University of Nevada, Reno

Development, Application and Validation of the Real-Time Coal Dust Monitoring Instrument

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mining Engineering

by

Ralston Thorlief Pedersen

Dr. Karoly (Charles) Kocsis/Thesis Advisor

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We recommend that the thesis
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RALSTON PEDERSEN

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Karoly (Charles) Kocsis, Ph.D., Advisor

Behrooz Abbasi, Ph.D., Committee Member

Javad Sattarvand, Ph.D., Committee Member

Carl Nesbitt, Ph.D., Committee Member

Ronald Breitmeyer, Ph.D., Graduate School Representative

David W. Zeh, Ph.D., Dean, Graduate School

May, 2019

Abstract

A real-time photoacoustic coal-dust monitor for underground mining applications has been developed to address the health and safety concerns associated with dust related illnesses. This instrument was co-developed with Patrick Arnott, Sarah Tesfasion and Apryl Witherspoon of the UNR Physics department. The primary goals addressed in development of this real-time coal-dust monitor were user portability, instrument durability and maintaining a low development cost. Instrument functionality and principles for operation were based off older, large and free-standing photoacoustic dust-monitors previously designed by Patrick Arnott. To scale down these instruments to a user portable size, the resonance chamber, pumps and controls were addressed. After prototype completion, the instrument was tested with Kerosene soot to determine efficacy and accuracy. Success from the kerosene test led to further testing against other dust-monitoring instruments at NIOSH laboratories in Philadelphia by Arnott, Tesfasion and Witherspoon. The current instrument has proven very effective for determining organic aerosols such as coal-dust; however, further development is planned to include a laser frequency that can more effectively accommodate silica dust. Further reducing the size of the current instrument is a major goal for future development to achieve a truly user-portable dust-monitor.

Dedication

This thesis is dedicated to my amazing wife, my new daughter, my mother and my father, for encouraging me to always pursue my dreams and always being by my side. I would also like to thank Dr. Charles Kocsis for being a friend and a mentor, without his guidance in pursuing my dream of a master’s degree, I would not have pursued the topic of pulmonary health in miners to discover the problems as well as possible solutions.

Acknowledgements

I would like to thank Charles and Annie Kocsis for always lending helping hand, being there to listen, and to provide support whenever I needed them. I would like to acknowledge Bob Watters for all his guidance in completing my thesis as well as being a sounding board for ideas. I would like to acknowledge the Mackay School of Earth Science and Engineering for their continued dedication to the earth sciences and the mines of tomorrow.

I would like to give a special acknowledgement to Patrick Arnot, Apryl Witherspoon and Sarah Tesfasion with the UNR Physics department for their significant help. Without their research, design and development of the 660nm photoacoustic monitor, my thesis would not have been possible.

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Introduction

With the inexorable push for more efficient and productive mines, technology has grown to meet demand in terms of equipment, ventilation and cooling. However, coal dust and other airborne contaminants remain the most prevalent risk to underground miners with a large number of coal workers pneumoconiosis (CWP) cases reported and growing with every passing year.

Steps have been taken to reduce the risk of CWP in underground coal miners through the implementation of dust masks and sealed cabs for operators, however, miners rarely use equipment such as dust masks for various reasons and this has contributed to the new increase in CWP cases. The reasons face masks are used so infrequently stems from lowered comfort levels, inability to communicate with co-workers, and strained breathing due to clogged filters. Miners frequently take off their face masks, so they can do their jobs. Miners have been trained to use “sniffers” underground that detect combustible levels of coal dust as well as dangerous and toxic gases such as methane and carbon monoxide, to great effect. Considering the success of these detectors in terms of implementation underground, having a “sniffer”, that reported dust levels in a similar way would undoubtedly have a positive effect on the health of underground coal workers.

There is a necessity in modern mechanized mines to update how the underground atmosphere is monitored for safety. Major technological leaps have been made in underground mines in areas such as transportation, equipment and mining methods, however technology has progressed more slowly for air quality measuring instruments and until recently has not been widely implemented. Past aerosol detectors which check air for more immediately dangerous contaminants such as methane, lack focus on dust and real time dust monitoring for the individual miner.

For miners surveyed by NIOSH from the mid 1990's to present day, there is a significant and growing trend of coal miners that are diagnosed with miner's pneumoconiosis (the "Black Lung") from less than 5% of miners under NIOSH surveillance to over 10% of miners with over 25 years in the coal mining industry (What is the Extent of the Problem, 2018). With a tenth of all veteran coal miners suffering from black lung, this epidemic is many times deadlier than the worst mine disasters.

In 2014 the limits for coal dust exposure underground were lowered from 2.0 mg/m^3 to 1.5mg/m^3 (Respirable Dust Rule, 2016, p.3) for a miner's average exposure during an 8-hour shift. These limits are meaningless without accurate and real time dust monitors to ensure that the high transient respirable coal dust concentrations are detected, and that the underground environment is in accordance with national regulation. Historic time-based methods of collecting underground dust samples such as through the NIOSH 7500 method provide total dust experienced in an underground atmosphere for a certain period. These time weighted averages do not express the peaks and troughs of dust concentrations experienced in real time underground, allowing for periods of significant dust exposure to go unnoticed. This lack of capability in measuring in real-time what the concentrations of dust miners are exposed to underground using time weighted measures is a possible contributing factor to the rise in black lung as well as emphasizing the necessity of the implementation of real-time dust monitors.

The NIOSH 7500 method of measuring crystalline silica is through the implementation of a cyclone and dust filter, where air is drawn into an apparatus at a certain rate based off the cyclone being used, anywhere from 1.7 to 2.5 liters per minute for nylon and aluminum, respectively (NIOSH Method 7500, 2003, p.1). Dust is collected on the filter throughout the instrument's operation underground. After a certain period of operation underground corresponding to a minimum and maximum volume requirement of 400-1000 liters (NIOSH Method 7500, 2003, p.1), respectively, the filter is taken out and sent to a lab to be dried and weighed. The weight of the dust on the filter is then used to calculate the average dust concentration, C, per hour experienced by the equipment and operator given the flow rates and time underground through the equation (NIOSH Method 7500, 2003, p.6):

$$C = \frac{\hat{I}_x * f(t) - b}{m * V}\ , mg/m^3$$

Where:

$\hat{I}_x$= normalized intensity for sample peak

b = intercept of calibration graph ($\hat{I}^{\circ}_x$ vs. μg)

m = slope of calibration graph, counts/μg

f(t) = -R ln T/(1-T^R) = absorption correction factor

R = sin (θ_{Ag})/sin ($\theta_{x)}$

T = $\hat{I}_{Ag}/(average\ \hat{I}^{\circ}_{Ag})$ = transmittance of sample

$\hat{I}_{Ag}$ = normalized silver peak intensity from sample

$\hat{I}^{\circ}_{Ag}$ = normalized silver peak intensity from media blanks (average of six values)

By focusing on user comfort (size, weight and shape), the implementation of a personal dust monitor (PDM) for individual use in an underground atmosphere would be easy and effective. A study by the Center for Disease Control (CDC) over miners and their perceptions of PDM's stated that size, weight and shape of PDM were the biggest deterrent to them wearing the equipment daily, regardless of the consequences of black lung (Peters, Vaught, Hall & Volkwein, 2008). There is no doubt that the effect of implementing real time dust monitors and monitoring equipment underground would lower the increasing rates of black lung being seen in US coal mines and possibly lead to an eradication of the disease altogether. A real time dust monitor that is miner portable, addressing the concerns of comfort and usability for the miner, while focusing on accurate data collection that can alert miners to dangerous dust concentrations would be an invaluable tool. This technology would ensure that the current generation of coal miners reduce their risk of contracting pulmonary diseases such as black lung and possibly eliminate the risk for the next generation of coal miners. Further, if the implementation of such real-time dust monitoring equipment were to be successful in the coal mining sector, this technology could be used for the hard rock mines found in the Western U.S. where dust in the underground atmosphere is also a major health and safety issue.

In the underground atmosphere, dust is accompanied by a variety of other airborne pollutants such as diesel particulate matter that greatly increase the health threats to miners. The introduction of new electric equipment that covers the entire spectrum of underground operations from LHD's, to haulage and even man transport is a valuable tool for improving the underground environment for the miners who operate in it. This new electric equipment would remove the secondary aerosols such as DPM as well as working to improve the underground atmosphere as there is no combustion byproducts like water being produced as well. Both the water vapor and DPM produced in current diesel equipment negatively impact the underground environment by increasing the relative humidity, the temperature of underground workings and the concentration of DPM aerosols. The exhaust from diesel equipment can also work to mobilize settled dust producing a dustier environment than what would be experienced with an electric vehicle of the same capacity. Secondary to this, electric equipment generates approximately 70% less heat than diesel equipment the same power rating. With lower airflow requirements, costs of ventilation will be greatly reduced and the chances of mobilized dust reaching farther into the mine through ventilation outlets would be reduced as well.

By implementing an all-electric fleet, there would be a quantifiable decrease in diesel particulate matter the humidity, a decrease in the volume of other airborne pollutants, as well as an overall temperature decrease in the mine environment. All these factored, provide for a safer underground environment for miners and reduce the amount of airborne pollutants.

Literature Review

There are a variety of personal dust monitors that vary by application and fundamental operation. Current technology being used for the monitoring of dust and coal dust in underground mining atmospheres are equipment such as follows in this section in the categories outlined.

Optical Ambient Dust Monitors

Using optical sensors, optical dust monitors are designed around the Tyndall effect of light dispersion with a constant wavelength on air and dust. Light scatters off dust particles and this dispersion of light is measured. In a broad sense, the following equipment can be viewed as nephelometers, or according to Oxford Dictionaries (2019), "an instrument for measuring the size and concentration of particles suspended in liquid or gas, especially by means of the light they scatter."

The ThermoFisher Scientific pDR-1500 is a belt wearable nephelometer. This piece of equipment weighs 2.6 lbs and can take measurements every second relaying the data back to the user (*personal* DataRAM™ pDR-1500, 2014). With the ability to collect over 500,000 measurements, it is a valuable tool for evaluating aerosol concentrations in a varying application of environments. The pDR-1500, in a lab setting, however tends to underestimate the concentration of aerosols when compared to the gravimetric method for diesel fumes and NaCl, although it has proven effective for coal dust (Halterman, Sousan, Peters, 2018).

Figure 1: ***personal*** **DataRAM pDR-1500 Aerosol Monitor (ThermoFisher Scientific, 2018)**

Drawbacks to the pDR-1500 include the requirement for constant calibration to ensure accurate measurements. Constant calibration requirements are often forgotten or simply not done in an active mining environment. A second drawback to the pDR-1500 is the price, at around six thousand dollars per unit, implementation of such a device on the scale required for a mine site could prove cost prohibitive for small and large mining companies alike.

The Sensidyne aerosol monitor is very similar to the pDR-1500 in function through application of a nephelometer. The Sensidyne nephelometer is also a belt portable unit with ruggedized rubber for durability in industrial applications such as underground mines. The Sensidyne aerosol monitor brings down unit cost by applying a smaller memory of up to 4,000 data log records as well as taking measurements over a slightly larger time frame of 60 seconds (Sensidyne Nephelometer, 2019). In each data log the Sensidyne equipment records the K-Factor of the airflow, the environmental factor name and STEL, maximum, minimum and average readings are included, which is useful in data evaluation as well as identifying possible errors in data collected by examining items such as the instruments K-factor.

Figure 2: Sensidyne Nephelometer - Aerosol Monitor (Sensidyne Nephelometer, 2018)

The Sensidyne nephelometer offers a comparable unit that is slightly less sensitive for around four thousand dollars a unit; however, this is still cost prohibitive when considering quantity for large underground mining operations.

Ambient Fine Dust Sampler PEM-ADS. This ambient fine dust sampler is effective for determining the concentration of in atmosphere particles of 2.5 microns or smaller (Ambient Fine Dust Sampler, 2016). When coupled with a WINS impactor with 2.5 microns cut stage, as well as an improved inlet and PM10 size separator, this instrument becomes the standard reference method instrument for PM10 testing. The PL-2 also comes with a gaseous sampling add-on which is useful for measuring concentrations of gaseous pollutants. (Ambient Fine Dust Sampler, 2016).

Figure 3: PEM-ADS 2.5µ/10µ Inner View (Ambient Fine Dust Sampler, 2018)

Although an effective instrument it is limited in application through both size and power requirements. The PEM-ADS measures 1.25 X 1.38 X 3.05 feet (380 X 420 X 930 mm) and the size of such equipment automatically disqualifies it from being used effectively by mine personnel as a wearable apparatus. Such equipment as the PEM-ADS also requires the use of a plug-in power system and a constant stream of 230 V or 110 V AC with the use of an adaptor.

Figure 4: Aeroqual Dust Sentry (Dust Sentry PM2.5, 2018)

Similar to the PEM-ADS is the Dust Sentry PM2.5 by AEROQUAL. Built around the use of a nephelometer (optical sensor) that, “measures particulate concentrations using laser light scattering” (Dust Sentry, 2019, p.6). Again, a very effective dust measurement tool, however incapable of being employed by mine personnel underground as a personal tool due to its size and power requirements.

Tapered Element Oscillating Microbalances (TOEM):

A relatively new development, Thermo Fisher Scientific has developed the PDM3700 dust monitor. This TOEM system operates through ambient air being drawn in through a hollow tapered tube at a constant flow rate. At the top of this tube is a filter, which collects particulate matter that corresponds to the filter size or larger. This hollow tube oscillates between two magnetic fields and with the increase in particulate mass collected on the filter, the frequency of the oscillation shortens (PDM3700 Personal Dust Monitor, 2018). Filter mass is detected as a frequency change in the oscillations of the tube using a Hall effect sensor (PDM3700 Personal Dust Monitor, 2018). A benefit to this type of equipment is the ability of the end of shift results to be reconciled gravimetrically through the weighing of the filter after use.

PDM3700 Personal Dust Monitor

Figure 5: PDM-3700 Personal Dust Monitor (PDM3700 Personal Dust Monitor, 2018)

Although this type of PDM is accurate for measuring a variety of particulate matters, the instrument does not consider particulate composition (silica dust from coal dust, etc.) and struggles with the measuring some specific types of particulate matter such as diesel particulate matter (DPM) (Halterman, Sousan & Peters, 2018). High concentration atmospheres can also cause the equipment to malfunction due to pressure drops across the filter generated by contaminant loading. This instrument also has a relatively low flow rate of 2.2 liters/minute (PDM3700 Personal Dust Monitor, 2018) when compared with other PDM equipment and a high price tag due to the complexity of the equipment. Further drawbacks include use of a sampling tube of over 36 inches to be used in correspondence with the equipment. Weight and dimensions are wearable at 4.4 lbs and 9.57 inches wide along with the 36-inch sampling tube (PDM3700 Personal Dust Monitor, 2018). The hollow tube of the instrument is also brittle, and when accidentally dropped, the instrument is rendered as useless until the tapered element oscillating microbalance is repaired.

Gravimetric Samplers:

The CIP-10 personal aerosol sampler, which can be adapted to measure several fractions of dust in the respirable range by changing out dust grain selectors such as the CIP-10-R (respirable fraction), CIP-10-T (thoracal-tracheal fraction), CIP-10-l (total fraction). (Lebecki, Malachowski & Soltysiak, 2016, p.127; Waclawik, 2010; CIP-10, 2004) The CIP-10 collects the fraction of dust the selector allows during operation in the mining environment by drawing in air at 10 l/min through the selector and depositing the dust onto a foam filter which is then dried and weighed. Accuracy of the CIP-10 relies on a series of factors such as the accuracy of the scale weighing the collected dust, to the uniformity of flow through the apparatus. After use, the calculation of the dust concentration on the foam filter (X_{resp}) is then applied through the equation (Lebecki et al., 2016):

$$X_{resp} = \frac{\Delta m}{vt}$$

Where

Δm - is the mass of coal dust on the filter

V – flow of air through dust sampler

t – measurement time (min)

To accurately calculate the dust concentrations, an accurate scale ($\pm 0.05 mg$) should be used and the error of the gravimetric measured dust must not exceed 3% that of the measured value (Lebecki et al., 2016, p.127).

Figure 6: Arelco CIP 10 (Specialty Scientific, 2019)

Although the CIP-10 functions off the gravimetric method, which is the recommended determination of dust hazards in the workplace, it does not offer a real-time showing of dust levels experienced by the user. The CIP-10 only offers the mean dust concentration for the time used in an underground atmosphere.

Contaminant Sources and Health Issues

The health concerns that follow exposure to coal dust are numerous. Coal dust has been a proven source of silicosis, pneumoconiosis, emphysema, chronic obstructive pulmonary disease (COPD), and chronic bronchitis (Wolfe & Colinet, 2009). Coal dust has been proven to cause respiratory inflammation as well as play a major role in respiratory morbidity.

The most consistent exposure sources of high-volume underground coal dust and silica are to workers who are placed near the long wall shearer, who act as a longwall jacksetter, who operates a continuous miner, who runs a surface drill, and who operate a roof bolter. These positions are most closely monitored by NIOSH for the development of dust related lung diseases and are an example of miners who could greatly benefit from the implementation of effective and accurate real-time dust monitoring tools.

By far the most dangerous factor of respirable coal dust is the potential for miners to develop Coal Workers Pneumoconiosis, colloquially known as “the black lung”. This is an irreversible lung disease that is caused by the, “inhalation and deposition of coal dust in the lung and the lung tissue’s reaction to its presence” (Wolfe & Colinet, 2009, p.3). Simple CWP can be symptomless, allowing workers to maintain their exposure to coal dust until it develops more severe symptoms such as shortness of breath and wheezing. As the disease advances, the lung develops progressive massive fibrosis (PMF). PMF is the development of fibrous tissues in the lung that become irritated and inflamed (Wolfe & Colinet, 2009). With PMF the lung can no longer inflate to its full extent and becomes stiff and inflexible causing a drop in the oxygen exchange that is needed for the body to function properly. Often, patients’ lips and fingernails will have a blue color from the lack of oxygen in the bloodsteam. These symptoms may lead to, or are associated with, signs of heart failure. Those with CWP and PMF also suffer from respiratory infection, respiratory failure, hypoxemia, pneumothorax (collapsed lung), cor pumonale (the right side of the heart becomes enlarged), and arrhythmias (unusual heart rhythm) (Wolfe & Conlinet, 2009, p.4).

Figure 7: Normal Lung (left) and a Lung from a Miner Diagnosed with CWP (right) (Colinet, Rider, Listak, Organiscak & Wolfe, 2010)

X-rays are used to identify CWP in coal miners where small opaque spots on the lungs have appeared in less than 10mm diameter. CWP can be stabilized in workers that have contracted the disease if they are removed from dusty areas; however, should they continue to work in high dust areas, simple CWP can easily develop into the even more debilitating PMF. Although PMF is more common in miners that have developed CWP, miners that have had no signs of CWP can also develop PMF (Wolfe & Colinet, 2009).

Silicosis, which is caused by the inhalation of crystalline silica (alpha quartz), is of an increasing threat to miners due to natural abundance of alpha quartz. Silicosis is a major threat to underground coal miners as exposure comes from the cutting, crushing and transporting of rock within the coal seams or adjacent to (Wolfe & Colinet, 2009). Studies have shown that exposure to crystalline silica dust is, “associated with the development of silicosis, lung cancer, pulmonary tuberculosis and airways diseases.” (Wolfe & Colinet, 2009, p.6). Exposure to crystalline silica can be further linked to the development of chronic renal disease, autoimmune disorders and other potentially deadly health effects.

Figure 8: Diseased and Healthy Lung. (Walrond, 2006)

Much like CWP, silicosis is caused from the development of fibrous tissues in the lungs from the inhalation of silica dust and comes in three types. The first type of silicosis is Chronic Silicosis, which occurs after a long-term exposure to low silica dust concentrations and is differentiated from the other two forms through the development of swollen lymph nodes in the lungs and chest as well as symptoms like those of COPD. The second form of silicosis is accelerated silicosis, which is generally developed after five or more years of exposure to silica dust and where swelling in the lungs occurs faster than that of chronic silicosis. The third form of silicosis is acute silicosis, where exposure to high concentrations of respirable silica dust after several years cause the lungs to become very inflamed and fluid filled.

Respiratory Health Effects of Coal Dust

Considering the confined spaces in which miners and underground equipment operators find themselves daily, exposure to DPM is extremely high when working around operating equipment.

The average healthy human male inhales approximately $10.8m^3$(Ristovski, Miljevic, Surawski, Morawska, Fong, Goh & Yang, 2012, p. 201) of air per day, at rest. This being said, inhalation is the primary mechanism responsible for underground miners' exposure to airborne toxins. Coal dust and silica as a product of normal underground operations is a predominantly fine particle size that is not only respirable, but able to travel into pulmonary portions of the lungs. (Brown, Gordon, Price & Asgharian, 2013)

Individuals with existing immunodeficiency, or airway diseases are in a higher at-risk level than other individuals, though the dangers associated with long term coal dust exposure permeate at-risk groups and into the broad spectrum of all individuals who work in confined underground environments.

Respiratory health effects of diesel particulate matter and coal dust are caused primarily through oxidative stress which is the mechanism by which coal dust becomes toxic. (Ristovski et al., 2012) This oxidative stress is most generally an imbalance of free radicals (generally uncharged molecules) and "the body's ability to counteract or detoxify their harmful effects through neutralization by antioxidants" (Mandal, 2018, p.1). When coal dust or silica enters the pulmonary system the inflammation that results is mediated by the body's immune system (Ristovski et al., 2012); however, high-risk individuals with COPD or other lung diseases such as asthma as well as those with weak or compromised immunes systems suffer largely due to the inflammatory response caused by coal dust. It is this inflammation caused from the presence of coal dust in the respiratory and pulmonary functions of the body that leads to long term health effects if an individual is constantly in the presence of elevated levels of coal dust.

Further, the organic matter present in coal dust molecules are related to the formation of certain DNA adducts that are commonly viewed as a preliminary cause to the development of cancer (Ristovski et al., 2012). These DNA adducts covalently bond to certain chemicals, organic carbon in the case of coal dust, and this chemical bond to the DNA can result in damage to DNA which results in abnormal replication and can lead to the development of cancer (Rajalakshmi, AravindhaBabu, Shanmugam & Mastham 2015).

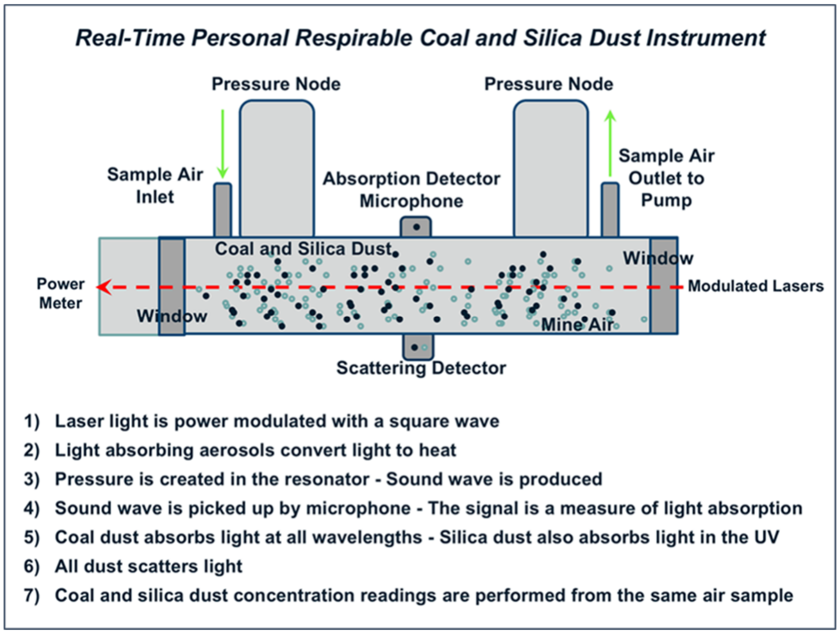
Without the proper monitoring of coal dust in a contained underground environment, the working population at large is potentially subject to dangerously high levels of finely respirable coal dust and silica particulate. The exposure, especially for individuals who are considered high-risk or those that spend a significant amount of time underground and around high dust areas such as long wall equipment, can lead to the worsening of or cause of respiratory diseases. Studies have already shown the relationship between PM intake relative to respiratory mortality which suggest a “.6-2.2% increase in respiratory mortality risk for a 10-µg/m^3 increase in ambient PM”. (Ristovski et al., 2012) Considering the ambient coal dust and silica quantities experienced in many heavily mechanized underground mines, finding a means to constantly monitor these conditions for the health and longevity of the employees is a necessary step in bringing the mining industry further into the future and on the cutting edge of health and safety practices.

Development

Ultimate goals in development of the real-time monitor were: ease of use, user portability, and accuracy. Ease of use and user portability run hand in hand with the efficacy of instrumentation to be used in an underground setting. Miners, especially tenured miners with 25+ years of experience, will commonly neglect the use of potentially lifesaving equipment if they deem it uncomfortable, unwieldy, or just a general nuisance. To combat this issue, instrument size needed to be addressed immediately following the first iteration of development.

The foundation upon which the real-time dust monitor was developed is photoacoustic spectroscopy. Photoacoustic spectroscopy was selected to be used in the instrument as it not only allowed for the detection and reporting of organic and in-organic airborne molecules, but also because it could be scaled down substantially after trials proved successful (Arnott, Moosmüller, Rogers, Jin & Bruch, 1999). To provide the most accurate results for coal dust exposure, the laser selected had to be optimal for the organic nature of coal dust. The 660nm laser exhibited the best scattering properties for use with airborne organic molecules such as coal dust, however due to the wavelength and scattering properties of silica, other lasers are being tested for use with the instrument to improve accuracy with silica dust (such as 220nm) (Utry, Ajtai, Pintér, Illés, Tombácz, Szabó & Bozóki, 2017).

A basic schematic of the real-time coal dust monitoring instrument is provided in Figure 9.



1) Laser light is power modulated with a square wave
2) Light absorbing aerosols convert light to heat
3) Pressure is created in the resonator - Sound wave is produced
4) Sound wave is picked up by microphone - The signal is a measure of light absorption
5) Coal dust absorbs light at all wavelengths - Silica dust also absorbs light in the UV
6) All dust scatters light
7) Coal and silica dust concentration readings are performed from the same air sample

Figure 9: Schematic of the real-time coal dust monitoring instrument

The solution is based on photoacoustic spectroscopy principles that are coupled to an advanced acoustic detection system. Through this method, the mine air is continuously drawn through a cyclone, which is installed at the inlet of the unit into the chamber of the acoustical resonator. A laser beam is directed through the air sample. The laser beam is power modulated, so that it rapidly goes “On” and “Off” at the resonance frequency of the acoustical resonator.

Within the mid visible to near-infrared region, only the coal particles, which are present in the air sample will absorb the electromagnetic energy from the laser beam. The absorbed energy will heat the carbon particles, which in turn will transfer the heat to the air sample inside the acoustical resonator. Due to the absorbed heat, the air pressure in the resonator will increase creating an acoustic pressure wave. The acoustic signal is measured by an advanced microphone attached to the resonator. The mass of the respirable coal dust is then determined from the acoustic signal and the mass absorption efficiency of coal dust, which is processed and analyzed through machine-language instructions controlled by specialty software running on the internal hardware of the unit.

Additionally, in the near-ultraviolet region, non-carbonate particles (e.g. silica dust), which are present in the air sample will also absorb the electromagnetic energy from the laser beam. Similarly, the absorbed energy will heat the silica particles, which in turn will transfer the heat to the air inside the resonator. The mass of the respirable silica dust is determined from the acoustic signal, the mass absorption efficiency of silica dust, and light scattering analysis. As a result, this real-time instrument may have the ability to sequentially provide respirable coal dust and respirable silica dust readings based on two independent acoustic signals, which are generated by the heated coal and silica particles.

The historic photoacoustic instruments this development started with consisted of a series of large individual instruments such as a stationary vacuum pump to draw air into the system, a lock in amplifier, such as the Stanford Research Systems Model SR 830 DSP as well as an individual signal analyzer such as the Hewlett Packard 35665A. Due to the scale of all pieces required to make the final unit, size was prohibitive. Early instruments had dimensions greater than 36 inches tall, 20 inches wide and 20 inches long. This was the basis for which scaling down was to begin, as the instruments had proven effective in earlier testing (Arnott et al., 1999).

Figure 10: Historic Dust-Monitor, Front

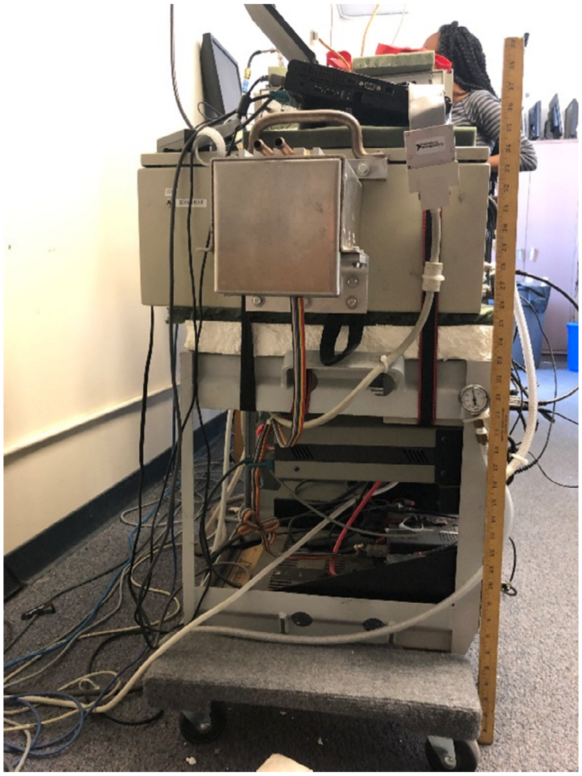


Figure 11: Historic Dust Monitor, Side

Initially, the early real-time dust monitor with the protective housing, measured approximately 36 inches x20 inches x20 inches. To bring the instrument into the realm of user portable, several key changes took place. Instrumentation such as the lock in amplifier and signal analyzer could be implemented using a Teensy Microcontroller. Not only was the Teensy Microcontroller chosen for size and ease of integration, it was also chosen due to high availability and a low cost per unit of $19.80 (Teensy USB Development Board, n.d.). Through use of the new microcontroller, the space that was required for older instrumentation was downsized from approximately 14 inches x 12 inches x 18 inches to a little over 1.4 inches x .7 inches.

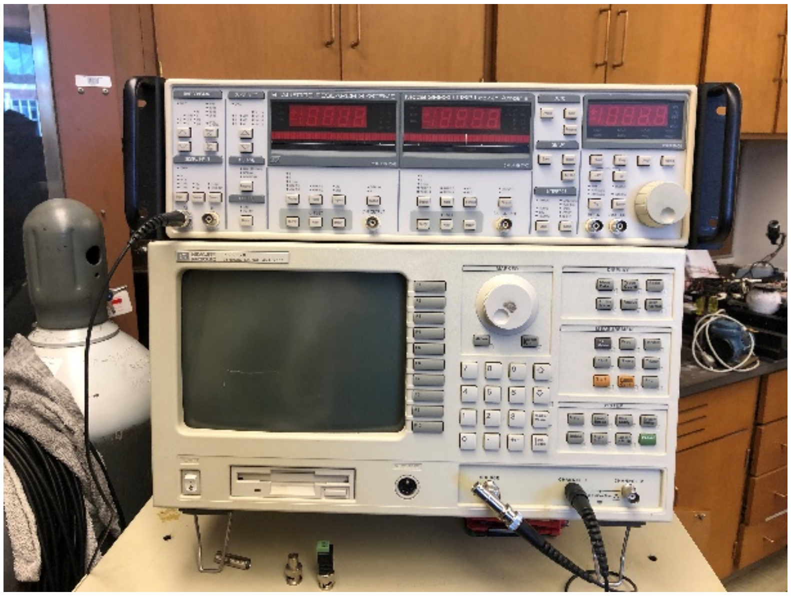


Figure 12: Original Lock-in Amplifier and Signal Analyzer

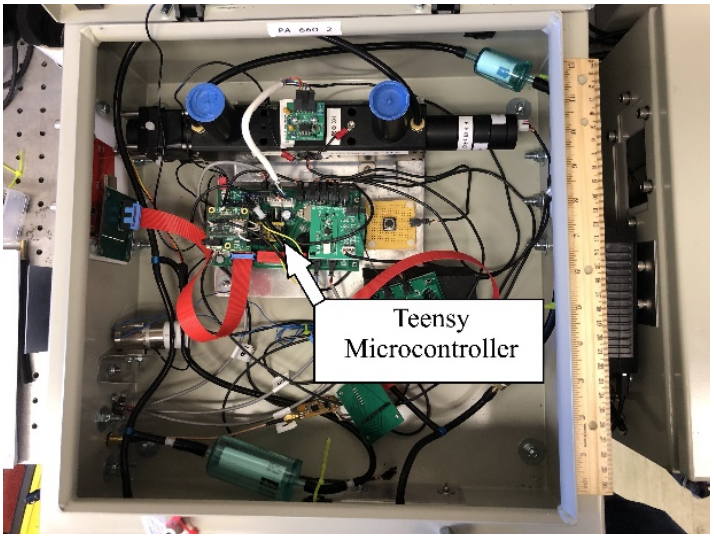


Figure 13: Teensy in Current Housing

To downsize the instrument even further, the resonance chamber length was reduced. Initially the resonance chamber length was around 12 inches for the historic instruments; however, the resonance chamber length was reduced to 7.5 inches to further minimize the overall instrument footprint and allow for the use of a much smaller housing. Through testing, the size reduction of the resonance chamber did not have a significant effect on the accuracy of the results and can be reduced in size even further to allow for a more compact unit.

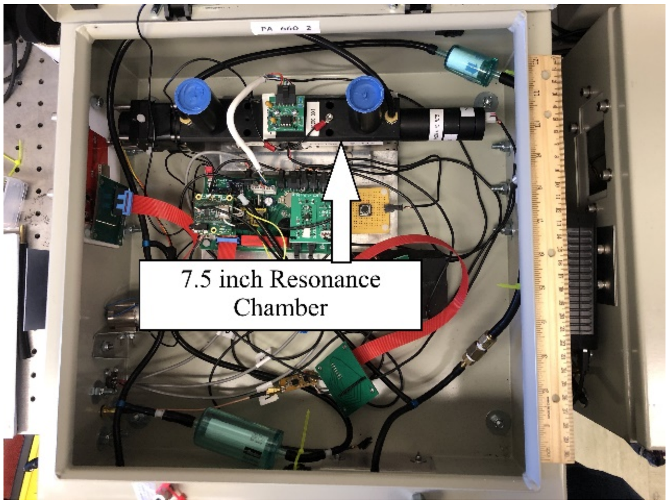


Figure 14: Resonance Chamber on Dust-Monitor

The microphones used for the downscaled instrument came in two variations. The initial testing was performed with a mylar membrane microphone which was sensitive to pressure changes as well as fluctuations in temperature. To improve the durability of the instrument while maintaining efficacy, a more durable Microelectro-Mechanical System (MEMS) microphone was implemented for testing of the instrument past the initial Kerosene tests. This MEMS microphone is much less sensitive to pressure changes or variations in temperature that can be found frequently in an underground atmosphere.

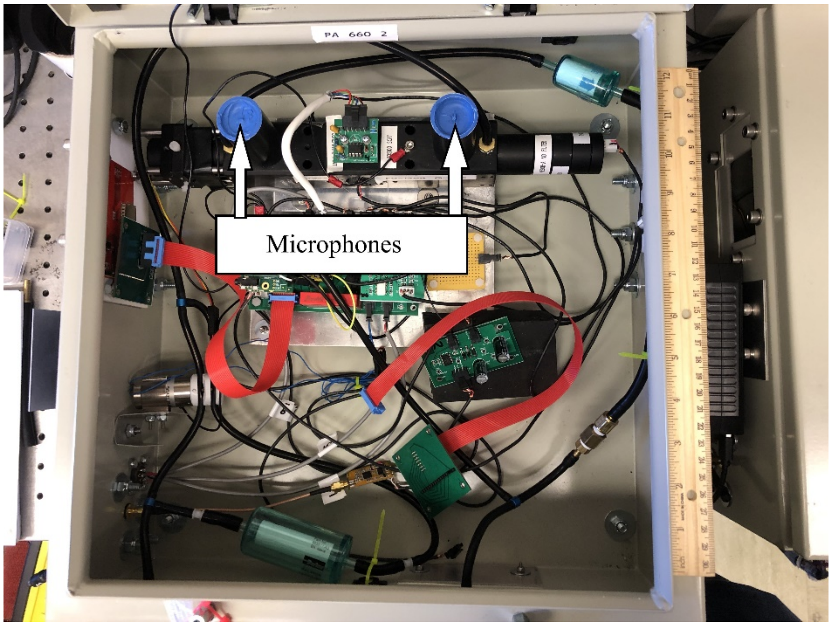


Figure 15: MEMS microphone placement

The vacuum pump used with the real-time dust monitor was originally a large and wired unit that was set up externally to the instrument housing. This pump stood at approximately 8 inches tall, 10 inches long and 6 inches wide while weighing over 10 lbs. With the dust monitor requiring an air flow much smaller than the pump could deliver, a period of trial and error yielded the result of a small 12-volt DC vacuum pump that could provide 10 liter per minute target for the instrumentation. This new pump greatly reduced the special requirements with overall dimensions of 2.36 inches tall, 1.49 inches wide and 3.4 inches long. This new pump also requires much less power to operate and will function for a full 10-hour period with one charge from an 11,000 mAh battery pack. Currently, even smaller pumps are being evaluate that could increase the battery life of the unit even longer.

Figure 16: Original Large Vacuum Pump

Figure 17: Small Vacuum Pumps used in Trials

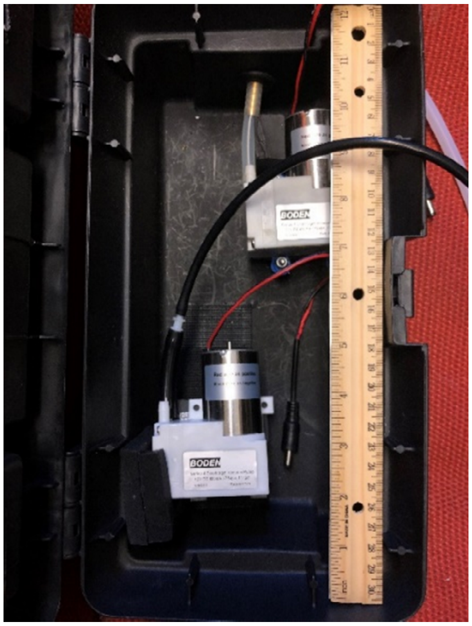


Figure 18: Current Pump Setup after Trials

Downsizing from the original casing allowed for further instrument portability as well as the opportunity to directly address any unforeseen issues that may arise in bringing the instrument down to a user portable size. The housing selected was a semi-custom computer case that measured 15 inches x 15 inches x 7 inches and had more than enough room to accommodate the necessary components. Although this new housing is still quite large in terms of user portability, a significant portion of the internal volume is unused with current components and could be scaled down. Without modifying any of the existing internal components, a housing of approximately 6 inches x 13 inches by 6 inches could be used for the instrument, greatly reducing the total unit size. With further size reduction of the resonance chamber, a final unit size would be even smaller than the 6 inches x 13 inches x 6 inches housing mentioned above.

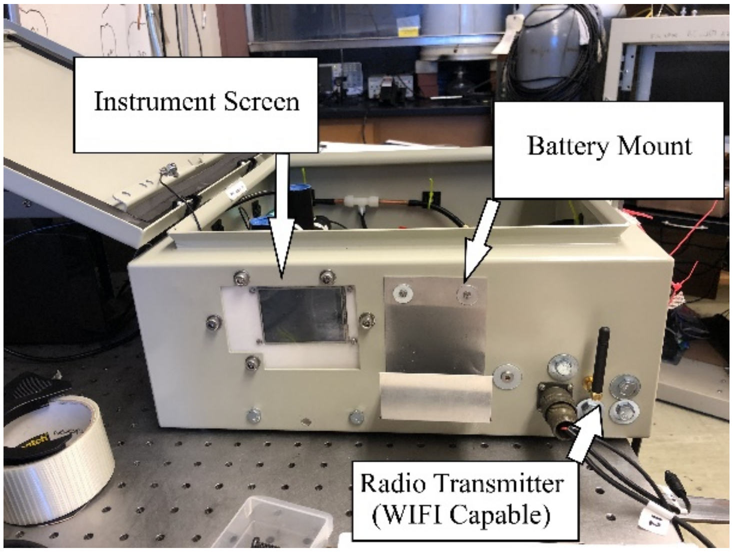


Figure 19: Front of Current Instrument Housing

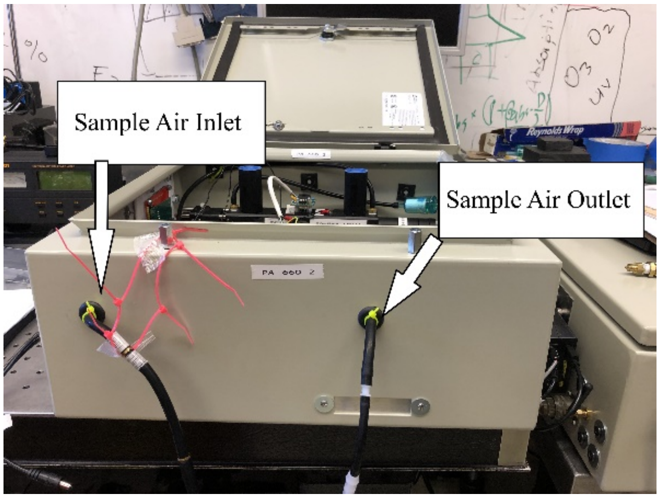


Figure 20: Side of Current Instrument Housing

To add further capability to the unit, as well as ensure easy integration with underground operations, both a radio and WIFI USB dongle can be added to wirelessly transmit data collected by the instrument. This wireless transmission allows for data collected by the instrument to be transmitted to an encrypted data storage device connected to underground WIFI, on the surface. Not only does this provide safety for the data collected, this WIFI capability allows the instrument to provide real-time atmospheric dust readings to mine personal. Having access to real-time dust conditions underground can better enable technical crews such as ventilation, to cater to high-concentration areas with the focus of lowering overall dust concentrations. To complement the data transmittal capabilities, the instrument is also compatible with solid state drives (SSD) that allow for data storage directly on the instrument. This SSD capability also acts as a fail-safe for data storage if WIFI or radio communications are lost underground.

The total cost of development for the 660nm photoacoustic monitor was $128,000. All of which was funded through private grants. It should be noted, that due to the low overhead that was generated in the development of this real-time dust monitor, that the cost to market would be expected to be low when compared to similar instruments such as the TOEM and pDR-1500 which cost $16,000 and $5,000 dollars, respectively. The cost to develop the Thermo Fisher TOEM was extremely high, and when compared to the TOEM in terms of cost to develop, the 660nm real time monitor is close to a factor of 100 times cheaper. This low development cost would be presented to the market in terms of a cheaper instrument while maintaining a high level of accuracy.

Methodology

Once calibrated the equipment is zeroed to account for any background particles that may exist. Zeroing for the laboratory testing was done using filtered air to establish an ideal zero. Once zeroed the photoacoustic monitor is ready to take both aerosol light absorption and aerosol light scattering measurements in real time sets of 400 consecutive measurements. Light absorption measurements are taken using the microphone pressure as well as the laser power every four seconds. Light scattering measurements are taken using the photodiode signal as well as the laser power and are useful for determining the particle sizes found in the aerosols (Arnott, Kocsis, Tesfasion, Witherspoon & Pedersen, 2018).

To achieve the best possible parallel to the underground work environment, closed chamber tests were used. To model organic and nonorganic aerosols, a series of tests were conducted using the photometric equipment designed at UNR.

The first test was using a kerosene lamp, which generated kerosene soot and could be monitored by the photoacoustic equipment for airborne pollutant densities. The kerosene soot monomers had diameters of around 50nm and absorbed and released heat quickly allowing for a net phase close to zero during high concentration periods from the particle's absorption of the laser energy and the purging of this energy as heat (Arnott et al., 2018).

In a second test, the burning of incense to produce smoke in the testing environment was used. This incense smoke test was used to determine the scattering calibration factor for the 660nm photoacoustic dust monitor. In this test, a well calibrated instrument would, "yield a ratio of 1 between extinction and scattering coefficients" (Arnott et al., 2018). The slope of the best fit line generated through testing would be used as the scattering calibration factor for the photoacoustic monitor.

The third test was the coal dust test, in which, a URG-2000-30ED cyclone was used to prevent coal particles larger than 2.5µm from entering the resonance chamber. Bituminous coal was ground by hand to produce the dust used in the experiment and yielded the need for the cyclone to prevent poorly ground particles from entering the equipment. The coal dust test was repeated under different relative humidifies to determine the instruments accuracy in various underground climates and in conditions previously known to interfere with dust monitoring accuracy. In this third test, coal dust was also mixed with silica dust in varying concentrations to determine efficacy with more than one aerosol present.

The fourth test was a silica sand test. This test consisted of silica sand that had been ground by hand much like the coal dust, and although silica dust exhibits a much higher scattering coefficient than coal dust the test results provided that both instruments provided accurate data in both absorption and scattering measurements.

To validate the results, a Dust Trak dust table top dust monitor was also used to calibrate the photometric monitor and to accompany the tested equipment in the controlled environment for testing. This Dust Trak monitor operated with an 870nm laser and provided accurate, reliable results that could be used to test and validate the new 660nm laser photoacoustic instrument designed at UNR.

Results

The testing of the first redeveloped iteration of the real-time dust monitor took place in a fume hood with the use of a kerosene lamp. In this test, a kerosene lamp was burned under a large bucket, in which the inlet for the instrument was set. The use of the bucket was to ensure a high density of airborne contaminants in the testing chamber would reach the instrument and resonance chamber.

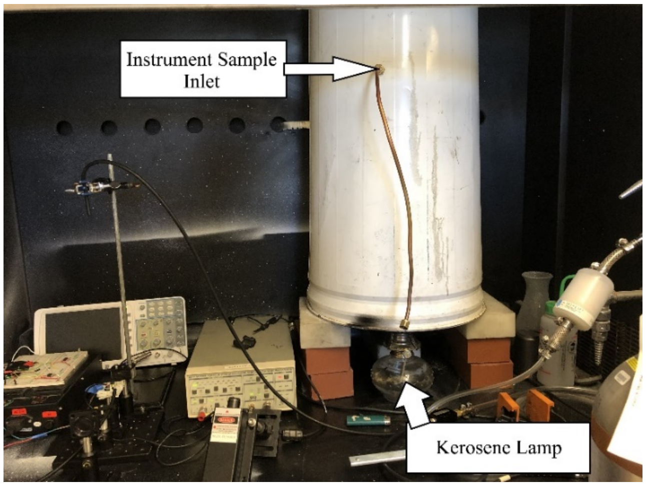


Figure 21: Kerosene Soot Test Setup

The results from the kerosene soot test proved the accuracy of the 660nm photoacoustic monitor when compared with the 870nm Dust Trak equipment. The 660nm laser instrument was faster returning to the random phase when aerosol concentrations decreased over the Dust Trak. The 660nm instrument was slightly more sensitive and was quicker to observe background when the concentrations dropped.

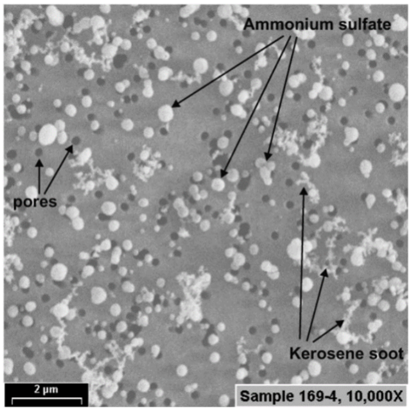


Figure 22: (NH4)2SO4 and kerosene soot aerosols collected during one of the RAOS sampling runs. Collection was from a 0.2µm por size membrane filter. (Arnott et al., 2018)

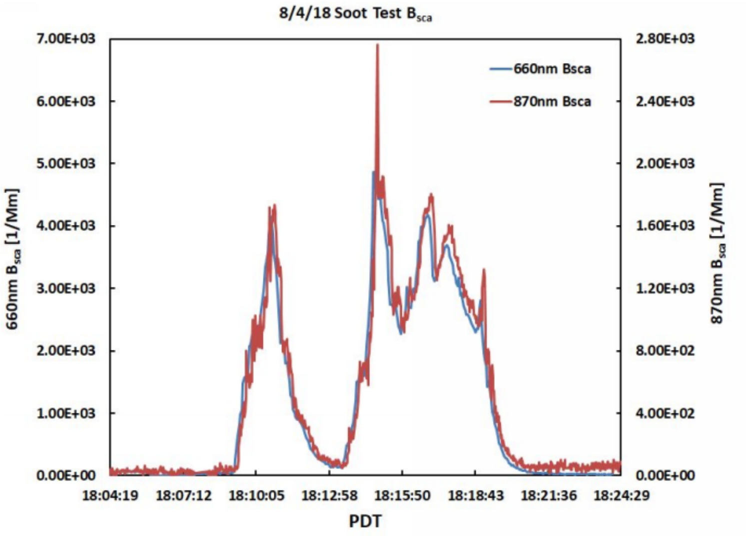


Figure 23: 660nm vs 870 nm Photoacoustic Monitor in Kerosene Test. (Arnott et al., 2018)

The time series graph above shoes the 660nm and 870nm equipment under the same conditions during the kerosene soot test. The concentration readings are very similar and validate the accuracy of the 660nm laser photoacoustic monitor.

<u>Incense Test:</u>

The results from the incense test were mostly used in determining the scattering calibration factor for the photoacoustic monitor due to the high scattering observed in smoke as well as observing the ratio of extinction for scattering. The best fit line generated from the test yielded an almost 80% match to the ideal condition of 1 for the observed data and scattering extinction. The scattering calibration factor determined in this test from the best fit graph, was used to calibrate the scattering of the photoacoustic instrument in all other tests (Arnott et al., 2018).

Silica Test:

Silica, unlike the coal dust and kerosene dust, exhibits a high scattering coefficient. Thus, the scattering is more valuable than the absorption characteristics of the silica dust. At the end of the test, the 660nm photoacoustic dust monitor was more sensitive to the peak silica dust concentrations as well as observing the peak silica dust concentrations before the 870nm equipment.

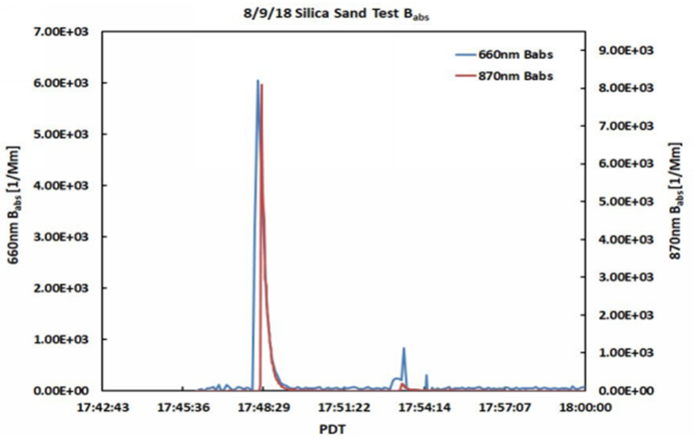


Figure 24: 660nm vs 870nm Photoacoustic Monitor with Silica Dust. (Arnott et al., 2018)

Coal Dust Tests:

During the initial coal dust test, the equipment was exposed to a high concentration of coal dust as it was released in the test environment. This test showed a slightly longer reaction time for the 870n, Dust Trak instrument in the measuring of the peak dust concentrations. This initial test also yielded higher absorption values than the kerosene soot test for both instruments (Arnott et al., 2018).

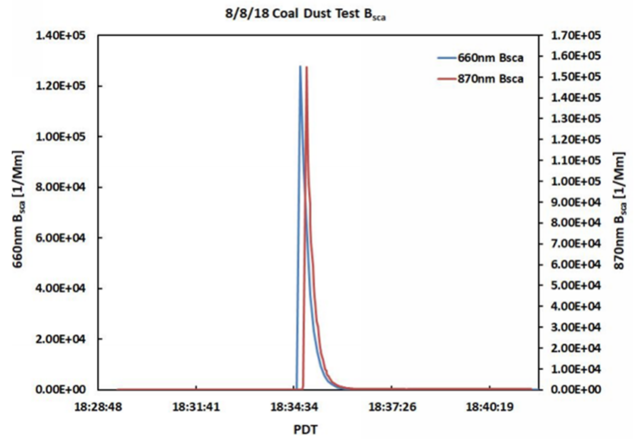


Figure 25: Initial coal dust test values for 660 and 870nm photoacoustic monitors. (Arnott et al., 2018)

At the NIOSH laboratory in Pittsburg Pennsylvania, the 660nm photoacoustic monitor was tested against a tapered element oscillating microbalance (TEOM) and other gravimetric monitors. The TOEM was viewed as the accuracy standard during the test and the 660nm instrument was plotted against it in all tests. The TEOM was also used to calibrate the 660nm and 870nm photoacoustic monitors. To measure and ensure particle density and distribution during the tests, NIOSH gravimetric instruments were set up in the test chamber with filters that were observed under scanning electron microscopes following the tests.

100% Coal Dust Low RH

In the 100% coal dust and low relative humidity test, the relative humidity was set to 25%. The TEOM operated during the entire 40-minute test while the 660nm and 870nm photoacoustic instruments were swapped out during the test to provide data on both instruments regarding performance. The 660nm instrument was time aligned with the TEOM data at the conclusion of the test and showed that the 660nm data closely correlated with the TEOM data with exception of slightly more noise.

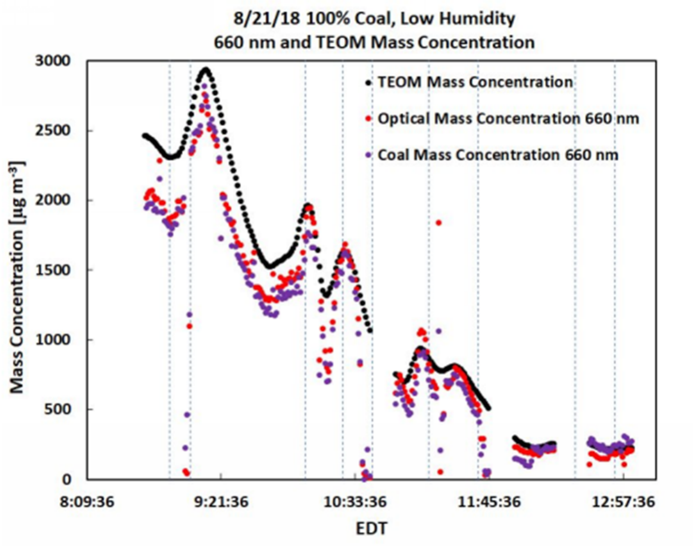


Figure 26: TOEM vs 660nm during Low RH 100% Coal Dust test. (Arnott et al. 2018)

As can be seen from the Figure 26 above, there is a direct correlation in the data between the 660nm and the TEOM. Given that the blue dotted lines on the above chart symbolize changes to the flow rate due to alterations in the inlet system for the 660nm device, the correlation could have been stronger without the alterations during testing.

<u>100% Coal Dust and High RH</u>

In the 100% coal dust in high relative humidity conditions, the relative humidity was set to 75% inside the testing chamber. During this test, the 660nm photoacoustic instrument was calibrated, time aligned and averaged with the TEOM (Arnott et al., 2018).

At the conclusion of this test, the 660nm data was very similar to that of the TEOM, as well as very similar mass concentration values for the two instruments. The 660nm instrument also exhibited a much smaller data trends in respect to noise as opposed to the low relative humidity test.

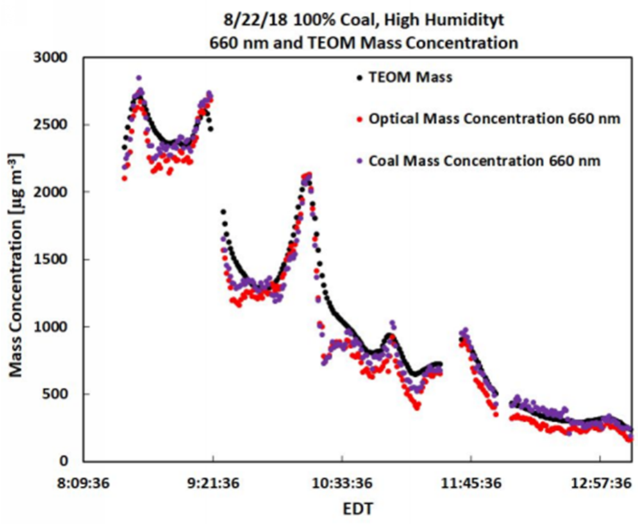


Figure 27: TEOM vs 660nm in 100% Coal Dust and High RH test. (Arnott et al., 2018)

75% Coal Dust and 25% Silica Dust Low RH Test

During this aspect of testing, the aerosols introduced into the testing chamber were a mixture of coal dust and silica dust with target proportions of the first test being 75% coal dust and 25% silica dust by mass (Arnott et al., 2018). The relative humidity was set to 25% in the testing chamber.

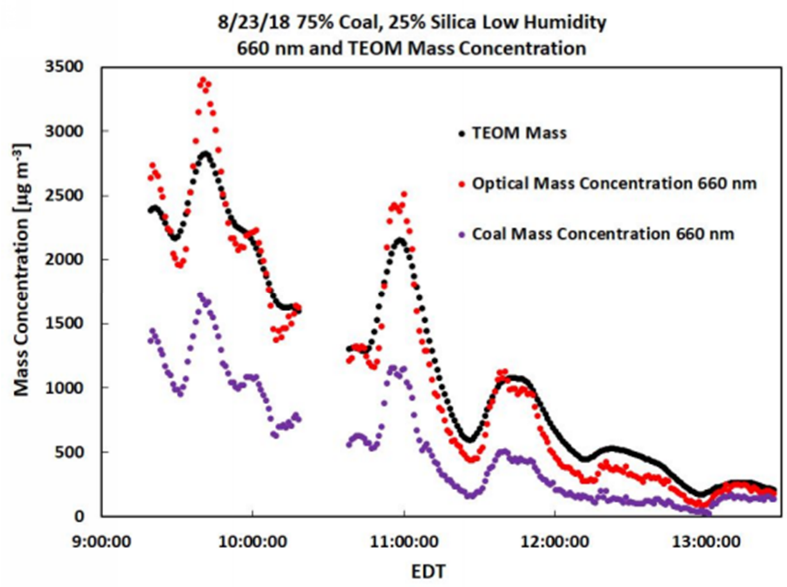


Figure 28: 660nm vs TEOM in 75% Coal Dust and 25% Silica Dust Low RH Test. (Arnott et al., 2018)

As can be seen by the scatter and absorption for the 660nm photoacoustic monitor, the coal dust, being a high absorption material as well as the silica dust being a high scattering material is directly reflected in the results. Coal dust mass scattering is about half that of silica dust and the specific gravity of the coal dust is about half of the silica dust. The conditions during testing meant that the 660nm photoacoustic dust monitor should have been equally sensitive to coal and silica dust (Arnott et al., 2018). The TEOM being a mass concentration tool, did not delineate between the types of dust present in the chamber; however, the total mass collected, when in comparison with the mass concentrations detected by the 660nm photoacoustic device, were very similar.

It was also noted that based off the readings, the percent of coal dust present in the testing chamber was closer to 57% rather than 75% based off the readings taken by the 660nm, 870nm photoacoustic dust monitors showing that what is introduced into the testing chamber may not necessarily become airborne (Arnott et al., 2018).

Discussion

There is no doubt that the need for real time personal dust monitors in the underground mines of today is necessary to aid in the reduction of the black lung epidemic as well as ensure the safety and longevity of current and future miners. Implementation of PDM devices has been slow, and workers often refuse to wear the technology that is currently on the market due to size, weight and comfort concerns as they view it as, “getting in the way too much” (Peters et al., 2008, p.13).

The research done on the 660nm photoacoustic dust monitor tested by the University of Nevada Reno’s physics department proves that personal dust monitors can be very accurate, monitor aerosols in real time and provide miners with potentially lifesaving information that they are not currently receiving while on the job. Not only did the 660nm photoacoustic equipment match the TEOM for coal dust and silica dust monitoring, it also had provided the capability to differentiate between what the highest exposure aerosol was. This 660nm photoacoustic dust monitor could be downsized to an exponential degree past what was used in testing to allow for a very lightweight and user-friendly unit, encouraging active use and participation by miners.

This is an invaluable tool for mine operators as well as miners as this data can be collected off of these instruments at the end of each shift and can be used to monitor which operators and miners underground are exposed to high levels of dust allowing for position rotations before black lung and similar lung diseases can even develop. It also allows for the wearer to remove themselves from areas of high dust concentrations to proactively avoid inhalation of dangerous dust aerosols, or trigger dust control measures that are available underground.

There are many PDM's on the market; however, implementation of these units has not been widespread. When PDM's are implemented there is sometimes poor adoption by the crews that need them. After validating the 660nm photoacoustic monitor through testing, it could be an extremely effective PDM for miners both in accuracy, comfort, and practicability. The real time coal dust instrument developed at UNR can be left unattended in the production area for a prolonged period of time to monitor respirable coal and silica dust concentrations.

There is also a major financial implication to not implementing the PDM monitors on mine site. Although it may cost over one-hundred-thousand dollars to implement PDM's at an underground mine site, depending on the staff size, the potential savings generated by eliminating black lung in the coal industry are immense. It costs the coal companies $1.10 per ton of coal produced annually in excise tax to help fund the Black Lung Disability Trust Fund, which could potentially be eliminated if Black Lung was eradicated (Coal Industry Tax Cut, 2018). The Black Lung Disability Trust Fund has also borrowed $6 Billion dollars from the federal government to continue the program and is looking to increase the current excise tax to maintain beneficiaries. In addition, the health insurance costs for companies skyrocket if the cause of black lung or other respiratory diseases are linked to the mine operator. Plus, disability payments on average are $644 a month to a single miner receiving benefits through Social Security according to a 2016 study (Social Security Administration, 2016). Further, if a coal mine produces 100,000 tons of coal in a year and pays over $100,000 in excise annually, those workers who do not find themselves beneficiaries of the Black Lung Fund later could easily aid in lowering the current excise tax levied against the coal industry.

By emphasizing the respiratory health of underground coal miners through the implementation of PDM's such as the 660nm photoacoustic dust monitor, companies could save the coal mining industry well over $800,000 in this excise tax alone, on top of the already cost prohibitive insurance expenses and workman's compensation claims.

Conclusions

Through the development of the real-time dust monitor for underground applications, the size has been significantly reduced from previous functional versions to the current prototype. Through implementation of new technologies in controls such as the Teensy Microcontroller to smaller and more power efficient pumps, major reductions in size have brought this real-time photoacoustic monitor into the realm of user portability. Following this, the new instrument has optimal functionality and durability for both an underground setting and a laboratory setting thanks to Wi-Fi and radio connectivity as well as compatibility with any variety of solid-state storage devices.

With future focus on reducing the size even further to remove the current void spaces in the housing, this instrument will be user portable and near realization for a market that desperately needs it. On top of this, the resonance chamber can be reduced to a size below the current 7.5 inches allowing for the design of an even smaller instrument housing, as well as reducing overall costs due to lower material requirements. A low cost, functional, durable and accurate monitor for underground miners that will significantly reduce exposure to high dust concentrations has been successfully developed. However, it is thorough the design of a new instrument housing in future efforts, as well as a final reduction in the size of the resonance chamber that will finally bring the instrument to user portable dimensions.

The final step in ensuring the successful deployment of the new real-time dust monitor is to ensure the instruments efficacy in accurately determining ambient coal dust as well as silica dust. This will be attempted using two resonance chambers on the same device. One chamber will be dedicated to the 660nm frequency for coal dust and another chamber at a lower frequency, such as 220nm, for most accurate silica dust measurement. This next step of development will require further testing; however, confidence is high that with the addition of a second resonance chamber the instrument will be exceptional in the underground environment.

Protecting the mine worker is the most valuable and cost-effective option to mine operators. As mining technologies and automation reach the mining workplace, production rates are increasing, mine depths are increasing, and profitability is increasing. However, miner’s health, which is crucial to sustained development over time, is being left in the dust as evidenced by current research. To combat this as well as to prevent the valuable handful of experienced miners and future generations of miners from leaving the industry due to health risks, considerations in equipment such as PDM’s is vital. It is the responsibility of the mine operators to make every available attempt at preserving their greatest resources, their miners. By implementing real time personal dust monitors such as the 660nm Photoacoustic Dust Monitor, companies will be investing not only in the longevity of their most precious human resources, but the longevity of the industry itself. Although expense is a consideration when exploring implementation of such technologies, the positive impact of implementation will undoubtedly decrease the current resurgence of black lung in the coal mining industry outweighing cost to preserving the mines most valuable asset, the miners.

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