with a Mason jar or flask. OSHA offers an alternative to the Jar Method, the Jarless Method that involves using an adjustable load and connecting the pump via a "T" connector to a water manometer. OSHA specifies that the BIOS DC-Lite calibrator cannot be used with the Escort ELF® pump because the operation of the pump can be affected. MSHA Coal and metal/nonmetal methods do not mention this limitation. There are also discrepancies in approved pump models and suggested flow rates.

4. Literature Review

This section outlines summaries of Informational Report 1240 along with other literature relating to the calibration and use of dust samplers. There are several discrepancies among manufacturer recommendations for both the personal sampling pump and the calibrator and MSHA coal calibration procedures. Sections 4.1-4.3 outline some benefits of the MSHA's approved sampling pump, Escort ELF®, as well as inconsistencies between approved calibration procedures and calibration equipment. MSHA respirable dust calibration techniques are not well studied however; several studies have been conducted involving MSHA's current TLV of respirable dust as well as the flow rate that MSHA requires for respirable dust sampling with a Dorr Oliver Cyclone, which are discussed in section 4.4.

4.1. Study Supporting the Escort ELF® Personal Sampling Pump

Gero, Parobeck, Suppers, and Jolson (1997) conducted a study to evaluate the effect of altitude, loading, and temperature on the MSA Escort Elf®. The Escort Elf® was designed to maintain constant volumetric flow even with changing environmental conditions such as changes in altitude and temperature. Two calibration methods, the bubble meter and the wet-test meter were compared. Ten pumps were calibrated under ambient laboratory conditions with a bubble meter. In order to check the accuracy of the bubble meter calibrations, a calibration was then performed using a wet-test meter. It was determined that the two calibration methods were within 1.6 percent of each other, which meets MSHA criteria of ±5 percent (Gero et al., 1997). The study identified the approval of the Escort Elf® personal sampling pump by MSHA for use in coal mine dust sampling in the late 1990s. The procedures for calibration using the bubble meter or the wet-test meter were not specified in this study.

MSHA calibration procedures approve the use of the Jar Method or the Tape method for both the bubble meter and the wet-test meter making it difficult to determine which method of calibration was used. The flow rates of the Escort ELF® pump were tested with a wet-test meter. Atmosphere was simulated using a vacuum pump and a sealed chamber, inlet loading was simulated by partially obstructing the pump, and temperature was tested by using an environmental chamber. It was determined that the Escort ELF® maintains volumetric flow within ±5 percent over a range of altitudes, sample inlet loadings, and temperatures.

4.2. MSHA Informational Report 1240

The Informational Report provides calibration and maintenance procedures for performing compliance sampling for MSHA. The current version of IR 1240 was approved in 1999. IR 1240 outlines step by step directions for the calibration of approved sampling equipment. The report also specifies the type of calibrators that can be utilized and maintenance procedures of the Escort ELF® pump. IR 1240 was updated from a previous version to include the use of fast response calibrators that contain a volumetric tube. This revision considered the use of additional primary calibrators however; no changes were made to the calibration methods.

4.3. Comparison of MSA Instruction Manual, Manufacturer Recommendations, and IR 1240

In 2007, the manufacturer of the Escort Elf Pump, Mine Safety Appliance Company (MSA), published a revised instruction manual that included calibration and maintenance procedures for the Escort ELF®. The instruction manual included two sections for calibration of Dorr Oliver Cyclones. The first section is for ELF® Sensor Calibration and the second section is for ELF® sensor calibration for pumps used in the U.S. Government MSHA Coal mine dust sampling program. These sections include a step by step procedure for calibration of the Escort

ELF® pump. The two differences between the procedures were the flow rate and the use of the BIOS DryCal with the Escort Elf®. The Elf® sensor calibration section specifies a pump flow rate of 2.50 lpm, while the MSHA sensor calibration section specifies a flow rate of 2.00 lpm. A note at the end of the ELF® sensor calibration section states that the BIOS DryCal requires the use of an isolating flow restrictor between the pump and the calibrator when calibrating the MSA Escort ELF® pump. The note further states that if the restrictor is not used it could cause a calibration error up to 2% (MINE SAFETY APPLIANCES COMPANY, 2007).

In comparison, the MSHA ELF® sensor calibration section does contain information about the use of BIOS DryCals (MSA, 2007). BIOS states that the use of calibration jars with BIOS primary standards is not recommended (Environmental Monitoring Systems, N.D.). According to BIOS, calibration jars insert a large gas volume between the filtration element and the standard thus introducing measurement error. BIOS recommends connecting the pump directly to the calibrator's outlet then connecting the cyclone to the calibrator's inlet. It is recommended to take a minimum of 20 measurements to average outflow variations caused by direct connection of the pump to the calibrator. Bios also states that calibration jars are not metrologically-sound by nature and typically introduce undetectable air leaks resulting in measurement error (Environmental Monitoring Systems, N.D.).

IR 1240 approves the use of any fast-flow calibrator which measures volume, and whose volumetric tube has a calibration traceable to the NIST. BIOS DryCal calibrators meet these qualifications. According to the Nevada Mining Association Industrial Hygiene Sampling Manual (Nevada Mining Association, 2008), the two different types of primary calibrators that can be used for respirable dust sampling are the Gilibrator Bubble Generator and the dry calibrator (Nevada Mining Association, 2008). IR 1240 also lists a wet-test meter as an approved calibrator for MSHA compliance sampling (Tomb & Parobeck, 1999). Wet-test meters however, are very large compared to a bubble meter or a DryCal, and can take longer to calibrate sampling pumps.

Considering the information provided by both MSA and BIOS, the use of a DryCal with an Escort ELF® pump or a calibration jar would not be recommended. BIOS also stated that the use of the jar is not recommended due to undetectable air leaks (Environmental Monitoring Systems, N.D.). Therefore, the Tape Method with a bubble meter or a wet-test meter would be the only other MSHA approved calibration method. IR 1240 does not mention possible calibration errors with the use of calibration jars or DryCals (Tomb & Parobeck, 1999).

4.4. Comparison of Flow Rates and Respirable PM Standards

NIOSH released a publication in 1995 entitled Criteria for a Recommended Standard; Occupational Exposure to Respirable Coal Mine Dust to provide scientific basis for new occupational safety and health standards (U.S. Department of Health and Human Services, NIOSH, 1995). NIOSH communicated these recommendations to OSHA and MSHA as required under The Federal Mine Safety and Health Act of 1977. The current MSHA respirable dust standard for coal dust is 2 mg/m^3 and was established 1977. However, epidemiological studies have shown that miners who are exposed to 2 mg/m^3 of respirable coal PM over a working lifetime have an elevated risk of developing respiratory diseases. NIOSH recommends that the MSHA's exposure limit for dust with less than 5% silica should be reduced to 1 mg/m^3 to reduce the risk of development of occupational respiratory diseases (U.S. Department of Health and Human Services, NIOSH, 1995). The current MSHA standard of 2 mg/m^3 is primarily based on studies of coal miners in the United Kingdom during the 1960s. The NIOSH recommendation of

1 mg/m^3 for respirable PM exposure is based on epidemiological exposure response studies of occupational respiratory disease among U.S. coal miners.

A study conducted in 1990 assessed biases in MSHA respirable Coal Mine Dust Data (Seixas, Robins, Rice, & Moulton, 1990). Possible sources of negative bias include infrequent pump calibration by MSHA, voiding of samples with oversized particles, and errors stemming from the use of the British Medical Research Establishment conversion factor. Other possible errors could be the truncation of data when being analyzed, mine operators falsifying data, and miners attempting to obtain falsely low concentrations. MSHA only requires sampling pumps to be calibrated every 200 hours (25 shifts) and no post-shift calibration is conducted. Therefore, if the pump did not maintain its airflow while sampling, the sample volume may be overestimated or underestimated resulting in an erroneous concentration of respirable PM (Seixas, et al., 1990)

Corn, et al., (1985) explains that current MSHA regulations do not recognize any commonly accepted criteria for respirable dust. Commonly accepted criteria for respirable dust have been derived from the British Medical Research Council (BMRC) or the United States Atomic Energy Commission (USAEC) while MSHA criteria come from the British Mining Research Establishment (BMRE). The USAEC criteria are more representative of the deposition of PM in the human respiratory tract. Both the BMRC and USAEC indicate that a flow rate of 1.7 lpm is the flow rate at which penetration through Dorr Oliver nylon cyclones best approximates the USAEC respirable dust criteria. Both the American Industrial Hygiene Association (AIHA) and OSHA recommend that a flow rate of 1.7 lpm be used with 10-mm nylon cyclones to evaluate respirable dust. MSHA requires a flow rate of 2.0 lpm when using a 10-mm nylon cyclone with the resultant weight multiplied by a factor of 1.38 in order to convert the results to BMRE equivalent concentrations. This study has concluded that operation of the cyclone at 2.0 lpm with a 1.38 multiplier is not a good estimate of respirable dust concentrations. Corn, et al., recommends that MSHA replace its current definition of respirable PM to be more consistent with current understandings of lung deposition as well as match procedures of other regulatory agencies. A flow rate of 1.7 lpm for 10-mm nylon cyclones is recommended, which is consistent with ACGIH respirable PM criteria (Corn, et al., 1985).

5. Methodology and Procedures

This study was conducted in Butte, MT on November 17, 2012. The temperature, pressure, and humidity were recorded before the start of each trial.

The common element of the OSHA, MSHA Coal, and MSHA Metal/Nonmetal calibration methods is to calibrate using a soap bubble film meter, such as a Gilian Gilibrator®, and a calibration jar. For this study, the Gilian Gilibrator® and SKC calibration jar were used as the control method for the original calibration of an MSA Escort ELF® model EX-94.C.46.2) pump. In addition to the jar calibration method, four different types of tape/clay were used for the tape method in three trials. All of the tape and modeling clay were purchased new for this study. Duct tape was selected based on a preliminary study that indicated Duct tape yielded the best results when compared to various other tapes. Electrical tape was a common method of sealing the inlet of the cyclone in coal mines therefore; it was selected for use in this study. Masking tape was selected because of its availability and likelihood of use. Modeling clay was used because it was specifically mentioned in IR 1240.

5.1. Calibration Using the Jar Method

Three trials were conducted using an SKC calibration Jar (model 225-100), a Dorr Oliver cyclone (model 456343), and a 37mm MSA filter (model 985221). The five variables in each trial were the calibration jar, modeling clay, duct tape, electrical tape, and masking tape. The order of administration the variables within each trial was determined by using a random-number generator. As discussed previously, the Jar Method is the only approved method by OSHA and MSHA; therefore, this method was used to calibrate the pump to 2.0 lpm before each trial. Prior to every trial, the pump was allowed to run for 10 minutes with nothing connected to it.

Calibration using the Jar Method included placing a Dorr Oliver Cyclone with a MSA filter into the calibration jar. Tubing was connected from the pump to the inlet of the jar lid. A second piece of tubing was connected from the outlet of the jar lid to the calibrator. The calibration jar was then allowed to run for an additional five minutes with the calibration train connected. The inlet of the cyclone was cleaned with isopropyl alcohol and allowed to dry before each trial. The first five readings with the Gilibrator® were not recorded in order to prime the Gilibrator®. Ten calibrations were performed and recorded using the calibration jar and the Gilian Gilibrator®. The Jar Method was used to calibrate the pump in between each Tape/Clay method to confirm that the pump was still running at the calibrated flow rate of 2.0 lpm. Figure 6 (Section 2.3.1) illustrates calibration using the jar method.

5.2. Tape Method with Gilian Gilibrator®

The previously calibrated Escort ELF® pump was connected to a Dorr Oliver cyclone with a MSA filter. The grit pot was removed from the bottom of the cyclone sampler and tygon tubing was connected from the bottom of the cyclone to the Gilibrator® inlet. The cyclone inlet was sealed with tape or modeling clay in the order that was selected in the random number generator. The pump was allowed to run for five minutes with the calibration train connected. The inlet of the cyclone was cleaned with isopropyl alcohol and allowed to dry before each trial. The first five readings with the Gilibrator® were not recorded in order to prime the Gilibrator®. Ten calibrations were performed and recorded using the Gilian Gilibrator® for each trial. This procedure was repeated using duct tape, electrical tape, masking tape, and modeling clay.

5.3. Statistical Analysis

Statistical analysis was performed using Minitab® statistical software. A one-way analysis of variance (ANOVA) with a Tukey comparison was performed on combined data from all three trials to determine if there were differences or correlations between the two calibration methods. The ANOVA was run with a 95% confidence interval, which means that if the p-value is less than 0.05, significance is found. A regression analysis was also performed on the data. However, since the r squared value was low (25%) (p=0.000), a regression correction value was not applied.

5.4. Assumptions and Limitations

The assumptions and limitations pertaining to this study may have an effect on the results. The assumptions were taken for granted as truth, but were not verified. The limitations are potential weaknesses in the study.

5.4.1. Assumptions

1. The calibration jar was sealed with the same tightness before every sample was taken.
2. The clay/tape sealed the inlet to the cyclone the same way in each trial.
3. The alcohol completely cleaned off all residues from the tape/clay that was used in previous trials thereby not affecting air flow.
4. The temperature, pressure and humidity did not affect the function of the pump

5.4.2. Limitations

1. Small sample size. A larger sample size is needed to more accurately determine significance between the types of tape used. There are several different varieties and brands of tape that could be tested as part of the Tape Method.
2. Use of only the Gilian Gilibrator® to calibrate. Using all of the MSHA Coal approved calibrators could have shown if there is also variation in the type of calibrator used which would introduce more error in addition to the Tape Method or the Jar Method.

6. Results

This section describes the results of three trials comparing MSHA Coal's Tape Method, using four types of tape/clay, and the industry recognized Jar Method. Table 2 depicts the number of data points, and their means, and standard deviations of the data for each method.

Table 2: Summary of Methods, Mean Flow Rates, and Standard Deviations

Calibration Method	Number of Data Points (n=240)	Mean Flow Rate (lpm)	Standard Deviation
Jar	120.00	2.02	0.02
Clay	30.00	1.93	0.03
Duct Tape	30.00	1.77	0.09
Electrical Tape	30.00	1.89	0.03
Masking Tape	30.00	1.92	0.04

* When comparing the Jar Method with the Tape Method the p-value is $p>0.000$.

The jar method was considered the control because it is a common calibration method for both MSHA and OSHA. The initial flow rates to which others were compared utilized this method. Thus, 120 of the 240 samples were collected with this method.

The Jar Method results were most consistent with the initial calibration of the pump. The Jar Method had a mean flow rate of 2.02 lpm and a standard deviation of 0.02 while the duct tape had the highest standard deviation, 0.09, and a mean flow rate of 1.77 lpm. When comparing the four methods tested as part of the Tape Method, the modeling clay had a mean flow rate of 1.93 lpm and a standard deviation of 0.03, which was the most consistent flow rate when compared to the initial jar calibration.

6.1. Statistical Tests

Statistical analysis was performed using Minitab® statistical software. A one-way analysis of variance (ANOVA) with a Tukey comparison was performed on combined data from all three trials to determine if there were differences between the flow rates of the calibration methods. The ANOVA was run with a 95% confidence interval which means that if the p-value is less than 0.05, significance is found. The flow rates of all three trials (n=240) were compared against the five calibration types that were performed in each trial (jar, duct, electrical, clay, and masking tape). When comparing flow rate and calibration type, a significant difference was found ($p < 0.000$). An R-squared value of 81.98% shows that almost 82% of the variations in the results are explained by the calibration types. Figure 8 shows the results of the One-Way ANOVA comparison of flow rate versus calibration method. See Appendix A for complete statistical analysis results.

A total of 240 data points were collected, stacked, and analyzed using one-way ANOVA. The Box plot in Figure 8 illustrates that when the flow rates were compared with calibration methods used, the Jar Method had the least amount of variance while all forms of the Tape Method (duct, electrical, masking, and modeling clay) had a significant amount of variance from the mean.

The black line on the box plot represents 2.00 lpm, which is the flow rate that the pump was calibrated to prior to starting each trial using the Jar method. The Jar method revealed a mean flow rate of 2.02 lpm while all forms of the tape method revealed lower mean flow rates; the lowest being duct tape at 1.77 lpm.

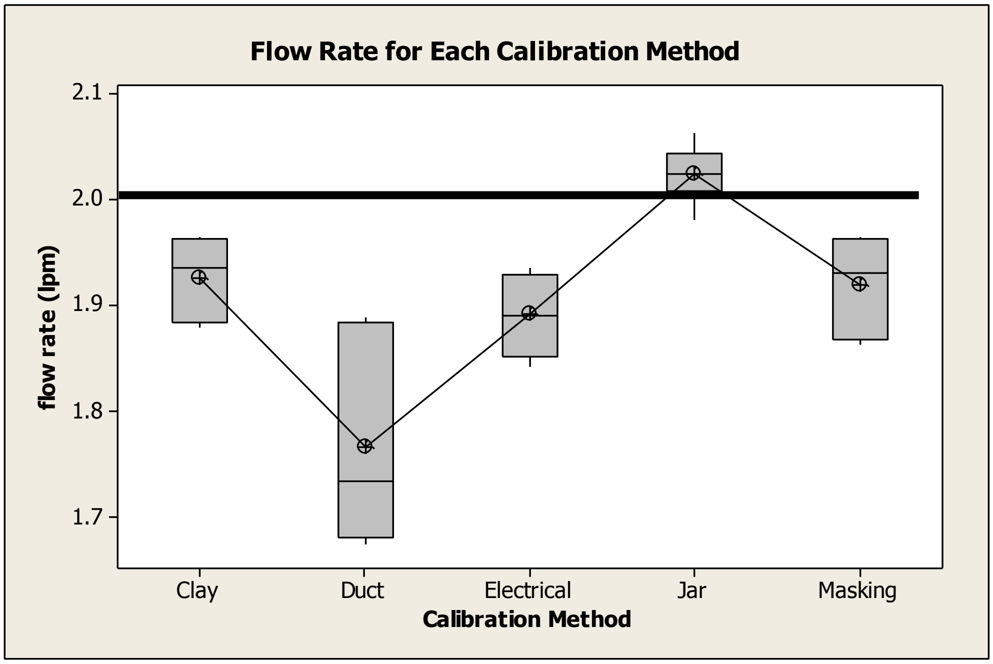

Figure 8: Comparison of Calibration Methods
The pump was set to run at 2.0 lpm as depicted by the black line

The ANOVA analysis established that there is a significant difference between the calibration methods (p=0.000). Therefore, the study indicates that we can reject the null hypothesis, which states that there is not a significant variation between calibration using the MSHA Coal Tape Method and the industry-standard Jar Method. The Tukey comparison showed that the jar and duct tape are significantly different from all the other methods. Tukey also showed that there was not a significance difference between the clay and masking tape or making tape and electrical tape. See Appendix A for the complete statistical analysis including the Tukey comparison.

Based on these results, it was established that there is a significant difference between the calibration types outlined in MSHA calibration procedures for coal mines. Therefore, the null hypothesis was rejected and the alternative hypothesis which states, There will be a significant difference ($p \leq 0.05$) in measured flow rates obtained with the MSHA Coal Tape Method vs. the standard Jar Method, was accepted.

7. Discussion

In this section the results are discussed in the context of the various aspects of this study, including calibration equipment, methods, and inaccuracy.

7.1. Calibration Equipment vs. BIOS Calibration Methods

Calibration of cyclone samplers has been performed using the Jar Method for several years and is the preferred method in most industries. This study indicates that the Jar Method, when used with a Gilian Gilibrator® provides more accurate and reliable results than other calibration methods. The function of the calibration jar is to create a sealed environment in which the air can flow through the calibration train in order to accurately assess the flow rate of the pump.

Within the past ten years, piston-style DryCal®s have been increasingly utilized to calibrate pumps. As illustrated in section four of this study, OSHA specifies that the BIOS DC-Lite calibrator, a piston-style DryCal®, cannot be used with the Escort ELF® pump because the operation of the pump can be affected by it (OSHA Technical Manual, 2008). BIOS, the manufacturer of the DC-Lite, states that calibration jars are not always usually airtight, which could introduce leaks resulting in measurement error. Bios also maintains that calibration jars insert large amounts of dead volume between the filtration element and the DryCal®, which introduces further measurement error (Calibrating Cyclones with Bios Defender, n.d.). The MSHA IR 1240 was updated from the previous versions in order to allow the use of fast-response calibrators. IR 1240, however, did not allow for any changes in the MSHA Coal approved calibration methods. There are only two calibration methods that can be used for respirable dust sampling in the Informational Report. The MSHA coal approved method is the Jar Method, which includes sealing the cyclone in an airtight container and is referred to as the preferred method for calibrating respirable dust samplers in coal mines (Tomb & Parobeck, 1999). The second MSHA Coal approved calibration method is the Tape Method, which includes removing the grit pot from the bottom of the cyclone, connecting the calibrator outlet to the bottom of the cyclone, and sealing the 2.0 by 2.0 mm cyclone inlet with "tape or modeling clay, (Tomb & Parobeck, 1999). Therefore, if a DryCal is used for calibration of cyclones then the Jar Method cannot be utilized per manufacturer recommendations, in which case the Tape Method will be the only option for calibration.

As shown in the results section, Table 2, there is significant variation between the types of tape/clay that were used for calibration. Results of this study involving the Tape Method has shown that using modeling clay would yield the most accurate flow rates with a mean flow of 1.93 lpm. Modeling clay however, is not an in item that is readily available in most industries and in my opinion would not typically be used for calibration. Masking tape had a mean flow rate that of 1.92 lpm and is not significantly different from the modeling clay as depicted in the ANOVA analysis using the Tukey Method. Masking tape is easier to obtain and therefore, might be used more often for calibration with the Tape Method. There are several variables that could be a factor in the difference in flow rates. The first variable is that the tape or clay might not seal correctly, which would allow air to pass through the inlet giving an erroneous flow rate reading. Another variable that could cause a difference in flow rates is the removal of the grit pot, which then changes the airflow through the cyclone. When calibrating with the Jar Method, the jar might not have been sealed in the same manner every time and so air leaks may have occurred inside the jar.

7.2. Potential Effect of Inaccurate Calibration

The primary objective of this study was to evaluate the coal mine respirable dust sampling calibration methods published by MSHA to determine if there are significant differences in flow rates achieved with the various methods. It was found that the use of the Tape Method results in inconsistent flow rates among types of tape and when compared with other calibration methods. Table 3 demonstrates the effects that inaccurate flow rates can have on the sampling results. The mean flow rate for the Jar Method and the means of the most accurate and least accurate of the Tape method from this study were used in the following example. It is assumed that a PM gravimetric mass concentration of 1.80 milligrams and sample duration of 480 minutes were obtained.

Table 3: Comparison of Theoretical Concentrations using Flow Rates from Different Methods. *Sample time of 8 hours and *Mass of Dust of 180 milligrams are fictitious numbers used for illustration.

Sample Volume Calculation (Flow Rate (L/min) X sample time (min))/1000=m^3					
Calibration Method	***Mass of Dust (mg)**	***Sample time (t) (min)**	**Flow Rate (Q) (L/min)**	**Sample Volume (V = Qt) m^3**	**Concentration (C = m / V) Mg/m3**
Jar	180 mg	480 minutes	2.02	0.97	1.86
Modeling Clay			1.93	0.93	1.94
Duct Tape			1.77	0.85	2.12

Accurate calibration is essential when quantifying exposure concentrations. In this example, the respirable dust standard is 2.0 mg/m^3. Thus, if the gravimetric concentrations are compared to the dust standard, the calibration jar and modeling clay both indicate that the results are below the standard while the duct tape method is above the standard. Using the correct flow rate is also important for proper operation of the cyclone. If no measures are taken to correct the pump flow rate, it could mean that unnecessary and potential costly measures might be taken to reduce the amount of respirable dust workers are exposed to.

When calibrating cyclones, the pre-calibration flow rate should be as close to the required flow as possible for proper separation of respirable dust. If the flow rate is not within ±5% of the set flow rate, the pump would need to be adjusted to the average flow rate that was determined by the calibrator. The pump would be adjusted so that it would speed up and the calibrator would read 2.0 lpm. In the example shown in Table 3, the Duct tape method had a mean flow of 1.77 lpm, which means the pump should then be adjusted. When adjusting pump speed, the pump would speed up approximately 0.23 lpm to reflect the flow rate determined by the calibrator. This could mean that the pump could actually be running at roughly 2.25 lpm, which would yield a gravimetric concentration of 1.67 lpm. Errors such as the one described above could be costly for employers and/or could affect the health of the employees. Erroneous increase of the pump speed could show that employees are not overexposed to respirable dust when, in fact, they might be. Inaccurate flow rate estimation affects both proper separation of respirable particles by the cyclone and the resulting estimation of concentration for comparison to exposure limits.

7.3. Discrepancies Between MSHA and Other Agencies

The development of MSHA-approved pump calibrators requires changes in acceptable methodology. Currently, MSHA Coal and OSHA both allow for the use of DryCal®s but neither agency has changed their required methodology for sampling. Since MSHA and OSHA both publish directions for calibration, it is reasonable to assume that the majority of people calibrating would not think to research the equipment or methods used. These agencies should adjust their methods to reflect changes in approved calibration equipment.

NIOSH publishes Criteria for a Recommended Standard documents to provide scientific basis for new occupational safety and health standards. In 1995, the recommended standard criterion was sent to MSHA with recommendations to reduce exposure limits from 2.0 mg/m^3 to 1.0 mg/m^3 in order to prevent development of occupational respiratory diseases in coal miners (U.S. Department of Health and Human Services, NIOSH, 1995). As of 2013, the MSHA respirable coal dust standard is still 2.0 mg/m3. Studies by Corn, et al., 1985 and Seixas, et al., 1990, have detailed biases in MSHA sampling methods including calibration frequency and using a flow rate of 2.0 lpm, which can cause error in sampling results.

8. Conclusion

The primary objective of this study was to evaluate the coal mine respirable dust sampling calibration methods published by MSHA to determine if there are significant differences in flow rates achieved with the various methods. It was found that the use of the Tape Method results in inconsistent flow rates among types of tape and when compared with other calibration methods. Accurate calibration is essential to quantifying exposure concentrations.

Based on the literature review and the results of this study, I recommend that MSHA use information that is published by NIOSH, such as reducing exposure limits from 2.0 mg/m^3 to 1.0 mg/m^3, and other studies related to calibration of cyclones (Corn, et al., 1985; Seixas, et al., 1990; U.S. Department of Health and Human Services, NIOSH, 1995). Updated equipment, information, and other recommendations should be evaluated and implemented in order to prevent occupational respiratory disease in miners.

MSHA did not use NIOSH's recommendations or other studies to change its criteria regarding sampling methods. Errors produced from inaccurate calibration methods discussed in this paper along with the errors resulting from using a flow rate that is not consistent with current knowledge of PM deposition indicate that data obtained from coal mine respirable dust samples are inaccurate. Without accurate data, workers could be inadvertently overexposed to respirable coal mine PM. Furthermore, MSHA's calibration methods and PM standards have remained the same since the 1970s.

Additional studies are needed to demonstrate inaccuracies in calibration techniques currently required for MSHA compliance sampling. Accurate calibration of sampling pumps is essential for obtaining accurate and reliable data regarding the amount of respirable PM that workers are exposed to.

9. Recommendations for Future Research

The following recommendations may be taken into account for future research projects that are based on this study:

1. Use a larger sample size. A larger sample size is needed to more accurately determine significance between the types of tape used. There are several different varieties and brands of tape that could be tested as part of the Tape Method.
2. Obtain a new calibration jar as an aged calibration jar could introduce leaks into the calibration train. Consider putting tape or another sealing device around the jar lid to minimize possible leaks.
3. Conduct a similar study comparing the different types of calibrators available. As discussed in this study new calibrators such as the DryCal might have different results when calibrating with the jar or tape method.
4. Conduct a similar study evaluating several different types of tape and recommend which tape/clay would provide the most accurate results should the Tape Method be used.
5. Follow this study up by actually adjusting the pump to the mean flow rate that was obtained for each calibration method. The samples that are obtained should then be sent to a lab for analysis. It would be beneficial to be able to display results based on real sample volumes and concentrations in order to show the effects of inaccurate calibration.

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Appendix A: Complete Statistical Analysis

4/13/2013 3:37:50 PM

```
Welcome to Minitab, press F1 for help.
Retrieving project from file: 'I:\THESIS STATS\RESULTS
STATS\MINITAB_RESULTS2.21.13.MPJ'
```

One-way ANOVA: flow rate versus Calibration Method

Source	DF	SS	MS	F	P
Calibration Method	4	1.83525	0.45881	267.31	0.000
Error	235	0.40336	0.00172		
Total	239	2.23862			

```
S = 0.04143   R-Sq = 81.98%   R-Sq(adj) = 81.67%


                                 Individual 95% CIs For Mean Based on
                                 Pooled StDev
Level         N    Mean   StDev   -+---------+---------+---------+--------
Clay         30  1.9261  0.0341                       (-*-)
Duct         30  1.7655  0.0896   (-*-)
Electrical   30  1.8919  0.0335                   (*-)
Jar         120  2.0247  0.0217                                    (*)
Masking      30  1.9200  0.0408                      (-*-)
                                  -+---------+---------+---------+--------
                                 1.760     1.840     1.920     2.000

Pooled StDev = 0.0414
```

Grouping Information Using Tukey Method

Calibration Method	N	Mean	Grouping
Jar	120	2.02466	A
Clay	30	1.92607	B
Masking	30	1.92000	B C
Electrical	30	1.89187	C
Duct	30	1.76553	D

Means that do not share a letter are significantly different.

Tukey 95% Simultaneous Confidence Intervals
All Pairwise Comparisons among Levels of Calibration Method

Individual confidence level = 99.36%

Calibration Method = Clay subtracted from:

Calibration Method	Lower	Center	Upper
Duct	-0.18996	-0.16053	-0.13111
Electrical	-0.06362	-0.03420	-0.00478
Jar	0.07533	0.09859	0.12185
Masking	-0.03549	-0.00607	0.02336

Calibration

```
Method       ---------+---------+---------+---------+
Duct               (-*-)
Electrical                  (-*-)
Jar                                  (-*)
Masking                       (-*-)
             ---------+---------+---------+---------+
                   -0.15      0.00      0.15      0.30


Calibration Method = Duct subtracted from:

Calibration
Method          Lower   Center    Upper
Electrical   0.09691  0.12633  0.15576
Jar          0.23586  0.25912  0.28239
Masking      0.12504  0.15447  0.18389

Calibration
Method       ---------+---------+---------+---------+
Electrical                            (-*-)
Jar                                             (*-)
Masking                                 (-*-)
             ---------+---------+---------+---------+
                   -0.15      0.00      0.15      0.30


Calibration Method = Electrical subtracted from:

Calibration
Method           Lower   Center    Upper
Jar            0.10953  0.13279  0.15605
Masking       -0.00129  0.02813  0.05756

Calibration
Method       ---------+---------+---------+---------+
Jar                                    (-*)
Masking                         (-*-)
             ---------+---------+---------+---------+
                   -0.15      0.00      0.15      0.30


Calibration Method = Jar subtracted from:

Calibration
Method           Lower    Center     Upper
Masking       -0.12792  -0.10466  -0.08140

Calibration
Method       ---------+---------+---------+---------+
Masking                (-*-)
             ---------+---------+---------+---------+
                   -0.15      0.00      0.15      0.30
```

Appendix B: Raw Data

Table 4: Raw Data

Trial 1	Time connected	Time Started	1	2	3	4	5	6	7	8	9	10
Jar	11:27 AM	11:32 AM	1.994	2.001	2.005	2.000	2.005	1.998	2.001	1.998	2.000	1.996
Duct	11:44 AM	11:49 AM	1.733	1.735	1.737	1.735	1.735	1.729	1.732	1.727	1.736	1.727
Jar	11:52 AM	11:57 AM	1.981	1.988	1.986	1.990	1.985	1.988	1.986	1.990	1.984	1.990
Clay	12:06 PM	12:11 PM	1.924	1.935	1.936	1.932	1.935	1.935	1.940	1.934	1.937	1.931
Jar	12:17 PM	12:22 PM	2.013	2.029	2.018	2.021	2.021	2.016	2.017	2.022	2.021	2.029
Masking	12:25 PM	12:30 PM	1.863	1.867	1.872	1.867	1.867	1.864	1.867	1.864	1.869	1.864
Jar	12:33 PM	12:38 PM	2.029	2.039	2.029	2.043	2.043	2.036	2.027	2.027	2.028	2.028
Electrical	12:44 PM	12:49 PM	1.887	1.887	1.891	1.886	1.891	1.887	1.893	1.892	1.895	1.891
Temperature	69.1 F											
Pressure	24.32 inHg											
Humidity	35.60%											
Pump turned on no calibration train	11:17 AM											
Trial 2	**Time connected**	**Time Started**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Jar	4:12 PM	4:17 PM	2.053	2.061	2.054	2.057	2.057	2.059	2.050	2.057	2.050	2.053
Clay	4:21 PM	4:26 PM	1.884	1.879	1.883	1.883	1.883	1.880	1.882	1.882	1.882	1.880
Jar	4:31 PM	4:36 PM	2.053	2.053	2.049	2.043	2.046	2.046	2.050	2.049	2.053	2.049
Duct	4:41 PM	4:46 PM	1.675	1.676	1.685	1.677	1.682	1.676	1.681	1.675	1.678	1.675
Jar	4:49 PM	4:54 PM	2.022	2.033	2.024	2.017	2.020	2.017	2.029	2.027	2.028	2.027
Electrical	4:56 PM	5:01 PM	1.928	1.935	1.936	1.936	1.935	1.930	1.932	1.929	1.932	1.928
Jar	5:03 PM	5:08 PM	2.020	2.022	2.029	2.018	2.020	2.024	2.022	2.021	2.028	2.025
Masking	5:09 PM	5:14 PM	1.960	1.962	1.964	1.962	1.964	1.962	1.963	1.959	1.965	1.962
Temperature	67.8 F											
Pressure	24.23											
Humidity	41%											

Pump turned on calibration train not connected	4:02 PM											
Trial 3	**Time connected**	**Time Started**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Jar	10:25 PM	10:30 PM	2.057	2.059	2.053	2.061	2.057	2.063	2.057	2.057	2.057	2.056
Clay	10:33 PM	10:38 PM	1.956	1.962	1.965	1.963	1.965	1.963	1.965	1.959	1.965	1.962
Jar	10:42 PM	10:47 PM	2.033	2.039	2.035	2.035	2.038	2.028	2.027	2.028	2.028	2.027
Electrical	10:49 PM	10:54 PM	1.842	1.847	1.849	1.847	1.848	1.847	1.851	1.852	1.875	1.877
Jar	10:56 PM	11:01 PM	2.009	2.008	2.01	2.008	2.01	2.006	2.008	2.008	2.009	2.004
Duct	11:03 PM	11:08 PM	1.885	1.889	1.889	1.884	1.886	1.884	1.886	1.884	1.887	1.886
Jar	11:10 PM	11:15 PM	2.004	2.013	2.012	2.016	2.012	2.005	2.005	2.001	1.998	2.001
Masking	11:17 PM	11:22 PM	1.928	1.932	1.937	1.936	1.939	1.93	1.93	1.925	1.928	1.928
Temperature	62.5 F											
Pressure	24.15 inHg											
Humidity	42.20%											
Pump turned on calibration train not connected	10:15 PM											

Appendix C: Set up of Trials

Table 5: Trial one set up

Trial 1	Time Connected	Time Started	1	2	3	4	5	6	7	8	9	10
Jar												
Duct												
Jar												
Clay												
Jar												
Masking												
Jar												
Electrical												

Table 6 Trial two set up

Trial 2	Time Connected	Time Started	1	2	3	4	5	6	7	8	9	10
Jar												
Clay												
Jar												
Duct												
Jar												
Electrical												
Jar												
Masking												

Table 7 Trial three set up

Trial 3	Time Connected	Time Started	1	2	3	4	5	6	7	8	9	10
Jar												
Clay												
Jar												
Electrical												
Jar												
Duct												
Jar												
Masking												

Appendix D: Random Number Generator Results

Figure 9: Random number generator for Trial 1
1= Duct, 2=Electrical, 3=Masking, 4=Clay

Figure 10: Random number generator for Trial 2
1=Duct, 2=Electrical, 3=Masking, 4=Clay

Figure 11: Random number generator for Trial 3
1=Duct, 2=Electrical, 3=Masking, 4=Clay

SIGNATURE PAGE

This is to certify that the thesis prepared by Nicole Santifer entitled "A Comparison of U.S. Coal Mine Respirable Dust Calibration Procedures and the Impact on Measured Flow Rates" has been examined and approved for acceptance by the Department of Safety, Health & Industrial Hygiene, Montana Tech of The University of Montana, on this 27th day of June, 2013.

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