Effects of Dust Controls and Dust Sources on Respirable Coal Mine Dust Characteristics

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(ABSTRACT)

Respirable coal mine dust (RCMD) continues to pose serious health hazards to workers. Over the past few decades, new regulations, monitoring technologies, and improved dust controls have emerged, and all are based on the presumption that limiting RCMD on the basis of mass will effectively mitigate the exposure hazards. Given the latency of exposure outcomes, it will be some time before the full impact of these strategies can be evaluated. In the meantime, there is increasing awareness that RCMD particle characteristics, in addition to mass, might be important. This dissertation comprises four separate studies which explore the effects of primary RCMD sources and/or engineering controls on particle size and constituents. To enable a direct comparison of dust generation from primary dust sources, a field study was conducted to investigate the dust generation and particle characteristics between coal and the rock strata. Results indicated that finer and more dust was generated when mining predominantly into the rock strata versus the coal strata, while the operation of a flooded bed scrubber and an increase in water sprays pressure and volume generally suppressed dust. Prior government research, conducted within the Mining Research Division of the National Institute of Occupational Safety and Health (NIOSH) evaluated the dust mass concentrations removal efficiency of different dust controls (i.e., a dry and wet scrubber, canopy air curtain, and a wet versus dry dust collection boxes). In the second and third studies, preserved samples from these prior NIOSH dust control studies were re-analyzed and evaluated to understand their effects on dust characteristics. Results indicated that the efficiency of dust controls was particle size dependent, as these controls mostly showed no appreciable effects on dust constituents. Generally, the cleaning of dust from a novel wet dust collection box versus a traditional dry dust box led to a reduction in operator exposure to hazardous dust. In the final study, a laboratory prototype flooded bed scrubber was evaluated to understand its efficiency on dust between different particle size bins (i.e., by particle count) ranging from 0.3-10 µm. From the results, removal efficiencies were generally low – and sometimes negative, for dust particles mostly in each of the size bins less than 2 µm. The results presented here highlight the need to holistically evaluate dust controls to understand their efficiency on dust of different particle sizes and constituents, so that informed decisions can be made on the best controls to adopt in mine operations.

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(GENERAL AUDIENCE ABSTRACT)

Coal production contributes significantly to steel making and electricity generation in the US. During the mining process, very fine dust is generated—called "respirable" dust— which represents a significant health hazard to workers. Indeed, many cases of occupational lung diseases linked to respirable dust have been reported over the past few decades, and disease rates remain high. Dust monitoring and control efforts are largely based on limiting the total mass of respirable dust. However, there is growing evidence that specific types of dust present disproportionate hazards—including the smallest particles, which do not contribute much to total mass, and mineral particles such as silica. The research in this dissertation explores the effects of primary dust sources and controls on respirable dust size and constituents. The major findings are as follows: when using typical equipment, mining into the rock strata that surrounds the target coal seam can generate much more dust than mining the coal itself. This dust generated can be finer and contain more mineral dust like silica and silicates. Furthermore, most dust controls used to suppress dust do not appear to be selective with respect to particle type but are generally less efficient for removing finer particles. This implies that, while dust mass removal efficiency may be high, controls might still be needed where very fine dust particles pose substantial hazards. Additionally, mine operations could develop monitoring techniques and re-orient their dust controls to target and better mitigate the most hazardous primary sources of dust such as dust from the rock strata.

Dedication

Dedicated to:

My late Dad

My mum

My wife

My siblings

I appreciate their love, prayers, patience, support and sacrifices they made for me throughout my entire PhD journey

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First, I would like to thank God for granting me good health and seeing me through this period.

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I am grateful to Mine 27 who provided me access to their operations to conduct dust sampling

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List of Abbreviations

CAC	Canopy Air Curtain
CM	Continuous Miner
CMPDSU	Coal Mine Dust Personal Sampling Unit
CPDM	Continuous Personal Dust Monitor
CWP	Coal Workers' Pneumoconiosis
DDS	Downstream of the face area cleaned by the Dry Scrubber
DS	Dry Scrubber
FBS	Flooded bed scrubber
FTIR	Fourier Transform Infrared Spectroscopy
MSHA	Mine Safety and Health Administration
NIOSH	National Institute for Occupational Safety and Health
PC	Polycarbonate
pDR	Personal Data RAM
PEL	Permissible Exposure Limit
PMF	Progressive Massive Fibrosis
PPE	Personal Protective Equipment

PVC	Polyvinyl Chloride
RCMD	Respirable Coal Mine Dust
RCS	Respirable Crystalline Silica
SEM-EDX	Scanning Electron Microscopy with Energy Dispersive X-ray
TGA	Thermogravimetric Analysis
UDS	Upstream of the Dry Scrubber
US	United States

Chapter 1

Introduction

1.1 Background

Coal production contributes significantly to the United States (US) economy and is mostly used for steel making and electricity generation. However, there are health and safety hazards linked with coal mining–including worker overexposure to deleterious airborne respirable dust hazards. At the turn of the 21st century, an alarming surge in cases of occupational lung diseases (such as Coal Workers' Pneumoconiosis (CWP) and its severe form, Progressive Massive Fibrosis (PMF)) amongst underground coal miners has been linked to overexposure to respirable coal mine dust (RCMD), and with disease rates even higher amongst miners with over 25 years tenure (see Figure 1.1) [1, 2, 3, 4, 5, 6, 7]. This contrasts almost three decades of disease decline, starting from when the 1969 Federal Coal Mine Safety and Health Act was promulgated and with the enhancement of dust surveillance [8]. Indeed, evidence from radiology and pathology research studies suggest that silica and silicates from the roof and floor rock strata surrounding the coal seam is also responsible for the surge in occupational lung disease cases [9, 10, 11, 12]. Recently, the depletion of coal seams in many mines has meant that there has been an increase in the cutting of rock strata to access the coal [4, 13]. Consequently, central Appalachia, a region characterized by thin seam coal mines is reported to have the highest cases of occupational lung diseases among US coal miners [14]. Contrary to the increasing cases of disease, mean respirable dust and quartz concentrations measured in samples collected for regulatory compliance monitoring by the Mine Safety and Health Administration (MSHA) have declined over the past few years (see Figure 1.2) – creating an unexpected contradiction [15].

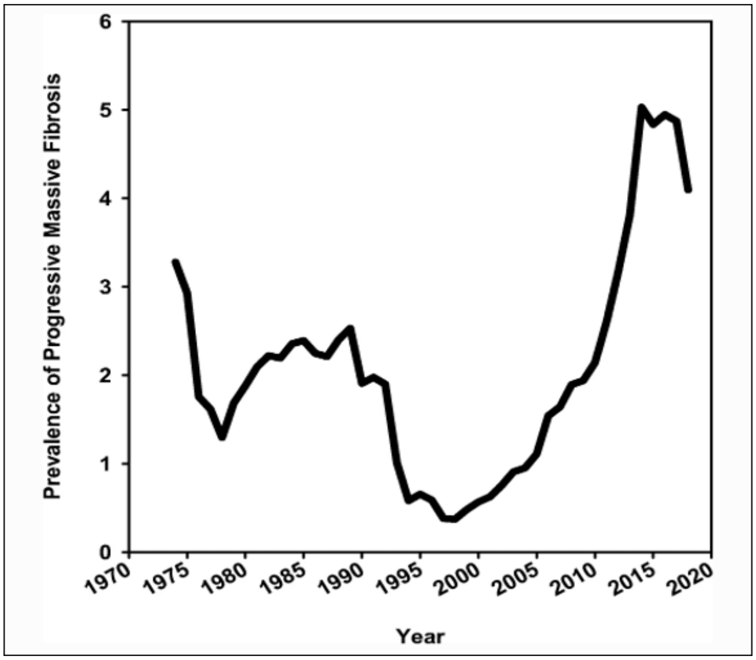

Figure 1.1: Incidence of PMF among central Appalachian coal miners (taken from [16]) based on data from the Coal Worker's Health Surveillance Program.

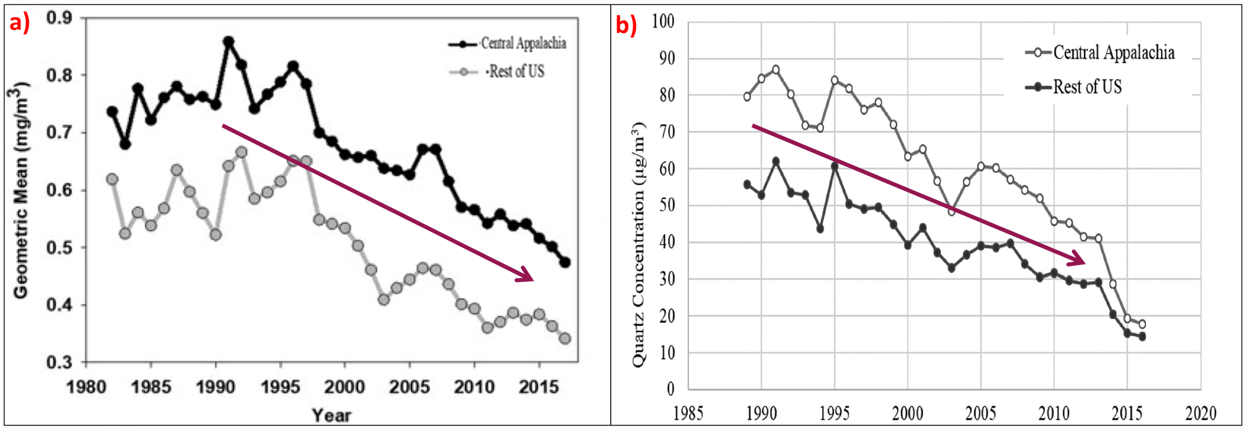

Figure 1.2: Reductions in a) geometric mean respirable dust concentrations (taken from [6]) and b) geometric mean quartz concentrations (taken from [17]) based on MSHA compliance monitoring data.

Despite several efforts made by government agencies, researchers and mine operators, occupational lung diseases are still a major concern in coal mines based on a recent health surveillance study conducted from 2014–2022 [18]. For instance, MSHA implemented a dust rule in February 2016 to reduce the average RCMD concentrations permissible exposure limits (PEL) from 2.0 mg/m^3 to 1.5 mg/m^3 for an entire shift [19] and require mine operations to use the continuous personal dust monitor (CPDM) for the improvement of compliance monitoring [8]. This has not yet yielded satisfactory results as some samples collected during MSHA compliance dust monitoring have exceeded PELs, particularly, those collected in central Appalachia [6]. In a further attempt at mitigating mine worker respirable silica exposure, MSHA recently implemented a new respirable silica dust rule to lower the average respirable silica dust concentration PEL for an 8-hour working shift to 50 µg/m^3 [20].

In addition to using the approach of quantifying miner exposure to respirable dust concentrations during monitoring, detailed characterization of RCMD has been recommended and explored as a potential solution to help explain and mitigate miner health and safety issues in coal mines [15]. As a result, several studies have been conducted at various operational locations in underground coal mines to characterize RCMD by determining their particle sizes and constituents, and to also identify the primary dust sources. [21, 22, 23, 24, 25, 26, 27].

Furthermore, different control mechanisms are used to mitigate respirable dust hazards in underground coal mining. These include elimination, substitution, engineering controls, administrative controls, and personal protective equipment (PPE) (see Figure 1.3). Ideally, elimination or substitution are the desired and most effective ways to mitigate hazards in every industry. However, using these hazard control methods is usually not possible, due to the inevitability or natural occurrence of dust generation during strata cutting in coal mines [28]. As a result, engineering controls are the alternative and next most preferred means to mitigate dust hazards in coal mining environments. To provide further protection for miners, administrative controls and PPEs could sometimes be implemented to supplement engineering controls in coal mining sections that generate elevated respirable dust concentrations [29, 30]. Indeed, the improvement of equipment design and technology has meant that various innovative dust controls have been developed to help mitigate miner exposure to respirable dust. The National Institute for Occupational Safety and Health (NIOSH) and others, in the past few decades, have been leading efforts to conduct research and implement various engineering dust controls geared towards mitigating coal miner exposure to RCMD. For instance, several research studies have been conducted on the respirable dust concentrations reduction efficiency of the following engineering dust controls: (i) auxiliary Scrubbers [31, 32, 33], (ii) roof bolter dust collection systems [34, 35], (iii) roof bolter canopy air curtain [36, 37, 38, 39, 40], (iv) water sprays and suppressants [41, 42, 43]. To some extent, most of these dust controls have been efficient in reducing respirable dust mass concentrations, and subsequently implemented in coal mines.

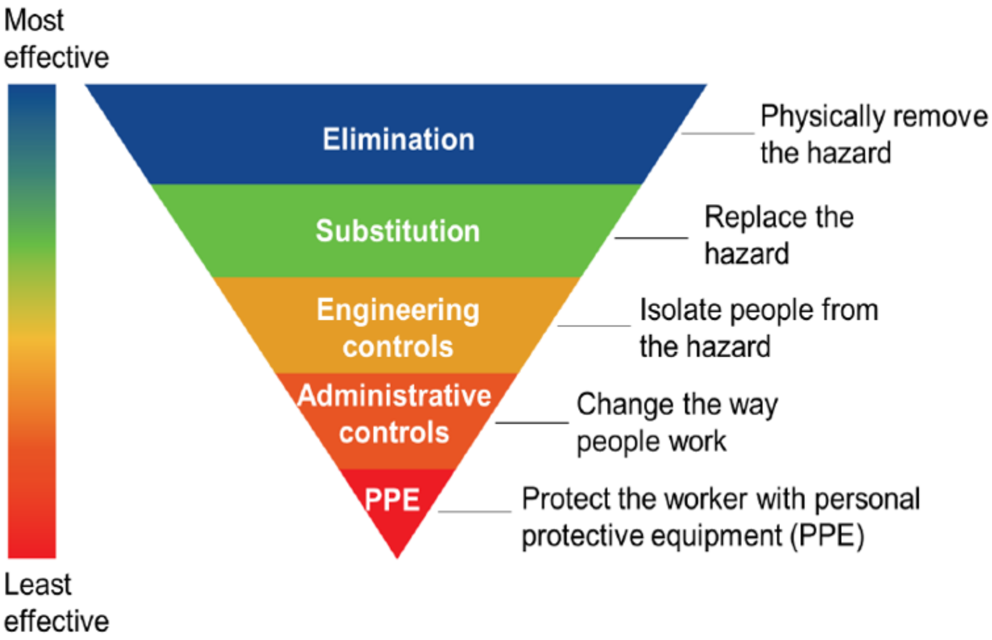

Figure 1.3: Hierarchy of controls used to mitigate hazards in the mining industry (taken from [8]).

Despite the improvement of dust laws and monitoring techniques, and the implementation of dust controls, cases of occupational lung diseases are still prevalent amongst underground coal miners. Clearly, there are some gaps in research that need to be addressed. For instance, while dust controls have been efficient in reducing RCMD on the basis of mass concentrations, the effects of these controls on RCMD characteristics have not been widely studied. In addition to their efficiency on RCMD concentrations, knowledge of the effects of these controls on specific dust constituents (i.e., coal, silica, silicates, and carbonates) and dust particle sizes will provide valuable and further insights into their protection efficiencies. For example, a dust control might be evaluated and deemed to remove over 98% of respirable dust concentrations in the mine airstream, but this efficiency could likely be influenced by the larger particles which make up most of the dust mass. This means that smaller dust particles do not often contribute much to the dust mass but they have been labeled more toxic to the human lungs when inhaled [44, 45]. Furthermore, while coal and rock strata have been identified as the primary dust sources, there is little information on the effects of mining into each individual strata (i.e., coal versus rock) on respirable coal mine dust (RCMD) characteristics. RCMD is often characterized when cutting or mining into the entire mining height (i.e., including the coal and rock strata).

1.2 Literature Review

1.2.1 Dust Monitoring and Sampling

The enactment of the 1969 Coal Mine Health and Safety Act (30 CFR 70.100) by MSHA required the regular monitoring of personal dust exposure of miners to keep coal mine dust exposure limits below 2 mg/m^3 during a full 8-hour shift [19]. For decades, operators used the traditional gravimetric coal mine dust personal sampling unit (CMDPSU) setup consisting of air sampling pumps, cyclones, and filters housed in cassettes to collect compliance respirable dust samples. These filter samples were usually sent to laboratories for analysis and the determination of the time-weighted average mass concentrations of miner dust exposure during a shift. This entire process usually took several days or weeks to complete and thus, leading to a delayed response in implementing mitigating measures to help improve the ventilation plan of mine operations [46]. Consequently, Volkwein et al. [47] reckon that the lack of swift corrective measures on dust control effectiveness and miner dust exposure management might have led to a rise in CWP cases from the late 90s. Also, it is alleged that there was operator tampering with compliance dust samples meant to be sent to MSHA. To address these issues, NIOSH, with the support of MSHA, and the government, worked to develop a robust CPDM suited for the underground coal mining industry, and capable of measuring accurate real-time dust concentrations [48, 49]. NIOSH eventually contracted Thermo Fisher Scientific to commercialize the instrument. The first model (PDM 3600) was certified in 2014 as intrinsically safe for use in underground coal mines for personal dust monitoring, and there is since a newer model – PDM3700 [8].

The implementation of the 2014 dust rule by MSHA required a switch from the use of gravimetric samplers to the CPDM for compliance sampling to quantify miner exposure to respirable dust. Indeed, beginning in February 2016, the new dust rule required all underground coal mine operators to use the CPDM to monitor the dust exposures of designated occupations (i.e., occupations expected to have the highest respirable dust concentration exposures). The CPDM data must be transmitted within 24 hours to MSHA for assessment to ensure that miner dust exposure is below the full shift average dust concentration of 1.5 mg/m^3 [15]. The reason for requiring the use of the CPDM for regulatory compliance is the fact that it is a real-time dust monitor that could determine miner exposure to RCMD concentrations. Hence, timely and necessary corrective measures could be implemented when samples from some occupations are above the dust concentration limits set in the standards. Another advantage of the CPDM is the fact that the miner wearing it could presumably adjust their activities or locations the displayed data indicates that their dust exposure is too high [8, 15]. In addition to personal exposure monitoring, the CPDM could also be used for studies to assess the effectiveness of dust controls, but its use in these types of studies must be approved by MSHA [50]. NIOSH researchers have used the CPDM in several studies to assess the dust reduction efficiency of some engineering controls [38, 39, 40].

Nevertheless, gravimetric samplers are still used to collect area samples in underground coal mines and to determine the respirable crystalline silica (RCS) content in samples. RCS is usually monitored in coal mines by measuring alpha-quartz. This is because alpha-quartz is the main form of RCS, and the terms RCS, silica and quartz are usually used interchangeably. Under the 2014 dust rule, gravimetric samplers are used to collect samples for compliance monitoring in surface coal mines. Another real-time personal dust monitor approved by MSHA for use in underground coal mines is the light-scattering personal Data RAM (pDR 1000s). This device is not used for compliance sampling but can be used by mine operations on a short-term basis to monitor dust exposures of operators at various locations [8]. Furthermore, the pDR is usually operated alongside a gravimetric sampler (see Figure 1.4), which is used to calibrate and improve the accuracy of pDR dust concentration data [34].

Undoubtedly, tracking exposure of coal miners to respirable dust and silica concentrations through compliance monitoring by MSHA is very important. However, given the alarming trends in occupational disease, there have been increasing calls to understand more about dust characteristics (e.g., particle size and constituents) [15, 26, 27]. With the changes in dust characteristics (i.e., increasing mining of rock-strata and smaller dust particle sizes) due

Figure 1.4: The CPDM 3700 sampler (left) and pDR/gravimetric samplers (Right) used for dust sampling and monitoring in coal mines (Taken from [8]).

to the advancement in modern mining equipment, knowledge of dust sources, dust particle sizes and individual constituents would be beneficial in improving miner safety and health.

1.2.2 Dust Characterization and Dust Sources

Several factors have been attributed to the rising cases of lung diseases and these include geological strata conditions, size of mines, thin seam mines, dust abatement techniques, advanced cutting technologies, etc., [1, 10, 51, 52, 53]. Detailed dust characterization to identify dust constituents, particle sizes, shapes, and their associated dust sources in coal mines are reported to be helpful in identifying hazards and understanding or explaining the health issues faced in these mines [15]. As a result, several dust characterization studies have been conducted in underground coal mines to help improve the health problems amongst coal miners. Indeed, from these studies, it has been identified that dust characteristics vary within and between mines [17, 21, 26, 27, 54, 55, 56, 57, 58, 59, 60, 61].

Dust Constituents

Around 50 inorganic elements, metals or oxides are associated with coal mine dust [62, 63]. Based on the compositions of these elements, RCMD can be classified into different mineralogies [58]. Coal, minerals (mostly silica and silicates), carbonates, and diesel particulate matter (DPM), have been identified as the major constituents in RCMD. These dust components are associated with different dust sources in underground coal mine environments. Coal is mostly sourced from the cutting of the coal seam at production face, and during its breakage and transport. Silica and silicates are usually sourced from roof bolting activities, and during the cutting of the roof and floor rock strata surrounding the coal seam. Carbonates occur in the mine environment as a result of rock dusting activities to control methane, while the formation of DPM is from diesel emissions [26, 27, 55, 64].

Typically, the rock strata in US coal mines consist of sandstone, shale, limestone and sandy shale [62]. Silica dust sourced from the rock strata has been deemed extremely hazardous by the International Agency for Research on Cancer (IARC), and overexposure to it could lead to the contraction of chronic lung disease like silicosis [8]. According to data from NIOSH, respirable silica is 20 times more toxic than respirable coal dust [65]. Indeed, silica and silicates have been reported to be key factors in the rising cases of PMF, which could be more deadly than CWP [9, 12, 66]. Several studies have shown that an inordinate amount of rock strata dust is generated when cutting into the rock strata versus coal seam at the mining production face [26, 54, 67]. More worrying is the fact that in these mines, the mining height of the coal strata was more than twice that of rock strata, and yet still the dust composition showed twice as much rock strata dust generated versus coal dust, as evidenced in Figure 1.5 [27, 54, 55, 67]. In addition, several studies have identified central Appalachia as a hot-spot for high rock strata dust production due to the relatively thinner seams of coal mined in this region [24, 26, 53, 64]. These findings are a cause for concern as silica has been identified as a major hazard in coal mines (as mentioned above). Compared to rock and coal dust, there is no evidence from research studies to suggest that rock dust might be harmful to human health. Furthermore, RCMD containing high amounts of bioaccessible iron (Fe) and polyaromatic hydrocarbon (PAH) linked to DPM, could play a role in lung inflammation and subsequent development of CWP due to the high oxidative stress associated with them [59]. Results from a study by Sarver et al. [26] showed that bioaccessible and acid-soluble metals and trace elements were found in respirable coal mine dust, but their amounts were lower than the permissible exposure limits (PELs).

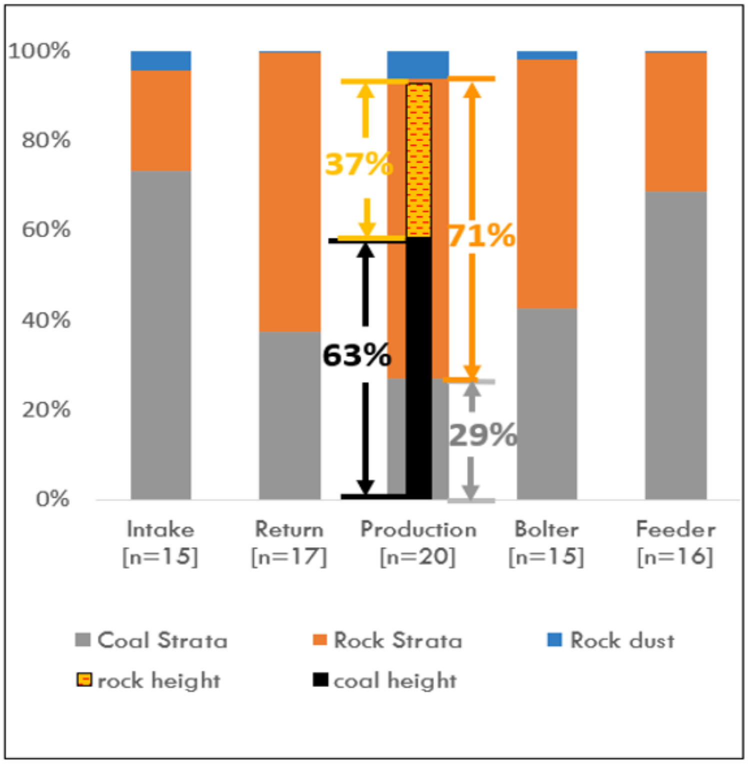

Figure 1.5: Dust characterization from 20 underground coal mines showing the major dust components, mining height, and an inordinate amount of rock strata dust generated versus coal at the production areas (Adapted from Jaramillo et al. [67]).

Dust Particle Sizes, Shapes and Toxicity

Apart from hazardous dust constituents, knowledge of particle sizes and shapes of dust particles can play a significant role in explaining health complications encountered by coal miners [68]. Respirable dust is defined as dust particles with aerodynamic diameter of less than 10 micron (10 µm) and with median passing of less than four micron (4 µm) [58]. The advancement of technology has meant that modern mining equipment generate smaller respirable dust particle sizes during drilling and cutting activities [52, 53]. Indeed, several studies have confirmed that smaller dust particle sizes could be very harmful to human health [44], but these particles only make up a smaller percentage of respirable dust mass concentrations [27]. These dust particles could be in the micron or nano-sized (submicron) fractions [21], which when inhaled through the human respiratory system could penetrate deeper to the alveoli and cause lung complications [8, 53]. Dust particle deposition into the lungs depends on the shape and size of the particle inhaled [27, 55]. Angular and smaller dust particles could easily be deposited into the lung tissues when inhaled than spherical and larger particles – causing respiratory complications [53, 69, 70]. In addition, submicron sized dust particles have high reactivity with lung tissues due to their larger surface area and high mobility and could influence the severity of lung diseases when contracted. Furthermore, submicron dust particles could easily lose their oxygen functional group as evidenced by the weak wetting behaviors exhibited by these particles, and this could expose miners to more submicron-sized dust particles [60, 71]. To put things into context, miners working in underground continuous mining coal operations in central Appalachia could be at risk of contracting lung diseases as these mines reportedly generate more submicron dust particles than any other locations in the US. Moreover, mines that have high diesel emissions could also run the risk of endangering their miners, as diesel particles are in submicron range [24, 26, 27, 53, 55].

Overall, knowledge of dust constituents and particle sizes generated in coal mines could help operations implement the right dust controls and effective dust monitoring schemes, which could aid in the suppression of dust and reduction of miner exposure [15, 22, 27]. Additionally, as mentioned above and observed in several dust characterization studies, it is obvious that most of the dust generated at the production face in underground coal mines come from the rock strata, which is deemed more harmful than dust from the coal strata. Therefore, operations should implement targeted controls aimed at suppressing the rock strata-sourced dust. Furthermore, research studies should focus on evaluating and understanding the respirable dust concentrations and characteristics generated when mining into coal versus rock strata.

1.2.3 Engineering Controls

Ventilation as a primary dust control

Ideally, the best way to reduce RCMD exposure of miners is to prevent dust generation from the initial source. However, the nature of mining activities such as cutting/drilling, blasting, loading, and hauling means that dust will always be generated, and this makes it impossible to eliminate. In underground coal mines, ventilation is the primary control used to remove dust and other toxic gases from the mine airstream [8, 28]. The ventilation air quantity determines how much dust is diluted from the airstream. Indeed, the right air quantities are required in mine workings to prevent miners from getting exposed to high concentrations of respirable dust. Additionally, air velocity typically determines the speed at which dust is removed from the airstream [72]. Indeed, MSHA requires mines to regularly provide and update a ventilation plan before they are permitted to continue operations. This ventilation plan usually contains a detailed description of the dust control measures implemented in each coal mine section to prevent miner exposure to RCMD and in accordance with the code of federal regulations (30 CFR 75.370) [19]. This plan specifies the minimum air quantities and air velocities employed in each mining section. The type of ventilation (blowing or exhausting), their mode of operations, and other dust mitigating strategies must also be stated in the ventilation plan [8, 28, 50, 73]. Despite the efficiency of ventilation in reducing coal miners' exposure to RCMD, the increasing concentrations of dust produced in coal mines suggest that using ventilation alone might not be enough to limit miner exposure. Consequently, other engineering dust controls are often used alongside ventilation to reduce respirable dust in coal mines [72], as seen in Figure 1.6. Table 1.1 summarizes some dust control studies conducted in the past few years to mitigate respirable dust hazards.

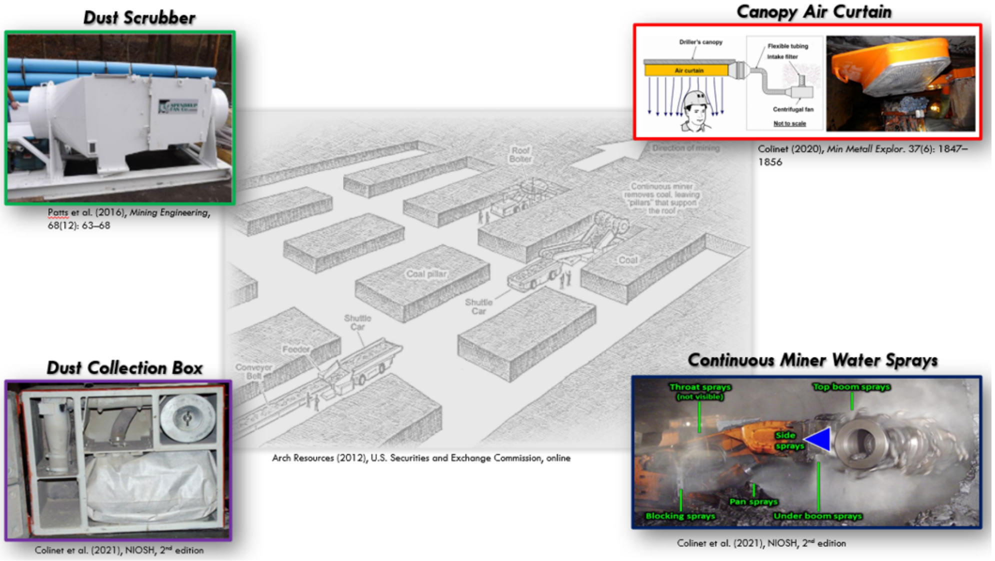

Figure 1.6: Overview of selected engineering controls employed in underground coal mines to suppress respirable dust (Taken from [15]).

Table 1.1: A summary of some major research studies conducted on dust controls.

Dust Control Type	**Major research studies**	**Associated authors**
Ventilation	“The Impact of Black Lung and a Methodology for Controlling Respirable Dust”	Colinet, J. F. [28].
Water Sprays	“Evaluation of the wet head continuous miner to reduce respirable dust”. “Examination of water spray airborne coal dust capture with three wetting agents”.	Listak et al. [41]. Organiscak, J. A. [42].
Dust scrubbers	“Field evaluation of an inline wet scrubber for reducing float coal dust on a continuous miner section”. “Reducing float coal dust: Field evaluation of an inline auxiliary fan scrubber”. “Examination of a newly developed mobile dry scrubber (DS) for coal mine dust control applications”.	Janisko et al. [31]. Patts et al. [33]. Organiscak et al. [32].
Roof Bolter Dust collection box	“Field comparison of a roof bolter dry dust collection system with an original designed wet collection system for dust control”. “A Second Case Study of Field Test Results for Comparison of Roof Bolter Dry Collection System with Wet Collection System”.	Reed et al. [34]. Reed et al. [35].
Roof Bolter Canopy Air Curtain (CAC)	“Field study results of a 3rd generation roof bolter canopy air curtain for respirable coal mine dust control”. “Field Testing of Roof Bolter Canopy Air Curtain Operating Downwind of the Continuous Miner”.	Reed et al. [40]. Reed et al. [39].
Continuous Personal Dust Monitor (CPDM)	“Performance of a New Personal Respirable Dust Monitor for Mine Use”.	Volkwein et al. [47].
Respirators	“Capability of the Airstream Helmet for Protecting Mine Workers from Diesel Particulate Matter”.	Noll et al. [29].

Water Sprays

Since ventilation does not consistently achieve a complete reduction of respirable dust, water sprays have been used as a complimentary dust control. Coincidentally, water sprays one of the first dust controls to have been investigated and used extensively for dust mitigation in underground coal mines [74]. Indeed, water sprays are used in coal mines to wet mined material for dust suppression, airborne dust capture, and for the re-direction of dust from the ventilating air [73]. Different water spray types are mounted on the continuous miner to achieve efficient wetting of mined material, as this would prevent respirable dust generation and dust mixing up with the ventilating air [50]. These sprays include cutting boom sprays, throat sprays, side sprays, pan sprays, and blocking sprays (see Figure 1.7) [8]. The CM cutting boom usually consists of sprays placed at the top and bottom of the boom and directed towards the bits on the cutting drum to wet the broken material and cool the bits for friction prevention [8, 28, 73]. Additional sprays (i.e., wetheads) are usually placed right behind the bits on the cutting drum to achieve a uniform and sufficient wetting of the mined material. Likewise, wetheads are placed at the back or front of the longwall shearer cutting bits to wet the broken material sufficiently [28, 43]. Consequently, different water spray types have been investigated to ascertain their ability to wet and reduce respirable dust generation. A study by Listak et al. [41] examined the respirable dust reduction efficiency of wetheads installed on continuous mining cutting drums at different mines. The study concluded that wetheads were somewhat efficient in reducing the respirable dust in some mines but results in other mines did not yield any dust reductions. Another study by Goodman [75] confirmed the respirable dust confinement and reduction capabilities of side sprays installed on a continuous miner from the study's results.

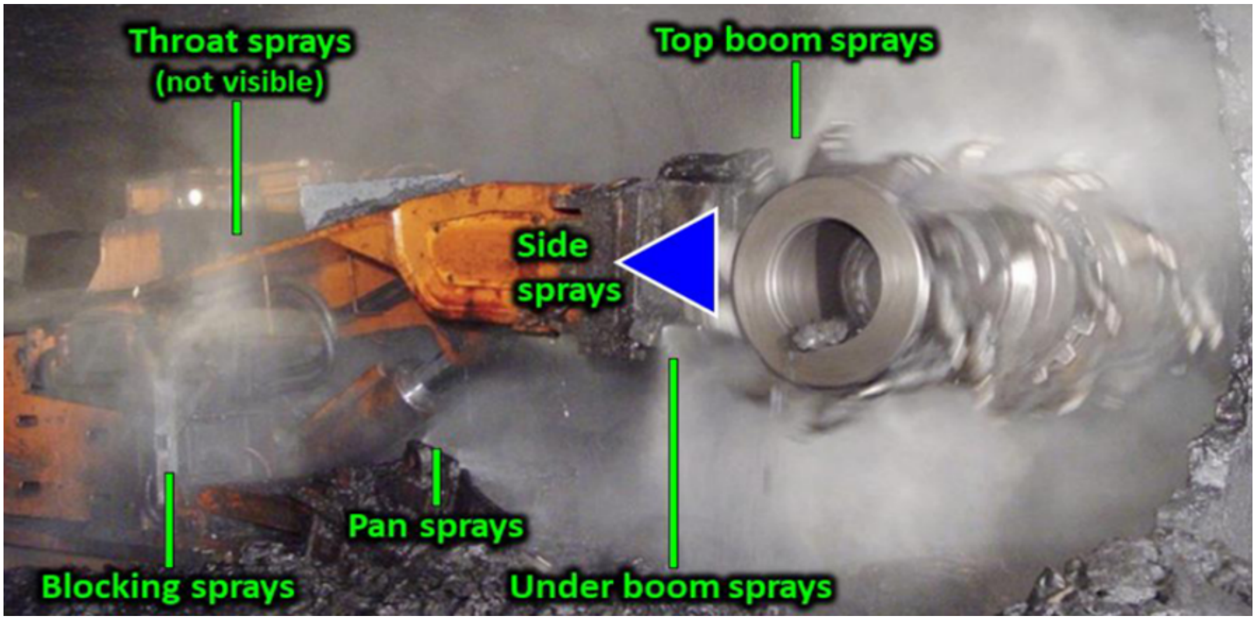

Figure 1.7: The various types of sprays employed on a continuous mining machine (taken from [8]).

To achieve optimal wettability and dust capture from water sprays, the proper spray nozzle must be selected and operated at an ideal pressure and volume of water [73]. Indeed, there is evidence that operating water sprays at a pressure greater than 100 psi could lead to efficient dust wetting and containment, but this could cause dust rollback into the ventilating air [76]. Also, there is evidence that the full cone and flat-fan spray nozzles could achieve sufficient respirable dust suppression and containment, respectively [8, 28]. However, there is no information on the effects of CM wetheads operating at different pressure and volume on dust generated from coal versus rock strata. Obviously, this information will be helpful in designing and orienting sprays to target dust from the rock strata, which is reported to generate more dust than coal strata.

Even though water sprays have efficiently reduced respirable dust in some coal mines, using them alone might not wholly suppress the dust generated. This is why wetting agents have been used together with water sprays to aid in suppressing and containing the dust, but studies yielded mixed results [42]. Alternatively, additional dust controls such as dust scrubbers have been investigated to evaluate their suitability for respirable dust suppression and to be used alongside water sprays [41].

Dust Scrubbers

Respirable dust (i.e., coal dust with particle diameter less than or equal to 10 µm) and float dust (i.e., coal dust with particle diameter less than or equal to 74 µm) generated during the cutting of coal at underground mine production areas could become airborne and then mix up with ventilating air [77]. Sometimes, this dust-laden air make its way to the return and other entries of the mine and thus, exposing miners to health and safety hazards [28]. While water sprays are usually used to dilute respirable dust from the cutting face, this dust might persist in the ventilating air [41]. Therefore, water sprays are mainly used concurrently with other dust controls to help reduce dust-laden air in the mine atmosphere. Fan-powered dust collectors such as the flooded-bed scrubber (see Figure 1.8), which are mostly mounted on continuous miners, have emerged as a desirable dust control in underground coal mines due to their ability to capture and remove respirable dust from the ventilating air – limiting miner exposure to respirable dust [8, 28, 78]. Indeed, the operation of the scrubber increases the air quantity supplied to the cutting face for the improvement of methane and respirable dust control [33]. The scrubber captures dust-laden air and directs it to the flooded-bed filter through its inlet. Water sprays create a mist that interacts with the dust-laden air to aid the flooded-bed filter trap and remove this dust from the mine airstream. After it has passed through the flooded-bed filter, the water droplets carrying the captured dust particles are removed from the system by a demister. The cleaner air is then exhausted through the scrubber and released into the mine atmosphere. [31, 32, 33].

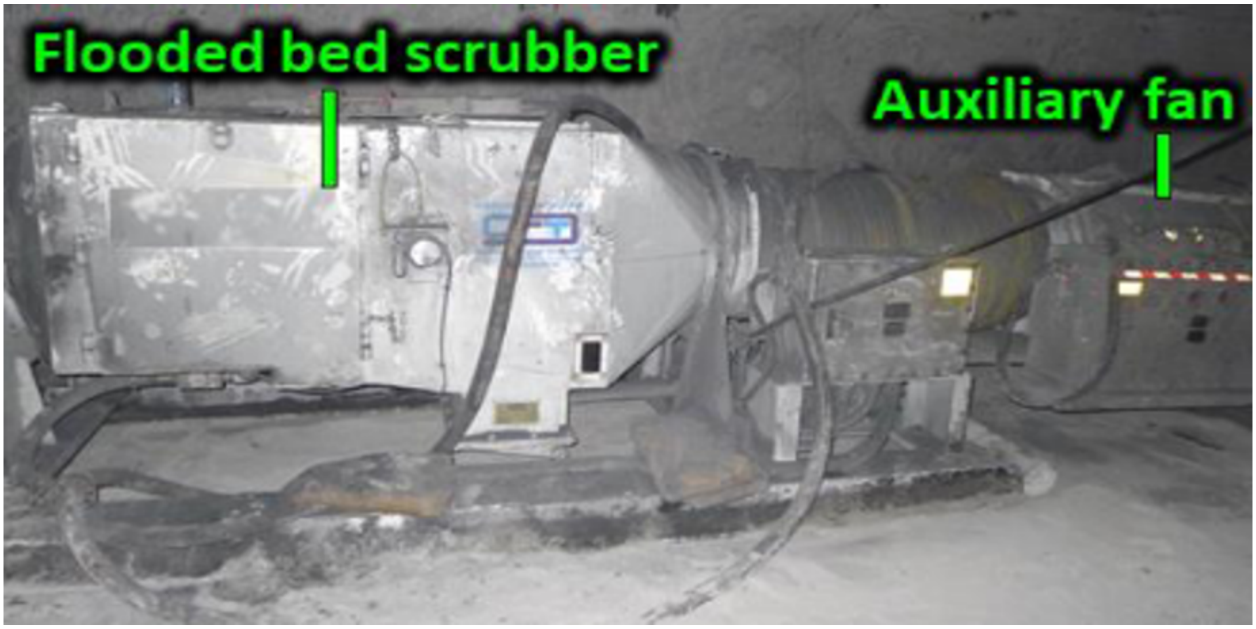

Figure 1.8: A stand-alone flooded bed scrubber used to suppress dust in underground coal mines (taken from [8]).

The scrubber's efficiency is determined by its ability to capture (i.e., controlled by the scrubber airflow) and collect or remove dust-laden air from the cutting face [79]. However, the efficiency of the scrubber could be constrained by the type of filter used. Denser filter panels have shown to improve the respirable dust collection efficiency of the scrubber but could increase the pressure drop and subsequently, reduce the scrubber ventilating airflow. In contrast, a less dense scrubber filter panel could reduce the scrubber collection efficiency, but no evidence suggests that scrubber airflow could be compromised [79, 80, 81]. Another factor that hinders scrubber performance is the clogging of filters by captured respirable dust. This can increase the scrubber pressure drop – causing a reduction in scrubber airflow [82]. Indeed, Schultz & Fields [83] reckon that filter clogging could reduce scrubber airflow by 75% after the first cut. Thus, cleaning the filters after use is critical in maintaining the scrubber's performance. A laboratory study by Organiscak et al. [32] found that cleaning reusable filters could re-entrain respirable dust into the mine atmosphere. Additionally, reusing these filters could increase scrubber noise levels. They also concluded that disposable filters improved the scrubber dust collection versus the washable or reusable filters. Furthermore, multi-layered stainless steel meshed fibrous filter panels are the most popular filters used in the mining industry [8]. However, there is evidence from laboratory and computational fluid dynamics (CFD) models study that non-clogging self-cleaning impingement filters could be suitable substitutes for these fibrous filters [81]. Therefore, it is essential that a scrubber operates at a good airflow and utilizes a filter with the proper density and less clogging attributes to improve its collection efficiency [79].

Flooded bed scrubbers mounted on continuous miners have proven efficient in collecting or removing respirable dust from the ventilating air, with collection efficiencies of up to 90% reported by Colinet & Jankowski [79]. While flooded-bed scrubbers mounted on continuous miners are efficient dust collectors, dust could persist in the mine atmosphere and travel downwind of the continuous miner into the return airstream. This dust could increase the exposure of roof bolter operators who sometimes work downwind of the continuous miner (i.e., if regulation permits), to high concentrations of respirable dust [80]. To control dust that escapes from the cutting face and travels downwind, stand-alone dust scrubbers have been strategically placed in the return of continuous miner sections and tested to determine their efficiency in collecting respirable and float dust. Studies by Janisko et al. [31] & Patts et al. [33], investigated the dust reduction efficiency of an in-line wet scrubber installed downwind of a continuous miner in the return. They concluded that the wet scrubber operation led to a 92% reduction in float dust concentrations and an 86% reduction in respirable dust concentrations. Likewise, laboratory and field studies conducted by Organiscak et al. [32] investigated the respirable dust reduction efficiency of a stand-alone dry scrubber installed downwind of a continuous miner. Consequently, the operation of the dry scrubber led to a 92% reduction in respirable dust concentrations in the laboratory study. In the field study, the operation of the dry scrubber yielded respirable dust concentration reductions of 91% and 50% at the scrubber exhaust and downstream face area cleaned by the scrubber, respectively. Moreover, a laboratory study by Arya et al. [78] investigated the suitability of a novel flooded-bed scrubber mounted on a longwall shearer, to reduce respirable dust concentrations in underground longwall coal mines. Consequently, the operation of the scrubber led to a 57% reduction in respirable dust concentrations in the return and a 74% respirable dust reduction at the longwall shearer walkway.

While flooded-bed scrubbers have demonstrated their ability to reduce respirable coal mine dust concentrations from the above studies, little is known about their impact on dust constituents. A study by Colinet et al. [84] did reveal in one such study that the flooded-bed scrubber could be more effective in removing coal dust than silica dust from the dust-laden air drawn into the scrubber. Hence, there is a need to determine the effects of the flooded-bed scrubbers on respirable dust constituents and particle sizes.

Roof Bolter Dust Collection Systems

Amongst underground coal mine occupations, roof bolter operators are the most susceptible to respirable crystalline silica exposure [85]. According to MSHA inspector roof bolter samples (N=924) collected from 1999-2008, 21.5% exceeded the silica permissible exposure limit (PEL), i.e., 100 µg/m^3. In addition, the geometric mean quartz levels in the samples from central Appalachia was around 7% (i.e., slightly above the MSHA established standard of 5% or less quartz in respirable coal mine dust), while other regions averaged quartz levels of 4% in the samples [6]. Even though these samples were collected from the roof bolter and other locations, silica exposure of miners in underground coal mines should be taken seriously. This is why MSHA recently introduced a new silica dust rule to help mitigate miners' exposure to silica [20].

The most common source of respirable silica exposure for roof bolter operators is during drilling and bolting activities into the roof rock consisting of shale, sandstone, and other rock types [63, 86]. Another source of roof bolter operators' exposure to respirable coal and silica dust is when working downwind of a continuous miner (CM) [80, 87], and this dust is even higher when the CM is not equipped with a scrubber [41]. According to Colinet et al. [88], a roof bolter operator is exposed to 42-55% respirable coal and silica dust when operating downwind of CM equipped with a scrubber. Furthermore, cleaning out and maintaining the dust collection box on the roof bolter generates more respirable dust that could harm miners' health [86].

The nature of roof bolter occupation means that dust generation is inevitable, and the only way to limit this hazard is by implementing engineering controls to reduce the spread of dust. First, drilling with the right drill bit minimizes dust production. For instance, a dust hog-type drill bit is much more efficient in drilling and capturing drill cuttings than a shank-type drill. Indeed, Divers et al. [89] observed a 63% increase in penetration rates when using the dust hog-type bits than the shank-type bits from a field study. Crucially, using a bit sleeve together with a dust hog-type bit further enhances the reduction of dust during cutting [90]. Bite depth has also been shown to be critical in respirable dust generation, as deeper bite depth is associated with lower respirable dust generation [91]. Jiang & Luo [92] used a roof bolter drilling control algorithm to monitor bit conditions and drilling performance, as this could lead to less respirable dust generation during roof bolter drilling and energy efficiency [93]. Moreover, wet drilling, which involves using water to pump through the drill steel to capture dust during drilling, has been used in the past. This effectively reduces respirable dust, but the water used could be uncomfortable for miners [8]. As an alternative, mist drilling, which uses less water but incorporates compressed air, efficiently suppresses respirable dust. However, vacuum drilling technology pulls dust through the bit, drill steel, and into a dry collection box system, which is much more efficient than the mist drilling system [94]. Furthermore, limiting the operation of the roof bolter downwind of the continuous miner could help reduce the exposure of the roof bolter operators to respirable dust. This is why MSHA requires operations to design a ventilation plan that limits the roof bolter activities downwind of the continuous miner [87]. Also, Roof bolter dust exposure could be further reduced when a stand-alone wet or dry scrubber is operated downwind of a working continuous miner [32, 80]. Improvement in mine ventilation could also be crucial in reducing roof bolter operators' exposure to respirable coal and silica dust [87]. A canopy air curtain and dust collection systems are dust controls usually employed on roof bolters to control respirable dust.

The dry dust box collection system (see Figure 1.9) installed on a roof bolter has been used in US underground coal mines to collect dust materials generated during drilling and bolting into the roof rock [34]. This is done to reduce the exposure of roof bolter operators to respirable crystalline silica. During drilling into the roof rock, a vacuum pump is used to pull drill cuttings/materials through a dust port of the drill bit and vertical drill steel, and then finally deposits the dust into the dust box via a pre-cleaner. The pre-cleaner is a cyclone that removes and dumps larger dust particles onto the mine floor while allowing the smaller-sized dust particles pass through into the dust box. The internal part of the dust box contains cyclones and a canister filter that are used to remove dust and filter out clean air through a muffler and into the mine airways [50]. There have been concerns about miners' exposure to dust being re-entrained when larger particles are dumped onto the mine floor by the pre-cleaner. Joy et al. [87] collected pre-cleaner and dust samples from underground coal mines to determine their silica content and particle sizes. Consequently, the silica content in the pre-cleaner dust samples ranged from 9.8% to 53%, while the silica content from the dust box dust ranged from 1% to 79%. Likewise, the pre-cleaner respirable dust particle sizes (i.e., less than 10µm) ranged from 5.3% to 35.4%, while the respirable dust particle sizes from the dust box ranged from 13% to 86.7%. Therefore, they concluded that while the pre-cleaner silica content was lower when compared to the dust box silica content, it could still pose some dangers for miners and needs to be controlled. Also, the study results confirmed that the pre-cleaner was removing larger dust particles.

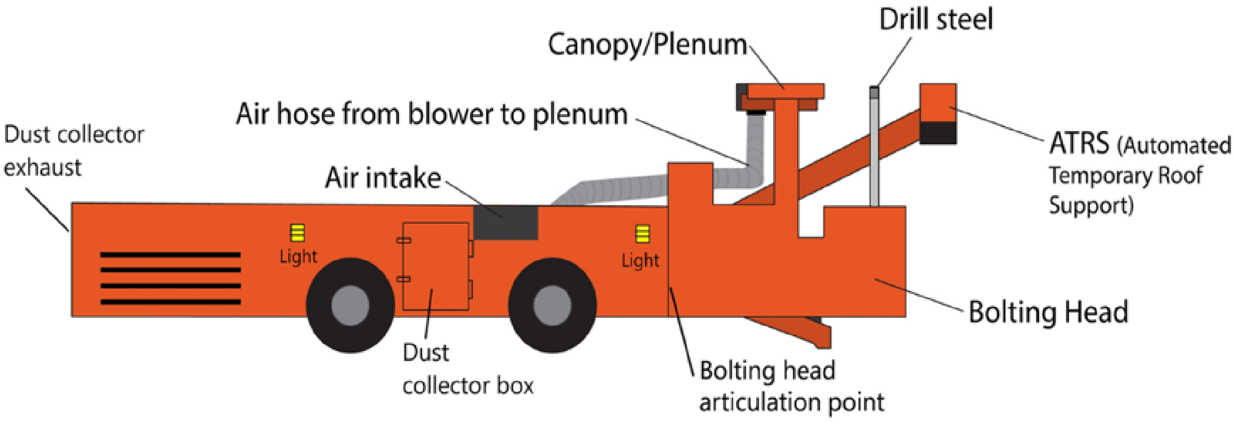

Figure 1.9: A roof bolter machine and the dust collection box (taken from [35])

One of the significant sources of respirable silica dust generation is during the cleanout of the dust box. A metal rake can sometimes be used to clean out dry box dust and deposit it onto the mine floor [35]. There are concerns that dust from the dry box cleanout deposited on the mine floor could be re-entrained into the production airstream and other mine areas [95, 96]. A laboratory study by Shankar & Ramani [95] found that varying air velocities and walking could re-entrain and increase dust concentrations from dust deposited on mine floors due to dry dust box cleanout. Another research by Colinet et al. [88] concluded that vehicular traffic yielded a negligible increase in dust concentrations produced from re-entrained dry box cleanout dust dumped on mine floors. Furthermore, from a laboratory and field investigation, using dust bags in the dry box to collect dust material proved to be more efficient in reducing miner exposure to silica dust during its cleanout than when using a dust box without a dust bag [97]. Similarly, the effects of using an open-top rigid box, metal rake, and a collector bag for dust collector box cleanout were investigated in the laboratory. The results showed that using the rigid box for dust box cleanout was much more effective in reducing miner dust exposure when compared to using the metal rake and the collector bag [98]. Therefore, to protect miners from dust generated during the dry box cleanout, maintenance and the proper selection of the cleanout method are crucial [99].

Due to the silica dust hazards associated with using the traditional dry dust collection box, a novel wet dust collection box has been tested and compared with the dry dust collection box in underground mines to evaluate the differences in their dust control capabilities [34, 35]. The components of the wet box are similar to that of the dry box except for the fact that: (i) the wet box incorporates the use of water sprays inside the box, (ii) pre-cleaner and other cyclones are not used in the wet dust box (iii) the wetted dust material can be removed from the wet box via a bottom drain (iv) the final canister filter in the wet box is water resistant [35]. In the initial study, the dust cleanout of the wet box resulted in a 60% reduction in respirable coal mine dust concentrations compared to the dry box dust cleanout – highlighting the efficiency of the wet box in reducing miner exposure to respirable dust [34]. A follow-up study conducted for three days at an underground operation compared the roof bolter respirable dust generated during the cleanout of the wet box versus the dry box. Indeed, the wet box cleanout yielded a 71-88% respirable dust concentration reduction than when cleaning the dry box. Also, the silica content from the wet box cleanout was 0%, while the silica content from the dry box cleaning was between 4.6-10.3% [35]. Clearly, a knowledge of the characteristics generated from the operator cleanout of wet versus dry dust boxes could also be helpful in understanding the protection efficiency of the novel wet dust box from dust hazards.

Canopy air curtain

To combat roof bolter operator exposure to RCMD and respirable crystalline silica, US Bureau Mines (USBM) or NIOSH researchers have conducted several studies to explore the possibility of adopting a roof bolter canopy air curtain (CAC) as a dust control method in underground coal mines (see Figure 1.10). A hydraulically powered fan (blower) installed on a roof bolter is usually connected to a plenum (traditionally placed underneath the roof bolter canopy) via a hose to provide filtered air to the breathing zones of the operator during bolting activities. The filtered air from the plenum also protects the operator by pushing away dust-laden air from the zone of influence of the CAC [8]. Unsurprisingly, outside of the USBM or NIOSH studies, there needs to be more information or studies on CACs.

Figure 1.10: A canopy air curtain plenum installed underneath the canopy of a roof bolter to provide filtered air to operators (taken from [8]).

The first CAC model was developed by Donaldson Company Inc. and tested in the 1970s on continuous miners (i.e., before the discovery of remote radios used to operate the CM) in an underground coal mine. The CAC was placed underneath the cab of the CM to provide filtered air to the operator. Indeed, this study yielded dust reductions of up to 69% [36]. Subsequent studies in the 1980s proved that the CAC could effectively minimize coal miners' dust exposure when installed on other machines, mainly when operating at different air velocities [100]. The first-ever test of CAC on a roof bolter conducted by Goodman & Organiscak [101] in the laboratory led to a 62% reduction in respirable dust. After this, Goodman et al. [102] proved that a CAC installed on a roof bolter could reduce respirable dust in a field test conducted in an underground coal mine. Even though these previous studies showed the dust reduction efficiencies of a roof bolter CAC, Listak & Beck [36] noted that the small size and square shape of the CAC plenum needed to be upgraded to provide sufficient protection to operators. Thus, laboratory and field tests of the re-modelled roof bolter CAC resulted in respirable dust reductions of up to 75% and 34%, respectively [36].

Moreover, further modifications were made to the plenum of the CAC to improve the airflow. Thus, a laboratory test of this model (i.e., named first generation) on a roof bolter led to respirable dust reductions of 14.2% to 24.5% [37]. Furthermore, with the help of computational fluid dynamics (CFD), the previous CAC model (i.e., first generation) was modified and tested on a roof bolter in an underground coal mine. Gravimetric samplers were used to collect operator vest samples when the roof bolter operator was working under the zone of influence of the CAC. At the same time, samples were also collected outside the area of influence of the CAC – to enable comparisons to determine the dust reduction efficiency of the CAC. This led to a respirable dust reduction range of -150% to 52%, with the negative percentage meaning that there was an increase in dust exposure of operators. The reasons identified for these increases in operator dust exposure included: (1) The operator moving inside and outside of the CAC during sampling, thus contaminating the samples, (2) low dust concentrations, (3) Larger distances between the CAC plenum and the operator, and (4) improper placement of samplers. Notwithstanding, the CAC showed a maximum protection efficiency of up to 90% when samples taken directly underneath the CAC were compared to samples collected outside the zone of influence of the CAC [38]. To address and improve the shortcomings in this study, another study was investigated to determine the respirable dust reduction efficiencies of the roof bolter CAC in an underground coal mine. Dust reductions of 3-60% were obtained when operator vest samples within the influence of the CAC were compared to the samples outside the zone of influence of the CAC. Likewise, the maximum reduction efficiency of the roof bolter CAC ranged from 30-79% [40]. Finally, since a roof bolter operating downwind of a continuous miner has been identified as a critical contributor to dust exposure of roof bolter operators [86], this scenario was tested in the field during installation and operation of CAC underneath the bolter canopy. The operation of the CAC led to respirable dust reductions of 11-40%. Importantly, studies by Zheng et al. [103] and Zheng & Reed [104] demonstrated that the CAC could reduce roof bolter operators' exposure to respirable dust in underground mine environments that employ blowing curtain ventilation and exhaust curtain ventilation, respectively.

Besides its use on a roof bolter to reduce miner exposure to respirable dust, the CAC has been trialed on ram cars and shuttle cars. A laboratory study demonstrated that the CAC installed on a shuttle car could reduce operators' exposure to respirable dust by 83% [105]. Subsequently, a field study tested the dust reduction efficiency of a CAC installed underneath the canopy of a ram car during different tramming operations. The ram car CAC undoubtedly showed an overall dust reduction of 11-34%. Notably, the continuous miner loading of coal onto the ramcar was an activity that led to respirable dust reductions of 57-65% when the CAC was installed. This finding was timely as the continuous miner loading of the ramcar with coal had been identified as an activity that generated high quantities of dust [106].

Administrative Controls and Personal Protective Equipment (PPE)

Administrative controls and PPEs are often employed in coal mines to supplement engineering dust controls. They are even more desirable when engineering controls are not providing coal miners the ideal level of protection required against respirable dust.

MSHA is the federal agency in charge of ensuring that federal regulations on dust control are efficiently implemented by operations. MSHA inspectors regularly monitor the progress of coal mine operators to ensure that they operate in compliance with dust rules set in the regulations (30 CFR 70.100), while punishments or recommendations are imposed on operations who break these laws [107]. Notably, every underground coal mine operation is required to submit a ventilation plan indicating how dust controls will be implemented at new production mining sections before they are granted permission by MSHA to begin operating in that section [8]. Furthermore, CPDMs are regularly used in underground coal mines to collect regulatory compliance monitoring dust samples on designated occupations and sent to MSHA who ensure that mines are operating within dust concentrations limits set in the regulations [15]. The CPDM measures real-time dust concentrations that an operator is exposed to within an entire shift.

The use of PPE is not mandatory in US coal mines but adopting them in sections of high dust production (e.g., longwall sections) could be helpful in reducing miners' respirable dust exposure [30]. Indeed, some mines use temporal PPE, such as a conventional respirator at locations with high dust concentrations and less effective engineering dust controls [29, 108, 109]. However, the protection efficiency of these PPE depends on their proper usage by mine personnel or the implementation of suitable management systems [8, 110]. Furthermore, the choice of respirator depends on operator-related factors (e.g., user acceptance), levels of respirable dust contaminants, and the tasks to be executed [110]. Conventional respirators have been used in coal mines to protect operators working in elevated dust concentrations. However, these conventional respirators have yet to produce the desired results due to problems such as low protection, lack of comfort, poor fit, inability to communicate while wearing the respirator, breathing restrictions, and visibility issues [111]. The airstream helmet has been used as an alternative respirator to overcome the problems that arise when using conventional respirators [29]. Currently, little research has been conducted on PPEs and their respirable dust reduction impacts in underground coal mines. With changing dust characteristics, new findings highlighting the increasing silica content in respirable coal mine dust and smaller dust particle sizes [27], it is imperative that research is conducted on the effectiveness of PPE on respirable dust constituents and particle sizes.

1.3 Research Overview

Based on literature, it is obvious that the implementation of dust controls in underground coal mines plays a crucial role in dust suppression. However, little is known about the effects of dust controls on particle characteristics. Clearly, knowledge of the efficiency of controls on different particle sizes of dust and on specific dust constituents (especially the more hazardous constituents), will be helpful in gaining further insights on the true dust protection capabilities of these controls. Furthermore, the coal and rock strata have been identified as some of the primary dust sources, but studies have often characterized dust from both strata when the mining strata height is being cut as a whole, rather than cuts into individual coal or rock strata. As a result, it is difficult to directly compare the differences in dust generation and particle characteristics between these primary dust sources (i.e., coal versus rock strata). Therefore, the primary aim of this research dissertation is to evaluate the effects of mining and operational conditions on respirable coal mine dust characteristics. Specifically, the work seeks to answer two main research questions:

1. How do respirable dust generation and particle characteristics vary between typical mining in primary dust sources (i.e., coal versus rock strata)?

2. How do dust controls affect RCMD constituents and particle size?

Overall, the findings in this dissertation will provide further insights and a comprehensive understanding of the effectiveness of engineering dust controls, while also holistically quantifying dust generated from individual primary dust sources (i.e., coal versus rock strata). This will help mine operations understand and identify the primary dust sources for efficient dust monitoring, which will also assist them in designing the right dust controls for effective dust mitigation.

1.3.1 Scope of work

To meet the research objectives and effectively answer the research questions, the work in this dissertation includes six chapters from four individual research studies. Two of these studies were fulfilled by using preserved samples sourced from NIOSH, while other two studies were completed by conducting field and laboratory studies (see Figure 1.11).

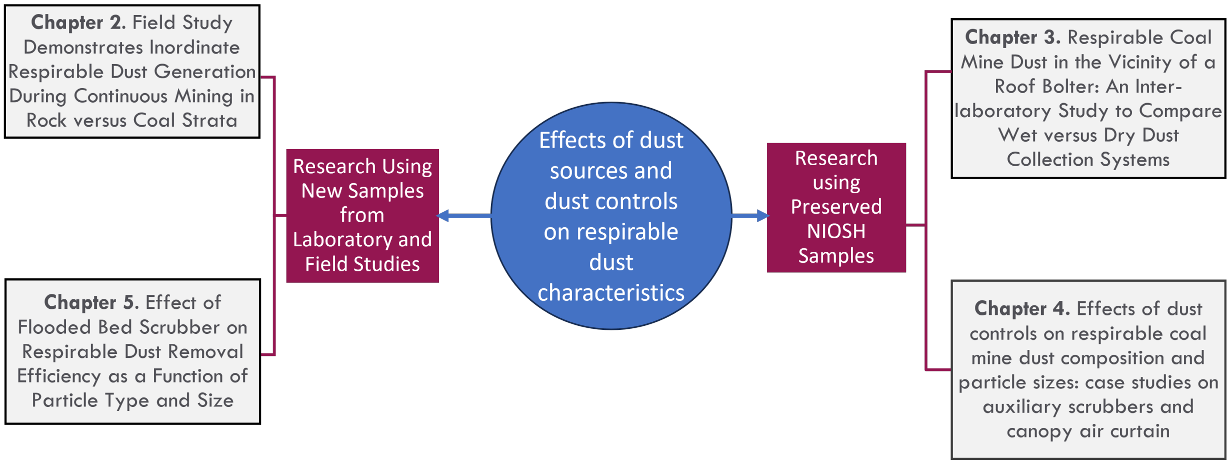

Figure 1.11: Summary of tasks in the dissertation.

Below is a summary of research work done under the other chapters:

Chapter 2 was a field study conducted in a room and pillar underground coal mine in central Appalachia to demonstrate the inordinate respirable dust generated during continuous mining in rock versus coal strata. The research work in this chapter relates to research question 1, which sought to understand how respirable dust generation and particle characteristics vary between typical mining in primary dust sources. The study evaluated the respirable dust concentrations and characteristics generated when the CM machine was primarily cutting into the coal strata and then primarily into the rock strata. The effects of different CM scrubber and ventilation conditions, and then increased CM spray water spray pressure and volume conditions on dust from coal versus rock strata was also be evaluated.

Chapter 3 presents an inter-laboratory study that evaluates the respirable coal mine dust in the vicinity of a roof bolter. This study relates to research question 2, which sought to evaluate the effect of dust controls on RCMD characteristics. The study included the collection of preserved samples relating to an original study conducted by NIOSH researchers to compare and evaluate the performance of a novel wet dust collection system versus a traditional dust collection box on a roof bolter. The available preserved samples (including one sample from each pair) were split into half and made available to the Virginia Tech and Michigan Tech laboratories. The study under this chapter analyzed these preserved samples to evaluate and understand the respirable dust characteristics generated around the vicinity of the operating roof bolter machine when either of the dust collection boxes were employed. Dust characterization results between three laboratories (i.e., NIOSH, Michigan Tech, and Virginia Tech labs) were compared, and this has never been done in any study.

Chapter 4 presents a study on the effects of dust controls on respirable coal mine dust composition and particle sizes: Case studies on auxiliary scrubbers and canopy air curtain. NIOSH has led research to test and evaluate the feasibility of implementing various dust controls in underground coal mines. These studies were promising as the dust controls tested showed good potential to reduce the respirable dust exposure of miners. Preserved samples from these dust control studies already conducted by NIOSH were made available for a follow up study. In order to answer the specific research question (i.e., research question 2) on how dust controls affect dust characteristics, these samples were suitable for executing this kind of task. Therefore, the research in this study involved the analysis of preserved samples from different dust control studies on an in-line wet auxiliary scrubber, dry auxiliary scrubber, and canopy air curtain to evaluate how they affected specific dust constituents and particle sizes.

Chapter 5 investigates the effect of flooded bed Scrubber (FBS) on respirable dust removal efficiency as a function of particle type and size and seeks to answer research question 2. Laboratory testing was conducted in the NIOSH Pittsburgh Mining Research Division (PMRD) dust gallery on a prototype FBS to evaluate its removal efficiency under controlled conditions as follows: three dust types (real coal, real rock, and a 50:50 blend of coal and rock, obtained from a partner mine and sieved through a 270 mesh), and two filter screen types run at different airflows (conventional 30-layer filter screen at 6000 CFM, impingement screen at 4000 CFM, and conventional 30-layer screen at 4000 CFM). During each test, a different material type (or mix of materials) was fed into the experimental apparatus (built and operated by PMRD) fitted with one of the scrubber filter types. The data from each test was evaluated to determine the particle counts per size bin by number, mineralogy distribution per size bin of each dust material type, the number removal efficiency per particle size bin, and the mass removal efficiency. These results revealed the scrubber efficiency in different particle sizes ranging from 0.3-10 µm.

Chapter 6 summarizes the major findings in the four research studies conducted, and briefly explains the implications of these studies on dust exposures of miners. This chapter also provided some recommendations for future work that could further expand and improve the research studies conducted here.

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Chapter 2

Field Study Demonstrates Inordinate Respirable Dust Generation During Continuous Mining in Rock versus Coal Strata[1]

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2.1 Abstract

In modern room and pillar coal mines, the coal is produced by continuous miner (CM) machines. The CM is used to mine the coal seam by continuously cutting at a vertical face. Depending on the seam thickness, quality and geotechnical properties, some roof, floor or interburden rock is often cut along with the coal. While CMs can be highly efficient

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in terms of production rates, they can also generate high concentrations of dust. Dust poses both safety (i.e., explosibility) and respiratory health hazards. Previous research has generally indicated that CM cutting in rock yields much more respirable dust than cutting in coal. Although in-mine studies have not been reported which directly evaluate this trend, understanding of relative dust generation from different geologic strata could have important implications. In many mines, for instance, the rock is the primary source of respirable silica and silicates, which can be especially hazardous. To mitigate dust generated by the CM, mines use a variety of controls including ventilation, on-board scrubber systems, and water sprays. However, the relative effects of controls on dust generated from different strata have also not been widely investigated. In this field study, respirable dust sampling was conducted in the intake and return airways of an active CM during periods when the cutting was targeted either primarily at the coal seam (bottom cut) or primarily at the roof rock (top cut) in a standard entry. Results indicated that CM cutting in rock strata generated somewhat finer particles and respirable dust concentrations that were 2.1-26× higher than cutting in coal strata, despite the fact that the coal height being cut was about 2.2-2.9× greater than the rock height—though analysis of dust mineralogy generally showed a mix of both carbonaceous (coal) and mineral particles regardless of the target strata. Additionally, the study was designed to evaluate the effects of two typical combinations of CM scrubber and ventilation conditions, and increased pressure and volume through the CM water sprays. In general, operation of the scrubber tended to yield lower and somewhat finer respirable dust concentrations, irrespective of the strata the CM was targeting. Increased water spray pressure and volume sometimes appeared to reduce the respirable dust concentration when the CM was targeting the roof rock; but no effect could be discerned when the CM was targeting the coal seam.

Keywords: Respirable coal mine dust, respirable silica, dust control, dust scrubber, water

sprays

2.2 Introduction

Room and pillar mining is one of the most common methods used to produce coal in underground operations. In modern operations, continuous miner machines (CMs) are typically used to cut the coal at a vertical face, advancing a grid of entries (i.e., rooms) and cross-cuts between them, and leaving pillars in place as roof support [1]. CMs are a major source of dust in underground coal mines [2, 3]. The respirable fraction of the dust presents a health hazard, especially if it contains respirable crystalline silica (RCS) [4, 5, 6, 7, 8, 9]. Due to the quality and geotechnical properties of the coal seam and surrounding rock strata, and considerations of equipment sizes and ergonomics, some rock (roof, floor or interburden) is often cut along with the coal. In many mines, the rock strata is the primary source of silica [10, 11] and therefore mines cutting substantial rock are more prone to high RCS concentrations [12]. Moreover, there is at least some evidence that RCS is more concentrated in the finer size fractions of dust generated from cutting rock [13, 14], which could further impact the relative health hazard.

Moreover, prior studies by the authors' research group have indicated that CM cutting into rock strata generates substantially more respirable dust than CM cutting into the coal seam itself [15, 16]. Using data from 18 different mines, Jaramillo et al. [15] conducted a simple source apportionment exercise based on a comparison of the composition of respirable dust samples collected just downwind an active CM and the composition of the raw coal and rock strata materials being cut by the CM at the face; on average, while the rock strata represented 37% of the total mining height (i.e., the other 63% of the height was in coal), it contributed 71% of the respirable dust generated by the CM. However, field studies have not been reported which enable direct evaluation of the concentration and characteristics of respirable dust generated from rock versus coal strata.

Likewise, there is limited data surrounding the effects of specific controls on dust sourced from different strata. In CM operations, there are typically three main types of controls used to mitigate dust around the production face. Ventilation is the most ubiquitous of these [17]. At the CM face, either blowing or exhausting ventilation schemes often involve the use of line curtain to efficiently direct dust (and liberated gas) toward the return air course, and prevent recirculation back into the intake where workers are positioned [18, 19]. In some cases, ventilation tubing is also used for additional dust control in CM sections [20].

CM machine-mounted flooded-bed scrubbers (FBS) are a second type of control, and they serve to capture dust generated at the production face [19]. FBSs operate by drawing dust-laden air through a wet filter screen, which removes some particles outright; and causes others to be taken up by water droplets that can then be captured in a demister before the cleaned air exits via the scrubber exhaust [3, 19, 21]. Several studies have looked at the relative efficiency of FBSs on particles of different sizes and types. A study by Animah et al. [22, 23] generally found that scrubber efficiency is size dependent, as scrubbers were more efficient on coarser dust. However, no appreciable differences could be observed in the removal efficiency by particle type. In a laboratory study, Colinet et al. [24] investigated scrubber efficiency on different particle types when using different filter screens. Results from the study showed that collection efficiencies were generally higher for respirable coal than respirable quartz dust. However, the effect of the scrubber on dust generated from specific strata have not been directly tested.

Water sprays are the third main type of dust control applied in CM operations. Sprays are typically mounted on the CM, with a variety of different nozzle designs and configurations devised to suppress, capture, and redirect dust [20, 25]. For example, sprays on the CM drum help to wet the face ahead of and during mining (dust suppression); sprays on the CM chassis and throat can capture airborne dust; and sprays on sides of the CM body can block dust movement toward the operator. Aside from these, some CMs (called 'wetheads') have water sprays built into the cutting bits on the shearer drum. The bit sprays are designed for cooling (i.e., to prevent sparking), but can also enhance dust suppression [26, 27, 28]. There have been numerous investigations into spray optimization for dust control, including the impact of increased water pressure and volume, but overall results have been mixed [29, 30, 31, 32, 33, 34, 35]. This might be due to variable field conditions, for instance, as related to CM operational parameters (e.g., power, drum rotational speed, bit wear) or the properties of the mine strata being cut by the CM—which could influence the concentrations, sizes and types of dust being generated. In general, it is well established that sprays are less effective on respirable dust (i.e., less than about 10 µm) than on coarser fractions [13, 17, 36], and the finest dust particles could even be re-aerosolized by the local turbulence induced by water sprays [32, 33].

To fill some of the knowledge gaps highlighted above, this field study was conducted to evaluate relative differences in respirable dust concentration and characteristics (particle size and mineralogy) generated from CM cutting in coal versus rock strata. This was achieved by modifying the normal practice for a full CM cut (i.e., wherein the CM cuts the entire height of the entry) to instead consist of two consecutive cuts, with the first targeting the coal seam (bottom cut) and second targeting the roof rock (top cut)—such that the dust generated from each cut could be sampled separately. The 'bottom, then top' cutting practice was repeated in a series of tests that also enabled evaluation of effects of (1) two typical FBS and ventilation conditions, and (2) increased pressure and volume through the CM water sprays.

2.3 Materials and Methods

2.3.1 Mine details

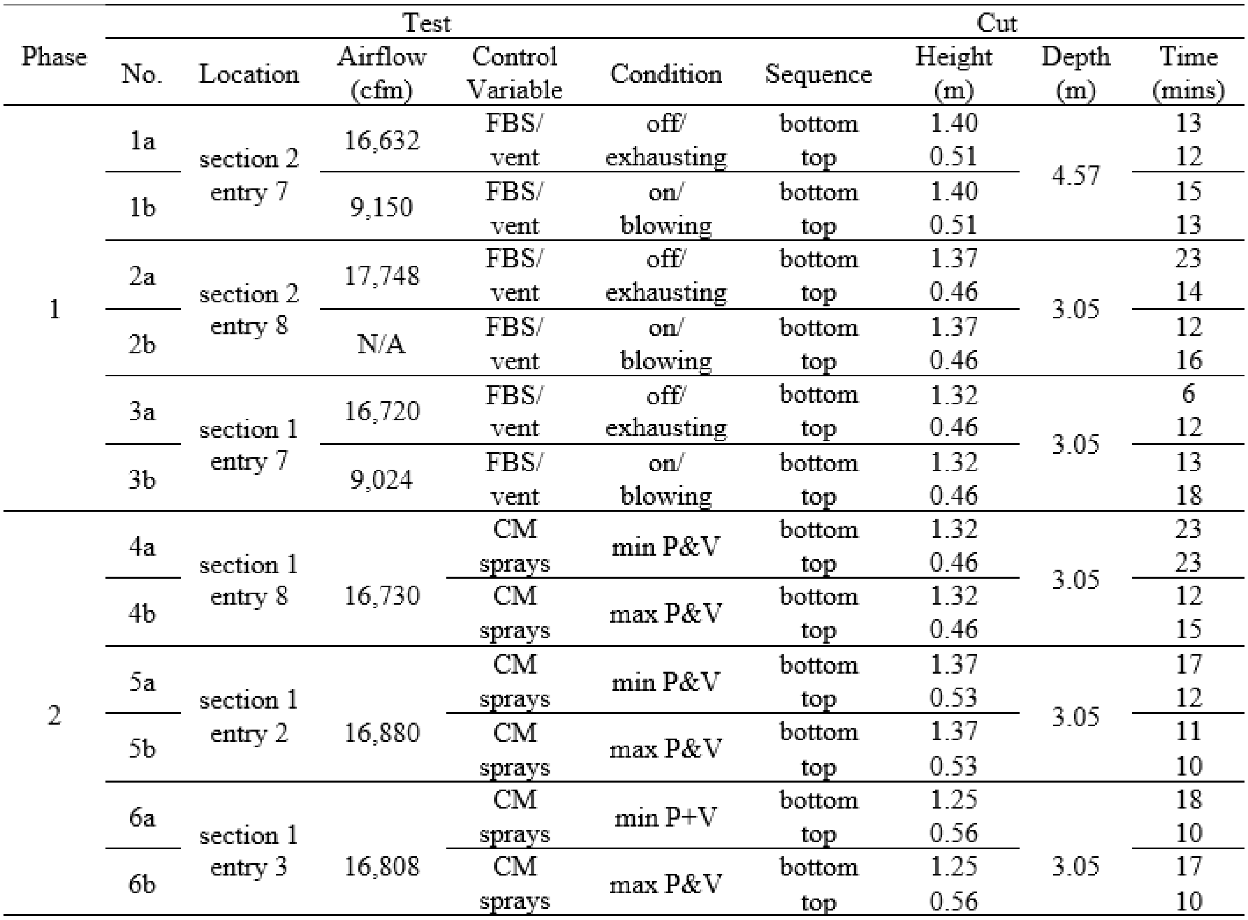
The study was conducted in an underground room and pillar mine in central Appalachia (termed 'Mine 27' from here). Mine 27 produces bituminous coal from the Pocahontas No. 3 seam in four separate sections. The average seam thickness across the entire mine is about 1.3 m and the total mining height is typically 1.8–2.0 m; rock in the mine usually consists of shale and sandy shale and is generally cut from the roof with limited extraction from the floor. For this study, sampling was only conducted in Sections 1 and 2, which are both 9-entry super sections. On each side of a super section, the mine runs a CM, twin-boom roof bolter and two shuttle cars. Sampling was conducted on non-production shifts, and there was no bolting upwind the CM. Ventilation in each section is split in the 9 entries with the intakes in the central entries and returns at the last two left and right entries. At the time of sampling, Mine 27's approved ventilation plan called for exhausting ventilation with line curtain and *without* the FBS operating for flush cuts (i.e., shallow depth into the heading); and for standard cuts (i.e., further into the heading), the plan called for blowing ventilation with line curtain and the FBS operating. All CMs at Mine 27 are equipped with a FBS and CM-body and drum water sprays, and most CMs (including those operated for this study) have wetheads. The mine's ventilation plan specifies a minimum spray pressure and volume that must be used for both the bit sprays and all other sprays.

2.3.2 Dust Sampling

In total, six different tests were conducted, with each test including 'bottom, then top' cuts under two different FBS or water spray conditions (Table 2.1). Figure 2.1 shows the relative heights for the bottom versus the top cut in each test. As mentioned, the CM operator targeted the coal seam for the bottom cut and the typical extent of roof rock extraction for the top cut. As shown, measurable bottom rock was cut with the coal in tests 3-6 (which is common in Mine 27); and a limited amount of bottom rock may have also been taken in tests 1 and 2. The separation between the bottom and top cuts was based on the visual interface between the coal and roof rock, and also the CM operator's experience in the 'feel' of the two strata (i.e., the rock is generally harder and more resistant to cutting). However, it must be acknowledged that the interface is imperfect, and the sheer size and maneuverability of the CM drum also limits the ability for precision cutting. Notably, for this study, the same operator performed all CM cuts, and he was highly experienced.

Per Table 2.1, the first three tests were considered Phase 1 and were aimed at evaluating the dust generated from each stratum (coal or rock) under typical FBS and ventilation conditions specified for flush cuts (i.e., FBS off, exhausting ventilation) versus the conditions specified for standard cuts (i.e., FBS on, blowing ventilation). The Phase 1 tests always started with the CM cutting a flush heading, such that the entire test could be conducted within a single entry (i.e., to minimize variation in the strata heights and composition). During the Phase 1 tests, all CM sprays were operated with the minimum water pressure and volume specified in the mine's ventilation plan. The final three tests were considered Phase 2 and were aimed at evaluating the effect of the CM's water spray pressure and volume under typical condition (i.e., at the minimum levels specified in the ventilation plan) versus maximum achievable pressure and volume (Table 2.2). All tests in Phase 2 were conducted under FBS and Exhausting ventilation conditions. Before each test (and for each ventilation condition in Phase 1 tests), the airflow across the CM was estimated (i.e., based on measured velocity and airway dimensions).

Table 2.1: Summary of tests conditions in Phase 1 and Phase 2 tests.



Phase	Test						Cut		
	No.	Location	Airflow (cfm)	Control Variable	Condition	Sequence	Height (m)	Depth (m)	Time (mins)
1	1a	section 2 entry 7	16,632	FBS/ vent	off/ exhausting	bottom	1.40	4.57	13
						top	0.51		12
	1b		9,150	FBS/ vent	on/ blowing	bottom	1.40		15
						top	0.51		13
	2a	section 2 entry 8	17,748	FBS/ vent	off/ exhausting	bottom	1.37	3.05	23
						top	0.46		14
	2b		N/A	FBS/ vent	on/ blowing	bottom	1.37		12
						top	0.46		16
	3a	section 1 entry 7	16,720	FBS/ vent	off/ exhausting	bottom	1.32	3.05	6
						top	0.46		12
	3b		9,024	FBS/ vent	on/ blowing	bottom	1.32		13
						top	0.46		18
2	4a	section 1 entry 8	16,730	CM sprays	min P&V	bottom	1.32	3.05	23
						top	0.46		23
	4b			CM sprays	max P&V	bottom	1.32		12
						top	0.46		15
	5a	section 1 entry 2	16,880	CM sprays	min P&V	bottom	1.37	3.05	17
						top	0.53		12
	5b			CM sprays	max P&V	bottom	1.37		11
						top	0.53		10
	6a	section 1 entry 3		CM sprays	min P+V	bottom	1.25		18
						top	0.56		10
	6b		16,808	CM sprays	max P&V	bottom	1.25	3.05	17
						top	0.56		10

Note: ‘on’ means when the CM scrubber was operating and ‘off’ means when the CM scrubber was not operating. ‘min P+V’ means when CM sprays were operating at standard pressure and volume of water conditions, and ‘max P+V’ means when the CM sprays were operating at the maximum pressure and volume of water.

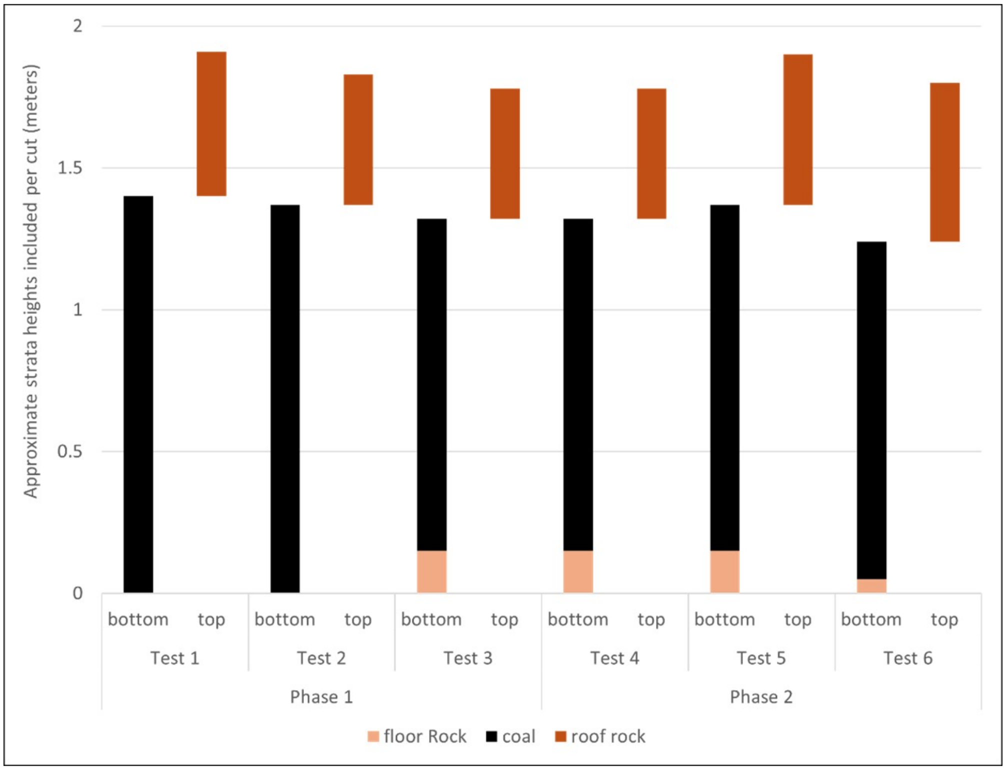
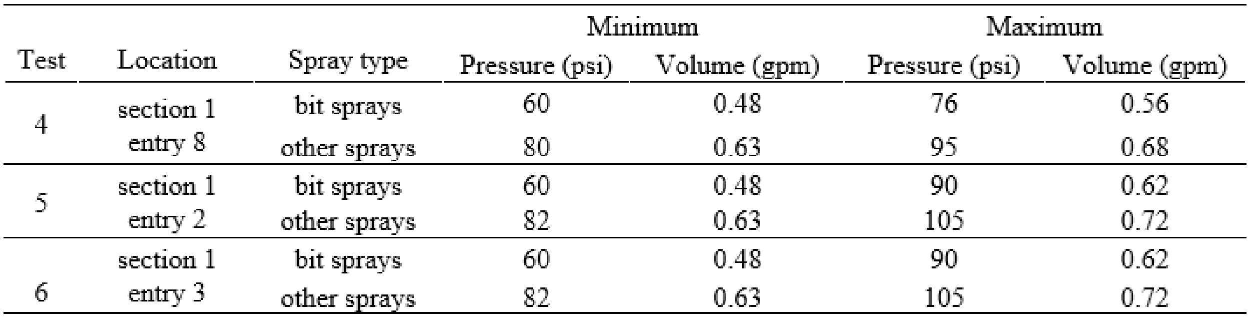


Figure 2.1: Approximate strata heights included in the bottom and top cuts during each test. The sum of the bottom and top cut heights is the total mining height in the entry.

Table 2.2: Summary of the CM spray pressure and volume for Phase 2 testing.



Test	Location	Spray type	Minimum		Maximum	
			Pressure (psi)	Volume (gpm)	Pressure (psi)	Volume (gpm)
4	section 1	bit sprays	60	0.48	76	0.56
	entry 8	other sprays	80	0.63	95	0.68
5	section 1	bit sprays	60	0.48	90	0.62
	entry 2	other sprays	82	0.63	105	0.72
6	section 1	bit sprays	60	0.48	90	0.62
	entry 3	other sprays	82	0.63	105	0.72

Sampling was conducted during each of the 24 total cuts shown in Table 2.1. For each cut, samples were collected in the CM intake and return (Figure 2.2) over the entire cutting time. In both locations, standard Coal Mine Personal Dust Sampling Units (CMPDSUs) were used to collect sets of filter samples. Each CMDPSU consisted of 10-mm Dorr Oliver nylon cyclone and an Escort ELF air pump operating at 2 L/min. (Zefon International, Ocala, FL) to collect just the respirable fraction of airborne dust directly onto a 37-mm filter housed in a 2-piece cassette. Each set of samples included three polycarbonate filters (PC, track-etched, 0.4 µm pore size). These were analyzed by scanning electron microscope to characterize particle size and mineralogy distributions (see below).

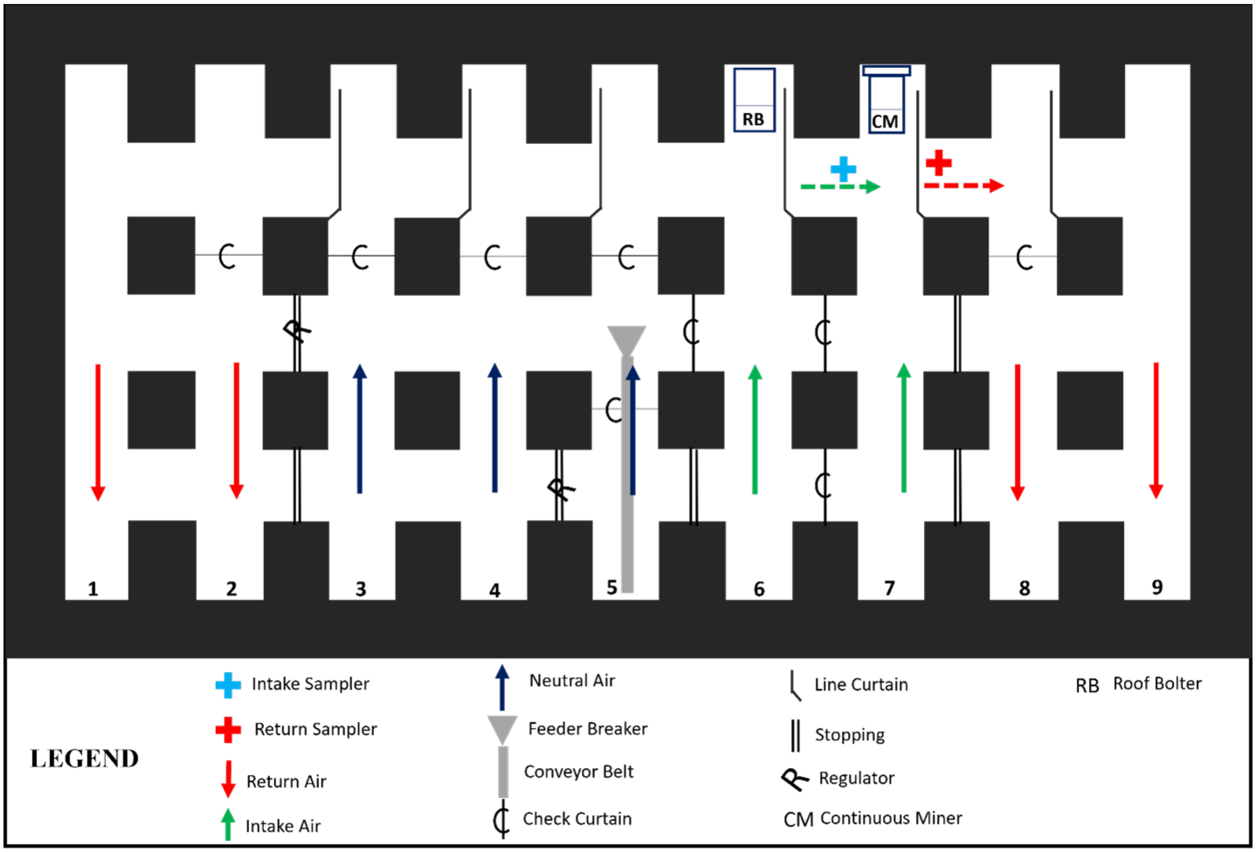


Figure 2.2: Schematic of ventilation and some select sampling locations in Mine 27.

While mass concentrations of respirable dust can also be measured with CMDPSU sampling, this requires collection of sufficient sample mass for gravimetric analysis. The sampling design here was not conducive to this approach given the relatively short cut times (i.e., typically between 10-20 minutes). Thus, an alternative approach was taken: In both the CM intake and return locations, an additional CMDPSU was paired with a Personal data RAM (pDR-1000; Thermo Fisher, Waltham, MA), and these two samplers were run for relatively long total sampling periods (i.e., about 5 hours on each day of the study). The CMDPSU collected dust onto a pre-weighed polyvinyl chloride filter (PVC, 5 m pore size), which was used for gravimetric analysis to determine the time-weighted average (TWA) mass concentration of dust for the entire sampling period (see below). The pDR was used to log time series data (on a 30-s interval) on particle concentrations in the respirable size range, which can be calibrated to mass concentration based on the TWA concentration derived the CMDPSU filter sample. This enabled mass concentrations to be determined for the intake and return locations during the time increments corresponding to each individual CM cut.

2.3.3 Dust Analysis

Figure 2.3 summarizes the dust analysis for this study. To determine respirable dust mass concentration in the CM intake and return locations for each cut, the pDR data from the respective location and sampling time increment was interpreted. Briefly, the PVC filter samples collected alongside each pDR were post-weighed using the same microbalance used to measure filter pre-weights (Sartorius MSE6.6S, Gottingen, Germany), and then the TWA respirable dust mass concentration for each filter (C_{filter}) was calculated by Equation 2.1:

$$C_{filter}(mg/m^3) = \frac{W_2 - W_1}{t \times f} * 1000 \tag{2.1}$$

where W_1 and W_2 are the PVC filter pre- and post-weight, respectively; t is the total PVC filter sampling duration; and f is the sampling flow rate.

Then, the ratio of filter sample TWA respirable dust mass concentration to pDR TWA particle concentration was determined as a calibration factor (R) for each pDR data set per Equation 2.2:

$$R = \frac{C_{filter}}{C_{pDR}} \tag{2.2}$$

where R is the calibration factor; and C_{pDR} is the TWA particle concentration measured by the specific pDR unit paired with filter sample from which C_{filter} was determined.

The calibration factor was applied to each pDR dataset to transform the time series particle concentration values to respirable dust mass concentration values. Finally, the concentration values corresponding to the time increment for each specific cut were averaged to estimate TWA respirable dust mass concentration for that cut.

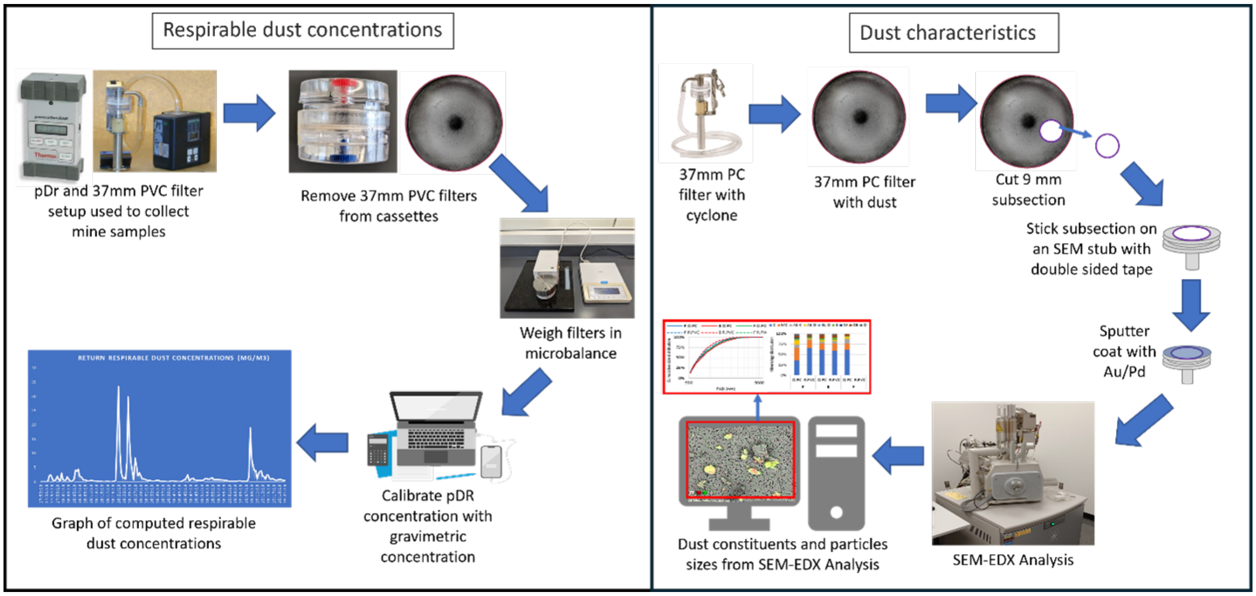


Figure 2.3: An illustration of the procedure used to obtain respirable dust concentrations and dust characteristics from collected samples in the study.

To estimate the particle size and mineralogy distributions of the respirable dust, one PC filter sample collected in the CM return location during each cut was analyzed by scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM-EDX). (Notably, while PC filters were also collected in the intake location, these generally did not have sufficient particle loading for analysis due to the short sampling times. The particle loading density for PC filter samples analyzed in the CM return location ranged from 0.0007-0.0154/μm^2.) The sample preparation and analytical procedure has been previously described in detail. Briefly, a stainless-steel trephine was used to take a 9-mm subsection of each PC filter selected for analysis. The subsection was mounted on an aluminum stub, and sputter coated with Au/Pd to render it conductive. The SEM-EDX analysis was conducted using a FEI Quanta 600 FEG Environmental SEM (Hillsboro, OR, USA) equipped with a backscatter electron detector and a Bruker Quantax 400 EDX spectroscope (Ewing, NJ, USA). Bruker's Espirit software was used to run computer-controlled routine (originally developed by Johann-Essex et al. [37]) to identify and characterize supra-micron particles (length between about 1-10 µm). The routine uses image contrast to identify particles, and then it automatically collects size (length and width) and EDX data from each particle. The routine was run at 1,000× magnification and proceeded through a series of pre-programmed field locations; up to 50 particles were analyzed per field and the routine proceeded until at least 500 particles had been analyzed.

Particle size distributions on each sample were determined on the basis of projected area diameter (PAD, which is effectively the average of particle length and width). To describe mineralogy, the EDX data was used to classify each particle per the criteria published by Sarver et al. [16]. The criteria are based on normalized atomic percentages of eight elements (carbon, oxygen, silicon, aluminum, calcium, magnesium, iron, and titanium), and were used to bin particles into one of the following classes: carbonaceous (C), mixed carbonaceous (MC), silica (S), silicates (including aluminum silicates, AS, and other silicates, SLO), carbonates (CB) and heavy minerals (HM). Particles that did not fit one of these classes were binned as “others” (O). In general, C and MC particles are typically interpreted as coal dust. In many mines, the CB particles are likely sourced from application of inert rock dusting products; and the geologic strata in Mine 27 (coal or rock) was not known to have substantial carbonate content. Other predominant minerals, including silica and silicates, are generally associated with the rock strata.

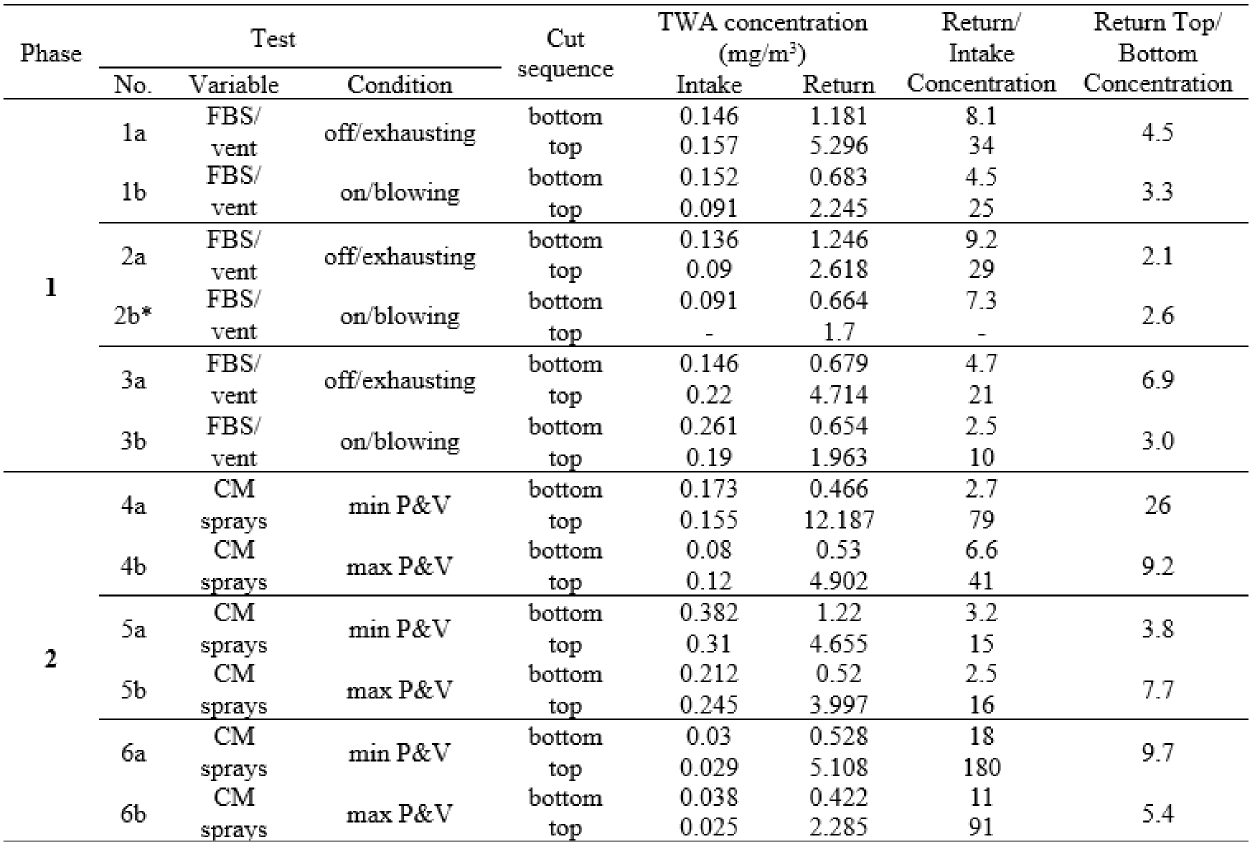
2.4 Results and Discussion

2.4.1 Respirable Dust Concentrations

Table 2.3 summarizes the TWA respirable dust concentrations for both the Phase 1 and Phase 2 tests. As expected, concentrations were consistently higher in the CM return than in the intake location. Comparing the results for each specific cut, the return concentration was between 2.5–180× higher than the intake concentration.

Based on the CM return sampling, the data in Table 4 shows the top cuts generated respirable dust concentrations that were 2.1–26× higher than their respective bottom cut; and a paired t-test showed the difference was significant at 95% confidence (i.e., P=0.0013, assuming unequal variance and two-tailed distribution). As reviewed above, previous research has suggested that CM cutting in rock should generate substantially more respirable dust than cutting in coal [15, 16, 38, 39]. However, the novel ‘bottom, then top cut’ experimental design in the current study enables a direct demonstration of this trend. In Table 4, there are six top and bottom cut pairs having the same dust control conditions—i.e., Tests 1a, 2a, 3a and 4a, 5a, 6a were conducted with the FBS off and exhausting ventilation, and with minimum required water spray pressure and volume. For these cut pairs, the ratio of top cut to bottom cut dust concentration was observed to be higher during Phase 2 (3.8–26×) than Phase 1 (2.1–6.9×). This might simply be due to the specific geology encountered in the different entries where the CM was operating during this study.

Table 2.3: TWA respirable dust concentrations for Phase 1 and Phase 2 tests.



Phase	Test			Cut sequence	TWA concentration (mg/m^3)		Return/ Intake Concentration	Return Top/ Bottom Concentration
	No.	Variable	Condition		Intake	Return		
1	1a	FBS/ vent	off/exhausting	bottom	0.146	1.181	8.1	4.5
				top	0.157	5.296	34	
	1b	FBS/ vent	on/blowing	bottom	0.152	0.683	4.5	3.3
				top	0.091	2.245	25	
	2a	FBS/ vent	off/exhausting	bottom	0.136	1.246	9.2	2.1
				top	0.09	2.618	29	
	2b*	FBS/ vent	on/blowing	bottom	0.091	0.664	7.3	2.6
				top	-	1.7	-	
	3a	FBS/ vent	off/exhausting	bottom	0.146	0.679	4.7	6.9
				top	0.22	4.714	21	
	3b	FBS/ vent	on/blowing	bottom	0.261	0.654	2.5	3.0
				top	0.19	1.963	10	
2	4a	CM sprays	min P&V	bottom	0.173	0.466	2.7	26
				top	0.155	12.187	79	
	4b	CM sprays	max P&V	bottom	0.08	0.53	6.6	9.2
				top	0.12	4.902	41	
	5a	CM sprays	min P&V	bottom	0.382	1.22	3.2	3.8
				top	0.31	4.655	15	
	5b	CM sprays	max P&V	bottom	0.212	0.52	2.5	7.7
				top	0.245	3.997	16	
	6a	CM sprays	min P&V	bottom	0.03	0.528	18	9.7
				top	0.029	5.108	180	
	6b	CM sprays	max P&V	bottom	0.038	0.422	11	5.4
				top	0.025	2.285	91	

*Intake TWA concentration during top cuts in test 2b was not recorded because the pDr inadvertently switched off.

With respect to the different dust control conditions tested, Table 2.3 shows that for both the bottom and top cuts the dust concentration in the CM return was always observed to be lower during the FBS on and blowing ventilation conditions (Tests 1b, 2b, 3b) than during the FBS off and exhausting ventilation conditions (Tests 1a, 2a, 3a). Across all three tests, this amounted to a mean reduction in dust concentration of about 31% for the bottom cuts and about 50% for the top cuts. However, based on paired t-tests, these differences were not statistically significant at 95% confidence (i.e., P=0.17 for bottom cuts, P=0.08 for top cuts) which is attributed to the relatively small number of tests conducted for this study (i.e., n=3 for each cut by dust control condition). Nevertheless, the observed trends align very well with findings by Xu et al. [17] which indicated that use of FBS on and blowing ventilation led to a 13-40% reduction in respirable dust versus FBS off and exhausting ventilation. Moreover, numerous other studies have shown that FBSs generally reduce respirable dust concentrations around the CM [2, 22, 23, 24, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49]. The relatively higher reduction in dust concentrations observed for the top versus bottom cuts with the FBS on and blowing ventilation might simply be related to the relatively large difference in dust concentrations generated from the top versus bottom cuts (i.e., the FBS may be more efficient when dust concentration moving through the system is higher). Additionally, there may be effects of specific particle characteristics or flow conditions. (It is noted that, while standard CMDPSU samplers were used in this field study to mimic typical respirable dust sampling procedures, isokinetic sampling would allow truer comparisons between tests where airflow varies substantially.)

Regarding the effect of water spray pressure and volume, Table 2.3 shows that dust concentrations in the CM return were typically lower with maximum pressure and volume (Tests 4b, 5b, 6b) versus the minimum required pressure and volume (Tests 4a, 5a, 6a). The mean reduction was 21% for bottom cuts and 43% for top cuts. However, paired t-tests did not indicate statistically significant differences at 95% confidence (i.e., P=0.40 for bottom cuts, P=0.21 for top cuts). Notably, during the bottom cut in Test 5a, it was observed that limiting the CM cutting at the coal-roof rock interface was more challenging than in other tests, and the CM was often cutting somewhat above the visual interface. This may explain the somewhat higher dust concentration associated with the bottom cut, and somewhat lower concentration associated with the top cut, in Test 5a (versus Tests 4a and 6a). As noted above, prior studies on the impact of increased spray pressure and volume have yielded inconsistent results [29, 30, 31, 32, 33, 34, 35]. In practice, however, this strategy is often considered when additional dust control is needed at the CM face. The results from the current study suggest that, under the conditions present in Mine 27, increasing the spray pressure and volume could indeed help to further reduce respirable dust concentration downwind the CM—and the greatest effect could be on the dust generated from the roof rock. While the mechanisms of (e.g., material wetting versus particle capture) and key factors contributing to this enhanced dust control (e.g., spray orientation) are outside the scope of the current work, they are deserving of additional study.

2.4.2 Particle Size and Mineralogy

Figure 2.4 summarizes the particle size data derived from the SEM-EDX analysis on PC filter samples collected in the return location during each CM cut. The plots show cumulative size distribution based on projected area diameter. In general, the dust generated from the top cuts was observed to be somewhat finer than dust generated from the bottom cuts. This is consistent with expectations from a few prior studies [13, 14], and is likely related to differences in material hardness between the roof rock targeted by the top cuts and the coal that made up most of the bottom cuts. It is notable that very little difference in particle size distribution is seen for Test 5; this could be related to the tendency of the CM cutting to cross further into the roof rock strata during the bottom cuts for this test, and also fits with the observation of minimal change in the dust concentration generated from the top cut when the spray condition was changed for this test (Table 2.3).

For the Phase 1 tests, the FBS and ventilation conditions may have had some effect on the particle size distribution. Comparing the bottom cuts in Test 2 and the top and bottom cuts in Test 3, dust was generally finer under the FBS on and blowing ventilation conditions than under FBS off and exhausting ventilation conditions; a similar but less substantial effect is also evident for the top cuts in Test 1. This is consistent with results of prior results indicating that FBSs have higher removal efficiency for relatively coarse particles [22, 23]. In Phase 2, however, no consistent trends in particle size are apparent with the increase in CM spray pressure and volume.

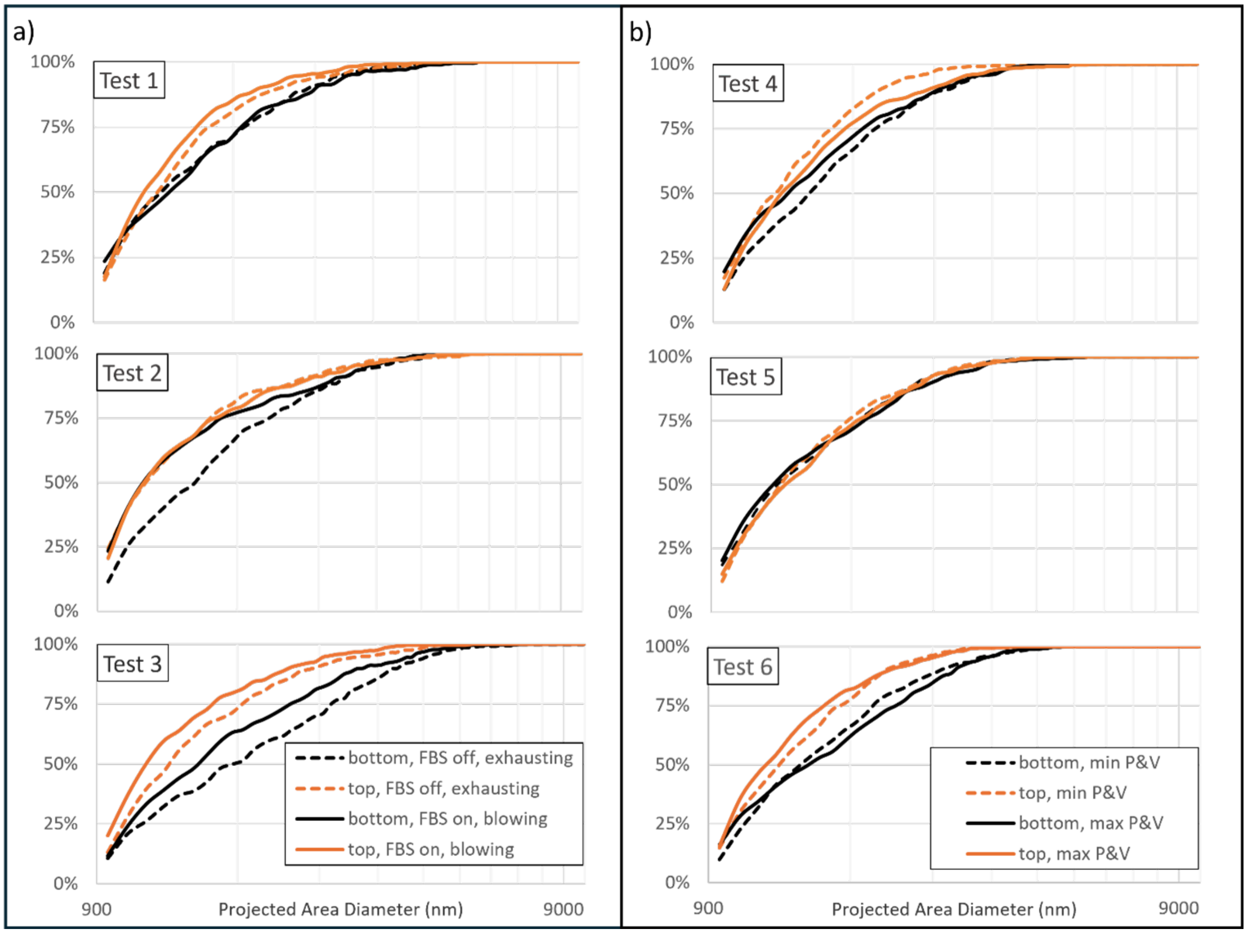


Figure 2.4: Respirable dust particle size distributions based on SEM-EDX analysis for (a) Phase 1 and (b) Phase 2 tests. The plots show the cumulative number percentage of particles that are finer than a given size.

Based on the SEM-EDX analysis of PC filter samples collected in the return location during each CM cut, Figure 2.5 presents the distribution of respirable dust particles by primary mineralogy classes. The plots show the mineralogy distribution based on particle number. Notably, the carbonaceous particles were observed to be somewhat finer than mineral particles (data not shown); so, if the results in Figure 2.5 were used to estimate mineralogy distributions on the basis of mass, carbonaceous content would appear somewhat lower whereas mineral contents would appear somewhat higher. The minimal abundance of carbonate particles suggests that rock dusting products were not a primary source of respirable dust in the CM return sampling location during this study.

Figure 2.5 shows that respirable dust generated from bottom cuts generally included more carbonaceous particles whereas dust generated from top cuts included more mineral particles. (Test 2 is a notable exception.) Overall, however, the dust composition was considerably mixed for most cuts—despite the targeted “bottom, then top” cut sequence used for this study. Mixed dust is not completely unexpected since the coal and roof rock strata should undoubtedly have impurities [15], and the interface between these strata is imperfect—and could be thought of more as a transition zone. As mentioned, in Test 5a, the CM was observed to cut somewhat above the visual interface between the coal and roof rock during the bottom cut; and indeed, the relative abundance of mineral particles from this bottom cut was the highest of all bottom cuts in the Phase 2 tests. Additionally, it should be reiterated that some floor rock was taken with the coal during many of the bottom cuts (per Figure 2.1). Nevertheless, these results clearly demonstrate that, even when CM cutting is aimed primarily at the coal seam, the respirable dust produced can contain substantial mineral content—including silica.

Figure 2.5 reveals no consistent effects of changing CM spray pressure and volume on the respirable dust composition. For the FBS and ventilation conditions, the results are nuanced.

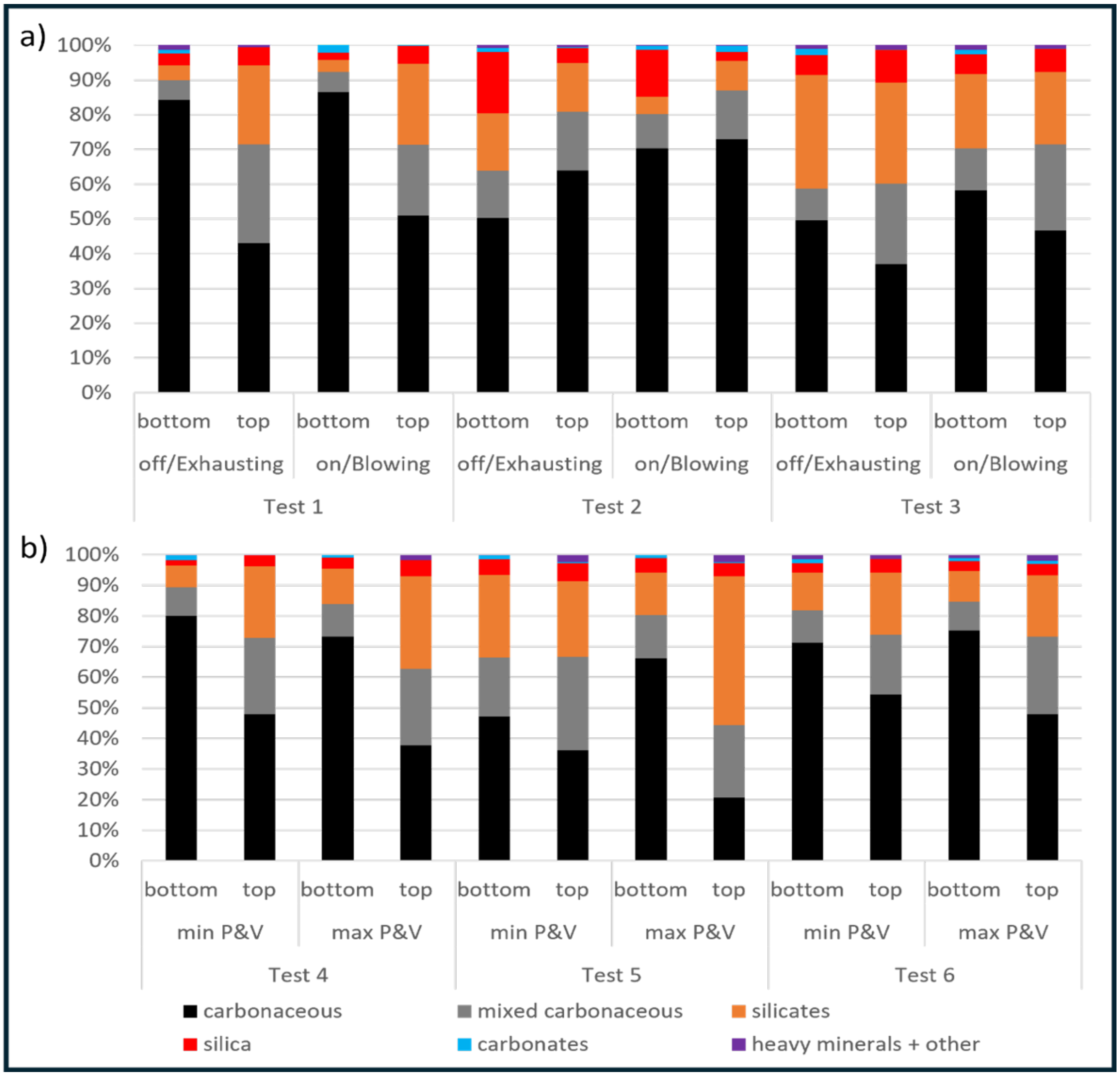


Figure 2.5: Mineralogy distribution of respirable dust particles by number percentage based on SEM-EDX analysis for a) Phase 1 and b) Phase 2 tests.

Dust sampled in the CM return under FBS on and blowing ventilation (versus FBS off and exhausting ventilation) exhibited a lower relative ratio of mineral to carbonaceous particles for Tests 2 and 3. However, this trend is not observed for Test 1, for which the dust particle size and mineralogy distributions appear similar between bottom or top cuts regardless of the FBS and ventilation condition. While field data on the relative effects of FBSs on different dust constituents is scarce, early laboratory studies by Colinet et al. [24] suggested that FBSs may be more efficient for reduction of coal dust versus silica. At least under the conditions tested in Mine 27, no such effect is evident here. Rather, the samples collected while the FBS was operating (Tests 1b, 2b, 3b) generally had slightly less silica (by both number and mass percentage) than their paired samples while the FBS was not operating (Tests 1a, 2a, 3a). However, paired t-tests indicate that the difference is not significant at 95% confidence for either bottom cuts (P=0.32 or P=0.80 based on number or mass percentage, respectively) or the top cuts (P=0.23 or P=0.13 based on number or mass percentage, respectively).

2.5 Study Implications and Conclusions

Previous studies by the authors research team have concluded that CM cutting into rock strata can generate an inordinate amount of respirable dust compared to cutting in coal [15, 16, 38, 39]. However, those studies relied on dust samples that represented the entire mining height in a typical entry, including both the target coal seam and any roof, floor or interburden rock that would normally be cut at the production face. The novel “bottom, then top” CM cutting sequence employed for the current study enables more direct insights regarding the concentration and characteristics of dust generated from rock versus coal strata. Results clearly show that CM cutting in rock generates much more respirable dust. As mentioned, top cuts (mostly in roof rock) yielded dust concentrations that were 2.1-26×

higher than their respective bottom cuts (mostly in coal)—and these findings are even more remarkable considering the relative strata heights being cut. Here, the bottom cut heights were about 2.2-2.9× greater than the top cut heights, which translates to a similar difference in volume of material extracted between bottom and top cuts since the cut depth remained constant. If the results observed here are generalizable, this could mean that CM cutting in rock might generate 4.6-75× more respirable dust than cutting in coal on a unit-height basis.

The observed differences in particle size between respirable dust generated from top and bottom cuts may also have important implications. Particle size is well established as an important factor in terms of lung dust deposition, mobility, and reactivity [50, 51, 52, 53, 54, 55, 56, 57]. Moreover, observations of mixed dust composition—despite efforts to target primarily coal versus rock strata—are noteworthy. While cutting rock can obviously generate higher concentrations of respirable dust, even selective mining to stay within the coal seam can generate dust with substantial mineral content. Limiting respirable silica concentrations, in particular, has been and will continue to be a major focus in coal mines [58].

CM-mounted FBSs are a common piece of the overall dust control strategy in many room and pillar mines. The results presented here suggested that, under blowing ventilation conditions, FBSs can be particularly effective at reducing respirable dust concentrations associated with roof rock cutting. To enhance dust suppression, increased water spray pressure and volume has often been considered. For the CM sprays tested in Mine 27, results here suggest this approach may have some effect to reduce dust concentration—perhaps more so for dust generated from the roof rock. Especially for mines that have the capacity to increase spray pressures and volumes, or that could experiment with reoriented sprays to target dust coming from the roof strata, engineering studies to this effect may prove useful.

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Contributions

F. Animah: Conceptualization and design, material preparation, data collection and analysis, methodology, data visualization, writing-original draft, and addressing reviews and edits.
E. Sarver: Conceptualization and design, resources, writing-review and editing, supervision, and funding acquisition

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Chapter 3

Respirable Coal Mine Dust in the Vicinity of a Roof Bolter: An Inter-laboratory Study to Compare Wet versus Dry Dust Collection Systems[1]

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3.1 Abstract

Among underground coal miners, roof bolter operators are generally considered to have some of the highest risks for hazardous respirable dust exposure. This is because bolting requires drilling into roof strata that can often be a source of silica and silicate dust, which are associated with occupational lung diseases. However, little is known about the variability of dust characteristics (e.g., mineralogy constituents, particle size) in the vicinity of the bolter—or when specific dust controls are applied. As part of a prior NIOSH study, respirable dust samples were collected during several different events in standardized locations around an active roof bolter, and personal samples were also collected from the operator during the cleanout of the bolter's dust collection system when it was equipped with a novel wet dust box versus a traditional dry box. Those samples were made available for follow-up analysis by scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDX), as well as direct-on-filter Fourier Transform infrared spectroscopy (FTIR). Results showed variability in dust constituents and particle sizes at locations around the roof bolter, and indicated some event-to-event differences in dust sources. Additionally, compared to the dry dust box, the wet dust box appeared to reduce (by 41-82%) the relative silica and silicate content in the respirable dust to which the operator was exposed during cleanout. Further, an inter-laboratory comparison demonstrated the reproducibility of a standardized direct-on-filter FTIR method for estimating quartz mass (i.e., the predominant form of crystalline silica) in respirable coal mine dust samples. However, for constituent analysis by SEM-EDX, differences observed between results from two independent labs indicate that standardization of the analytical protocol is necessary to enable comparability of results.

Keywords: Roof bolter . Respirable dust . Dust collection box . SEM-EDX . Silica

3.2 Introduction

3.2.1 Background

Starting in the late 1990s, the prevalence of occupational lung disease among US coal miners began to rise precipitously, especially in central Appalachia, and rates remain high [1, 2, 3]. To fully explain this trend, significant attention has been drawn to the characteristics of respirable coal mine dust (RCMD) that may be responsible [4]. Properties such as the size and shape of particles, which impact lung deposition [5, 6, 7, 8], and their chemistry, which affects lung response and toxicity [9, 10, 11, 12], are important considerations for assessing RCMD exposure. Indeed, studies have suggested that certain dust constituents, especially fine silica and perhaps silicates, have played a key role in the resurgence of lung disease among US coal miners [13, 14]. Among the various occupations in underground coal mines, roof bolter operators are well known for having a relatively high exposure risk in regard to RCMD [15, 16]. Recent studies have shown that dust in the general vicinity of active roof bolting is often finer and contains higher concentrations of silica and silicate content than those in other locations of coal mines [17]. This is because dust in the roof bolter location is predominately sourced from the roof rock strata that sits above the target coal seam [18, 19].

Since roof bolting became standard practice in underground coal mines in the US, dust generated from drilling (i.e., necessary to install the bolt) has been recognized as a health hazard and addressed through the application of water and the use of dust collectors [20]. To reduce roof bolter operators' exposure to respirable dust, a dust collection system is typically used on the roof bolter. The system essentially uses a vacuum to draw dusty air at the rock-drill interface through the hollow drill steel and then a pre-cleaner cyclone. Coarse particles in the airstream are deposited onto the mine floor, while fine airborne particles are directed into a "box"; and air in the box is cleaned by a high-efficiency filter before exhausting back into the mine [21, 22]. Traditionally, this is a dry process—and while it is generally effective for capturing dust directly from the drilling process, roof bolter operators can still be exposed to an above-normal concentration of RCMD. Such exposures can happen during the periods when the dust collection system is operating less efficiently or when the roof bolter is working downwind of active mining (i.e., normally by the continuous miner).

Relatively high exposures can also happen inadvertently when the roof bolter operator is emptying the dust collection box [21, 23, 24]. Dust box cleanout typically involves opening the box and emptying the collected dust onto the mine floor, which can lead to a rapid re-aerosolization that results in a relatively brief but higher concentration of dust exposure. Results obtained from a previous study indicated that respirable dust levels during the box cleanout may be between 6 and 14 mg/m^3 [25]. One solution to this problem has been to use dust collector bags within the dust collection box [21]. This is analogous to the use of a vacuum cleaner bag within a rigid receptacle: when the bag is full, it can be removed without spilling the contents. While the dry-dust bag approach is simple and generally effective, there are several drawbacks including a) the periodic need to replace and handle it for disposal and b) the possibility that the bag can rupture. Goodman & Organiscak observed dust from the outside of the bags being reintroduced to the air stream when the bags were flexed during handling [25]. As an alternative approach to the dry dust collection system, a wet system has been considered [26, 27, 28].

3.2.2 Summary of NIOSH Study on Wet Dust Collection System for a Roof Bolter

For a recent case study published by Reed et al. [27], researchers at the National Institute of Occupational Safety and Health (NIOSH) partnered with Blue Mountain Energy's Deserado Mine to test a wet dust collection system on a JH Fletcher model CHDDR dual-boom roof bolter. The wet system was designed as a modification to a standard dry dust collection system. It maintained the use of the vacuum pump to pull dust from drilling, but eliminated the pre-cleaner; instead, all material was wetted by a nozzle spray as it entered the dust collection box and was then deposited as a sludge inside the dust box. A drain with a rotary valve was installed in the bottom of the box. When drilling was completed, the rotary valve was opened to allow the sludge to empty, depositing the sludge onto the mine floor. The box exhaust air was still filtered through the final filter.

For the Reed et al. [27] study, the sampling plan included pairs of respirable dust samples collected during four separate events (i.e., shifts) in six standardized locations (Figure 3.1). Two of the events corresponded to the use of the wet dust box on the roof bolter, and the other two corresponded to the use of the dry box. Five of the locations were sampled during active roof bolting: in the intake air upwind of the roof bolter; pre-cleaner for the left (P-left) and right (P-right) bolters on the machine; at the exhaust of the dust collection system; and in the return air coming off the bolter. For the particular roof bolter studied, the pre-cleaners and dust boxes for both booms were located on the right side of the machine; and the pre-cleaner sampling locations were placed at the dust box doors for the respective boom in an attempt to sample any dust emanating from the pre-cleaners. During testing of the wet box, the pre-cleaners were removed from the bolting machine, but the P-left and P-right samplers were placed in the same locations as for the dry box testing. The sixth location was on the vest of the roof bolter operator, and these samples were collected only during the time when the operator was cleaning out the dust collection system.

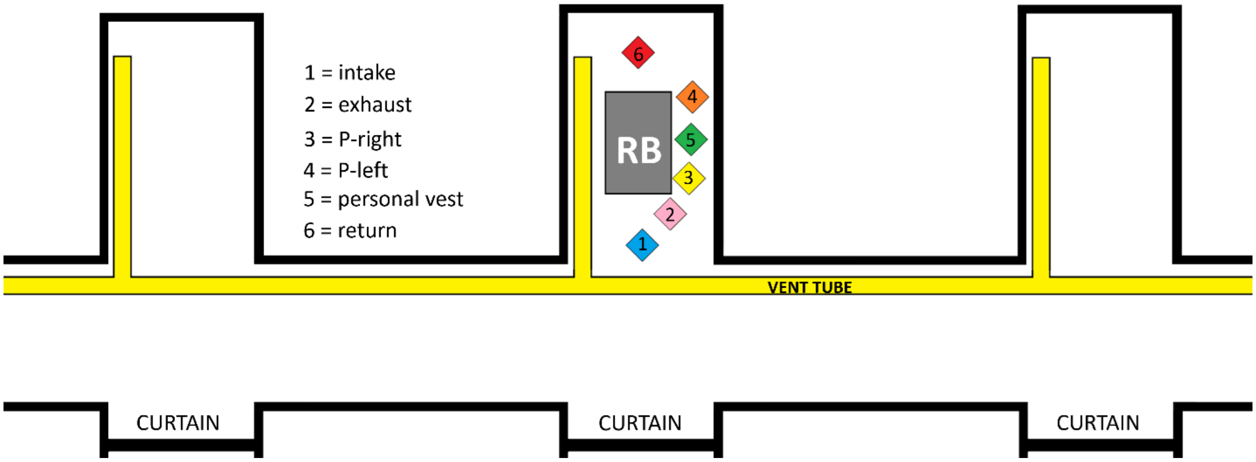

Figure 3.1: Standardized sampling locations used by NIOSH to evaluate dust concentrations during the use of a wet dust collection box (versus a traditional dry box) on a roof bolter (adapted from [27]).

With the intent to compare respirable dust mass concentrations (mg/m^3) and crystalline silica mass content (%) in each sampling location for each event, Reed et al. [27] collected filter samples via standard coal mine dust personal sampling units (CMDPSU); these consist of an air pump (operated at 2.0 L/min) and 10-mm nylon cyclone to collect the respirable particles onto a 37 mm polyvinyl chloride filter (PVC, 5 µm pore size) inside a 3-piece cassette. Unfortunately, a problem with the measurement of sample filter pre-weights prevented the intended dust analysis. However, the samples were analyzed for quartz[2] mass by Fourier Transform infrared spectroscopy (FTIR) per the non-destructive direct-on-filter method outlined by Chubb and Cauda [29]. This yielded an estimate of crystalline silica mass (µg) but, since the total sample weight was uncertain, the mass percentage could not be determined. Though not reported by Reed et al. [27] the FTIR data was archived by at NIOSH and, importantly, the pairs of filter samples were preserved.

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[2] In coal mines, quartz is typically the dominant form of respirable crystalline silica.

In each location, Reed et al. [27] also used a light scattering particle monitor (Thermo Fisher pDR-1000) to log time-series data [27]. Typically, this data is calibrated to mass concentration post-hoc using the time-weighted average mass concentration determined from a collected filter sample [30]. Due to the problem mentioned with filter pre-weight measurements, the pDR data could not be calibrated. Nonetheless, Reed et al. [27] were able to use the data to study changes in the relative dust concentration between sampling events for a given standardized location (i.e., because the same pDR unit was always used in the same location). As expected, they found that the dust collection system type (i.e., wet versus dry) did not seem to influence the respirable dust concentration in the vicinity of the active roof bolter. However, the operator's vest samples showed that use of the wet system reduced the exposure by an average of 60% during dust box cleanout.

In a second NIOSH study of the roof bolter wet dust collection system, Reed et al. [28] reported similar results (i.e., reduction in respirable dust exposure by 71-88% when cleaning out the wet versus dry collection system). They were also able to show that respirable quartz exposure, specifically, was reduced during dust box cleanout when using the wet versus dry collection system. Notably, in the second study, there was no issue with obtaining filter weight measurements; so, quartz analysis was performed by the standard NIOSH Method 7603, which is destructive. Thus, no dust samples were preserved.

3.2.3 Research Objectives

While the Reed et al. studies [27, 28] demonstrated the potential benefits of the novel wet dust collection system for reducing roof bolter operator exposure to respirable dust in terms of mass concentration, detailed dust characterization was not part of the original study designs. Increasingly, however, there is significant interest in understanding the whole composition of respirable coal mine dust—including the distribution of various constituents and particle sizes—and the effects of different dust sources and engineering controls on such characteristics [4]. Accordingly, there is interest in the development and application of standardized analytical methods for dust characterization.

The current work leverages availability of preserved dust samples from the first study by Reed et al. [27] to both investigate respirable dust characteristics and to explore analytical methods. Specifically, the first research objective was to: evaluate the variability in dust constituents and particle sizes as a function of sampling location (per Figure 1), event, and the type of dust collection system installed on the roof bolter (i.e., wet or dry). For this, dust analysis was performed using scanning electron microscopy with energy dispersive X-ray (SEM-EDX). SEM-EDX is a common technique for analysis of particles in the micron size range and has been applied in numerous studies of respirable coal mine dust [19, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43]. While methodologies have been developed and standardized internally within some research groups [17, 44, 45], wider standardization does not yet exist; and comparisons have not been done across different labs using their own methods to gauge the similarity of results. Since the preserved dust samples from the Reed et al. [27] study were collected in pairs (i.e., duplicates), their availability for follow-up work presented an added opportunity for intra-laboratory comparison. Thus, the second research objective of the current work was to: compare results of respirable coal mine dust characterization by SEM-EDX between two academic laboratories using their own, internally developed, methods. Moreover, given that the available dust samples had already been analyzed by NIOSH using the standardized direct-on-filter FTIR method (per [29]), and one of the academic labs represented here is also equipped to perform this analysis, another opportunity for intra-laboratory comparison was recognized. Thus, a third objective of this work was to: compare the quartz mass results determined using direct-on-filter FTIR between the NIOSH and academic laboratories. This method is relatively new and has not been widely adopted in the field, but it is of significant interest for enabling end-of-shift silica monitoring [4].

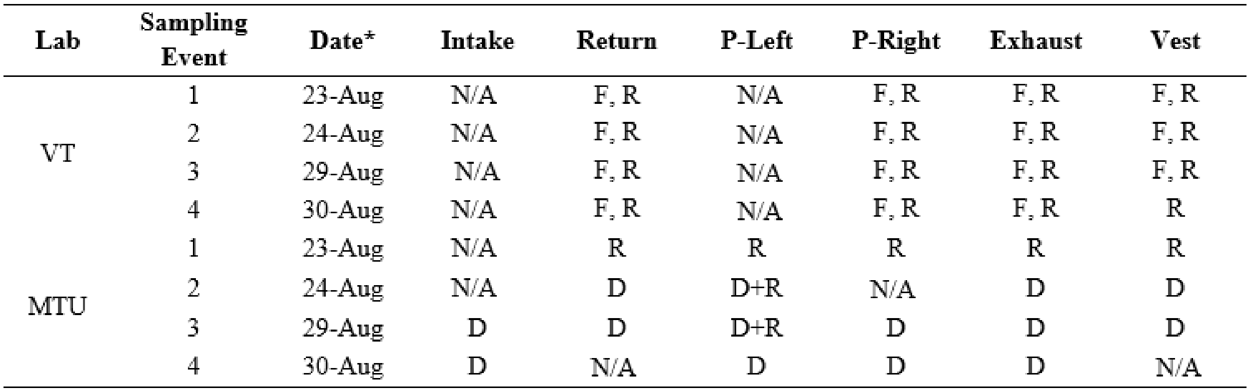
3.3 Materials and Methods

A total of 48 respirable dust samples (representing 24 pairs of duplicates) collected by NIOSH for the Reed et al. [27] study were made available for the current work. The samples were split (one from each pair) between two laboratories represented by the authors: Virginia Tech (VT) and Michigan Technological University (MTU). Each lab performed its own SEM–EDX analysis on a subset of the received samples, and results were compared on the basis of numerous variables as shown in Table 3.1. The VT lab, while using a redeposition protocol for SEM-EX analysis, also performed direct-on-filter FTIR analysis of received samples to compare with earlier results from NIOSH on quartz mass. The MTU lab performed both direct-on-filter analysis on PVC filters using the SEM/EDX analysis and a redeposition protocol onto polycarbonate (PC) filters followed by an SEM/EDX analysis. No FTIR analyses were performed by MTU.

3.3.1 FTIR Method

As noted, the respirable dust samples had been collected on PVC filters, which are appropriate for direct-on-filter FTIR analysis [29]. To enable an inter-laboratory comparison (NIOSH to VT), the VT lab performed the same FTIR analysis on 23 of the 24 received sample filters (one filter was prepared for SEM–EDX analysis before it could be routed for FTIR). The FTIR analysis was completed using a Bruker Optics ALPHA II FTIR Spec-

Table 3.1: Summary of respirable dust samples selected for analysis by each lab. F denotes samples that were analyzed by FTIR. For SEM-EDX analysis, D denotes samples that were analyzed directly on the sample filter; R denotes samples from which dust was recovered and redeposited prior to analysis. (N/A denotes that a sample was not analyzed).



Lab	Sampling Event	Date*	Intake	Return	P-Left	P-Right	Exhaust	Vest
VT	1	23-Aug	N/A	F, R	N/A	F, R	F, R	F, R
	2	24-Aug	N/A	F, R	N/A	F, R	F, R	F, R
	3	29-Aug	N/A	F, R	N/A	F, R	F, R	F, R
	4	30-Aug	N/A	F, R	N/A	F, R	F, R	R
MTU	1	23-Aug	N/A	R	R	R	R	R
	2	24-Aug	N/A	D	D+R	N/A	D	D
	3	29-Aug	D	D	D+R	D	D	D
	4	30-Aug	D	N/A	D	D	D	N/A

* Sampling date per [27]

trometer (Billerica, Massachusetts, USA). To analyze a filter, it was carefully removed from its original cassette and placed inside a fourpiece cassette that was designed for the direct-on-filter FTIR; the four-piece cassette fits in a special cradle that enables precise alignment in the FTIR instrument during scanning. The absorbance spectra (4000 to 400 cm—1) were recorded from 16 scans of a 6-mm spot on the filter center using the Bruker's OPUS software (version 8.2.28), and then blank corrected (i.e., by subtracting the spectra generated on a blank PVC filter). Then, crystalline silica mass was determined using the publicly available FAST software developed by NIOSH [46], which includes a correction for the possible interference of kaolinite in the sample [38, 47, 48, 49, 50].

3.3.2 VT SEM-EDX Method

A total of 16 samples were selected for SEM-EDX analysis in the VT lab (Table 1). Dust was first recovered from the PVC filters and redeposited onto 47 mm track-etched polycarbonate filters (PC, 0.4 µm pore size). This is because the fibrous nature of PVC filters might hinder particle identification or classification under the microscope. Dust recovery and redeposition were performed using the following procedure: (1) each PVC filter was placed in a glass tube and submerged in isopropyl alcohol (IPA); (2) the tube was placed in an ultrasonic bath at 30^0C for 3 minutes to dislodge particles from the filter; (3) the PVC filter was removed from the tube; (4) the IPA and suspended dust were poured into a vacuum filtration unit to redeposit the particles onto a clean PC filter and allowed to dry completely; and (5) a 9 mm circular subsection was cut at the center of the filter and mounted onto an aluminum SEM stub and sputter coated with Au/Pd for analysis.

For SEM-EDX analysis, the VT lab utilized an FEI Quanta 600 FEG environmental scanning microscope (Hillsboro, OR, USA) with a Bruker Quantax 400 EDX spectroscope (Ewing, NJ, USA). Bruker's Esprit software (Version 1.9.4) was used to run an automated routine on each prepared sample stub using the backscatter electron detector and settings shown in Table 3.2. Per Johann-Essex et al., the routine scans multiple fields of view that are spaced to ensure data collection across the sample stub area [45]. To achieve a target of 500 total particles analyzed per sample, the routine limits analyzed particles per field to 50, such that at least 10 fields are scanned. In each field, particles are identified by contrast (i.e., against the smooth PC filter background) and then data are collected for up to 50 particles (moving from left to right and top to bottom) with diameter between 0.9-10µm. For each particle, the routine recorded length, width and projected area (i.e., used to compute a projected area diameter, PAD). EDX spectra was also captured, and normalized atomic % values for eight elements (C, O, Al, Si, Ca, Mg, Fe, Ti) were used to classify it into one of nine mineralogy constituent classes (Table 3.2). Classification criteria were previously published by [17]; for this study, some classes were collapsed to enable direct comparisons with data from the MTU lab (see Table 3.2). The classification criteria for the collapsed bins are shown in Table 3.3.

Table 3.2: SEM-EDX parameters and constituent classes used by the VT and MTU labs.

Operating parameters			**Constituent Classes**	
Parameter	**VT**	**MTU**	**VT**	**MTU**
Accelerating voltage	15 kV (imaging, EDX)	15 kV (imaging), 12 or 9 kV (EDX)	Carbonaceous (C) Mixed Carbonaceous (MC)	Coal
Spot size	5.5 µm	6.0 µm	Aluminosilicates-kaolinite (ASK)	Silicates
Magnification	1,000x	2,000x	Aluminosilicates-other (ASO)	
Particle length	0.9-10 µm	0.9-10 µm	Other silicates (SLO)	
Field area	14,025 µm^2	2,127 µm^2	Silica	Silica
Max particles per field	50	60	Carbonates	Carbonates
Min fields per sample	10	8	Heavy minerals (HM)	Others
Target particles per sample	500	400	Others	

Table 3.3: Particle classification criteria based on normalized atomic % values derived from SEM-EDX analysis. The VT lab method included elements C, O, Ca, Mg, Al, Si, Ti, and Fe, and the MTU lab method included C, O, Ca, Mg, Al and Si.

	VT Lab								**MTU Lab**					
Constituent Class	C	O	Ca	Mg	Al	Si	Ti	Fe	C	O	Ca	Mg	Al	Si
Coal	≥75	<29	≤0.50	≤0.50	<0.35	<0.35	≤0.60	≤0.60	>70	-	<3	<3	<1	<1
Silicates	-	-	<3	<3	≥0.35	≥0.35	-	-	-	-	<3	<3	>1	>1
Silica	-	-	-	-	-	≥0.33	-	-		-	<3	<3	<1	>5
Carbonates	<88	>9	>0.50	>0.50		-	-	-	-	-	>3	>3	<1	<1
Others	does not fit another class								does not fit another class					

3.3.3 MTU SEM-EDX Method

The MTU laboratory performed SEM-EDX analysis on the samples shown in Table 3.1 using two approaches: 1) particles were analyzed directly on the PVC filter and 2) particles were analyzed following dust recovery from the PVC filter and redeposition onto a PC filter. For the direct analysis, two 8 mm square subsections were cut from the PVC filter (i.e., one from the center and one from the edge). Both were mounted on an aluminum stub and sputter coated with Pt, then analyzed with a Philips XL40 Environmental Scanning Electron Microscope (Houghton, MI) using the parameters given in Table 3.2. This analysis was conducted manually (rather than with a computer-controlled routine) and was limited to particles having a diameter greater than approximately 0.9 µm to enable comparison with the VT lab results. (It is noted however that individual particle sizes were not recorded during the analysis). Images for particle identification were obtained using the backscatter electron detector (at 15 kV), and EDX analysis to classify individual particles was accomplished using the secondary electron detector (at 9-12 kV). (The use of low accelerating voltage for the EDX analysis was to avoid interference of reflected signals from the filter substrate and nearby dust particles). The MTU lab used normalized atomic % values for six elements (C, O, Al, Si, Ca, Mg) to classify each particle into one of the five constituent classes shown in Table 3.2. The classification criteria are shown in Table 3.3. For samples that were subjected to dust recovery and redeposition onto PC prior to SEM-EDX analysis, the MTU lab approach was similar (but not identical) to that of the VT lab: A quarter of the original PVC sample filter was added to a clean glass beaker filled with 5 mL of IPA, and the beaker was sonicated for about 5 seconds. Then, the PVC filter was removed from the beaker and a Luer-lock syringe was used to take a 2 mL aliquot of the dust-loaded IPA suspension. The suspension was filtered using a syringe-filter assembly containing a clean 10-mm PC filter (0.2 µm pore size). The PC filter was dried overnight and prepared for SEM-EDX analysis by mounting it on an aluminum stub and coating it with Pt. The SEM-EDX analysis protocol for the redeposited dust samples was the same as described above for the direct analysis on the original PVC filters.

3.4 Results and Discussions

The approach to sample selection for SEM-EDX analysis was in consideration of the aforementioned research objectives. Related to the first objective, the aim was to evaluate variability in dust characteristics in the vicinity of the roof bolter, spatially (i.e., between standardized locations), temporally (i.e., between sampling events), and with respect to the dust collection system (i.e., wet versus dry dust box). For this, samples from 16 of the 24 total pairs were selected for SEM-EDX analysis using the VT lab's method (Table 3.1). This method has been developed and improved over several iterations [40, 44, 45], and was recently used to characterize respirable dust from 25 coal mines [17, 51]. The 16 samples represent the same four locations sampled during each of the four events: the bolter dust collection system pre-cleaner for the right-side bolter (p-right), the collector exhaust, the return air from the bolter, and the personal (vest) sample from the operator during dust box cleanout. Since the wet dust collection system was tested during events 1 and 2, whereas the dry system was tested during events 3 and 4, it is also possible to compare results based on the specific collection system. (It is noted that samples from the bolter intake airway and the left-side pre-cleaner location (p-left) were not selected for the VT lab's SEM-EDX).

The MTU lab analyzed a total of 19 samples by SEM-EDX (Table 3.1). Related to the second research objective, 13 of these were from sample pairs also analyzed by the VT lab (comparison of results is discussed in Section 3.4 below); and the other six were from the bolter intake and p-left locations, which further enabled some understanding of the dust characteristics in these sampling locations. While the majority of the MTU lab's analysis was conducted directly on a portion of the sample filter, it is noted that for two samples the MTU lab also analyzed dust particles that were recovered and redeposited from another portion of the filter.

3.4.1 Dust Constituents and Size Distributions by Location, Event, and Dust Collection System

Table 3.4 and Figure 2.2a show the constituent distribution of particles (number %) observed in the 16 samples analyzed by the VT lab; and Table 3.5 and Figure 2.2b show these results for the 19 samples analyzed by the MTU lab. Across the three locations analyzed around the roof bolter (i.e., p-right, exhaust, return) during all sampling events, coal was the most dominant dust constituent—accounting for about 43-72% of all particles per VT results, and 29-94% per MTU results. Some coal dust might have been generated by the roof bolter activity, and some might have entered the roof bolter area with the intake air due to upwind activities (e.g., if the continuous miner was operating upwind the bolter). Carbonates—which could be sourced from dolomite-rich roof rock or application of limestone rock dust product in the mine—were also present to some extent (3-32% per VT, and 2-26% per MTU) in samples from all three locations around the roof bolter. The balance of the dust particles were silicates (4-18% per VT, and 2-55% per MTU) and silica (5-20% per VT, and 0-15% per MTU), which are expected to be sourced from the roof bolting activity, and possibly activities upwind of the roof bolter area. Samples analyzed from the intake location showed high coal (77% for event 3 and 70% for event 4 per MTU), with minor percentages of silicates, silica and carbonates. Notably, no consistent trend was observed when comparing samples analyzed by the MTU lab at the p-left versus p-right locations.

Table 3.4: Summary of results for samples analyzed by the VT lab. For the SEM-EDX analysis, dust constituent distributions are shown on the basis of number %, and the overall D10, D50 and D90 particle sizes is shown. It is noted that all samples were recovered and redeposited for SEM-EDX analysis (R). The table also shows results of the direct-on-filter FTIR analysis for both the VT and NIOSH labs. It is noted that all but one sample received by VT (n=23) were analyzed by FTIR, however SEM-EDX analysis was limited to just 16 of the samples. (N/A denotes that a sample was not analyzed. <LOD denotes FTIR-derived silica mass was below the limit of detection based on corrected integrated spectral peak area for quartz).

		SEM Results								**FTIR Results**	
Sampling Event	**Location (SEM analysis)**	**Dust Constituents (number %)**					**Particle Size**			**Quartz Mass (μg)**	
		Coal	**Silicates**	**Silica**	**Carbonates**	**Other**	**D10 (nm)**	**D50 (nm)**	**D90 (nm)**	**VT**	**NIOSH**
Event 1 (wet box)	intake (R)	N/A								<LOD	<LOD
	return (R)	53	10	12	20	1	963	1330	2392	6.62	6.46
	p-right (R)	62	6	11	20	1	963	1232	2249	<LOD	<LOD
	p-left (R)	N/A								3.82	4.51
	exhaust (R)	69	5	5	18	0	963	1197	2268	<LOD	<LOD
	vest (R)	85	4	3	8	0	918	1161	3047	<LOD	<LOD
Event 2 (wet box)	intake (R)	N/A								<LOD	<LOD
	return (R)	57	13	17	9	2	963	1330	2424	4.56	5.30
	p-right (R)	60	7	15	15	1	963	1314	2528	<LOD	<LOD
	p-left (R)	N/A								<LOD	<LOD
	exhaust (R)	58	18	20	3	0	918	1143	1813	26.89	28.68
	vest (R)	60	9	15	14	1	963	1298	2464	<LOD	<LOD
Event 3 (dry box)	intake (R)	N/A								<LOD	<LOD
	return (R)	57	14	16	10	0	963	1377	2903	19.09	19.83
	p-right (R)	61	14	11	11	0	963	1642	4247	6.21	8.09
	p-left (R)	N/A								16.00	12.19
	exhaust (R)	72	9	6	13	1	963	1480	3031	<LOD	<LOD
	vest (R)	55	17	23	4	1	1006	1536	2677	15.78	<LOD
Event 4 (dry box)	intake (R)	N/A								<LOD	<LOD
	return (R)	63	4	10	22	1	918	1232	2053	<LOD	<LOD
	p-right (R)	43	10	14	32	1	1006	1466	3306	4.89	6.73
	p-left (R)	N/A								<LOD	<LOD
	exhaust (R)	56	8	10	24	1	963	1346	2429	<LOD	<LOD
	vest (R)	53	19	22	5	1	963	1392	2548	N/A	<LOD

Table 3.5: Summary of results for 19 samples analyzed by the MTU lab using SEM-EDX. Dust constituent distributions are shown on the basis of number %. It is noted that samples from Event 1 were recovered and redeposited for analysis (R), while samples from Events 2-4 were analyzed by the direct-on-PVC filter method (D); for two samples (i.e., p-left in Events 2 and 3) both recovered and direct analysis were conducted. (N/A denotes that the sample was not analyzed).

Sampling Event	**Location (SEM analysis)**	**SEM Results**				
		Dust Constituents (number %)				
		Coal	Silicates	Silica	Carbonates	Other
Event 1 (wet box)	intake (R)			N/A		
	return (R)	63	20	13	3	1
	p-right (R)	89	3	1	6	0
	p-left (R)	83	10	7	1	0
	exhaust (R)	94	2	0	4	0
	vest (R)	90	5	3	2	0
Event 2 (wet box)	intake (D)			N/A		
	return (D)	50	26	12	9	3
	p-right (D)			N/A		
	p-left (D)	65	22	2	8	3
	p-left (R)	78	6	2	14	0
	exhaust (D)	29	55	14	2	0
	vest (D)	74	20	5	1	0
Event 3 (dry box)	intake (D)	77	10	6	7	0
	return (D)	59	22	11	7	1
	p-right (D)	76	16	5	2	1
	p-left (D)	50	16	17	15	2
	p-left (R)	57	23	3	10	6
	exhaust (D)	78	12	2	6	2
	vest (D)	52	30	14	4	0
Event 4 (dry box)	intake (D)	70	19	7	4	0
	return (D)			N/A		
	p-right (D)	46	18	7	26	3
	p-left (D)	63	13	4	20	0
	p-left (D)	32	28	15	25	0
	exhaust (D)			N/A		

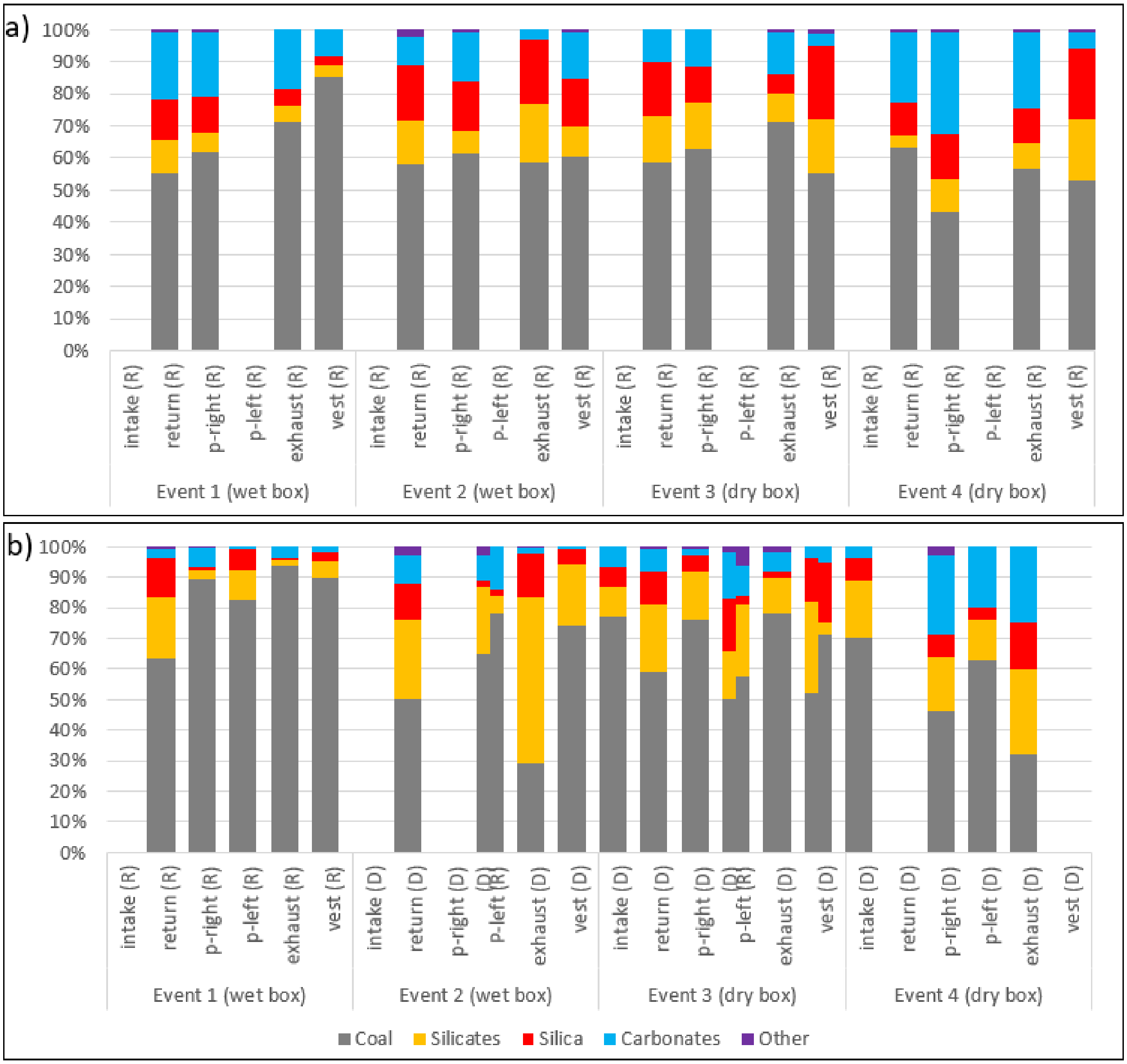


Figure 3.2: Constituent distribution (on the basis of particle number %) of dust particles analyzed by SEM-EDX observed by a) the VT lab and b) the MTU labs. The analysis method is noted for each sample (i.e., either recovered dust, R, or direct-on-PVC sample filter, D).

While variability between the three locations around the bolter is clear for all four sampling events, there does not appear to be a consistent trend. For example, during events 1 and 3, the sample from the bolter's dust collection system exhaust had somewhat less silicates (5% and 9% were observed by VT; 2% and 12% by MTU) and silica (5% and 6% observed by VT; 0% and 2% by MTU) than the samples from the p-right and return locations; however, this was not the case for events 2 and 4. This is most likely due to variability in local air circulation conditions and dust sources between the sampling locations from event to event. Notably, the MTU analysis that was conducted directly on the PVC filters also showed variability between locations—but again it was not consistent from event to event. On the other hand, the carbonates and silicates+silica contents suggest an overall variability in dust sources based on the specific sampling event. In events 1 and 4, the carbonate content was relatively high (18-32% observed by VT; 3-26% by MTU[3]) in all three locations analyzed around the bolter, while the silicates+silica content was relatively low (10-24% observed by VT; 2-43% by MTU). However, the opposite was generally observed for events 2 and 3, wherein carbonates were relatively low (3-15% observed by VT; 2-9% for MTU) and silicates+silica were higher (15-38% observed by VT; and 14-69% by MTU). These event-to-event variations could be due to differences in roof rock geology from location to location. Other variations could be due to rock dust from rock dusting at the mine site and differences in the bolter activity (e.g., drilling depth, rotational pressure, and total drilling time).

With respect to the wet versus dry dust collection system, no discernable trends were observed in dust constituents between the three locations analyzed around the roof bolter. This is consistent with expectations since both systems should pull the respirable dust fraction into the containment box; exhaust from the box is through a high-efficiency filter; and, in the case of the wet system, the sludge discharged from the box during operation should result

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[3] Event 1 carbonates as analyzed by MTU were lower than VT carbonates, ranging 3–6% MTU versus 18–20% VT. No significant explanation for the large difference can be provided.

in little re-entrainment of dust particles from the mine floor. Indeed, neither the Reed et al. [27] study from which the samples used here originated nor the Reed et al. [28] follow-up study of the wet dust collection system, indicated any consistent differences in dust concentrations around the operating roof bolter that were attributable to the dust collection system type.

However, the work by Reed et al. [27] did indicate that the wet system (compared to the dry) yielded lower dust concentrations for the roof bolter operator during dust box cleanout (i.e., 0.475 versus 1.188 mg/m^3, respectively) [27]. Here, the SEM-EDX results for the operator's vest samples can provide further insights: When the operator was cleaning out the dry dust box (events 3 and 4), the vest samples contained relatively more silicates+silica (40% for event 3 and 41% for event 4 were observed by VT; 44% for event 3 by MTU) than did the samples collected around the operating roof bolter just preceding box cleanout i.e., the return, p-right and exhaust samples for the same event (15-30% for event 3 and 14-24% for event 4 were observed by VT; 14-33% for event 3 by MTU). In other words, the silicates and silica content appeared to be concentrated in the respirable dust generated during the dry box cleanout. However, when the operator was cleaning out the wet dust box (events 1 and 2), the vest samples generally contained relatively less silicates+silica than the samples collected around the operating roof bolter. In addition, when compared to the dry dust box, the wet box appeared to reduce the relative silicates+silica content in the operator's vest sample during the box cleanout (i.e., from 40 and 41% for the dry box to 7 and 24% for the wet box as observed by VT; from 44% for the dry box to 8% and 25% for the wet box by MTU). Considering the results from both labs, this represents a reduction of about 41-82%. Taken together with the Reed et al. [27] results, this suggests that, not only did the wet dust collection system reduce the respirable dust concentration, but it also reduced the relative hazard of the dust based on contained constituents. As noted earlier, silica is considered the most hazardous of typical RCMD constituents, and there is evidence that silicates may also play a role in occupational lung disease in coal miners [13, 52, 53].

For context, in the second study of the wet dust collection system by NIOSH, Reed et al. [28] reported that silica (quartz) content was reduced in the operator's samples during the cleanout of the wet box as compared to the dry box—consistent with the findings presented here. Moreover, according to Reed et al. [27], the wet dust collection box seems to accumulate less material than the dry box during bolting activities. This lesser accumulation is due to the frequent dumping of sludge material through the drain (by opening the rotary valve) in the time between bolting rows in the entry. This frequent dumping means that it requires a less frequent cleanout. In addition, once the entire entry is bolted, the wet box can be emptied through the rotary valve in the drain to avoid frequent cleanout with a hose (i.e., as was tested in the Reed et al. [27, 28] studies). These factors should further decrease the potential for hazardous exposure to respirable silica dust.

The SEM-EDX work performed by the VT lab also enabled analysis of particle size. (As stated above, the MTU lab did not record particle size data during SEM-EDX work, which was conducted manually.) For all 16 samples analyzed by the VT lab, Figure 3 shows the overall particle size distributions; and Table 3.4 provides the D10, D50, and D90 particle sizes, which represent the size at which 10, 50 and 90% of the particles are finer. Similar to variability in dust constituents, there appears to be some event-to-event variability in terms of size. For instance, samples from event 3 generally had somewhat coarser particles than those from other events, which can be visualized in Figure 3.3 and observed by comparing the D50 and D90 sizes in Table 3.4. Moreover, samples from the bolter's dust collection system exhaust had relatively fine particles, which fits with expectations given that the exhaust was filtered. And samples from the p-right location had relatively coarse particles when the pre-cleaner was in use (i.e., during the dry dust collection system testing in events 3 and 4).

As mentioned earlier, the role of the pre-cleaner is to remove coarse dust from the airstream headed into the dust collection box [23], so relatively coarser dust (even in the respirable fraction) makes sense in this location—and has in fact been observed in prior studies [22, 54].

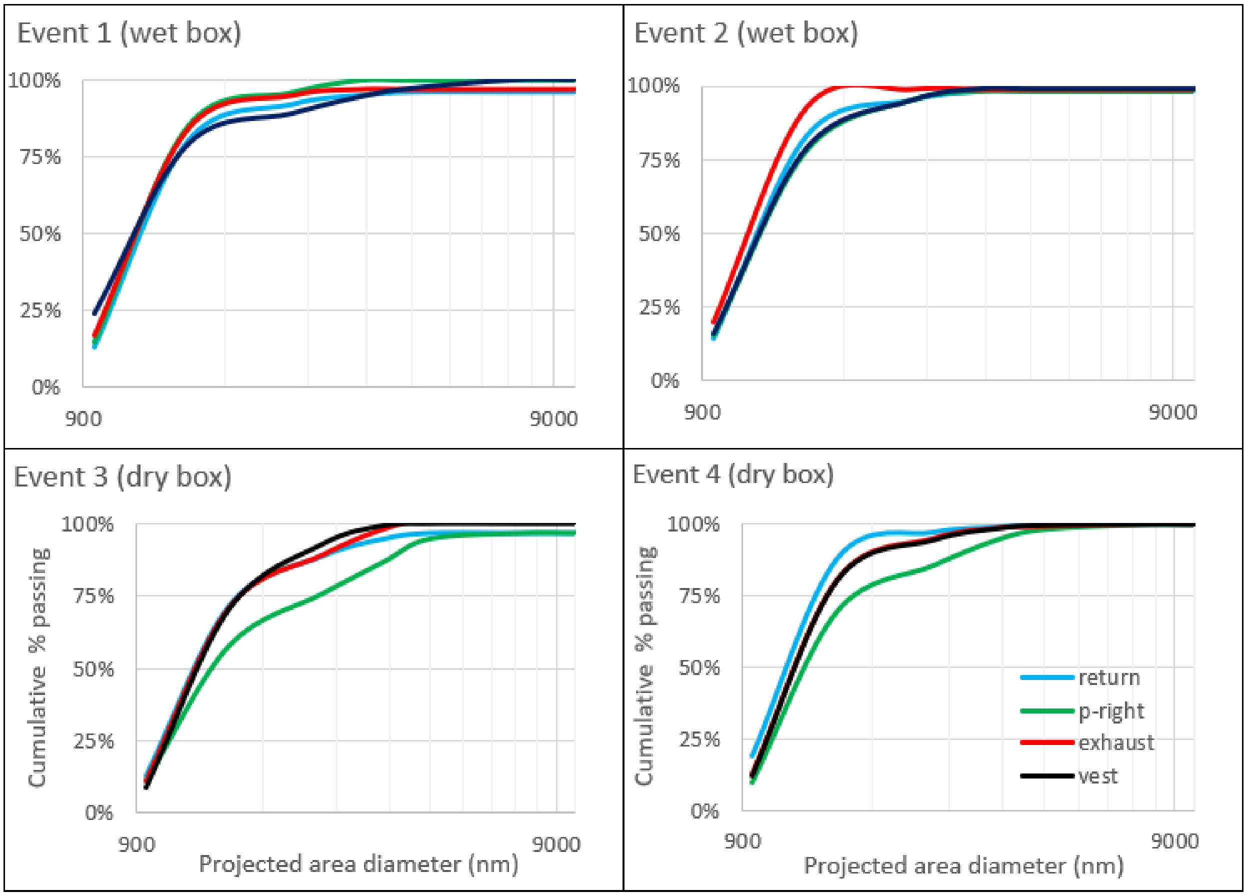

Figure 3.3: Overall particle size distributions determined from the VT lab SEM-EDX analysis. Each plot shows results for the return, p-right, exhaust and vest samples from a given sampling event.

Regarding the operator's vest samples, figure 3.3 shows that dust during the wet box cleanout was slightly coarser than dust in the three locations around the roof bolter during operation, whereas for the dry box cleanout this was not necessarily the case. Given that finer particles are generally considered to pose greater hazards, this could suggest yet another advantage of the wet dust collection system. That said, it should be reiterated that the SEM-EDX analysis conducted for this study did not examine submicron particles, and the overall size distribution for the vest samples across all four events was fairly similar. Other factors—aside from the use of the wet versus the dry dust collection system—such as the variability in the depth of drilling and drill bit sharpness could lead to the generation of different dust concentrations and particle sizes being deposited in the dust collection box during each sampling event [55]. Thus, additional testing to reduce event-to-event variability would be valuable to further evaluate the influence of the wet (versus dry) dust collection system on particle size during box cleanout.

3.4.2 Interlaboratory Comparisons

As mentioned, the second and third objectives of the current work were focused on comparison of dust analysis results obtained by different labs.

Results based on SEM-EDX Analysis

A comparison of the results obtained by the MTU lab versus the VT lab are shown in Figure 3.4. In total, there were 13 pairs of results that could be compared: nine pairs from events 2-4 for which MTU performed direct analysis of particles on the original PVC sample filter and VT performed analysis on recovered dust particles, and four pairs for which both labs performed analysis on recovered dust particles.

While the relationship between the two lab results shown by the trendlines in Figure 3.4 are not particularly strong, they do demonstrate fair agreement between the MTU and VT labs in terms of relative abundance of primary dust constituents. For example, both labs found that the majority of dust particles in most samples were coal with the remainder of particles divided between the other primary classes (i.e., silicates, silica and carbonates). The trendline slopes shown in Figure 3.4 indicate that, in general, the MTU lab tended to classify more particles as coal and silicates than did the VT lab (i.e., the slope is 1.4098 and 2.5501 for coal and silicates, respectively). The opposite trend is seen for silica and carbonates (i.e., slope of 0.7284 and 0.6665 for silica and carbonates, respectively). Additional statistical analysis (t-test, correlation, etc.) were not conducted for the SEM-EDX results. The subsequent discussion concerning the variability of results are reasons for not conducting these additional statistical analyses.

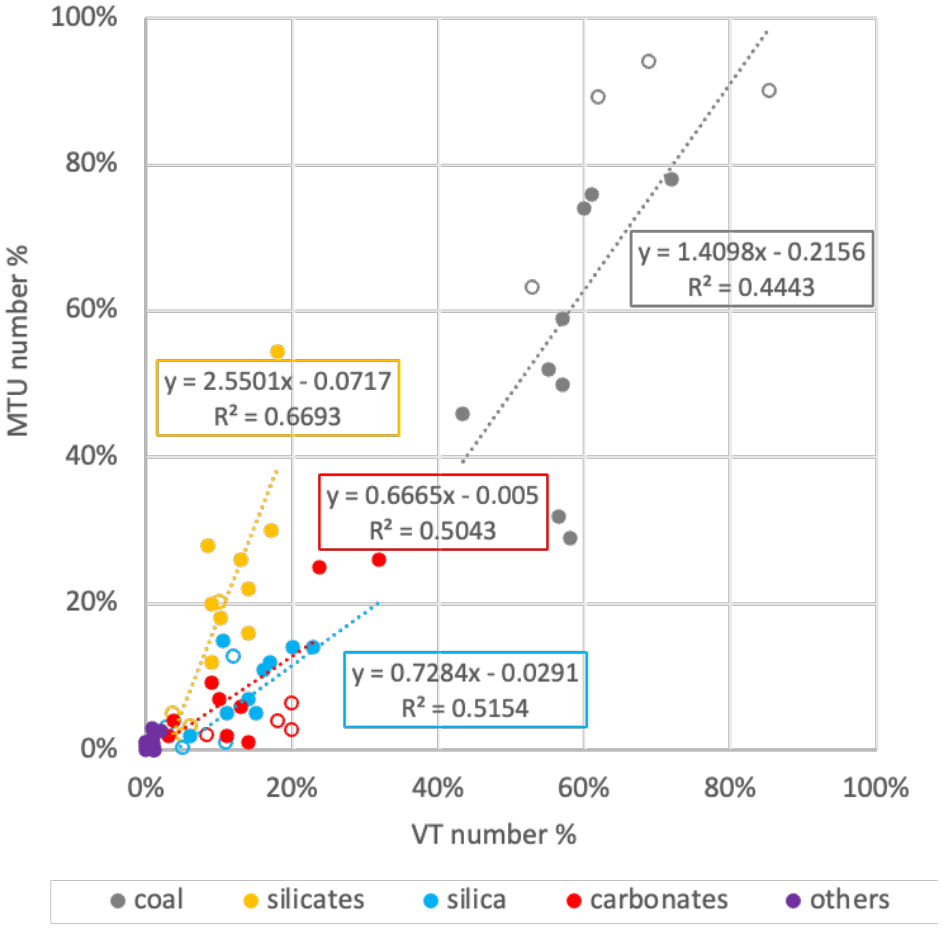

Figure 3.4: Plots showing comparisons of the different dust constituents from samples analyzed by both VT and MTU labs. (NB: the plot only contains results from exhaust, p-right, return and vest since VT didn't analyze the intake and p-left samples. From each dust constituent plot, the filled circles represent direct MTU-recovered VT data points, while the open circles represent the recovered MTU-recovered VT data points).

It is important to note that, even if two labs gather elemental data on the same particle, the use of different SEM-EDX instrumentation, settings and routines could lead to some variability in the results. However, here, the main differences between the MTU and VT results are probably related to two other factors. First, analysis was conducted on pairs of samples—with each lab analyzing one sample from a given pair—rather than on the same samples. While paired samples of respirable coal mine dust are expected to be similar in terms of dust constituents [41], it is of course possible (even probable) that two samples collected side by side are not identical. Second, the two labs utilized different sample preparation and particle classification criteria.

To elaborate on particle classification, each lab took a similar approach to applying classification rules, whereby a particle's elemental content was compared to set thresholds for each constituent class (e.g., see Table 3.3 for thresholds from both labs). For instance, for both labs' criteria, coal particles are characterized by "minimal" content of analyzed elements other than C and O. However, the definition of "minimal" varied between the two labs such that the MTU coal classification allowed more Al, Si, Ca and/or Mg content in the coal class than did the VT classification. This helps explain the observed tendency of the MTU lab to find more coal particles in most samples. On the other hand, for the carbonates class, the MTU criteria was more restrictive than the VT criteria, which helps explain the tendency of the MTU lab to find less carbonates. For the silicates and silica classes, both labs essentially split Si-bearing particles based on their Al content; but the MTU criteria for silica was again more restrictive than the VT criteria. Thus, the MTU lab tended to find less silica but more silicates than the VT lab.

Aside from differences in particle classification, and any inherent differences between the samples in each pair, differences in sample preparation between the two labs are also worth mentioning. While the VT lab only performed SEM-EDX analysis on recovered dust particles, most of the MTU analysis was directly on the surface of the original PVC filters. For direct-on-filter SEM-EDX analysis, sample collection is generally preferred on a smooth filter substrate, but this was not part of the original design of the Reed et al. [27] study during which these samples were collected—thus, both approaches utilized here have their drawbacks. While recovery and redeposition of dust can be subject to some losses, contamination, and/or deagglomeration of particles, analysis directly on a PVC filter can be subject to bias with respect to particles that are on the filter surface versus those that embedded in the fibrous structure of the filter. Therefore, the direct analysis probably included somewhat coarser particles since finer particles could have been effectively hidden. Conversely, the dust recovery procedure (i.e., including sonication in IPA) may yield a somewhat finer size distribution due to deagglomeration of particles [56]. Both of these factors might influence the apparent distribution of dust constituents. The MTU lab conducted direct and recovered dust analysis on two samples (i.e., from the p-left location in events 2 and 3). The direct analysis indicated somewhat lower abundance of coal particles, but higher silicates+silica, compared to the recovered dust analysis (see Table 3.5). This might mean that the coal dust particles were relatively fine, and therefore more easily embedded in the PVC. Moreover, it is possible that directly analyzed coal particles were influenced to some extent by associated mineral particles. For example, a coal particle that is agglomerated with silicates might have been classified as a silicate particle during the direct analysis; but deagglomeration could enable the coal particle to be classified as such during the recovered dust analysis.

Results based on FTIR Analysis

NIOSH had already analyzed the 48 filter samples available for this study using direct-on-filter FTIR to estimate silica mass (i.e., as quartz). That analysis was repeated on the samples received by the VT lab (i.e., 23 of 24 total samples) following the same analytical method (i.e., as described by Chubb & Cauda [29]. Figure 3.5 compares the NIOSH and VT results (tabulated in Table 3.4) for all samples (n=8) with quartz above the limit of detection (LOD). Especially considering the shipment, handling, and storage time of samples, the relationship between lab results appears very good, from the review of the trendline in Figure 3.5 (i.e., slope of 0.9792 with minimal intercept). This demonstrates very good reproducibility of quartz measurement in respirable coal mine dust by the direct-on-filter FTIR method (and FAST software). It is noted that a direct comparison of the FTIR (i.e., µg of quartz) to SEM-EDX data (i.e., number % of silica) is not possible since the total sample weights could not be determined. Additionally, conducting a two-sample t-test (assuming equal variances) at a 95% confidence indicated no significant difference in the mean results for the NIOSH versus VT analysis (p = 0.90).

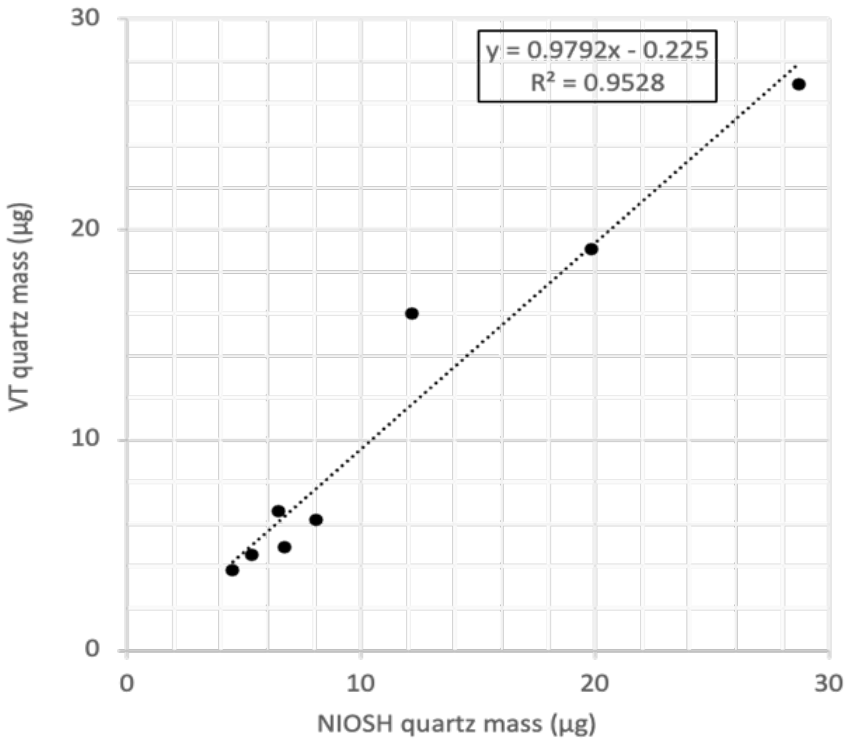

Figure 3.5: VT and NIOSH estimates of quartz mass by the direct-on-filter FTIR method.

Per Table 3.4, of the 8 samples with NIOSH and VT FTIR results > LOD, all were from the p-right, p-left or return locations except for one from the exhaust location. Notably, this trend was also observed for the additional NIOSH results for the 24 samples not provided to the VT lab (data not shown). This trend makes sense given the data reported by Reed et al. [27] too. While respirable dust concentrations could not be determined definitively in that study (i.e., due to the aforementioned problem with measuring filter sample masses), the estimates reported by Reed et al. do indicate dust concentrations were typically higher in the p-right, p-left, and return locations than in the exhaust location—which means the p-right, p-left, and return filter samples likely had greater masses, such that a $>$ LOD FTIR result was also more likely.

Moreover, for the single sample (of 23) where the NIOSH and VT results did not agree (i.e., the vest sample from event 3), the Reed et al. [27] data indicates a relatively high concentration during the corresponding dust box cleanout event (i.e., a time-weighted average of about 1.240 mg/m^3 can be computed) relative to that in events 1, 2 and 4 (i.e., computed averages of about 0.564, 0.391 and 0.462 mg/m^3, respectively). Though the sample mass is expected to be fairly low (i.e., since the cleanout events and corresponding sampling times were fairly short), it was sufficient for the VT lab to obtain an FTIR result $>$ LOD. (Incidentally, this sample also showed significant silica content by SEM-EDX.) It is unclear why the NIOSH FTIR result for this sample was $<$ LOD but might be due to factors such as a slightly off-center scan of the sample filter. Since the dust deposition pattern on filters collected in 3-piece cassettes is center-heavy [57], an off-center scan will yield a low result—and, in the case of this sample, it could have caused the $<$ LOD result.

3.4.3 Research Implications

The current work has several implications for future research. First, it shows that preserved samples can be used to analyze respirable dust characteristics—and, depending on the level of information available about the original sampling design, results might be interpreted to assess variability with specific parameters. As demonstrated here, if the samples originate from a well-documented study, it could be possible to assess spatial (location to location) or temporal (event to event) effects, or the effects of certain dust controls (wet versus dry roof bolter dust collection system). However, there may also be opportunities to analyze samples with other origins (e.g., compliance dust sampling) to shed light on a number of other questions (e.g., how do dust characteristics vary between specific occupations? Between different mines? Between different regulatory eras?)

In any case, it is important to note that the most valuable datasets for evaluating respirable dust exposure hazards are likely to be those which include both concentration and characterization results. In essence, this is a problem of both quantity and quality. For the sample set investigated here, which was originally collected by Reed et al. [27], some understanding of respirable dust concentration was gained by the original study and this follow-up investigation added constituent and size distributions. The combined results indicate that use of the wet dust collection system on the roof bolter not only reduced the respirable dust concentration (mg/m^3) to which the operator was exposed during box cleanout, but it also reduced the proportion of silica+silicates in the respirable dust—and may have reduced the proportion of very fine particles in the dust too. In this case, it is appropriate to conclude that, based on the available data, the wet dust collection system is expected to reduce the overall hazard of respirable dust exposure for the operator. However, conclusions may be more nuanced in cases where the control (or other study parameter) appears to yield competing effects on dust concentration versus characteristics. Thus, it seems prudent for future studies of respirable dust—whether in coal mines or other occupational or environmental settings—to include both concentration and characterization.

The current work additionally offers some key insights related to dust characterization methods, particularly with regard to particle-level analysis by SEM-EDX. While analysis of paired samples from two independent labs yielded generally similar results with respect to primary dust constituents, it is obvious that standardized methods are needed to enable robust comparisons between results obtained in different labs. Specifically, standardization should be pursued for: sample handling, particle recovery and redeposition procedures; particle analysis and data collection routines; analytical instrumentation capabilities and settings; particle classification criteria; and nomenclature.

Finally, it is worth mentioning that the direct-on-filter FTIR analysis for quartz mass has been proposed for end-of-shift silica monitoring [4, 29, 46, 47, 49]. The results presented here lend some evidence in support of this concept; specifically, quartz measurements were in agreement across two labs—even considering significant sample storage times, transport, and handling. That said, more effort is needed to investigate the accuracy of the method in the field and to train would-be analysts.

3.5 Conclusion

To investigate respirable dust characteristics in the vicinity of an active roof bolter, preserved samples from a prior NIOSH study (i.e., Reed et al. [27]) were analyzed by SEM-EDX. Results demonstrated that dust constituents and particle sizes varied around the operating roof bolter, likely due to local air circulation patterns and the influence of particular components of the machine's dust collection system (e.g., dust around the system pre-cleaner was relatively coarse, whereas it was relatively fine at the system exhaust). Event-to-event differences also suggested that specific sources of dust in the vicinity of the roof bolter were variable, perhaps due to changes in the roof geology or relative contribution of coal or rock dust product in the intake air entering the bolter area. Moreover, dust characteristics were examined in a subset of the preserved NIOSH samples that represented the roof bolter operator's potential exposure during cleanout of the dust collection system. When the system was equipped with a novel wet dust collection box—as opposed to a traditional dry box—results indicated the operator's vest samples consisted of dust with less silicates+silica content (i.e., the constituents expected to be primarily sourced from the bolter drilling into to roof rock strata). The dry dust box vest samples silicates+silica content ranged from 40-44%, while the wet dust box vest samples silicates+silica content ranged from 7-25% —a reduction of 41-82%. This is further evidence (i.e., beyond that reported by Reed et al. [27, 28]) that the wet dust box can reduce hazardous respirable silica dust for the roof bolter operator.

The current study additionally allowed for inter-laboratory comparisons. When two labs independently applied a standardized method to determine quartz mass in the available respirable dust samples using direct-on-filter FTIR analysis, results were in very good agreement. This demonstrates method reproducibility. On the other hand, when two labs independently applied their own sample preparation and SEM-EDX analysis methods to evaluate dust constituents, more variability was observed. Importantly, the results presented here should not be used to imply a determination of performance by either of the participating labs. Rather they highlight the need for standardization of such particle-level analysis to enable comparison across labs.

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Contributions

F. Animah: Conceptualization and design, data collection and analysis, methodology, data visualization, writing-original draft & addressing reviews and edits.
S. Afrouz: VT sample preparation
C. Keles: VT SEM-EDX methodology
A. Greth: VT sample preparation
T. Akinseye: MTU sample preparation and MTU SEM-EDX methodology
L. Pan: writing-review and editing, supervision, MTU Funding acquisition
W.R. Reed: preserved NIOSH dust samples, writing-review and editing
E. Sarver: Conceptualization and design, writing-review and editing, supervision, and VT funding acquisition

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Chapter 4

Effects of dust controls on respirable coal mine dust composition and particle sizes: case studies on auxiliary scrubbers and canopy air curtain[1]

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4.1 Abstract

Control of dust in underground coal mines is critical for mitigating both safety and health hazards. For decades, the National Institute of Occupational Safety and Health (NIOSH) has led research to evaluate the effectiveness of various dust control technologies in coal mines. Recent studies have included the evaluation of auxiliary scrubbers to reduce respirable dust downstream of active mining and the use of canopy air curtains (CACs) to reduce respirable dust in key operator positions. While detailed dust characterization was not a focus of such studies, this is a growing area of interest. Using preserved filter samples from three previous NIOSH studies, the current work aims to explore the effect of two different scrubbers (one wet and one dry) and a roof bolter CAC on respirable dust composition and particle size distribution. For this, the preserved filter samples were analyzed by thermogravimetric analysis and/or scanning electron microscopy with energy dispersive X-ray. Results indicate that dust composition was not appreciably affected by either scrubber or the CAC. However, the wet scrubber and CAC appeared to decrease the overall particle size distribution. Such an effect of the dry scrubber was not consistently observed, but this is probably related to the particular sampling location downstream of the scrubber which allowed for significant mixing of the scrubber exhaust and other return air. Aside from the insights gained with respect to the three specific dust control case studies revisited here, this work demonstrates the value of preserved dust samples for follow-up investigation more broadly.

Keywords: Respirable dust . Dust control . SEM-EDX . Scrubber . Canopy air curtain . Silica

4.2 Introduction

Dust in coal mines presents both safety and health hazards. Control of airborne float dust (dust that contains particles up to 75 µm) is a critical strategy for mitigating explosibility hazards [1], and control of respirable coal mine dust (particles < 10 µm) is for preventing occupational lung disease [2, 3]. Indeed, dust control has been a key focus of the mining research portfolio at the National Institute of Occupational Safety and Health (NIOSH)—including work on scrubbers [4, 5, 6, 7, 8, 9]. In coal mines, fan-powered dust collectors such as scrubbers are commonly used on continuous miner machines (CM) to capture dust being generated at the cutting face, and thus prevent its transport into the return airways and contamination of the ventilating air more broadly. These scrubbers are usually operated along with water sprays to limit miner exposure to respirable dust [10]. Indeed, the operation of the CM-mounted scrubbers, referred to as flooded-bed scrubbers, increase the air quantity supplied to the cutting face for the improvement of methane and respirable dust control [9]. Scrubbers essentially capture particles by forcing the dust-laden air through an inlet before reaching a wet filter where they either deposit or attach to water droplets that are removed by a demister. Finally, the scrubber fan pulls and filters out dry air through the scrubber exhaust and releases it into the return airways. The scrubber efficiency is determined by its ability to capture (i.e., controlled by the scrubber airflow) and collect or remove dust-laden air from the cutting face [9, 10]. To improve dust control in other priority areas of underground coal mines (i.e., not necessarily coupled with the CM operation), auxiliary (stand-alone) scrubbers could be another option. Recently, NIOSH has conducted field studies of a wet auxiliary scrubber (i.e., based on the traditional flooded-bed type) [6, 9], as well as a dry unit that can provide even more flexibility in terms of placement in the mine [7].

For more direct protection of some equipment operators from respirable dust exposure, NIOSH has also investigated the performance of canopy air curtains (CACs) [11, 12, 13, 14, 15, 16, 17]. The CAC is an underground coal mining dust control designed by NIOSH researchers to be employed under the canopy of roof bolting machines and provide filtered air into the breathing zone of miners during bolting activities to reduce their exposures to respirable dust. The operation of the CAC involves the use of a hydraulically powered fan (blower) installed on a roof bolter which is usually connected to a plenum (traditionally placed underneath the roof bolter canopy or incorporated into the canopy design) via a hose to provide filtered air to the breathing zones of the operator during bolting activities. The filtered air from the plenum protects the operator by pushing dust-laden air away from the zone of influence of the CAC [10]. The CAC was initially designed for CM operators when CM machines had cabs [13]. Once CM cabs were eliminated in favor of local remote operation, the CAC was redesigned and tested for roof bolter operators since they typically have one of the highest risk occupations in terms of respirable dust and crystalline silica exposures [18]—either due directly to roof drilling [19] and bolting activities or working downstream of the CM [4, 20, 21]. After several iterations of preliminary CAC designs in separate studies, Reed et al. [22] tested the ability of a third-generation CAC to reduce roof bolter operator exposure to respirable dust.

Given that respirable dust exposures are regulated based on mass concentration, much of NIOSH's research that has investigated the effects of engineering controls on respirable dust has focused on the effectiveness to reduce mass concentration. However, an understanding of dust composition and particle characteristics is increasingly of interest [23]. Fortunately, even though detailed dust characterization was not the original intent, NIOSH preserved the respirable dust samples collected for some of its field studies—which can now enable further analysis. In the current work, preserved samples were obtained from three prior NIOSH studies surrounding the aforementioned wet and dry auxiliary scrubbers, and the roof bolter CAC. These samples were used to investigate the possible effects of each control on dust composition and particle size. (It should be noted that a portion of the results associated with the auxiliary scrubbers was previously published in a conference paper [24]. The work has been expanded here to include additional analysis of the dust samples from the scrubber studies, and the CAC study.)

4.3 Summaries of Original NIOSH Studies

The sections below provide an overview of the three original NIOSH studies and available dust samples which are the subject of the current work.

4.3.1 Wet Scrubber Study

As reported by Janisko et al. [6] and Patts et al. [9], NIOSH tested the performance of an inline wet scrubber (Compact Filter Technic type HCN 600/1 model) to reduce airborne float dust and respirable dust concentrations downstream of a CM. The CM was operating on the left side of a four-entry section operated in similar fashion as a super section (i.e., two pairs of CM and roof bolter operated on opposite sides of the section) for longwall development at the study mine (called "Mine A"). An auxiliary fan was used to pull air through ventilation tubing from the CM to the scrubber, which was located in the return entry (Figure 4.1). The airflow through the scrubber was about 8.0 m^3/s (17,000 cubic feet per minute, CFM) while the overall airflow in the return was about 28.8 m^3/s (61,000 CFM). To avoid interference of rock dusting with the scrubber evaluation, rock dust application was halted in the return during sample collection; however, Janisko et al. [6] noted that rock dust that had already been applied was re-entrained into the air by the auxiliary fan which operated along with the scrubber.

Dust samples were collected during each of six separate CM cuts, which were made in different entries over a total of three shifts. The production rate was consistent across all cuts. The cutting time was between about 60-80 minutes per cut, and sampling was done

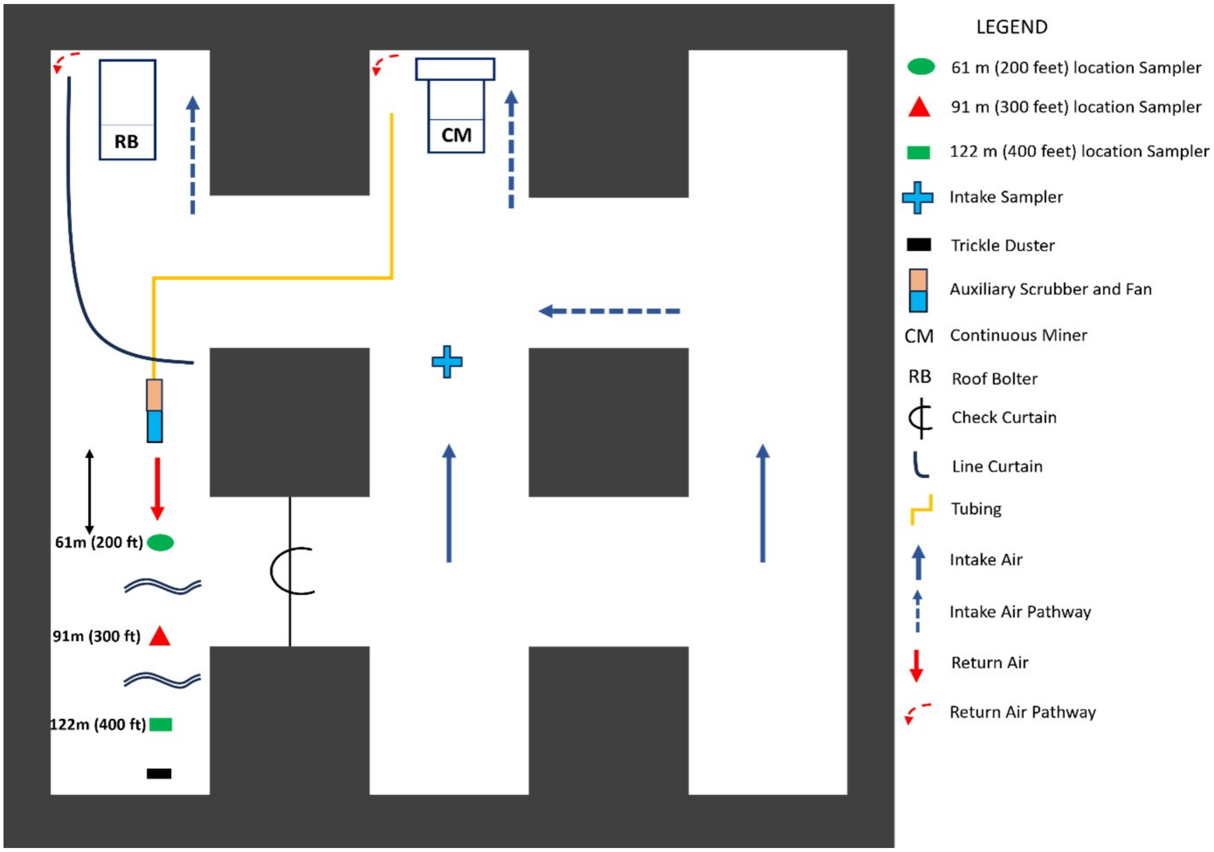


Figure 4.1: Schematic of sampling locations in NIOSH's studies of an auxiliary wet scrubber in Mine A (modified from Patts et al. [9]). Only samples from the locations denoted by green symbols were included in the current work.

for the full duration of each cut. On the first shift (Cuts 1-2), the wet scrubber was not in place. On the later shifts (Cuts 3-6), the wet scrubber was in place and operating; NIOSH noted scrubber power interruption on Cut 3 and so associated data was excluded from their study [9]. Sampling was done at the intake and in locations that were spaced 61, 91, and 122 m (200, 300 and 400 feet) downstream of the wet scrubber location in the return entry. In each location, respirable dust samples were collected using gravimetric samplers consisting of a standard air pump at 2.0 L/min and 10-mm nylon cyclone (i.e., D50 of about 4 µm). (It is noted that total airborne float dust was also collected in each location, and additional dust samples were collected in some locations using custom cyclones; but only the respirable dust samples from the 61 and 91 m (200 and 400 feet) locations are included in the follow-up investigation reported here.

Based on the comparison of dust concentrations (mg/m^3) during the two CM cuts without the wet scrubber versus the three cuts with it operating, results indicated the scrubber yielded an 86% reduction in respirable dust, and more than 92% reduction in float dust in Mine A [6, 9].

4.3.2 Dry Scrubber Study

Organiscak et al. [7] tested the performance of a dry scrubber to reduce respirable dust concentration downstream of a CM and/or roof bolter in a different mine (called "Mine B"). Testing was conducted during six trials, which included three trials in each of two super sections in Mine B (called "Section 1" and "Section 2"), yielding a total of six sets of test data. The scrubber is a self-propelled unit manufactured by J.H. Fletcher & Co of Huntington, WV, which uses a vane axial fan (with a power rating of 22.4 kW at 480 V) to pull air through an on-board filter (with a 99% efficiency rating for 2 µm particles). It was originally designed to protect the roof bolter operator when working downstream of the CM. However, to simplify the field tests (i.e., not move the scrubber to follow CM and roof bolter movements), Organiscak et al. [7] placed the scrubber in the last open crosscut of the section being evaluated and allowed it to operate continually (except for when the CM was mining in the return entry). The scrubber airflow quantities ranged from about 1.3–2.3 m^3/s (2,700–4,900 CFM), while the initial airflow supplied to the face areas (i.e., without the scrubber operating) was 0.8–2.3 m^3/s (1,600–4,900 CFM). (It is worth noting that Organiscak et al. [7] reported that during the trials in Section 1 the scrubber intermittently turned off and had to be restarted.)

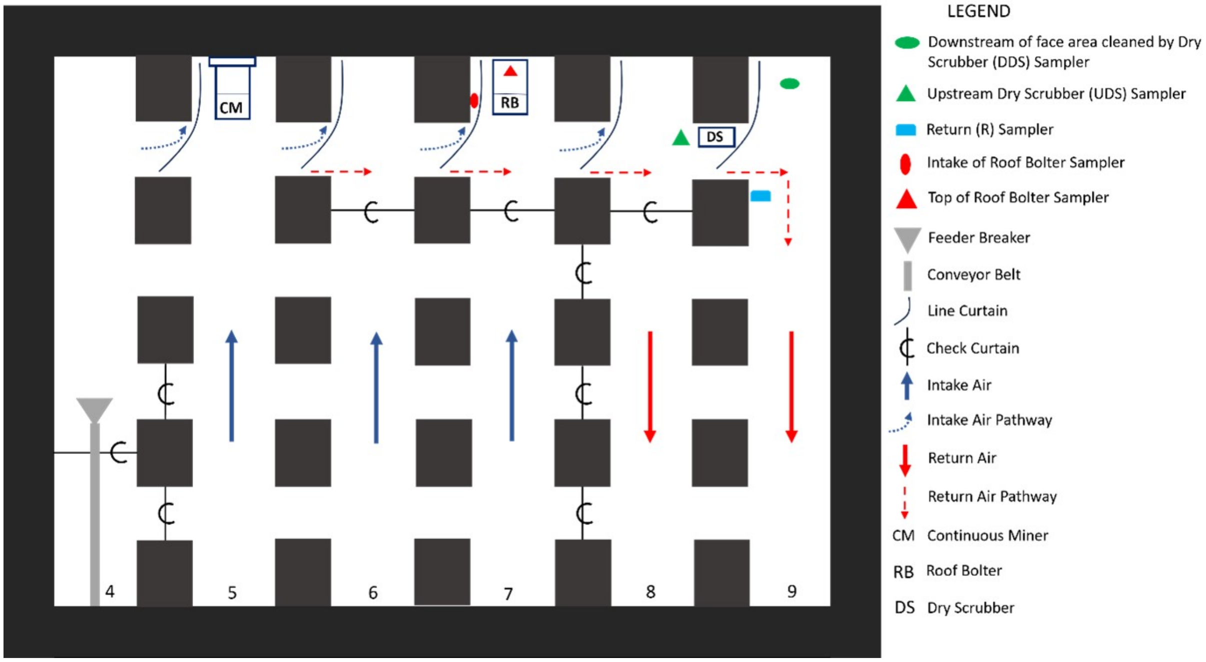


Figure 4.2: Schematic of sampling locations in NIOSH study of an auxiliary dry scrubber in Mine B (modified from Organiscak et al. [7]). Only samples from the locations denoted by green and blue symbols were included in the current work.

During each trial, Organiscak et al. [7] sampled in three stationary locations as shown in Figure 4.2: just upstream of the scrubber (UDS), downstream of the face area cleaned by the scrubber (DDS) (i.e., the face in the return entry), and further downstream in the return. (Samples were also collected in the roof bolter intake and on the roof bolter, though these are not included in the current work.) The sampling duration for each trial was between about 340-400 minutes. In each location, respirable dust samples were collected using the same equipment, flowrate, filters, and cassettes as used in the wet scrubber study for respirable dust. Additionally, a personal DataRam sampler (pDR 1000, Thermo Scientific, Waltham, MA) was used alongside the gravimetric samplers in each location to collect time-series data. The pDR is a light scattering device that can record data in real time, but it must be calibrated (i.e., using paired gravimetric samples) in order to estimate respirable dust concentration [25]. Organiscak et al. [7] was able to utilize the pDR data to interrogate various time periods of interest during each scrubber trial, including short periods when the instrument was used to monitor right at the scrubber exhaust (i.e., before mixing with other air could occur in the face area that should be cleaned).

4.3.3 Canopy Air Curtain (CAC) study

Reed et al. [22] evaluated the ability of a third-generation CAC to reduce respirable dust concentrations around an active roof bolter. Testing was conducted in the Lively Grove underground room and pillar mine (called "Mine C" from here) owned by Prairie State Energy. The mine employs blowing face ventilation with line curtain, and during the CAC testing, dust sampling was conducted while the roof bolter was working upstream of the CM (Figure 4.3). The sampling was conducted over two consecutive days. The roof bolter worked in two entries on Day 1 for a total of 140 minutes, and in four entries on Day 2 for a total of 420 minutes. Ventilation measurements were conducted in the intake airway to each entry (between the rib and the line curtain), and airflow quantities ranged from about 2.6–3.3 m^3/s (5,400 – 6,900 CFM). The only exception was for the fourth entry on Day 2 when the line curtain was not installed; in this case, the entire entry was considered the intake and the airflow was about 13.0 m^3/s (27,400 CFM).

Dust sampling was conducted in multiple locations per Figure 4.3: Intake samples were collected at the entrance and exit of the line curtain (left side of the roof bolter); bolter midpoint and rear samples were collected between the left and right booms and at the rear of the machine, respectively, which should be outside the CAC protection zone; return samples were collected in the airway downstream the bolter, just into the crosscut; and CAC area and personal samples were collected directly underneath the CAC plenum and on the vest of the roof bolter operator, respectively, on both the left and right side of the machine. The

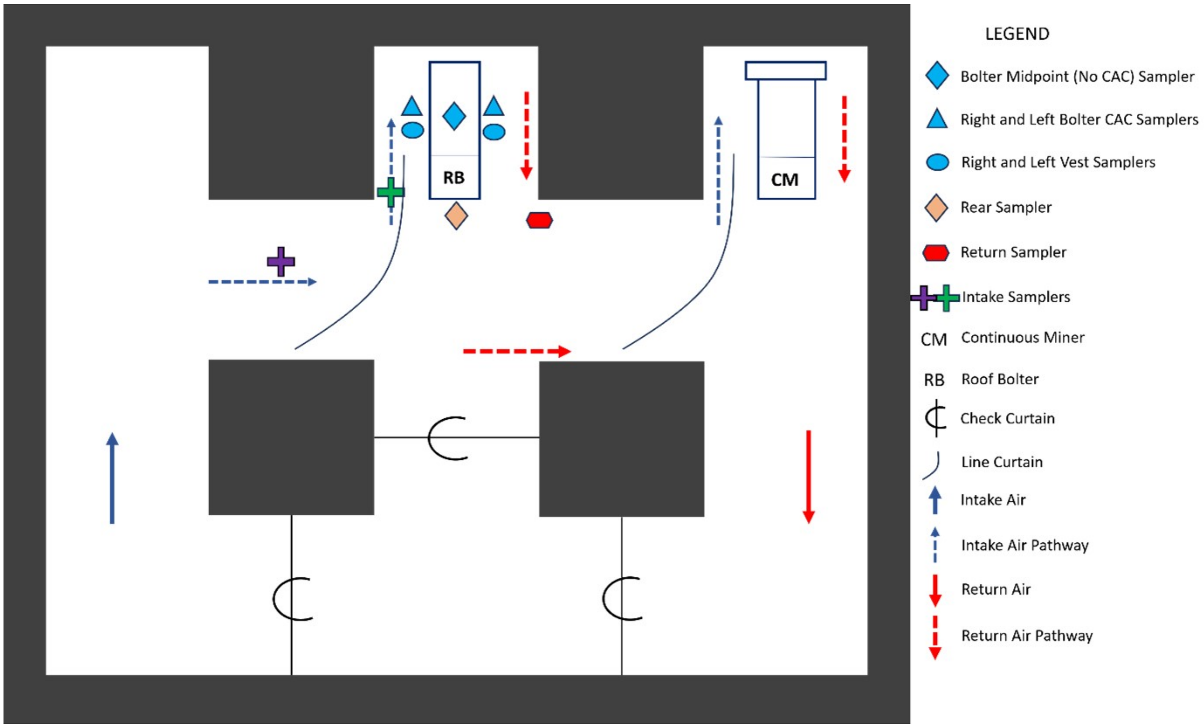


Figure 4.3: Schematic of sampling locations in NIOSH study of a roof bolter canopy air curtain in Mine C (modified from Reed et al. [16]). Only samples from the locations denoted by blue symbols were included in the current work.

area CAC samples should only represent the protection zone. However, since the operators occasionally moved from beneath the CAC plenum, the personal CAC samples represent the actual operator exposure.

Respirable dust samples were collected (in duplicate) in each of the above locations using the same standard equipment and filter media as was used in the wet and dry scrubber studies. (Notably, as the bolter moved from entry to entry each day, the samplers were also moved and set up in the same location in the next entry—but the sampling cassettes were not replaced between entries. Thus, each sample represents the total sampling time for all entries on a single day.) In addition to the gravimetric samplers, one pDR-1000 unit was used in each location to gather time-series data.

Reed et al. [22] determined CAC personal protection efficiency by comparing respirable dust concentrations measured using the personal vest samples (i.e., typically within the zone of influence of the CAC) versus the bolter midpoint samples (i.e., outside the zone of influence of the CAC). The personal protection efficiency was observed to be 26–60% on the left side of the bolter, and 3–47% on the right side. Moreover, the maximum protection efficiency was determined by comparing the concentrations measured with CAC area samples versus the bolter midpoint samples. The maximum protection efficiency was observed to be 55–79% on the left side of the bolter, and 40–67% on the right side.

4.4 Materials and Methods

In the three NIOSH studies summarized above, the PVC filter samples were only used for determining dust mass (and hence mass concentrations), which is non-destructive. However, NIOSH preserved many of the samples, and they were made available for the current work. Here, they were analyzed by scanning electron microscopy with energy dispersive X-ray (SEM-EDX) to determine mineralogy and particle size distributions, and/or by thermogravimetric analysis (TGA) to estimate the mass fractions of coal, non-carbonate minerals, and carbonates. These fractions can loosely approximate the major sources of dust in many mines (i.e., coal and rock strata being mined, and rock dust products being applied, respectively) [26, 27].

From the wet scrubber study, a total of 10 respirable dust samples were analyzed. These represent the locations that were 61 m (200 feet) and 122 m (400 feet) from the scrubber exhaust (Figure 4.1) for five different CM cuts (i.e., two without the scrubber installed, three with the scrubber operating). All 10 samples were analyzed by TGA, and nine were also analyzed by SEM-EDX; unfortunately, the tenth sample did not have enough dust for both analyses.

From the dry scrubber study, a total of 18 samples were analyzed. These represent the UDS, DDS and return locations (Figure 4.2) that were sampled on each of the six trials. For this study, all samples were analyzed by TGA, but only the UDS and DDS samples were analyzed by SEM-EDX. This is because the UDS and DDS samples were considered most likely to enable the assessment of any changes in dust characteristics related to the dry scrubber.

From the roof bolter CAC study, a total of 20 samples were analyzed. These represent duplicate samples from each of the two sampling days in the following five locations: the bolter midpoint, left and right CAC, and left and right personal vest locations (Figure 4.3). For this study, sample masses were generally low, so a decision was made to forego the TGA analysis to ensure that enough dust could be recovered for the SEM-EDX analysis.

4.4.1 Dust Sample Handling

Respirable dust samples were obtained directly from NIOSH in their original sampling cassettes (i.e., either MSA cassettes or 2-piece cassettes), in which they had also been stored since collection. Upon receipt, each sample that was to undergo both TGA and SEM-EDX analysis (i.e., those from the wet and dry scrubber studies) was carefully removed from its cassette and a stainless-steel trephine was used to cut a 9-mm subsection. The subsection was placed in a clean test tube and prepared for SEM-EDX, and the rest of the filter was placed into a separate clean test tube and prepared for TGA. For samples only routed for SEM-EDX analysis, larger subsections were cut and prepared.

4.4.2 TGA Analysis

TGA is an analytical technique that has been used in several previous studies to fractionate respirable coal mine dust samples into three primary mass components (i.e., coal, carbonates, and non-carbonate minerals) [26, 27]. The TGA instrument essentially consists of a highly controlled furnace chamber and microbalance. As a sample is heated in a specific atmosphere, the weight loss is monitored. In the case of respirable coal mine dust heated in high purity air, Agioutanti et al. [26] showed that weight loss can generally be observed in two main temperature regions corresponding to coal decomposition (between about 200-480 °C) and then carbonate decomposition (between about 480-800 °C). The residue at the end of the TGA routine is attributed to oxides produced from the carbonate decomposition plus (thermally inert) non-carbonate minerals. Accordingly, Agioutanti et al. [26] worked out a series of TGA mass balance equations to fractionate the total sample mass between the three primary components, and Jaramillo et al. [27] demonstrated the method on real respirable coal mine dust samples.

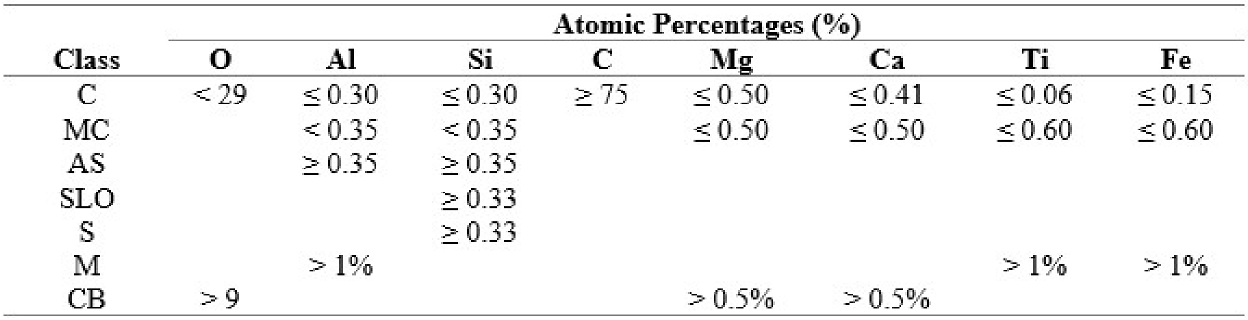
For the current work, TGA analysis was conducted following the method described by Jaramillo et al. [27]. Briefly, to each test tube with the available portion of the filter for this analysis, enough isopropanol (IPA) was added to completely submerge the filter (about 5-10 mL). The tube was capped and sonicated for approximately three minutes to dislodge the dust, and then the filter was carefully removed. The dust suspension was centrifuged for 10 min (at 2500 rpm) to settle the particles, and then a clean pipette was used to transfer the recovered dust to a clean, tared TGA pan. After the IPA had completely evaporated, recovered dust was analyzed by the same TGA instrument used by Jaramillo et al. [27] and Agioutanti et al. [26] (Q500, TA Instruments, New Castle, DE) and using the same thermal routine. The resulting thermogram was used to estimate the mass fractions of coal, carbonates and non-carbonates following the approach of Agioutanti et al. [26]. Notably, Agioutanti et al. [26] derived their equations using lab-generated respirable dust samples collected on polycarbonate (PC) filters (i.e., rather than PVC, as were available for the current work). Thus, prior to analysis of the mine dust samples in the current work, a series of lab-generated samples on PVC were used to modify the mass balance equations—again following the approach of Agioutanti et al. [26].

4.4.3 SEM-EDX Analysis

SEM-EDX is an analytical technique that can be used to study particle morphology (i.e., determined from image analysis) and elemental composition (i.e., determined from EDX spectra). This approach has been used widely for analysis of dust particles in air samples, including respirable coal mine dust [28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38]. Generally, some subset of particles in the sample are analyzed and binned by size (and possibly shape factors) and mineralogy to characterize the expected distributions for the entire sample.

For this study, samples were prepared for SEM-EDX analysis following the method detailed by Greth et al. [39] as follows: The 9-mm PVC filter subsections mentioned above were each placed in test tubes containing 5 mL of IPA, and then sonicated for 2 minutes to recover dust from the filter. Then, either a vacuum filtration unit or a syringe filter attachment was used to redeposit the particles from the IPA suspension onto a clean PC filter (track-etched, 0.4 µm pore size); the smooth, uniform PC filter is ideal for SEM-EDX work on respirable-sized particles. The PC filter was allowed to dry completely in a fume hood before preparation for SEM-EDX work. For this, a 9-mm subsection of the PC filter was cut, mounted on an aluminum stub, and sputter-coated with Au/Pd to render it conductive. As described by Sarver et al. [36, 37], SEM-EDX analysis was conducted on a FEI Quanta 600 FEG environmental SEM (Hillsboro, OR, USA) equipped with a backscatter electron detector (BSD) and a Bruker Quantax 400 EDX spectroscope (Ewing, NJ, USA). Bruker's Esprit software (Version 1.9.4) was used to run a computer-controlled routine for supra-micron (1-10µm) particles (originally described by Johann-Essex et al. [40]). The routine identified, sized, and collected EDX spectra on about 500 particles per sample. For each particle, the EDX spectra was used to determine the normalized atomic percentage for each of the eight elements (C, O, Al, Si, Ca, Mg, Fe, Ti). Using the classification criteria defined by Sarver et al. [37] (see Table 4.1), each particle was then binned into one of seven defined mineralogy constituent classes: Carbonaceous (C), Mixed carbonaceous (MC), Aluminosilicates (AS), Other Silicates (SLO), Silica (S), Heavy minerals (M) and Carbonates (CB). Any particle that did not fit into one of the pre-defined classes was placed into an "others" (O) class. Particle size data is reported here using projected area diameter (nm).

Table 4.1: The pre-defined criteria used to classify particles into the pre-defined constituent classes based on the normalized atomic % of each element (modified from Sarver et al. [37]).



	Atomic Percentages (%)							
Class	**O**	**Al**	**Si**	**C**	**Mg**	**Ca**	**Ti**	**Fe**
C	< 29	≤ 0.30	≤ 0.30	≥ 75	≤ 0.50	≤ 0.41	≤ 0.06	≤ 0.15
MC		< 0.35	< 0.35		≤ 0.50	≤ 0.50	≤ 0.60	≤ 0.60
AS		≥ 0.35	≥ 0.35					
SLO			≥ 0.33					
S			≥ 0.33					
M		> 1%					> 1%	> 1%
CB	> 9				> 0.5%	> 0.5%		

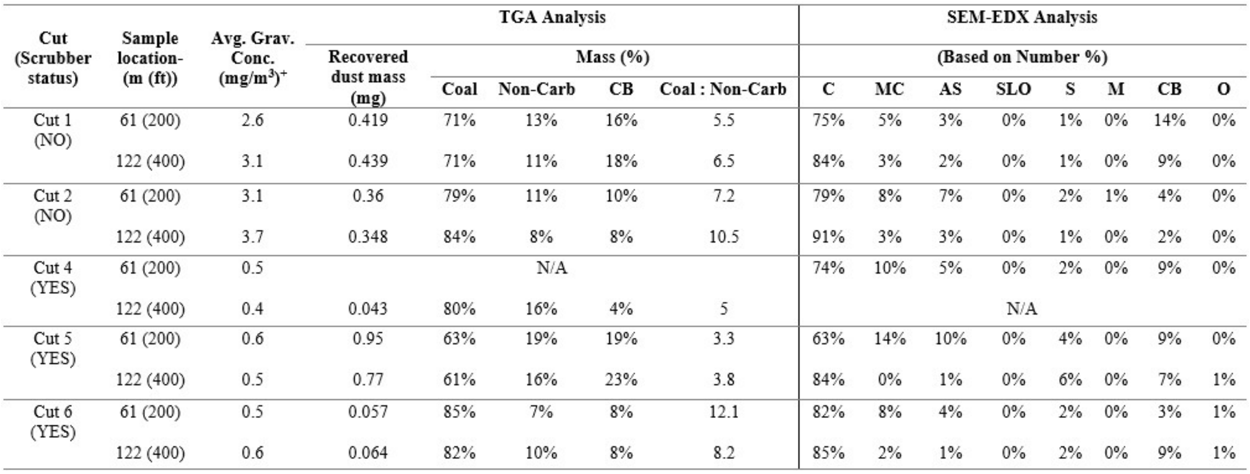
4.5 Results and Discussion

4.5.1 Wet Scrubber

Table 4.2 summarizes the gravimetric, TGA, and SEM-EDX results for the dust samples collected during the wet scrubber testing in Mine A. The relatively small recovered-dust masses for Cuts 4-6 (versus Cuts 1 and 2) are consistent with the relatively low dust concentration reported in the section return when the scrubber was being operated upstream [6, 9].

With respect to dust composition, the TGA results in Table 4.2 show that coal ranged from 61–85% of the dust mass during a given cut, with the average from all cuts being 75 ± 5.5% (95% confidence); the non-carbonate content ranged from 7–19%, with the average being 12 ± 2.5%; and the carbonates ranged from 4–23%, with the average being 13% ± 4.0%. However, no consistent trends are observed related to the scrubber status, per se, and given the small number of tests under each condition (scrubber operating versus not installed) statistical tests were not utilized here.

Table 4.2: Summary of dust characterization results for samples collected during the wet scrubber study in Mine A.



Cut (Scrubber status)	**Sample location- (m (ft))**	**Avg. Grav. Conc. $(mg/m^3)^+$**	**TGA Analysis**					**SEM-EDX Analysis**							
			Recovered dust mass (mg)	**Mass (%)**				**(Based on Number %)**							
				Coal	**Non-Carb**	**CB**	**Coal : Non-Carb**	**C**	**MC**	**AS**	**SLO**	**S**	**M**	**CB**	**O**
Cut 1 (NO)	61 (200)	2.6	0.419	71%	13%	16%	5.5	75%	5%	3%	0%	1%	0%	14%	0%
	122 (400)	3.1	0.439	71%	11%	18%	6.5	84%	3%	2%	0%	1%	0%	9%	0%
Cut 2 (NO)	61 (200)	3.1	0.36	79%	11%	10%	7.2	79%	8%	7%	0%	2%	1%	4%	0%
	122 (400)	3.7	0.348	84%	8%	8%	10.5	91%	3%	3%	0%	1%	0%	2%	0%
Cut 4 (YES)	61 (200)	0.5	N/A					74%	10%	5%	0%	2%	0%	9%	0%
	122 (400)	0.4	0.043	80%	16%	4%	5	N/A							
Cut 5 (YES)	61 (200)	0.6	0.95	63%	19%	19%	3.3	63%	14%	10%	0%	4%	0%	9%	0%
	122 (400)	0.5	0.77	61%	16%	23%	3.8	84%	0%	1%	0%	6%	0%	7%	1%
Cut 6 (YES)	61 (200)	0.5	0.057	85%	7%	8%	12.1	82%	8%	4%	0%	2%	0%	3%	1%
	122 (400)	0.6	0.064	82%	10%	8%	8.2	85%	2%	1%	0%	2%	0%	9%	1%

+ data was obtained from NIOSH with the filter samples, but it was not included in their published reports [6, 9].*N/A the entire filter was used for TGA so nothing was available for SEM.

That said, the TGA results do show variability between different CM cuts. For example, the relative percentages of coal and non-carbonate contents in the dust—which are likely sourced primarily from the coal and rock strata at the production face, respectively—vary from cut to cut. This is probably due to variability in the relative heights of coal and rock mined at the face during each cut; and a simple ratio between the coal to non-carbonates ratio can be used as a crude indicator. For example, Cuts 2 and 6 appear to show a high coal to non-carbonate content ratio, suggesting more of the mining height was in coal than in rock during these cuts (as compared to Cuts 4 and 5). Given that the most hazardous constituents in respirable coal mine dust (e.g., respirable silica) are generally associated with rock strata-sourced dust [31, 41], a consistent trend in the coal to non-carbonate ratio with respect to the scrubber operation would certainly be of interest—however, none is observed here.

In Mine A, the carbonate content was likely sourced from rock dusting activities in the mine (i.e., rather than any geologic strata), and rock dust products are generally not considered as respiratory hazards [42]. From Table 4.2, the TGA results again primarily indicate differences between cuts. For instance, Cuts 1 and 5 show more carbonates than Cuts 2, 4, and 6. While rock dusting was halted during NIOSH's dust sampling for this study, Janisko et al. [6] reported that operation of the auxiliary fan with the scrubber appeared to re-entrain rock dust that had been applied earlier. This could explain the relatively high carbonates content during Cut 5, though high carbonates during Cut 1 (when the auxiliary fan and scrubber were not in place) indicates that rock dust also contributed to the respirable fraction during some periods without the fan. This is consistent with observations of CM section return samples in other mines [36].

The SEM-EDX results in Table 4.2 are based on number percent per mineralogy class. While they do not exactly match the TGA data—which is consistent with expectations from earlier work by Pokhrel et al. [34]—the two datasets generally trend together in terms of major groups of constituents. For example, like the TGA results, the SEM-EDX indicated that coal dust (represented by the C and MC classes) accounted for the majority of particles in all samples (i.e., 86% ± 3.1%). Thus, the rock strata-sourced dust (represented by the AS, SLO and S classes, analogous to TGA non-carbonates) and the rock-dusting-sourced dust (represented by the CB class, analogous to TGA carbonates) accounted for smaller percentages (i.e., 6 ± 2.0% and 7 ± 2.0%, respectively). Also consistent with the TGA results, the SEM-EDX results show variation in dust constituents from cut to cut—though, again, no clear effect of the wet scrubber can be seen.

The SEM-EDX data was additionally used to investigate particle size. Figure 4.4 shows the overall size distributions (i.e., when particle sizes from all constituent classes are combined), as well as distributions for major groups of constituents (i.e., C+MC, AS+SLO+S, and CB). (A summary of the particle size data per constituent class is given in Table A.1 in appendix A.) The relative differences between the size distribution for each group help explain some of the differences between the number-based SEM-EDX results and the mass-based TGA results. For example, the coal dust particles are somewhat finer than the other particles, which can equate to less coal dust mass even when particle numbers are high.

From Figure 4.4, the respirable dust was finer overall in both the 61 m (200-feet) and 122 m (400-feet) locations when the wet scrubber was in operation (Cuts 4, 5, and 6) versus when it was not installed (Cuts 1 and 2). Finer size with operation of the scrubber is consistent with expectations as the scrubber should be more efficient in removing coarser particles [10]. Since the coal dust accounted for most of the particle counts in all samples, the C+MC size distributions follow a similar trend to the overall distributions. The particles sourced from rock strata (AS+SLO+S) also follow this trend, with the exception of the distribution from the 61 m (200-feet) location in Cut 1. Consistent trends in particle size distribution with the scrubber status were not observed for the CB particles, but this makes sense given that CB particles were probably from rock dust that had been applied downstream of the scrubber. Thus, while the CB particles were more likely to be re-entrained in the airflow due to the operation of the scrubber, the particles may not have moved through the scrubber and been subject to removal by it. Figure 4.4 also shows that respirable dust was generally finer at the 122 m (400-feet) location than at the 61 m (200-feet) location, though the shift in distributions is fairly small. This is not surprising since most respirable-sized particles

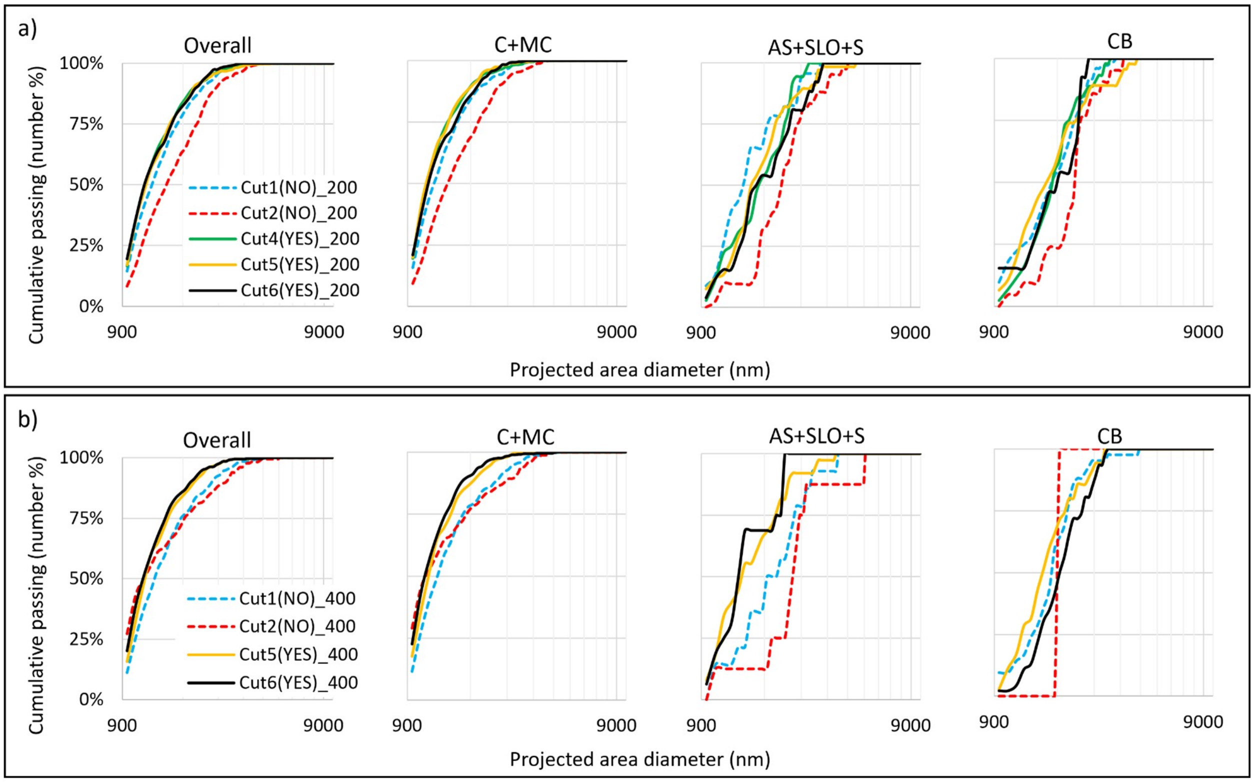


Figure 4.4: Particle size distributions derived from SEM-EDX analysis of respirable dust samples collected in Mine A at locations a) 61 m (200 feet) and b) 122 m (400 feet) from the wet scrubber location. The left plots show the overall size distribution (i.e., considering all particles) and the other plots show major groups of constituents. [Cuts 1-2 scrubber not operating; Cuts 4-6 scrubber operating].

should remain entrained in the mine air over long distances [1, 43].

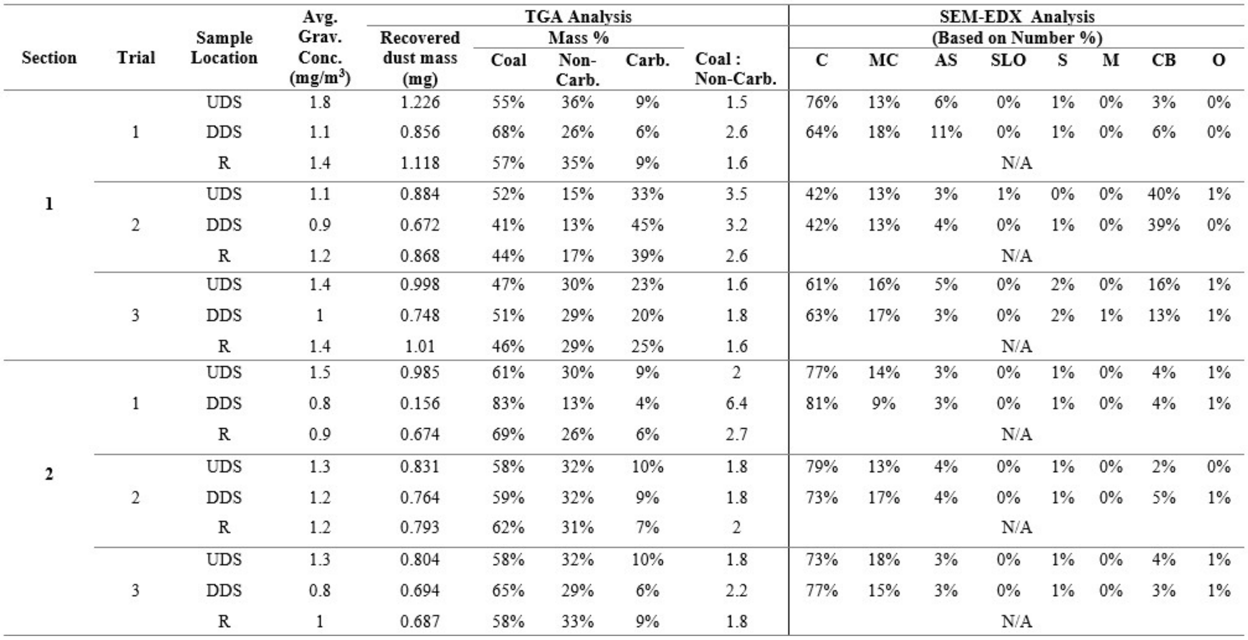
Given the increasing attention on enhanced hazards of fine inhalable particles, including submicron and nano-particles [28, 36, 37, 44, 45, 46, 47], the effect of the wet scrubber to shift the overall particle size distribution might seem concerning. However, it must be reiterated that the data here indicates that the reduction in particle size occurred concurrently with a reduction in dust concentration (i.e., comparing Cuts 1 and 2 to Cuts 4, 5 and 6 in Table 4.2). To properly evaluate the relative hazard of a dust exposure, particle size, chemistry and concentration should be considered. Thus, to evaluate the effect of a specific control, the particle removal efficiency per class and size bin is important and could be determined via paired measurements up- and downstream of the control. Though not possible with the samples available for the current studies, such an experiment could be conducted in the future.

4.5.2 Dry Scrubber

Table 4.3 shows the gravimetric, TGA and SEM-EDX results for the respirable dust samples collected from Mine B during the dry scrubber testing. For each trial, the difference between the dust concentration measured in the UDS and DDS locations illustrates the effect of the dry scrubber to improve the air quality in the face area it was supposed to clean. The dust concentrations in the return (R) location are similar to those in the UDS locations, however, which indicates that the cleaning effect of the scrubber was limited to the DDS face area. As explained by Organiscak et al. [7], the scrubber has a high dust collection efficiency, but it only treats a portion of the mine air; in Mine B, the scrubber exhaust was gradually mixed with other air in the return entry.

From the TGA results in Table 4.3, dust composition seems to have varied from trial to trial. For example, carbonate content in the three sampling locations was relatively low (i.e., not more than 10%) during all trials in Section 2, but was higher (i.e., between 20–45%) in two of the trials in Section 1. In Mine B, the carbonate content is again expected to be associated with rock dusting activities (i.e., rather than geologic strata), so the elevated carbonate content is probably due to active rock dusting (somewhere upstream of the scrubber) during or just before those two trials or due to re-entrainment of applied rock dust. While the coal and non-carbonates percentages also seem to vary by trial, Table 4.3 indicates that the coal to non-carbonate ratio was typically somewhat higher in the DDS location versus the UDS location—which suggests that the dry scrubber may have been more efficient at removing non-carbonate dust than coal dust in this study. For the DDS location, the ratio ranged from 1.8–6.4, with the average being 3.0 ± 1.7 (at 95% confidence); and for the UDS location, it ranged from 1.5–3.5, with the average being 2.0 ± 0.7. However, a two-sample t-test (assuming unequal variances and = 0.05) indicated that the difference in the means is not statistically significant (p = 0.1269).

Table 4.3: Summary of dust characterization results for samples collected during the dry scrubber study in Mine B.



Section	Trial	Sample Location	Avg. Grav. Conc. (mg/m^3)	TGA Analysis					SEM-EDX Analysis							
				Recovered dust mass (mg)	Mass %			Coal : Non-Carb.	(Based on Number %)							
					Coal	Non-Carb.	Carb.		C	MC	AS	SLO	S	M	CB	O
1	1	UDS	1.8	1.226	55%	36%	9%	1.5	76%	13%	6%	0%	1%	0%	3%	0%
		DDS	1.1	0.856	68%	26%	6%	2.6	64%	18%	11%	0%	1%	0%	6%	0%
		R	1.4	1.118	57%	35%	9%	1.6	N/A							
	2	UDS	1.1	0.884	52%	15%	33%	3.5	42%	13%	3%	1%	0%	0%	40%	1%
		DDS	0.9	0.672	41%	13%	45%	3.2	42%	13%	4%	0%	1%	0%	39%	0%
		R	1.2	0.868	44%	17%	39%	2.6	N/A							
	3	UDS	1.4	0.998	47%	30%	23%	1.6	61%	16%	5%	0%	2%	0%	16%	1%
		DDS	1	0.748	51%	29%	20%	1.8	63%	17%	3%	0%	2%	1%	13%	1%
		R	1.4	1.01	46%	29%	25%	1.6	N/A							
2	1	UDS	1.5	0.985	61%	30%	9%	2	77%	14%	3%	0%	1%	0%	4%	1%
		DDS	0.8	0.156	83%	13%	4%	6.4	81%	9%	3%	0%	1%	0%	4%	1%
		R	0.9	0.674	69%	26%	6%	2.7	N/A							
	2	UDS	1.3	0.831	58%	32%	10%	1.8	79%	13%	4%	0%	1%	0%	2%	0%
		DDS	1.2	0.764	59%	32%	9%	1.8	73%	17%	4%	0%	1%	0%	5%	1%
		R	1.2	0.793	62%	31%	7%	2	N/A							
	3	UDS	1.3	0.804	58%	32%	10%	1.8	73%	18%	3%	0%	1%	0%	4%	1%
		DDS	0.8	0.694	65%	29%	6%	2.2	77%	15%	3%	0%	1%	0%	3%	1%
		R	1	0.687	58%	33%	9%	1.8	N/A							

Like for the wet scrubber study in Mine A, the SEM-EDX and TGA results for the dry scrubber study in Mine B do not match exactly but they tend to trend together. Table 3 shows that samples with the highest or lowest TGA-derived mass percentages of coal, non-carbonates, or carbonates generally also had the highest or lowest SEM-EDX-derived number percentages of particles in the analogous constituent groups (i.e., C+MC, AS+SLO+S, or CB, respectively). Moreover, differences in particle size distributions for the three constituent groups (Figure 4.5) can again help to explain some of the apparent differences in the SEM-EDX and TGA results. Similar to the results from Mine A, the C and MC particles in Mine

B—despite being high in number percentage—appear to be finer than other particles, which might explain the relatively lower TGA mass percentage of coal dust. Conversely, the AS, SLO and S particles were typically coarser, which might explain the relatively higher TGA mass percentage of non-carbonate dust. A summary of the particle size data per constituent class is given in Table A.2 in Appendix A.

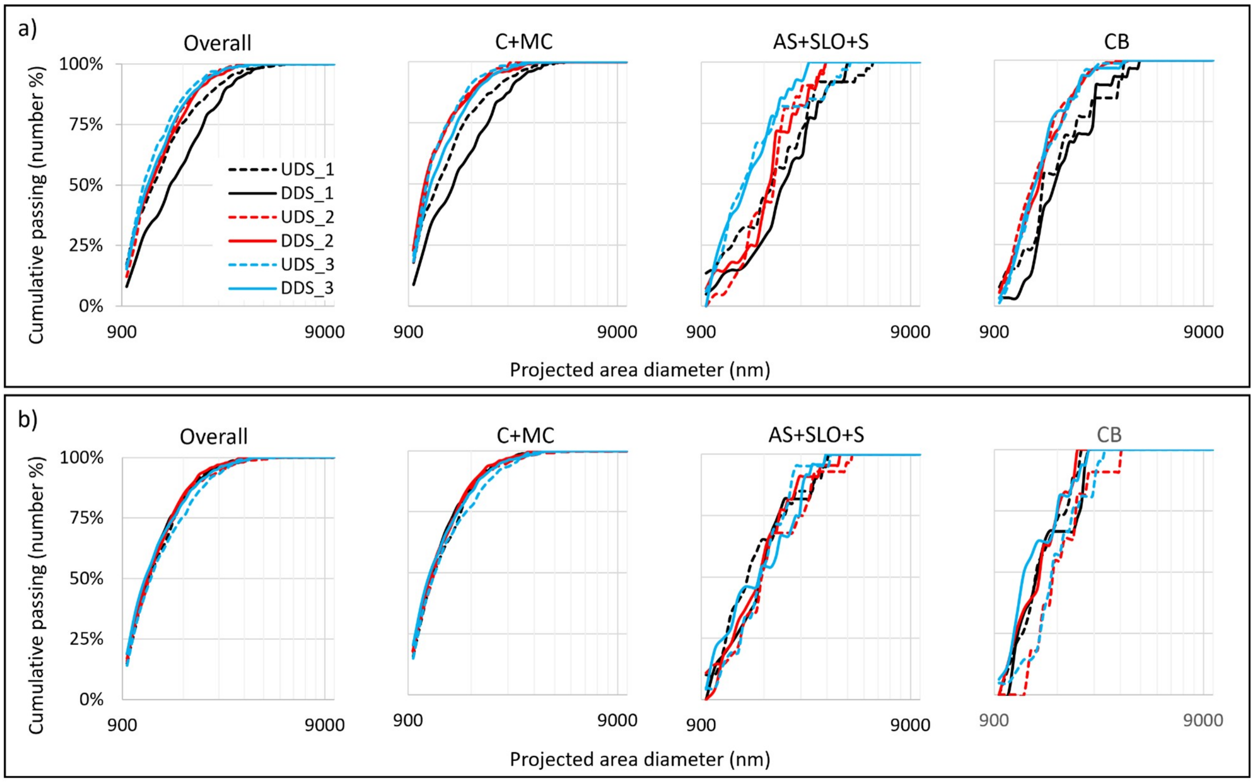


Figure 4.5: Particle size distributions derived from SEM-EDX analysis of respirable dust samples collected in Mine B during the dry scrubber trials in a) Section 1 and b) Section 2. The left plots show the overall size distribution (i.e., considering all particles) and the other plots show major groups of constituents.

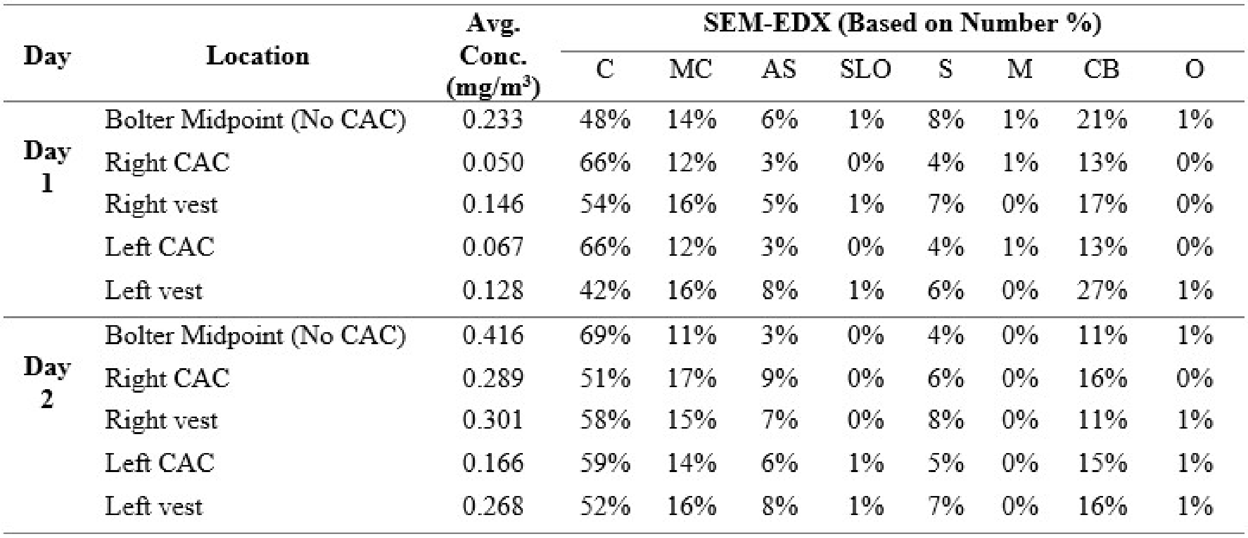
Unlike for the wet scrubber study, a consistent effect of the dry scrubber on particle size cannot be observed in Figure 4.5. In fact, the expected trend toward finer particle sizes in the DDS location versus the UDS location can only be seen in the overall size distributions for the third trial in Section two. In all other trials, the DDS and UDS overall size distributions are either very similar, or the DDS distribution is actually somewhat coarser than the UDS distribution (e.g., the first trial in Section 1). While this might seem contrary to expected behavior for the particle size distributions, it must be reiterated that the DDS samples do not perfectly represent the size distribution at the dry scrubber exhaust, but rather the distribution at the face area that was supposed to be cleaned by the scrubber. Thus, DDS samples represent a mix of the scrubber exhaust and other mine air in the return entry face area—and the true particle size reduction yielded by the dry scrubber is likely muted in the DDS samples. Moreover, Organiscak et al. [7] noted an issue with the scrubber intermittently turning off and needing to be restarted during the testing in Section 1. It is possible that these startup events dislodged coarse particles from the scrubber filter, which might have affected the size distribution results in the DDS location.

4.5.3 Canopy Air Curtain

Table 4.4 shows the gravimetric and SEM-EDX results for the respirable dust samples collected during the roof bolter CAC testing in Mine C. As reported by Reed et al. [22], dust concentrations on both days of testing were higher at the bolter midpoint location (i.e., outside the CAC zone of protection) than in the locations directly under the CAC or measured on the operator's vest—which demonstrates the effectiveness of the CAC. Notably, the concentrations under CAC were lower than those measured on the operator's vest, which is attributed to the fact that the operators occasionally moved out of the CAC zone Reed et al. [22]. The tendency for the concentrations on the left side of the bolter to be lower than concentrations on the right is attributed to the ventilation direction in the mine; per Figure 4.3, the intake air was on the left of the bolter.

While TGA was not performed on any of the preserved dust samples from this study, the SEM-EDX results can be used to examine constituents. Table 4.4 shows that, like for the scrubber studies in Mines A and B, the respirable dust in Mine C was dominated by coal particles. The C+MC (number %) ranged from 58–80%, with the average being 71 ± 4.1%. The rest of the dust included various minerals, including silicates (AS+SLO, 12 ± 3.7%), silica (S, 5.9 ± 1.6%) and carbonates (CB, 16 ± 4.9%). Although the AS, SLO and S particles were likely sourced from the rock strata being drilled by the roof bolter (or re-entrained from previous mining by the CM), the source of the CB particles in Mine C is not straightforward. This is because the roof rock strata in Mine C can include limestone, which is dominated by calcium carbonate. Thus, the higher CB content observed in Table 4 as compared to the other mine locations in this study may be sourced from the roof bolter activities. In any case, the source of the CB particles is likely the same for all the sampling locations analyzed for the CAC study, and therefore should not affect the ability to compare results across locations.

Table 4.4: Summary of dust characterization results for samples collected during the roof bolter CAC study in Mine C. (Note: Each value represents the average of duplicate samples for that specific location and day)



Day	Location	Avg. Conc. (mg/m^3)	SEM-EDX (Based on Number %)							
			C	MC	AS	SLO	S	M	CB	O
Day 1	Bolter Midpoint (No CAC)	0.233	48%	14%	6%	1%	8%	1%	21%	1%
	Right CAC	0.050	66%	12%	3%	0%	4%	1%	13%	0%
	Right vest	0.146	54%	16%	5%	1%	7%	0%	17%	0%
	Left CAC	0.067	66%	12%	3%	0%	4%	1%	13%	0%
	Left vest	0.128	42%	16%	8%	1%	6%	0%	27%	1%
Day 2	Bolter Midpoint (No CAC)	0.416	69%	11%	3%	0%	4%	0%	11%	1%
	Right CAC	0.289	51%	17%	9%	0%	6%	0%	16%	0%
	Right vest	0.301	58%	15%	7%	0%	8%	0%	11%	1%
	Left CAC	0.166	59%	14%	6%	1%	5%	0%	15%	1%
	Left vest	0.268	52%	16%	8%	1%	7%	0%	16%	1%

Reviewing Table 4.4, the CAC does not appear to have a consistent influence on dust constituents. For example, on Day 1, the bolter midpoint sample had less coal (C+MC) and more minerals (AS+SLO+S+CB) than most of the samples protected by the CAC; but on Day 2, the opposite was observed. However, the particle size distributions (Figure 4.6) suggest that the CAC may have had some influence on particle size. A summary of the particle size data per constituent class is given in Table A.3 in appendix A. The Day 1 results show that, overall, the bolter midpoint sample had slightly coarser dust than the samples protected by the CAC; and the main differences were specifically for the AS+SLO+S constituent group. The particles in that group were particularly fine under the CAC on the right side of the bolter, and in the right-side operator's vest sample. This may be partially explained by the fact that the airflow through the CAC is filtered using a MERV 13 filter. Taken together, these findings might suggest that the CAC is more effective at filtering the mine air that flows over the miner, pushing away coarser particles from outside mine air preventing them from entering the CAC zone of influence, or that there is an inherent difference in particle size on different sides of the bolter. Regarding the latter, one explanation could be that coarser particles on the left side are due to airflow dynamics. Since the intake air moves from left to right over the bolter in the particular setup studied in Mine C, the airflow over the right bolter may have accumulated coarse particles generated from the left bolter. Another explanation could be differences in the dust generation during bolting operations on the left and right side of the bolter.

Unfortunately, the Day 2 results offer little insight since the particle size distributions are very similar across all five of the sampling locations analyzed here (Figure 4.6). It is worth mentioning that the samplers were not paused between completion of each bolting pattern and the subsequent move into another entry [22]. Thus, any dust collected during roof bolter break and move times, is included in the samples analyzed here. The sampling during break and move times may have diluted the impact of the CAC influences on the samples. There is no way to remove the effect of dust collection during roof bolter breaks and move times on these collected samples. Therefore, it is not possible to discern the effect of sample collection during these times. Given that the Day 1 samples only represent two entries (i.e., one break/-move event) and the Day 2 samples represent four entries (i.e., three break/move events), this might have had some impact on the results—especially the operator vest samples, since the operator moved from under the CAC during these events [22].

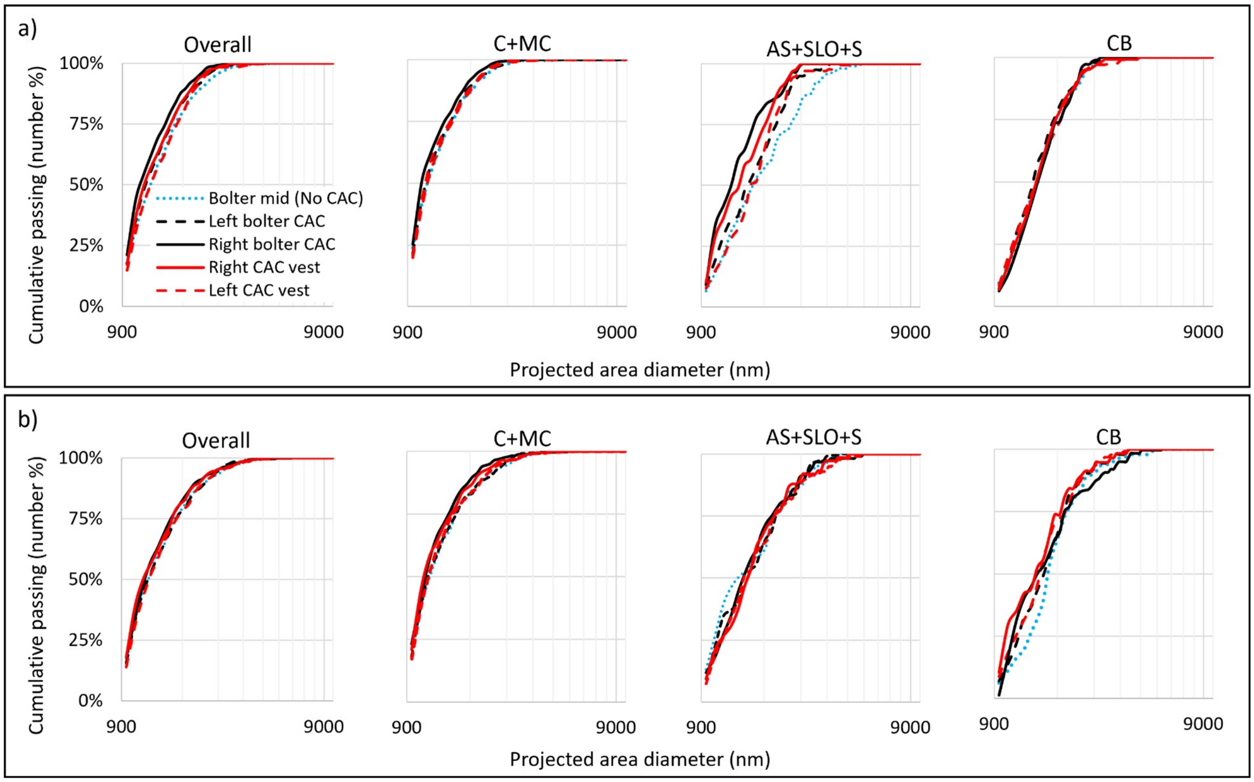


Figure 4.6: Particle size distributions derived from SEM-EDX analysis of respirable dust samples collected in Mine B during the dry scrubber trials in a) Section 1 and b) Section 2. The left plots show the overall size distribution (i.e., considering all particles) and the other plots show major groups of constituents.

4.5.4 Research Implications and Limitations

The current work demonstrates that detailed dust analysis can be performed on appropriate samples preserved from prior studies [48]. This approach has obvious merits: it enables further insights to be gained about the effects of particular dust controls or sampling conditions on respirable dust characteristics, without the significant time, cost and logistical efforts needed to conduct new field work. Indeed, in another recent investigation by the authors [48], preserved dust samples were used to explore the effects of a novel wet dust collection system for a roof bolter on respirable dust characteristics; results suggested the wet system may be particularly effective for reducing silica and silicates exposure of the roof bolter operator during dust box cleanout, which added to the findings of the original study for which the dust samples were collected [49].

Nevertheless, it is also important to acknowledge the limitations of such follow-up sample analysis, including the fact that analytical options and interpretation of results is constrained by the original study design. Regarding NIOSH's original studies that were revisited for the current work, their sampling designs were geared toward specific research objectives, which did not include the sort of dust sample analysis performed here. For example, samples were not collected at the wet scrubber intake or dry scrubber exhaust, which somewhat limits the conclusions that can be drawn about the direct effects of either scrubber on particle sizes or specific dust components. Similarly, the fact that samplers used in the CAC study were not paused after completion of sampling in each entry but allowed to continuously run prior to the start of the subsequent test, might have limited the conclusions that could be drawn of the impacts of the CAC on dust constituents and sizes. This meant that the operator moved out of the zone of influence of the CAC on a few occasions during testing, which might have led to the mixing of the CAC vest sample with air from other parts of the mine.

It is also important to reiterate that, while the current study only used the SEM-EDX to analyze particles in the supra-micron range, there is increasing attention on the possible risks of exposure to finer, even nano-sized, particles in mine environments [33, 35, 36, 37, 44, 45, 46, 47]. Analysis well into the submicron range is possible with modern SEM instruments, and has been demonstrated previously [33, 36, 37, 44]. Future studies related to respirable dust controls and exposure monitoring should extend analysis to finer particles to fill the knowledge gap in this area.

4.6 Conclusions

Since dust generation due to strata cutting in mining is inevitable, engineering controls are employed to control respirable dust hazards in underground coal mines. Engineering controls such as auxiliary scrubbers and canopy curtains investigated by NIOSH in prior research have proven to be efficient in reducing coal miner exposure to respirable dust concentrations. In this study, preserved samples from three such NIOSH studies on dry and wet auxiliary scrubbers, and a roof bolter canopy air curtain system were analyzed by TGA and SEM-EDX to evaluate the effects of the controls on respirable dust characteristics (i.e., dust composition and particle sizes).

The samples from all studies were dominated by coal dust particles, with varying amounts of mineral particles—sourced either from the rock strata being drilled or cut in the mine, or from the application of rock dust products. No consistent effect of any of the three controls on dust composition could be demonstrated—at least under the sampling conditions for the original NIOSH studies. That said, the results for the dry scrubber, though not statistically significant, suggested that there might be some differential effect on coal versus mineral particles. Specifically, the samples collected in the face area downstream of the dry scrubber (versus those collected just upstream of the scrubber) were generally found to have somewhat higher ratios of coal to rock-strata sourced dust. This might mean that the scrubber was slightly more efficient on the mineral dust particles, which could be related to a number of factors including particle size or surface characteristics. This point begs for further investigation.

Furthermore, the operation of the wet scrubber appeared to shift the size distribution toward finer particles and the canopy air curtain appeared to also slightly reduce dust particle sizes within its zone of influence. Although a similar trend was not evidenced for the dry scrubber, this might have been due to the specific sampling location downstream the scrubber, which enabled mixing of the scrubber exhaust with other return air.

While this study demonstrates that preserved dust samples can be revisited for follow-up analysis, it presents various limitations related to gap between original study objectives and the questions that might be asked by follow-up research. To further explore the effects of dust controls on dust characteristics, future testing should be specifically designed to investigate efficiencies related to dust concentration reduction as well as changes in composition and sizes. Particular attention should be given to the efficiency for reducing concentrations of the most harmful constituents such as respirable silica. For this work, samples should ideally be collected at locations just up- and downstream of a given control to validate the various efficiency metrics. Additionally, a focus on sub-micron (and even nano-sized particles) would be valuable in light of growing evidence that finer particles can present increased hazards.

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Contributions

F. Animah: Conceptualization and design, material preparation, data collection and analysis, methodology, data visualization, writing-original draft, and addressing reviews and edits.
C. Keles: VT SEM-EDX methodology, writing-review and editing
W.R. Reed: preserved NIOSH dust samples, writing-review and editing
E. Sarver: Conceptualization and design, resources, writing-review and editing, supervision, and funding acquisition

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Chapter 5

Effect of Flooded Bed Scrubber on Respirable Dust Removal Efficiency as a Function of Particle Type and Size[1]

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5.1 Abstract

Scrubbers are commonly used to control dust generated from continuous miner machines in underground coal mines and prior research has demonstrated they can be effective in reducing

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respirable dust by mass. However, little is known about the effect of scrubber performance on particle characteristics, specifically very fine respirable dust. In this study, a newly built experimental apparatus at NIOSH's Pittsburgh Mining Research Division was used to test a flooded-bed scrubber (FBS) prototype under variable conditions with respect to the FBS filter type (i.e., either a conventional 30-layer screen or novel impingement screen) and dust feed material (i.e., derived either from raw coal, rock, or a blend of these). Dust sampling was conducted upstream and downstream of the scrubber to collect respirable dust (i.e., less than 10 µm, with about 50% collection efficiency for 4 µm particles) and real-time particle monitors (i.e., to count between 0.3-10 µm). While average mass removal efficiencies based on gravimetric analysis of filter samples ranged between 40–78%, particle removal efficiencies (by counts) were observed to be much lower—and sometimes negative—based on data derived from filter sample analysis by electron microscopy and the real-time monitors. This trend was driven by particles in the size bins less than 2 µm, which might be related to relative changes in agglomerated particles as they move through the system. The results suggest the destruction of agglomerates can increase the abundance of fine particles downstream of the FBS versus the upstream location. The formation of agglomerate could explain a higher abundance of mid-sized particles (i.e., 1-3 µm size bins). Nevertheless, consistent differences in particle removal efficiencies could not be discerned between the conventional and impingement filter screens when tested at the same airflow volume, nor between the different dust types.

5.2 Introduction

Airborne dust continues to be a serious occupational safety and health concern for coal miners in the US and elsewhere. Excessive float dust creates an imminent explosibility hazard, and overexposure to respirable coal mine dust (RCMD) can lead to lung disease [1, 2, 3]. While dust standards and related monitoring programs have long focused on limiting mass concentrations, for RCMD there is increasingly an awareness that particle number concentration may also be important [4]. Although the finest particles generally do not make up much of the RCMD mass concentration, they have the potential to penetrate deep into the lung and have high surface area which can promote physiochemical reactions [5, 6].

Coal mines use a variety of dust controls, many of which can be beneficial for both float dust and RCMD. Flooded-bed scrubbers (FBSs) are extensively used on continuous miner (CM) machines to limit dust at the source [7, 8, 9]. In essence, they work by drawing dust-laden air from the active production face through a wet filter screen (sometimes called a 'mesh'), which traps some of the particles; and a downstream demister can capture more particles before dry air is discharged through the scrubber exhaust [10]. Even though the demister's primary function is to remove water droplets from the scrubber system, it indirectly facilitates in the removal of dust particles captured in these water droplets. Numerous studies, mostly by the Mining Research Division of NIOSH, have shown FBSs can be effective for reducing RCMD mass concentrations, with up to 90% removal efficiencies [11, 12, 13, 14]. Further improvements have been observed when FBSs were operated in concert with specific water spray and face ventilation parameters [15, 16, 17].

However, the effects of FBSs on specific dust particle sizes and constituents have not been widely investigated. Indeed, only a few reports could be found in the published literature [11, 12, 18, 19]. In one laboratory study by Colinet et al. [11], a Joy 40-layer filter screen was tested using a blend of coal and silica dust (i.e., 90%/10% by mass). Results indicated removal efficiencies were somewhat higher for respirable silica than respirable coal (i.e., 94.6% versus 90.2% by mass). In a follow-up study, Colinet & Jankowski [12] tested additional FBS screens at different airflows using another coal/silica blend (this time 80%/20% by mass). They found that silica removal efficiency was greatest (95% by mass) for a conventional

30-layer screen operated at the higher of two airflows tested (i.e., 7,900 versus 5,000 CFM). Kumar et al. [20] recently conducted a lab study to compare the conventional filter to a novel 'impingement' filter design. (Notably, the impingement filter aims to reduce scrubber downtime for filter unclogging, which is required for conventional filters since they gradually cake with dust, which reduces airflow and thus overall air cleaning capacity.) Kumar et al. [20] concluded that the impingement filter offers comparable RCMD mass removal efficiency to the conventional filter. In that study, particle size data was collected, but it was limited to particles >2 µm, and most RCMD particles are likely to be finer (e.g., see Sarver et al. [21]). In a recent field study, Animah and Sarver (n.d.) sampled RCMD just downwind an active CM during periods with and without the FBS in operation and analyzed particle size down to 1µm; dust was finer when the FBS was operating, indicating it was more effective on coarser particles. This is consistent with expectations for a physical filtration process. It also fits with separate observations of Animah et al. [19] when analyzing samples that had been collected downwind of CMs with and without the use of auxiliary scrubbers. However, while both works by Animah et al. [19]&[n.d] included analysis of RCMD constituents in addition to particle size, appreciable effects of the scrubbers were only found for size.

The study reported here aimed to explore the effect of FBSs on respirable dust as a function of particle size (i.e., in the range of about 0.3-10 µm) and type (i.e., either coal or mineral). To this end, a series of tests was conducted using a newly built experimental apparatus in the NIOSH dust gallery facility in Pittsburgh, PA. The apparatus includes a prototype FBS, which can be tested with different filters, and enables sampling up- and downstream under controlled airflow and dust feed conditions. For this study, key variables included the FBS filter type (i.e., conventional 30-layer screen or novel impingement filter), the airflow through the system (i.e., 6,000 or 4,000 CFM), and the dust feed material (i.e., generated from either raw coal or roof rock from the same mine).

5.3 Materials and Methods

The sections below provide a summary description of the experimental apparatus, test conditions and dust sampling and analysis. Additional details are given in Appendix B1.

5.3.1 Apparatus and Test Conditions

Primary elements of the experimental apparatus are illustrated in Figure 5.1. In essence, it consists of modular duct sections with key FBS elements installed (i.e., filter, water spray, demister, and fan), with sampling ports up and downstream. The upstream duct is rectangular (24.7-inch wide by 13.2-inch-high), and the downstream duct is round (24.0-in diameter). Dust is fed by an ejector to a distribution system to promote even distribution of particles as they enter the duct.

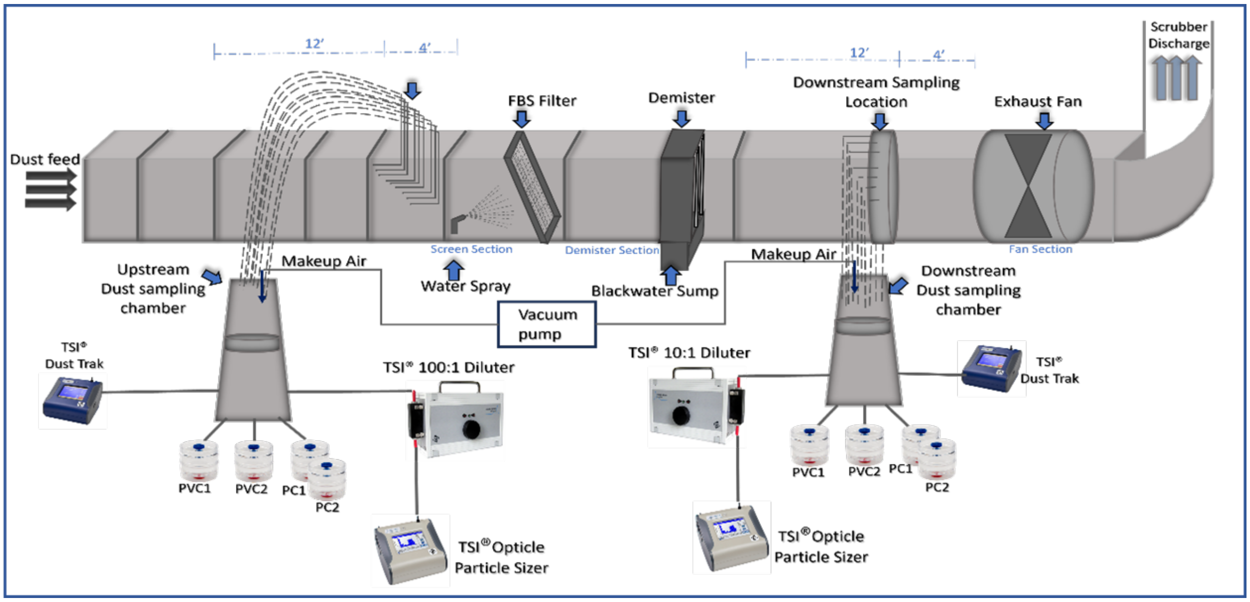


Figure 5.1: Major components of the experimental apparatus (not to scale).

A conventional 30-layer filter screen (which is standard for most CM-mounted FBSs in US mines) and a novel impingement screen (i.e., as described by Kumar et al. [20] were used for testing. To simulate a realistic airflow rate, the conventional screen was tested at 6,000 CFM. However, the maximum airflow that could not achieved when the impingement screen was installed was 4,000 CFM (i.e., due to limited fan power), so this airflow was used for impingement filter tests—and the conventional filter was also tested at 4,000 CFM. Thus, there were three filter conditions, i.e., conventional filter at 6,000 CFM ("CF-6000"), conventional at 4,000 CFM ("CF-4000"), and impingement at 4,000 CFM ("IF-4000").

The testing also included three dust conditions, which varied by the material feed type: fine raw coal, fine raw rock, and a 50%/50% blend by mass of the same coal and rock materials ("coal+rock"). The raw coal and rock were obtained as bulk materials from a partner mine located in central Appalachia. The rock represents the roof strata (described as sandy shale) that was being extracted along with the coal when the materials were collected. The bulk materials were pulled directly from the production belt, and hand sorted in the lab. Then, each was pulverized and sieved to minus 270 mesh (i.e., top size of about 53 µm) to ensure a fine feed for the scrubber testing (particle size distribution for each material is given in Table B.3 in Appendix B).

For each scrubber filter condition, tests were conducted in at least triplicates using only the coal feed material, and only the rock feed material; and for two filter conditions (i.e., CF-6000 and IF-4000), tests were also conducted with the coal+rock feed. Four additional tests were conducted on coal, with two each on CF-6000 and IF-4000 conditions. This yielded a total of 8 unique filter × dust conditions and 28 individual tests. (The blended material was not tested with CF-4000 due to time constraints.) During each test, the dust material was fed at a constant rate of 30 g/min.

5.3.2 Dust Sampling

Two nearly identical systems were used for simultaneous dust sampling from fixed locations up- and downstream of the FBS. Each system used nine isokinetic sampling probes to pull air from the duct into a sampling chamber (at about 2.0 L/min per port, for a total of 18 L/min). Another 18 L/min of makeup air was also introduced to each chamber through a GAST 0523 vacuum pump. Dust sampling from each chamber was conducted using five isokinetic probes. In essence, two probes were used for real-time monitors and three were used for collection of filter samples.

The real-time instruments were dust mass monitors (DustTrak) and optical particle sizers (OPS 3300) both from TSI (Shoreview, MN). The DustTrak samples at 2.0 L/min and estimates mass concentration on a 1-second interval, and the data were used to monitor the stability of the dust concentration. The OPS samples at 1.0 L/min and can count particles in bins between 0.3-10 µm on a 1-second interval, and data were used to evaluate particle removal efficiency (see below). To avoid overwhelming the OPS, the sample from the upstream chamber was diluted at a ratio of 100:1 and the sample from the downstream chamber was diluted at 10:1. Notably, on Day 1, a single OPS unit was used, and sampling was alternated between the up- and downstream chambers. This strategy was used to limit any uncertainty related to agreement between two different instruments (i.e., do measurements by unit A match unit B?) However, the particle concentrations were observed to drift somewhat between measurements taken from one location during different time increments of the same test. Therefore, to enable data collection in both locations over the entirety of the test period, on Days 2-5 two OPS units were used with each being dedicated a particular chamber. Before this, though, both instruments were used to sample from the same location (i.e., by splitting the air from a single inlet stream) to check agreement between their measurements; the ratio of Unit A to Unit B was observed to be about 1.3 and thus the instruments were considered to be in agreement.

For the filter samples, three ports from each chamber were typically used to collect a total of four filters. A manifold with three subsonic orifices was used to maintain a 2.0 L/min flow rate through each port. Inside the chamber, air for each port was pulled through a Higgins Dewell cyclone (i.e., to remove oversized particles), and the dust was deposited onto a 37-mm filter in a closed cassette located outside the chamber. This setup allowed filter cassettes to be replaced without opening the chamber. One or two ports were used to collect samples on pre-weighed polyvinyl chloride (PVC) filters, with sampling over the entire test duration; these samples were used for gravimetric analysis (i.e., for determination of time-weighted average, TWA, respirable dust concentration). The third port was used to collect two samples on polycarbonate (PC) filters, each during a different time increment; these were available for direct analysis by scanning electron microscopy (SEM). Upstream, the PC filter samples were collected for five- or six-minute increments at the start and midpoint of the test; and downstream the samples were collected for six or 10 minutes at the start and midpoint. This strategy was used to prevent high particle loading densities on the PC filters, which can challenge direct analysis by SEM [22, 23, 24, 25].

5.3.3 Testing Protocol

Testing was completed over five days (Table 5.1), following preliminary work to investigate the relative effects of variables such as background particle counts (i.e., in the intake air to the apparatus) and water droplets, and to check for system losses (i.e., particle removal even without a scrubber filter installed). Additionally, preliminary testing was used to verify the dilution factors and gain experience with the dust feeder to maintain a steady upstream concentration in the apparatus.

Table 5.1: Summary of Test Schedule

Day	**Coal**			**Rock**			**Coal+Rock**	
	CF-6000	CF-4000	IF-4000	CF-6000	CF-4000	IF-4000	CF-6000	IF-4000
1	3		3					
2	1	3	1					
3	1		1	1	1	1		
4				2	2	2	2	1
5							1	2

At the beginning of each day, background data was collected to confirm negligible particle concentrations. This was done using the OPS in the up- and downstream locations after the target airflow was achieved (i.e., 4,000 or 6,000 CFM) but without the dust feed; airflow was determined using the centerline velocity and the cross-sectional area of the ducting. To start the first test of the day, the feed was initiated and the DustTrak was used to monitor the mass concentration for 5 min to ensure it was stable, and then the filter samplers and OPS were started. The filter samplers were switched off/on per the explanation above, and the OPS units were allowed to sample for a total of 30 min (i.e., end of test). At the end of each test, the demister and scrubber filter were cleaned out; and, before tests that involved changing dust feed material, the entire system was thoroughly cleaned out to minimize contamination.

5.3.4 Filter Sample Analysis

Each PVC filter sample was reweighed (using the same microbalance as for pre-weights), and sample mass was determined as a simple difference between the pre- and post-weights. Then, TWA mass concentration was determined using the sampling flow rate and time).

For the PC filters, a single pair of up- and downstream samples (i.e., from the same test) was selected for each test condition (n=16) and used for SEM analysis. The SEM work was conducted with energy dispersive X-ray spectroscopy, such that both particle size and mineralogy distributions could be estimated. To prepare the samples for analysis, a 9- mm subsection was carefully cut from the center of each PC filter, mounted on an aluminum stub, and sputter coated with Au/Pd. The analysis was conducted with a TESCAN field emission SEM using TESCAN's integrated mineral analyzer (TIMA; Warrendale, PA). This system enabled automated counting, sizing and chemical analysis of particles on the PC background. Key instrument and software parameters for this work included pixel size of 0.2 µm, minimum brightness of 18, 'high-resolution mode' for detailed analysis, scanning speed of 4 (3.2 µs/pixel), and standard segmentation. (These parameters were set based on previous efforts to calibrate TIMA results on respirable dust against results achieved with another automated SEM-EDX routine using a different instrument-software combination.) On each sample, analysis was conducted on a single field (area of 200x200 µm), and TIMA identified, sized, and collected elemental data on all particles (0.3-10 µm), Then the elemental data was used to bin particles into one of the following mineralogy classes: carbonaceous (C), mixed carbonaceous (MC), silica (S), aluminosilicates (AS), carbonates (CB), heavy minerals (HM), or mixed particles (X).

5.3.5 Data Analysis

For each test with paired PVC filter samples collected in the up- (U) and downstream (D) locations, dust mass removal efficiency (R) was computed per Equation 5.1.

$$R(\%) = \frac{U - D}{U} * 100\% \tag{5.1}$$

Similarly, particle removal efficiency was also computed using the OPS- and SEM-derived data. The OPS logs particle concentrations ($\#/\mathrm{cm}^3$) in 17 size bins between 0.3-10 µm. To analyze these data, the appropriate dilution factors were applied and the time-weighted average concentration per bin and overall (i.e., total of all bins) was determined at the up- and downstream locations for each test, and removal efficiencies were computed per Equation 5.1. Since OPS data was available for multiple tests within the same scrubber filter × dust condition, results were averaged per condition. (Notably, there was an unexplained error with the upstream OPS unit on Day 4. Comparing data from tests on Day 4 to tests on other days with the same airflow and dust types [see Table 5.1], the DustTrak, gravimetric analysis, and downstream OPS data indicated relatively similar dust concentrations between days. However, the upstream OPS data for tests on Day 4 was about 5-8x lower than tests on other days. Thus, the Day 4 OPS data was excluded from analysis for this study.) For each sample analyzed by SEM, particle counts per size bin were normalized by the analyzed filter area and the sampling duration; and then Equation 1 was used to compute the particle removal efficiency per bin for paired up- and downstream filters. Additionally, the mineralogy distribution of particles on each sample was determined as number percentage per class.

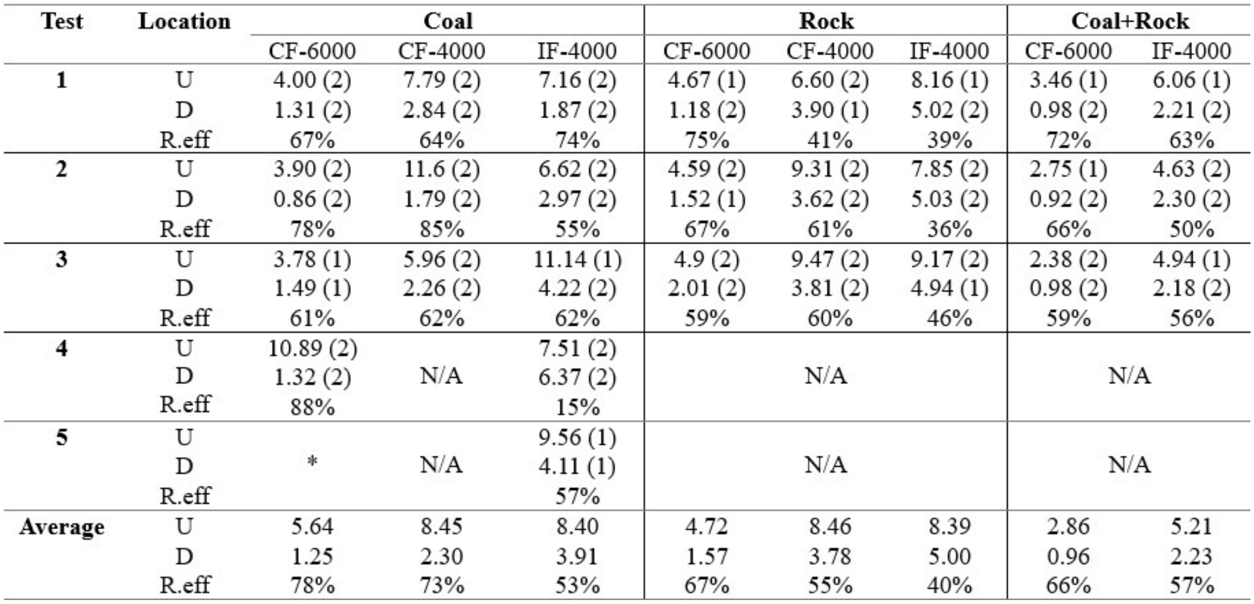
5.4 Results and Discussions

5.4.1 Dust concentrations and particle distributions

Dust concentrations are shown in Table 5.2. (Notably, the upstream concentrations observed for the CF-6000 condition were lower than for the CF-4000 condition, which is explained by the constant dust feed rate.) Trends between upstream and downstream concentrations are generally consistent with expectations. The average dust mass removal efficiency per condition ranged from 40-78% (with individual tests between 15-88%). These values are lower than typically reported for field testing of FBSs [9, 13, 14], which can be attributed to at least three main factors. First, the airflow utilized in some of the tests (especially tests at 4,000 CFM) here are lower than the recommended 7,000 CFM airflow employed by CM-mounted FBSs in underground coal mines [26]. Second, this study utilized clean scrubber filters, whereas in practice the CF gradually loads, which can increase the dust removal efficiency (at least until the backpressure reaches a critical threshold to require cleaning). Third, the dust feeds used here were much finer overall than would be present in a real mine setting (i.e., where the CM creates a wide range of dust particle sizes). Additionally, tests in this study were run with a low dust feed rate to avoid overwhelming the real time monitors. Per the average mass removal efficiencies of tests scrubber filters at 4,000 CFM, the CF performed slightly better than the IF. This is likely due to the multi-layered structure and smaller mesh pore sizes of the CF, which could make it somewhat more efficient on finer particles than the IF—at least at the relatively low airflow rate tested here. Additionally, the IF removes particles primarily through the impaction mechanism, which is more effective at higher velocities. This means that the IF should be more efficient at airflow velocities higher than the 4,000 CFM tested in this study. While results indicated slightly lower mass removal efficiencies for rock versus coal (i.e., 54% versus 68%), for the impingement filter versus the conventional filter (i.e., 50% versus 64% at 4,000 CFM), and for the conventional filter at low 4,000 CFM versus at 6,000 CFM (i.e., 64% versus 70%), too few tests were conducted to observe statistical significance.

As noted, the SEM-EDX analysis was conducted on a single sample pair (i.e., up- and downstream samples) for all eight test conditions. Figure 5.2 shows the mineralogy distributions by size bin (and overall). In general, most particles were classified into one of the following classes: C, interpreted as coal dust; X, interpreted as agglomerated particles (i.e., two or more particles clustered together); and AS, S, and MC, interpreted as mineral dust. (Note that MC is interpreted as mineral dust for this study due to the very fine particle sizes analyzed. Particles in this class are characterized by high carbon and oxygen content, but their

Table 5.2: Average mass concentration (mg/m^3) for up- (U) and downstream (D) location, and the dust removal efficiency (R.eff) in each test (The number of filter samples used to determine the average mass concentration is shown in parentheses.)



Test	**Location**	**Coal**			**Rock**			**Coal+Rock**	
		CF-6000	CF-4000	IF-4000	CF-6000	CF-4000	IF-4000	CF-6000	IF-4000
1	U	4.00 (2)	7.79 (2)	7.16 (2)	4.67 (1)	6.60 (2)	8.16 (1)	3.46 (1)	6.06 (1)
	D	1.31 (2)	2.84 (2)	1.87 (2)	1.18 (2)	3.90 (1)	5.02 (2)	0.98 (2)	2.21 (2)
	R.eff	67%	64%	74%	75%	41%	39%	72%	63%
2	U	3.90 (2)	11.6 (2)	6.62 (2)	4.59 (2)	9.31 (2)	7.85 (2)	2.75 (1)	4.63 (2)
	D	0.86 (2)	1.79 (2)	2.97 (2)	1.52 (1)	3.62 (2)	5.03 (2)	0.92 (2)	2.30 (2)
	R.eff	78%	85%	55%	67%	61%	36%	66%	50%
3	U	3.78 (1)	5.96 (2)	11.14 (1)	4.9 (2)	9.47 (2)	9.17 (2)	2.38 (2)	4.94 (1)
	D	1.49 (1)	2.26 (2)	4.22 (2)	2.01 (2)	3.81 (2)	4.94 (1)	0.98 (2)	2.18 (2)
	R.eff	61%	62%	62%	59%	60%	46%	59%	56%
4	U	10.89 (2)	N/A	7.51 (2)	N/A			N/A	
	D	1.32 (2)		6.37 (2)					
	R.eff	88%		15%					
5	U	*	N/A	9.56 (1)	N/A			N/A	
	D			4.11 (1)					
	R.eff			57%					
Average	U	5.64	8.45	8.40	4.72	8.46	8.39	2.86	5.21
	D	1.25	2.30	3.91	1.57	3.78	5.00	0.96	2.23
	R.eff	78%	73%	53%	67%	55%	40%	66%	57%

N/A denotes test was not performed; * denotes filter samples not collected for gravimetric analysis.

content of other elements such as aluminum and silicon is too high to be binned as C; for very fine particles, the high carbon and oxygen is attributed to the PC filter background.)

Overall, the mineralogy results are consistent with expectations. In the tests with only coal feed, C particles were predominant, and minerals particles are attributed to impurities in the coal. In the tests with only rock feed, mineral particles were predominant, including those contained in the X class. However, substantial C particles were apparent in the finest size bin; this might be due to misclassification (i.e., due to carbon and oxygen signals from the PC background) and/or coal impurity (which skews fine) in the rock material. In the tests with coal+rock feed, C particles are somewhat more abundant than mineral particles. While the materials were blended on an equal mass basis, the density of coal is lower than rock so there should indeed be more coal particles in these tests. Moreover, for all dust conditions, the SEM-EDX results indicate an increasing abundance of X particles with size.

This is unsurprising given agglomerates of particles are likely to be larger, on average, than individual particles—and TIMA should also be more capable of identifying agglomerates as the size of their constituents increases (i.e., due to pixel size).

Regarding differences between up- and downstream sampling locations, Figure 5.2 generally shows somewhat higher abundance of X particles downstream the scrubber for the size bins above 1 or 2 µm. One interpretation is that agglomerates are forming as particles move through the system—though no consistent trend is observed with respect to the scrubber filter or dust feed conditions. Indeed, the overall mineralogy results (driven by trends in the finest size bins) are almost identical within each pair of up- and downstream samples. This implies that, under the conditions tested here, the effect of the scrubber is not dependent on particle type. This fits with observations in the recent field studies mentioned above (i.e., [18, 19], which suggested that FBSs and auxiliary scrubber efficiency varied with particle size, but could not observe effects with particle type.

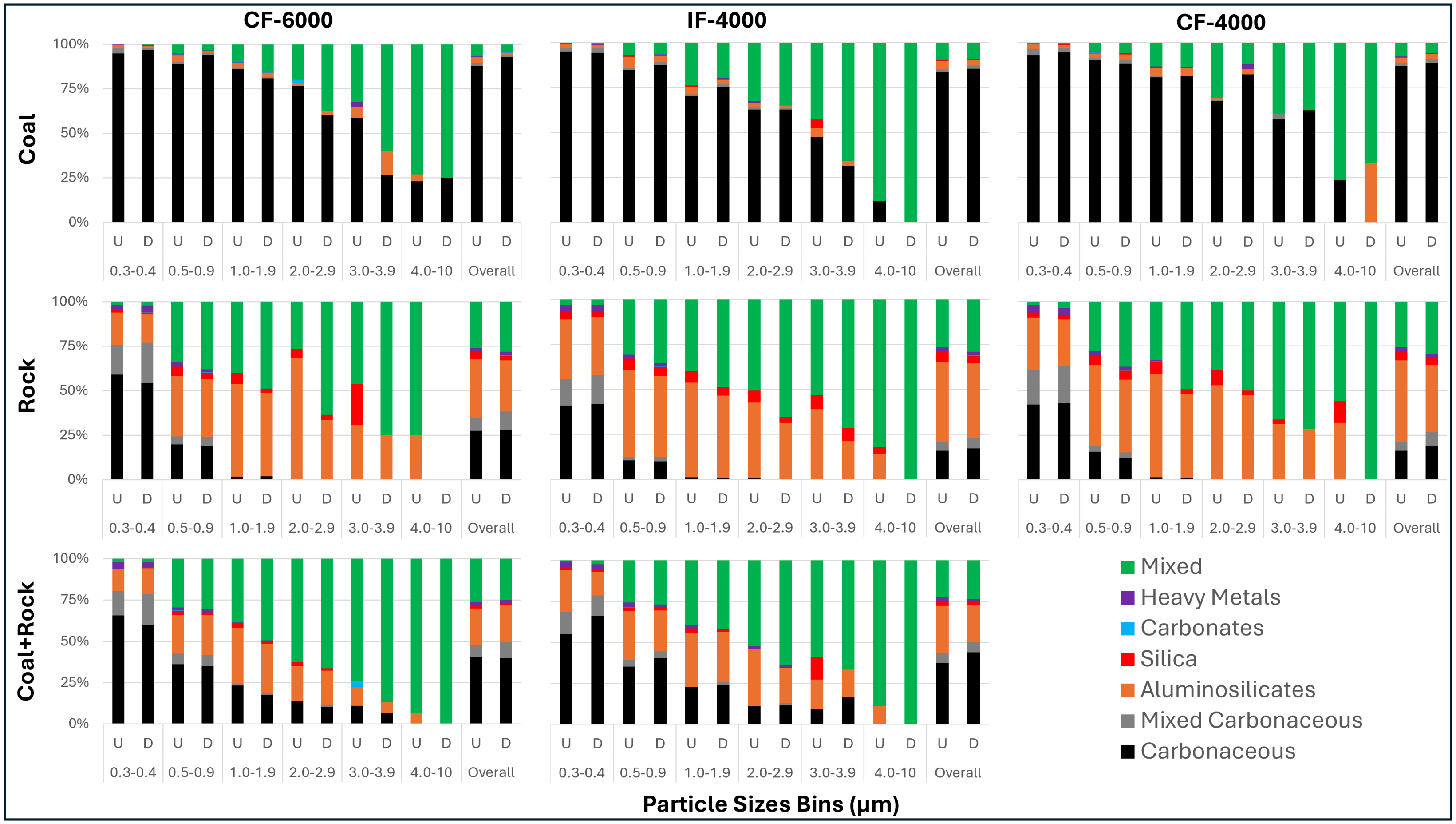


Figure 5.2: Mineralogy distribution for samples collected up (U) and downstream (D) of the scrubber for each of the eight filter × dust conditions tested; distributions are shown as number (%) per size bin and overall.

For all eight test conditions, Figure 5.3 shows the TWA number concentration of particles per size bin based on the SEM-EDX and OPS results. (Note that the scale for SEM and OPS-derived concentrations are very different. This is because SEM results represent particle counts per analyzed area of the sample filter, whereas OPS results represent the counts per volume of air. However, the general shape of the size distributions can be compared.) By both measures, particles less than about 1 µm accounted for more than 75% of the total count, while particles greater than about 2 µm accounted for less than 5% (see extra details in Figure B.3 in appendix B). Further, both measures indicate similar concentrations between the up- and downstream locations for most test conditions, with the exception of IF-4000×coal (i.e., substantially lower up- than downstream concentrations) and CF-6000×coal (i.e., slightly lower down- than upstream concentrations). Also, within each measure, the shape of the size distribution curves is similar between up- and downstream samples in the same condition. These observations provide some confidence in the general trends of the data. The fact that size distribution curves are shaped consistently across a given dust type (for either the OPS or SEM data) indicates that the filter condition had little effect; rather, the distribution is dependent on the dust type. Interestingly, while the OPS indicates a more peaked curve for coal and flatter curve for rock, the SEM data indicates the opposite. This might be related to the quality of assumptions made by the OPS (e.g., related to shape factor, refraction index) for different particle types.

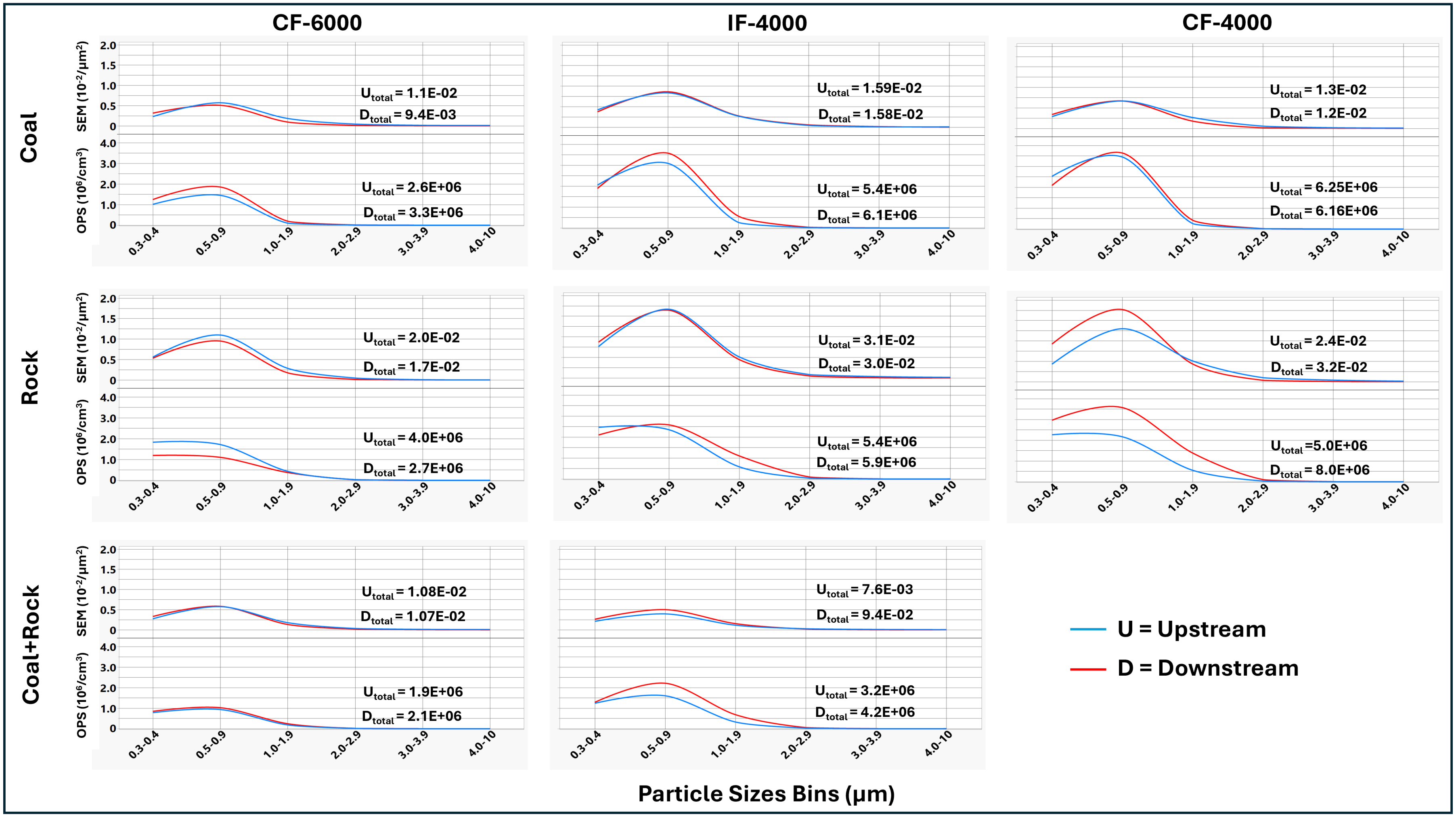


Figure 5.3: Total particle counts per size bin (by number) for samples collected up (U)- and downstream (D) from OPS and SEM-EDX analysis of each of the eight filter × dust conditions tested. U_{total} and D_{total} are the total up- and downstream particle counts respectively.

5.4.2 Particle Removal Efficiency

Figure 5.4 presents the particle removal efficiency (by number) per size bin for all eight test conditions (i.e., based on the data shown in Figure 5.3). (Also, see Table B.2 and Table B.3 in appendix B for more details). The overall particle removal efficiency and the mass removal efficiency (averaged across all tests in each condition per Table 5.2) are also annotated on the plots. Unsurprisingly, the particle removal efficiencies were typically lower than the mass-based values, which should be driven by the largest particles. However, differences in the particle removal efficiency could not be discerned with respect to different scrubber filter and dust conditions tested here. Nevertheless, the results in Figure 5.4 do have some interesting implications. The general trend of the SEM-derived results indicates that particle removal efficiency increases with bin size, with values between about 60-80% for particles greater than about 3 µm. This trend fits with expectations based on prior studies of FBS scrubbers [26, 27]. However, for most test conditions, the SEM-derived removal efficiency in the finest bins appears to be negative, and negative values are also observed for the OPS-derived data even for the mid-sized bins. From a practical perspective, these results imply that particles are somehow being generated by the system.

One explanation for negative particle removal efficiency, especially in the finest size bins, could be a tendency to break up agglomerated particles as they move through the system. For each agglomerate destructed (or partially destructed), this would effectively create multiple finer particles. To understand the possible role of the scrubber filter itself in destruction of agglomerates, the OPS data from the preliminary test to check system losses is also shown in Figure 5.4 (dashed lines in upper left plot); this test was conducted with coal dust feed at 6,000 CFM but without a scrubber filter installed. Whereas the particle removal efficiency for the finest size bins (i.e., less than about 1 µm) was negligible for the preliminary test, it was negative for the test with the same dust feed and airflow but with the CF installed.

This suggests the scrubber filter may break up agglomerates.

On the other hand, formation of some mid-sized agglomerates could explain the characteristic dip in particle removal efficiency observed for the OPS-derived data (and the SEM-derived data in some conditions). This could be due simply to the high dust concentration within the system and is likely further promoted by the wet conditions (e.g., coagulation of dust particles and water drops). The mineralogy distribution results (Figure 5.2) provide some evidence for the possibility of agglomerate formation, with the relative abundance of X particles in the mid-sized bins (i.e., about 1-4 µm) being somewhat greater in down- versus upstream samples for most test conditions. However, it must be acknowledged that X particles do not represent all agglomerates because those with like constituents (e.g., an agglomerate made up of only coal or only silicate particles) are not easily classified. Also, fine agglomerates are probably missed due to the resolution of analysis. In any case, if the preliminary test data (i.e., no scrubber filter installed) in Figure 5.4 is again compared to the data with the CF installed, it appears that formation of agglomerates is not only due to the scrubber filter—though it might be enhanced by it.

It is also worth noting that, while both the SEM- and OPS-derived data indicate low (and sometimes negative) particle removal efficiency, the shapes of the curves shown in Figure 5.4 are distinct. One reason for this could be differences in the treatment of the sample flow. Whereas the filter samples for SEM-EDX analysis were collected using a cyclone (i.e., to cut out oversized particles), the OPS does not use such a pre-selector. Prior work has suggested that a cyclone could break up agglomerate particles [28, 29].

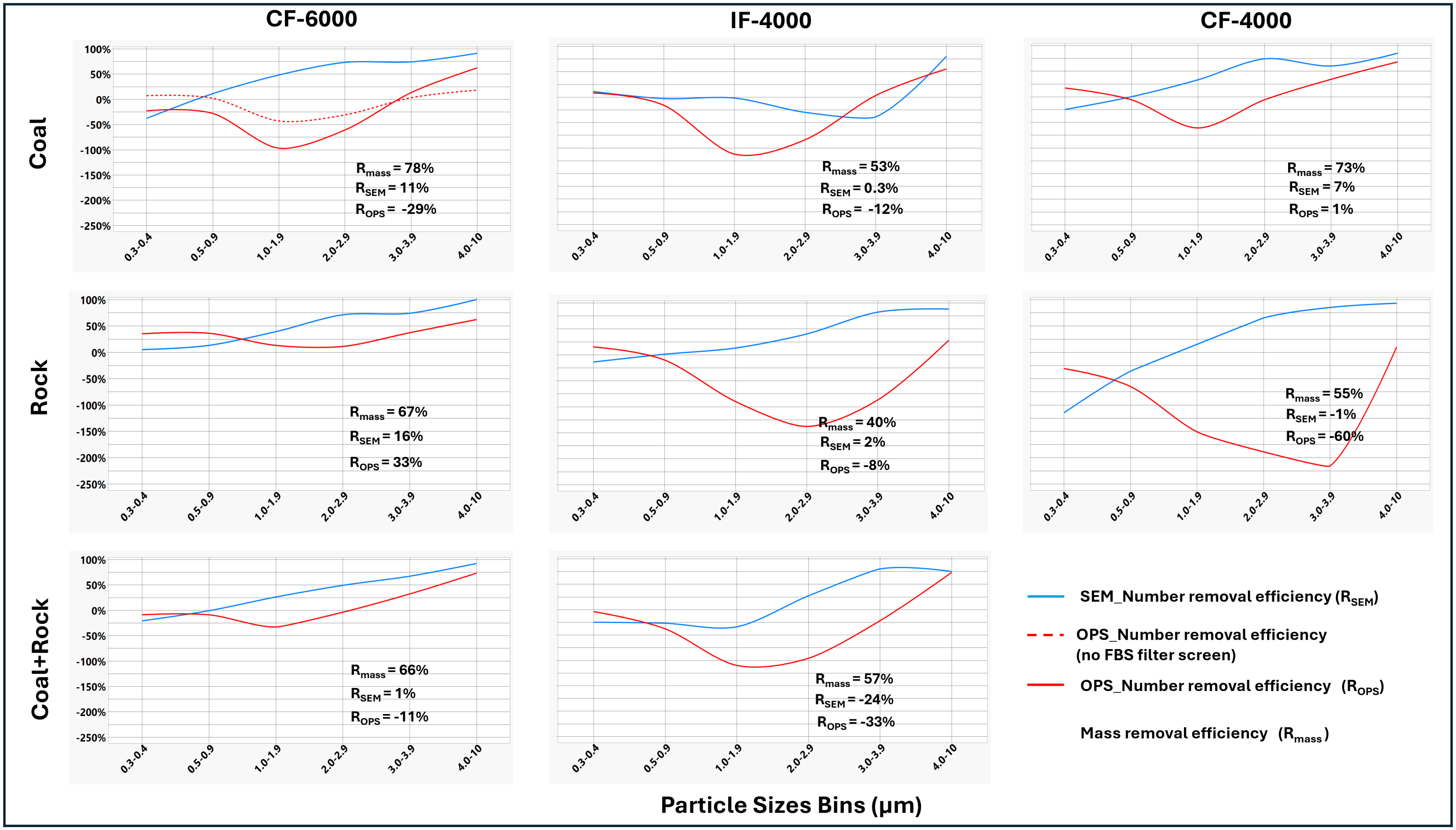


Figure 5.4: Scrubber removal efficiencies by number for samples collected up (U)- and downstream (D) from each of the eight filter × dust conditions tested. For comparison, the average mass removal efficiency for each condition is also shown.

5.5 Conclusions

FBSs represent a primary engineering control for RCMD generated from continuous miners. While their effectiveness for this purpose is generally evaluated based on mass removal efficiency, there is increasing interest in understanding particle removal efficiency (i.e., by count). This study represents a preliminary exploration using a newly built experimental apparatus with a full size FBS prototype. Consistent with expectations, results clearly demonstrated that large differences existed between particle and mass removal efficiencies for both conventional FBS filter screens and a novel impingement screen. Under the laboratory conditions tested here, particle removal efficiencies were observed to be very low, and even negative, for particles less than about 2 µm. One explanation for negative values is relative changes in agglomeration as particles move through the system. Effects of sampling, especially on SEM-derived results, are also possible. Nevertheless, consistent differences in the particle removal efficiency were not observed with respect to the various scrubber filter and airflow conditions nor dust feed conditions investigated. Future work should follow-up with more realistic conditions with respect to filter screen loading, system airflow, and size distribution of the dust feed.

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Contributions

F. Animah: Conceptualization and design, material preparation, data collection and analysis, methodology, data visualization, writing-original draft, and addressing reviews and edits.

M. Uluer: Material preparation, data collection, writing-review and editing.

T. Beck, S. Klima, H. Jiang, D. Zheng, A. Bugarski: Experimental setup design and development, NIOSH testing facility, writing-review and editing

S. Schafrik: impingement filter provision, technical input, and writing-review and editing

E. Sarver: Conceptualization and design, resources, writing-review and editing, supervision, and funding acquisition

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Chapter 6

Conclusions and Recommendations

6.1 Summary and Major Findings

Since the late 1990s, there has been a surge in cases of occupational lung diseases among US coal miners linked to overexposure to respirable coal mine dust (RCMD). This situation has spurred considerable reaction: MSHA has updated its dust rules to reduce RCMD PELs and increase monitoring frequency [1, 2]; NIOSH (via its Mining Research Division) and other funding organizations (e.g., the Alpha Foundation for the Improvement of Mine Safety and Health) have led or supported significant research on dust sources and engineering controls; and many mine operators have evaluated and improved their exposure control practices. However, the latency of dust-related diseases means it will be some time before the impacts of these efforts are fully known—and in the meantime disease prevalence is still high [3, 4, 5, 6].

A major gap in the current knowledge surrounding RCMD exists with respect to the characteristics of dust generated from different sources, and the relative effects of engineering controls [7]. The research included in this dissertation can help fill this gap. This research sought to i) investigate the dust generation and particle characteristics during typical mining in primary dust sources (coal versus rock strata), and (ii) investigate the effects of dust controls on RCMD characteristics. The summary of the major findings and implications of this study on dust sources and dust controls are discussed in the sections below.

6.1.1 Dust Sources

In US coal mines, it is common to extract substantial amounts of rock along with the coal during mining. This is because the target coal seams can be relatively thin or may have frequent and thick partings. In the eastern US where 'thin seam' mining is most common, rock strata adjacent to the coal seam (i.e., in the roof, floor or partings) is often characterized as sandstone, shale or slate, and fire clay can also be present; in other regions, limestone strata also occurs [8, 9, 10]. Prior studies have indicated that mining into the rock strata generates more dust than mining into the coal strata [11, 12, 13]. However, heretofore there have not been in-mine studies designed to directly evaluation this notion. As part of the current work, a simple study was undertaken to enable dust sampling when a continuous miner (CM) was predominantly cutting into the target coal versus the roof rock strata (i.e., mostly consisting of shale or sandy shale) that would typically be extracted with the coal in a partner mine. This study provides important insights to the most dust-intensive and hazardous dust sources, as results indicated that cuts targeting the roof rock strata generated finer and more dust i.e., (2.1-26X) than the coal strata. These results are consistent with expectations, as the relative strength of the rock strata versus the coal strata means that more energy is required to excavate it, and this leads to the generation of more and finer dust [10, 14, 15]. The results also revealed that even if the coal seam is selectively mined, the CM would still cut into some of the bottom and top rock surrounding the coal seam.

These results have major implications for mine operations as they strive to keep their working environments safe for miners. First, it is important that mines operations comprehensively study and understand the geological composition of their mines, especially the various roof and floor rock strata present in production areas. Knowledge of the composition, strengths and weaknesses of these strata is vital for the optimal design of cutting bits. If technically feasible, operations should test different machine cutting bits on various rock and coal strata in their mines to understand the dust generation mechanisms associated with each specific bit. This approach will aid in the right selection of machine cutting bits that will not only increase production rates through efficient mine strata excavation but also minimize dust generation. Consequently, with the use of appropriate bits and an understanding of the dust generation mechanisms in the mine, targeted controls should be designed to suppress this dust, especially dust from the rock strata. Additionally, a conscious effort should be made by operations to develop and simplify monitoring techniques that will be used to collect data on dust generated from different sources in their mines. Furthermore, an adoption of administrative controls such as varying operator locations away from the dust source, would further enhance rock strata dust abatement, even though implementation of these controls would require efficient leadership.

6.1.2 Dust Controls

Previous dust control studies by NIOSH have evaluated their ability to reduce respirable dust based on mass concentrations. These studies concluded that dust controls (i.e., wet and dry auxiliary scrubbers, canopy air curtains, roof bolter wet and dry collection boxes) have generally been efficient in reducing dust concentrations in mine environments. A field study here (i.e., in Chapter 2) also confirmed that the use of different dust control conditions (i.e., FBS and increased water sprays pressure and volume) led to a reduction in dust mass concentrations. In addition to mass concentrations, knowledge of the efficiency of dust controls on dust characteristics (i.e., hazardous dust constituents and particle sizes) would add more insights into their dust protection capabilities. Therefore, preserved samples from NIOSH's past dust control studies and samples from the field study conducted in Chapter 2 were analyzed to evaluate the effects of dust controls used in these studies on particle characteristics. Results generally suggested that the efficacy of these controls on respirable particles was more related to particle sizes than particle type. However, these results did not include the dust removal efficiency (i.e., based on particle count) of controls on particles of different sizes.

Furthermore, in Chapter 5, a laboratory study was conducted in the NIOSH dust gallery laboratory in Pittsburgh to understand the particle removal efficiency of a prototype FBS on different dust particle sizes from 0.3-10 µm and dust material types. For these tests, two clean FBS filter types (conventional and impingement) and three dust material types (raw coal, raw rock and a 50:50 blend of both coal and rock) were used. Generally, results revealed that FBS removal efficiency based on mass concentrations was high, while removal efficiency per size bin (i.e., based on particle count) was consistently low, and even negative in some cases. Negative removal efficiencies were mostly influenced by particles in size bins less than 2 µm, which mostly increased in number at the downstream location – due to agglomeration and deagglomeration. It must be noted that, the fine dust feed, clean FBS filter, and low airflow used in these tests do not necessarily represent realistic conditions encountered in the field. These conditions contributed to the low removal efficiencies on the finer dust particles. Additionally, a slightly clogged FBS, higher airflow, and a more realistic dust feed would have helped in increasing the scrubber removal of finer dust particles. Notwithstanding, the results in this study highlight the importance of understanding the efficiency of dust controls on finer dust of different particle sizes.

These results have major implications on how dust controls should be evaluated and implemented in mines. Exposure standards are based on mass concentrations, but increasingly there is concern that fine particles pose significant health risks. If common engineering controls in coal mines are inefficient on fine particles, alternative strategies are be needed to mitigate exposures. These include the evaluation of the efficiency novel engineering controls on dust concentrations and characteristics to fully understand their control capabilities before they are implemented in mines. The results in Chapter 5 also have implications for researchers. The study highlights the need for better sampling techniques to fully understand particles as they occur in mines. The effects of sampling procedures, equipment, and the artefacts of the sampling on results should be fully understood before data is collected. For instance, variables such as water droplets, ambient air, the use of diffusion dryers and diluters would disturb samples. Therefore, the design of studies investigating fine particles need to adopt standardized study protocols so that the effects of different variables on the results are understood and addressed. The work here also confirmed that the cleaning out of a novel roof bolter wet dust box reduced the hazardous dust exposure of the operator than when cleaning out the traditional dry dust box. Even though the implementation of the wet dust box would be beneficial in reducing operator dust exposures, this would be an expensive undertaking for some mine operations. For mine operations who cannot afford the wet dust box, efficient but easy to implement alternative control measures should be used in and around the dry dust box areas to minimize operator exposure to respirable dust. For instance, the use of a properly maintained dry bag collection system, and the installation of water sprays around the roof dry dust box should be implemented by mine operations.

Overall, this work shows that: identification of major dust sources and evaluation of the dust characteristics improves the understanding of hazards and facilitates the implementation of better controls that would minimize the dust exposures of miners. Moreover, evaluation of controls on the basis RCMD mass partly reveal their true efficiency, but an additional evaluation of dust characteristics (especially size) provides extra insights for informed decision making on controls to be implemented in mine operations.

6.2 Recommendation for Future Work

This research revealed valuable insights about the effects of RCMD sources and controls on particle characteristics, however there were some limitations that should be addressed in future studies.

- **An emphasis on sub micron particles**. Although the studies in Chapters 2, 3 and 4 utilized SEM-EDX to characterize supra micron particles (i.e., particle size ranges from 1-10 µm), future work should extend into the sub micron range (i.e., less than 1 µm) to understand the effects of dust sources and controls on respirable dust characteristics. Since sub micron dust particles are of increasing interest due to the health implications that they pose, it would have been important to understand the number of these particles that are generated from the primary dust sources and how controls are efficient in suppressing these dust particles. Therefore, future studies should expand on the work here to investigate the effects of dust sources and controls and respirable dust particle size and constituents, with focus on sub micron particle dust analysis of samples from studies.
- **Broader field studies**. Future studies on dust generation and particle characteristics during CM mining into coal versus rock strata should be repeated in different mines, as this would further facilitate a broader comparison and understanding of dust from primary dust sources.
- **Further lab testing of controls**. The FBS prototype tested in the laboratory study in Chapter 5 is still undergoing improvements. Moreover, some of the testing conditions were not fully representative of those in mining environments. For instance, tests were conducted at scrubber airflows of 4,000 CFM and 6,000 CFM, which are lower than the recommended 7,000 CFM airflow for optimal efficiency of the system in mines

[16]. Additionally, the scrubber filters tested were cleaned after each tested while the conventional filters used in mines gradually accumulate dust over time, and potentially facilitate dust removal. Also, the objectives of this study meant that fine dust feed at a low rate (i.e., 30 g/min) was used for testing but these conditions do not accurately represent the dust generated in mines. Therefore, future studies should focus on testing an improved system under more realistic conditions to investigate the effects of filter clogging on scrubber removal efficiency of different dust particle sizes and material types.

- **Effects of different cutting bits on the rock strata types in underground coal mines**. As discussed in Chapter 2, it was observed that dust from cuts targeting the roof rock strata (versus the coal strata) was fine and high. Clearly, it is important to understand the dust generation mechanisms from the different rock strata types when using various machine cutting bits. Generally, the choice of cutting bits by operations is mostly driven by their ability to efficiently extract the coal seam to increase production rates and improve machine utilization. However, with the new silica dust rule implemented recently [2], mine operations must now balance high production efficiency with the need to reduce dust generation from the rock strata. This would be achieved by employing cutting bits that balance both factors. Laboratory studies have compared the respirable dust concentrations and characteristics generated when using three conical picks at different wear stages to cut into three rock samples (i.e., concrete, sandstone and limestone samples) [17, 18]. A similar approach should be applied in future field studies to investigate the dust concentrations and particle characteristics generated by different cutting bits when cutting into the various rock strata in underground coal mines (i.e., shale, sandstone, limestone and sandy shale). Such research will inform the selection of cutting bits that maximize production while reducing hazardous dust generation.

- **Testing of engineering controls to understand their efficiencies on finer particles**. The data in Chapter 4 strongly suggests dust removal efficiencies of auxiliary scrubbers (i.e., wet and dry) and canopy air curtains are size dependent. As a result, the follow-up study in Chapter 5 showed that FBS removal efficiency (i.e., by particle count) was mostly low and sometimes negative for finer dust particles that were less than 2 µm. Outside of these studies, little is known about the efficiency of engineering dust controls on finer dust particle sizes, as these controls are often evaluated based on their efficiency on respirable mass concentrations. Therefore, new and already existing engineering dust controls should be evaluated in future studies to fully understand their efficiency on finer dust particles sizes, along with their efficiency on mass concentrations. This approach will help in the understanding and implementation of the controls best suited to mitigate finer dust particles.

- **Research to understand the hazard of "finer" dust**. There is increasing attention on finer dust particles due to their high surface area and potential for deeper penetration into the lung, which might influence the severity of lung disease. In mines, the focus has always been on monitoring mass of respirable dust, which is defined as the fraction of airborne dust that can deposit in the air exchange region of the lung. However, little is known about how the size distribution of the respirable dust fraction has changed over time. Additionally, while there is some general understanding that fine particles might be more hazardous, few studies have investigated the relative hazard of mine dust particles of different sizes. Therefore, future studies should be conducted to understand the relative hazard of mine dust particles of different sizes, which could inform monitoring and controls.

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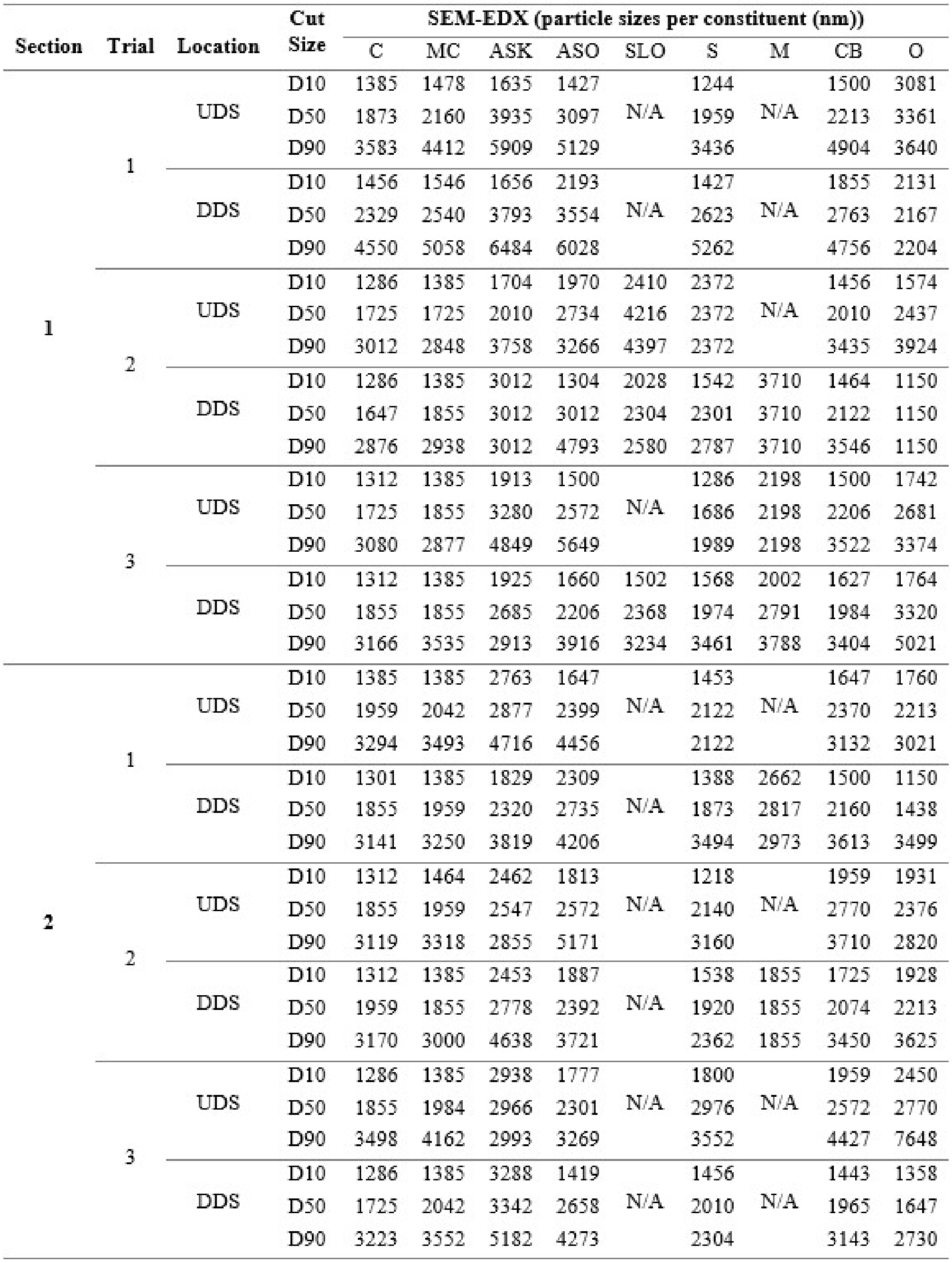
Appendices

Appendix A

Table A.1: Particle sizes (i.e., D10, D50, and D90) per constituent class derived from SEM-EDX analysis of respirable dust samples collected in Mine A at locations a) 200 feet and b) 400 feet from the dry scrubber location. (N/A indicates there were no particles in the class).

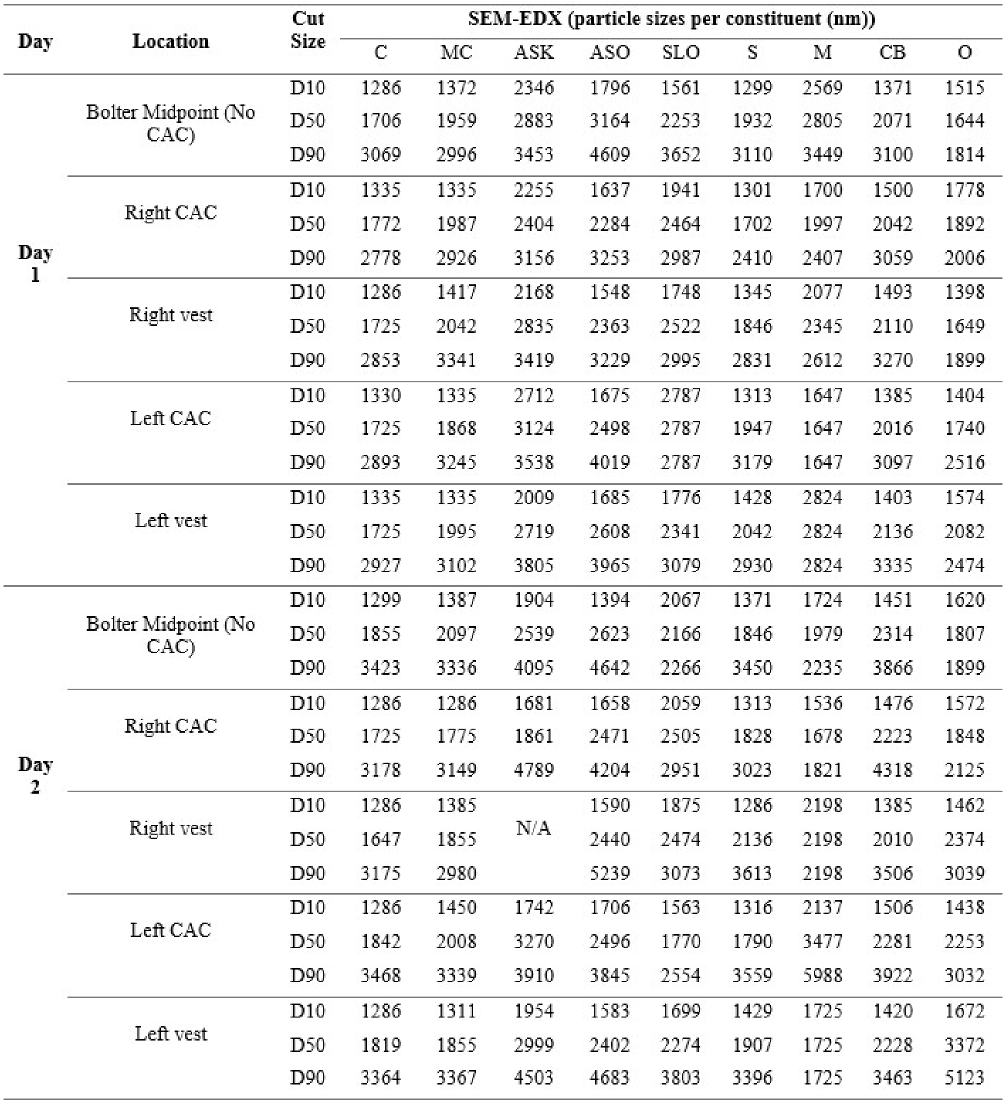
Cut	**location**	**Cut Size**	**SEM-EDX (particle sizes per constituent (nm))**								
			C	MC	ASK	ASO	SLO	S	M	CB	O
Cut 1 (No)	200	D10	1385	1482	2556	1671	1540	1647	N/A	1500	3451
		D50	1959	2074	3294	2129	2158	1647		2572	3451
		D90	3417	4838	3807	3091	2777	2834		3820	3451
	400	D10	1385	1482	1820	2515	N/A	1799	2053	1647	1500
		D50	1873	2372	2198	3097		2914	2225	2335	1500
		D90	3824	2763	4994	4282		4191	2397	3449	1500
Cut 2 (No)	200	D10	1500	1487	2283	2329	N/A	1481	1615	1855	N/A
		D50	2213	2041	3657	2932		2697	2934	3342	
		D90	4152	2880	6062	3963		3813	3189	4026	
	400	D10	1500	2011	2998	4057	N/A	1615	N/A	2564	N/A
		D50	2098	2534	3253	4579		2074		2685	
		D90	4397	3005	3871	6913		2534		2884	
Cut 4 (Yes)	200	D10	1286	1385	1716	1873	N/A	1489	N/A	1544	1851
		D50	1725	1855	2652	2904		2098		2487	2664
		D90	2876	2772	3508	4020		2797		4083	3478
Cut 5 (Yes)	200	D10	1286	1441	1361	1589	N/A	1595	1855	1563	1500
		D50	1725	2010	2677	2452		2183	1855	2198	1500
		D90	2921	2742	4323	4177		3148	1855	4558	1500
	400	D10	1380	3460	2445	N/A	N/A	1380	NA	1552	1386
		D50	1850	3460	3675			1915		2370	1960
		D90	3100	3460	5035			3216		3830	3138
Cut 6 (Yes)	200	D10	1301	1448	2143	1847	N/A	1539	N/A	1663	1819
		D50	1819	2098	3097	3012		1916		2572	2932
		D90	3098	3111	3968	4481		2388		3400	3177
	400	D10	1290	1385	2070	2021	N/A	1600	N/A	1870	1290
		D50	1730	1930	2070	2685		1850		2710	1850
		D90	2770	3089	3014	3595		3156		3895	2190

Table A.2: Particle sizes (i.e., D10, D50, and D90) per constituent class derived from SEM-EDX analysis of respirable dust samples collected in Mine B during the dry scrubber trials in a) Section 1 and b) Section 2. (N/A indicates there were no particles in the class).



Section	Trial	Location	Cut Size	SEM-EDX (particle sizes per constituent (nm))								
				C	MC	ASK	ASO	SLO	S	M	CB	O
1	1	UDS	D10	1385	1478	1635	1427	N/A	1244	N/A	1500	3081
			D50	1873	2160	3935	3097		1959		2213	3361
			D90	3583	4412	5909	5129		3436		4904	3640
		DDS	D10	1456	1546	1656	2193	N/A	1427	N/A	1855	2131
			D50	2329	2540	3793	3554		2623		2763	2167
			D90	4550	5058	6484	6028		5262		4756	2204
	2	UDS	D10	1286	1385	1704	1970	2410	2372	N/A	1456	1574
			D50	1725	1725	2010	2734	4216	2372		2010	2437
			D90	3012	2848	3758	3266	4397	2372		3435	3924
		DDS	D10	1286	1385	3012	1304	2028	1542	3710	1464	1150
			D50	1647	1855	3012	3012	2304	2301	3710	2122	1150
			D90	2876	2938	3012	4793	2580	2787	3710	3546	1150
	3	UDS	D10	1312	1385	1913	1500	N/A	1286	2198	1500	1742
			D50	1725	1855	3280	2572		1686	2198	2206	2681
			D90	3080	2877	4849	5649		1989	2198	3522	3374
		DDS	D10	1312	1385	1925	1660	1502	1568	2002	1627	1764
			D50	1855	1855	2685	2206	2368	1974	2791	1984	3320
			D90	3166	3535	2913	3916	3234	3461	3788	3404	5021
2	1	UDS	D10	1385	1385	2763	1647	N/A	1453	N/A	1647	1760
			D50	1959	2042	2877	2399		2122		2370	2213
			D90	3294	3493	4716	4456		2122		3132	3021
		DDS	D10	1301	1385	1829	2309	N/A	1388	2662	1500	1150
			D50	1855	1959	2320	2735		1873	2817	2160	1438
			D90	3141	3250	3819	4206		3494	2973	3613	3499
	2	UDS	D10	1312	1464	2462	1813	N/A	1218	N/A	1959	1931
			D50	1855	1959	2547	2572		2140		2770	2376
			D90	3119	3318	2855	5171		3160		3710	2820
		DDS	D10	1312	1385	2453	1887	N/A	1538	1855	1725	1928
			D50	1959	1855	2778	2392		1920	1855	2074	2213
			D90	3170	3000	4638	3721		2362	1855	3450	3625
	3	UDS	D10	1286	1385	2938	1777	N/A	1800	N/A	1959	2450
			D50	1855	1984	2966	2301		2976		2572	2770
			D90	3498	4162	2993	3269		3552		4427	7648
		DDS	D10	1286	1385	3288	1419	N/A	1456	N/A	1443	1358
			D50	1725	2042	3342	2658		2010		1965	1647
			D90	3223	3552	5182	4273		2304		3143	2730

Table A.3: Particle sizes (i.e., D10, D50, and D90) per constituent class derived from SEM-EDX analysis of respirable dust samples collected in Mine C during the roof bolter CAC testing on a) Day 1 and b) Day 2. (N/A indicates there were no particles in the class).



Day	**Location**	**Cut Size**	**SEM-EDX (particle sizes per constituent (nm))**								
			C	MC	ASK	ASO	SLO	S	M	CB	O
Day 1	Bolter Midpoint (No CAC)	D10	1286	1372	2346	1796	1561	1299	2569	1371	1515
		D50	1706	1959	2883	3164	2253	1932	2805	2071	1644
		D90	3069	2996	3453	4609	3652	3110	3449	3100	1814
	Right CAC	D10	1335	1335	2255	1637	1941	1301	1700	1500	1778
		D50	1772	1987	2404	2284	2464	1702	1997	2042	1892
		D90	2778	2926	3156	3253	2987	2410	2407	3059	2006
	Right vest	D10	1286	1417	2168	1548	1748	1345	2077	1493	1398
		D50	1725	2042	2835	2363	2522	1846	2345	2110	1649
		D90	2853	3341	3419	3229	2995	2831	2612	3270	1899
	Left CAC	D10	1330	1335	2712	1675	2787	1313	1647	1385	1404
		D50	1725	1868	3124	2498	2787	1947	1647	2016	1740
		D90	2893	3245	3538	4019	2787	3179	1647	3097	2516
	Left vest	D10	1335	1335	2009	1685	1776	1428	2824	1403	1574
		D50	1725	1995	2719	2608	2341	2042	2824	2136	2082
		D90	2927	3102	3805	3965	3079	2930	2824	3335	2474
Day 2	Bolter Midpoint (No CAC)	D10	1299	1387	1904	1394	2067	1371	1724	1451	1620
		D50	1855	2097	2539	2623	2166	1846	1979	2314	1807
		D90	3423	3336	4095	4642	2266	3450	2235	3866	1899
	Right CAC	D10	1286	1286	1681	1658	2059	1313	1536	1476	1572
		D50	1725	1775	1861	2471	2505	1828	1678	2223	1848
		D90	3178	3149	4789	4204	2951	3023	1821	4318	2125
	Right vest	D10	1286	1385	N/A	1590	1875	1286	2198	1385	1462
		D50	1647	1855		2440	2474	2136	2198	2010	2374
		D90	3175	2980		5239	3073	3613	2198	3506	3039
	Left CAC	D10	1286	1450	1742	1706	1563	1316	2137	1506	1438
		D50	1842	2008	3270	2496	1770	1790	3477	2281	2253
		D90	3468	3339	3910	3845	2554	3559	5988	3922	3032
	Left vest	D10	1286	1311	1954	1583	1699	1429	1725	1420	1672
		D50	1819	1855	2999	2402	2274	1907	1725	2228	3372
		D90	3364	3367	4503	4683	3803	3396	1725	3463	5123

Appendix B

B.1 Experimental Details

Two almost identical systems were used for simultaneous dust sampling and measurement at fixed locations upstream and downstream of the FBS. Each of these sampling and measurement systems consist of two major components, the sampling section of the duct, and the sampling and measurement train. The sampling section of the duct houses nine isokinetic sampling probes located inside the FBS. These isokinetic probes with diameter of 1.75 mm are spaced 254 mm apart in the horizontal direction and 127 mm apart in the vertical direction. Each of the sampling and measurement trains positioned at the upstream and downstream locations of the FBS consists of the sampling and measurement chamber, sampling and measurement chamber flow controls, and filter sampling trains (see Figure B.1 for the sampling and measurement train setup).

The sampling and measurement chamber consists of the inlet section, mixing section, sampling and measurement section, and the exhaust section. A flow straightener is placed within the inlet section and exhaust section for consistent airflow and accurate sampling in the chamber. The inlet section contains a single makeup air port and nine inlet ports. During testing and sampling, a total of 18 liters per minute (Lpm) of dust (i.e., 2 Lpm per each of the nine probes) is drawn into the chamber from the FBS duct by a conductive tubing connected to both the nine chamber inlet ports and the nine isokinetic sampling probes in the duct. The sampling and measurement section of the chamber contains three isokinetic probes that are distributed radially at 2 inches (51 mm) from the center of the chamber and 120^0 apart are used for collecting filter samples. Another three isokinetic probes that are distributed radially at 4.25 inches (108 mm) from the center of the chamber and 120^0 apart are used for sampling with the particle counters. These probes can be differentiated by their lengths protruding outside of the chamber. The exhaust section contains three main flow ports and one calibration or cleaning port.

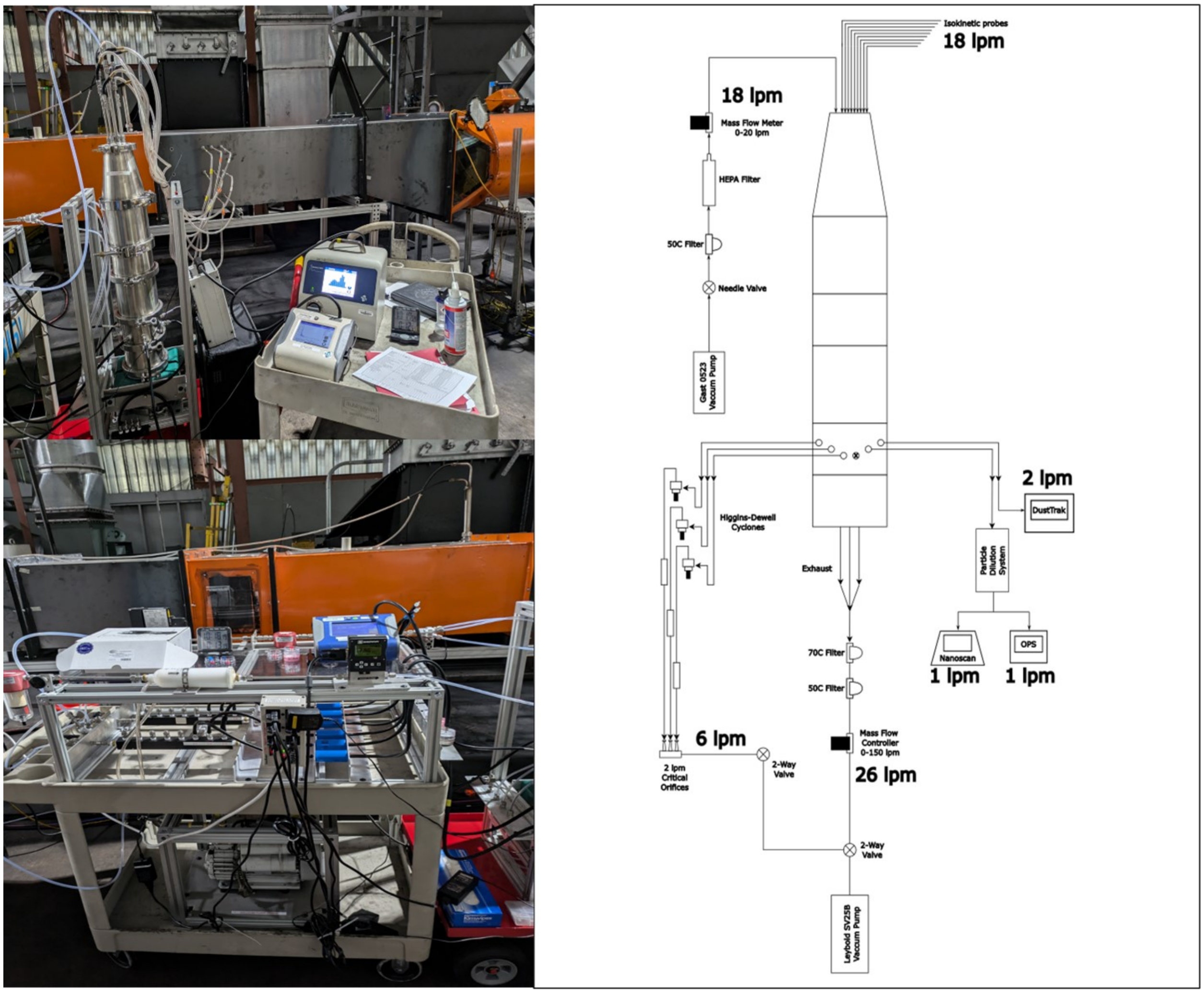


Figure B.1: The dust sampling and measurement system setup

The sampling and measurement chamber flow controls consist of the makeup air supply system and the main flow control system. Makeup air of around 18 lpm was supplied by a single GAST 0523 pump into each of the upstream and downstream sampling chambers through their inlet makeup air ports. The mass flow rate of the makeup air was measured with a Sierra SmartTrack 100 mass flow meter (M100L, 0-20 lpm), controlled by a needle valve, and cleaned by Headline 50C filter and a HEPA filter. The vacuum for the main flow was supplied by a Leybold SV25B pump with ball valve, while the mass flow rate at the exhaust of the chamber was controlled by Sierra C100M mass flow controller (upstream 0-150 slpm and downstream 0-120 slpm) and set to run at 26 lpm at each location to maintain the balance of air entering and exiting the sampling chamber. Headline two stage filtration systems (i.e., 50C and 70C) were used to filter the flow through the mass flow controller.

The sampling and measurement system also consists of two filter sampling trains for the collection of samples triplicate samples. The Leybold SV25B pump was also used to supply vacuum to the two sampling trains. Each of the two sampling trains had a sampling ball valve and a manifold with three subsonic orifices used to provide and maintain a volumetric flow rate of 2.0 lpm for each sample to be collected. Three HEPA filters were used to protect the three orifices from each train.

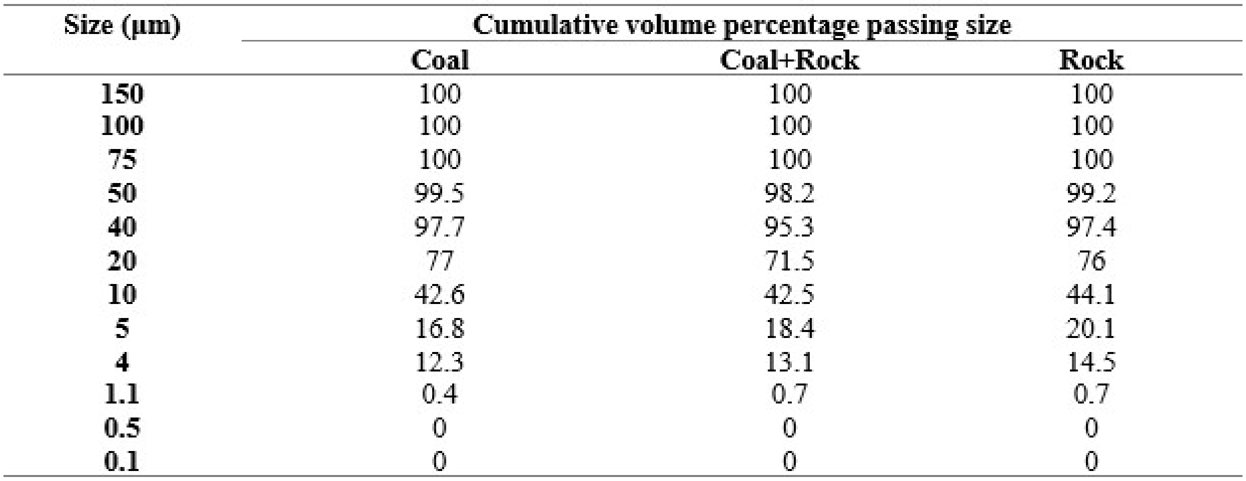
Sampling equipment used for testing at each location included real-time particle counters (i.e., TSI 3330 Optical Particle Sizer (OPS)), real-time dust concentration monitor (i.e., two TSI DustTraks DRX Aerosol Monitor 8530), and four standard filter samplers (i.e., standard coal mine dust personal sampling units (CMDPSUs)) to collect filter samples (see Figure 1 above for the sampling equipment setup). The OPS 3330 counts dust particles in the micron-sized bins (i.e., from 0.3-10 µm). In addition, the DustTrak tracked the mass concentrations of dust particles in different sized fractions (i.e., PM=1, PM2.5, respirable, PM10, and PM total). Dust was drawn into each of these three real-time instruments through the ports of the three 4.25 inches isokinetic probes in the sampling chamber. The air from the upstream sampling probes and the downstream probes required dilution to ensure that the real time instruments were not overwhelmed. Therefore, the TSI 100:1 and 10:1 aerosol diluters were used at the upstream and downstream locations respectively, to dilute dust flowing into the particle counters.

The filter sampling set up consisted of two 37-mm polycarbonate (PC) filters and two polyvinyl chloride (PVC) filters, with each housed in a 3-piece cassette and connected to a Higgins-Dewell cyclone. Samples collected on the PVC filters (i.e., gravimetric samples) are used to obtain mass concentrations upstream and downstream of the FBS, while the PC filter samples are used for SEM-EDX analysis. It is noted that the two sampling trains from the dust sampling and measurement system mentioned above were each designed to collect samples for dust mass analysis and SEM-EDX analysis. However, due to a defect in one of the sampling trains, only one sampling train was used. Dust was drawn from the sampling chamber and onto the filters through the three 2-inch probes, and the three subsonic orifices which were each working at a flow rate of 2.0 lpm. Since the sampling train had three orifices to collect triplicate samples, two PVC filters were assigned and connected to two orifices via a tubing to collect dust for the entire sampling time, while the third orifice was alternated between the two PC filter samples. The two PC filter samples were each collected for a total of five or six minutes at the upstream location and six or ten minutes at the downstream location, during the start and midpoint of each test. The reason for not collecting dust on the PC filter for the entire duration of each test was to avoid filter loading, as these samples were going to be used for SEM-EDX analysis. Notably, high filter loading has been postulated to lead to high particle agglomeration and possible misclassification during particle analysis by SEM-EDX (Gonzalez, Keles, & Sarver, 2022; Gonzalez, Keles, Pokhrel, et al., 2022; Greth et al., 2023). A dummy filter was used whenever sampling was completed for each of the PC filters to maintain the flow dynamics in the dust. The total air flow rate of dust drawn from the sampling chamber by the six samplers was approximately 10 L/min at each location. Overall, around 36 lpm of air and dust was introduced into the sampling chamber, while 36 lpm exited the chamber for a consistent flow dynamic up- and downstream of the scrubber. See Figure B.2 below for the scrubber testing setup.

Figure B.2: Scrubber and sampling setup during testing.

B.2 Particle Size Distribution

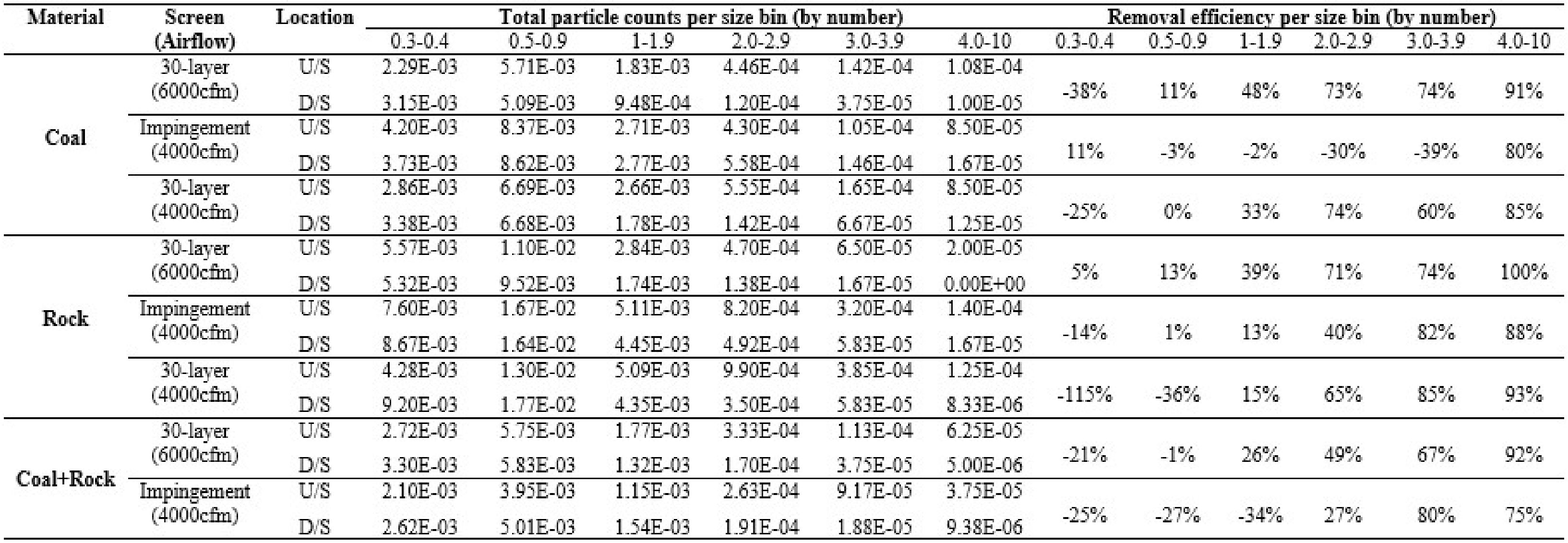
Table B.1: The particle size distributions of the Mine 13 dust materials used for testing.



Size (µm)	Cumulative volume percentage passing size		
	Coal	Coal+Rock	Rock
150	100	100	100
100	100	100	100
75	100	100	100
50	99.5	98.2	99.2
40	97.7	95.3	97.4
20	77	71.5	76
10	42.6	42.5	44.1
5	16.8	18.4	20.1
4	12.3	13.1	14.5
1.1	0.4	0.7	0.7
0.5	0	0	0
0.1	0	0	0

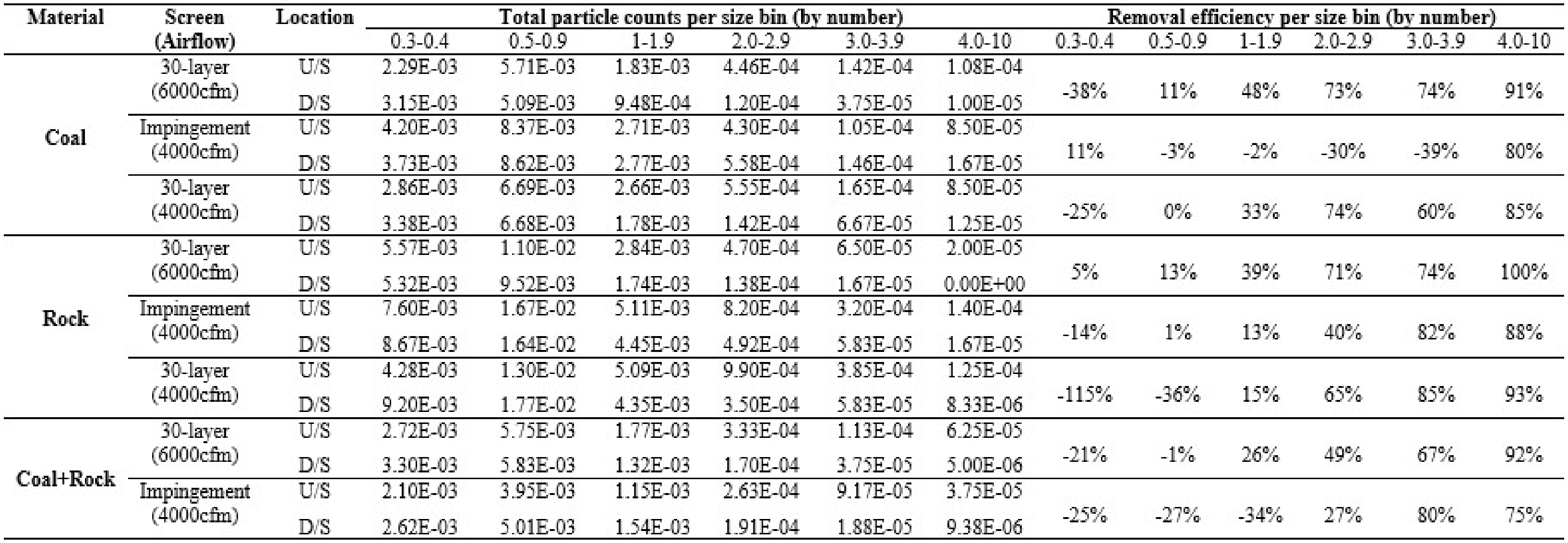
B.3 Results from SEM-EDX and OPS analysis

Table B.2: Total particle counts and removal efficiency per size bin (by number) from SEM-EDX Analysis.



Material	**Screen (Airflow)**	**Location**	**Total particle counts per size bin (by number)**						**Removal efficiency per size bin (by number)**					
			0.3-0.4	0.5-0.9	1-1.9	2.0-2.9	3.0-3.9	4.0-10	0.3-0.4	0.5-0.9	1-1.9	2.0-2.9	3.0-3.9	4.0-10
Coal	30-layer (6000cfm)	U/S	2.29E-03	5.71E-03	1.83E-03	4.46E-04	1.42E-04	1.08E-04	-38%	11%	48%	73%	74%	91%
		D/S	3.15E-03	5.09E-03	9.48E-04	1.20E-04	3.75E-05	1.00E-05						
	Impingement (4000cfm)	U/S	4.20E-03	8.37E-03	2.71E-03	4.30E-04	1.05E-04	8.50E-05	11%	-3%	-2%	-30%	-39%	80%
		D/S	3.73E-03	8.62E-03	2.77E-03	5.58E-04	1.46E-04	1.67E-05						
	30-layer (4000cfm)	U/S	2.86E-03	6.69E-03	2.66E-03	5.55E-04	1.65E-04	8.50E-05	-25%	0%	33%	74%	60%	85%
		D/S	3.38E-03	6.68E-03	1.78E-03	1.42E-04	6.67E-05	1.25E-05						
Rock	30-layer (6000cfm)	U/S	5.57E-03	1.10E-02	2.84E-03	4.70E-04	6.50E-05	2.00E-05	5%	13%	39%	71%	74%	100%
		D/S	5.32E-03	9.52E-03	1.74E-03	1.38E-04	1.67E-05	0.00E+00						
	Impingement (4000cfm)	U/S	7.60E-03	1.67E-02	5.11E-03	8.20E-04	3.20E-04	1.40E-04	-14%	1%	13%	40%	82%	88%
		D/S	8.67E-03	1.64E-02	4.45E-03	4.92E-04	5.83E-05	1.67E-05						
	30-layer (4000cfm)	U/S	4.28E-03	1.30E-02	5.09E-03	9.90E-04	3.85E-04	1.25E-04	-115%	-36%	15%	65%	85%	93%
		D/S	9.20E-03	1.77E-02	4.35E-03	3.50E-04	5.83E-05	8.33E-06						
Coal+Rock	30-layer (6000cfm)	U/S	2.72E-03	5.75E-03	1.77E-03	3.33E-04	1.13E-04	6.25E-05	-21%	-1%	26%	49%	67%	92%
		D/S	3.30E-03	5.83E-03	1.32E-03	1.70E-04	3.75E-05	5.00E-06						
	Impingement (4000cfm)	U/S	2.10E-03	3.95E-03	1.15E-03	2.63E-04	9.17E-05	3.75E-05	-25%	-27%	-34%	27%	80%	75%
		D/S	2.62E-03	5.01E-03	1.54E-03	1.91E-04	1.88E-05	9.38E-06						

Table B.3: Total particle counts and removal efficiency per size bin (by number) from OPS data.



Material	**Screen (Airflow)**	**Location**	**Total particle counts per size bin (by number)**						**Removal efficiency per size bin (by number)**					
			0.3-0.4	0.5-0.9	1-1.9	2.0-2.9	3.0-3.9	4.0-10	0.3-0.4	0.5-0.9	1-1.9	2.0-2.9	3.0-3.9	4.0-10
Coal	30-layer (6000cfm)	U/S	2.29E-03	5.71E-03	1.83E-03	4.46E-04	1.42E-04	1.08E-04	-38%	11%	48%	73%	74%	91%
		D/S	3.15E-03	5.09E-03	9.48E-04	1.20E-04	3.75E-05	1.00E-05						
	Impingement (4000cfm)	U/S	4.20E-03	8.37E-03	2.71E-03	4.30E-04	1.05E-04	8.50E-05	11%	-3%	-2%	-30%	-39%	80%
		D/S	3.73E-03	8.62E-03	2.77E-03	5.58E-04	1.46E-04	1.67E-05						
	30-layer (4000cfm)	U/S	2.86E-03	6.69E-03	2.66E-03	5.55E-04	1.65E-04	8.50E-05	-25%	0%	33%	74%	60%	85%
		D/S	3.38E-03	6.68E-03	1.78E-03	1.42E-04	6.67E-05	1.25E-05						
Rock	30-layer (6000cfm)	U/S	5.57E-03	1.10E-02	2.84E-03	4.70E-04	6.50E-05	2.00E-05	5%	13%	39%	71%	74%	100%
		D/S	5.32E-03	9.52E-03	1.74E-03	1.38E-04	1.67E-05	0.00E+00						
	Impingement (4000cfm)	U/S	7.60E-03	1.67E-02	5.11E-03	8.20E-04	3.20E-04	1.40E-04	-14%	1%	13%	40%	82%	88%
		D/S	8.67E-03	1.64E-02	4.45E-03	4.92E-04	5.83E-05	1.67E-05						
	30-layer (4000cfm)	U/S	4.28E-03	1.30E-02	5.09E-03	9.90E-04	3.85E-04	1.25E-04	-115%	-36%	15%	65%	85%	93%
		D/S	9.20E-03	1.77E-02	4.35E-03	3.50E-04	5.83E-05	8.33E-06						
Coal+Rock	30-layer (6000cfm)	U/S	2.72E-03	5.75E-03	1.77E-03	3.33E-04	1.13E-04	6.25E-05	-21%	-1%	26%	49%	67%	92%
		D/S	3.30E-03	5.83E-03	1.32E-03	1.70E-04	3.75E-05	5.00E-06						
	Impingement (4000cfm)	U/S	2.10E-03	3.95E-03	1.15E-03	2.63E-04	9.17E-05	3.75E-05	-25%	-27%	-34%	27%	80%	75%
		D/S	2.62E-03	5.01E-03	1.54E-03	1.91E-04	1.88E-05	9.38E-06						

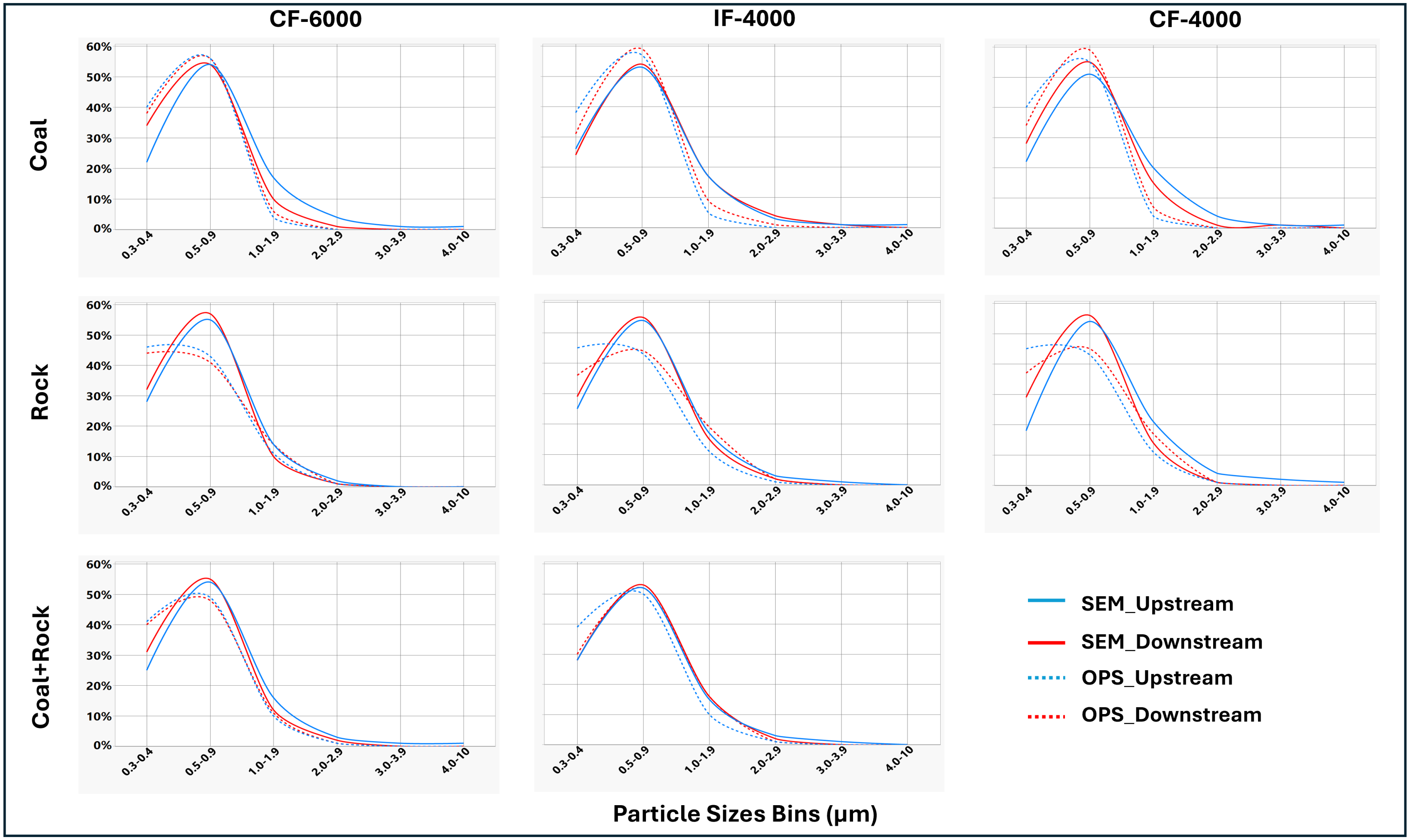
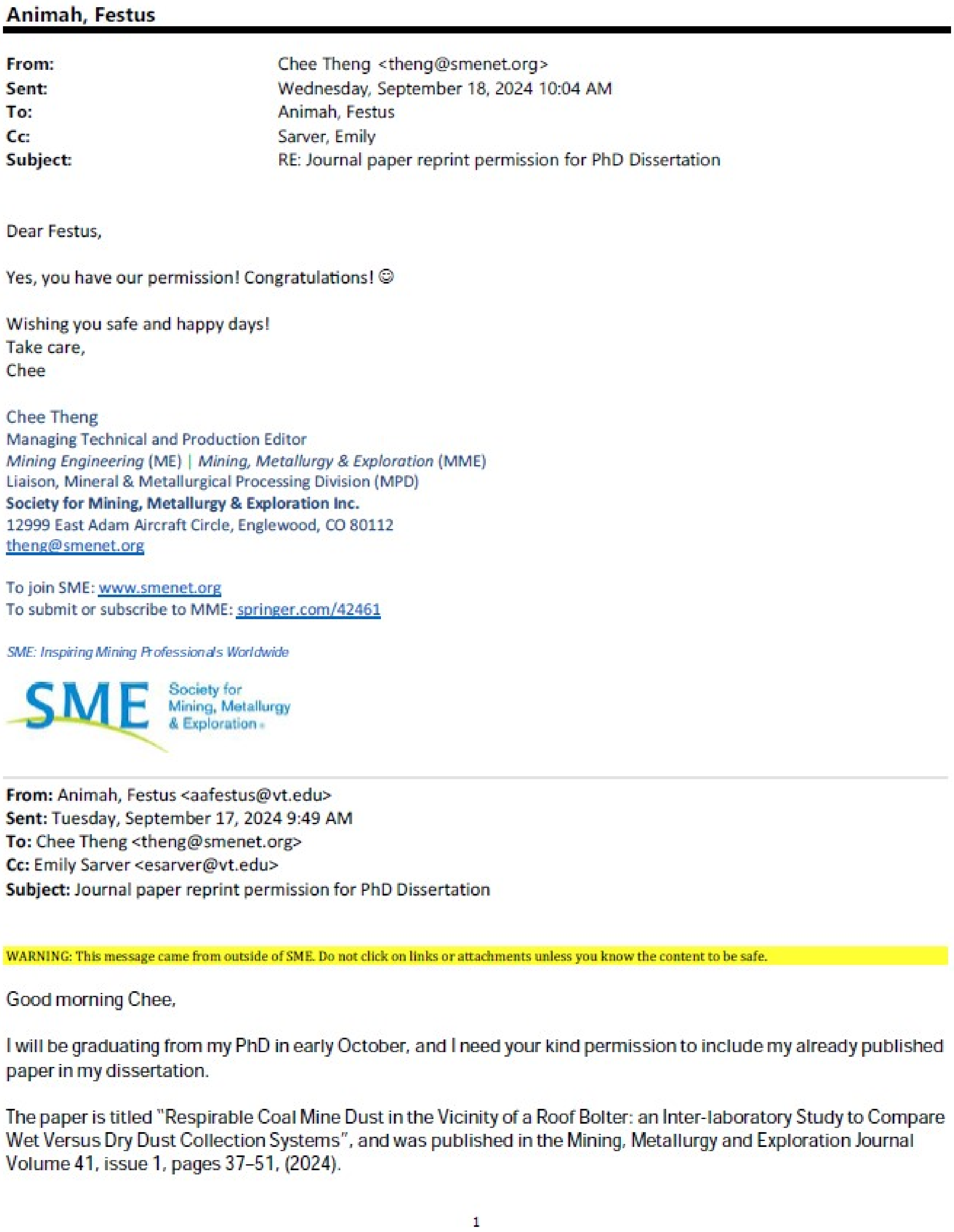


Figure B.3: Particle size distribution by size bin measured upstream (U) and downstream (D) of the scrubber for each of the eight filter × dust conditions. Results are shown based on SEM and OPS data.

Appendix C

C.1 Journal Paper Reprint Permissions

Figure C.1: Mining, Metallurgy, and Exploration Journal Publication Permission for Chapter 3



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Dear Festus,

Yes, you have our permission! Congratulations! ☺

Wishing you safe and happy days!
Take care,
Chee

Chee Theng
Managing Technical and Production Editor
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Good morning Chee,

I will be graduating from my PhD in early October, and I need your kind permission to include my already published paper in my dissertation.

The paper is titled "Respirable Coal Mine Dust in the Vicinity of a Roof Bolter: an Inter-laboratory Study to Compare Wet Versus Dry Dust Collection Systems", and was published in the Mining, Metallurgy and Exploration Journal Volume 41, issue 1, pages 37–51, (2024).

The article can be accessed through the following link: https://link.springer.com/article/10.1007/S42461-023-00901-3 .

Please let me know if it would be possible to include this article in my dissertation.

Thank you!

Best,
Festus

Festus Animah
Graduate Research Assistant
Mining and Minerals Engineering
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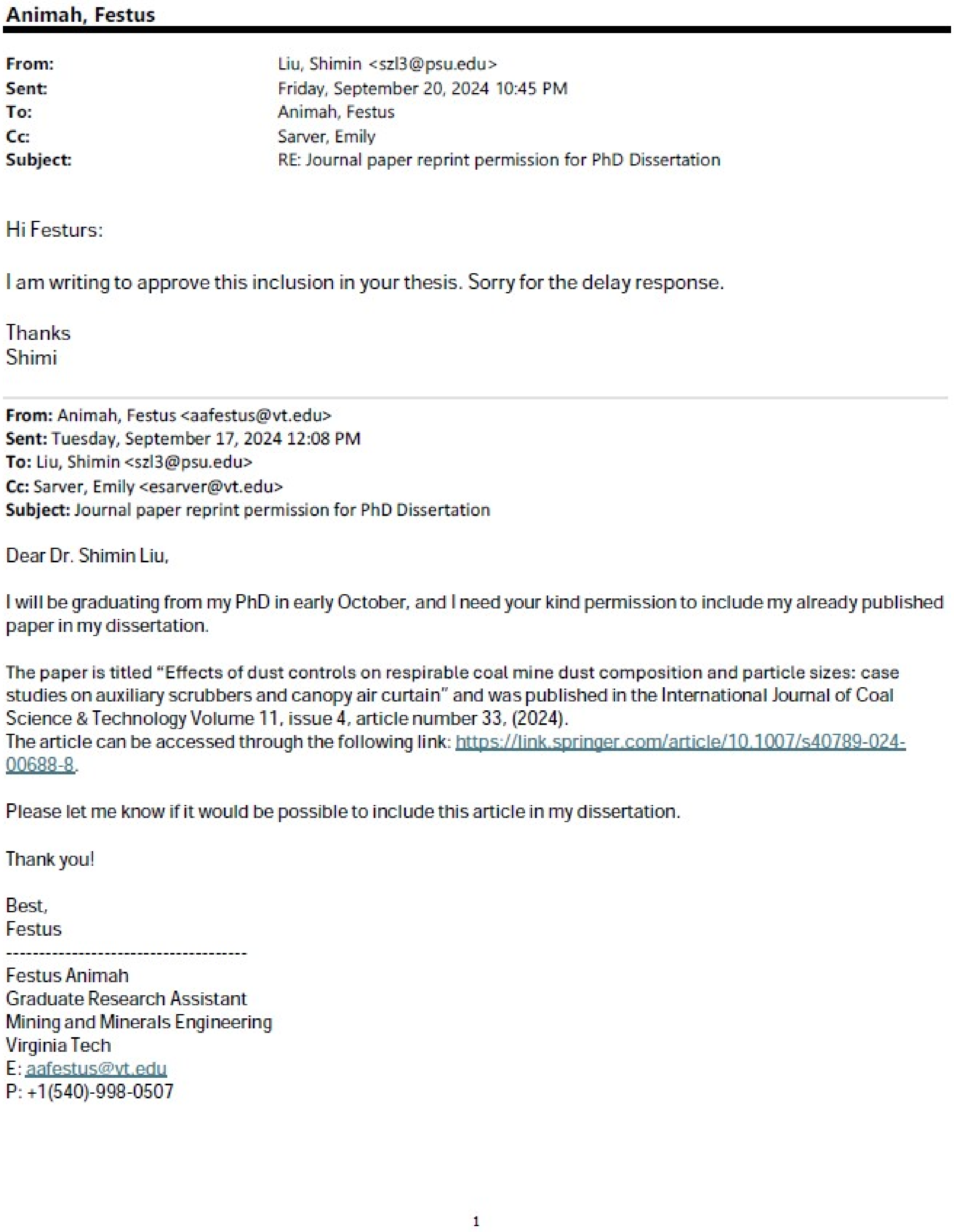
Figure C.2: International Journal of Coal Science & Technology Publication Permission for Chapter 4



Animah, Festus

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Thanks
Shimi

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Cc: Sarver, Emily <esarver@vt.edu>
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Dear Dr. Shimin Liu,

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The paper is titled “Effects of dust controls on respirable coal mine dust composition and particle sizes: case studies on auxiliary scrubbers and canopy air curtain” and was published in the International Journal of Coal Science & Technology Volume 11, issue 4, article number 33, (2024).
The article can be accessed through the following link: https://link.springer.com/article/10.1007/s40789-024-00688-8.

Please let me know if it would be possible to include this article in my dissertation.

Thank you!

Best,
Festus

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