# Preprint 22-072

## A SUMMARY OF RESPIRABLE COAL MINE CRYSTALLINE SILICA DUST RESEARCH ACCOMPLISHED THROUGH THE MINER ACT UNDER THE NIOSH OFFICE OF MINE SAFETY AND HEALTH RESEARCH

**W. R. Reed**, CDC NIOSH, Pittsburgh, PA
**G. W. Luxbacher**, CDC NIOSH, Atlanta, GA

### ABSTRACT

As directed by the MINER act of 2006, the NIOSH Office of Mine Health & Safety Research (OMSHR) has annually awarded contracts to enhance mine safety and health. OMSHR has a history of research that focuses on both respirable coal mine dust and respirable crystalline silica (or quartz) dust, and contracts have been awarded since 2010 in support of our intramural research efforts. In 2018, a National Academies of Science consensus study report recommended expansion of respirable dust research. As a result, beginning in 2018 through 2021, eighteen contracts were awarded focusing on this area. These contracts can be grouped in three topic areas: characterization of coal/dust, development of real time monitors, and improvement of respirable dust controls. This paper summarizes the outcomes of completed contracts and the progress of current contracts.

### INTRODUCTION

The Mine Improvement and New Emergency Response Act of 2006 (MINER Act) permanently established the Office of Mine Safety and Health Research (OMSHR) within the National Institute for Occupational Safety and Health (NIOSH) under the direction of an Associate Director. One purpose of this office is to enhance the development of new technology and technological applications, and to expedite the commercial availability and implementation of such technology in mining environments. The MINER Act grants the OMSHR the authority to (1) award competitive contracts and grants to institutions and private entities to encourage the development and manufacture of mine safety equipment and (2) award contracts to education institutions or private laboratories for the performance of product testing or related work with respect to new mine technology or equipment [1].

One focus area for contract awards has been respirable coal mine dust (RCMD) and respirable crystalline silica dust (RCSD). Crystalline silica is a major constituent in quartz and quartz is referenced in the Federal Mine Safety and Health Act of 1977, as amended, rather than silica; quartz is defined there as "crystalline silicon dioxide ($SiO_2$) not chemically combined with other substances and having a distinctive physical structure". Since, from an MSHA regulatory perspective, quartz is considered to be silica, crystalline silica has been used as the preferred term in this paper.

Health effects of exposure to coal and silica dusts can lead to the occupational respiratory diseases coal workers' pneumoconiosis (CWP), silicosis, emphysema, and chronic bronchitis, collectively referred to as "black lung". CWP and silicosis occur through exposure to respirable dust, consisting of particles with a $D_{50}$ of 4.0 µm [2]. The $D_{50}$ represents the median diameter of a particle size distribution. For respirable dust $D_{50}$ = 4.0 µm; therefore, 50% of particles are less than 4.0 µm and 50% are greater than 4.0 µm. Both occupational respiratory diseases are irreversible, have no cure, and are ultimately fatal [3, 4]. The only way of avoiding the diseases is through prevention of exposure to respirable dusts.

Overexposure to respirable dust remains a significant health hazard in U.S. coal mines. Despite significant improvements that occurred after passage of the Federal Coal Mine Health and Safety Act of 1969 (Public Law 91-173), which established respirable dust level limits for the first time, NIOSH continues to identify CWP cases in U.S. coal miners [5]. After reaching a low in 1999, the prevalence of CWP in 2015 was approximately 5% in all U.S. coal workers with 20–24 years of tenure and over 10% in coal workers with >25 years tenure [6]. Miners with shorter tenure follow a similar pattern. Figure 1 shows the trend of the prevalence of CWP in miners in the Central Appalachia and other locations except Central Appalachia [7]. In Central Appalachia (Figure 1 left), the situation is more severe, with coal workers with 20–24 years of tenure in 2015 having a prevalence of CWP of approximately 7% to 8%, and Central Appalachia coal workers with >25 years tenure having a prevalence of approximately 20% [7].

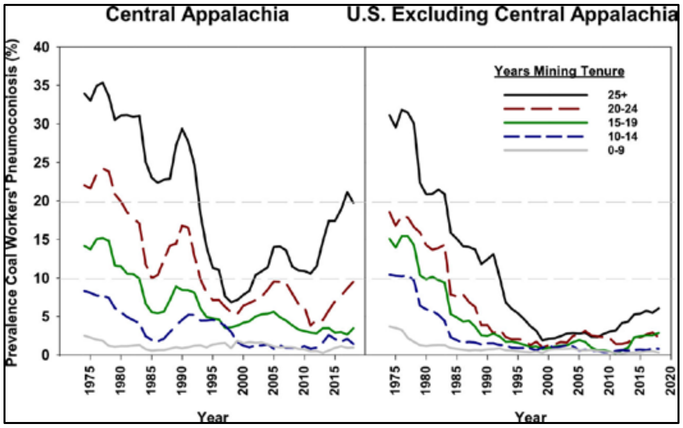


**Figure 1**. Prevalence of coal workers' pneumoconiosis among those working underground in (left Central Appalachia and (right) the U.S. excluding central Appalachia [from Hall et al. 2019].

Additional data show that the percentage of miners in Central Appalachia with r-type opacities has increased from 1980 to 2018 (Figure 2). The r-type opacities are small, rounded opacities identified on chest radiographs of US underground coal miners ranging from 3 to 10 mm in diameter and are associated with silicosis lung pathology [8]. It can be seen that the percentage of r-type opacities in U.S coal miners excluding Central Appalachia has remained consistent at <0.5% over the last four decades. However, it has increased in Central Appalachia to approximately 2.0% in the 2010s compared to < 0.5% in the 1980s [8]. The percentage of r-type Central Appalachia is associated with silicosis, which may associate the increases in CWP to increases in silica exposure in Central Appalachia miners.

The reason for the possible increase in silica exposure is due to cutting roof or floor rock to maintain seam height and continuous miner cutting into rock to reach coal seams [9]. Cutting of rock is much easier as machine input voltages have increased which translates to increased horsepower which translates to better performance [10]. This increased horsepower has facilitated greater productivity and allowed cutting rock types other than coal [11]. Not only does this roof rock contain higher silica content, but it also causes increased bit wear which produces more respirable dust due to the grinding action that occurs as the bit wears instead of the cutting action with new bits [12]. The amount of respirable dust generated due to cutting rock can overwhelm water sprays, scrubbers, and personal protective equipment [9,12].

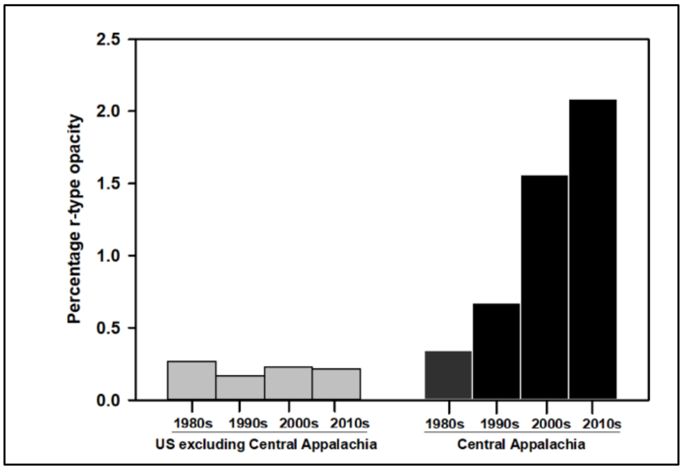


**Figure 2**. Percentage of r-type opacities by region and decade, 1980-2018 [from Hall et al. 2018].

With increased exposure to respirable dust, many of these miners exhibited symptoms of silicosis, shortness of breath (dyspnea) with exertion progressing to dyspnea at rest, fatigue, and pulmonary hypertension and respiratory failure in advanced cases. Additional complications as a result of overexposure to respirable quartz dust include mycobacterial infections such as tuberculosis, bronchitis, emphysema, asthma, etc. [13]. Miners who acquire CWP eventually cannot work to provide for their families. As a further demonstration of the relatively recent uptick in CWP, NIOSH has reported on clusters of progressive massive fibrosis (PMF), a severe form of CWP, at local clinics in Kentucky (60 miners) and Virginia (416 miners) [14, 15].

CWP presents a significant economic burden, with benefits paid by the Social Security Administration and the Black Lung Disability Trust Fund of almost $200 million in fiscal year 2021 [16]. Since inception of the federal Black Lung Benefits Program in 1970, over 723,000 [17] claims have been filed and $47.6 billion in total benefits have been paid out to former miners and their dependents through these funds [16], not including benefits paid for by the identified responsible coal mine operators and insurers. Over 30,000 miners and dependents continue to receive some form of benefits [18], down from a high of almost 490,000 in 1974 [19].

The only method to prevent CWP and silicosis is through elimination of exposure to RCMD and crystalline silica (quartz). The Federal Coal Mine Health and Safety Act of 1969 enacted a RCMD standard limiting respirable coal dust to 3.0 mg/m$^3$. Three years after enactment the of the 1969 Act, the RCMD standard was reduced to 2.0 mg/m$^3$ which remained the standard in use for over 40 years [5]. Beginning in August 2016 the RCMD standard was lowered to 1.5 mg/m$^3$ for a full working shift [20]. If the RCMD contains more than 5% quartz, the applicable respirable dust standard is reduced; calculated as 10 divided by the percent quartz present [21] so that the effective exposure limit for respirable quartz dust is 0.1 mg/m$^3$ for a full working shift.

Additionally, the rulemaking mandates that the continuous personal dust monitor (CPDM) be used for operator underground coal mine sampling [22]. Originally, only a coal mine dust personal sampler unit (CMDPSU) was specified [23]. The CPDM is a near real-time sampler that is mandated for use in underground coal mines. While mining companies have switched to the CPDM for regulatory compliance purposes, the CMDPSU is still used by the MSHA inspectorate in their scheduled sampling for respirable quartz dust.

These new standards and sampling units were implemented specifically to prevent occurrences of these occupational respiratory diseases. A recent study of miners identified with PMF showed that the mean time from a normal radiograph to a radiograph that has a first determination of PMF is 20.7 years. The composition of miners for the mean time of first determination of PMF was 16.6% progression to PMF < 10 years, 35% progression within 11 – 20 years, and 48.5% progression in > 20 years [24]. Due to the latency of the respiratory diseases, 10 years or more, the impact of these new standards and the mandated use of the CPDM may not be perceived yet.

Due to the continuing issues of CWP and silicosis in coal mining (Black Lung), NIOSH OMSHR has made this a focus of our external contracting efforts throughout the annual Broad Agency Announcement to compliment the Mining Program intramural program. As a result, 18 different contracts have been awarded to address the respirable dust issue (Tables 1, 2, & 3, see APPENDIX). The contracts can be apportioned among three different topics: Characterization of Coal Dust, Dust Control, and Development of Dust Monitors. The ensuing discussion provides the description and progress of each contract.

## CHARACTERIZATION OF COAL DUST

Characterization of coal dust is a topic that was recommended in the 2018 National Academies Study Report on “Monitoring and Sampling Approaches to Assess Underground Coal Mine Dust Exposures.” Recommendations 4, 8, and 9 relate to this category. Recommendation 4 suggests NIOSH evaluate the current relationship between the particle-size distributions of RCMD samples and particles deposited in the lung that are associated with or implicated in the development of coal mine dust lung diseases. Recommendation 8 advises NIOSH to conduct a systematic evaluation of changes in mining technology and activities, related to increased rock extraction and disease hot spots. Recommendation 9 advises that NIOSH should perform an assessment of RCMD particle characteristics, including their variability, because different particle characteristics (for example, composition and surface area) can pose different health hazards. This assessment would also characterize and quantify important source contributions to airborne RCMD, including rock dusting and extraction of rock strata adjacent to the mined coal seam [25]. The following 6 contracts relate to this category. Given that four technology and two capacity build contracts were issued in 2019 to universities related to characterization, while outside the scope of a typical contract, NIOSH asked the group to participate in a joint kickoff, followed by annual meetings. Our goal has been to facilitate interaction, collaboration, and cooperation, particularly with regard to facilities and equipment, data collection, and information exchange. We provided the researchers with the papers included in the 18-volume compendium from the former USBM Generic Mineral Technology Center for Respirable Dust, managed by West Virginia and Penn State from 1983 through 1998 (these papers have also been posted on www.OneMine.org). Three of these review meetings have been held and NIOSH has been extremely pleased with the results.

### Temporal and Spatial Characterization of Respirable Coal Mine Dust (RCMD) - Michigan Tech with the University of Utah

Researchers from Michigan Tech are collecting samples to determine temporal and spatial variation of RCMD within a mine using the CMDPSU for area (fixed-site) sampling. The goal is to provide more information on the variation of the RCMD during the mining cycle at multiple locations within the mine to reduce cumulative miner exposure to RCMD. Three characterization technologies are being used including x-ray (micron and nano) computed tomography, field-flow fractionation, and micro x-ray fluorescence spectroscopy to determine size and composition from individual particles.

RCMD samples from intake, return, bolter, and miner locations in underground coal mines were collected using various sampling protocols and methods including both short-period sampling and long-period sampling protocols. The RCMD samples collected using short-period sampling protocol were characterized using Scanning Electron Microscope (SEM) coupled with X-ray energy-dispersive spectroscopy (EDX). The results from the SEM/EDX were analyzed to determine mineral composition of dust particles at the micron-size fraction, and particle size distribution was determined from the image analyses of SEM images. Composition categories were coal, diesel, calcite, dolomite, illite, kaolin, quartz, and others. Particles equivalent disc diameter ranged from 1 to 5 µm. Images showed the presence of a significant number of nanoparticles [26Pan et al 2021]. Several of the RCMD samples were characterized by dynamic light scattering (DLS) and asymmetrical flow field -flow fraction (AsFIFFF) to determine particle size distribution, most specifically the nano sized coal dust. Particle size ranges were 105-1000 nm (405 nm peak) with a few particles in 4000-6500 nm range (5560 nm peak) for the miner location. The bolter location particles ranged from 60-1100 nm (200 nm peak) and 1200-6500 nm (1200 nm peak). Feeder location particles ranged from 40-100 nm (62 nm peak) and 110-600 nm (327 peak). The results of DLS and AsFIFFF methods were consistent with methods using SEM/EDX particle counting [26Pan et al 2021].

**Respirable Crystalline Silica Characteristics and Sources in U.S. Underground Coal Mines - VA Tech**

VA tech researchers are investigating toxicity-relevant RCS characteristics, particle size and surface characteristics, in real coal mine dust samples and in samples representative of major dust sources. Dust sources include mined coal and rock strata. Characterization of the particle size distribution and presence or absence of particle surface occlusion in RCS from real coal mine dust samples are underway. Particle size distributions were calculated using SEM/EDX to conduct particle counting on specially prepared samples. Composition of the sampled material was also completed for C, O, Al, Si, Ca, Mg, Ti, and Fe. This allowed categorization of sample into mineralogical categories. Results showed that for the size range analyzed by the SEM/EDX, about 67% of silica, other aluminosilicate, and heavy minerals particle, 52% of carbonates and kaolinite-like aluminosilicate particles, and 40% of other silicates and other particles have a projected area diameter less than 1000 nm. Further analysis was then conducted to provide information on mineralogy distributions on a percent mass basis for different samples from differing operating locations in the mine; roof bolter (B), feeder breaker (F), intake (I), production (P), and return(R); providing information on material composition for those sample locations. These results confirmed that dust control and monitoring in areas of roof bolting and production are essential and should continue, but rock dusting activities do have an effect the material composition of respirable dust and should be considered in assessing exposure risk. [27].

Work has also been initiated using Fourier-transform infrared (FTIR) spectroscopy to compare with the SEM/EDX and thermo gravimetric analysis (TGA). FTIR can be influenced by use of different sampling cassettes due to the differing loading of sample material on filters by different sampling cassettes [28]. Therefore, the use of different sampling cassette types requires the use of correction factors to calibrate the different cassettes to a standard. This work is currently in process.

**Respirable Coal Mine Dust: Mineral Content Sources, Monitoring and Control, and Building Capacity to Protect Miner Health - VA Tech**

This research, which is a capacity building contract –a contract with the primary intent to develop masters and PhD graduates in specialized focus areas for the mining industry– focuses on advancing the understanding the mining and geological conditions that influence contribution of mineral content, especially strata-sourced minerals such as silicates and silica, to RCMD. Such knowledge should provide critical insight to design and operation of mining systems that protect worker health. The contract will also provide demonstration and training opportunities to advance the use of rapid silica analysis by coal mines and develop new expertise in mine health and safety, particularly as it relates to monitoring and controlling respirable dust exposures.

This work has utilized FTIR, TGA, and SEM/EDX to analyze respirable dust samples collected at various underground coal mines in the U.S. Preliminary results comparing the FTIR to SEM/EDX show reasonable agreement. Additional results comparing TGA to SEM/EDX show that for specific components of the dust, low mass contributes to large differences between TGA and SEM/EDX results. Above a specific threshold SEM/EDX overpredicts noncarbonates while underpredicting coal [29]. A case study was conducted comparing FTIR and SEM/EDX analysis on respirable dust samples obtained from a room and pillar coal mine in Southern West Virginia. The samples were obtained from various locations using gravimetric methods with 37mm filters. SEM/EDX was used to obtain material composition from the samples. Material identified was carbonaceous (C), mixed carbonaceous (MC), aluminosilicates-kaolinite (AS-K), aluminosilicates-other (AS-O); other silicates (OS); silica (S); heavy minerals (M), and carbonates (CB). FTIR was used to identify quartz (Q) and kaolinite (K) and compared with SEM/EDX S and ASK categories. Reasonable results of silica measurements, within ±6%, were obtained. For ASK and K comparison, the SEM/EDX tended to overpredict the FTIR result. In this study, the SEM/EDX measured at most 37% ASK while FTIR measured 20% K for the same sample [29, 30].

TGA was also evaluated for characterization of composite RCMD consisting of three categories of dust type: coal, carbonate, and non-carbonates. Analysis of the composite samples produced results classifying the components of the material into each of the three categories on a percentage basis. Comparison of results was completed comparing the observed values with expected values. The expected values for each category were derived from previous TGA analysis of material that consisted solely of a single source material of each category. The results demonstrated good comparability of observed results with expected results. Overall deviations were within ±10% with the exception of only a few samples [31].

Additional work is planned to promote the use of FTIR and NIOSH's FAST (Field Analysis of Silica Tool) software for end of shift silica analysis from 37mm filters in 3-piece cassettes [32, 33]. However, Covid-19 delayed the ability to travel to mine sites to demonstrate the process. VA Tech researchers created a video that demonstrates the silica measurement process to distribute to mines interested in implementing the technique.

**Respirable Coal Mine Dust (RCMD) Research: Characterization, Deposition, Monitoring, and Mitigation of RCMD and Capacity Building for Mine Health and Safety - New Mexico Tech**

This work, also a capacity building contract, will include a comprehensive study of the characterization, respiratory deposition, monitoring, and mitigation of RCMD. The investigators plan to use an innovative Mobile Aerosol Lung Deposition Apparatus (MALDA) to estimate the RCMD respiratory deposition and the effect of the RCDM characteristics on the respiratory deposition. The effort should advance the understanding of dust control through the study of the surface chemistry of the RCMD and its interaction with water droplets and potential methods to enhance the capturing efficiency, an evaluation of the efficacy of ultrasonic atomizing nozzle system to mitigate submicron dust particles, and investigation of the deposition of agglomerated particles in the human lung.

During the beginning of the project, literature reviews and database analysis were conducted for dust regulations, sampling methods, methods for characterization of material, prevalence of CWP, etc. [34]. Some of the factors analyzed from MSHA databases for CWP prevalence were mine type, mine size, seam thickness, and geographic location [35]. In the second year, samples of RCMD have been collected from coal mines in the western and eastern coal regions of the U.S., and characterization studies have commenced. Reference samples and RCMD samples are being prepared for analysis by SEM/EDX, X-ray diffraction (XRD), and FTIR. During ongoing characterization, it has been observed that there are a large number of submicron particles that make up the particle count by SEM/EDX, but they do not represent a large portion of the mass of the sample. Initial tests have been conducted dissolving the RCMD into the simulated lung fluid followed by acid digestion. Preliminary results showed that Fe, Al, Cu, Sr, Ba, and Pb may have been dissolved from the RCMD. The MALDA has been setup and is undergoing preliminary testing.

**Characterization of Submicron-/Nano-scale Coal Dusts and Their Effects on Miners' Pneumoconiosis and Lung Cancer for Underground Coal Mines - Penn State**

This research contract will characterize the submicron/nano-scale coal dust particles of different grades of coal and analyze the interaction between nano-scale coal dust (NCD) and lung cells. The toxicity of coal dust and its varying composition could be primary factors for CWP. Recent studies have confirmed that nano-sized particles are potentially more toxic due to their unique physicochemical properties and easier uptake by living organisms. The underlying mechanism of miners' lung diseases due to the exposure of nano-coal-dusts (NCDs) is not well-understood and their role in CWP is largely unknown.

NCDs were generated using hand crushing with mortar and pestle and a cryo-mill circulating liquid nitrogen to prevent heating during generation of the NCD sample. Bulk samples were analyzed using laser diffraction and dynamic light scattering. Results showed evidence of a significant amount of NCD. Additional samples were aerosolized and sampled using a Dekati low pressure impactor [36]. These samples were further analyzed using field emission scanning electron microscopy, x-ray photoelectron spectroscopy (XPS), XRD, and free radical analysis. The total carbon content was approximately 83 wt% with H and O being similar at 4 wt%. The sample also contained 1 wt% N and 0.4 wt% S. XPS showed that C increases from micron sized coal to nano sized coal while O decreases from micron sized to nano sized coal. Results also showed that NCD has higher surface area and pore volumes. The higher surface area of NCD and lower O, which could be related to weaker wetting behavior, indicates that inhalation of NCD could have potentially higher adverse effects on miners' health [36].

**Characterization of Coal Mine Dust Size Distribution, Chemical Composition, and Source Contributions - University of Nevada-Reno with the Desert Research Institute**

A comprehensive assessment of RCMD particle characteristics is proposed because different particle characteristics (for example, composition and surface area) can potentially pose different health hazards. An extensive literature review has been completed reviewing RCMD measurement methods, particle size characterization, and chemical composition and methods of determination [37]. The collection of RCMD samples at various locations in underground coal mines has also been completed. These samples will be analyzed to characterize the particle size distribution and determine the chemical composition of the material. Preliminary results provide concentrations of RCMD at the locations sampled. Expectedly, the returns and the tailgates of the longwalls had the highest RCMD concentrations ranging from 5.5 to 14.2 mg/m$^3$ in the returns and 18.6 to 19.1 mg/m$^3$ in the tailgates. The preliminary particle size distributions of these samples showed the mean mass aerodynamic diameter ranging from 8.4 to 15.9 µm, with 8.4 µm at the longwall face and 15.9 µm at the feeder (continuous miner 10.3µm; roof bolter 9.6 µm). So far, these preliminary size distributions compared with past literature for RCMD size distributions do not show any significant changes from past mining techniques to those currently in use [38]. The results of chemical the composition of source and ambient samples will be used to create receptor-based source apportionment models that will be used to estimate contributions from major RCMD sources (e.g., dust from cutting, drilling, or crushing coal or rock strata, rock dust application, intake air, and diesel exhaust). Preliminary results of the samples show that RCSD was >10% for longwall, feeder, continuous miner, conveyor belt, headgate, and floor locations [38]

## DUST CONTROL

The Dust Control category is an important category. This category aligns with NIOSH intramural research. Current NIOSH dust control projects related to respirable dust include controlling exposures to diesel aerosols, developing sensing and controls in metal/nonmetal mining, improving existing respirable dust controls in underground mining including float dust, and understanding elongated mineral particle exposure. As a result of decades of research in respirable dust control, a recent publication "Best Practices for Dust Control in Coal Mining, 2$^{nd}$ Edition," was published [39]. This publication is a definitive collection of USBM and NIOSH research conducted for coal mine respirable dust control. The four contracts listed complement the NIOSH intramural respirable dust program.

**Improving Health and Safety of Mining Operations Through Development of the Smart Bit Concept for Automation of Mechanical Rock Excavation Units and Dust Mitigation - Colorado School of Mines**

The research developing a Smart Bit or Smart Pick concept has the potential to advance a key component of automating the mechanical excavation units in various mining operations, permitting the removal of the miner from the dust generation sources. This work will develop a load sensing system to monitor the cutting forces on the pick, wireless communication of the data from the drum to the machine, and pattern recognition algorithms to identify the rock being cut using machine learning (ML) and artificial intelligence (AI) systems. These systems, combined with remote and automated machine control, will enable the machines to operate without the need for exposure of personnel to possible health and safety risks. This capacity building contract –a contract with the primary intent to develop masters and PhD graduates in specialized focus areas for the mining industry– will support multiple PhD students and thesis projects.

Excavation of soft rock in mining applications is dominated by mechanical excavation units such as roadheaders, continuous miners (CM), etc. The cutting tools used on these machines are primarily drag type tools including conical/point attack picks and radial tools. The tools are the interface between the machine and the rock and pass through various geologic formations at the face while working. Researchers are currently instrumenting the picks to measure the cutting forces in a real-time basis and then communicate that information with machine operators. This information is a critical part of the automation of the excavation units, and it can be used to identify the various formations being cut, which allows for horizon control. The measured forces will also allow the operators to identify missing or broken tools, as well as picks that have lost their tip or are dull. Ongoing testing on large test blocks of different rock types in this contract has shown that worn tools tend to generate more respirable sized dust which confirmed an earlier study [40]. As tools wear, the cutting forces of machines must gradually increase to make up for the decrease in bit sharpness, further grinding down the bits. Dull tools or picks that have lost their tip require more energy to cut, which in turn generates more dust in when mining the face compared to a new tool or pick [41]. However, having the ability to sense the load on the cutters should allow operators to monitor bit conditions and change them as needed to minimize dust generation at the source.

**Maintenance Free Filters for Continuous Miner Scrubber Systems - University of Kentucky**

University of Kentucky (UKY) researchers have developed a redesigned, maintenance-free scrubber filter for the Flooded-bed scrubber that can be installed in continuous miners currently in service [42]. Flooded-bed dust scrubbers are installed on many continuous miners to capture the dust-laden air from the active face. The scrubbers are powered by vane axial fans with series of inlet ducts to pull dust-laden air through a water-flooded mesh screen filter and a demister. The screen is the primary filter element and captures dust from the airstream on water-flooded layers of metal mesh filter medium. Laboratory research conducted for this contract demonstrated cleaning efficiencies for a 20-layer filter of 75% and 90% for coal particle sizes at 4.07 µm and 6.20 µm, respectively. If the scrubber throughput of airflow and the water are increased, then the scrubber has the ability to remove finer coal particles at 75% and 90% cleaning efficiencies, with the particle sizes being 2.78 µm and 4.52 µm, respectively [43]. Continual deposition of dust on the screen surface clogs it, causing low airflow through the scrubber which can increase dust exposure of miners underground. The continuous miner operator should clean the screen before this occurs, however if the miner is in a cutting sequence, this step might be deferred, resulting in the increased dust exposure. Requirements for screen cleaning should be based upon MSHA requirements for shift examinations. Requirements for shift examination include evaluating scrubber airflow and correcting any deficiencies [44]. This requirement could necessitate the screen be cleaned once per shift. Two different field studies by NIOSH were conducted to evaluate scrubber use. NIOSH recommended cleaning the screens after every 20-ft or 40-ft cut [45, 46].

The UKY maintenance free filter incorporates impactor impingement technology in a series of filter plates. Using results from computational fluid dynamics modeling, the individual plates are optimally designed such that the airflow through the filter must make sharp turns to pass through the filter. The sharp turns and pressure changes between the screens cause the particles to dropout as they cannot follow the airflow due to inertia. The water spray used in the scrubber then washes the particles from the screen layers. Laboratory testing at UKY's Georgetown mine facility has shown the maintenance free filter has a cleaning efficiency at 90% for coal particles >3.5 µm and requires significantly less maintenance than the typical metal mesh filter medium.

**Coal Mine Dust Mitigation Through Novel Scrubber Development and Numerical Modeling - University of Kentucky**

University of Kentucky researchers, in this capacity building contract – a contract with the primary intent to develop masters and PhD graduates in specialized focus areas for the mining industry, addressed the problem of dust in coal mines using two methods: 1. dust removal using a novel scrubber technology and 2. numerical modeling of dust through the mine ventilation network.

The Vortecone scrubber was developed to capture paint overspray particles in the automobile industry. UKY researchers transferred this technology for use in the mining industry to capture respirable dust as an advanced version of the flooded bed scrubber. Dust laden air flows are accelerated in lobes of the scrubber resulting in particles centrifugally cast towards the chamber walls where they are captured by a water film that flows on the inside walls of the scrubber. CFD modeling was used to optimize the Vortecone scrubber design for use in laboratory testing. This Vortecone model was small-scale and had a max airflow capacity of 800 cfm. Test results of the Vortecone scrubber model demonstrated 90% cleaning efficiencies of particles ≥3.2 µm. Higher airflows improve performance, while a change in water flows showed no impact on dust capture [47]. Scale model analysis shows that sizing the scrubber to the airflow should maintain the capture efficiency. A modification of the Vortecone was developed for a horizontal orientation to fit on a continuous miner in an underground entry that maintains the cleaning efficiency and increases the power efficiency [48].

Researchers investigated the transport of dust in an underground coal mine. The focus was on determining a model to predict the transport of float coal dust, which consists of all particles <75 µm. CFD modeling was used to determine the transport and deposition rates of coal particles. Coal particles 20 to 30 µm were not able to escape the deep cuts used in continuous mining operations. Coal particles of 10 µm settled in the return of the continuous miner entry, while particles 1 to 5 µm continued to be airborne with the airflow stream. Dust sampling and CFD modelling could not directly determine float dust deposition trends in underground entries. Possible reasons for no deposition trends could be due to turbulent flow in entries of non-uniform dimensions, the dust generation zone is not a controlled environment, and re-entrainment of dust due to other activities occurring in the entry [49, 50, 51]. The data obtained from CFD modeling and float coal dust sampling was used to conduct a simulation using Mfire; to determine if MFire's fume transport is similar to float dust transport. MFire can be used to predict the dust concentration in a complex mining network, especially the drop in dust concentration as ventilation progresses away from the source of dust. This research highlighted improvements to MFire's capability for use in dust modeling. Currently gravity impact on dust is not possible in MFire, high ventilation airflows do not result in accurate dust concentrations throughout the model, and several parameters have to be set to zero when modeling dust [51].

**Development of Dust Control Units for Underground Coal Mines – J.H. Fletcher & Co.**

This contract developed a self-tramming stand-alone dry scrubber. The dry scrubber is a machine with dimensions of 1.22 m wide x 1.22 m high x 4.79 m long (4 ft wide x 4 ft high x 15.7 ft long). It is remotely operated and trams using hydraulic powered crawlers. The machine consists of a 22.4 Kw (30 hp.) vane axial fan (480 V) with variable frequency drive speed controller. The filtration method uses dual 71-cm (28-in.) O.D. cylindrical air filters rated at 99% efficiency for 2-µm particles. It is powered using 480 V via a trailing cable [52].

The dry scrubber was placed in the lab to determine its efficiency for removing respirable dust. It was tested operating at airflows of 1.42 and 4.25 $m^3/s$ (3000 and 9000 cfm). Respirable dust sampling was conducted 3.05 m (10 ft) upwind of the dry scrubber intake and 3.05 (10 ft) downwind of the dry scrubber exhaust. Two sets of filters were tested: a disposable filter and a washable filter. The respirable dust collection efficiency using the disposable filter averaged 95%. Testing for this filter was conducted for 12 hours. However, after 8 hours of operations, the airflow could not be maintained above 4.00 m3/s (8500 cfm). The washable filter respirable dust collection efficiency was less, ranging from 88% to 90% with a gradual peak at 97% at 5 hours into testing and then reducing to 66% at the 14$^{th}$ hour. Testing for this filter was conducted for 14 hours. The dry scrubber was able to maintain the selected airflow throughout the testing with the washable filters. Sound level measurements were also taken during the lab study. Sound levels were higher at the exhaust than at the inlet of the dry scrubber. As the airflows increased, the sound levels increased. Loading on the filters also increased the sound levels. It was noted that at the operating point of 2.83 $m^3/s$ (6000 cfm) the sound levels were within MSHA permissible exposure levels. Operating the dry scrubber at higher airflows could overexpose miners working nearby [52].

Underground testing was completed at a room and pillar operation at an underground coal mine using blowing face ventilation. The dry scrubber was located in the last open crosscut before the last entry at the return, i.e., the crosscut before entry #9 of a 9-entry section. The exhaust of the dry scrubber was oriented to provide air into entry #9. Testing was also completed with a similar setup for a 12-entry section. Samplers were located upwind of the dry scrubber and at the face of the entry downwind of the scrubber. During operation, the respirable dust efficiency of the dry scrubber ranged from 46.3% to 59.9% when no equipment was operating downstream of the dry scrubber. During testing a set of samplers were placed directly in the dry scrubber exhaust to ascertain its respirable dust collection efficiency. The dry scrubber direct respirable dust collection efficiencies were found to be 93.2% and 99.3% both times the exhaust was sampled. The lower entry respirable dust efficiencies of 46.3% to 59.9% were thought to be reduced due to the section return air mixing with the air of the exhaust discharge of the dry scrubber. During operation, the dry scrubber was able to maintain the selected airflows throughout the duration of the test. It was also seen that the dry scrubber was able to provide a 1.4 to 1.7 increase in airflows to the face over the initial ventilation airflow measurements conducted prior to operation. This research demonstrated that the dry scrubber is a viable dust control method to mitigate roof bolter dust exposures when operating downstream of the continuous miner [52]

## DEVELOPMENT OF DUST MONITORS

This category is also a topic that was recommended in the 2018 National Academies Study Report. Recommendations 5 and 6 relate to this category. Recommendation 5 suggests NIOSH develop a real-time crystalline silica monitor. Recommendation 6 advises NIOSH to continue to facilitate the development of a less costly and less ergonomically stressful real-time RCMD monitoring device for compliance and/or non-regulatory dust monitoring. This recommendation also includes developing appropriate filter media that is compatible with an end-of-shift analyzer for respirable crystalline [25]. The following 8 contracts relate to this category.

**Development of a Personal Real-Time Respirable Coal Dust and Respirable Silica Dust Monitoring Instrument Based on Photoacoustic Spectroscopy - University of Nevada-Reno**

The focus area of this research which builds upon work completed on the Alpha Foundation Grant AFC518-54 is to develop a real-time personal coal and silica dust (RTPCSD) monitoring instrument. The new monitor's dust assessment system will be based on photoacoustic spectroscopy using optical design principles. In summary, a dust sample will be injected into a RTPSCD test chamber. A laser with a specific wavelength (mid visible to near infrared region or approximately 660 nm) will be projected through two windows at opposite ends of the chamber to infiltrate the sample. Coal particles will absorb energy from the laser causing heating of the carbon particles. This absorbed heat will create increase pressure causing an acoustic pressure wave which will be measured. The results will provide information for an algorithm developed to output a dust concentration. Non carbonate particles will be tested in a similar manner, except using a different laser wavelength (near ultra-violet region or approximately 365 nm).

A prototype, which uses a tunable quantum cascade laser, has been developed for lab testing with results showing that the RTPSCD is capable of measuring airborne silica in real-time when compared with the NIOSH FTIR transmission method. Water vapor and kaolinite can interfere with silica measurements. However, the addition of a humidity sensor in the RTPSCD airflow can allow for correction due to water vapor. Correction for kaolinite and coal particles can be accomplished through adjusting the tunable quantum cascade laser [53]. Additional testing is underway along with development of a smaller portable unit to make it suitable for field use.

**Development of Non-regulatory Runtime Respirable Coal and Silica Dust Monitor Using Quantum Cascade Laser-based Ringdown Spectroscopy - RingIR**

RingIR proposes to utilize a new laser-based infrared spectroscopic modality, runtime cavity ringdown spectroscopy, for the development of a highly sensitive coal and silica dust sensor. This work continues work completed for Queensland Government Australia, Department of Natural Resources, Mines & Energy, and the Australian Coal Association Research Program. The quantum cascade laser (QCL)-based direct absorption spectroscopy will be used to develop the first mid-infrared real time mining dust monitor capable of measuring ambient concentrations of non-regulatory silica and coal dust present in the mining environment. A cavity-enhanced direct optical absorption method coupled with QCLs will be used. RingIR's patented direct optical absorption technology utilizes broadly tuning mid-infrared QCLs to produce a field-deployable runtime cavity ringdown (rtCRD) spectrometer for gas tracking and leak detection. This system can reach high parts-per-trillion (ppt) (> 0.1 ppt) sensitivity with low false positives (<0.01%), when utilized for gas measurement. Initial studies have identified two wavelengths of mid-infrared absorption for coal and silica: 7500-7600 nm and 8600-9100 nm, respectively [54]. These results demonstrate the potential for measuring concentrations of silica and coal dust, providing instant results allowing workers to take immediate actions to prevent overexposure to respirable coal and silica dust.

**Development of a Silica Dust Direct Reading Sampler with Sensitivity for Dust Components and Size - Colorado State University**

The objective of this contract which builds upon an Alpha Foundation Grant AFC518-16, is to develop a device and construct a sensor for dust differentiation. A 25-mm personal sampler containing a capacitive sensor, which collects/measures respirable particles, has been designed and used to collect dust during drilling activities to collect numerous nano- to micrometer-sized particles. The collected particle agglomerates on the filter primarily measured a few micrometers to submicrometers in size, as analyzed by SEM. This device will use capacitive sensors to monitor the volume of deposited particles and convert the detection results to a real-time exposure level; and use coordinated optical and capacitive sensor responses to determine the total quantity of silica [55].

A new design for the sampler will be developed to accommodate a 37-mm filter, because past direct on filter measurement methods were conducted on 25-mm filters which are not used in mine dust sampling [56]. The optical sensor will measure the optical reflectance or transmittance on the deposited particle film, and in conjunction with a capacitive sensor (for mass detection) will provide information regarding the proportions of silica and carbon (coal) in the dust to aid estimation of their concentrations. When operated during a full work shift, the proposed device will provide real-time mass measurements of respirable dust. When operated for short-term samplings, the collected particles can be analyzed off-line using a microscope to obtain information regarding particle composition, morphology, size distribution, and number [55].

**Miniaturized Wearable Personal Dust Exposure Monitor for Respirable and Alveolar Dust in Underground Coal Mines - University of Illinois-Chicago**

This contract designed and developed a miniaturized low-cost personal dust monitor that could be worn on a lapel or clipped to a miner's clothing. The low-cost device integrated several technologies to analyze the separated components of the dust sample and offer the wearer a real-time readout of their dust exposure. The instrument consists of an elutriator, fractionator, dryer, and a dual fraction mass sensor. The elutriator is designed for a $D_{50}$ of 10 µm to remove larger particles. Then, as the flow progresses, particles greater than 4 µm are removed by a fractionator before it enters a heater. After drying is completed, the flow is separated again by removing particles greater than 1.2 µm. These particles are collected on a quartz crystal microbalance (QCM) via inertial impaction. The flow, which contains particles < 1.2 µm, are collected on a mass sensor resonator (MSR). The QCM oscillates at its resonate frequency which changes as mass changes. The QCM surface has been designed with micropillars to enhance its collection efficiency [57]. The MSR collects particles based upon thermophoresis forces, created by heaters, on the surface of a film-bulk acoustic resonator (FBAR). The testing was completed using particle diameters of 0.5, 1, 2, 3, 4, and 5 µm; each diameter was tested separately. The results using collection efficiency showed the viability of this system [58]. The result of this research is the WEARDM a low-cost prototype instrument (dimensions 16 cm tall x 6 cm wide x 3 cm deep -without the elutriator) that can provide real-time respirable dust concentrations to the wearer.

**Feasibility Testing of a Near Real Time Respirable Silica Monitor - Thermo Environmental Instruments**

The intent of this work is to develop hardware and a measurement system that could eventually be developed into a wearable configuration to measure respirable silica dust during a miner's working shifts. The goal of the contract is to determine the performance of QCL technology as it relates to a potentially field deployable, wearable, near real-time silica measurement system that supports OSHA and MSHA silica standards. A laboratory scale prototype was developed, and experiments were conducted on three different configurations for the infrared source (laser), filter (contains dust sample), and infrared detector; using reflectance and absorbance (configuration 1), absorption and transmission (configuration 2) and reflectance (configuration 3) of the laser (800 $cm^{-1}$) upon the filter. These experiments were conducted for silica identification, detection limit, and repeatability. All three configurations performed well for silica measurements. However, when coal dust was introduced configuration 2 and 3 performed better than Configuration 1 with Configuration 3 performance with the coal and silica mixtures being preferable. System stability when exposed to various environmental factors; temperature, humidity, and vibration were tested. Effects from temperature were detectable, but not large when compared to the background instrument noise. Humidity and vibration did not seem to degrade the performance of silica measurements at absorption peaks of 780 $cm^{-1}$ and 800 $cm^{-1}$. Power consumption tests for the QCL showed that more power was consumed at higher temperatures than lower. The results of these tests show that the battery may need to have a larger capacity of the instrument is to be operational for an entire shift. However, tradeoffs in lower powered electronics and utilization of sleep mode could be made. Overall, the results demonstrate that this QCL technique can measure respirable crystalline silica dust at microgram levels. There can be interference due to coal dust, detection levels were still better than 10x the 8-hour shift exposure limit for respirable crystalline silica dust. Further research could be conducted to improve the performance.

**Novel application of Fourier-Transform Infrared Spectroscopy and optical particle counting for the real-time quantification of respirable crystalline silica and dust in the mining environment - Microaeth Corp.**

This contract proposes to integrate an FTIR spectrometer and suitable light source with the hardware of an AethLabs MA200 Black Carbon instrument, a palm sized, battery-powered, wearable, multiwavelength instrument with a mechanized filter tape advance mechanism, in order to develop a wearable RCS monitor. Candidate FTIR interferometers, detectors and light sources will be evaluated. A FTIR has been selected to incorporate into the design to finalize the development of the integrated analyzer. A performance comparison of this unit to a laboratory grade FTIR for quantification of RCS lab generated and field collected samples will be completed.

Further development of prototype monitors, targeting a miniaturized wearable monitor for RCS, producing at least 2 units is planned. The size of the system components will be reduced, with a target of operation through an 8 to10 hour work shift with a quick and easily replaceable lightweight battery. Ideal dimensional specifications will be identified for the product relying on examples of existing wearable mining technology such as the Thermo PDR3700 wearable dust monitor and NIOSH collaborator expertise to help guide the design. As size, weight and power are important feasibility constraints for a wearable RCS monitor, the applicability of the off-the-shelf commercially available interferometers and spectrometers that have been evaluated in previous miniaturization efforts will be determined. The end focus will be to ready a fully contained, reproducible device that can be used to make real RCS measurements in the smallest possible form factor.

**Caplamp Particulate Monitoring System - Strata Safety Products**

Strata Products contract plans to develop a Caplamp Particulate Monitoring Systems (CPMS) – an integrated silica monitoring and tracking device which is integrated into existing equipment that mine workers currently wear. It will allow tracking of the mine worker and monitor silica exposure, which can result in CWP, silicosis and chronic obstructive pulmonary disease. This system will use infrared spectrophotometry and multi-wave Raman LIDAR (light detection and ranging) to identify the optimal emitter and detector for the measurement of crystalline silica. The system will consist of the following components: an intrinsically safe (MSHA-approved) waist battery pack for the Strata Personal Alarm Device and an intrinsically safe underground cap lamp which will be redesigned to house the intrinsically safe silica detection system. This commercial, intrinsically safe CPMS will alert miners when silica personal exposure has reached unsafe levels, or when an individual miner's exposure to particulates has reached an unsafe level. There are two barriers to be overcome: 1) identify the commercially available emitters and detectors that can be utilized, and 2) successfully integrate all the components into the helmet while meeting size and power restrictions of a cap lamp headpiece and waist-worn battery. LIDAR technology has progressed, incorporating Raman scattering measurements, to allow development of the CPMS. The prototype will be developed through identification of optimal Raman Backscattering wave-length emitters and detectors, testing and evaluation of commercially available off-the-shelf emitter and detectors on custom printed circuit boards, and integration of the emitter and detector into the cap lamp.

**Next Generation Continuous Personal Dust Monitor (CPDM) - Thermo Environmental Instruments**

Thermo Environmental Instruments plans to produce a new prototype version of a next generation CPDM: reducing the size and weight of the current CPDM (PDM 3700), improving the thermal performance of the instrument, and improving the battery life and instrument runtime. Modifications include upgrading the sample pump to provide the best performance with low power consumption. Battery life is improved by using a hot swappable battery pack, using a small internal battery that will allow the CPDM to operate while switching batteries. The swappable batteries will be rechargeable via an external charging port. The programmable printed circuit board assembly has been upgraded to replace obsolete circuits and components. The display, while smaller than the current display, is replaced with a graphical display to provide more flexibility in providing key information to the mine worker. Overall, the volume has been reduced by 35%. The weight of the CPDM will be established once the prototypes are finalized, but the CPDM is expected to be considerably lighter than the current version. Improved thermal control will result in the ability of the instrument to be operated over a wider shift temperature operating range while still providing accurate near-real-time dust concentration measurements and accurate end-of-shift exposure results as required by MSHA. Overall, this next generation CPDM will be smaller, lighter, and quieter while designed to comply with NIOSH and MSHA approval criteria.

## SUMMARY AND CONCLUSION

Coal production has been decreasing in the U.S. to its lowest level, from 897 million short tons in 2015 to 535 million short tons in 2020 [59EIA Oct. 2021a], while metallurgical coal production has ranged from 14 million short tons in 2015 to 10 million short tons in 2020 [60EIA Oct. 2021b]. Even though production has decreased, coal still contributes to 23-24% of the energy used to generate electricity [61EIA Oct. 2021c]. Therefore, there is still the potential for CWP or silicosis to occur in underground coal miners in the U.S.

The six contracts in the Characterization of Coal section show promising results for characterizing the particle size distributions and chemical components of the RCMD and RCSD. An important finding is that airborne NCD-sized particles are present in working sections as determined from sampling at underground mines. While there are large number of NCD-sized particles, they do not make up a significant mass of the sample. Implications of airborne NCDs remain to be investigated in several of these contracts.

The four contracts in the Dust Control section show innovative methods to control dust. For example, the Vortecone scrubber is a technology from the automobile industry that seems to be easily transferred to the coal industry. Research on Smart picks may advance automating cutting head machinery by providing information on surrounding geology as it is being mined thereby improving horizon control. The maintenance free scrubber screen may improve miner health through improved dust capture efficiency and allow increases in coal production by minimizing the need to clean the scrubber filters on continuous miners. The dry scrubber, as demonstrated by its evaluation, is a viable dust control to reduce roof bolter operator RCMD exposure when working downwind of the continuous miner in underground coal mines.

The eight contracts in the Development of Dust Monitors section are developing new types of dust monitors for RCMD and RCSD. The technology to develop these new monitors includes componentry based upon photoacoustics, QCL, Raman light scattering, FTIR, and LIDAR. The miniaturization of electronics has made it possible to potentially create these new dust monitors in a package that is wearable and unobtrusive to miners.

As these contracts continue, the characterization, control, and monitoring of RCMD and RCD will be enhanced. The success of many of these contracts will improve the health and safety of U.S. miners. NIOSH OMSHR plans to continue awarding contracts to develop technologies related to mine safety and health through the broad agency announcement (BAA) program. This solicitation is for concept papers to conduct research, exploratory development, testing, or evaluations of new technologies to improve mine safety, or to adapt technologies from other industries for application in mining environments. The BAA is generally posted on www.SAM.gov in mid-November with concept papers due in January. The OMSHR extramural program, particularly these respirable dust contracts awarded through BAA program, has been successful in advancing the technology for improved RCMD and RCD characterization, control, and monitoring.

## REFERENCES

1. Miner Act. 2006, Public Law 109–236, Sec 6, 109th Congress, June 15, 2006
2. World Health Organization. 1999. Hazard Prevention and Control in the Work Environment: Airborne Dust. WHO/SDE/OEH/99.14 (Geneva Switzerland: Occupational and Environmental Health, Department of Protection of the Human Environment, World Health Organization).
3. Lara, A.R. 2020a. "Black Lung" The Merck Manual, Consumer Version. (Kenilworth NJ: Merck & Co. Inc.) Website: https://www.merckmanuals.com/home/lung-and-airway-

disorders/environmental-lung-diseases/coal-workers-pneumoconiosis Last accessed: Sept 2021

4. Lara, A.R. 2020b. "Silicosis" The Merck Manual, Consumer Version. (Kenilworth NJ: Merck & Co. Inc.) Website: https://www.merckmanuals.com/home/lung-and-airway-disorders/environmental-lung-diseases/silicosis Last accessed: Sept 2021.

5. U.S. Department of Labor, 2019. "Federal Coal Mine Health and Safety Act of 1969, Public Law 91-173, 91st Congress, S. 2917 December 30, 1969." U.S. Department of Labor, Mine Safety and Health Administration (MSHA). Accessed Sept. 17, 2019, https://arlweb.msha.gov/SOLICITOR/COALACT/69act.htm

6. Blackley, D.J., Halldin, C.N., and Laney, A.S. 2018a. "Continued increase in prevalence of coal workers' pneumoconiosis in the U.S., 1970-2017." Am J Public Health, Published online ahead of print. July 19, 2018, e1-e3. https://doi.org/10.2105/AJPH.2018.304517

7. Hall, N.B., Blackley, D.J., Halldin, C.N., and Laney, A.S. 2018. "Continued increase in prevalence of r-type opacities among underground coal miners in the USA." Occup Environ Med, Epub ahead of print, May 1, 2019. https://doi.org/10.1136/oemed-2019-105691

8. Hall, N.B., Blackley, D.J., Halldin, C.N., and Laney, A.S. 2019. "Current Review of Pneumoconiosis Among US Coal Miners." Curr Environ health Rep, 6(3), pp. 137-147 https://doi.org/10.1007/s40572-019-00237-5

9. Reynolds, L.E., Blackley, D.J., Colinet, J.F., Potts, J.D., Storey, E., Short, C., Carson, R., Clark, K.A., Laney, A.S., & Halldin, C.N. 2018. "Work Practices and Respiratory Health Status of Appalachian Coal Miners with Progressive Massive Fibrosis." Journal of Occupational and Environmental Medicine, 60(11), e575–e581. https://doi.org/10.1097/JOM.0000000000001443

10. Wilson, J. 2003. "High Voltage Continuous Miners." Coal Leader. http://www.coalleader.com/2003/high_volt_cont_miners.htm

11. Komatsu. 2021. "Komatsu Introduces Innovations for Room and Pillar Mining at MINExpo 2021." Press Release, September 13, 2021. https://www.komatsu.com/en/newsroom/2021/komatsu-introduces-innovations-for-room-and-pillar-mining/

12. Pollock, D.E., Potts, J.D., and Joy, G.J. 2010. "Investigation into Dust Exposures and Mining Practices in Mines in the southern Appalachian Region." Mining Engineering, Vol. 62, No. 2.

13. Stansbury R.C., Petsonk E.L., Parker J.E. 2015. "Coal Workers' Lung Diseases and Silicosis." Fishman's Pulmonary Diseases and Disorders, Fifth Edition Eds. Michael A. Grippi, et al. (New York, NY: McGraw-Hill), Last accessed May 2, 2019. http://accessmedicine.mhmedical.com/content.aspx?bookid=1344&sectionid=81194652.

14. Blackley, D.J., Crum, J.B., Halldin, C.N., Storey, E., and Laney, A.S. 2016. "Resurgence of progressive massive fibrosis in coal miners –Eastern Kentucky, 2016." Centers for Disease Control and Prevention MMWR, Vol. 65, No. 49. http://dx.doi.org/10.15585/mmwr.mm6549a1

15. Blackley, D.J., Reynolds, L.E., Short, C., Carson, R., Storey, E., Halldin, C., and Laney, A.S. 2018b. "Progressive massive fibrosis in coal miners from 3 clinics in Virginia." JAMA Vol. 319, No. 5, pp. 500-501. https://doi.org/10.1001/jama.2017.18444

16. U.S. Department of Labor, 2021a. "Black lung program statistics, Division of Coal Mine Workers' Compensation (DCMWC), "Black Lung Program Benefit Payment Totals by Year." U.S. Department of Labor, Office of Workers' Compensation Programs, Division of Coal Mine Workers' Compensation (DCMWC). Accessed November 5, 2021, https://www.dol.gov/agencies/owcp/dcmwc/statistics/TotalBenefitsPayment

17. U.S. Department of Labor, 2021b. "Black lung program statistics, Division of Coal Mine Workers' Compensation (DCMWC), "Distributions of Part C Black Lung Claims and Disbursements by State, FY 2021." U.S. Department of Labor, Office of Workers' Compensation Programs, Division of Coal Mine Workers' Compensation (DCMWC). Accessed November 5, 2021, https://www.dol.gov/agencies/owcp/dcmwc/statistics/bls2021/DistributionOfClaimsByState2021

18. U.S. Department of Labor, 2021c. "Black lung program statistics, Division of Coal Mine Workers' Compensation (DCMWC), "Total Number Black Lung Beneficiaries, FY 2004-2006." U.S. Department of Labor, Office of Workers' Compensation Programs, Division of Coal Mine Workers' Compensation (DCMWC). Accessed November 5, 2021, https://www.dol.gov/agencies/owcp/dcmwc/statistics/PartBandCBeneficiaries

19. U.S. Department of Labor, 2021d. "Black Lung Benefits, Table 9.D1 Benefits currently payable to miners, widows, and dependents, December 1970-2006." U.S. Department of Labor, Social Security Administration, Research, Statistics & Policy Analysis, Annual Statistical Supplement 2007. November 5, 2021, https://www.ssa.gov/policy/docs/statcomps/supplement/2007/9d.html

20. Code of Federal Regulations 30 CFR 70.100. 2017, CFR Title 30, Chapter I, Subchapter 0, Part 70-Mandatory Health Standards-Underground Coal Mines, Subpart B-Dust Standards, 70.100 Respirable dust standards., U.S. Government Printing Office, Washington, D.C.: National Archives and Records Administration.

21. Code of Federal Regulations 30 CFR 70.101. 2017, CFR Title 30, Chapter I, Subchapter 0, Part 70-Mandatory Health Standards-Underground Coal Mines, Subpart B-Dust Standards, 70.101 Respirable dust standards when quartz is present., U.S. Government Printing Office, Washington, D.C.: National Archives and Records Administration.

22. Code of Federal Regulations, 30 CFR 70.201. 2017, CFR Title 30, Chapter I, Subchapter 0, Part 70-Mandatory Health Standards-Underground Coal Mines, Subpart C-Sampling Procedures, 70.201 Sampling; general and technical requirements., U.S. Government Printing Office, Washington, D.C.: National Archives and Records Administration.

23. Code of Federal Regulations, 30 CFR 74.3. 2000, CFR Title 30, Chapter I, Subchapter 0, Part 74-Coal Mine Dust Personal Sampling Units, 74.3 Specifications of sampler unit., U.S. Government Printing Office, Washington, D.C.: National Archives and Records Administration.

24. Laney A.S., Blackley D.J., Halldin C.N. 2017. "Radiographic disease progression in contemporary US coal miners with progressive massive fibrosis." Occup Environ Med. 74:517–520. https://doi.org/10.1136/oemed-2016-104249

25. National Academies of Sciences, Engineering, and Medicine. 2017. "Monitoring and Sampling Approaches to Assess Underground Coal Mine Dust Exposures." Washington, DC: The National Academies Press. https://doi.org/10.17226/25111.

26. Pan, L., Golden, S., Assemi, S., Sime, M.F., Wang, X., Gao, Y., and Miller, J. 2021. "Characterization of Particle Size and Composition of Respirable Coal Mine Dust" Minerals 11, no. 3: 276. https://doi.org/10.3390/min11030276

27. Sarver, E., Keleş, C., and Afrouz, S.G. 2021. "Particle size and mineralogy distributions in respirable dust samples from 25 US underground coal mines." International Journal of Coal Geology, Volume 247, https://doi.org/10.1016/j.coal.2021.103851

28. Miller, A.L., Drake, P.L., Murphy, N.C., Cauda, E.G., LeBouf, R.F., and Markevicius, G. 2013 "Deposition Uniformity of Coal Dust on Filters and Its Effect on the Accuracy of FTIR Analysis for Silica"

 

Aerosol Science and Technology, 47:7, 724-722. https://doi.org/10.1080/02786826.2013.787157

29. Pokhrel, N., Agioutanti, E., Keles, C., Afrouz, S., and Sarver, E.A. 2021. “Comparison of Mineral Content in Respirable Coal Mine Dust Samples Estimated Using FTIR, TGA, and SEM-EDX.” Tukkaraja, P. Ed. Proceedings of the 18th North American Mine Ventilation Symposium (NAMVS 2021), June 12-17, 2021, Rapid City, South Dakota, USA. pp. 233-241. https://doi.org/10.1201/9781003188476-27

30. Gonzales, J., Pokhrel, N., Jaramillo, C., Keles, C., and Sarver, E. 2021. “Respirable Dust Characterization Using SEM-EDX and FT-IR: A Case Study in an Appalachian Coal Mine.” Tukkaraja, P. Ed. Proceedings of the 18th North American Mine Ventilation Symposium (NAMVS 2021), June 12-17, 2021, Rapid City, South Dakota, USA. pp. 233-241. https://doi.org/10.1201/9781003188476-19

31. Agioutanti, E., Keles, C., and Sarver, E. 2020. “A thermogravimetric analysis application to determine coal, carbonate, and non-carbonate minerals mass fractions in respirable mine dust.” Journal of Occupational and Environmental Hygiene, 17:2-3, 47-58, https://doi.org/10.1080/15459624.2019.1695057

32. Hart, J.F., Autenrieth, D.A., Cauda, E., Chubb, L., Spear, T.M., Wock, S., and Rosenthal, S. 2018. “A comparison of respirable crystalline silica concentration measurements using a direct-on-filter Fourier transform infrared (FT-IR) transmission method vs. a traditional laboratory X-ray diffraction method.” Journal of Occupational and Environmental Hygiene, 15:10, 743-754, https://doi.org/10.1080/15459624.2018.1495334

33. NIOSH. 2021a. “FAST – Field Analysis of Silica Tool.” Software. Webpage: https://www.cdc.gov/niosh/mining/works/coversheet2056.html last accessed: November 8, 2021.

34. Shekarian, Y., Rahimi, E., Rezaee, M., Su, W.-C., and Roghanchi, P. 2021a. “Respirable Coal Mine Dust: A Review of Respiratory Deposition, Regulations, and Characterization.” Minerals 2021, 11, 696. https://doi.org/10.3390/minl1070696

35. Shekarian, Y., Rahimi, E., Shekarian, N., Rezaee, M., and Roghanchi, P. 2021b. “An analysis of contributing mining factors in coal workers’ pneumoconiosis prevalence in the United States coal mines, 1986–2018.” Int J Coal Sci Technol. https://doi.org/10.1007/s40789-021-00464-y

36. Zhang, R., Liu, S., and Zheng, S. 2021. “Characterization of nano-to-micron sized respirable coal dust: Particle surface alteration and the health impact.” Journal of Hazardous Materials, Volume 413, https://doi.org/10.1016/j.jhazmat.2021.125447

37. Abbasi, B., Wang, X., Chow, J.C., Watson, J.G., Peik, B., Nasiri, V., Riemenschnitter, K.B, Elahifard, M. 2021. “Review of Respirable Coal Mine Dust Characterization for Mass Concentration, Size Distribution and Chemical Composition.” Minerals, 11, 426. https://doi.org/10.3390/min11040426

38. Abbasi., B. 2021. “Characterization of Respirable Coal Mine Dust Size Distribution, Chemical Composition, and Source Contributions.” PowerPoint Presentation Respirable Dust Contracts Update Meeting, Sept. 16 & 17, 2021.

39. NIOSH. 2021b. “Best practices for dust control in coal mining, second edition.” By Colinet JF, Halldin CN, Schall J. Pittsburgh PA: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2021-119, IC 9532. https://doi.org/10.26616/NIOSHPUB2021119

40. Organiscak, J.A., Khair, A.W., and Ahmad, M. 1996. “Studies of Bit Wear and Respirable Dust Generation.” Society for Mining, Metallurgy, and Exploration, Inc. Transactions, Vol 198, 1874-1879.

41. Slouka, S., Rostami, J., and Brune, J. 2021. “Characterization of Respirable Dust Samples Generated from Picks at Differing Stages of Wear.” Tukkaraja, P. Ed. Proceedings of the 18th North American Mine Ventilation Symposium (NAMVS 2021), June 12-17, 2021, Rapid City, South Dakota, USA. pp. 198-207. https://doi.org/10.1201/9781003188476-20

42. Kumar, A.R., Schafrik, S., Velasquez, O., and Wedding, W.C. 2020. “Filter Assembly and Scrubber Section for a Continuous Miner.” Patent 16/533395. https://uspto.report/patent/app/20200122072

43. Gupta, N., Kumar, A., and Schafrik, S. 2021. “Laboratory Determination of Coal Dust Cleaning Efficacy of a Fibrous Filter for Flooded-Bed Dust Scrubber.” Minerals, 11, 295. https://doi.org/10.3390/min11030295

44. Code of Federal Regulations, CFR 75.362. 2021, CFR Title 30, Chapter I, Subchapter 0, Part 75 Subpart D, 75.362 On-shift examination., U.S. Government Printing Office, Washington, D.C.: National Archives and Records Administration.

45. NIOSH. 2011. “Evaluation of Face Dust Concentrations at Mines Using Deep-Cutting Practices.” By Potts JD, Reed WR, Colinet JF. Pittsburgh, PA: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication 2011–131, RI 9680.

46. NIOSH. 2013. “Impact on Respirable Dust Levels When Operating a Flooded-bed Scrubber in 20-foot Cuts.” By Colinet JF, Reed WR, Potts JD. Pittsburgh, PA: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication 2014–105, RI 9693.

47. Kumar, A.R., Schafrik, S., and Novak, T. 2020. “Multi-phase computer modeling and laboratory study of dust capture by an inertial Vorte-cone scrubber.” International Journal of Mining Science and Technology, Vol. 30, No. 3, pp. 287-291. https://doi.org/10.1016/j.ijmst.2020.03.014

48. Kumar, A.R., Schafrik, S., and Taylor, A. 2021. “Efficient Non-Clogging Inertial Vortex Type Particle Scrubber.” Patent 17/084073. https://uspto.report/patent/app/20210138379

49. Kumar, A.R., Kumar, A., and Schafrik, S. 2019a. “CFD Modeling of Dust Transportation and Deposition Under Newtonian Forces in the Reduced Scale Model of a Typical Room and Pillar Mine.” Preprint 19-131, SME Annual Meeting, Feb. 24-27, Denver, CO.

50. Kumar, A., Schafrik, S., and Kumar, A.R. 2019b. “Float Coal Dust Sampling and Preliminary Analysis.” Preprint 19-135, SME Annual Meeting, Feb. 24-27, Denver, CO.

51. Schafrik, S. 2019. “Coal Mine Dust Mitigation through Novel Scrubber Development and Numerical Modeling.” NIOSH Contract 200-2014-59922, (Pittsburgh, PA: Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, Office of Mine Safety and Health Research).

52. Organiscak, J.A., Noll, J., Yantek, D., and Kendall, B. 2016. “Examination of a Newly Developed Mobile Dry Scrubber (DS) for Coal Mine Dust Control Applications.” Preprint 16-010, SME Annual Meeting, Feb. 21-24, Phoenix, AZ.

53. Nascimento, P., Taylor, S.J., Arnott, W.P., Kocsis, K.C., Wang, X.L., and Firouzkouhi, H. 2021. “Development of a Real Time Respirable Coal Dust and Silica dust Monitoring Instrument Based on Photoacoustic Spectroscopy.” Tukkaraja, P. Ed. Proceedings of the 18th North American Mine Ventilation Symposium (NAMVS 2021), June 12-17, 2021, Rapid City, South Dakota, USA. pp. 233-241. https://doi.org/10.1201/9781003188476-24

54. Harb, C.C., Rajapaksha, R.D., Moya, X., Roberts, J., Hemp, P., Uecker, L., Rawson, T., and Roganchi, P. 2021. "Development of Non-Regulatory Runtime Respirable Coal and Silica Dust Monitor." Tukkaraja, P. Ed. Proceedings of the 18th North American Mine Ventilation Symposium (NAMVS 2021), June 12-17, 2021, Rapid City, South Dakota, USA. pp. 242-247. https://doi.org/10.1201/9781003188476-25

55. Tsai, C.SJ. and Theisen, D. 2018. "A sampler designed for nanoparticles and respirable particles with direct analysis feature." J Nanopart Res 20, 209. https://doi.org/10.1007/s11051-018-4307-2.

56. Cauda, E., Miller, A., and Drake. P. 2016 "Promoting early exposure monitoring for respirable crystalline silica: Taking the laboratory to the mine site," Journal of Occupational and Environmental Hygiene, 13:3, https://doi.org/10.1080/15459624.2015.1116691

57. Hajizadehmotlagh, M. and Paprotny, I. 2019. "Effect of micropillars with varying geometry and density on the efficiency of impaction-based quartz crystal microbalance aerosol sensors." Journal of Applied Physics, Vol. 127, Issue 18 184903. https://doi.org/10.1063/1.5125895

58. Hajizadehmotlagh, M. and Paprotny, I. 2019. "Miniaturized Wearable Respirable Dust Monitor (WEARDM) for Underground Coal Mines: Designs and Experimental Evaluation," IEEE SENSORS, 2019, pp. 1-4, https://doi.org/10.1109/SENSORS43011.2019.8956817

59. U.S. Energy Information Administration. Oct. 2021a. "Annual Coal Report 2020." U.S. Dept. of Energy, Independent Statistics and Analysis. https://www.eia.gov/coal/annual/pdf/acr.pdf

60. U.S. Energy Information Administration. October 2021b. "Quarterly Coal Report, April – June 2021." https://www.eia.gov/coal/production/quarterly/pdf/tes2p01p1.pdf

61. U.S. Energy Information Administration. October 2021c. "Short-Term Energy Outlook October 2021." https://www.eia.gov/outlooks/steo/pdf/steo_full.pdf.

## APPENDIX

**Table 1.** Listing of NIOSH OMSHR contracts awarded related to respirable dust and respirable crystalline silica dust: Topic -Characterization of Coal Dust.

| | Title | Contractor | Start Date | End Date |
|---|---|---|---|---|
| 1 | Temporal and Spatial Characterization of Respirable Coal Mine Dust (RCMD) | Michigan Tech | 9/1/2019 | 4/30/2022 |
| 2 | Respirable Crystalline Silica Characteristics and Sources in U.S. Underground Coal Mines | Virginia Tech | 9/1/2019 | 2/28/2022 |
| 3 | Respirable Coal Mine Dust: Mineral Content Sources, Monitoring and Control, and Building Capacity to Protect Miner Health | Virginia Tech | 9/3/2019 | 8/31/2024 |
| 4 | Respirable Coal Mine Dust (RCMD) Research: Characterization, Deposition, Monitoring, and Mitigation of RCMD and Capacity Building for Mine Health and Safety | New Mexico Tech | 9/15/2019 | 8/31/2024 |
| 5 | Characterization of Submicron-/Nano-scale Coal Dusts and Their Effects on Miners' Pneumoconiosis and Lung Cancer for Underground Coal Mines | Pennsylvania State Univ. | 8/27/2019 | 8/31/2022 |
| 6 | Characterization of Coal Mine Dust Size Distribution, Chemical Composition, and Source Contributions | Univ. of Nevada – Reno | 9/1/2019 | 9/15/2022 |

**Table 1**. Listing of NIOSH OMSHR contracts awarded related to respirable dust and respirable crystalline silica dust: Topic -Characterization of Coal Dust: Topic – Dust Control.

| | Title | Contractor | Start Date | End Date |
|---|---|---|---|---|
| 1 | Improving Health and Safety of Mining Operations Through Development of the Smart Bit Concept for Automation of Mechanical Rock Excavation Units and Dust Mitigation | Colorado School of Mines | 9/13/2019 | 8/31/2024 |
| 2 | Maintenance Free Filters for Continuous Miner Scrubber Systems | Univ. of Kentucky | 9/1/2019 | 12/31/2021 |
| 3 | Coal Mine Dust Mitigation Through Novel Scrubber Development and Numerical Modeling | Univ. of Kentucky | 9/1/2014 | 8/31/2019 |
| 4 | Development of Dust Control Units for Underground Coal Mines | J.H. Fletcher & Co. | 9/1/2010 | 8/27/2015 |

**Table 2**. Listing of NIOSH OMSHR contracts awarded related to respirable dust and respirable crystalline silica dust: Topic -Characterization of Coal Dust: Topic – Development of Dust Monitors.

| | Title | Contractor | Start Date | End Date |
|---|---|---|---|---|
| 1 | Development of a Personal Real-Time Respirable Coal Dust and Respirable Silica Dust Monitoring Instrument Based on Photoacoustic Spectroscopy | University of Nevada – Reno | 9/1/2019 | 8/31/2022 |
| 2 | Development of Non-regulatory Runtime Respirable Coal and Silica Dust Monitor Using Quantum Cascade Laser-based Ringdown Spectroscopy | RingIR | 9/1/2020 | 3/31/2022 |
| 3 | Development of a Silica Dust Direct Reading Sampler with Sensitivity for Dust Components and Size | Colorado State University | 9/1/2020 | 8/31/2023 |
| 4 | Miniaturized Wearable Personal Dust Exposure Monitor for Respirable and Alveolar Dust in Underground Coal Mines | University of Illinois – Chicago | 9/1/2016 | 12/20/2020 |
| 5 | Feasibility Testing of a Near Real Time Respirable Silica Monitor | Thermo Environmental Instruments | 9/24/2018 | 3/15/2021 |
| 6 | Novel application of Fourier-Transform Infrared Spectroscopy and optical particle counting for the real-time quantification of respirable crystalline silica and dust in the mining environment | MicroAeth Corp. | 9/15/2020 | 7/31/2022 |
| 7 | Caplamp Particulate Monitoring System | Strata Products, Inc. | 9/15/2020 | 3/31/2022 |
| 8 | Next Generation Continuous Personal Dust Monitor (CPDM) | Thermo Environmental Instruments | 9/24/2018 | 12/31/2022 |