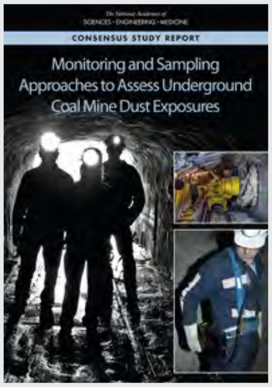

Monitoring and Sampling Approaches to Assess Underground Coal Mine Dust Exposures

DETAILS

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Monitoring and Sampling Approaches to Assess Underground Coal Mine Dust Exposures

Committee on the Study of the Control of Respirable Coal Mine Dust Exposure in Underground Mines

Board on Earth Sciences and Resources

Board on Environmental Studies and Toxicology

Board on Health Sciences Policy

Division on Earth and Life Studies

Health and Medicine Division

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This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

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Preface

Dust generated during underground coal mining operations includes particles small enough to be deposited in the airways and the gas-exchange region of a miner's lung, when inhaled. Chronic exposure to those particles, referred to as respirable coal mine dust (RCMD), puts miners at risk for various lung diseases, including coal workers' pneumoconiosis, emphysema, silicosis, and chronic bronchitis. This report is about methods for monitoring and sampling miners' exposure to RCMD. Results from the implementation of those methods are used for determining whether miners' exposures are within regulatory limits and informing mine operators' efforts to reduce those exposures.

The Mine Safety and Health Administration (MSHA) is the federal agency responsible for setting and enforcing mine safety and health standards. On May 1, 2014, MSHA's final rule, entitled *Lowering Miners' Exposure to Respirable Coal Mine Dust, Including Continuous Personal Dust Monitors*, was issued as part of an ongoing effort to protect miners from the health risks of lung diseases associated with RCMD inhalation. (Chapter 1 of this report provides an overview of the rule's main requirements.)

Some coal mine operators and mining associations had expressed various concerns about the efficacy of the monitoring and sampling protocols in MSHA's new rule in aiding decisions regarding the control of RCMD and mine worker exposure. For example, MSHA's dust rule requires the use of a continuous personal dust monitor (CPDM) for measurement of RCMD mass concentrations in near real time and determining compliance with the regulatory exposure limit. Concerns were expressed as to whether CPDM measurements will accurately reflect the concentration of particles in coal mine dust that are of relevance to coal mining–related respiratory diseases. CPDM measurements of RCMD also include limestone particles or other types of rock dust that are typically applied in mines to meet requirements for controlling the combustibility of coal dust.

In the Fiscal 2016 Consolidated Appropriations, Congress directed the National Institute for Occupational Safety and Health (NIOSH) to arrange for a study with the National Academy of Sciences to consider monitoring technologies and sampling protocols used in the United States and in similarly industrialized countries for the control of RCMD exposure in underground coal mines; effects of rock dust mixtures and their application on RCMD measurements; and the efficacy of current monitoring technologies and sampling approaches. The request also called for science-based conclusions regarding optimal monitoring and sampling strategies to aid mine operators' decision making related to reducing respirable coal mine dust exposure to miners in underground coal mines.

In response to the congressional request, the National Academies of Sciences, Engineering, and Medicine assembled a committee of 10 members who had expertise in underground mine air quality, exposure science, mine worker health and safety regulations, industrial hygiene, occupational medicine and environmental health, mining engineering, and international perspectives. (The committee's formal statement of task is presented in Appendix A and biographical sketches of the members are presented in Appendix B.)

In responding to the request from Congress, the committee was asked to identify important research gaps regarding monitoring and sampling protocols for controlling miners' RCMD exposures. It was asked not to recommend changes to the requirements of MSHA's final rule for lowering miners' exposure to respirable coal mine dust, as the development of those requirements involves considerations beyond the scientific and technical focus of this study.

In the course of preparing its report, the committee held public information-gathering sessions during four of its meetings to hear presentations from members of Congress' professional staff; representatives of MSHA, NIOSH, National Mining Association, several coal mining companies, United Mine Workers of America, a rock dust manufacturer; and relevant experts from Australia and the Republic of South Africa. Two of the committee's information-gathering sessions were held in Charleston and Morgantown, West Virginia, to receive input from individual coal miners and others living in areas where underground coal mining occurs. The committee gratefully acknowledges the individuals listed in Appendix C for their presentations to the committee during the public sessions.

Members of the committee visited the Dana Mine in Mount Morris, Pennsylvania, and the Arch/Coal Leer Mine in Grafton, West Virginia. The committee is very appreciative of the personnel at those mines for allowing members to observe coal mine operations, *in situ* use of CPDMs, and exposure reduction practices. The committee also appreciates receiving extensive written materials from MSHA, NIOSH, coal mine companies, and other organizations.

The committee is grateful for the assistance of the project staff members for the support they provided.

Thure E. Cerling, *Chair*
Committee on the Study of the Control
of Respirable Coal Mine Dust Exposure in
Underground Mines

Abbreviations

AFC	armored face conveyor
CDE	cumulative dust exposure
CFR	Code of Federal Regulations
CMDLD	coal mine dust lung disease
CMDPSU	coal mine dust personal sample unit
CMHSA	Coal Mine Health and Safety Act
COPD	chronic obstructive pulmonary disease
CPDM	continuous personal dust monitor
CVD	cardiovascular disease
CWHSP	Coal Workers' Health Surveillance Program
CWP	coal workers' pneumoconiosis
DA	designated area
DDF	dust-related diffuse fibrosis
DGMS	Directorate General of Mine Safety
DO	designated occupation
DPM	diesel particulate matter
DWP	designated work position
EC	elemental carbon
FTIR	Fourier-transform infrared spectroscopy
GAO	U.S. Government Accountability Office
GSD	geometric standard deviation
HEG	homogenous exposure group
HRSA	Health Resources and Services Administration
MMCRDM	machine-mounted continuous respirable dust monitor
MMU	mechanized mining unit
MRE	Mining Research Establishment
MSHA	Mine Safety and Health Administration
NIOSH	National Institute for Occupational Safety and Health
NMA	National Mining Association
NOS	not otherwise specified
ODO	other designated occupation
OEL	occupational exposure limit
OMP	occupational medical practitioner
PDM	personal dust monitor
PMF	progressive massive fibrosis
PNOS	particles not otherwise specified
PPE	personal protective equipment
PSD	particle size distribution
RCMD	respirable coal mine dust
RCS	respirable crystalline silica
RDD	respirable dust dosimeter
RPP	rapidly progressive pneumoconiosis
SEG	similar exposure group
SEM-EDX	scanning electron microscopy and energy dispersive x-ray spectroscopy
SIMTARS	Safety in Mines Testing and Research Station

TEOM	tapered-element oscillating microbalance
TGA	thermogravimetric analysis
TWA	time-weighted average
XRF	x-ray fluorescence

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Summary

Coal remains one of the principal sources of energy for the United States, and the nation has been a world leader in coal production for more than 100 years. According to U.S. Energy Information Administration projections to 2050, coal is expected to be an important energy resource for the United States. Additionally, metallurgical coal used in steel production remains an important national commodity.

Coal production, like all other conventional mining activities, creates dust in the workplace. Respirable coal mine dust (RCMD) comprises the size fraction of airborne particles in underground mines that can be inhaled by miners and deposited in the distal airways and gas-exchange region of the lung.[1] Occupational exposure to RCMD has long been associated with lung diseases common to the coal mining industry, including coal workers' pneumoconiosis (CWP), also known as "black lung disease." In the 1960s, this disease was found in more than 30 percent of coal miners who had worked at least 25 years in underground coal mines (Figure S-1). Recognition that coal mine dust exposure caused CWP was one of the factors that led Congress to pass the Federal Coal Mine Health and Safety Act of 1969. Title II of the act stated that "it is the purpose of this title to provide, to the greatest extent possible, that the working conditions in each underground coal mine are sufficiently free of respirable dust concentrations in the mine atmosphere to permit each miner the opportunity to work underground during the period of his entire adult working life without incurring any disability from pneumoconiosis or any other occupation-related disease during or at any time at the end of such period."[2]

RCMD has many sources, including particles generated by coal extraction (coal and minerals associated with the coal being mined), rock adjacent to the coal seam being mined, rock dust products used to control explosions in mines,[3] and other particles associated with mining activities (for example, diesel fuel burning and belt abrasion). Likewise, RCMD has many components, including coal particles, crystalline silica,[4] silicate minerals, carbonates (especially associated with rock dusting), and particulate matter from diesel engines.

No specific medical treatment is effective in reversing coal mine dust lung disease or in controlling disease progression. Consequently, efforts to minimize RCMD exposure along with medical surveillance for early disease detection and removal from exposure are the mainstays in protecting a miner's health. Over the years, U.S. federal regulations have placed increasingly stringent upper limits on the allowable airborne RCMD concentrations in underground mines to

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[1]For dust sampling and regulatory compliance purposes, respirable dust has been defined as dust collected with a sampling device approved by the Secretary of Labor and the Secretary of Health and Human Services. See Chapters 1 and 4.

[2]Title II, Sec.201(b).

[3]Coal dust represents an explosion hazard in underground coal mines, which often can be mitigated effectively through a proper rock-dusting program. The practice involves applying an inert rock dust material to the surfaces of an underground coal mine and maintaining sufficient quantities so that the incombustible content of the combined coal dust, rock dust, and other dust is not less than 80 percent (30 Code of Federal Regulations [CFR] 75.403).

[4]Crystalline silica is a collective term that refers to quartz, cristobalite, tridymite, and several other rare silica minerals. All of the crystalline silica minerals have the same chemical composition but have different crystal structures and are thus termed polymorphs. Quartz is the most common form of crystalline silica. See Appendix D.

which coal miners can be exposed. A limit of 3.0 mg/m^3 was established in 1969. The limit was lowered to 2.0 mg/m^3 beginning in 1972. In 2014, the Mine Safety and Health Administration (MSHA)[5] issued a dust rule that reduced the limit to 1.5 mg/m^3, effective August 1, 2016.[6] The concentration limit for respirable crystalline silica (technically, quartz) remained at 0.1 mg/m^3 (100 micrograms per cubic meter or µg/m^3).

Those regulatory requirements, beginning in 1969, were followed by several decades of decreased prevalence of CWP in underground coal miners, such that by 2000 the recognized prevalence of disease in underground coal miners with more than 25 years of work tenure decreased from more than 30 percent in 1970 to about 5 percent in 2000. However, since around 2000 there has been an unexpected increase in the proportion of CWP in coal miners with 25 or more years of work tenure, and with an increase or plateau of disease prevalence in those with shorter mining tenure. Moreover, recent reports have described rapidly progressive, severe and fatal forms of disease including progressive massive fibrosis occurring mainly in the central geographic region of Appalachia.

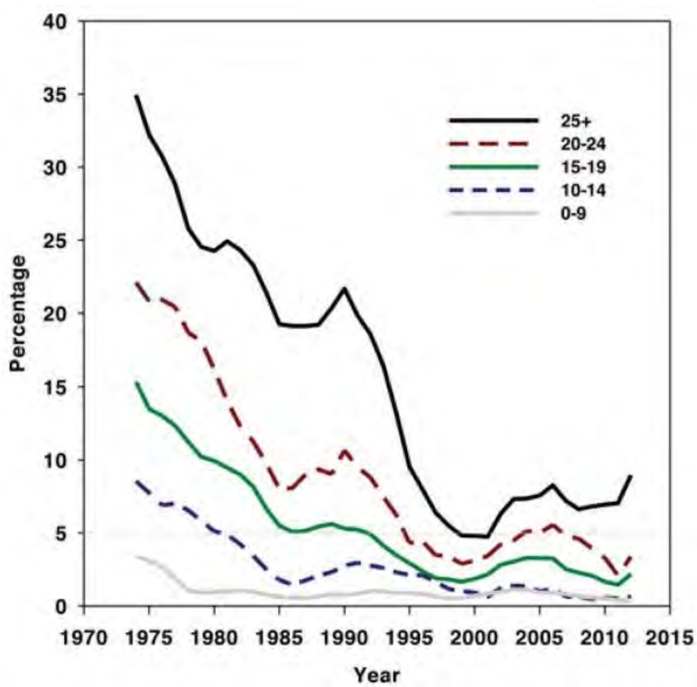

FIGURE S-1 Percentage of examined U.S. underground miners with coal workers' pneumoconiosis (CWP), for 1970 to 2012. Data are presented as 5-year moving averages. Separate plots represent various years of work tenure. The plots show an overall decline in CWP following enactment of the 1969 Coal Mine Health and Safety Act, followed during the past two decades by an increasing prevalence of CWP in coal miners with 15 or more years of tenure, and especially for miners with 25 or more years. SOURCE: Laney and Weissman, 2014.[7] Reprinted with permission; copyright 2014, *Journal of Occupational and Environmental Medicine*.

[5]As part of the U.S. Department of Labor, MSHA develops and enforces safety and health rules for all U.S. mines and provides technical, educational, and other types of assistance to mine operators.

[6]Lowering Miners' Exposure to Respirable Coal Mine Dust, Including Continuous Personal Dust Monitors (79 Fed. Reg. 24,814 [2014]).

[7]Laney, A. S., and D. N. Weissman. 2014. Respiratory diseases caused by coal mine dust. *Journal of Occupational and Environmental Medicine* 56 (Suppl 10):S18-S22.

As late as 2014, personal exposures to airborne RCMD were monitored using a device that collected a gravimetric sample of particles onto a filter during a miner's work shift. The sample was then sent to an analytical laboratory to obtain a single value of RCMD mass concentration that was used to represent a miner's exposure during the entire sampling period or calculate a time-weighted average exposure for a standard period (such as 8 hours).[8] That approach imposed a time lag in getting the monitoring results and initiating appropriate dust controls to reduce elevated exposure concentrations. It was anticipated that the use of a personal monitoring device, being developed with the capability of measuring RCMD concentrations in near real time, could result in lower dust exposures because coal mine operators and miners could respond quickly if an increase in dust concentrations occurred. That capability came to fruition with the availability of the continuous personal dust monitor (CPDM). The 2014 dust rule required monitoring of personal dust concentrations using a CPDM beginning in February 2016. The CPDM must be used to monitor miners in occupations expected to be exposed to the highest RCMD concentrations and miners who have medical findings of CWP and who have opted to transfer to a less dusty job in the mine. CPDM readings obtained for regulatory compliance must be transmitted within 24 hours to MSHA. For the period from August 2016 to May 2017, with the allowable exposure limit of 1.5 mg/m^3 in place for airborne RCMD mass concentration, MSHA reported that, for 25,441 valid measurement samples submitted by mine operators, greater than 99 percent of those samples were in compliance with the regulatory limit. It is important to note, however, that most miners incurred much of their exposures when previous regulations were in effect. Given that the latency period of CWP disease onset is typically 10 or more years, sufficient time has not elapsed to assess the effect of the 2014 requirements on disease rates and severity.

There are likely a number of factors that have contributed to an increase in the prevalence and severity of coal mine dust related lung diseases. Determining the causes of that increase and eliminating occupational lung disease in coal miners is a complex scientific, engineering, medical, regulatory, social, political, economic and legal problem. However, a full analysis of that problem is beyond the scope of this report. The primary focus of this report is an examination of monitoring and sampling approaches for the control of RCMD and miners' exposure.

As dust-generating processes in mining have intensified over the past several decades associated health hazards might increase if there have been unanticipated changes in the characteristics of RCMD exposures that are important to the risk of coal mine dust lung diseases. Also, questions might arise as to whether the monitoring required by the 2014 dust rule is targeting the most important exposures metrics.

Currently, dust control technologies are widely available and have the potential to protect miners' health from RCMD exposure. As discussed in later chapters, optimal strategies are needed to assure that the recent surge in prevalence and severity of coal mine dust lung diseases does not continue.

THE COMMITTEE'S STUDY

In the Consolidated Appropriations Act of 2016, Congress directed the National Institute for Occupational Safety and Health (NIOSH) to arrange for a study by the National Academies of Sciences, Engineering, and Medicine to assess monitoring and sampling approaches for informing underground coal mine operators' decision making regarding the control of miner exposure to RCMD.[9] The study comprised four aspects:

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[8]The same general approach is currently required to determine the respirable quartz concentration in the RCMD.

[9]NIOSH is a research agency focused on the study of worker safety and health, and empowering employers and workers to create safe and healthy workplaces. NIOSH is part of the U.S. Centers for Disease Control and Prevention in the U.S. Department of Health and Human Services.

- Compare the monitoring technologies and sampling protocols (including sampling frequency) currently used or required in the United States, and in similarly industrialized countries for the control of RCMD exposure in underground coal mines.
- Assess the effects of rock dust mixtures and their application, as required by current U.S. regulations, on RCMD measurements.
- Assess the efficacy of current monitoring technologies and sampling approaches.
- Develop science-based conclusions regarding optimal monitoring and sampling strategies to aid mine operators' decision making related to reducing RCMD exposure to miners in underground coal mines.

Those four aspects are specified in the committee's formal statement of task.[10] In addition, the committee was asked to identify important research gaps regarding monitoring and sampling protocols for controlling miners' exposure to RCMD. It was asked not to recommend changes to the requirements of MSHA's 2014 final rule for lowering miners' exposure to RCMD, as the development of those requirements involves considerations beyond the scientific and technical focus of this study.

TRENDS IN DISEASE EPIDEMIOLOGY AND MINING PRACTICES

The regulatory focus on controlling the RCMD mass concentration and the mass concentration of respirable crystalline silica in the RCMD has not changed over the past several decades. As described above, this approach was associated with a substantial decline in CWP prevalence from 1970 to 2000 across all coal mining regions in the United States. However, since around the year 2000, an increase in prevalence and severity of CWP has been observed in various hot-spot geographic areas. The reasons for this increase are not obvious but could be related to changes in mining practices and conditions (for example, increases in equipment size and horsepower and mining increasingly thinner coal seams) leading to the increased extraction of rock containing crystalline silica and other RCMD components.

The 2014 dust rule lowered the allowable airborne RCMD mass concentration in underground mines and improved other protections for miners. However, as mentioned previously, given that the latency period of CWP disease onset is typically 10 or more years, sufficient time has not elapsed to assess the effect of the 2014 requirements on disease rates and severity. It is important to note, that compliance with regulatory requirements by itself is not an adequate indicator of the rule's effectiveness in protecting miners' health.

EFFICACY OF CURRENT MONITORING AND SAMPLING IN UNDERGROUND MINES IN THE UNITED STATES

Effective exposure control is a key means of addressing the occurrence of CWP in coal miners, which continues to be an important and complex problem. Effective monitoring technologies and sampling approaches would provide information on not only the RCMD mass concentrations for meeting regulatory requirements, but also the RCMD particle characteristics (such as composition) of greatest relevance to disease risk in miners. That information would inform a continual assessment of the RCMD standard and, ultimately, approaches for optimal protection of the health of the miners.

The CPDM is an important technological advancement compared to monitoring methods used previously, as it provides near-real-time readings of airborne RCMD concentrations in the workplace. If a measurement collected over a full shift exceeds allowable limits, mine operators

[10]The committee's formal statement of task is presented in Appendix A. Biosketches of the committee members are provided in Appendix B.

must take corrective actions immediately. In addition, miners wearing CPDMs receive information about their personal exposures and sometimes can modify their activities or locations within a mine in response to elevated readings.

However, only a small fraction of coal miners are required to use a CPDM during any given shift, and it is possible that those coal miners using the CPDMs are not representative of the dust exposure to other miners who are not using the CPDMs. When miners wearing CPDMs react to high monitor readings to limit their personal dust exposure (for example, by altering their locations while carrying out their job duties), the required RCMD sampling might no longer be representative of the miners with the highest exposures. Whether the airborne RCMD concentration is being maintained at or below the permissible limit for only those miners wearing the CPDM, or all personnel in the work area, is unknown.

In addition, changes in mining technologies over the past several decades might have led to changes in typical particle size distributions of RCMD. If so, there might have been a change in the relationship between CPDM measurements of RCMD mass concentrations and the health effects associated with particle type, size, concentration, and deposition in the lung.

OPTIMAL MONITORING AND SAMPLING STRATEGIES

Historically, the primary focus of RCMD monitoring and sampling efforts had been based on compliance with federal regulations. Additional monitoring efforts were undertaken by coal mine operators to support improvements in mine ventilation and other dust controls, for instance, to resolve noncompliance conditions. Over three decades, the compliance-driven approach led to a significant reduction in the incidence of lung diseases associated with occupational exposure to RCMD among U.S. coal mine workers. However, it has not resulted in attainment of the ultimate goal of the Coal Mine Health and Safety Act of 1969, which is to eliminate such diseases. Given current uncertainties about the cause of increase in disease prevalence and severity, the committee noted the possibility that high rates of operator compliance with the 2014 dust rule requirements may not guarantee that RCMD exposures will be controlled adequately or that future disease rates will decline. To continue progress toward reaching this goal, a fundamental shift is needed in the way that coal mine operators approach RCMD exposure control and, thus, sampling and monitoring.

Optimal sampling and monitoring strategies are created for the protection of miner health through the control of RCMD exposure. Those strategies would embrace additional voluntary monitoring and sampling that go beyond regulatory compliance to gain information on potentially important factors affecting miners' health as well as the temporal and spatial variation of RCMD within a mine. Optimal strategies are implemented in the context of practical constraints (such as cost, availability of technology, existing regulatory requirements, and program acceptance by various stakeholders). The committee concludes that optimal monitoring and sampling strategies manifest as programs that, in principle, exhibit these attributes:

> *Aiding mine operators' decision making related to reducing RCMD exposures in a maintainable manner with data that are representative of high-exposure episodes and cumulative exposures over the long-term for all workers throughout the mine, not only those wearing a monitoring instrument.* A focus on reducing cumulative exposures for all miners during their entire working life underground is important because silicosis, CWP, and the spectrum of lung diseases related to RCMD exposures occur over the long term and the level of disease risk is related to cumulative exposure and dose.

> *Supporting the decision-making ability of individual mine workers to protect themselves through training in the use of CPDMs and education concerning factors that affect exposure-response relationships.* Such industry-wide training and education will enhance miners' ability to make informed decisions to take precautions that reduce RCMD exposures

and minimize disease risk. It is important to ensure that training and education programs are implemented in an effective manner across the coal mining industry.

Monitoring characteristics of RCMD particles that are directly related to the risk of occupational lung disease. Using appropriate tools and methods to collect samples that are representative of the dust to which mine workers are or may be exposed. Since around the year 2000, an increase in prevalence and severity of CWP points to a need for a more in-depth understanding of risk factors, some of which may not be captured by measuring the RCMD mass concentration. The potential role of exposure to respirable crystalline silica warrants greater focus on developing improved sampling and monitoring techniques.

Applying various monitoring technologies in engineering studies of RCMD exposure variability and exposure mitigation approaches. Although CPDMs have the potential to be used by operators for engineering studies of exposure mitigation approaches, the predominant use is for determining regulatory compliance by providing end-of-shift readings. Disincentives for CPDM use in nonregulatory applications include the size and cost of the device, and requirements to notify MSHA in advance of using the CPDM for purposes other than determining compliance.

Integrating RCMD monitoring data with associated contextual information, such as sampling locations and frequencies, environmental and operational conditions during sampling and other periods, and relevant health risks. For example, area monitoring, which is intended to determine the RCMD concentrations in workplace areas where miners might go, provides a means for tracking RCMD spatial and temporal variability within a mine.

Involving a suitable and acceptable system of medical surveillance that provides regular, no-cost medical examinations for all miners to help assess the efficacy of exposure reduction efforts. Medical surveillance of miners that includes comprehensive occupational histories containing details of mining processes and exposures (for example, chronology of specific mine employment, duration of work at the coal face, job titles and duties, and use of respiratory protection) is an important tool for understanding disease trends and risk factors and assessing the efficacy of exposure reduction efforts. Limited worker participation in medical surveillance impairs the effectiveness of that tool for assessing the efficacy of exposure reduction efforts.

Making integrated data readily available, accessible, and usable for timely decision making. Beyond reliability (that is, quality) of the RCMD metrics derived from sample analysis and associated information, the availability, accessibility, and usability of those data largely determine their value with respect to program objectives. If data are not available to the appropriate stakeholders in a timely manner, or if their capture or presentation format is not easily understood, they have little value in ensuring worker health protection, supporting process (engineering) control, or predicting conditions that may result in elevated RCMD exposures.

Striving for continuous improvement in disease risk reduction, including modifications following periodic performance reviews or changes in previous constraints (such as availability of new technologic capabilities). Through evaluation, program data outputs can be reviewed to determine whether objectives are being met, and to identify and prioritize areas in need of improvement (for example, locations with high RCMD exposure risks).

MONITORING AND SAMPLING PRACTICES USED IN DIFFERENT INDUSTRIALIZED COUNTRIES

In its statement of task, the committee was asked to compare the monitoring technologies and sampling protocols currently used or required in the United States, and in similarly industrialized countries for the control of RCMD exposure in underground coal mines. In addition to the United States, the committee selected the countries of Australia, Germany, India, the People's Republic of China, Poland, and the Republic of South Africa to compare monitoring technologies and sampling practices for the control of RCMD exposure in underground coal mines. Required medical surveillance programs for detection of diseases in coal miners were also included. Those countries are among the leading coal producers and have regulatory programs in place for RCMD monitoring and miner health surveillance. Differences in exposure monitoring and sampling approaches among major coal-producing countries make it difficult to compare exposure measurements among different countries directly.

Despite those differences, there are important commonalities, such as using gravimetric sampling devices to monitor mass concentrations of RCMD and respirable crystalline silica. Those commonalities point to potential opportunities for harmonizing monitoring data collected in different countries, including RCMD and silica content. Additionally, a more complete understanding of international approaches to medical surveillance for coal mine dust diseases, including strengths and limitations, would lead to opportunities for improved understanding of the relationships between RCMD exposure and disease prevalence and ensuring that monitoring approaches are targeting the most important aspects of RCMD exposure.

The various approaches to medical surveillance among coal-producing countries warrant an in-depth and appropriately critical analysis, which was beyond the scope of this report. Such an analysis would provide insight into the country-specific prevalence of coal mine dust lung disease over time and would inform an understanding of the success of various strategies for monitoring and controlling exposures.

EFFECTS OF ROCK DUSTING ON RCMD MEASUREMENTS

The committee was asked to assess the effects of rock dusting on RCMD measurements in underground coal mines. Rock dusting (that is, the application of rock dust products) is a proven practice that has been utilized in some way since the early 1900s. Most of the commercially available rock dust is composed of pulverized limestone or marble, although regulations allow for other materials. Rock dust particles must be small enough to pass through a sieve having 20 meshes per linear inch and 70 percent or more of the particles must be able to pass through a sieve with 200 meshes per linear inch (30 CFR 75.2).[11] Smaller rock dust particles (approaching the size of respirable particles) are more effective than larger ones at mitigating explosion risks. Smaller particle sizes have a greater surface area per unit mass than larger particles and thus greater ability to absorb heat. Because rock dust products that meet the regulatory size requirements also contain particles in the respirable size range, rock dusting can contribute substantially to the RCMD mass concentration measured by CPDMs.

Rock dust used in U.S. coal mines may contain no more than a small percentage of respirable crystalline silica (4 to 5 percent by mass, per 30 CFR 75.2). Rock dusting's contribution to the respirable silica exposure of miners relative to the contribution from dust created by mining operations has not been documented. The percentage that rock dusting contributes to a miner's silica exposure would vary according to the percentage of silica in the coal and the surrounding

[11]Mesh refers to the number of openings across one linear inch of screen. As the mesh number increases, the size of the openings decreases. The openings of a 200 mesh sieve are approximately 74 µm.

rock being extracted, as well as the proportion that rock dust contributes to the total mass of airborne RCMD in the mine.

Sustained high exposures to rock dust and other so-called nuisance dusts, for which constituent-specific exposure limits are not specified, may trigger respiratory symptoms of irritation and cough and could contribute to a higher risk of chronic obstructive pulmonary disease (COPD). However, in general, the committee found few case reports or studies implicating rock dust exposure in risk for clinically significant coal mine dust lung disease.

Although rock dust contributes substantially to the total mass of RCMD, it is not possible to determine the percent contribution of rock dust using the currently required monitoring technology. As a result, two mines using different rock-dusting approaches (such as dusting at different times and rates during mining operations) might have very different RCMD compositions and yet exhibit similar measured mass concentrations. Therefore, heavy contributions of rock dust could distort health assessments of relationships between RCMD exposure and diseases caused by dust components insignificantly contributed by rock dust.

Measurements of airborne RCMD concentrations include respirable rock dust particles, by definition. However, it appears that complying with the rock-dusting requirements (30 CFR 75.2 and 75.402-403) has not been an obstacle to demonstrating compliance with the 2014 dust rule. It is critical that efforts to comply with both the rock-dusting requirements and RCMD requirements not compromise the effectiveness of either explosion mitigation or RCMD exposure reduction.

RECOMMENDATIONS

The committee identified important information gaps regarding monitoring and sampling protocols for controlling miners' RCMD exposures. Research and development efforts are needed for better understanding of relationships between miners' exposures and disease, including studying effects of changes in mining practices, improving monitoring approaches, and increasing participation in medical surveillance programs. Likewise, enhanced worker education and mine operators' monitoring and sampling efforts would help ensure that all coal miners' exposures are adequately controlled, in addition to those whose individual exposures are being measured for regulatory compliance purposes.

The recommendations provided below include research and development activities to address the gaps. The recommendations are amplified and expanded in the chapters. The sequence in which they are presented is not intended to imply a sense of priority.

Challenges in Implementing Optimal Monitoring and Sampling Practices

NIOSH and other organizations, such as the National Mining Association and the unions representing miners, should conduct a comprehensive investigation to identify key challenges that coal mine operators face in implementing an optimal, beyond-compliance approach to RCMD exposure monitoring and sampling for informing exposure control efforts. The organizations conducting the investigation also should recommend practical solutions for overcoming those challenges. (Recommendation 1)

Considerations of All Miners' Exposures

- Conduct studies to evaluate the exposures of miners not wearing CPDMs to ensure that the approach of detecting and mitigating high exposures for designated occupations reliably results in mitigating high exposures of all miners. (Recommendation 2)
- NIOSH and MSHA should carry out a systematic examination of the content and implementation of training and education programs with respect to RCMD exposure. The examination should focus not simply on curricula but also on the way adults learn. It should

seek ways of implementing education and training programs in an effective and consistent manner across the coal mining industry. As a part of being effective, the programs should be relevant to all miners, not just the ones who wear CPDMs, as well as to operators and regulators. Programs should be assessed after they have been implemented for a few years to determine their overall effectiveness. (Recommendation 3)

Monitoring Devices

- NIOSH, in collaboration with MSHA, should evaluate whether 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 (CMDLD) is similar to the relationship established decades ago, when the monitoring devices used for sampling were first adopted. In studying the particle-size distribution in modern-mining RCMD samples and their relationship to the particles deposited in the lung, it is important to consider associations with or implications in the development of CMDLD. (Recommendation 4)
- Develop a real-time crystalline silica monitor. As an interim measure, NIOSH should continue its efforts to develop an end-of-shift silica monitor. (Recommendation 5)
- NIOSH should continue to facilitate the development of a less costly and less ergonomically stressful real-time RCMD monitoring device that would facilitate the use of the personal monitors for engineering studies and other purposes in addition to compliance monitoring. As part of that effort, NIOSH should incorporate appropriate filter media that is compatible with an end-of-shift analyzer for respirable crystalline. (Recommendation 6)
- Explore the broader use of area (fixed-site) monitoring devices for gathering trends information on RCMD concentrations and particle characteristics in underground mines. (Recommendation 7)

RCMD Exposure and Disease Rates

- Conduct a systematic evaluation of changes in mining technology and activities to determine the extent to which those changes have caused increased extraction of rock and the extent to which past rock extraction had been co-located with disease hot spots. The evaluation should identify important focus areas for optimal sampling and monitoring strategies in the future. (Recommendation 8)
- NIOSH should conduct or facilitate a comprehensive assessment of RCMD particle characteristics, including their variability, to help target future exposure studies, because different particle characteristics (for example, composition and surface area) can pose different health risks. In addition, the assessment should characterize and quantify important source contributions to airborne RCMD, including rock dusting and extraction of rock strata adjacent to the mined coal seam. To the extent possible, NIOSH should assess how RCMD characteristics have changed over time and consider making provisions for tracking temporal trends in the future. Further research and development are needed to improve analytic methods for evaluating source contributions of RCMD. (Recommendation 9)
- Link medical surveillance programs directly with exposure monitoring programs and integrate health-related data on active and retired miners. (Recommendation 10)

- Elucidate factors that act as disincentives for participation in the voluntary portions of the NIOSH medical surveillance programs and in the MSHA Part 90 Program,[12] with the goal of addressing those disincentives. (Recommendation 11)
- Conduct a comprehensive assessment of the requirements for exposure monitoring, including RCMD and silica mass content, and medical surveillance as well as the implementation of those requirements in major coal-producing countries. The assessment should identify opportunities for data harmonization and the use of those data for improving exposure monitoring approaches and conducting epidemiologic research. (Recommendation 12)

Research Capacity and Resources

NIOSH, MSHA, and other organizations should set priorities for addressing the committee's recommendations and develop a strategy for addressing them. Federal agencies should provide the capability for research to be conducted in an experimental underground mine. Federal, academic, and coal mine industry researchers should seek opportunities for conducting collaborative research and development activities. (Recommendation 13)

IN CONCLUSION

Coal mine dust lung disease continues to be an important and complex problem affecting coal miners in the United States. Reliable information on RCMD exposures in underground coal mines is crucial for predicting, reducing, and preventing mine workers' disease risks. Additionally, medical surveillance of miners, combined with comprehensive exposure assessment, are important tools for understanding disease trends and risk factors and assessing the efficacy of exposure reduction efforts.

The committee has provided recommendations concerning the efficacy of current monitoring technologies and sampling approaches and developing optimal strategies to aid mine operators' decision making related to voluntary measures for reducing RCMD exposure to mine workers.

Those recommendations include studies to ensure that the approach of detecting and mitigating exposures for designated occupations reliably results in controlling exposures of all workers, including those not using a CPDM. In addition, training and education programs should be evaluated and enhanced. Improvements in monitoring technology should include reduction in cost and weight of CPDMs. Such improvements also should include development of a real-time silica monitor and, as an interim measure, the continued development of a commercially available end-of-shift monitor, because silica dust is known to pose a serious health risk. Better understanding of health risks from RCMD exposure could result from expanded worker participation in periodic medical surveillance, and from studies that evaluate changes in dust characteristics related to changes in mining practices over the past five decades.

[12]The Part 90 Program is for coal miners who have medical findings of pneumoconiosis and who opt to transfer to a less dusty job in the mine (30 CFR 90).

1

Introduction

The United States has approximately 21 percent of the world's coal resources (EIA, 2014). Despite recent declines in the number of active coal mines in the United States and the miners they employ, thermal coal, which is used to generate electricity from steam turbines, will continue to play an important role as an energy source for the foreseeable future. Coal is projected to produce 29 percent of electricity worldwide and 17 percent of U.S. electricity through 2050 (EIA, 2017c). Additionally, metallurgical coal used in steel production remains an important commodity produced in the United States. Coal is currently mined in 25 states. Production reached a high of 1,172 million tons in 2008 and declined to 728 million tons in 2016 (NMA, 2017a).

The two major types of coal extraction are surface mining and underground mining. In surface mining, soil and rock over the coal seam are removed to expose the coal, which is fragmented and removed. Underground mining involves accessing a coal seam by suitable openings from the surface, called shafts, slopes, or drifts. Surface mining's share of coal production in the United States was about 66 percent in 2015 (EIA, 2012; NMA, 2017b). In absolute terms, surface coal production in 2015 was 589 million tons, representing a more than a fourfold increase from 139 million tons in 1950 (EIA, 2012; NMA, 2017b). In recent years, there has been an overall decline in coal production in the surface and underground sectors.

The trends toward increased surface mining, increased production and productivity from new technology, consolidation of mining companies, closure of smaller operations, and increased use of natural gas for electricity generation have all contributed over the years to a continuous decline in the number of underground mines and the number of miners employed in those mines. For the 12 months ending January 2010, there were 424 active underground coal mines and 47,004 active coal mine workers[1] in those mines (including 6,685 independent contractors at 232 active mines, excluding office employees) (MSHA, 2014). (See Appendix E for additional details on coal mining in the United States.)

Following passage of the Coal Mine Health and Safety Act in 1969, improved ventilation and dust abatement strategies led to substantial declines in disease prevalence among U.S. coal miners. However, since around 2000, a resurgence in disease prevalence and severity (Antao et al., 2005; Suarthana et al., 2011), particularly in central Appalachia, has prompted renewed focus on the need for more effective exposure control in underground coal mines and is the underpinning for this report. This chapter provides a general overview of underground coal mining processes, inhalational exposures in coal mines, the spectrum of lung diseases related to respirable coal mine dust (RCMD) exposures, historical trends in the prevalence and severity of those diseases, and changes in U.S. coal mine dust regulations that are important in informing exposure control strategies aimed at disease prevention. This chapter lays a foundation for the committee's statement of task addressed in this report.

[1]The term "coal mine worker" often includes active miners as well as former (retired, disabled, or otherwise employed) coal miners; those who have worked for coal mine operators or their contractors; and those who have worked in various coal mine job duties.

COMMITTEE'S STATEMENT OF TASK

In response to a congressional request in the fiscal 2016 Congressional Appropriations (Public Law 114-113),[2] the National Academies of Sciences, Engineering, and Medicine formed an ad hoc committee to assess monitoring and sampling approaches for informing underground coal mine operators' decision making regarding the control of RCMD and mine worker exposure. (The committee's formal statement of task is presented in Appendix A.) The committee's task includes these components:

- Compare the monitoring technologies and sampling protocols (including sampling frequency) currently used or required in the United States, and in similarly industrialized countries, for the control of RCMD exposure in underground coal mines.
- Assess the effects of rock dust mixtures and their application for controlling explosions in mines, as required by current U.S. regulations, on RCMD measurements.
- Assess the efficacy of current monitoring technologies and sampling approaches and develop science-based conclusions regarding optimal monitoring and sampling strategies to aid mine operators' decision making related to reducing RCMD exposure to miners in underground coal mines.

The committee was also asked to identify important research gaps regarding monitoring and sampling protocols for controlling miners' RCMD exposures. The committee was specifically asked not to recommend changes to the requirements of the Mine Safety and Health Administration's (MSHA's) final rule, Lowering Miners' Exposure to Respirable Coal Mine Dust, Including Continuous Personal Dust Monitors (79 Fed. Reg. 24,814 [2014]).[3,4] The development of those requirements involves considerations beyond the scientific and technical focus of this report.

RESPIRABLE COAL MINE DUST: CONSTITUENTS AND SOURCES

RCMD comprises the size fraction of airborne particles in underground mines that can be inhaled by miners and deposited in the distal airways and lung gas-exchange region (WHO, 1999). The 2014 dust rule states, "Any respirable dust in the mine atmosphere is considered respirable coal mine dust to which miners are exposed and, when measured, is counted for determining compliance with the respirable dust standard" (79 Fed. Reg. 24,866). For regulatory purposes, RCMD is defined as "that dust collected with a sampling device approved by the Secretary (of Labor) and the Secretary of HHS in accordance with (30 CFR) part 74 (30 CFR 74)." The current regulation requires monitoring of RCMD mass concentrations (mg/m^3) and the respirable quartz concentration in the RCMD. Aside from quartz content, there is no regulatory requirement related to the composition of RCMD mass, how the composition varies, and the sources of the constituents.

The constituents of RCMD are complex and heterogeneous and depend on mine geology and mining methods that generate the dust. There are three major sources of airborne dust particles in coal mines: particles entering the mine with the intake air; dust generated from cutting, drilling, or crushing coal and rock strata during the mining process; and application of rock dust products. Dust particles generated from abrasion of cutting or drill bits or other tools themselves may also be present in coal mines. Additionally, diesel exhaust represents another major source of airborne particles in many mines.

[2]See Division H: Departments of Labor, Health and Human Services, and Education, and Related Agencies Appropriations Act, 2016.

[3]The rule affects 30 Code of Federal Regulations (CFR) 70, 71, 72, 75, and 90.

[4]In this report, the final rule is referred to as the 2014 dust rule.

Forms of coal range from soft (lignite) to hard coals (bituminous and anthracite) with higher carbon content. Anthracite, historically mined in Pennsylvania, has the highest carbon content (86 to 97 percent) and now accounts for only around 8 percent of coal production in the United States and 0.04 percent of the nation's underground mining (EIA, 2017a,b). Bituminous and subbituminous coal (35 to 45 percent carbon) accounts for most coal production in the United States and 99 percent of underground mining production, the majority from mines west of the Mississippi (EIA, 2017a,b). Lignite (25 to 34 percent carbon) is mined mainly in Texas and North Dakota and constitutes 10 percent of U.S. coal production (EIA, 2017b). RCMD in underground coal mines is estimated to contain 40 to 95 percent coal (Walton et al., 1977; NIOSH, 1995).

In addition to coal, RCMD may contain crystalline silica[5] and silicates, diesel exhaust particles, rock dust products (mainly calcium carbonate) used for explosion mitigation (see Chapter 2), metals, and other organic compounds. Other possible components of the coal mine atmosphere include gases, such as methane, radon, and carbon monoxide; chemicals, such as isocyanates used in roof bolting glues; microbial bioaerosols in water sprays used for dust suppression; and particles not otherwise specified (sometimes referred to as nuisance dust for which constituent-specific exposure limits are not specified).

Several studies have investigated specific characteristics that may be important in understanding health risks, such as bioavailable iron content of coal (Huang et al., 2005) and rare earth element concentration (Schatzel and Stewart, 2012), but few have considered the whole composition of RCMD. A recent study of RCMD particle characteristics analyzed 210 samples collected from stationary locations (that is, area samples) in eight underground coal mines from three regions in Appalachia (Johann-Essex et al., 2017). Overall, percentages of coal were relatively low (that is, less than 40 percent by number count), and statistically significant differences (95 percent confidence level) were observed between particle distributions between mine regions. Higher percentages of aluminosilicates and quartz[6] were found in the samples from central Appalachia compared to those from northern Appalachia, which contained higher percentages of carbonate from rock dusting (that is, the application of rock dust products). Significant differences in particle mineralogy and size were also found between distinct sampling locations. For instance, samples collected near active cutting or drilling operations (for example, by roof bolters, continuous miners, or longwall shearers) and in the return airways had smaller and more elongated dust particles than those in intake airways or near the feeder breaker. Such findings highlight the variability in particle mineralogy, size, and shape that can exist in mine environments, and may be important in understanding health risks and devising exposure controls (Sellaro and Sarver, 2014). While diesel exhaust is not directly monitored in coal mine atmospheres (due to analytical interference that may be posed by coal particles), it is well established that diesel particulates tend to occur in the sub-micron range (about 10-1,000 nm); and represent a complex mixture of components, which tend to be dominated by elemental and organic carbon, with minor fractions of sorbed volatiles and metals (Kittelson, 1997).

OVERVIEW OF UNDERGROUND COAL MINING METHODS AND JOB DUTIES

The variability in RCMD composition and concentration is linked to coal mining processes and mine locations. To mine coal economically, mining companies seek to identify a sufficiently large seam of coal for extraction, either underground or at the surface. Underground coal mining, which occurs in an enclosed space, is associated with generally higher dust concentrations than

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[5]Crystalline silica is a collective term that refers to quartz, cristobalite, tridymite, and several other rare silica minerals. All of the crystalline silica minerals have the same chemical composition but have different crystal structures and are thus termed polymorphs.

[6]The 2014 dust rule defines quartz as crystalline silicon dioxide (SiO_2) not chemically combined with other substances and having a distinctive physical structure. Quartz is the most common form of crystalline silica.

14 Monitoring and Sampling Approaches to Assess Underground Coal Mine Dust Exposures

surface mining. Geological features in underground mines, such as faults and seam splits containing noncoal layers together with the coal, might require cutting through rock to extract the coal.

Mining methods are important determinants of RCMD exposure. The two major methods of underground mining are the room-and-pillar method and the longwall method. In room-and-pillar mining, the roof is supported by pillars of coal and roof bolts are used to prevent rock falls from the roof strata. A continuous miner (a machine with a rotating cutter on a boom) cuts the coal. Longwall methods permit higher productivity, which creates the potential for greater dust generation. In longwall mining, a machine removes a strip of coal from the coal face, while shields support the roof. As the face advances, the mined out area is allowed to collapse. Details of underground mining methods are presented in Appendix F.

Miners' job titles and duties are associated with different RCMD exposures. Miners working in proximity to the coal face, where a continuous miner or longwall machines liberate coal from surrounding rock, are likely to have the highest exposures (Colinet et al., 2010). As discussed below, for regulatory compliance purposes in the United States, personal monitors are required for miners working in designated occupations considered to have the highest RCMD exposures. Those occupations include the continuous miner operator, roof bolter operators, headgate and tailgate shearer operators, and jack setters (shield operators). In addition, RCMD samples are required to be collected from specific areas in the mine.

While RCMD exposures in surface mines are generally lower than those underground, the full spectrum of lung diseases related to RCMD exposure have been observed in surface miners (CDC, 2012; Halldin et al., 2015b). Surface mine workers involved in drilling have higher respirable quartz exposures (Amandus and Piacitelli, 1987; Piacitelli et al., 1990).

TOXICITY AND DISEASES ASSOCIATED WITH COAL MINE DUST EXPOSURE

There is a clear relationship between duration and intensity of RCMD exposure and risk of lung disease associated with coal mining. The most widely recognized respiratory disease from coal mining is coal workers' pneumoconiosis (CWP). CWP can progress even after exposure removal (Halldin et al., 2015a), and risk for progression is related to concentration and duration of RCMD exposure and probably also to particular constituents of the dust. Estimated cumulative dust exposure has been found to be associated with higher prevalence of CWP and coal rank[7] has shown some correlation with higher CWP disease prevalence for high rank coal (Attfield and Seixas, 1995).

Lung cellular damage and inflammation from exposure to RCMD results in injury that can lead to chronic lung disease, with disease progression likely a result of sustained inflammatory effects of retained mineral dust. Mechanisms of lung injury include (1) direct lung damage due to oxidant generation by RCMD particles and (2) stimulation of alveolar macrophages and lung epithelial cells by RCMD, with generation of oxidants, release of inflammatory mediators, and stimulation of fibrogenic factors (Lapp and Castranova, 1993; Castranova and Vallyathan, 2000). Exposure to high concentrations of respirable silica is associated with greater lung injury (Castronova, 2000). Additionally, researchers have examined potential biological pathways to explain higher CWP prevalence in workers from mining regions with higher concentrations of bioavailable iron in coal (Huang et al., 2002). A systematic review of scientific literature on occupational exposure to coal dust and the risk of interstitial lung diseases found evidence to suggest an independent effect of the nonquartz part of coal on disease development and progression (Beer et al., 2017).

The spectrum of coal mine dust lung diseases includes simple and complicated CWP; silicosis and mixed dust pneumoconiosis; dust-related diffuse fibrosis; and chronic obstructive pulmonary diseases, including emphysema and chronic bronchitis (Petsonk et al., 2013; Perret et al.,

[7]Coal rank is a classification of coal based on fixed carbon, volatile matter, and heating value. It indicates the progressive geological alteration (coalification) from lignite to anthracite.

2017). All of those are diseases of long latency; that is, it typically takes at least 10 years (and often 20 to 30 years) before disease becomes clinically apparent. Effective diagnosis of a coal mine dust lung disease relies on a comprehensive occupational history; medical and social histories; findings on chest imaging, lung function testing, and arterial blood gas testing at rest and with exercise; and consideration of other diseases that may mimic these conditions.

Historically, the diagnosis of CWP relied mainly on findings from the chest radiograph. There are two main radiographic categories of classical CWP: simple and complicated CWP. Simple CWP is defined by the presence of opacities less than 10 mm in the longest dimension. Complicated CWP (also called progressive massive fibrosis [PMF]) is defined by the presence of radiographic opacities larger than 10 mm in size (Figure 1-1). The chest radiographic findings in simple and complicated silicosis are similar to and often indistinguishable from those of CWP, with a radiographic diagnosis of CWP based on the occupational history of exposure to RCMD, whereas a radiographic diagnosis of silicosis is based on the history of exposure to respirable silica in noncoal mining environments (for example, in metal/nonmetal mining, stone/sand/gravel mining, sandblasting, stone cutting industries, and others). Dust-related diffuse fibrosis is characterized on chest radiograph by irregular rather than rounded opacities and on lung tissue analysis by findings of bridging fibrosis connecting macular, nodular, or progressive massive fibrosis lesions, often with pigmented interlobular septal thickening (McConnonchie et al., 1988).

Obstructive lung diseases including emphysema and chronic bronchitis can occur in miners with and without radiographic pneumoconiosis, and emphysema can occur in nonsmoking coal miners (Attfield, 1985; Attfield and Hodous, 1992; Seixas et al., 1992). Emphysema severity in miners is related to cumulative RCMD exposure and lung dust content (Kuempel et al., 2009). Notably, coal mine dust injures the airways in an additive way with tobacco smoke exposure, and contributions from RCMD exposure and cigarette smoking are similar in predicting emphysema severity (Attfield and Hodous, 1992; Kuempel et al., 2009).

No specific medical treatment is effective in reversing coal mine dust lung diseases or in controlling disease progression. Consequently, efforts to minimize RCMD exposure along with medical surveillance for early disease detection and removal from exposure are the mainstays in protecting a miner’s health.

A number of Class I human carcinogens, including silica, radon, and diesel exhaust, are found in coal mine environments, and excess lung cancer mortality among coal miners (especially those exposed to respirable crystalline silica) remains a concern (Attfield and Keumpel, 2008; Miller and MacCalman, 2010; Blackley et al., 2016, 2018). In addition, exposure to RCMD, mainly particles less than 2.5 µm in aerodynamic diameter, may increase miners’ risk for cardiovascular diseases, particularly in combination with other occupational cardiovascular risk factors such as noise, vibration, and shift work (Enterline, 1972; Weiner et al., 2007; Eller et al., 2009; Skogstad et al., 2016; Eriksoon et al., 2018).

RECENT TRENDS IN COAL MINE DUST LUNG DISEASES AND IN MINING

Trends in Disease Epidemiology

The National Institute for Occupational Safety and Health (NIOSH) Coal Workers’ Health Surveillance Program was established by the Federal Coal Mine Health and Safety Act of 1969 to prevent early CWP from progressing to disabling disease. Since 1970, NIOSH has administered this program for eligible miners. Mandatory chest radiograph examinations must be provided by a NIOSH-approved facility for each miner at the beginning of their coal mine employment and within 3 years after the initial examination (42 CFR 37). Voluntary examinations must be offered at least every 5 years. Under the 2014 Coal Workers’ Health Surveillance Program, a coal miner or contractor working at an underground or surface mine receives a free chest x-ray, lung function test, and health assessment and symptom questionnaire.

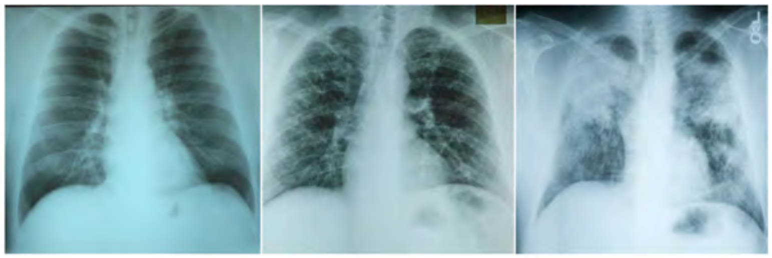

FIGURE 1-1 Chest radiographs of normal lung, simple CWP, and progressive massive fibrosis. SOURCE: Laney, 2017.

Beginning around 2000, data from the NIOSH Coal Workers' Health Surveillance Program has shown an unexpected increase in the proportion of miners with CWP, based on abnormal chest radiographic findings (Laney and Attfield, 2010). That increase followed 30 years of decline in cases of CWP after the Federal Coal Mine Health and Safety Act of 1969 established limits on RCMD exposure (Figure 1-2).

In 2005, NIOSH found that, among miners with CWP, 35 percent showed rapidly progressive pneumoconiosis, including 15 percent with PMF (the most severe form of CWP) (Antao et al., 2005). Rapidly progressive pneumoconiosis is defined as an increase in small opacity profusion or development of progressive massive fibrosis within a period of less than 5 years, a substantially shorter period for disease progression than is typical for CWP.

When the data on cases of rapidly progressive pneumoconiosis were mapped by geographic location, "hot spot" mining regions with high rates of the disease were identified (Figure 1-3), mainly in Appalachian coal fields in Kentucky, Virginia, and West Virginia (Figure 1-4). Compared to other miners, those with CWP in these three states were younger (median age 52 years compared to 55 years in other states) and more likely to be employed in smaller mines with fewer than 155 miners (Laney et al., 2012).

Because participation by active coal miners in the NIOSH Coal Workers' Health Surveillance Program is voluntary, concern about potential bias in participation rates has been raised. However, differential participation by disease status is unlikely, as surveillance recruitment efforts by NIOSH have been aimed at all miners, and many miners are unaware that they have chest x-ray evidence of pneumoconiosis (which may be demonstrated on a chest x-ray in a miner without symptoms). Moreover, rates of participation in the NIOSH Coal Workers' Health Surveillance Program have remained relatively stable over time (Laney and Attfield, 2013). Despite limitations from incomplete participation, findings of increased disease prevalence and severity underscore the need for effective dust control measures as well as the ongoing importance of medical surveillance of U.S. coal miners.

Trends in Underground Coal Mining and Employment That May Affect Disease Risk

Major changes have occurred over the past several decades in underground coal mining practices and coal mining conditions, some of which might have affected RCMD exposures and contributed to changing disease patterns. Lengths of continuous mining cuts and longwall passes (coal-face cutting) extended; cutting sequences changed to bi-directional cutting on longwalls and supersection continuous mining[8] increased in use. Increased sizes and horsepower of mining equipment, more-efficient coal preparation methods, and an increased volume and speed of coal loading and transporting activities have led to increases in coal mine extraction productivity. Higher productivity certainly increases the total dust load generated.

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[8]The simultaneous operation of two sets of mining equipment that share a common dumping point on the same section, with each set being ventilated by a separate split of intake air.

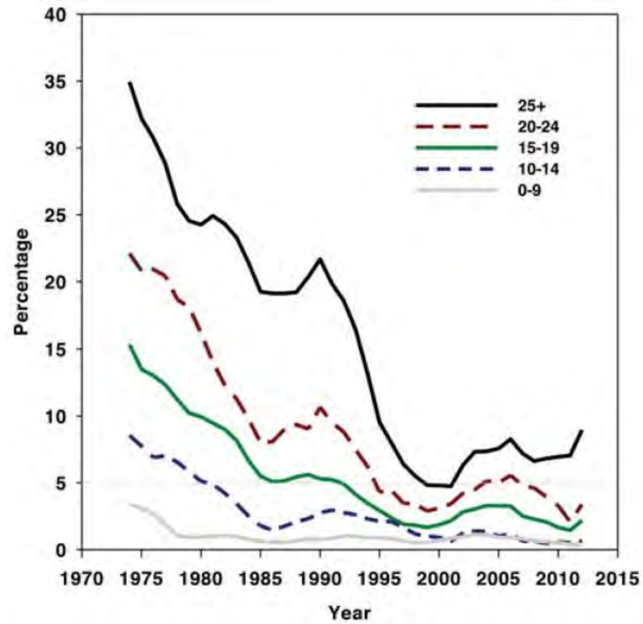

FIGURE 1-2 Percentage of examined U.S. underground miners with coal workers' pneumoconiosis (CWP), for 1970 to 2012. Data are presented as 5-year moving averages. Separate plots represent various years of work tenure. The plots show an overall decline in CWP following enactment of the 1969 Coal Mine Health and Safety Act, followed during the past two decades by an increasing prevalence of CWP in coal miners with 15 or more years of tenure, and especially for miners with 25 or more years. SOURCE: Laney and Weissman, 2014. Reprinted with permission; copyright 2014, *Journal of Occupational and Environmental Medicine.*

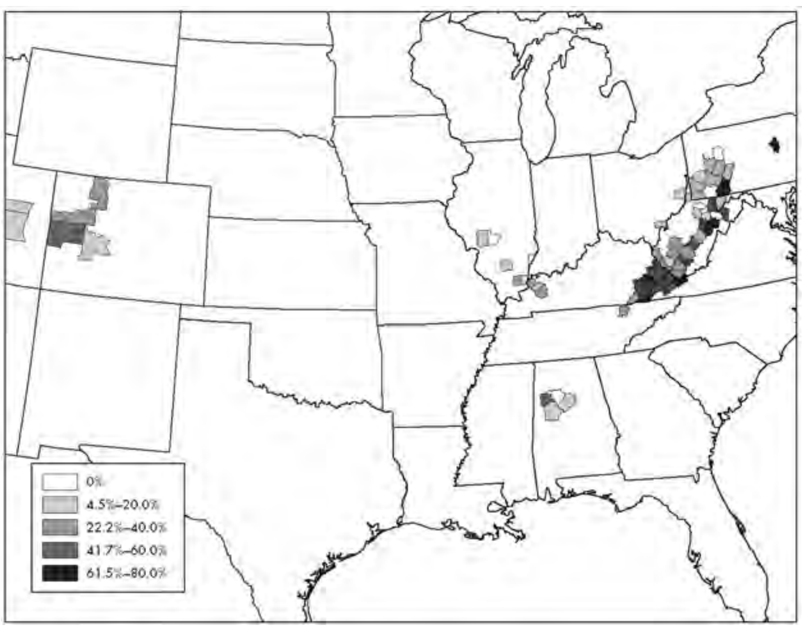

FIGURE 1-3 Map of CWP "hot spots" by county, showing a particularly high proportion of evaluated miners with CWP in central Appalachian areas of West Virginia, Virginia, and Kentucky. SOURCE: Antao et al., 2005. Reprinted with permission; copyright 2014, *Journal of Occupational and Environmental Medicine.*

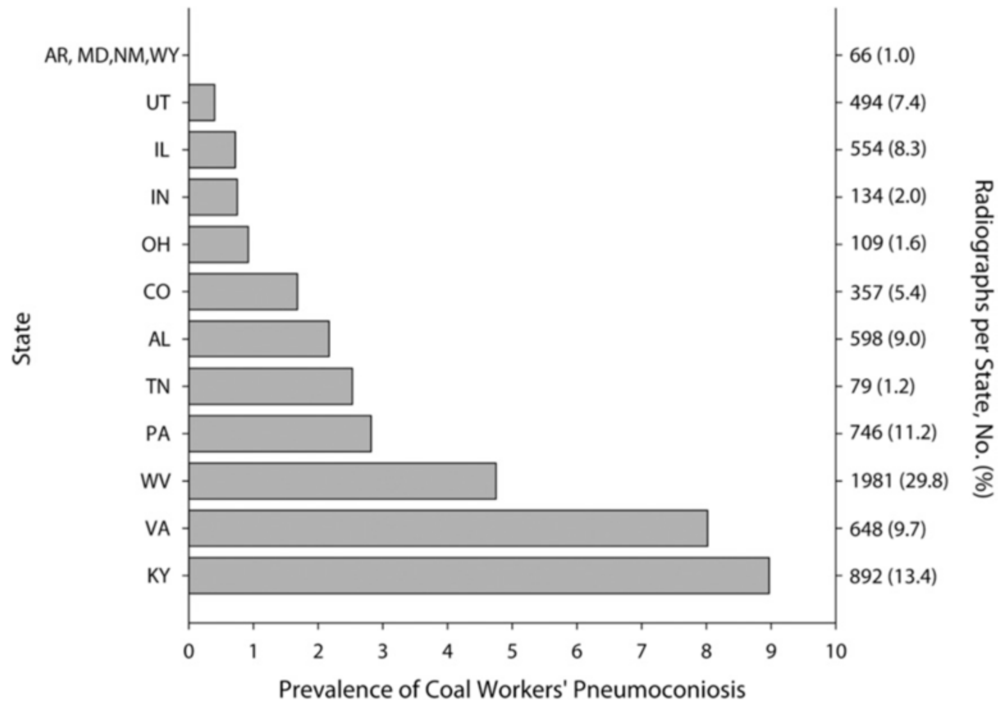

FIGURE 1-4 Prevalence of coal workers' pneumoconiosis by state: Enhanced Coal Workers' Health Surveillance Program, 2005–2009. Prevalence is defined by the authors as the percentage of radiographs contributed by miners from each state that were identified as showing the presence of coal workers' pneumoconiosis. As noted by the authors, data from AR, MD, NM, and WY were aggregated because of the small number of radiographs contributed by miners from those states. Data in the right column are the number and percentage of radiographs contributed by miners from each state. SOURCE: Laney et al., 2012. Reprinted with permission; copyright 2012, *Occupational and Environmental Medicine*.

Concurrent with changes in mining practices, there was a shift to thin seam mining, as relatively thick and high-quality coal seams became depleted in the United States. To ensure adequate head room for miners and equipment, more rock strata were mined as thin coal seams were being extracted for continuous mining and longwall mining. The actual section of strata mined may include portions of roof or floor or both. In some cases, the coal seam itself may contain partings of shale or clay materials that are mined along with coal. Mining surrounding rock along with the coal likely results in changes in particle size, shape, composition, and concentration, and probably increasing miners' exposure to respirable crystalline silica from adjacent rock (Laney et al., 2010; Petsonk et al., 2013).

Increased silica exposure appears to explain at least some of the observed cases of rapidly progressive pneumoconiosis. Surveillance chest radiographs of Appalachian coal miners show an increasing proportion of r-type pneumoconiotic opacities (rounded pneumoconiotic opacities exceeding 3 mm), suggesting greater exposure to silica and silicates (Laney et al., 2010). A study of lung tissue specimens from 13 coal miners with rapidly progressive pneumoconiosis found that features of accelerated silicosis and mixed dust pneumoconiosis were common (Figure 1-5). Tissue samples contained a large amount of birefringent mineral dust particles suggestive for silica and silicates; carbonaceous coal dust was less prominent (Cohen et al., 2016).

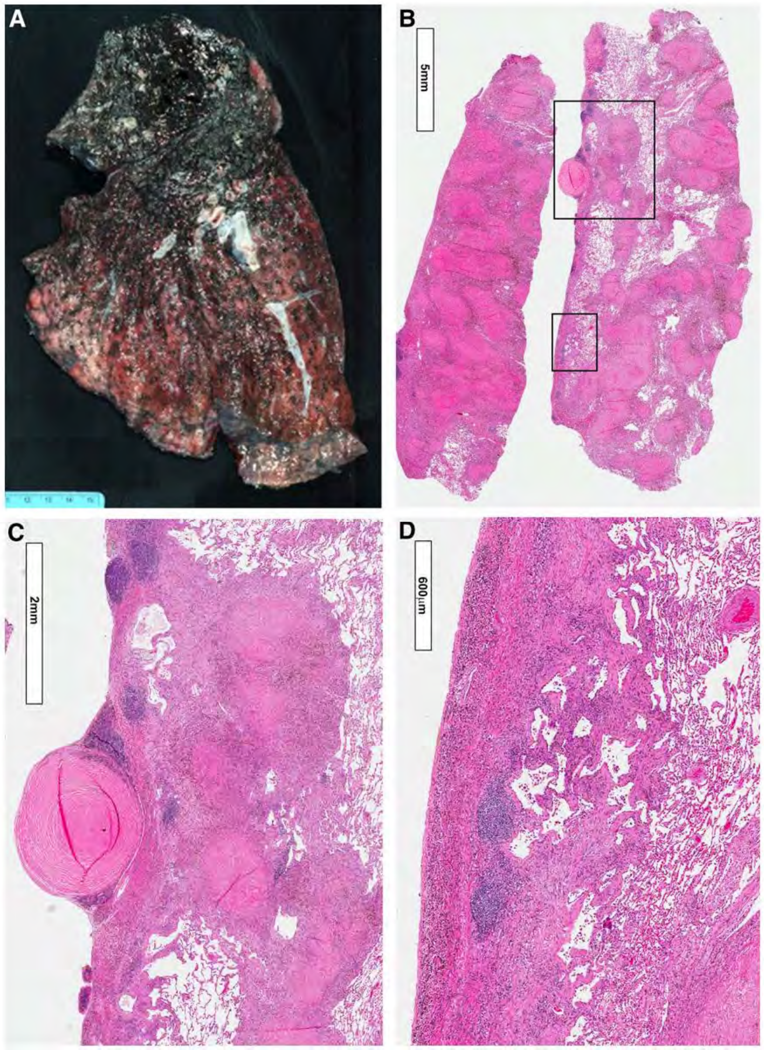

FIGURE 1-5 (A) Photograph of a left lung removed from a coal miner with rapidly progressive pneumoconiosis. The upper lobe is completely replaced by progressive massive fibrosis (PMF). Pale nodular areas can be seen within the PMF, indicative of silicosis. The top segment of the lower lobe is also involved with PMF. Elsewhere the lung shows nodular lesions of pneumoconiosis (B) low magnification (scale is 5 mm) views show on the left the area of PMF and on the right the area involved with simple coal workers' pneumoconiosis. Both areas show predominantly silicotic lesions. (C) Close-up (scale is 2 mm) of upper boxed area shown in B. A silicotic nodule can be seen on the pleura surface (left), together with additional silicotic nodules. marked lymphoid reaction in the pleura. (D) Close-up of lower boxed area (scale is 600 µm) in B showing pleural thickening with fibrosis and aggregates of cells in the lung tissues. SOURCE: Cohen et al., 2016. Reprinted with permission; copyright 2016, *American Journal of Public Health.*

Regarding employment factors, shifts in the mining economy (such as fluctuations in commodity price and decreases in mining jobs) resulted in a reduction of crew sizes on mine sections and extended work shifts, which tended to increase the duration of miners' exposure. Economic shifts also have the potential to cause changes in the extent of workforce training, as well as experience and skill levels. If changes in the mining economy result in fewer unionized mines, the influence of mine safety committees could decrease. If more overtime, longer workweeks, and longer work shifts are relied upon to respond to economic changes, changes in patterns and amounts of RCMD exposure are likely to occur. As miners who work for smaller mining companies tend to change employment locations and employers more frequently, their job duties also tend to vary and exposures during their mining tenures become more difficult to characterize. Also, smaller mining companies tend to have fewer health-directed resources. Those factors present challenges in understanding cumulative exposures over multiple years and other risk factors associated with coal mine dust lung diseases.

EARLY REGULATORY EFFORTS AND PAST RECOMMENDATIONS

With enactment of the Federal Coal Mine Health and Safety Act of 1969, mandatory standards for control of airborne RCMD were established for the first time in 30 CFR Part 70. In setting mandatory health standards in Title II of the Act (Interim Mandatory Health Standards), Congress stated that the purpose is "to provide to the greatest extent possible, that the working conditions in each underground coal mine are sufficiently free of respirable dust concentrations in the mine atmosphere to permit each miner the opportunity to work underground during the period of his entire adult working life without incurring any disability from pneumoconiosis or any other occupation-related disease during or at the end of such period." That goal was to be achieved through mandatory RCMD exposure standards, medical examinations, and compensation programs, which were to be supported by enforcement as well as research and development programs. (Appendix G supplements the information provided in this section.)

According to the 1969 Coal Act, which became effective on June 30, 1970, the average RCMD concentration in the active sections of underground coal mines was to be maintained at or below 3.0 mg/m^3. On December 30, 1972, the exposure limit was reduced to 2.0 mg/m^3. The act also stated that the standard would be further reduced whenever the quartz content in RCMD was greater than 5 percent. The intended effect of the reduced limit was to keep the quartz concentration at or below 0.1 mg/m^3. The significance of achieving those RCMD standards in mines was compelling, as a U.S. Bureau of Mines survey of 29 mines in 1968-1969 had found average dust concentrations in excess of 6 mg/m^3 (Shepich, 1983). The Government Accountability Office (GAO, 1975) noted the general agreement among the miners, mine operators, union officials, and government agencies that significant reductions had been made in RCMD concentrations in mines. However, the report also identified weaknesses in the dust-sampling program that affect the accuracy and validity of the RCMD results and make it virtually impossible to determine how many mine sections complied with allowable dust concentration.

In the early 1990s, concerns were raised by MSHA, miners, and operators about the effectiveness of the regulatory dust program, including monitoring technology and sampling protocols, for meeting the stated purpose of the 1969 Coal Act in establishing the interim mandatory health standards. In May 1991, the Secretary of Labor directed MSHA to form a task force for conducting a review of the administration's program to control RCMD concentrations and recommend program improvements. The review concluded that, even though there were significant reductions in RCMD concentrations since 1969, MSHA was not conducting the prescribed number of dust sampling inspections nor was it adequately monitoring the operator sampling program (MSHA, 1992).

A number of studies and program reviews were undertaken during that period to improve the effectiveness of the program from a compliance standpoint. At the same time, a search was under way for improved methods of dust control and new monitoring technology, sampling protocols, and compliance procedures.

In September 1995, NIOSH published a criteria document for occupational exposure to RCMD (NIOSH, 1995) that stated: "Excess prevalence of CWP, progressive massive fibrosis, and decreased lung function is estimated to be substantially reduced if lifetime average exposure to respirable coal mine dust is reduced from 2 mg/m^3 to 0.5 mg/m^3. However, even at a mean concentration of 0.5 mg/m^3, miners have a greater than 1/1000 risk of developing these conditions." The document presented the following recommendations:

- RCMD exposures should be limited to 1 mg/m^3 as a time-weighted average concentration for up to 10 hours/day during a 40-hour workweek measured according to existing MSHA methods.
- The Recommended Exposure Limit (REL) represents the upper limit of exposure for each worker during each shift. For single, full-shift samples used to determine compliance, no upward adjustment of the REL should be made to account for measurement uncertainties.
- Exposures to respirable crystalline silica should not exceed 0.05 mg/m^3 as a time-weighted average concentration for up to 10 hours/day during a 40-hour workweek.

Also in 1995, the Secretary of Labor established an Advisory Committee on the Elimination of Pneumoconiosis Among Coal Mine Workers. The report issued by the advisory committee recommended that MSHA exposure limits for coal mine dust and silica be lowered and established separately (MSHA, 1996). The report also concluded that continuous monitoring data are useful for evaluating the adequacy of dust control through hazard surveillance, in addition to using the data for compliance monitoring. The report emphasized the need for an appropriate balance among exposure monitoring and sampling strategies for determining compliance with RCMD exposure limits: personal (individual miner), occupational (such as a designated occupation), and environmental (such as a designated area). The report also noted the low participation rate of miners in the NIOSH Coal Worker's Health Surveillance Program and recognized the difficulty in balancing out an individual miner's right to confidentiality and the need for MSHA, NIOSH, mine operators, and fellow miners to know where and how much RCMD-related lung disease is occurring. The report concluded that "early recognition of hot spots where there is increased disease can further the primary preventive strategies."

Monitoring technology and sampling strategies for respirable RCMD measurement have evolved to assist miners, mine management, and mine inspectors in their efforts to comply with the prevailing ambient airborne RCMD standards. In 2000, MSHA and NIOSH jointly proposed a rule to use a single, full-shift sample to determine the average concentration of RCMD. During that period, work had proceeded on the development of a continuous dust-monitoring device, including field-testing of prototypes. The eventual development of a continuous personal dust monitor (CPDM) for near-real-time measurement of RCMD concentrations was seen as the arrival of an important tool for exposure assessment and timely control (Volkwein et al., 2004). In 2010, MSHA and NIOSH published a final rule for approval requirements for the existing RCMD personal samplers, and new approval requirements for the CPDM. (See Chapter 4 for a description of the CPDM.)

DUST CONTROL MEASURES

While prevention of dust formation and prevention of dust from becoming airborne are two primary means to reduce the problem of airborne RCMD, the provision of adequate ventilating air to dilute the airborne dust and carry it away from the workers, and keeping the workers away from being downwind of the dust sources, are equally important to reduce exposure to RCMD. The application of those strategies has been greatly aided over the years by a number of developments in equipment design considerations and operating practices (for example, ventilation at the coal face and spray systems).

Every underground coal mining section in the United States operates under a MSHA-approved mine ventilation plan, which contains provisions for methane and dust control, as specified in 30 CFR 75.370. The dust control portion of the ventilation plan is specifically developed by the mine operator for each section in the mine and approved by the MSHA District Manager. Additional requirements for dust control provisions are specified in 30 CFR 90.300 and 90.301 for Part 90 miners, who have been diagnosed with coal mine dust disease. The dust control plan provides detailed descriptions of dust control measures to control miners' exposures at less than the allowable limit. In addition, it specifies sampling locations for monitoring purposes and serves to assess the performance of the process controls for respirable dust generation, entrainment, dispersion and control. The dust control plan provisions must be measurable and verifiable. (See Appendix F for information on dust control methods and examples items included in dust control plans.)

THE 2014 DUST RULE

MSHA's 2014 dust rule changed the allowable limits, measurement technology, and sampling protocols for RCMD exposure (79 Fed. Reg. 85, May 1, 2014). The rule, which has been fully implemented, contains the following key features with respect to underground coal mines:

- The airborne RCMD concentration limit was lowered to 1.5 mg/m^3. The RCMD limit is 0.5 mg/m^3 for intake airways of the mine and in the mine atmosphere to which Part 90 miners are exposed (coal miners who have medical findings of pneumoconiosis and who opt to transfer to a less dusty job in the mine). The concentration limit for respirable quartz remained at 0.1 mg/m^3 (100 micrograms per cubic meter or $\mu g/m^3$).[9,10]
- Mine operators are required to use the CPDM to monitor RCMD exposures of underground coal miners in occupations associated with the highest concentrations. The CPDM also is to be used to monitor the exposures of Part 90 miners. Use of the CPDM is optional for nonproduction areas of underground coal mines.
- The term "normal production shift" is redefined to require that underground mine operators take RCMD samples in the mechanized mining unit (MMU) when production is at least 80 percent of the average production over the last 30 production shifts.
- The operator must collect RCMD samples for the full shift that a miner works. If a miner works a 12-hour shift, samples must be taken with an approved sampling device for the entire work shift. The previous RCMD regulation required monitoring for only 8 hours, even if shifts were longer.
- MSHA inspectors will use single, full-shift samples to determine compliance with the standard for RCMD concentrations.
- Immediate corrective actions to lower RCMD concentrations are required when a single, full-shift operator sample meets or exceeds the excessive concentration value for the RCMD standard. The excessive concentration value ensures that MSHA is 95 percent confident that the applicable standard has been exceeded and allows for the margin of error when measuring RCMD with an instrument. Tables of excessive concentration values are provided in the regulations for the applicable standard and device. See 30 CFR 70.206 and 70.207.
- Spirometry testing, occupational history, and symptom assessment have been added to the periodic chest radiographic (x-ray) examinations required to be offered by mine operators to underground miners through the NIOSH Coal Worker's Health Surveillance Program.
- Certified persons who perform sampling of RCMD concentrations and who maintain and calibrate sampling equipment must complete an MSHA course of instruction and must pass an MSHA examination to demonstrate competency in the tasks needed for RCMD sampling procedures and in maintenance and calibration procedures. Procedures have been added that allow MSHA to revoke a person's certification for failing to carry out the required sampling or maintenance and calibration procedures in a proper manner. Operators are required to provide training to all miners expected to wear a CPDM.

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[9]The Occupational Safety and Health Administration's permissible exposure limit for crystalline silica is 50 $\mu g/m^3$ (81 Fed. Reg. 16,286 [2016]).

[10]Measured concentrations are to be expressed as equivalent concentrations. See 30 CFR 70.2.

Operators are required to collect all samples quarterly on consecutive shifts. The sampling frequency for each designated occupation (DO) and other designated occupation (ODO) is 15 consecutive shifts per quarter, and the sampling frequency for designated areas and Part 90 miners is five shifts per quarter.[11] The DOs and ODOs must not be sampled concurrently. Sampling devices must be worn or carried directly to the MMU or designated area sampled and must be operated portal-to-portal. Sampling devices must remain with the occupation or designated area being sampled and must be operational during the entire shift, which includes the total time spent in the MMU or designated area and while traveling to and from the mining section or area being sampled (30 CFR 70.201). The operator's approved ventilation plan must show the specific locations in the mine for taking the designated area samples.

If a single, full-shift sample measurement collected by a mine operator meets or exceeds the excess concentration value, the operator must make approved respiratory equipment available to affected miners. The operator also is required to take corrective action immediately. Examples of corrective actions include modifications of engineering or process controls (for example, ventilation and water sprays) and changes in work practices (for example, miner and equipment positioning). A violation is considered to occur when 3 out of 15 designated occupation or other designated occupation samples meet or exceed the excess concentration value or the average of all 15 samples meets or exceeds the excess concentration value. For operators' samples of designated areas and Part 90 miners, noncompliance occurs when 2 out of 5 or the average of the 5 samples meets or exceeds the excess concentration value. Data from the CPDM sampling for regulatory compliance must be transmitted to MSHA within 24 hours after the sampling shift.

When sampling is done by MSHA, the instrument used is the personal respirable sampler with gravimetric analysis. The sample so collected is used to determine both compliance with the RCMD mass-based standard and the quartz concentration in the RCMD. Noncompliance occurs when one MSHA sample meets or exceeds the excess concentration value.

Trends in Regulatory Compliance Sampling

In contrast to the increasing rates of more severe and rapidly progressive forms of CWP, recent operator and MSHA samples in underground coal mines for regulatory compliance determinations show that measured airborne RCMD concentrations have decreased since implementation of the 2014 dust rule. A 2006 *Morbidity and Mortality Weekly Report* presented RCMD concentration data collected by MSHA inspectors and mine operators in Lee and Wise Counties, Virginia (Antao et al., 2006). In those two Appalachian counties, where cases of progressive massive fibrosis have been reported recently, samples collected for determining regulatory compliance showed that measured concentrations of RCMD and silica declined steadily.

Data provided to the committee by MSHA (Meikle, 2017) indicate that samples provided by mine operators showed a greater than 99 percent rate of regulatory compliance with the exposure limit in the 2014 dust rule. Since February 2016, all mine operator sampling underground has been performed with the CPDM; since August 1, 2016, the RCMD concentration limit has been 1.5 mg/m^3. It is evident from the reported data from April 2016 to March 2017 that noncompliance is rare and that average RCMD concentrations of the submitted data were well below the allowable level (Table 1-1). Quarterly data for that period are presented in Appendix G. It is important to note, however, that 99 percent operator compliance with the RCMD allowable exposure limit of 1.5 mg/m^3 over an entire shift does not mean that the exposures of 99 percent of the

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[11]Designated occupation is the occupation on a mechanized mining unit (MMU) that has been determined by results of RCMD samples to have the greatest respirable dust concentration. In addition, other occupations on an MMU that are designated for sampling are referred to as other designated occupations. Designated areas are specific locations in the mine where samples will be collected to measure sources of airborne RCMD in the active workings (that is, any place in a coal mine where miners are normally required to work or travel) (see 30 CFR 70.2).

TABLE 1-1 Reported RCMD Concentrations in Underground Coal Mines by Mining Method, April 2016 to March 2017

Mining Method	Type of Sample	Number of Samples	Average Concentration, mg/m^3	Number of Noncompliance	Percent Compliance
Longwall	DO	2,474	0.907	15	99.4
Longwall	ODO	2,161	0.768	7	99.7
Continuous Mining	DO	27,758	0.679	58	99.8
Continuous Mining	ODO	25,248	0.647	46	99.8

NOTE: DO = designated occupation; ODO = other designated occupations.
SOURCE: Meikle, 2017.

miners are less than the allowable limit. Even stringent regulations cannot ensure that flaws in dust control practices are eliminated completely (Weeks, 2006; Pollock et al., 2010). It is also important to note that most miners incurred much of their exposures when previous regulations were in effect. Given that the latency period of CWP disease onset is typically 10 or more years, sufficient time has not elapsed to assess the effect of the 2014 requirements on disease rates and severity.

CONCLUSION

There are likely multiple factors that have contributed to an increase in the prevalence and severity of coal mine dust related lung diseases. Determining the causes of that increase and eliminating occupational lung disease in coal miners is a complex scientific, engineering, medical, regulatory, social, political, economic and legal problem. However, a full analysis of that problem is beyond the scope of this report. The primary focus of this report is an examination of monitoring and sampling approaches for the control of RCMD and miners' exposure.

As dust-generating processes in mining have intensified over the past several decades associated health hazards might increase if there have been unanticipated changes in the characteristics of RCMD exposures that are important in the risk of coal mine dust lung diseases. Also, questions might arise as to whether the monitoring required by the 2014 dust rule is targeting the most important exposures metrics.

Currently, dust control technologies are widely available and have the potential to protect miners' health from RCMD exposure. As discuss in later chapters, optimal strategies are needed to assure that the recent surge in prevalence and severity of coal mine dust lung diseases does not continue.

ORGANIZATION OF THE REPORT

In Chapter 2, the committee discusses the current technology and application for rock dusting to control explosions in coal mines, the composition and particle size distribution of available rock dust products, and the effect of rock-dusting practices on measurements of RCMD concentrations and compliance with respirable dust standards. Chapter 3 provides an overview of sampling and monitoring practices used in several major coal-producing countries. In considering the requirements for those practices and their implementation, the committee identified important commonalities and dissimilarities. Chapter 4 assesses the efficacy of current monitoring technologies and sampling approaches for informing decision making related to reducing RCMD exposures in the United States. In assessing efficacy, the chapter examines scientific and technical bases of key assumptions that those monitoring technologies and sampling approaches rely upon. As compliance sampling focuses mainly on the personal exposures of specific miners, the committee's considerations included how those data might relate to airborne RCMD exposures of nonmonitored workers who share that mine environment. Chapter 5 discusses optimal monitoring and sampling strategies to aid mine operators' decision making related to lowering RCMD exposures. The committee considered strategies that go beyond strict compliance with current regulations and include consideration of other factors not reflected in the sampling results that may be important in understanding relationships between miners' exposures and disease risk. Strategies were considered for maintainable reductions in RCMD exposures to all miners, not just particular mine workers wearing a CPDM during a particular shift. In addition to informing mine operators' decision making, the committee considered strategies to aid mine workers' decisions in responding to near-real-time CPDM measurements. Chapter 6 presents the committee's overall conclusions, identifies important research gaps, and recommends research and development activities for addressing those gaps.

REFERENCES

Amandus, H. E., and G. Piacitelli. 1987. Dust exposures at U.S. surface coal mines in 1982-1983. *Archives of Environmental Health* 42(6):374-381.

Antao, V. C., E. L. Petsonk, L. Z. Sokolow, A. L. Wolfe, G. A. Pinheiro, and M. D. Attfield. 2005. Rapidly progressive coal workers' pneumoconiosis in the United States: Geographic clustering and other factors. *Occupational and Environmental Medicine* 62(10):670-674. doi:10.1136/oem.2004.019679.

Antao, V., E. L. Petsonk, and M. D. Attfield. 2006. Advanced cases of coal workers' pneumoconiosis—Two counties, Virginia, 2006. *Morbidity and Mortality Weekly Report* 55(33):909-913.

Attfield, M. D. 1985. Longitudinal decline in FEV1 in United States coalminers. *Thorax* 40(2):132-137.

Attfield, M. D., and T. K. Hodous. 1992. Pulmonary function of U.S. coal miners related to dust exposure estimates. *American Review of Respiratory Disease* 145(3):605-609.

Attfield, M. D., and E. D. Kuempel. 2008. Mortality among U.S. underground coal miners: A 23-year follow-up. *American Journal of Industrial Medicine* 51(4):231-245.

Attfield, M. D., and N. S. Seixas. 1995. Prevalence of pneumoconiosis and its relationship to dust exposure in a cohort of U.S. bituminous coal miners and ex-miners. *American Journal of Industrial Medicine* 27:137-151.

Beer, C., H. A. Kolstad, K. Søndergaard, E. Bendstrup, D. Heederik, K. E. Olsen, Ø. Omland, E. Petsonk, T. Sigsgaard, D. L. Sherson, and V. Schünssen. 2017. A systematic review of occupational exposure to coal dust and the risk of interstitial lung disease. *European Clinical Respiratory Journal* Blackley, D. J., C. N. Halldin, and A. S. Laney. 2014. Resurgence of a debilitating and entirely preventable respiratory disease among working coal miners. *American Journal of Respiratory and Critical Care Medicine* 190(6):708-709. doi:10.1164/rccm.201407-1286LE.

Blackley, D., J. Crum, C. Halldin, E. Storey, and A. Laney. 2016. Resurgence of progressive massive fibrosis in coal miners—Eastern Kentucky, 2016. *Morbidity and Mortality Weekly Report* 65:1385-1389. doi:10.15585/mmwr.mm6549a1.

Blackley, D. J., L. E. Reynolds, C. Short, R. Carson, E. Storey, and C. N. Halldin. 2018. Progressive massive fibrosis in coal miners from 3 clinics in Virginia. *JAMA* 319(1):500-501.

Castranova, V. 2000. From coal mine dust to quartz: Mechanisms of pulmonary pathogenicity. *Inhalation Toxicology* 12:7-14.

Castranova, V., and V. Vallyathan. 2000. Silicosis and coal workers' pneumoconiosis. *Environmental Health Perspectives* 108(Suppl 4):675-684.

CDC (Centers for Disease Control and Prevention). 2012. Pneumoconiosis and advanced occupational lung disease among surface coal miners – 16 states, 2010–2011. *Morbidity and Mortality Weekly Report* 61(23):431.

Cohen, R. A., E. L. Petsonk, C. Rose, B. Young, M. Regier, A. Najmuddin, J. L. Abraham, A. Churg, and F. H. Green. 2016. Lung pathology in U.S. coal workers with rapidly progressive pneumoconiosis implicates silica and silicates. *American Journal of Respiratory and Critical Care Medicine* 193(6): 673-680.

Colinet, J. F., J. P. Rider, J. M. Listak, J. A. Organiscak, and A. L. Wolfe. 2010. *Best Practices for Dust Control in Coal Mining*. Pittsburgh, PA: NIOSH.

EIA (U.S. Energy Information Administration). 2012. Annual Energy Review 2011. Table 7.2 Coal Production, 1949-2011 (Million Short Tons) [online]. Available at https://www.eia.gov/totalenergy/data/annual/showtext.php?t=ptb0702 (accessed December 22, 2017).

EIA. 2014. Coal Recoverable Reserves 2014 [online]. Available at https://www.eia.gov/beta/international/rankings/#?cy=2014&aid=6&pid=1 (accessed December 22, 2017).

EIA. 2017a. Annual Coal Report 2016. Available online at https://www.eia.gov/coal/annual/pdf/acr.pdf (accessed December 22, 2017).

EIA. 2017b. Coal Data Browser. Aggregate Coal Mine Production: All Coal: Underground 2016. Available online at https://www.eia.gov/beta/coal/data/browser/ (accessed December 22, 2017).

EIA. 2017c. International Energy Outlook 2017. Data. Available online at https://www.eia.gov/outlooks/aeo/data/ (accessed December 22, 2017).

Eller, N. H., B. Netterstrøm, F. Gyntelberg, T. S. Kristensen, F. Nielsen, A. Steptoe, and T. Theorell. 2009. Work-related psychosocial factors and the development of ischemic heart disease: a systematic review. Cardiology in review 17(2): 83-97.

Enterline, P. E. 1972. A review of mortality data for American coal miners. Annals of the New York Academy of Sciences 200(1):260-272.

Eriksson, H. P., E. Andersson, L. Schiöler, M. Söderberg, M. Sjöström, A. Rosengren, and K. Torén. 2018. Longitudinal study of occupational noise exposure and joint effects with job strain and risk for coronary heart disease and stroke in Swedish men. BMJ open 8(4):e019160.

GAO (U.S. Government Accountability Office). 1975. Improvements Still Needed in Coal Mine Dust-Sampling Program and Penalty Assessments and Collections [online]. Available at http://www.gao.gov/assets/120/114174.pdf (accessed July 30, 2017).

Halldin, C. N., A. L. Wolfe, and A. S. Laney. 2015a. Comparative respiratory morbidity of former and current U.S. coal miners. *American Journal of Public Health* 105(12):2576-2577.

Halldin, C. N., W. R. Reed, G. J. Joy, J. F. Colinet, J. P. Rider, E. L. Petsonk, J. L. Abraham, A. L. Wolfe, E. Storey, and A. S. Laney. 2015b. Debilitating lung disease among surface coal miners with no underground mining tenure. *Journal of Occupational and Environmental Medicine* 57(1):62.

Huang, C., J. Li, Q. Zhang, and X. Huang. 2002. Role of bioavailable iron in coal dust-induced activation of activator protein-1 and nuclear factor of activated T cells: Difference between Pennsylvania and Utah coal dusts. *American Journal of Respiratory Cell and Molecular Biology* 27(5):568-574.

Huang, X., W. Li, M. D. Attfield, A. Nadas, K. Frenkel, and R. B. Finkelman. 2005. Mapping and prediction of coal workers' pneumoconiosis with bioavailable iron content in the bituminous coals. *Environmental Health Perspectives* 113(8):964-968.

Johann-Essex, V., C. Keles, M. Rezaee, M. Scaggs-Witte, and E. Sarver. 2017. Respirable coal mine dust characteristics in samples collected in central and northern Appalachia. *International Journal of Coal Geology* 182:85-93.

Kittelson, D. 1997. Engines and Nanaoparticles: A Review. *Journal of. Aerosol Science*, 29(5):575–588.

Kuempel, E. D., M. W. Wheeler, R. J. Smith, V. Vallyathan, and F. H. Y. Green. 2009. Contributions of dust exposure and cigarette smoking to emphysema severity in coal miners in the United States. *American Journal of Respiratory and Critical Care Medicine* 180:257-264.

Laney, A. S. 2017. Presentation to Committee on the Study of the Control of Respirable Coal Mine Dust Exposure in Underground Mines, Morgantown, WV, June 29, 2017.

Laney, A. S., and M. D. Attfield. 2010. Coal workers' pneumoconiosis and progressive massive fibrosis are increasingly more prevalent among workers in small underground coal mines in the United States. *Occupational and Environmental Medicine* 67(6):428-431.

Laney, A. S., and M. D. Attfield. 2013. Examination of potential sources of bias in the U.S. Coal Workers' Health Surveillance Program. *American Journal of Public Health* 104(1):165-170.

Laney, A. S., E. L. Petsonk, and M. D. Attfield. 2010. Pneumoconiosis among underground bituminous coal miners in the United States: Is silicosis becoming more frequent? *Occupational and Environmental Medicine* 67(10):652-656.

Laney, A. S., E. L., Petsonk, J. M. Hale, A. L. Wolfe, and M. D. Attfield. 2012. Potential determinants of coal workers' pneumoconiosis, advanced pneumoconiosis, and progressive massive fibrosis among underground coal miners in the United States, 2005-2009. *American Journal of Public Health* 102(Suppl 2):S279-283.

Laney, A. S., and D. N. Weissman. 2014. Respiratory diseases caused by coal mine dust. *Journal of Occupational and Environmental Medicine* 56 (Suppl 10):S18-S22.

Lapp, N. L., and V. Castranova. 1993. How silicosis and coal workers' pneumoconiosis develop: A cellular assessment. *Occupational Medicine* 8(1):35-56.

McConnochie, K., F. H. Y. Green, V. Vallyathan, J. C. Wagner, R. M. E. Seal, and J. P. Lyons. 1988. Interstitial fibrosis in coal workers—experience in Wales and West Virginia. *Annals of Occupational Hygiene* 32:553-560.

Meikle, G. 2017. Presentation from the Chief of Health for Coal Mine Safety and Health, MSHA to Committee on the Study of the Control of Respirable Coal Mine Dust Exposure in Underground Mines, Morgantown, WV, June 29, 2017.

Miller, B. G., and L. MacCalman. 2010. Cause-specific mortality in British coal workers and exposure to respirable dust and quartz. *Occupational and Environmental Medicine* 67(4):270-276.

MSHA (Mine Safety and Health Administration). 1992. Review of the Program to Control Respirable Coal Mine Dust in the United States. Report of the Coal Mine Respirable Dust Task Group, June 1992 [online]. Available at https://arlweb.msha.gov/s&hinfo/blacklung/Reports/1992ReviewCoalMineDust.pdf (accessed November 17, 2017).

MSHA. 1996. Report of the Secretary of Labor's Advisory Committee on the Elimination of Pneumoconiosis among Coal Mine Workers. Washington, DC: Department of Labor.

MSHA. 2014. Regulatory Economic Analysis For Lowering Miners' Exposure to Respirable Coal Mine Dust Including Continuous Personal Dust Monitors Final Rule. Available online at https://arlweb.msha.gov/endblacklung/docs/REAFinalRule.pdf (accessed December 22, 2017).

NIOSH (National Institute for Occupational Safety and Health). 1995. Criteria for a Recommended Standard. Occupational Exposure to Respirable Coal Mine Dust. Cincinnati, Ohio: NIOSH.

NIOSH. 2008. Work-Related Lung Disease Surveillance System (eWoRLD). Respirable coal mine dust: Geometric mean exposures and percent exceeding designated occupational exposure limits by MSHA coal mine district and state, MSHA inspector and mine operator samples, 1979-2003. Available online at https://www.cdc.gov/eworld/Data/295 (accessed December 22, 2017).

NMA (National Mining Association). 2017a. U.S. Coal Production By State, 2005-2016. Available online at https://nma.org/wp-content/uploads/2017/06/coal_production_by_state_2016.pdf (accessed December 22, 2017).

NMA. 2017b. U.S. Coal Production Trends, 1980-2016 (Million Short Tons). Available online at https://nma.org/wp-content/uploads/2017/06/us_coal_production_trends_2016-2.pdf (accessed December 22, 2017).

Perret, J. L., B. Plush, P. Lachapelle, T. S. Hinks, C. Walter, P. Clarke, L. Irving, P. Brady, S. C. Dharmage, and A. Stewart. 2017. *Respirology* 22(4):662-670.

Petsonk, E. L., C. Rose, and R. Cohen. 2013. Coal mine dust lung disease. New lessons from old exposure. *American Journal of Respiratory and Critical Care Medicine* 187(11):1178-1185.

Piacitelli, G. M., H. E. Amandus, and A. Dieffenbach. 1990. Respirable dust exposures in U.S. surface coal mines (1982-1986). *Archives of Environmental Health* 45(4):202-209.

Pollock, D. E., J. D. Potts, and G. J. Joy. 2010. Investigation into dust exposures and mining practices in mines in the southern Appalachian Region. *Mining Engineering* 62(2):44-49.

Schatzel, S. J., and B. W. Stewart. 2012. A provenance study of mineral matter in coal from Appalachian Basin coal mining regions and implications regarding the respirable health of underground coal workers: A geochemical and Nd isotope investigation. *International Journal of Coal Geology* 94: 123-136.

Seixas, N. S., T. G. Robins, M. D. Attfield, and L. H. Moulton. 1992. Exposure-response relationships for coal mine dust and obstructive lung disease following enactment of the Federal Coal Mine Health and Safety Act of 1969. *American Journal of Industrial Medicine* 21(5):715-734.

Sellaro, R., and E. Sarver. 2014. Characterization of respirable dust in an underground coal mine in Central Appalachia. *Transactions of the Society for Mining, Metallurgy & Exploration* 336:457-466.

Shepich, T. J. 1983. Welcome remarks. Pp. 3-6 in Proceedings of the Symposium on Control of Respirable Coal Mine Dust, Mine Safety and Health Administration, Washington, DC.

Skogstad, M., H. A. Johannessen, T. Tynes, I. S. Mehlum, K. C. Nordby, and A. Lie. 2016. Systematic review of the cardiovascular effects of occupational noise. Occupational Medicine 66(1):10-16.

Suarthana, E., A. S. Laney, E. Storey, J. M. Hale, and M. D. Attfield. 2011. Coal workers' pneumoconiosis in the United States: Regional differences 40 years after implementation of the 1969 Federal Coal Mine Health and Safety Act. *Occupational and Environmental Medicine* 68:908-913. doi:10.1136/oem.2010.063594.

Volkwein, J. C., R. P. Vinson, L. J. McWilliams, D. P. Tuchman, and S. E. Mischler. 2004. Performance of a new personal respirable dust monitor for mine use. *Report of Investigations* 9663:1-25. Pittsburgh, PA: NIOSH.

Walton, W. H., J. Dodgson, G. G. Hadden, and M. Jacobsen. 1977. The effects of quartz and other non-coal dusts in coal-workers' pneumoconiosis. In *Inhaled Particles IV*, Part 2. W. H. Walton, Ed. Oxford, U.K.: Pergamon Press.

Weeks, J. L. 2006. The Mine Safety and Health Administration's criterion threshold value policy increases miners' risk of pneumoconiosis. *American Journal of Industrial Medicine* 49(6):492-498.

Weiner, J., L. Barlow, and B. Sjögren. 2007. Ischemic heart disease mortality among miners and other potentially silica-exposed workers. American journal of industrial medicine 50(6):403-408.
WHO (World Health Organization). 1999. *Hazard Prevention and Control in the Work Environment: Airborne Dust*. Geneva, Switzerland: WHO.

2

Effects of Rock Dust Applications on Coal Mine Dust Measurements

The practice of rock dusting involves the use of an inert rock dust material applied to the surfaces of an underground coal mine. The statement of task for this study (see Appendix A) asks the committee to assess the effects of rock dust mixtures and their application, as required by current U.S. regulations, on respirable coal mine dust measurements. The definition of rock dust and requirements for its content and application are provided in the U.S. Code of Federal Regulations (see Table 2-1). Those requirements are applicable to all underground coal mines in the United States.

Rock dusting is a proven practice that has been utilized in some way since the early 1900s (Harris et al., 2010). A review of rock-dusting practices by Harteis et al. (2016) and the references cited therein provide ample evidence that

- Coal dust represents an explosion hazard in underground coal mines, which has been demonstrated collectively by experimental work and documentation of coal mine explosion disasters, and
- Coal dust explosion hazards often can be mitigated effectively through a proper rock-dusting program.

TABLE 2-1 U.S. Rock Dusting Regulations

Definition 30 CFR 75.2	*Rock dust.* Pulverized limestone, dolomite, gypsum, anhydrite, shale, adobe, or other inert material, preferably light colored, 100 percent of which will pass through a sieve having 20 meshes per linear inch and 70 percent or more of which will pass through a sieve having 200 meshes per linear inch; the particles of which when wetted and dried will not cohere to form a cake which will not be dispersed into separate particles by a light blast of air; and which does not contain more than 5 percent combustible matter or more than a total of 4 percent free and combined silica (SiO_2), or, where the Secretary finds that such silica concentrations are not available, which does not contain more than 5 percent of free and combined silica.
Application 30 CFR 75.402-403	All underground areas of a coal mine, except those areas in which the dust is too wet or too high in incombustible content to propagate an explosion, shall be rock dusted to within 40 feet of all working faces, unless such areas are inaccessible or unsafe to enter or unless the Secretary or his authorized representative permits an exception upon his finding that such exception will not pose a hazard to the miners. All crosscuts that are less than 40 feet from a working face shall also be rock dusted. Where rock dust is required to be applied, it shall be distributed upon the top, floor, and sides of all underground areas of a coal mine and maintained in such quantities that the incombustible content of the combined coal dust, rock dust, and other dust shall be not less than 80 percent. Where methane is present in any ventilating current, the percent of incombustible content of such combined dust shall be increased 0.4 percent for each 0.1 percent of methane.

It is important to understand that coal dust explosion hazards are real and documented, and rock dusting is currently the leading practice available to mitigate that hazard. The practice is of interest in this study because of the size fraction of particles that are respirable (less than 10 µm in aerodynamic diameter) and available for entrainment in working environments in typical rock dusts currently used in the United States. This chapter discusses the current technology and its application for rock dusting, composition and particle size distribution of available rock dusts, and effect of rock-dusting practices on measurements of respirable coal mine dust (RCMD) and compliance with the 2014 dust rule, and potential health effects of rock dust exposure.

ROCK DUST TECHNOLOGY AND PRACTICES

Recent history has shown that coal mine explosions present a risk for fatal incidents in the United States and underscore the importance of rock-dusting practice for the safety of underground coal mining. Volumes of research have been published on the effectiveness of rock-dusting practices for mitigating coal dust explosions. A presentation by Belle to the committee on October 5, 2017, showed evidence that coal mine explosion fatalities have decreased since the early 1900s. Much of that decrease is likely attributable to the practice of rock dusting, particularly in U.S. coal mines (see Figure 2-1). The fatalities significantly dropped following the decade from 1920 to 1930—a significant period considering the use of rock dust to mitigate coal dust explosions.

Much of the definitive work for rock-dusting requirements began with the work of the U.S. Bureau of Mines in the 1920s and 1930s. Bulletin 369 presents the foundation for the particle size distribution and specification required by federal regulations (Bureau of Mines, 1933).

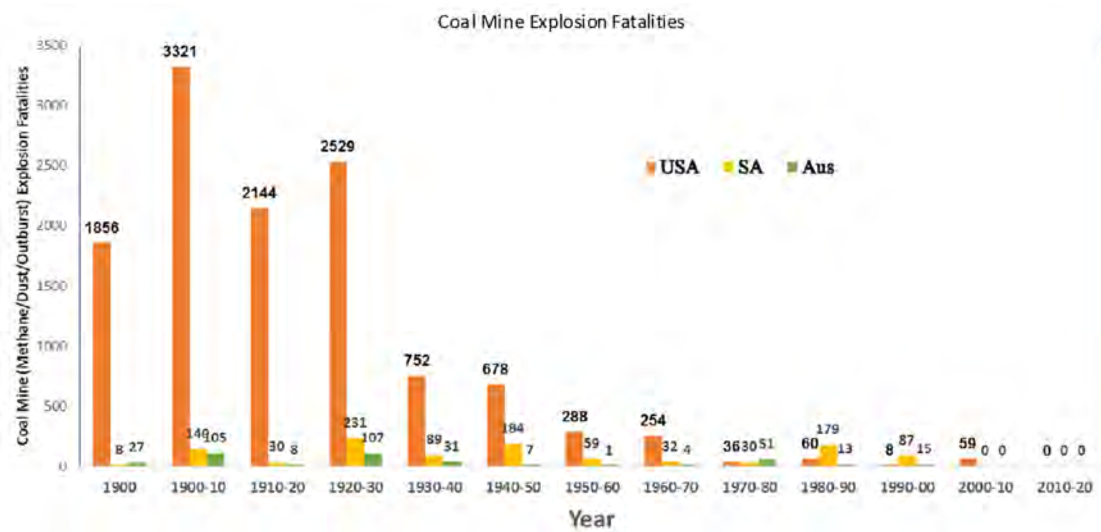

FIGURE 2-1 Time series of coal mine explosion fatalities in the United States (USA), Republic of South Africa (SA), and Australia (Aus). SOURCE: Belle, 2017.

In September 2011, the National Institute for Occupational Safety and Health (NIOSH) Office of Mine Safety and Health Research tested 393 rock dust samples gathered from underground coal mines and found that 47 percent did not permit the requisite amount of particles to pass through a 200 mesh sieve.[1] Overall, 51 percent of the 278 underground mines, where samples were taken, used rock dust that did not permit 70 percent or more to pass through a 200 mesh sieve. In addition, NIOSH studied very fine rock dust particles, which enhance caking potential when wet. NIOSH concluded that all 10 samples it analyzed tended to form a cake when wet and could not be dispersed easily with a light blast of air (NIOSH, 2011). Those findings were inconsistent with the definition of rock dust in 30 CFR 75.2.

After much work related to determining coal dust particle sizing and a large suite of information generated through years of explosibility testing at the Lake Lynn Experimental mine and the Bruceton Mine under the Bureau of Mines and NIOSH, Harris et al. (2010) recommended: “In view of these results, there is a need to re-examine the particle size specifications for rock dusts and determine the material specific requirements relevant to the incombustible content needed to prevent explosion propagation.” The authors also recommended that, “In view of current results from the NIOSH coal dust particle size survey in US mines and preliminary size analyses of rock dusts, the effect of rock dust particle size in preventing coal flame propagation should be re-examined through large-scale explosion tests.” Since the nature of coal dust explosions has been researched extensively, much of the current research focuses on rock dust composition. Prior research had used rock dust specifications detailed in Bulletin 369 and subsequently detailed in federal regulations. An evaluation under current mining conditions and coal mine dust parameters was needed in order to create recommendations to improve the performance of rock dusting practices.

Prior research has shown that mean particle size is important for rock dust performance. In small-scale laboratory tests, the larger the rock dust particle size, the more rock dust is required to inert[2] the coal dust and prevent an explosion from propagating. It has been shown in various small chamber tests that by reducing the size of the rock dust particles, the surface area of the rock dust increases and promotes greater radiant heat absorption (Dastidar et al., 1997).

Several types of rock-dusting methods can be employed. Regulations allow for dry dust application and wet dust applications, in some cases.

Dry dusting can be performed by a machine, which slings dry dust onto surfaces of the mine. Dry dusting can also be performed by workers, who manually carry bags of rock dust and scoop out the material and throw it onto the exposed surfaces. Dry dusting typically performs better than wet dusting with respect to lift and dispersion in the event of an explosion. However, stringent respirable dust regulations can hamper productivity with respect to dry rock dusting. If dry dusting is taking place on the intake ventilation course, dust which does not adhere to the exposed surfaces floats along the air course up to the active section where mining personnel are operating equipment. Because the volume of rock dust which can be dispersed over a given time frame is limited by the 2014 dust rule, that rock dust application method tends to limit productivity of the mine and does not allow for a timely dusting of the mine's virgin, exposed coal seam, thereby increasing the amount of coal mine dust that has the potential to be fuel in the event of an explosion because it is not inerted enough by rock dust. To counteract the RCMD generated by dry dusting, some mines have moved to wet dusting. Some operations have managed compliance with the 2014 dust rule by not dusting while personnel are inby (toward the mine interior) at the active working sections during production, thus reducing the exposure to workers on the section. For example, a letter from a coal mine operator to the committee states that changes in rock dusting on belt entries during designated area sampling have occurred to ensure compliance with the 2014 dust rule during these shifts.[3] That issue is of particular concern because the conveyor belt in the belt entry is a major source of coal dust. Continual rock dusting is often required to maintain the 80 percent incombustible material limit in these entries.

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[1]Mesh refers to the number of openings across one linear inch of screen. As the mesh number increases, the size of the openings decreases. The openings of a 200 mesh sieve are approximately 74 µm.

[2]The action of mitigating coal dust explosion hazards by rock dust is often referred to as inerting the coal dust.

[3]Letter from E. Patrick Brady (Murray Energy Corp.), dated April 27, 2017.

It needs to be emphasized that immediate safety is compromised for miners when insufficient incombustible material is present in coal entries. In addition, operators may choose not to rock dust during shifts where a continuous personal dust monitor (CPDM) is in use (see Chapter 1). Although some operators have expressed that no changes to rock-dusting practices have occurred since the adoption of the CPDM requirement and reduced RCMD exposure limit, it is evident from the operator sampling data reported by the Mine Safety and Health Administration (MSHA)[4] that the use of the CPDM has driven some changes in rock-dusting behavior. However, it is critical that efforts to comply with the rock-dusting requirements and RCMD requirements not compromise the effectiveness of either explosion mitigation or RCMD exposure reduction.

Wet dusting involves mixing dry dust with water and then spraying the mixture onto the exposed mine surfaces. While this method initially alleviates the respirable dust problems associated with dry dusting, a new set of problems arises.[5] Wet rock dust that is applied to surfaces of underground coal mines must dry before it is able to prevent an explosion from propagating. Wet dusting also commonly produces clumps of rock dust, which is termed caking. Caked rock dust retains some weight of the water and, in the event of an explosion, the caked dust will not disperse into the entry where it could extinguish the flame front. In essence, a completely new set of problems arises with wet dusting.

With the problems associated with each respective dusting application, mine operators are forced to employ nonideal application practices concerning explosion hazard mitigation. If they choose dry dusting, miners at the mining face are exposed to increased RCMD concentrations and production slows. If they choose wet dusting to alleviate the dry dust problems, the desired properties and purpose of the rock dust might not be attained.

In addition, several companies are developing technologies for including additives in wet dust mixes to allow for a more friable and thus dispersible dried rock dust product following application. Companies are also working on treating rock dusts with chemicals, such as stearic acid, oleic acid, and sodium oleate, to prevent caking and thus maintain particle size distributions and dispersibility in varying mine atmospheric environments (IMERYS, 2014; Huang et al., 2015; Perry et al., 2015).

Technologies are being developed by Dywidag Systems International (DSI) (now controlled by Jennmnar Inc.) and Strata Worldwide (Strata) in an effort to alleviate the problems and hindrances seen from dry and wet dust applications. With the use of proprietary technology, each system utilizes a wet dust mixture with respective additives (such as polymers and foams) to create a substance which can be sprayed onto exposed mine surfaces. Each system has the potential to reduce the amount of respirable dust generated largely, in a way that is similar to wet dusting applications but dries in a timely manner and has little to no caking. Such methods are intended to allow for greater, more consistent surface coverage when compared to dry dust slinging operations, yet still provide lift characteristics similar to that of dry dust when exposed to explosions. Those technologies and others are being evaluated by multiple research organizations and companies.

During the process of developing new rock dust technologies, the particle size distribution of feed rock dust has come under much scrutiny. Determination of the optimum rock dust particle size distribution is necessary to develop optimized solutions that mitigate the possibility of massive coal dust explosions and protect miners from respiratory hazards associated with RCMD exposure.

Other concepts have been investigated for mitigating coal dust explosions. Many of these concepts involve passive and active trigger barriers that employ concentrated sources of dispersible rock dust at specific areas of underground mines. Passive barriers include systems of concentrated rock dust (or water) that are expected to be dispersed by a coal dust explosion in progress. The dispersed rock dust is designed to arrest the progression of the explosion. Many types of barriers have been designed that include tray systems, bags, and tanks that are easily ruptured or overturned by the dis-

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[4]In a presentation to the committee on June 29, 2017, Gregory Meikle (MSHA) indicated that 99.7 percent of the samples collected from Aug 1, 2016, to May 31, 2017, were in compliance with the sampling requirements of the 2014 dust rule.

[5]Dry dust must be applied over wet rock dusted areas once the wet rock dust has dried (75.403 Maintenance of Incombustible Content of Rock Dust Section updated July 2015\Release V-51; MSHA Program Policy Manual).

turbance of the explosion approaching and passing. Actively triggered systems utilize sensing technology to detect the arrival of a coal dust explosion front precisely and trigger a response that disperses the concentrated rock dust (or water) with the use of energetic materials (such as chemical propellants) or compressed gas (Zou and Panawalage, 2001). Research on those methods for mitigating coal dust explosions is less extensive than the volume of research available on more typical rock dust applications.

PARTICLE SIZE DISTRIBUTIONS OF ROCK DUST

Most of the commercially available rock dust is composed of limestone or marble, although regulations allow for other materials (see Table 2-1). As the particle size distribution of rock dust is important for its ability to mitigate coal dust explosions, explosibility of coal dust is dependent on the particle size distribution of the coal dust. Prompted by the disaster at Upper Big Branch in 2010 (MSHA, 2011), research has intensified to classify and understand the effects of both.

Figure 2-2 shows the results of work performed by Cashdollar et al. (2010) with typical specification rock dust, as defined in Bulletin 369. The figure outlines the basis for a regulatory target of 80 percent incombustible material in mine intake entries, because propagation did not occur above 80 percent incombustible content. The figure does not include the variable of rock dust size distribution. Evaluation of coal dust size distribution by Cashdollar et al. found that smaller particle size distributions required a higher percent content of incombustible material. The lack of investigation into the effects of rock dust particle size has left considerable doubt concerning the effectiveness of larger rock dust particles, such as those found in the NIOSH 2011 investigation, where most rock dust samples did not meet the 200 mesh requirement (NIOSH, 2011). That is evidenced by the fact that a higher quantity of incombustible content with a majority of materials smaller than 200 mesh is needed for smaller coal dust particle sizes (Figure 2-2). The relationship between particle sizes of rock dust and coal dust and the fundamental function of rock dust as a coal dust explosion inhibitor is not fully characterized in the literature. Data presented in Figure 2-2 suggest that coal mines are susceptible to explosion propagation even at 80 percent incombustible content of coal mine dust, given high content of minus 200 mesh coal dust material. It also suggests that smaller particle size distributions in the rock dust applied may provide a better heat sink and allow for the lower incombustible contents required to prevent propagation.

It is important to consider the effectiveness of different particle size distributions of rock dust to mitigate coal dust explosions generated by different size distributions of coal dust. With newer technology and advances in mining techniques, the traditional definition of the size distribution of coal dust that has been used in much research to date may not represent current conditions. More-recent work shows that fine particles are more effective at mitigating coal dust explosions definitively. Harris states:

> The PSDs [particle size distributions] of the rock dusts vary greatly with some having multiple peaks in the distribution and although sieving can be used to characterize the PSD of rock dusts, the most effective particles for inerting lie in the respirable size range and cannot be sieved. To better characterize such wide variations, multiple and varying sized sieves would be required and the finest size to be assessed would typically be 38 µm or possibly 20 µm (635 mesh sieve not widely available commercially). However, the respirable portion of rock dust is the most effective and cannot be assessed using sieves. (Harris et al., 2015)

This statement is supported by work presented by Man and Harris in 2014. Figure 2-3 shows that smaller size distributions of rock dust particles require a smaller percentage of incombustible content of coal mine dust (shown as percent rock dust) to mitigate explosions than do larger particle size distributions. Each curve represents different percentages of rock dust that were added to the experimental chamber (x-axis) and the resulting explosion pressure in the chamber (y-axis). Explosion pressures at 1 bar represent an event where no explosion occurred. For each particle-size curve, there is a distinct percentage above which the rock dust is able to mitigate the explosion. Data show that the smaller particle sizes begin inerting the coal dust explosions at lower percent rock dust. For example, the curve for particle size less than 38 μm had explosion pressures greater than 6 bar until the percentage of rock dust reached 50 percent, where explosion pressures are listed at 1 bar.

The culmination of recent work is summarized well by Harris et al. (2015). The authors conclude that rock dust particles smaller than 38 μm are more effective than larger ones at inerting coal dust. The authors recommend a particle size distribution with 95 percent of material finer than 200 mesh for mitigating the propagation of coal mine dust explosions. In addition, the authors describe a way of correlating specific surface area of rock dust particles to performance. It is expected that specific surface area will be investigated further in future work.

It is evident that more comprehensive research is needed to identify optimum rock dust particle size distributions with different particle sizes of coal dust. Investigation of a maximum particle size of rock dust capable of inerting coal dust explosions is necessary to determine if eliminating the respirable size (less than 10 μm) particles from rock dust would be an effective means of reducing the contribution of rock dust to RCMD exposures. That work also would be pertinent to finding effective rock-dusting practices based on work performed by Sapko et al. (2007) regarding the particle size distribution for coal mine dust in U.S. coal mines.

Because of ongoing debates concerning the effectiveness of rock dust requirements in mitigating coal mine dust explosions, it is appropriate to discuss the implications of making such a change to the requirements. Take, for example, the case of implementing the recommendation for 95 percent of material minus 200 mesh. Figure 2-4 (left-hand side) shows particle size analysis for a typical sample of rock dust that would be supplied to a mine for rock-dusting applications. The sample is 78 percent minus 200 mesh and the respirable-size portion of the dust is 43.5 percent passing 10 μm. The right-hand side of Figure 2-4 illustrates a sample that would be created to meet a requirement for 95 percent minus 200 mesh. The sample is 98 percent minus 200 mesh and the respirable portion of this dust is 55 percent passing 10 μm (Phagan, 2017). The figure indicates that employing rock dust to mitigate explosions and reducing RCMD concentrations attributable to rock dusting are competing goals.

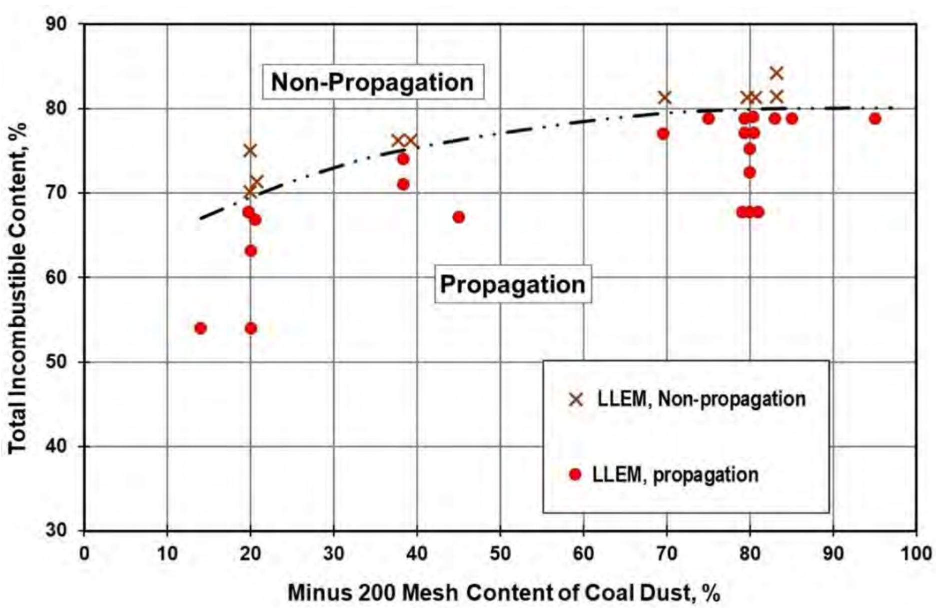

FIGURE 2-2 Incombustible content required with varying coal dust size distributions using Bulletin 369 specification rock dust. LLEM = Lake Lynn Experimental Mine. SOURCE: Cashdollar et al., 2010.

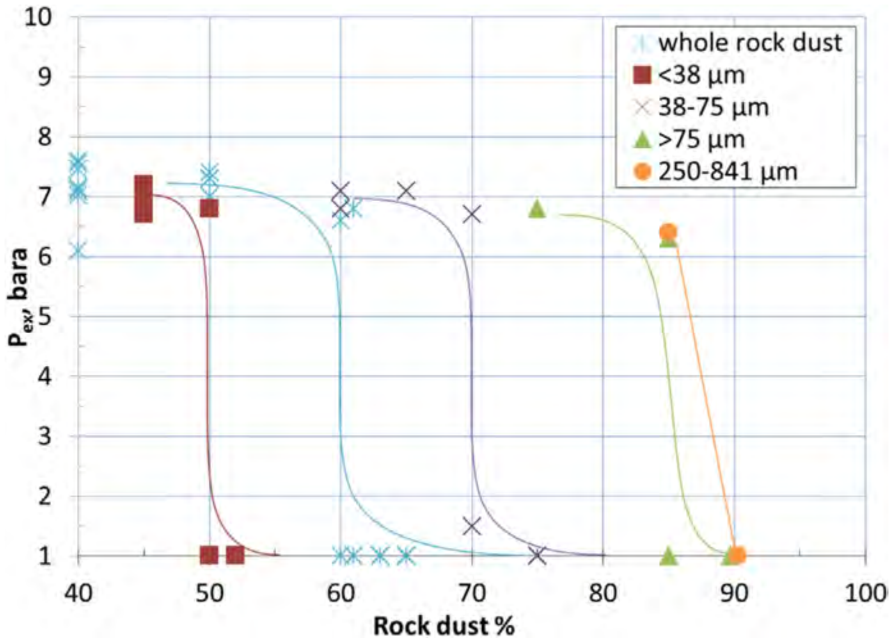

FIGURE 2-3 Inerting pulverized Pittsburgh coal with limestone rock dust including sieved size fractions and 250-841 μm (60-20 mesh) particles in the 1 m^3 chamber. Whole rock dust is rock dust that was not sized and partitioned. Explosion pressure (absolute) is shown in bar units. SOURCE: Man and Harris, 2014. Reprinted with permission; copyright 2014, *Journal of Loss Prevention in the Process Industries.*

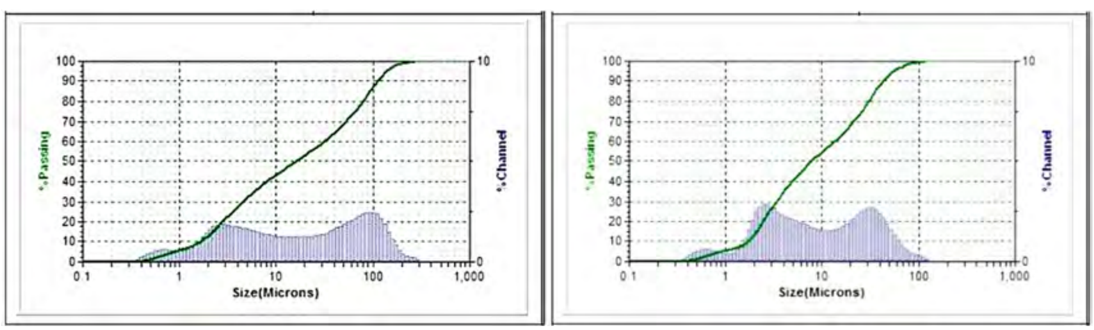

FIGURE 2-4 Left: In this sample, 78 percent passes 200 mesh, 66 percent passes 325 mesh, and 43.5 percent passes 10 μm. Right: In this sample, 98 percent passes 200 mesh, 91 percent passes 325 mesh, and 55 percent passes 10 μm. SOURCE: Phagan, 2017.

It is apparent that respirable particles are present in rock dust products that are available for use in underground coal mines. A presentation provided by NIOSH, dated June 2, 2016, describes some of the ways that rock-dusting practices affect CPDM measurements and provides recommendations on how to mitigate RCMD exposure from rock dusting (NIOSH, 2016). The presentation describes the concern that rock dust can be entrained in the mine atmosphere by the flow of ventilation air, moving equipment, and the process of rock dusting itself. A few recommendations, such as wetting the floor following dusting and using surfactants, are presented, but little research has been done to describe how those actions would affect rock dust effectiveness in mitigating explosions.

The 2016 NIOSH presentation shows preliminary results from a study of CPDM measurements taken upwind and downwind from the application of treated and untreated rock dust (NIOSH, 2016). The study revealed that concentrations of RCMD downwind from rock dusting operations ranged from 489 to 1,100 mg/m^3. Those values are much greater than the 1.5 mg/m^3 exposure limit in the 2014 dust rule. More concerning is that the rock dust that was treated to prevent caking and allow for greater dispersibility in the event of an explosion was more likely to elevate RCMD concentrations even after rock-dusting operations were completed. Resultant concentrations downwind were in concentrations of up to 4.38 mg/m^3 even when wetting the floor to prevent entrainment. One concern regarding those results is that rock dusting during mine operations is not advisable because it can elevate RCMD concentrations. The other concern is that treated rock dust is more susceptible to entrainment for the very same reasons that it is probably more effective at long-term protection from coal mine dust explosions.

SILICA CONTENT OF ROCK DUST

As indicated in Table 2-1, current regulations require that rock dust not contain more than 5 percent combustible matter and not more than a total of 4 percent free and combined silica (SiO_2) or, where the Secretary finds that such silica concentrations are not available, that it not contain more than 5 percent of free and combined silica. Silica is considered to be the mineral of primary concern for silicosis and other related diseases. The term free silica refers to pure SiO_2 phases, which are generally in the form of the mineral quartz. Combined silica refers to the silicate minerals containing other elements in stoichiometric proportions, such as feldspar ($NaAlSi_3O_8$ $KAlSi_3O_8$) or kaolinite ($Al_2Si_2O_5(OH)_4$), or in rare cases silicate glass; such phases have 40 to 70 percent SiO_2 by weight.

The silica requirement is a general definition for rock dust that is applicable in underground coal mines. Most commercially available rock dust products are generated from pulverized limestone or marble. Quartz is the predominant form of respirable silica observed in the air of underground coal mines. The concentration of respirable quartz in the mine atmosphere must be less than 100 $\mu g/m^3$. The sampling for quartz concentration must be performed using the coal mine dust personal sample unit (CMDPSU, also referred to as a gravimetric sampler) rather than the CPDM that is now required for RCMD sampling in underground coal mines. The CPDM is not capable of measuring quartz concentration. MSHA collects CMDPSU samples and monitors quartz concentration to determine regulatory compliance. Filters containing dust samples from a CMDPSU are sent to a laboratory for analysis, which can take several days to complete.

Analysis of bulk samples of treated and untreated limestone dust and treated and untreated marble rock dusts showed that quartz content in the respirable size component was less than 1.5 percent (Soo et. al., 2016). That analysis also showed the quartz content in marble rock dust samples was negligible.

The contribution of rock dust to the quartz concentration relative to the contribution from dust created by mining operations has not been documented. Furthermore, the contribution of rock dust to the concentration of RCMD has not been evaluated fully. Elevated amounts of silica, including quartz, in rock materials immediately surrounding coal deposits in Appalachian coal mines have been reported (Schatzel, 2009). The requirement for a low-silica content in rock dust products suggests that the silica contribution from rock dusting to airborne RCMD in coal mines would be limited in the presence of higher concentrations of silica in rock materials surrounding coal seams. However, the silica exposure contribution from rock dusting would vary, in part, according to the amount of silica in the surrounding rock and the coal being mined, as well as the proportion that rock dust contributes to the total mass of airborne RCMD.

POTENTIAL HEALTH EFFECTS OF ROCK DUST EXPOSURE

Even with the undisputed importance of rock dust in explosion mitigation, questions arise about potential health hazards associated with rock dust exposure. As described previously, major sources of rock dust are marble (calcite or dolomite) and limestone (mainly calcium carbonate), with respirable silica constituting no more than 4 to 5 percent for regulatory compliance in U.S. coal mines (30 CFR 75.2). Generally speaking, marble and limestone are among the least harmful of the inorganic dusts and no constituent-specific exposure limits have been specified for them. Those dusts are often referred to as low-toxicity dust not otherwise specified, nuisance dust, or particles not otherwise classified or regulated (Hearl, 1998).

A number of early studies and case reports describe lung health effects in workers in marble and limestone industries including mining, quarrying, and stone cutting. Doig (1955) described silicosis and emphysema in eight limestone grinders and miners after sustained high exposure beginning in the 1920s to limestone dust containing silicates. Bridge and Nagelschmidt (1956) report that a clinical and chest x-ray survey of 14 limestone workers exposed to dust containing less than 1 percent quartz found no evidence of pneumoconiosis. Based on the occupational processes and exposures described in those early studies, their relevance to current rock-dusting-related risk is questionable.

A more recent case report of a limestone quarry worker describes lung function abnormalities, radiographic nodular opacities, and surgical lung biopsy findings of foreign body granulomas composed of birefringent particles containing calcium, aluminum, and silicon, suggestive for limestone pneumoconiosis (Crummy et al., 2017). A case of autoimmune systemic sclerosis occurring in a marble worker with lung biopsy findings of nodular pneumoconiosis, suggestive for silicosis, has also been described (Bello et al., 2015).

Contamination of rock dust with free silica, even in small concentrations, can add to a miner's cumulative exposure to respirable silica and thus contribute to risk for a number of adverse silica-related health outcomes. Inhaled silica particles of respirable size can trigger a cascade of lung inflammation and injury that over time increases the risk for silicosis, emphysema, and chronic bronchitis. Crystalline silica is considered a Class I carcinogen by the International Agency for Research on Cancer and, in high concentrations, can increase the risk for kidney and some autoimmune diseases. In general, the committee found few case reports or studies implicating rock dust exposure in risk for clinically significant coal mine dust lung disease.

Rock dust adds to the total RCMD exposure experienced by miners. Cumulative dust exposure increases the risk of both respiratory diseases and cardiovascular diseases (CVDs). A number of studies have found causal relationships between CVD and long-term exposure to particulate matter with an aerodynamic diameter less than 2.5 µm (EPA, 2009). Recent studies have used brachial-ankle pulse wave velocity (baPWV), which reflects the stiffness of both central and peripheral muscular arteries as a predictor of cardiovascular events and mortality. In a case-control study of more than 1,000 Chinese coal miners with CWP, increased baPWV was associated with increased risk for CVD risk factors and CDE (Zheng et al., 2017).

In addition to reducing visibility (with potential safety implications), rock dust that deposits in the upper airways can trigger eye, nose, and throat irritation symptoms (runny nose, watery eyes, cough, and phlegm). Long-term exposure to low-toxicity dust may lead over time to rhinitis or bronchitis, and may contribute to risk for chronic obstructive pulmonary disease even at concentrations that are less than currently acceptable concentrations (Cherrie et al., 2013). A survey of chronic respiratory symptoms among 70 high-exposed limestone production workers in Zambia found that, after controlling for age, smoking, previous jobs, and respiratory illnesses, the more highly exposed workers had a significantly increased relative risk of persistent daily cough and sputum production compared to lower exposed workers (Bwalya et al., 2011).

CONCLUSIONS

1. Rock dusting is a proven and necessary technique for mitigating coal mine dust explosion hazards. Previous assessments, such as those done by the Rock Dust Partnership (NIOSH, 2016), have highlighted the need for developing and evaluating rock-dusting systems that can provide adequate coverage of coal mine surfaces, be applied wet (or with low amounts of entrained dust), and dry to an easily dispersible state.
2. Measurements of RCMD concentrations include respirable rock dust particles, by definition. However, it appears that complying with the rock-dusting requirements (30 CFR 75.2 and 75.402-403) has not been a large obstacle to demonstrating compliance with the sam-

pling requirements of the 2014 dust rule. It is critical that efforts to comply with the rock-dusting requirements and RCMD requirements not compromise the effectiveness of either explosion mitigation or RCMD exposure reduction.

3. Smaller rock dust particles (approaching the respirable size of less than 10 µm aerodynamic particle diameter) are more effective than larger ones at mitigating explosion risks. Smaller particle sizes mean greater surface area per unit mass than larger particles and thus greater heat sink ability.
4. Continued research is needed on rock-dusting application practice and mine worker training to ensure explosion mitigation effectiveness is not compromised in an effort to meet mine air quality standards. Full-scale underground mine testing, such as was conducted at the Lake Lynn Experimental Mine, is needed to determine the effectiveness of such systems.
5. It is evident that more comprehensive research is needed to identify optimum rock dust particle size distributions for applications in underground mines with different particle sizes of coal mine dust. Investigation of a maximum particle size of rock dust capable of inerting coal mine dust explosions is necessary to determine if eliminating the respirable-size particles from rock dust is a viable solution. That work also would be pertinent for finding effective practices based on work performed by Sapko et al. (2007) regarding the particle size distribution for coal mine dust in U.S. coal mines.
6. Although rock dust contributes substantially to the total mass of RCMD, it is not possible to determine the percent contribution of rock dust using the currently required monitoring technology. As a result, two mines using different rock-dusting approaches (such as wet instead of dry application methods or dusting at different times and rates during mining operations) might have very different RCMD compositions and yet exhibit similar measured mass concentrations. Therefore, heavy contributions of rock dust could distort health assessments of relationships between RCMD exposure and diseases caused by dust components insignificantly contributed by rock dust.
7. The requirement for a low-silica content in rock dust products suggests that the silica contribution from rock dusting to airborne RCMD in coal mines would be limited in the presence of higher concentrations of silica in rock materials surrounding coal seams. However, the silica exposure contribution from rock dusting would vary according to the amount of silica in the surrounding rock and the coal being mined, as well as the proportion that rock dust contributes to the total mass of airborne RCMD. Sustained high exposures to rock dust and other so-called nuisance dusts, for which constituent-specific exposure limits are not specified, may trigger respiratory symptoms of irritation and cough and could contribute to a higher risk of COPD. However, in general, the committee found few case reports or studies implicating rock dust exposure in risk for clinically significant coal mine dust lung disease.
8. Although the quartz content of rock dust particles in the respirable size range is generally less than 1.5 percent, the potential for rock dust to contribute to silica exposure is an important concern. Exposures to the highest rock dust concentrations are likely to occur at air-intake areas of mines when rock dust is applied or from dust reentrainment by man-trip vehicles used for transporting miners to and from their work areas in the mine.

REFERENCES

Belle, B. 2017. Coal Mine Dust Exposure Monitoring and Sampling in Underground Mines in Selected Industrialized Countries. Presentation from Principal Ventilation and Gas Manager for Anglo American group's Coal Business unit at the Sixth Meeting on Occupational Exposure to Respirable Coal-Mine Dust, October 5, 2017, Washington, DC.

Bello, S., A. Rinaldi, S. Trabucco, L. Serafino, C. Bonali, and G. Lapadula. 2015. Erasmus syndrome in a marble worker. Reumastismo 67(3):116-122.

Bridge, D. S., and G. Nagelschmidt. 1956. Report on the absence of pneumoconiosis among workers in pure limestone. *British Journal of Industrial Medicine* 13:6-8.

Bureau of Mines. 1933. Explosion Tests of Pittsburgh Coal Dust in the Experimental Mine, 1925 to 1932. Bureau of Mines, Bulletin 369, 44 pp.

Bwalya, D., M. Bråtveit, and B. E. Moenet al. 2011. Chronic respiratory symptoms among workers at a limestone factory in Zambia. Archives of Environmental & Occupational Health 66(1):47-50.

Cashdollar, K. L., M. J. Sapko, E. S. Weiss, M. L. Harris, C. Man, S. P. Harteis, G. M. Green. 2010. Recommendations for a New Rock Dusting Standard to Prevent Coal Dust Explosions in Intake Airways. Pittsburgh, PA: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2010-151, (RI 9679), 2010 May; 49 pp.

Cherrie, J. W., L. M. Brosseau, A. Hay, and K. Donaldson.et al. 2013. Low-toxicity dusts: Current exposure guidelines are not sufficiently protective. Commentary. Occupational Hygiene 57(6):685-691.

Crummy, F., I. Carl, C. H. S. Cameron, and L. G. Heaney. 2017. A possible case of pneumoconiosis in a limestone quarry worker. *Occupational Medicine* 54(7):497-499.

Dastidar, A. G., P. R. Amyotte, and M. J. Pegg. 1997. Factors influencing the suppression of coal dust explosions. Fuel 76(7): 663-670.

Doig, A. T. 1955. Disabling pneumoconiosis from limestone dust. *British Journal of Industrial Medicine* 12:206-216.

EPA (U.S. Environmental Protection Agency). 2009. Integrated Science Assessment (ISA) for Particulate Matter. Final Report. Washington, DC: U.S. Environmental Protection Agency.

Harris, M. L., E. S. Weiss, S. P. Harteis, G. V. R. Goodman, and M. J. Sapko. 2010. Rock dusting considerations in underground coal mines. In S. Hardcastle and D. L. McKinnon, eds. Proceedings of the 13th Mine Vent Symposium (Laurentian University, Sudbury, Ontario, Canada, June 13–16, 2010). Sudbury, Canada: MIRARCO, pp. 267-271.

Harris, M. L., M. J. Sapko, I. A. Zlochower, I. E. Perera, and E. S. Weiss. 2015. Particle size and surface area effects on explosibility using a 20-L chamber. *Journal of Loss Prevention in the Process Industries* pp. 37:33-38. doi:10.1016/j.jlp.2015.06.009.

Harteis, S. P., D. W. Alexander, M. L. Harris, M. J. Sapko, and E. S. Weiss. 2016. Review of rock dusting practices in underground coal mines. Pittsburgh, PA: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2017-101 (IC 9530), 89 pp.

Hearl, F. J. 1998. Current exposure guidelines for particulates not otherwise classified or regulated: History and rationale. *Applied Occupational and Environmental Hygiene* 13(8), Workshops on Airways Disease and Occupational Exposure to Particulates Not Otherwise Classified/Regulated.

Huang, Q., R. Honaker, K. Perry, and B. Lusk. 2015. Oleate-modified rock dust for wet applications in underground coal mines. Transactions of the Society for Mining, Metallurgy, and Exploration 338(1).

IMERYS. 2014. Development of an anti-caking rock dust. NIOSH Broad Agency Announcement (BAA):2012-N-14257, Contract No. 200-2012-52496, April.

Man, C. K., and M. L. Harris. 2014. Participation of large particles in coal dust explosions. *Journal of Loss Prevention in the Process Industries* 27:49-54.

MSHA (Mine Safety and Health Administration). 2011. Fatal underground mine explosion, April 5, 2010. Performance Coal Company Upper Big Branch Mine–South, Massey Energy Company, Mine ID:46-08436. Arlington, VA: U.S. Department of Labor, MSHA, December 6, 2011.

NIOSH (National Institute for Occupational Safety and Health). 2011. Non-conforming rock dust. 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. HID 16, p. 4.

NIOSH. 2016. Rock Dust Partnership Meeting: Attributes of Rock Dust to Prevent Coal Dust Explosions. June 2, 2016. Pittsburgh Mining Research Division.

Perry, K. A., B. T. Lusk, R. Q. Honaker, R. Q. Eades, and Q. Huang. 2015. Modern Rock Dust Development and Evaluation. Final Report submitted to Commonwealth of Kentucky per Contract Doc ID No. PON2 127 1300001705 1. Kentucky Energy and Environment Cabinet Department for Energy Development and Independence, May.

Phagan S. 2017. Production and Characteristics of Rock Dust Applied in Underground Mines, Presentation to Committee on April 13, 2017, Morgantown, WV.

Sapko, M. J., K. L. Cashdollar, and G. M. Green. 2007. Coal dust particle size survey of U.S. mines. *Journal of Loss Prevention in the Process Industries* 20(1):616-620.

Schatzel, S. J. 2009. Identifying sources of respirable quartz and silica dust in underground coal mines in southern West Virginia, western Virginia, and eastern Kentucky. *International Journal of Coal Geology* 78:110-118.

Soo, J. C., T. Lee, W. P. Chisholm, D. Farcas, D. Schwegler-Berry, and M. Harper. 2016. Treated and untreated rock dust: Quartz content and physical characterization. *Journal of Occupational & Environmental Hygiene* 13(11):D201-D207. doi: 10.1080/15459624.2016.1200195.

Zheng, Y., L. Liang, T. Qin, G. Yang, S. An, Y. Wang, Z. Li, Z. Shao, X. Zhu, T. Yao, S. Wu, and J. Cai. 2017. Cross-section analysis of coal workers' pneumoconiosis and higher brachial-ankle pulse wave velocity with Kailuan study. *BMC Public Health* 17:148.

Zou, D. H., and S. Panawalage. 2001. Passive and Triggered Explosion Barriers in Underground Coal Mines – A Literature Review of Recent Research. Report to CANMET Natural Resources Canada.

3

Exposure Monitoring and Sampling Approaches Used in Different Industrialized Countries

The committee's statement of task calls for a comparison of the monitoring technologies and sampling protocols (including sampling frequency) currently used or required in the United States, and in similarly industrialized countries for the control of respirable coal mine dust (RCMD) exposure in underground coal mines (see Appendix A). In comparing monitoring technologies and sampling protocols, the committee described relevant regulatory requirements and identified apparent commonalities and dissimilarities among the different countries. Required medical surveillance programs for detection of diseases in coal miners are also included. The committee relied upon scientific literature, regulatory background documents, discussions with experts outside the committee (see Appendix C), and the expertise of its members.

The committee considered it beyond the scope of this study to assess the implementation of the requirements, rates of compliance with the regulations, and the extent to which the regulatory programs are successful in controlling RCMD exposures. Also, the committee did not attempt to compare associations between current monitoring and sampling approaches and disease prevalence data for individual countries. As discussed in Chapter 1, diseases related to RCMD exposures typically have a long latency (at least 10 years and often 20 to 30 years) and prevalence data are not reflective of current approaches for monitoring and controlling exposure. However, the potential for using compiled multinational exposure data and medical surveillance data for further assessments is considered in this chapter.

In 2015, about 8.8 billion tons (8 billion metric tons) of coal were mined in more than 50 countries and more than 50 percent of that production came from underground mining. The committee identified a set of countries that, based on its judgment, provides a reasonable representation of the range of monitoring and sampling approaches used in industrialized countries. The set of countries includes Australia, Germany, India, the People's Republic of China, Poland, the Republic of South Africa, and the United States. Table 3-1 lists typical underground mining practices, mandated exposure limits, and required monitoring devices for several leading coal-producing countries.

MONITORING AND SAMPLING APPROACHES REQURIED IN SELECTED COUNTRIES

United States

In 2015, total U.S. coal production was approximately 897 million short tons (EIA, 2017) and underground coal mining accounted for about 34 percent (NMA, 2017). Two major methods of underground mining (the room-and-pillar method and the longwall method) are used in the United States (see Appendix F). In 1970, underground coal mining accounted for more than 60 percent of U.S. coal production, with longwall production being less than 5 percent of that production; in 2015, about 60 percent of underground production came from longwall mines. Underground mining in central Appalachian states, such as in Kentucky, Virginia, and West Virginia, included a large number of small-sized underground mines (fewer than 50 employees) that accounted for a small percent of the total production. (See Chapter 1 and Appendix E for discussions of trends in mining methods and employment that might affect disease risk.)

TABLE 3-1 Coal Mining and Underground Miner Exposure Monitoring in Selected Countries

	Total Production in 2015[a]		Underground Mining		
Country	Rank	Thousand Short Tons	Est. Percent of Total Production[a]	Typical Method	Dust Exposure Limits and Required Monitoring Device
People's Republic of China	1	4,376,984	90%	Longwall	Depending on a silica content ranging from 5% to 50%, exposure limits are between 6 and 1 mg/m^3 for RCMD and between 20 and 2 mg/m^3 for total coal mine dust, using a personal gravimetric sampler.
United States	2	896,941	34%	Room-and-pillar, longwall	RCMD exposure limit is 1.5 mg/m^3, using a continuous personal dust monitor. Quartz exposure limit is 0.10 mg/m^3, using a personal gravimetric sampler.
India	3	643,720	10%	Room-and-pillar, longwall	RCMD exposure limit is 2 mg/m^3, when the silica content is less than 5%, using a monitoring device approved by the Indian government. When the silica concentration is 5% or more, the exposure limit is calculated as 10 divided by the percent silica content in the RCMD.
Australia	4	560,714	20%	Longwall	New South Wales: Exposure limits: 2.5 mg/m^3 for RCMD with a quartz content less than 5%, 10 mg/m^3 for the inhalable fraction (particles less than 100 μm in diameter), and 0.12 mg/m^3 for quartz. Personal gravimetric sampling is used. Queensland: Exposure limits: 3 mg/m^3 for RCMD with a quartz content less than 5%, 10 mg/m^3 for the inhalable fraction, and 0.10 mg/m^3 for quartz. Personal gravimetric sampling is used.
Republic of South Africa	7	256,876	50%	Room-and-pillar, some longwall	Exposure limit is 2 mg/m^3 for RCMD with a quartz content less than 5%. If the quartz content is greater than 5%, an exposure limit for quartz is 0.1 mg/m. Personal gravimetric sampling is used.
Germany	8	203,613	3%	Longwall	Using a dose-based approach, limiting cumulative exposure for a 2-year, 220-shift exposure would be an estimated dose accumulated from an average exposure of 4.0 mg/m^3. Area gravimetric sampling is used.
Poland	9	149,147	53%	Longwall	Exposure limits: 1 mg/m^3 for RCMD containing free crystalline silica from 2% to 50%, 4 mg/m^3 for total dust. Personal gravimetric sampling is used.

[a]EIA, 2017. International Energy Statistics. Online. Available at https://www.eia.gov/beta/international/rankings/#?cy=2015&pid=7 (accessed May 16, 2018).

Exposure Limits

The current exposure limit for RCMD in underground mines is 1.5 mg/m^3; the limit for quartz is 100 μg/m.[3] Additional information, including a description of early regulatory efforts, is provided in Chapter 1 and Appendix G.

Monitoring Technology and Sampling Protocols

The exposure monitoring and sampling program for regulatory compliance involves coal mine operators and Mine Safety and Health Administration (MSHA) inspectors, using approved personal devices to obtain required dust measurements. After nearly two decades of research and development, the use of a continuous personal dust monitor (CPDM) is now required. The CPDM is a sampler and gravimetric analysis instrument that is worn by a miner and provides a display of a cumulative-mass concentration of RCMD (see Chapter 4). Mine operators are required to use the CPDM to monitor personal dust exposures of miners in designated occupations (DOs) that are considered to be exposed to the highest RCMD concentrations, miners in other designated occupations (ODOs) that are frequently exposed to high RCMD concentrations, and miners who have medical findings of pneumoconiosis and who opt to transfer to a less dusty job in the mine (Part 90 miners).

Use of the CPDM is optional for meeting sampling requirements for designated areas (DAs), such as the point where coal is loaded onto a conveyor belt, and designated work positions (DWPs) at the surface of an underground mine that are exposed to the highest RCMD concentrations.

The operator must collect respirable dust samples for the full shift that a miner works. The sampling frequency for DOs and ODOs is 15 shifts per quarter. The DO and ODO cannot be sampled concurrently. DAs and Part 90 miners must be sampled during five shifts per quarter. For each DWP, one valid sample must be obtained every quarter. Data from the CPDM sampling for regulatory compliance must be transmitted within 24 hours to MSHA.

In addition to the monitoring carried out by operators, MSHA uses a personal gravimetric sampler to measure RCMD concentrations and the concentration of quartz in the mine atmosphere. Samples are collected onto filters that are mailed to a laboratory for quartz analysis using an infrared spectroscopy method referred to as the MSHA P-7 method (MSHA, 2013).

Medical Surveillance

As indicated in Chapter 1, the National Institute for Occupational Safety and Health (NIOSH) Coal Workers' Health Surveillance Program requires that mandatory chest radiograph examinations be provided by a NIOSH-approved facility for each miner at the beginning of their coal mine employment and within 3 years after the initial examination. Voluntary medical examinations must be provided at least every 5 years. The program also includes a medical and occupational history questionnaire along with spirometry testing via a mobile examination unit that travels to the mine site (Antao and Pinheiro, 2016).

Australia

In 2015, Australia was the fourth largest coal producer in the world at about 561 million short tons (EIA, 2017). Nearly 80 percent of its production comes from surface mining (Mishra et al., 2013; Minerals Council of Australia, 2018). Longwall mining accounts for nearly 90 percent of the underground coal production. Australian underground coal mines tend to be large, operate on thick seams, and mostly incorporate modern longwall methods.

Underground coal mining is regulated on a state-by-state basis in Australia. The states of New South Wales (NSW) and Queensland (QLD) are the major producers of coal in the country and are the focus of this discussion.

Exposure Limits

For RCMD with a quartz content less than 5 percent, NSW's exposure limit is 2.5 mg/m³ and QLD's exposure limit is 3.0 mg/m³. Both states have an exposure limit of 10 mg/m³ for the inhalable fraction (particles less than 100 µm in diameter). NSW and QLD have an exposure limit of 0.10 mg/m³ for respirable crystalline silica (NSW, 2006, 2007; Coal Services, 2016; QLD, 2017a).

All exposure limits for NSW and QLD mentioned above are for time-weighted measurements averaged over an 8-hour shift. Exposure standards may require adjustments when work shifts are longer or the workweek exceeds 5 days, to account for the greater exposure and decreased recovery time between shifts (Ren, 2017). In 2017, a parliamentary committee in QLD recommended that the exposure limit be lowered to1.5 mg/m³ for RCMD and 0.05 mg/m³ for respirable crystalline silica (QLD, 2017a).

Monitoring Technology and Sampling Protocols

The monitoring and sampling procedures used in each state adhere to the Australian standards for sampling and gravimetric determination of respirable dust in workplace atmospheres and inhalable dust (Australian Standard, 2009). Those standards are very similar to the ones specified by the International Organization of Standardization (ISO, 1995).

Specific requirements for underground coal mines in NSW are based on Order 42 of the Coal Industry Act of 2001 (NSW, 2011) and the Work Health and Safety (Mines) Act 2013 (NSW, 2014). In general, production shifts are monitored at a frequency of 6-12 months depending on the crew's location, tasks undertaken, and exposure-related health risk. Typically, samples are collected from the breathing zones of at least five persons on the crew during the shift being monitored. The approved sampling method adopted by the coal industry in NSW is personal gravimetric sampling, using a battery-operated pump and cyclone (Ren, 2017). All monitoring is conducted by NSW Coal Services, which is a collaborative organization with independent monitoring authority that includes participants from industry, NSW government, unions, and mine workers. All results of required dust samples are sent to the mine operator where samples were taken and to other organizations, including the relevant NSW government agency, the union representing the miners, and an expert advisory committee. All government-required dust sampling results from across the industry are maintained in a single database (NSW, 2017).

QLD monitoring and sampling requirements are based on the Coal Mining Safety and Health Act of 1999 and Recognized Standard 14 (QLD, 2016). The Safety in Mines Testing and Research Station, which was established by the QLD government (QLD, 2017b), and other commercial organizations conduct and provide coal mine dust monitoring functions at a cost to the mines. Mine operators are required to review their safety and health management system and report monitoring results on a regular basis. In cases of an exceedance of the exposure limit, operators must check within 2 weeks for the success of revised dust control measures (QLD, 2017a). Operators are required to keep monitoring records for at least 30 years.

QLD monitoring involves the use of similar exposure groups (SEGs). SEGs are established by the site's senior executive and are based on mining operations (such as longwall operations), development operations, or maintenance activities. The number of mandatory initial samples for each SEG (minimum of eight) that are collected to obtain a baseline depends upon the number of workers employed within the SEG and the type of sampling performed (QLD, 2016). The statistical basis for that approach is the NIOSH Occupational Exposure Sampling Strategy Manual

(NIOSH, 1977). The number and frequency of periodic sampling after the baseline has been established is based on the ratio of the initial measurement results to the exposure limit. Depending on the ratio, the required sampling frequency is monthly (ratio greater than 0.75), quarterly (ratio between 0.5 and 0.75), annually (ratio less than 0.5 and greater than 0.1), or none (ratio less than 0.1). One sample is collected for every 10 miners in the SEG.

In addition to the requirements for the number and frequency of periodic sampling, a minimum of 8 to 10 samples must be taken quarterly for SEGs involved in longwall production and development production (QLD, 2016).

In general, personal sampling is used for compliance purposes, and area sampling (static sampling) is used for engineering dust control purposes. (Personal sampling provides a concentration measurement of airborne dust to which an individual is exposed; area sampling provides a concentration that reflects the general dust concentration at a fixed location in the workplace.)

Medical Surveillance

In NSW, a preemployment medical examination is mandatory for coal miners. In addition, miners must undergo a medical examination every 3 years. Additional chest radiography is required every 6 years for miners considered to be at high risk from dust exposure (Ren, 2017).

In QLD, coal workers' pneumoconiosis (CWP) screening is done according to the Coal Workers' Health Scheme (Queensland-based scheme), established by the Coal Mining Safety and Health Regulation 2001. Preemployment health assessments are mandatory for potential mine workers and are required to be provided periodically by the employer's Nominated Medical Adviser. At a minimum, medical surveillance must be conducted at least once every 5 years. In addition, coal miners can request medical examinations at the expense of the employer at the time of their retirement (QLD, 2017a,b).

Several years after concluding that the problem of RCMD-related lung disease had been eliminated in Australia, in-depth investigations showed that cases of CWP were occurring in active and retired coal miners but had not been identified by the Coal Worker's Health Scheme (QLD Parliament, 2017c). A number of recommendations were made:

- Identification and surveillance of coal mine dust respiratory disease should be explicit;
- Designated high-dust-exposure jobs should be linked to clearly stated frequency of health assessments and chest radiographs for workers in these areas;
- Medical staff performing the health assessments should be trained to perform high-quality spirometry and chest x-ray B readings;
- Electronic data collection, aggregate analysis, and reporting should be implemented; and
- Plans for communication of medical surveillance results with individual miners and medical referral, as needed, should be developed (QLD Parliament, 2017c).

Germany

Germany was the eighth largest coal producer in the world in 2015, having produced more than 203 million tons of coal (lignite, bituminous, and anthracite) in that year (EIA, 2017). About 3 percent of that total was from underground production, which constitutes all of the bituminous and anthracite coal still mined in Germany (Yearbook of the European Energy and Raw Materials Industry, 2017). Due to unfavorable economic conditions, underground mining of bituminous and anthracite coal will terminate in Germany by the end of 2018.

In the past, underground coal mining has been carried out in three different regions: Saar district, Ruhr district, and northwest Germany. Those mines have employed several thousands of miners (Falk et al, 2016). All of Germany's underground coal mining is done by the longwall method. Nearly all mines operate at depths greater than 2,600 ft (800 m). With very few exceptions, the seams have been comparably thin.

Exposure Limits

The German Federal Hazardous Substances Ordinance (BAuA, 2017) and the Health Protection Mining Ordinance (BMJV, 2017) provide a basis for regulating miners' exposures to hazardous substances in underground coal mines in Germany. RCMD (often referred to in Germany as fibrogenic mine dust) is the regulatory focus for disease prevention of in coal miners. The RCMD component of greatest concern is respirable crystalline silica, whose amount in the dust depends on the mine, the coal seam being mined, and the work location within the mine. That regulatory focus on RCMD is based on several decades of research on the health protection of coal miners (North Rhine Westphalia Ministry of Economy, 1991) which resulted in these conclusions, among others:

- Crystalline silica in RCMD is responsible for the development of pneumoconiosis in coal miners.
- The crystalline silica in RCMD displays varying toxicity. For example, RCMD in anthracite mines was found to be much more toxic than the RCMD from mining of bituminous coal mines.
- The cumulative dose of RCMD in miners' lungs is a more important consideration than the short-term exposure concentration regarding the development of pneumoconiosis. However, all actions taken to lower the RCMD concentration in underground mines will lower the accumulated dose as well.
- It is very important to conduct frequent medical surveillance of miners with respect to lung diseases and take appropriate actions in response to the results.

In general, little focus has been placed on individual measurements of dust exposure. Instead, emphasis is placed on the classification of workplace exposure types, personal registration of cumulative exposures for individual workers, and relocating miners to different work areas depending on their individual cumulative dust exposures. Based on the above-mentioned conclusions, the airborne concentration of crystalline silica in coal mines in Germany is not determined separately from RCMD. Only RCMD concentrations are monitored, and sampling is conducted gravimetrically to obtain an average exposure over an 8-hour shift for all workers in the specific work area.

The mass concentration measurements are weighted with factors to take into account the variability of crystalline silica attributable to specific mining environment, which was sampled (see below). The monitored concentration is used to calculate the average RCMD exposure of all workers in a specific work area. The number of shifts that each miner works in that work area is recorded in a miner's personal exposure file and exposures are accumulated over a 2-year period. Depending on the estimated individual risk, relocation of a miner to a workplace with lower RCMD exposures might be required or done voluntarily. That approach involves the classification of all workplaces into four dust burden classes, ranging from zero to three, with dust burden class "zero" being the least dusty one and nobody being allowed to work above the highest dust concentration of dust burden class "three."

There are no regulations for short-term exposure, and the values classifying the dust burden classes cannot be directly compared to an exposure limit concentration. However, the limiting cumulative exposure for a miner that would result in a mandatory relocation is based on working at an average concentration of 4 mg/m^3 for 220 shifts per year and for 2 years (i.e., 440 shifts) (Morfeld et al., 2002).

Monitoring Technology and Sampling Protocols

The above-mentioned health-protection mining ordinance does not specify the use of a particular monitoring technology or sampling protocol, but it requires that coal mine operators establish them. In addition, it requires that persons performing the monitoring and data processing have special qualifications and training. Monitoring and sampling follow a specific protocol, which has been developed by RAG (the major coal mining company) and the mining inspection institution of the State of North Rhine Westphalia (RAG DSK, 2006).

Generally, sampling is carried out by means of an area approach that involves the use of the pressurized-air-driven MPG II (Dahmann et al., 2001) working with a BMRC-type (Johannesburg) pre-separator (horizontal elutriator). The sampling is performed at specific sites within a longwall operation or other workplaces. RCMD samples are collected onto glass fiber filters by trained personnel of the mining company for subsequent analysis. Inspectors may perform additional measurements at irregular intervals. Under very special circumstances, for example, in case of encountering a geological anomaly in the seam, the general procedure might be replaced with a specific set of measures only during the time in which mining is performed at the site of the anomaly. In these cases, every miner at that site is required to wear a personal respirable sampler (a French CIP 10 device; Stacey et al., 2014) and personal dust protection masks. Also, in these cases the analytical determination has to be done externally by an accredited laboratory.

After the dust RCMD concentration has been determined, the result is multiplied by a factor depending on the actual workplace. (As mentioned previously, the factor is intended to take into account the variability of crystalline silica in RCMD.) Currently only two factors are applied: 1.0 (for example, mining low-volatility coal) or 0.7 (for example, mining medium-volatility coal).

Optical, tyndalometric (light-scattering) measurements have been used regularly to identify episodes of high concentrations for informing decisions concerning engineering dust controls. An empirical formula is applied to those measurements to develop an average exposure concentration with a safety margin for an entire shift. That approach may be used only for the lower RCMD concentration classes.

Frequency of the measurements is directly related to the results of earlier measurements. For example, in the highest dust-burden class (greater than 6 mg/m^3), sampling has to be repeated within 7 days. On the other hand, in the lowest class (less than 2 mg/m^3), measurements have to be repeated every 6 months.

All data are stored and processed by the mining company. The inspectors may see the data at any time. The personal dust exposure data of an individual employee may be reviewed by that employee at any time. The workers' union has the right to see the data at any time. In addition, union representatives are present at nearly all stages of mining company decision making, up to and possibly including the senior management level.

Medical Surveillance

The nature and frequency of medical surveillance is regulated in the Health Protection Mining Ordinance (BMJV, 2017). Mine operators may employ people only for whom no medical concern has been raised about working in the intended workplaces (BMJV, 2017). The miner is medically examined before employment begins and at regular intervals during employment. The frequency of examinations depends upon the individual worker's situation. The most common frequency is every 2 years. The physician issues a written report to the worker and the employer, without details on the individual diagnosis. The operator must offer the worker a less dangerous occupation, if concern was raised. The miner's employment is precarious only if the operator proves that it does not have a suitable alternate work assignment. In cases of serious medical impairment, the social security system (BG RCI) would pay a pension. In addition, the miners have the right to be examined after they have left the mining operation (either as pensioners or in a different job). The mining company is required to pay for all examinations.

Germany requires accident insurance (BG RCI, 2017) to provide for compensation, prevention, and rehabilitation of occupational diseases. BG RCI will compensate every case of coal miners' pneumoconiosis (depending on the degree according to the latest ILO classification scheme).

Although the system of regular mandatory medical surveillance for coal miners will not be changed for German underground mining of bituminous and anthracite coal (scheduled to end in 2018), in all other workplaces the requirement has been abolished. Miners who are not underground coal miners will still have the right to see a doctor but may individually decide not to be examined. If they agree to be examined, any positive results do not need to be forwarded to their employer. The worker can continue to work under conditions where high dust exposures might occur.

India

In 2015, India was ranked third in the world in coal production at about 644 million short tons (EIA, 2017). In the past four decades, the coal production growth in India has largely been in the surface mining sector, and underground mining accounts for about 10 percent of the current coal production (Jha, 2011; Mishra et al., 2013). Mechanized longwall mining accounts for less than 10 percent of the underground production. Room-and-pillar mining, using either a mechanized or semimechanized system, employs a comparatively larger workforce relative to the longwall mining method, which accounts for the low productivity of the Indian mines (Mishra et al., 2013).

Exposure Limits

The Indian Directorate General of Mine Safety (DGMS) established an RCMD exposure limit of 2 mg/m^3 for an 8-hour time-weighted average, when the silica concentration in the dust is less than 5 percent. When the silica concentration is 5 percent or higher, the exposure limit is calculated as 10 divided by the percent silica content in the RCMD (Gazette of India: Extraordinary, 2017). In 2010, DGMS advised that the crystalline silica concentration in underground mines in India be kept at less than 0.1 mg/m^3 (DGMS, 2010).

Monitoring Technology and Sampling Protocols

The Indian government requires coal mine dust sampling at least every month, using a monitoring device approved by DGMS. Examples of approved devices include the Mine Research Establishment, 113A Gravimetric Dust Sampler, and personal samplers (AFC 123), Cassella, London (Mukherjee at al., 2005). Sampling requirements are provided in Box 3-1. In addition, mine managers are required to prepare and implement a monitoring and sampling scheme that specifies the following:

- Location, frequency, timing, duration, and pattern of sampling;
- Instruments and accessories to be used for sampling;
- Laboratory at which the RCMD content of samples and quartz content are to be determined;
- Format in which the results of measurements of dust concentration and other particulars are to be recorded;
- Organization for dust monitoring and for the examination and maintenance of dust prevention and suppression measures and dust respirators; and
- Manner of making all persons concerned with the implementation of the dust control measures fully conversant with the nature of work to be performed by each in that behalf (Gazette of India: Extraordinary, 2017, see pp. 238-239).

BOX 3-1 Indian Sampling Requirements

143. Precaution against dust.–

(3) The owner, agent or manager of every mine shall, within three months of the coming into force of these regulations and once at least in every month thereafter or whenever the Regional Inspector so requires by an order in writing, cause the air at every work place where airborne dust is generated, to be sampled and the concentration of respirable dust therein determined: Provided that, such measurements shall also be made immediately upon the commissioning of any plant, equipment or machinery or upon the introduction of any new work practice or upon any alteration therein that is likely to bring about any substantial change in the level of airborne respirable dust.

(4) The samples drawn under sub-regulation (3) shall as far as practicable, be representative of the levels of dust exposure of work-persons and for this purpose, the sampler shall be positioned on the return side of the point of dust generation and within one meter of the normal working position of but not behind the operator or other worker whose exposure is deemed to be maximum in his working group.

(5) Based on the results of static or personal sampling, the representative dust exposure profiles for different categories of workers shall be estimated by portal to portal monitoring of selected workers whose exposure is deemed to be representative of their working groups.

SOURCE: Gazette of India: Extraordinary, 2017, p. 236.

Medical Surveillance

DGMS recommended in 2010 that medical examinations of coal miners be conducted annually and that the results be correlated with RCMD exposure profiles of the mine or the process within the mine. Among other additional recommendations, DGMD indicated that, if a person is diagnosed with pneumoconiosis or silicosis: "the details regarding the [miner's] work profile, degree of disability, medical history and expenses, compensation and the status of health and rehabilitation measures taken by the company, etc. should be sent to this Directorate immediately" (DGMS, 2010, p. 5).

People's Republic of China

China is currently the world's largest coal producer. In 2015, the country's coal production was nearly 4.4 billion short tons (EIA, 2017). The vast Chinese coal industry comprises a wide diversity of mine sizes, mining methods, technology, and number of employees per mine. Nearly 90 percent of the Chinese coal production is from underground mines. Chu et al. (2016) reported that the average mine depth in 2010 was about 2,300 ft (700 m). The Chinese coal mining industry is undergoing rapid changes, including a dramatic reduction in the number of mines, an increase in mine sizes, and an increased application of mechanized longwall mining and associated safety practices (Peng, 2010).

Exposure Limits

Chinese regulations for airborne dust control in mines cover RCMD and total dust, and the exposure limits are related to the amount of silica content in the dust. The Safety Regulations in Coal Mines requires an exposure limit between 2 and 20 mg/m^3 for total coal mine dust, and between 1 and 6 mg/m^3 for RCMD, depending on the silica content, which can range from 5 to 50 percent (Yinlin et al., 2016).

Monitoring Technology and Sampling Protocols

National standard methods specify the use of a gravimetric personal sampler for coal mine dust and the pyrophosphate method for the determination of free silica content (Shen et al., 2013).

Medical Surveillance

In 2002, a national law went into effect for the prevention and control of occupational diseases (National People's Congress, 2016). It requires employers to make arrangements and pay for preemployment, in-service, and job-leaving occupational health exams of workers and to inform the workers of the results (see Article 35 of the law). Employers are required to keep medical files that indicate a worker's professional history, history of exposure to occupational disease hazards, the results of occupational health checkups, diagnosis and treatment of occupational diseases, and other information related to the worker's health (see Article 36 of the law). A national network of occupational disease information allows for Internet reporting to the Institute of Occupational Health and Poisoning Control. The reporting includes real-time data on the number of cases of pneumoconiosis and prevalence trends (Antao et al., 2015).

Poland

Approximately 149 million short tons of coal were produced in Poland in 2015 (EIA, 2017). Of that amount, about 53 percent was produced from underground mines. The average working depth of the mines is almost 2,000 ft, with more than 90 percent of coal produced by longwall systems. Coal is expected to play a major role in Polish energy production for many years to come (Euracoal, 2018).

Exposure limits for coal mine dust containing crystalline silica from 2 to 50 percent are 4 mg/m^3 for the total fraction and 1 mg/m^3 for RCMD. Annual measurements are required using a personal gravimetric method (Lebecki et al., 2016). Medical surveillance examinations are carried out based on agreements with individual employers at facilities that mainly offer services to the general population (Grzesik and Sokal, 2003).

Republic of South Africa

The Republic of South Africa's (RSA's) coal production of about 257 million short tons in 2015 ranked seventh in the world (EIA, 2017). The production is distributed nearly evenly between underground and surface mining methods (Eberhard, 2011; Universal Coal PLC, 2018). The bulk of the production is from 5 companies and from about 11 mines. The room-and-pillar mining method, using continuous miner machines, is the dominant extraction method. Longwall mining accounts for about 10 percent of the underground production. Frequent geologic intrusions into coal seams, such as dykes and clay veins, present mining difficulties.

Exposure Limits

RSA's Department of Minerals and Energy requires that RCMD concentrations not exceed 2 mg/m^3, measured as a time-weighted 8-hour-shift average. The respirable fraction is defined according to ISO/CEN standards (CEN, 1993; ISO, 1995). The crystalline silica content of RCMD should be less than 5 percent by mass. If the content is greater than 5 percent, an exposure limit is invoked for crystalline silica of 0.1 mg/m^3, time-weighted average (RSA DOL, 1995). The regulations require the formation of homogenous exposure groups (HEGs) for uniform sampling areas, which are defined as having common intake and return air. HEGs are further subdivided into “activity areas,” for example, conventional mining and development.

Monitoring Technology and Sampling Protocols

Personal sampling for gravimetrical analysis is performed according to NIOSH 0600 (Higgins-Dewell cyclones and polyvinyl chloride[PVC] filters; NIOSH, 1998) or the similar United Kingdom Methods for the Determination of Hazardous Substances 14-4, using Institute of Occupational Medicine (IOM) samplers, cyclones, and 25-mm PVC filters (HSE, 2014). There is recent evidence that the Higgins-Dewell cyclones applied in South Africa do not conform to respirable size-selective specifications (Belle, 2018). Sampling within an HEG is performed during an entire full shift on a random selection of either five workers or 5 percent of the workers in the group (whichever is greater). When the actual shift time deviates from 480 minutes, a time-weighting correction factor is applied to the individual measurement results (Brouwer, 2017). The HEG results are grouped into three exposure categories and assigned a minimum sampling frequency of quarterly, semiannually, or annually.

The mine operators are responsible for obtaining coal mine dust measurements, but they often delegate those activities to approved subcontractors (RSA DOL, 2012). The results have to be reported regularly to the Department of Mineral Resources, that is, the federal government. The frequency of reporting is aligned to the sampling requirements (exposure groups).

Also, the sampling results are supposed to be communicated back during monthly meetings to the individual miner who wore the sampling instruments. Later, sampling results are disseminated to the general public by the Mine Health & Safety Inspectorate.

According to Brouwer (2017), the construction of HEGs using job titles sometimes appears to be arbitrary, there seems to be no statistical evaluation of current or historical exposure data, and real-time direct-reading monitoring techniques play no role in the required sampling.

Medical Surveillance

The miners fill out routine health questionnaires every year. They also receive annual physical examinations (Brouwer, 2017). In certain cases, medical examinations can be given semiannually or quarterly, depending on the miner’s health status. In addition, there is a preemployment examination to assess a miner’s health status. Upon leaving employment, an exit medical examination is performed and copies of the results are given to the employee and the employer. Employers are required to keep these records for 40 years. If safety or health concerns are raised by employer or employee, a special examination can be conducted on an ad hoc basis. The mining companies are informed about the numbers of miners with a certain occupational problem rather than provided with names of people with those conditions (confidentiality issues).

The occupational medical practitioner (OMP, physician) informs the employer of a possible risk associated with a particular exposure and also the OMP will recommend what steps should be taken ranging from preventing or limiting further exposure to removing an employee from a dangerous environment.

A COMPARISON OF REQUIREMENTS

The occurrence of diseases caused by coal mine dust exposures has been recognized as an important occupational health problem by major coal-producing countries, and strategies for monitoring and controlling miners’ exposures to reduce disease prevalence have been implemented in those countries. In general, RCMD has been clearly defined and sampled according to well-documented methods since the early 1990s.

The countries considered by the committee tend to establish exposure limits that are focused on controlling mass concentrations of RCMD and silica in the air of underground mines. As discussed in Chapter 1, the U.S. exposure limit for RCMD was lowered to 2 mg/m^3 in 1972, and that allowable limit was reduced further whenever the respirable crystalline silica content of the RCMD was greater than 5 percent. The intended effect was to keep the silica concentration at less than 0.1 mg/m^3. In 1995, NIOSH recommended that RCMD exposures be limited to 1 mg/m^3 and silica exposures not exceed 0.05 mg/m^3. The U.S. exposure limit for RCMD was lowered to 1.5 mg/m^3 in 2016 and the limit for silica was not changed. In most cases, other countries considered by the committee have RCMD exposure limits either equal to or greater than 2 mg/m^3 and a silica exposure limit equal to or greater than 0.1 mg/m^3. Several states in Australia also have set exposure limits for the inhalable size fraction of coal mine dust particles.

CONCLUSIONS

1. The monitoring device that is commonly identified in the regulations for RCMD measurement is a gravimetric personal sampler, which contains a battery-powered pump, a cyclone for selecting the respirable fraction from the total airborne dust, and a filter assembly for collecting the selected fraction. Some countries, such as RSA and Australia, are considering the use of CPDM-type instruments for personal sampling, as is now required in the United States. Differences in one or more of the factors discussed below make it difficult to compare exposure measurements among different countries directly.
2. While almost all regulations require determination of the crystalline silica concentration in RCMD, most do not advocate a specific analytic method for determining the concentration. The U.S. regulations prescribe the use of the P-7 method (an infrared spectroscopy method) for RCMD samples collected on a filter; laboratories and contractors in other countries use infrared (IR) and x-ray diffraction methods. It is important to note that the results of these techniques are dependent on the size distribution of the RCMD sample, and calibration and other test procedures.
3. Sampling requirements mainly target an individual miner or group of miners during a shift in the mine, occupations that have a potential for high exposures, and areas of mines where miners are likely to come into contact with elevated dust concentrations. A significantly different approach has been taken in Germany, where regulations have focused on monitoring the cumulative exposure of miners, using area sampling of RCMD to characterize the personal exposure of each miner in the respective area. There is variability among countries regarding required sampling frequencies, number of samples, and the organizations responsible for conducting the monitoring.
4. Most regulations call for mandatory medical surveillance of miners just prior to employment and either mandatory or voluntary surveillance at periodic intervals after that. However, it is not apparent how medical surveillance findings are used to revise procedures for monitoring and controlling RCMD exposures.
5. Requirements for exposure monitoring and medical surveillance have developed over many years in different coal-mining countries. Some of the dissimilarities in those requirements are likely due to differences in social, legal, and administrative structures. Examples include the strong federal influence on the compensation system for occupational diseases in Germany and the decentralized administration of requirements in Australia at the state level, rather than at the national level. In addition, some countries have experienced changes within their regulatory structures over the years, which likely have resulted in changes in exposure monitoring requirements.
6. Various geologic factors, including the depth and thickness of a coal seam and the nature of rock strata surrounding the seam, influence the kind of coal mining conducted in a particular country. Those factors can contribute to differences in the amount of underground mining conducted relative to surface mining, the choice of mining methods, the

extent of mechanization, and the amount of surrounding rock strata that is removed, which in turn can influence RCMD particle characteristics (for example, composition) and the kinds of exposures experienced by miners.

7. The commonalities among multinational exposure monitoring approaches suggest potential opportunities for using compliance data for scientific investigations of linkages between miners' exposure monitoring data and medical surveillance results collected from across a broad range of underground mining conditions in different countries. That could help improve the understanding of exposure-response relationships, RCMD aspects of greatest relevance to disease risk, and approaches for monitoring and controlling exposures.
8. A comprehensive assessment is needed to determine the potential for using compliance data from major coal-producing countries for conducting epidemiologic research and improving exposure monitoring approaches. Considerations in conducting the assessment include detailed descriptions of

- Procedures and systems that mines have used to demonstrate regulatory compliance, processes for inspecting the mines, and how historical sampling and analysis methods compare with currently accepted practices.
- Extent to which data on miners' long-term cumulative exposures had been collected, and whether there are indicators of how the use of those data for exposure controls had influenced the prevalence, and possibly the severity, of coal-mine-dust-related diseases.
- Feasibility of accounting for differences in monitoring and sampling practices by applying correction factors, algorithms, or other appropriate techniques of retrospective exposure assessment (for example, see Naidoo et al., 2006, and Dahmann et al., 2008).
- Potential for the introduction of bias into epidemiologic studies of coal miners from the use of regulatory compliance data (for example, see Pearce and Douwes, 2008; Dahmann, 2016).
- Extent to which standardized approaches are used for medical diagnoses in multiple countries. For example, widespread use of the International Labour Office B reader program for categorizing radiographic abnormalities for pneumoconiosis (International Labour Office, 2011) as well as use of standards recommended by the American Thoracic Society/European Respiratory Society (Culver at al., 2017) for characterizing miners' lung function would facilitate international comparisons and strengthen efforts to prevent coal-mine-dust-related diseases.

REFERENCES

Antao, V. C., and G. A. Piinheiro. 2015. Surveillance for occupational respiratory diseases in developing countries. *Seminars in Respiratory and Critical Care Medicine*. 36(3):449-454. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4549969/#R24.

Australian Standard. 2009. Workplace atmospheres—Method for sampling and gravimetric determination of respirable dust. AS 2985-2004 [online]. Available at https://ablisui.business.gov.au/ACT/resource/COP9253.pdf (accessed February 20, 2018).

BAuA (Die Bundesanstalt für Arbeitsschutz und Arbeitsmedizin). 2017. Hazardous Substances Ordinance ("Gefahrstoff-Verordnung"). Federal Institute for Occupational Safety and Health, Germany [online]. Available at https://www.baua.de/DE/Themen/Arbeitsgestaltung-im-Betrieb/Gefahrstoffe/Arbeiten-mit-Gefahrstoffen/pdf/Hazardous-Substances-Ordinance.pdf?__blob=publicationFile&v=2 (accessed December 5, 2017).

Belle,B. 2018. Evaluation of Gravimetric Samplers and Proposal for the Use of a Harmonised Performance Based Dust Sampler for Exposure Assessment, Proceedings of the 18th Coal Operators' Conference, Mining Engineering, University of Wollongong, 305-318.

BG RCI (Berufsgenossenschaft Rohstoffe und chemische Industrie). 2017. Trade Association Raw Materials and Chemical Industry [online]. Available at https://www.bgrci.de/ (accessed December 5, 2017).

BMJV (Das Bundesministeriums der Justiz und für Verbraucherschutz). 2017. Bergverordnung zum gesundheitlichen Schutz der Beschäftigten (Gesundheitsschutz-Bergverordnung – GesBergV). Federal Ministry of Justice and Consumer Protection, Germany [online]. Available at http://www.gesetze-im-internet.de/gesbergv/GesBergV.pdf (accessed December 5, 2017).

Brouwer, D. 2017. Coal Mine Dust Exposure Monitoring and Sampling in Underground Mines in South African Mining Industry. Presentation at the Sixth Meeting on Occupational Exposure to Respirable Coal-Mine Dust, October 5-6, 2017, Washington, DC.

CEN (European Committee for Standardization). 1993. Workplaces Atmospheres - Size Fraction Definitions for Measurement of Airborne Particles. Report No. BS EN 481:1993. London: British Standards Institute.

Chu, C., R. Jain, M. Muradian, and G. Zhang. 2016. Statistical analysis of coal mining safety in China with reference to the impact of technology. *Journal of the Southern African Institute of Mining and Metallurgy* 116:73-78.

Coal Services (Coal Services Pty Limited). 2016. Protecting Against Airborne Dust Exposure in Coal Mines. [online]. Available at https://www.coalservices.com.au/wp-content/uploads/2016/12/NEW-CS-Dust-Booklet_Final-artwork.pdf (accessed May 20, 2018).

Culver, B. H., B. L. Graham, A. L. Coates, J. Wanger, C. E. Berry, P. K. Clarke, T. S. Hallstrand, J. L. Hankinson, D. A. Kaminsky, N. R. MacIntyre, M. C. McCormack, M. Rosenfeld, S. Stanojevic, and D. J. Weiner on behalf of the ATS Committee on Proficiency Standards for Pulmonary Function Laboratories. 2017. Recommendations for a standardized pulmonary function report. An official American Thoracic Society Technical statement. *American Journal of Respiratory and Critical Care Medicine* 196(11):1463-1472.

Dahmann, D. 2016. Exposure assessment: Methods. In *Indoor and Outdoor Nanoparticles: Determinants of Release and Exposure Scenarios*. M. Viana, ed. Vol. 48. Springer International. pp. 51-72.

Dahmann, D., G. D. Hartfiel, and J. Jackisch. 2001. Intercomparison and performance of stationary aerosol samplers. *Gefahrstoffe. Reinhaltung der Luft*. 61:201-206.

Dahmann, D., H. D. Bauer, and G. Stoyke. 2008. Retrospective exposure assessment for respirable and inhalable dust, crystalline silica and arsenic in the former German uranium mines of SAG/SDAG Wismut. *International Archives of Occupational and Environmental Health* 81(8):949-958.

DGMS (Directorate General of Mines Safety, Government of India). 2010. Respirable Dust Measurements and Control to Prevent Pneumoconiosis in Mines. DGME (Tech.) (S&T) Circular No. 01. January 21, 2010. Available at https://elibrarywcl.files.wordpress.com/2015/02/dgms-tech-st-circular-no-01-of-2010-respirable-dust.pdf1T (accessed February 8, 2018).

Eberhard. 2011. The Future of South African Caol: Market, Investment, and Policy Challenges. Working Paper No. 100. Program on Energy and Sustainable Development. Available at https://fsi.stanford.edu/sites/default/files/WP_100_Eberhard_Future_of_South_African_Coal.pdf (accessed May 20, 2018).

EIA (U.S. Energy Information Administration). 2017. International Energy Statistics: Primary Coal Production 2014 [online]. Available at https://www.eia.gov/beta/international/rankings/#?pid=7&cy=20141T (accessed January 3, 2018).

Euracoal. 2018. Poland. https://euracoal.eu/info/country-profiles/poland/ (accessed January 3, 2018).

Falk, H., E. Meller, G. Milojcic, L. Möhring, H. Müller, E. Rapphun, M. Schmidt, and F. J. Wodopia. 2016. Jahrbuch der europäischen Energie und Rohstoffwirtschaft, 2017. Essen, Germany: VGE.

Gazette of India: Extraordinary. 2017. Ministry of Labour and Employment Notificatio. Part II-Sec. 3(i); November 27, pp. 160-280. Available at http://www.dgms.net/Coal%20Mines%20Regulation%202017.pdf (accessed May 20, 2018).

Grzesik, J. P., and J. A. Sokal. 2003. Occupational Hygiene and Health Care in Polish Coal Mines. Institute of Occupational Medicine and Environmental Health Sosnowiec, Sosnowiec. Available at www.aiha.org/aihce03/handouts/rt236grzesik.pdf (accessed May 20, 2018).

HSE (Health and Safety Executive). 2014. General Methods for Sampling and Gravimetric Analysis of Respirable, Thoracic and Inhalable Aerosols. Methods for the Determination of Hazardous Substances MDHS 14/4 [online]. Available at http://www.hse.gov.uk/pubns/mdhs/pdfs/mdhs14-4.pdf (accessed December 29, 2017).

International Labour Office. 2011. Guidelines for the use of the ILO international classification of radiographs of pneumoconioses. Geneva, Switzerland. Available at http://www.ilo.org/safework/info/publications/WCMS_168260/lang--en/index.htm (accessed May 20, 2018).

ISO (International Organization for Standardization). 1995. Air Quality: Particle Size Fraction Definitions for Health-Related Sampling. ISO 7708:1995.

Jha, N. C. 2011. Meeting of the Indo-US Coal Working Group. March 24, 2011. New Delhi. https://coal.nic.in/sites/upload_files/coal/files/captiveblockold/INDO-US/India%27s%20coal%20industry%20&%20CIL.pdf (accessed May 20, 2018).

Lebecki, K., M. Malachowski, and T. Soltysiak. 2016. Continuous dust monitoring in headings in underground coal mines. *Journal of Sustainable Mining* 15(4):98125-98132.

Minerals Council of Australia. 2018. Australian Coal Industry. Available at http://www.minerals.org.au/resources/coal/production_and_resources (accessed May 20, 2018).

Mishra, D. P., M. Sugla, and P. Singha. 2013. Productivity improvement in underground coal mines: A case study. *Journal of Sustainable Mining* 12(3):48-53.

Morfeld, P., B. Noll, S. F. Büchte, R. Derwall, V. Schenk, H. J. Bicker, H. Lenaerts, N. Schrader, and D. Dahmann. 2009. Effect of dust exposure and nitrogen oxides on lung function parameters of German coalminers: A longitudinal study applying GEE regression 1974-1998. *International Archives of Occupational and Environmental Health* 83(4):357-371.

MSHA (Mine Safety and Health Administration). 2013. Method P-7. Infrared Determination of Quartz in Respirable Coal Mine Dust. Available at https://arlweb.msha.gov/TECHSUPP/pshtcweb/MSHA%20P7.pdf (accessed May 20, 2018).

Mukherjee, A. K., S. K. Bhattacharya, and H. N. Sayed. 2005. Assessment of respirable dust and its free silica contents in different Indian coalmines. *Industrial Health* 43(2):277-84. Available at https://www.ncbi.nlm.nih.gov/pubmed/15895842 (accessed May 20, 2018).

Naidoo, R., N. Seixas, and T. Robins. 2006. Estimation of respirable dust exposure among coal miners in South Africa. *Journal of Occupational and Environmental Hygiene* 3(6):293-300.

National People's Congress. 2001. Law of the People's Republic of China on Prevention and Control of Occupational Diseases. Available at http://www.china.org.cn/english/government/207413.htm (accessed May 20, 2018).

NIOSH (National Institute for Occupational Safety and Health). 1977. Occupational Exposure Sampling Strategy Manual. DHEW (NIOSH) Publication No. 77-173 [online]. Available at https://www.cdc.gov/niosh/docs/77-173/pdfs/77-173.pdf (accessed January 3, 2018).

NIOSH. 1998. Particulates Not Otherwise Regulated, Respirable. Method 0600 [online]. Available at https://www.cdc.gov/niosh/docs/81-123/pdfs/0600.pdf (accessed December 29, 2017).

NMA (National Mining Association). 2017. U.S. Coal Production Trends, 1980-2016 (Million Short Tons). Available at https://nma.org/wp-content/uploads/2017/06/us_coal_production_trends_2016-2.pdf (accessed December 22, 2017).

North Rhine Westphalia Ministry of Economy. 1991. Ergebnisse von Untersuchungen auf dem Gebiet der Staub- und Silikosebekämpfung im Steinkohlenbergbau, Band 18. Minister fur Wirtschaft, Mittelstand und Verkehr des Landes NordrheinWestfalen. Detmond: Hermann Boesmann GmbH.

NSW (New South Wales Government). 2006. Coal Mine Health and Safety Regulation, 2006 [online]. Available at http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0018/101745/CMHS-Regulation-2006.pdf (accessed December 29, 2017).

NSW. 2007. Official Notices. Coal Mine Health and Safety Act 2002, Coal Mine Health and Safety Regulation 2006. *New South Wales Government Gazette* 185:10480-10481, December 21 [online]. Available at https://www.resourcesandenergy.nsw.gov.au/__data/assets/0pdf_file/0009/203202/Airborne-dust-limits,-collection-and-analysis.pdf (accessed February 21, 2018).

NSW. 2011. Coal Industry Act 2001, Order No. 42, Coal Services – Monitoring Airborne Dust. *New South Wales Government Gazette* 14:568-570 [online]. Available at https://www.coalservices.com.au/wp-content/uploads/2016/11/Order42Gazette.pdf (accessed December 29, 2017).

NSW. 2014. Work Health and Safety (Mines) Regulation, 2014 under the Work Health and Safety (Mines) Act 2013 [online]. Available at https://www.legislation.nsw.gov.au/inforce/500011c6-2a99-440f-8799-8cbf39393930/2014-799.pdf (accessed December 29, 2017).

NSW. 2017. Prevention of Pneumoconiosis NSW: Information for Workers in the NSW Mining Industry [online]. Available at https://www.coalservices.com.au/wp-content/uploads/2017/03/Prevention-of-Pneumoconiosis-in-NSW-information-for-workers-February-1-1.pdf (accessed January 3, 2018).

Pearce, N., and J. Douwes. 2008. Environmental and occupational epidemiology. In *International Encyclopedia of Public Health*. New York: Academic Press, pp. 352-361.

Peng, S. S. 2010. Understanding the Chinese coal industry. *Coal Age* 115:24-29.

QLD (Queensland). 2016. Recognised standard 14. Monitoring respirable dust in coal mines.

QLD. 2017a. Coal Mining Safety and Health Regulation, 2017 [online]. Available at https://www.legislation.qld.gov.au/view/pdf/asmade/sl-2017-0165 (accessed December 29, 2017).

QLD. 2017b. Safety in Mines, Testing and Research Station (SIMTARS) [online]. Available at https://www.dnrm.qld.gov.au/simtars/home (accessed December 19, 2017).

QLD Parliament. 2017c. Black Lung White Lies. Inquiry into the Re-identification of Coal Workers' Pneumoconiosis in Queensland. Interim Report. Report No. 2, 55th Parliament Coal Workers' Pneumoconiosis Select Committee, May 2017.

RAG DSK (Die Deutsche Steinkohle AG). 2006. Plan for the Determination of Dust Exposure in Workplaces of Coalmining ("Staubmessplan") [in German] [online]. Available at http://esb.bezreg-arnsberg.nrw.de/druck/druck.php?site=../a_4/a_4_004 (accessed December 28, 2017).

Ren, T. 2017. Presentation at the Sixth Meeting on Occupational Exposure to Respirable Coal-Mine Dust, October 5-6, 2017, Washington, DC.

RSA DOL (Republic of South Africa Department of Labour). 1995. Hazardous Chemical Substances Regulations. Government Notice. R: 1179, August 25, 1995 [online]. Available at http://www.labour.gov.za/DOL/legislation/regulations/occupational-health-and-safety/regulation-ohs-hazardous-chemical-substances (accessed December 29, 2017).

RSA DOL. 2012. Requirements for Approval as an Approved Inspection Authority: Occupational Health and Hygiene [online]. Available at http://www.labour.gov.za/DOL/downloads/documents/useful-documents/occupational-health-and-safety/aiapamphlet.pdf (accessed December 29, 2017).

Shen, F., J. Yuan, Z. Sun, Z. Hua, T. Qin, S. Yao, X. Fan, W. Chen, H. Liu, and J. Chen. 2013. Risk identification and prediction of coal workers' pneumoconiosis in Kailuan colliery group in China: A historical cohort study. *PLoS ONE* 8(12):e82181. doi:10.1371/journal.pone.0082181.

Stacey, P., T. Lee, A. Thorpe, P. Roberts, G. Frost, and M. Harper. 2014. Collection efficiencies of high flow rate personal respirable samplers when measuring Arizona road dust and analysis of quartz by x-ray diffraction. *Annals of Occupational Hygiene* 58(4):512-523.

Universal Coal PLC. 2018. Coal Mining in South Africa. Available at http://www.universalcoal.com/our-projects/coal-mining-in-south-africa/ (accessed May 20, 2018).

Yearbook of the European Energy and Raw Materials Industry. 2017. Available at http://www.energie-jahrbuch.de/ (accessed May 20, 2018).

Yinlin, J., R. Ting, W. Peter, W. Zhijun, M. Zhaoyang, and W. Zhimin. 2016. A comparative study of dust control practices in Chinese and Australian longwall coal mines. *International Journal of Mining Science and Technology* 26(2):199-208.

4

Efficacy of Current Monitoring Technologies and Sampling Approaches

The committee's statement of task (see Appendix A) calls for an assessment of the efficacy of current monitoring technologies and sampling approaches for informing underground coal mine operator's decision making related to reducing respirable coal mine dust (RCMD) exposure to miners in underground coal mines.

Efficacy is often considered to be the capability of a monitoring technology and sampling approach to characterize RCMD exposure concentrations within the accuracy and precision desired, in the time and expense allotted, and with the functional ability to document the outcome. In addition to providing measurements for determining compliance with the regulatory mass-based concentration limit for RCMD (see Chapter 1), effective monitoring technologies and sampling approaches provide information on the hazardous aspects of RCMD that are of greatest relevance to disease risk in mine workers. That information allows for continual assessment of the effectiveness of regulatory requirements in reducing miners' exposures and, ultimately, optimal health protection of miners. Important aspects of hazard assessment include determination of the deposited dose of RCMD particles in miners' lungs, spatial variability of airborne RCMD concentrations within the mine, concentrations of various RCMD components, and the toxicity of those components at the measured concentrations.

As discussed in Chapter 1, the 2014 dust rule of the Mine Safety and Health Administration (MSHA) sets forth a respirable dust standard that limits miners' exposures to airborne RCMD in underground coal mines to 1.5 mg/m^3 during the full shift that the miner works (30 Code of Federal Regulations [CFR] 70.100). In addition, the rule requirements include the following:

- Increased sampling of airborne RCMD by mine operators, relative to previous sampling requirements;
- Use of new monitoring technology to obtain RCMD measurement results in near real time;
- Immediate corrective action when excessive RCMD concentrations are observed; and
- A method for determining regulatory noncompliance based on a single sample collected by MSHA.

Use of the continuous personal monitoring device (CPDM) by underground coal miners has been required since 2016 (see Chapter 1). It can continuously monitor RCMD concentrations and provide measurements of exposure concentrations in near real time to the miners wearing the device. CPDM readings provide wearers the opportunity to take steps deemed appropriate to reduce their exposures, where possible. The readings also indicate to mine operators when controls and work practices need to be assessed for corrective actions.

As regulatory requirements specify the RCMD monitoring technologies and sampling approaches to be used by operators in coal mines in the United States, this chapter considers efficacy with respect to several key potential outcomes of those requirements and several underlying assumptions, which are associated with potential information gaps (see Table 4-1). This chapter focuses on the operator's required use of the CPDM to monitor RCMD and MSHA's use of gravimetric monitoring to obtain measurements of crystalline silica content in RCMD. The committee did not assess MSHA's program for RCMD sampling inspections.[1]

TABLE 4-1 Potential Outcomes and Assumptions for Required Monitoring and Sampling Methods

Method	Potential Outcomes	Assumptions
	1. Determine compliance with the RCMD standards for designated occupations (DOs) on sampled shifts.[a]	**A1a. Data Are Representative:** Required dust exposure data are representative of underground coal miners for all periods. When and where RCMD mass and silica content are monitored is sufficient to ensure health protection of miners.
		A1b. No Change in Particle Size Distribution: The proportionality between dust exposure and the mass of material deposited in the lung is unchanged.
For miners considered to be exposed to the highest RCMD concentrations, conduct CPDM sampling during 15 shifts per quarter, when production is at least 80% of a specified average.	2. Inform workers in DOs of a need to change behavior in response to dust concentration readings while conducting tasks.	**A2. Training And Behavior Modification:** Current training and education programs are implemented in a consistent manner across the coal mine industry so that all mine workers are knowledgeable of RCMD exposures, resulting in behavior modification for dust exposure avoidance in response to information gathered from the CPDM.
	3. Provide information to mine operators for addressing airborne dust issues through process control.	**A3. Process Control:** Mining process control of dust is assured by determining compliance with dust regulations.
	4. Determine sample variability for designated areas (DAs) and DOs.	**A4. RCMD Mass And Silica Only:** RCMD mass concentration (without specifying composition) and silica content are the characteristics of coal mine dust most strongly associated with health effects.
Personal gravimetric monitoring of DOs for RCMD mass and crystalline silica content.	5. Provide information on crystalline silica exposure for DOs.	**A5. No Silica Monitor:** Continuous, real-time measurement of crystalline silica content of RCMD is not achievable.

[a]Designated occupation (DO) is the occupation on a mechanized mining unit (MMU) that has been determined by results of RCMD samples to have the highest respirable dust concentration. In addition, other occupations on an MMU that are designated for sampling are referred to as other designated occupations. Designated areas (DAs) are specific locations in the mine where samples will be collected to measure sources of airborne RCMD in the active workings (that is, any place in a coal mine where miners are normally required to work or travel) (see 30 CFR 70.2).

[1]MSHA (2016) presents the agency's procedures and guidelines for conducting RCMD sampling inspections, evaluating sampling results, establishing and removing sampling entities, establishing reduced dust standards because of silica concentrations, and monitoring operators' RCMD control and sampling programs.

DETERMINE COMPLIANCE WITH RCMD STANDARDS FOR DESIGNATED OCCUPATIONS ON SAMPLED SHIFTS

Miners' exposures vary widely because of differences in the mining environment and the kinds of activities the miners perform. Individual (personal) monitoring is important to ensure that the unique features of RCMD exposures are characterized, recorded, and controlled. Personal monitoring involves the use of a sampling device placed on an individual miner to obtain breathing-zone measurements of airborne dust concentrations to which that miner is exposed (Tebbens, 1973; Mark et al., 1986).

While progress was made in the monitoring of airborne RCMD concentrations after passage of the 1969 Coal Mine Health and Safety Act, there remained an issue with getting the measurement results of collected samples in a timely manner to inform exposure control decisions. In addition, it was recognized that real-time monitoring devices for measurements of airborne RCMD concentrations in the underground mine environment, were needed for more effective control. By 1980, there were several instruments that offered instantaneous measurement of mass concentrations of airborne dust that had been tested for use in mines (Thompson et al., 1981). The principles employed in those instruments included light scattering (for example, Tyndallometer, real-time aerosol monitor [RAM-1], and Safety in Mines Scattered Light Instrument [SIMSLIN II]); beta-ray attenuation (for example, Radioactive Decay Module [RDM 101, RDM 201, and RDM 301]) and the change in resonant frequency of a piezoelectric crystal. While those instruments were used in research studies, they were not used widely for routine mine monitoring because of problems of size, intrinsic safety considerations, calibration with mass collection devices and expense. Improvements in technology for continuously monitoring RCMD concentrations, however, has followed along several lines since the early 1990s. The research included an accelerated program to evaluate state-of-the-art technologies with the potential for developing a fixed-site RCMD monitor (Peluso, 1996). In addition, the Bureau of Mines and later NIOSH investigated technologies for personal monitoring and fixed-site area monitoring throughout that same time period.

Representativeness of Exposure Monitoring Data

The 2014 dust rule requires that a continuous personal dust monitor (CPDM) be worn by a miner in a designated occupation and other designated occupations to provide measurements for determining regulatory compliance.[2] The mine operator and the miner who wears the monitor receive an indication of RCMD exposure concentrations in near-real-time and they can determine whether the airborne RCMD exposure limit of 1.5 mg/m^3 is exceeded during the production shift that the miner works. That is a marked improvement over the previous monitoring method. It affords miners working in designated occupations with the potential opportunity during the course of the shift to reduce their exposures by moving to a less dusty location, while carrying out their job duties. It also indicates to the mine operator when an operating procedure might need to be modified to diminish the amount of dust being generated.

The point of the required monitoring is to determine regulatory compliance. As such, sampling is used presumably to identify worst-case exposures for addressing and eliminating those exposures. That approach is in contrast to traditional epidemiologic approaches where random samples may be collected to find an average exposure (Seixas et al., 1997; Rando et al., 2001). Using the results from sampling for regulatory compliance, the outcome of an epidemiologic

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[2]The designated occupation is the occupation on a mechanized mining unit (MMU) that has been determined by results of RCMD samples to have the highest RCMD concentration. Other designated occupations on an MMU that are designated for sampling are referred to as ODOs. The 2014 dust rule indicates that sampling the DOs and ODOs is the most effective method for protecting all miners from excess exposure to respirable coal mine dust (see 79 Fed. Reg. 24,903, May 1, 2014).

assessment informs a determination of the efficacy of the regulations, but that outcome may not necessarily be applicable to any other regulatory framework (Attfield and Morring 1992; Attfield and Seixas 1995).

However, there is a potential contradiction in Assumption A1a (Data Are Representative) listed in Table 4-1 that underlies the above-mentioned approach. From past experience, the miner in the designated occupation is believed to represent the highest exposure of all the occupations likely to be near where the work of that miner is undertaken. The designated occupation is at a location often considered to represent the highest dust output of the mining process. If the designated occupation is found not to be overexposed, it is assumed the mining process is unlikely to overexpose workers in other job categories in the vicinity. In addition, a determination of compliance with the regulatory requirements would represent a safe and healthy work environment for all miners in a designated area.[3]

According to that reasoning, it would be unnecessary, in theory, to require workers in other occupations to be monitored because the approach is considered to be a check on process control of airborne RCMD concentrations. Although the personal exposure of the designated occupation (and other designated occupation) are quantified, exposures of other miners are not. Therefore, in the event that the designated occupation was overexposed, there would be no way of knowing from the samples taken by the operator by how much any of the other occupations were overexposed. Although assuming the other occupations are overexposed in such a case would seem to be protective, there would be no indication of the extent to which the assumed overexposures were reduced. As a result, there is a lack of data indicating whether an unmonitored individual miner had experienced a high, cumulative exposure by the end of his or her career, regardless of how many days the airborne RCMD concentrations in the mine sections where the miner worked were determined to be greater or less than the regulatory exposure limit.

There also is difficulty in trying to adapt a historical approach to the more modern technology of direct-reading instruments by relying on the assumption that the designated occupation remains the highest exposed individual. When the miner in the designated occupation wears a CPDM unit and is able to determine when conditions are unfavorable in terms of RCMD exposure, that miner might be able to alter his or her location to mitigate the exposure while carrying out the designated occupation's job duties. In that case, the miner may no longer have the highest exposure in the mine section. There is a need to evaluate the exposures of mine workers not wearing CPDMs to ensure that the approach of detecting and mitigating high-exposure concentrations for designated occupations reliably results in mitigating high exposures of all workers.

Respirable Dust Particle Size and Lung Deposition

The measurement of RCMD exposure from coal mining operations is usually accomplished using a size-selective sampling device for particles in a size range meeting a respirable sampling convention. There are several ways to describe the meaning of the term respirable dust. One definition is "that fraction penetrating through the conductive airways of the head and tracheobronchial tree and available for deposition in the nonciliated alveolar zone airspaces where the dusts can cause lung fibrosis" (Lippmann, 1970). That area is typically considered to be the region where the exchange of carbon dioxide and oxygen occurs between the lung and blood, and it includes the alveoli and respiratory bronchioles.

The regulatory definition of RCMD, however, is not based on human anatomy. The Code of Federal Regulations (30 CFR 70.2) defines respirable dust as "Dust collected with a sampling

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[3]Designated areas are specific locations (in outby areas) in the mine where samples will be collected to measure sources of airborne RCMD in the active workings (that is, any place in a coal mine where miners are normally required to work or travel). Designated areas are identified by the operator in the mine ventilation plan (30 CFR 75.371). On February 1, 2016, designated areas associated with an MMU were redesignated as other designated occupations.

device approved by the Secretary [of Labor] and the Secretary of HHS in accordance with [30 CFR] part 74 (Coal Mine Dust Sampling Devices) of this title." That definition of respirable dust is more practical from a legal standpoint than the first definition. To implement a regulation based on the first definition, it would be necessary to determine the particle mass in the collected sample that is established as the respirable size fraction. In addition, it would be necessary to assess the characteristics of each miner's lung that affect the actual particle penetration rate into the noncilliated alveolar region, or at least determine an average penetration rate for humans under relevant conditions. While from a toxicological standpoint that approach might be preferable, the interpersonal variability of human anatomy and physiology would present a formidable barrier to the application of that definition in a legal context.

However, particle measurements obtained according to the regulatory definition of respirable dust are used for health-related studies. However, in using data obtained according to the regulatory definition of RCMD, caution is needed in bridging the gap between practical applications and theoretical considerations. Consider, for example, an epidemiologic investigation to develop a dose-response relationship, which seeks to estimate the response of a biological receptor to an amount of material delivered to the target biological system, organ, or cell where it can produce an outcome. Airborne dust concentrations are often used as a prime source of information for epidemiologic studies, as the measurements represent the potential amount of material that the individuals of interest can be exposed to over a specified period. Because regulatory compliance programs require record keeping for airborne dust measurements, the records also incorporate how, when, and where the measurements were made. The airborne RCMD concentrations are used as a surrogate for dose.

Measurements of airborne RCMD, as defined in 30 CFR 70.2, are not necessarily a dose measurement (that is, the mass of material deposited into the gas-exchange region of the lung). Also, the definition of respirable dust in Lippmann (1970) given above does not include the deposition of dust (that is, penetration of dust through the conductive airways of the head and tracheobronchial tree). The size range of particles that deposit in the noncilliated alveolar zone airspaces of the lung is only a fraction of the size range of dust that penetrates to that region. The difference is apparent in Figure 4-1. That figure uses an instrument-based expression for respirable dust (Souëf, 1999). The expression is actually a compromise of the previous definitions of particle sizes collected by two different instruments: the gravimetric dust sampler with a horizontal elutriator developed by the Mining Research Establishment (30 CFR 70.2) (sometimes called the MRE sampler) and the 10 μm Dorr-Oliver nylon cyclone. Those two instruments were the basis of measurements used in the epidemiologic derivation of the exposure limits in 30 CFR 70 (Tomb et al., 1973). The difference in size distribution between dust particles deposited in the lung and the respirable dust particles measured by an instrument is a function of the size distribution of the dust being inhaled (Figure 4-2). Dose, therefore, varies with the size distribution of the dust in the mine environment (Fisher and McCawley, 1997). Generally, the aerodynamic diameter of particles in coal mines are in the range 1 to 30 μm with a mean particle size (by mass) of approximately 10 μm (Figure 4-2). If RCMD particles were predominantly larger than 3 μm in aerometric diameter, exposure monitoring devices conforming to the respirable sampling criterion should reasonably represent the dose concentration given to the noncilliated alveolar region of the lung (Figure 4-2). However, if particles smaller than 3 μm make up a substantial portion of the mass collected by the respirable sampler, this mass might overestimate lung deposition. Therefore, it is important to understand whether new mining practices widely adopted since the early 1990s, when particle size distribution data were initially measured, have resulted in a change in the size distribution of mining-related air aerosols.

In 1959 at a conference in Johannesburg, South Africa, information on particle lung deposition as a function of particle size was first presented and shown to be similar to the size-selective sampling characteristics of the two proposed samplers noted above (Orenstein, 1960). Early attempts to define the size of coal mine dust particles that deposit in the lungs were based on miner autopsy data (Davies, 1952). Microscopic examination of the dust found in pathological specimens of former coal miners' lungs revealed that the diameter of the dust particles that penetrated into the air-exchange region of the lung was generally less than 5 μm.

A limitation is that the available data only covered a range of deposition values for particle sizes between approximately 10 and 3 μm. Responses to concerns expressed about the limitations of the size range that had been studied were based on the assumption that coal mines contained very little mass of dust in particle sizes less than 2 or 3 μm. It, therefore, would make little difference knowing the mass of particles in the smaller size range that was deposited in the lung or knowing how closely the size range of particles collected by the proposed samplers matched the lung deposition curve for particle sizes less than 3 μm. For coal mine dust, that assumption was correct. When aerodynamic size separation was made possible using impactors several decades later, it was found that the aerodynamic mass size distribution of coal mine dust was almost entirely greater than 3 μm (Burkhart et al., 1987; Potts et al., 1990). As indicated in Figure 4-1, the percent difference between the RCMD penetration curve and the lung deposition curve changes much less for the larger particle sizes, that is, the range of particle sizes likely to occur in underground coal mines. Thus, instruments conforming to the RCMD criterion used in underground coal mines should produce measurements of particles in a size range that are reasonably constant in proportion to the size range of deposited particles or dose of coal mine dust. This should allow, as would seem to be the case for data from epidemiologic studies of underground coal miners, a reasonable association between the measurement of RCMD and the prediction of coal workers' pneumoconiosis.

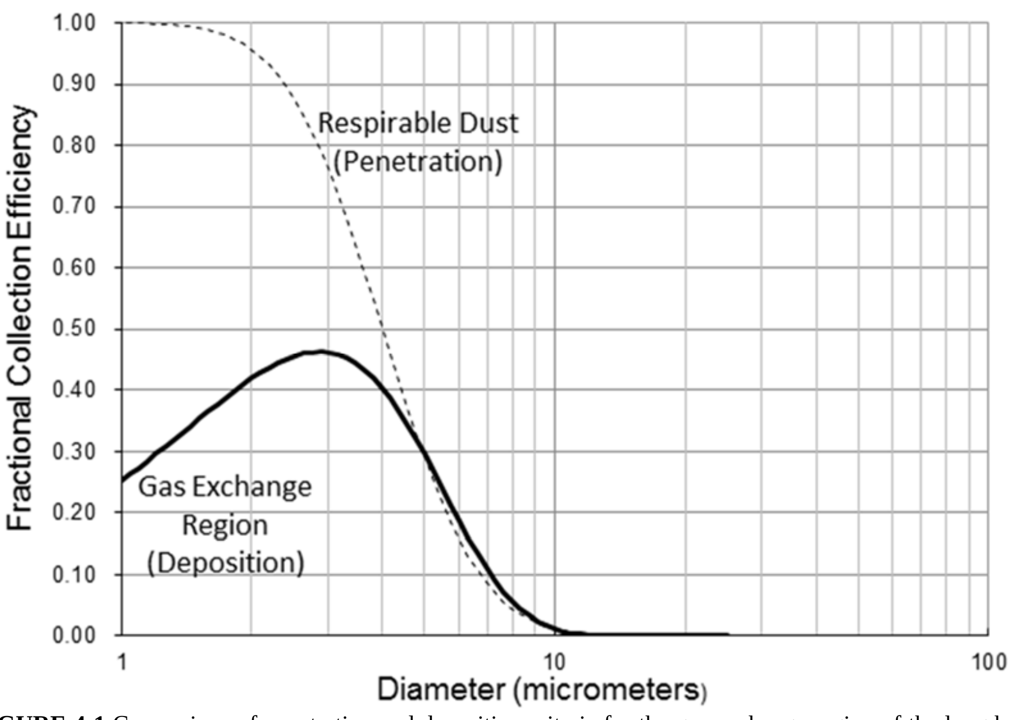

FIGURE 4-1 Comparison of penetration and deposition criteria for the gas-exchange region of the lung by particle mass. Note that deposition and penetration overlap beginning approximately at an aerodynamic particle diameter equal to 7 μm. See Hewett (1991) and Esmen et al. (2002). That is also around the predominant particle diameter of various size distributions for coal mine dust shown in Figure 4-2. SOURCE: Adapted from Hewett, 1991.

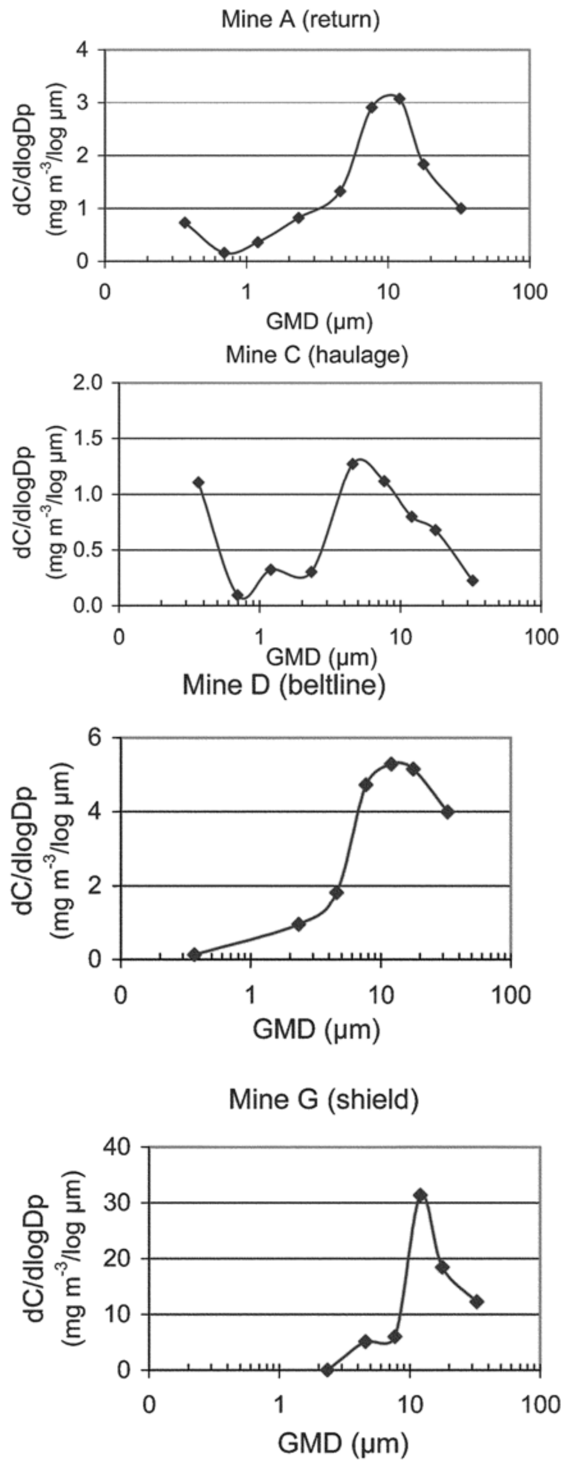

FIGURE 4-2 Aerodynamic particle size distributions from mass measurements for selected underground coal mines showing the predominance of particle sizes 10 µm and greater. On the y axes, C is total carbon and Dp is particle diameter. On the x axes, GMD is geometric mean diameter. SOURCE: Birch and Noll, 2004. Reprinted with permission; 2004, *Journal of Environmental Monitoring*.

Therefore, the RCMD criterion is potentially different, in theory, from the amount of dust that might be expected to be deposited in the human lung (that is, for values greater than 0 percent in Figure 4-3). When comparing toxicological exposure studies (where the dose can be directly measured) to epidemiologic data (where the dose is estimated from monitoring results using a sampler that may be sensitive to particle size distribution changes occurring due to process changes), this potential difference in respirable dust measurements needs to be taken into account. Also, should the mean particle size of the dust be less than 2 or 3 µm, potential differences in previous dose-response relationships need to be considered and perhaps quantified. A decrease in the mean particle size might happen, if, for example, new processes are introduced that create dust of a smaller median size particle. It may also occur if the operation being sampled is not used in an underground coal mine that is similar to those of the study cohorts from which the majority of the health effects data were derived. Therefore, it would be prudent with any measurement of RCMD to have some indication of the size distribution from which that sample is drawn.

In the range of dust sizes between 1 and 10 µm, the difference between estimates of exposure based on samples of airborne dust and the actual lung dose could vary between 0 and 250 percent. For example, a change in a process that originally generated a dust particle size distribution with a 100 percent overestimate of the dose could result in a new dust size distribution, which could have only a 50 percent overestimate of the dose. If the changed process still generated the same measured RCMD concentration, it would result in twice the dose because twice as much of the dust would be expected to deposit in the lung. Although a change in a size distribution will not necessarily change the total mass being generated, there could be a change in the

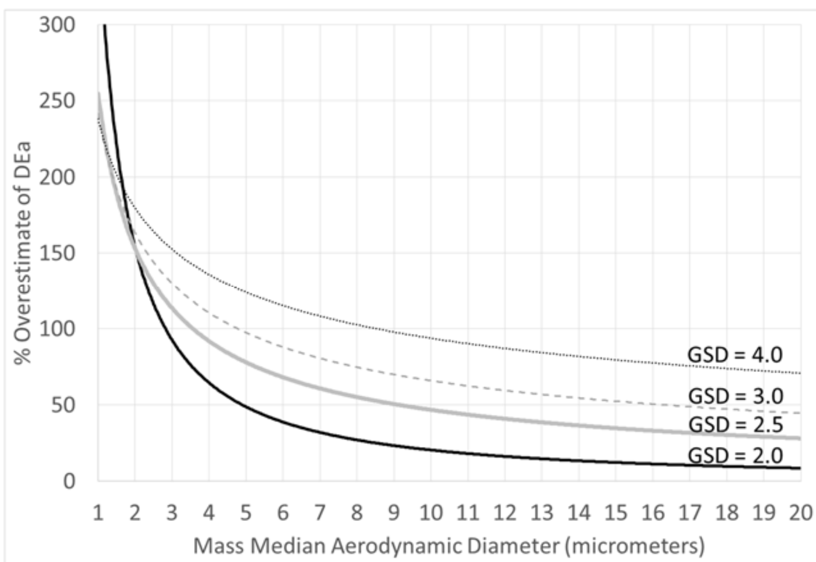

FIGURE 4-3 The amount by which the RCMD criterion differs from the mass of material predicted to be deposited in the gas exchange region (DEa) of the lungs (ICRP, 1994), where coal workers' pneumoconiosis occurs, is a function of the aerodynamic equivalent mass size distribution of the dust. The size distribution is determined from two parameter values of the size distribution equation: mass median aerodynamic diameter and the geometric standard deviation (GSD). For simplification, curves for only a few GSD values are shown to illustrate the general trend. A dose overestimate of 50 percent would result from the relationship shown in this figure and an analysis of the data in Figure 4-2, which indicates a mass median diameter of approximately 10 µm and a GSD of approximately 2.5 for typical size distributions in the mines sampled. If that size distribution narrowed slightly to a GSD of 2.0, the dose overestimation would be reduced from 50 percent to approximately 20 percent, meaning the dose to the lung would increase. See Hewett (1991) and Esmen et al. (2002). SOURCE: Adapted from Hewett, 1991.

percent of the total mass being deposited which would presumably cause an increased risk of pneumoconiosis. Such a change in lung deposition could likely go unnoticed because current monitoring methods crudely approximate the amount of dust deposited in the gas-exchange region of the lungs for particles outside the range of the dust size distribution established previously for underground coal mines. Such a case points to potential uncertainties regarding Assumption A1b in Table 4-1 (No Change in Particle Size Distribution).

INFORM WORKERS IN DESIGNATED OCCUPATIONS OF A NEED TO CHANGE BEHAVIOR IN RESPONSE TO DUST CONCENTRATION READINGS WHILE CONDUCTING TASKS

The training requirements of the 2014 dust rule for miners who are to wear the CPDM are contained in 30 CFR 70.201(h) and 90.201(h). The mine operator must provide the training before miners will be wearing the device and every 12 months thereafter. The training must convey the importance of monitoring dust concentrations and properly wearing the CPDM. It also must provide an explanation of the basic features and capabilities of the CPDM, the various types of information displayed by the device, how to access that information, and how to start and stop a short-term sample run during compliance sampling. Paragraph (h) of the above-mentioned CFR section requires that the operator record the dates of the training, the names of the miners trained, and the subjects covered. The records must be kept for 24 months and made available on request to miners' representatives and the U.S. Departments of Labor and Health and Human Services (that is, MSHA and the National Institute for Occupational Safety and Health [NIOSH]).

Sections 70.202 and 90.202 specify that only certified persons may conduct the RCMD sampling program (30 CFR 71.202). Those charged with maintaining and calibrating the equipment are certified separately (Sections 70.203 and 90.203). To become certified, an applicant must complete a training course and pass an MSHA examination initially and every 3 years thereafter. MSHA can revoke either certification for failure to carry out the required procedures. The regulations do not specify the length of the courses, but they are typically 8 hours and are mostly offered by the MSHA district offices.

There is no requirement that the training be carried out by a certified trainer, although 30 CFR 48 can be read to require that it be done by an MSHA-approved trainer, or an experienced supervisor or miner. It is typically done by the person certified to conduct the sampling.

Miners are not tested or required to demonstrate proficiency in the use of the CPDM. The device is relatively easy to use, putting aside the serious issues of its weight and bulk. Based on presentations to the committee at its April 2017 meeting (see Appendix C), the degree to which the first required element—the importance of the dust monitoring—is included in the training, appears to vary widely. Also, no amount of training can resolve this paradox inherent in the current use of the CPDM. As discussed previously, a miner wearing the monitor receives near-real-time exposure data and can sometimes move to a less dusty position. That is one of the main virtues of this cumbersome device. In fact, the mine operator may require the miner to move, as it could be viewed as unethical to require a miner to stay in a high-exposure location, as indicated by the CPDM, when a safer location is available. However, when the CPDM is used for compliance monitoring, a change in a miner's location might cause that person to no longer be representative of the miners with the highest exposures.

Mine operators are demonstrating almost universal compliance with the allowable RCMD exposure limit of 1.5 mg/m^3. It is unknown whether compliance is being achieved only for those miners wearing the CPDM, or for all miners in the work area. An analysis of the time-series data contained in the CPDM might help elucidate the issue by providing information about when the highest exposures are occurring, what might have been happening during that time in the mining process, and how long it took to address the issue.

A current conceptual model for characterizing the process of learning from available CPDM measurements (Peters et al., 2008) is based on several lines of psychological research (Bandura, 1977, 2004; Janz and Becker, 1984; Kluger and DeNisi, 1996; Janz et al., 2002). The model proposed by Peters et al. (2008) is illustrated in Figure 4-4.

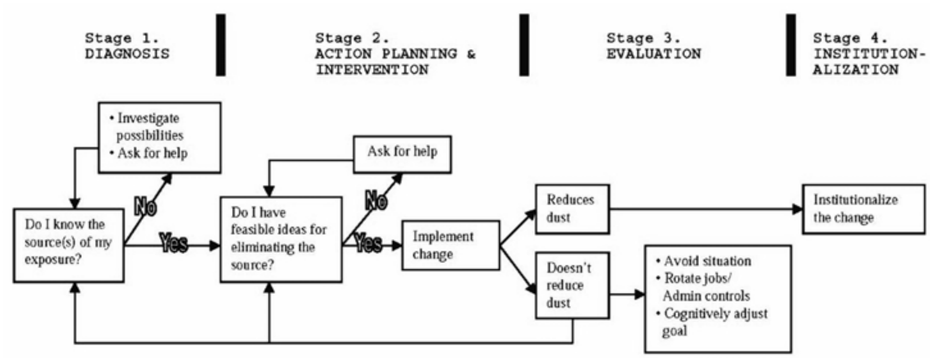

FIGURE 4-4 Conceptual model of how information from the CPDM might be used to develop institutional change. SOURCE: Peters et al., 2008.

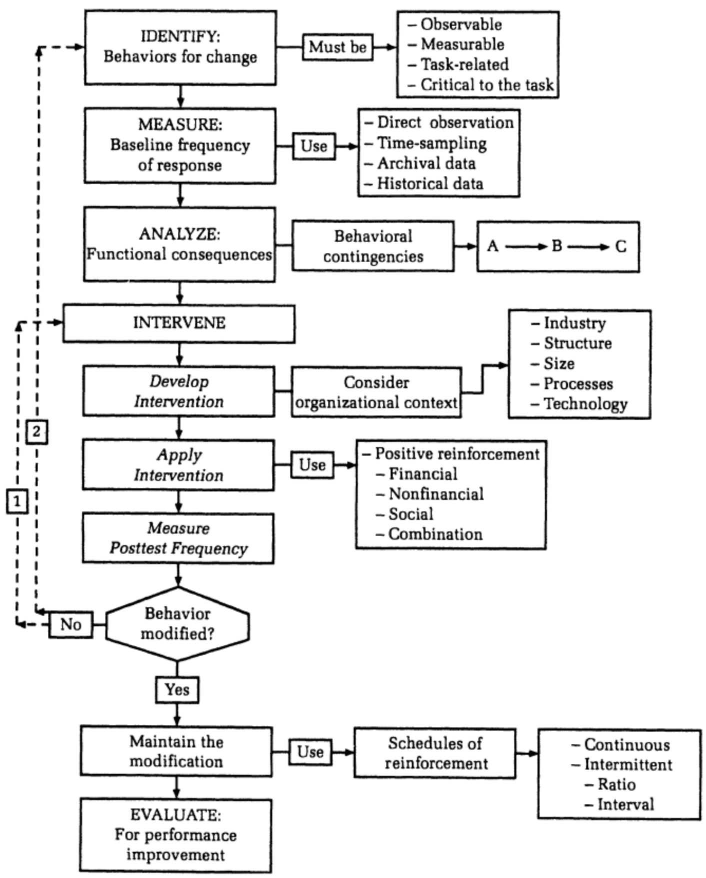

FIGURE 4-5 Process chart for effecting a behavioral change. SOURCE: Stajkovic and Luthans, 1997. Reprinted with permission; 1997, *Academy of Management Journal*.

The conceptual model proposes attitudinal changes leading to action, which eventually is incorporated and solidified into institutional change. The rewards are primarily social rewards realized through the social contract between employer and employee. Although the eventual financial health benefits of the change cannot be ignored, the time frame in which those benefits take place is long and the gains are a matter of an absence of effect. Nonetheless, social rewards can be used for behavior modification in combination with nonfinancial interventions, such as performance feedback (Figure 4-5). Those effects on performance can significantly improve even beyond the effect produced by financial rewards, although significance is not demonstrated in a statistical sense. When a number of studies are considered by conducting a meta-analysis (Figure 4-6), the overall effect over time appears to be an average improvement in performance of 17 percent (Stajkovic and Luthans, 1997).

It is clear that current changes in regulatory compliance, presumably by modification of behavior based on feedback from the CPDM, are substantially greater than those reported in other types of literature on behavioral change. According to Ajzen (1985):

> Beliefs represent the information people have about a behavior: its likely consequences, the normative expectations of others, and the likely impediments to its performance. Behavioral interventions provide information that change some of these beliefs, or that lead to the formation of new belief. As a result, intentions and behavior will often revert to what they were prior to the intervention. Only when the new beliefs accurately reflect reality can we expect that the effect of the intervention will persist over time.

Therefore, in addition to exploring the impetus for change of work habit in the coal mines it will also be necessary to determine if the change persists and for how long. Pointing to uncertainties regarding Assumption A2 in Table 4-1 (Training and Behavior Modification), those considerations introduce the question as to whether behavioral changes related to information from the CPDM are akin to changes associated with the use of personal protective equipment (PPE). In both cases, there is the ability to control exposure through personal action that can have a major influence on the resulting exposures. A study by Olson et al. (2009) concerning the use of PPE suggests that, again, social modeling is a potentially powerful determinant of prevention behaviors within workgroups. A review of 20 industrywide applications of behavior-based safety programs demonstrated that mandated behavior-based safety programs had greater involvement, trust in management, trust in coworkers, and satisfaction with the training than did programs where participation was entirely voluntary (DePasquale and Geller, 1999). Another evaluation of up to 5 years of injury data from 73 companies, drawn from a target population of 229 companies who implemented behavior-based safety programs, showed pre- to post-initiative incident levels across groups had a significant decrease in incidents following the behavior-based safety implementation (Krause et al., 1999). Employers need to be aware of the potential impacts of social modeling on prevention behaviors, such as PPE use, especially among newly hired workers. The Olson et al. study also confirms the general value of implementing and maintaining behavioral safety processes, which are designed to measure the prevalence of safe behaviors and conditions regularly and provide workers with feedback and reinforcement for meeting prevention goals. No such behavioral reinforcement program seems to be in effect in the coal mines for use with adoption of the CPDM. This draws into question whether the effectiveness seen to date will be permanent. On the other hand, behavior-based safety programs have been criticized as being a way of shifting the blame to the worker (Frederick and Lessin, 2000). The reported successes mentioned above and the lack of current programs to accompany the introduction and use of the CPDM suggests research and development that could be done longitudinally to determine if current successes are maintained as the program matures.

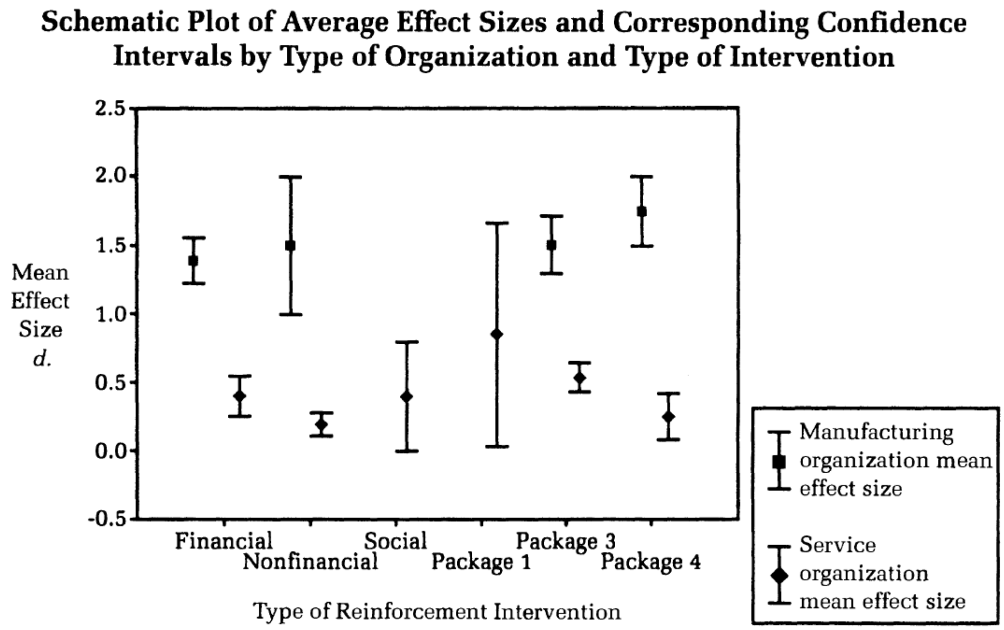

FIGURE 4-6 Magnitude of the effect of behavioral changes by type of reinforcement. The effect size "d" is the number of standard deviations between two means. The term is generally used in meta-analyses of multiple studies to compare the results of those studies in some uniform manner. The larger the value of "d" the greater the probability that the two means are different and there has been an effect of the treatment not due to chance alone. SOURCE: Stajkovic and Luthans, 1997. Reprinted with permission; 1997, *Academy of Management Journal*.

PROVIDE INFORMATION TO MINE OPERATORS FOR ADDRESSING DUST ISSUES THROUGH PROCESS CONTROL

As mentioned previously, personal monitoring involves the use of a device mounted on a miner that indicates the airborne dust concentrations to which a miner is exposed as he or she moves from place to place. In this case, personal exposure would therefore be that amount of RCMD measured in the breathing zone of the miner.

Because spatial and temporal variability of airborne RCMD particle characteristics are large, area monitoring has been widely employed to assess sources of dust and the effectiveness of dust control technology (Burkhart et al., 1987; Kissel and Sacks, 2002). Area monitoring involves the use of static (fixed-site) sampling devices to obtain measurements of the general concentration of dust in a workplace.

A review of the top ic suggests that the use of personal exposure monitoring, by itself, is an unreliable method for assessing process control actions to mitigate airborne RCMD concentrations (Kissel and Sacks, 2002). The ratios of measurements from personal exposure monitors to those made by area monitors were found to range up to more than 30-fold. While the authors note that this does not meet the NIOSH +/- 25 percent criterion, it pales in comparison to that of 3 to 10 for occupational settings (Rodes et al., 1991). Personal monitoring adds variability to the RCMD sampling results beyond the variability contributed by the intrinsic fluctuations in the process itself. Personal monitoring results reflect not only the RCMD concentrations contributed by the process, but also the variability of an individual miner's actions, in general, and the particular actions, which generate dust apart from the process.

Those effects represent uncertainties in the basis for Assumption A3 (Process Control) listed in Table 4-1, as the performance of the coal mine operator's dust control plan is assessed by the sampling results of the personal monitoring required in the 2014 dust rule. Process control is likely to be better informed through a plan that includes the regular use of area monitors that are fixed in an appropriate location. For example, Corn (1985) offers a scheme that includes options for determining personal exposure and area concentrations. Use of both types of monitoring would be appropriate to maintain a healthful working environment.

For underground coal mines, there is no established proportionality between the exposure measurements of the designated occupation and other miners who work in the same mine section and do not wear a CPDM. Exposure measurements of the designated occupation provide information to investigate whether process control measures should be adjusted, as discussed previously. However, that information is likely inadequate for that purpose because the approach does not quantify exposure for anyone but the miner in that occupation. That concern is consistent with cautions expressed by Esmen and Hall (2000) regarding reliance on limited exposure data that can result in seriously misleading conclusions.

A combination of sampling methods might be warranted for various sampling purposes, such as those listed in Table 4-2. Corn (1985) points out that a zoning method can be used to group employees based on similarities in either job or environment in which they work. Employees in each zone are selected randomly for personal sampling. The zoning approach is more efficient than a random sampling approach for determining high-exposure areas, since the zoning approach focuses on identified problem areas. Area sampling is effective for evaluating sources of contamination and identifying when the need for process changes should be investigated.

DETERMINE SAMPLE VARIABILITY FOR DESIGNATED AREAS AND DESIGNATED OCCUPATIONS

CPDM Considerations

NIOSH has described the CPDM in detail (see Box 4-1). CPDM components are illustrated in Figure 4-7. Public comments on the CPDM have noted that cost, size, and weight are important drawbacks regarding the routine use of the instrument. Mine operators commented that the high unit cost limits the number of instruments likely to be purchased and used in the mine for purposes other than regulatory compliance, especially engineering studies of dust control. Miners have commented that the large size of the CPDM makes it difficult to wear the monitor in such a way that makes the readout display easily observable by the wearer for instantaneous feedback to inform behavior modification. Miners also commented that the weight of the CPDM makes the device burdensome to wear, considering the amount and weight of other equipment that must be worn by the miners.

TABLE 4-2 Selected Purposes of Air Sampling

Evaluation of Individual Employee Exposure	Evaluation of Sources of Contaminant in a Work Area	Evaluation of Trends of Workplace Air Contamination
Conformance with a regulated standard (in the United States an 8-hour permissible exposure level or short-term ceiling limit)	Process change effects	In terms of employee exposure
Long-term average exposure (for epidemiologic studies)	Process efficiency monitoring	
Long-term average exposure of group members with similar exposures	Daily controls for process control or employee management (administrative controls)	In terms of selected "air parcels" at fixed locations

SOURCE: Corn, 1985.

BOX 4-1 NIOSH Description of the Continuous Personal Dust Monitor

The PDM [personal dust monitor or CPDM] is a person-wearable respirable dust sampler and gravimetric analysis instrument designed for use in underground coal mines. Components of the device include a sampling inlet line, HD [Higgins-Dewell] cyclone, air heater, pump, dust sensor, battery for the sampler, electronic control and memory boards, a display screen, and Windows®-based computer interface software.

The sampling inlet line is designed to be clipped to the miner's lapel or other clothing within their personal breathing zone (Figure 4-8). The air to be sampled is drawn through a round inlet and carried through a 0.48-cm (0.19-inch) internal-diameter conductive silicone rubber tube to the PDM instrument. At the instrument, dust is separated using an HD cyclone into coarse and respirable fractions. When operated at a flow rate of 2.2 L/min [liters/minute], this cyclone (Bartley et al., 1994) best approximates the classification of dust according to the ISO definition of respirable dust (ISO, 1995). The coarse dust remains in the cyclone grit pot while the respirable fraction continues into the analytical portion of the unit.

The sample is heated to a constant temperature, selected during instrument programming, in an elliptical cross-section metal tube designed for low particulate loss. The sampled dust is then deposited on a 14-mm-diam[eter] Teflon-coated glass fiber filter. The filter is mounted on an inertial mass detector (TEOM) [tapered-element oscillating microbalance] (Patashnick and Rupprecht, 1991). The TEOM has been miniaturized and stabilized using proprietary technology to enable its use as a person-wearable device (Patashnick et al., 2002).

Custom software is used to program the PDM through any personal computer. The mass on the TEOM filter is analyzed by the internal electronics, and several concentrations based on flow rate and times are calculated. These data are displayed on the top of the instrument. Concentration data and other operational parameters (flow rate, filter pressure, tilt status, shock status, temperature, and TEOM frequency data) are simultaneously recorded to internal memory.

A lithium-ion battery pack powers the sampler. A combination charging and down loading cradle is used to charge the battery. In addition, the cradle provides contacts that connect the sampler to a computer's RS [Recommended Standard]-232 data port.

The instrument may be operated in shift or engineering modes. The shift mode is programmed through the personal computer software interface. In this mode, a technician programs the instrument to start at a specific time and run for the expected duration of the shift. Also during programming, various sample identification codes may be entered into the instrument in a form typical of the currently used dust sampling data card. Once programmed, the only way to alter the instrument is to use the original computer interface. At the end of the programmed shift time, the unit retains the final exposure data in the screen display until the memory from the sampler is downloaded by a personal computer. Depending on the number and frequency of recording data, several shifts of data can be retained in the instrument's internal 2-megabyte memory recording. A typical shift file size varies from 40 to 250 kilobytes. Shift data are retained in the instrument until memory capacity is reached,; then the oldest data are overwritten. If a new program is not loaded into the PDM after a download, the instrument may be operated in the engineering mode. This mode allows manual startup and control of the instrument through a series of button presses on the top of the battery pack without need of a personal computer.

SOURCE: Volkwein et al., 2004, pp. 3, 4.

Figure 4-9 Continuous personal dust monitor (PDM3700) with cover panel removed. White foam spacer is in place of the battery required for the caplight on the earlier model shown in Figure 4-7 (Thermo Fisher Scientific, 2016).

The precision of readings obtained in the past from approved regulatory compliance sampling equipment appears to have been sufficient to provide reliable mass-based measurements of airborne RCMD, as illustrated in Figure 4-10. The CPDM measurements, which are provided in near real time, were found to correlate closely with measurements obtained from using a coal mine dust personal sampler unit (CMDPSU) (Figure 4-11).

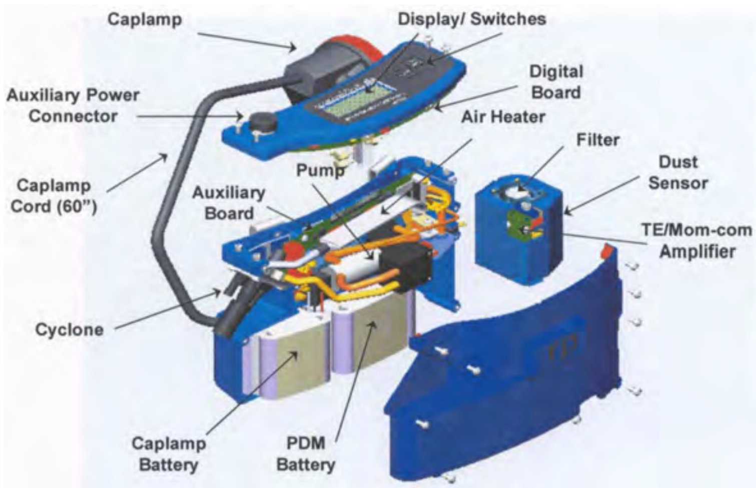

FIGURE 4-7 Internal view of components of CPDM earlier model with caplamp and caplamp battery. SOURCE: Volkwein et al., 2004.

FIGURE 4-8 CPDM (PDM3700) with sampling inlet line designed to be clipped to the miner's lapel or other clothing within the miner's personal breathing zone. SOURCE: Thermo Fisher Scientific, 2016. Reprinted with permission; 2016, Thermo Fisher Scientific.

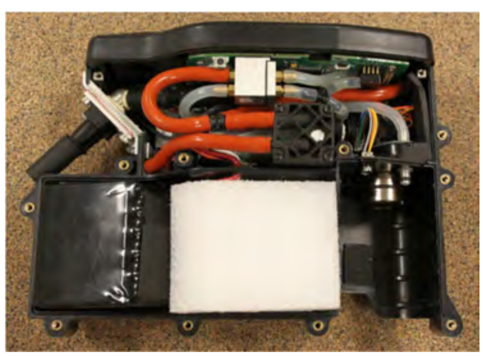

FIGURE 4-9 Continuous personal dust monitor (PDM3700) with cover panel removed. White foam spacer is in place of the battery required for the caplight on the earlier model shown in Figure 4-7. SOURCE: Thermo Fisher Scientific 2016. Reprinted with permission; 2016, Thermo Fisher Scientific.

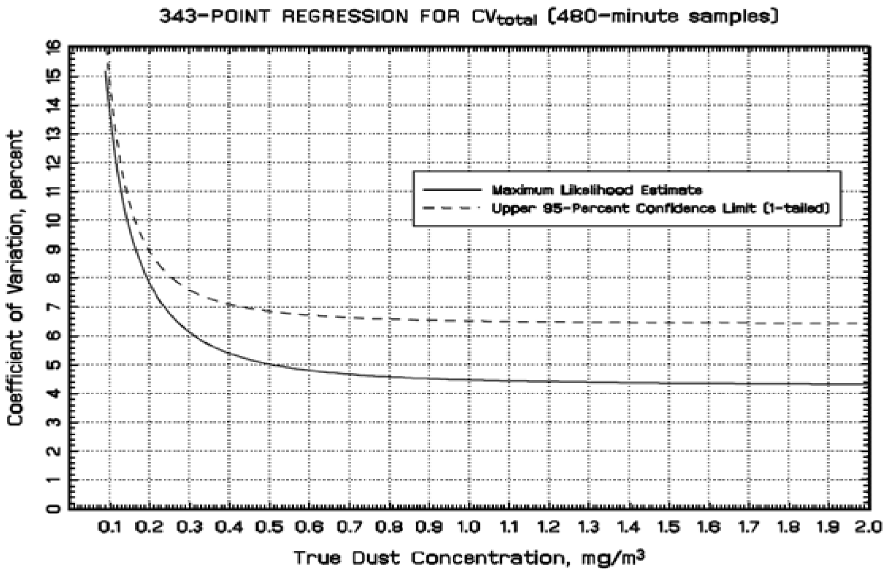

FIGURE 4-10 Expected measurement imprecision (estimated coefficient of variation in dust concentration measurements) as a function of time-weighted average dust concentration sampled for 480 minutes. Measurements were made using gravimetric techniques and samplers incorporating flow control technology. SOURCE: Kogut et al., 1997. Reprinted with permission; 1997, *Journal of Occupational and Environmental Hygiene*.

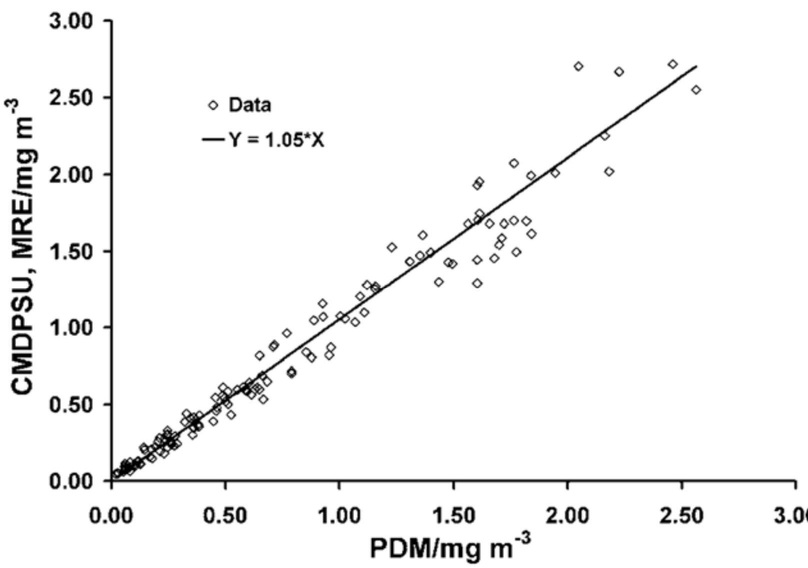

FIGURE 4-11 Comparison of measurement data form a coal mine dust personal sampler unit (CMDPSU) and a precommercial personal dust monitor (PDM, later referred to as the CPDM) with bias corrections. CMDPSU data incorporate a 1.38 multiplier historically used to estimate the British Medical Research Council and Mining Research Establishment (MRE) equivalency to the mass of particles meeting a definition of respirable coal mine dust. The slope of the regression line indicates that the PDM is within 5% of the CMDPSU. This meets the NIOSH criterion of +/-25% for a valid method. SOURCE: Page et al., 2008. Reprinted with permission; 2008, Journal of Environmental Monitoring.

CPDM Sampling and Exposure Variability

In general, the following are considered to be the three main purposes for collecting RCMD samples:

- *Demonstration of compliance*. Sampling is conducted to determine whether an exposure limit is exceeded during a single shift (Leidel et al., 1977). It is not intended to assess associations between exposure and disease. Workplace exposures are affected by many sources of variability and they can vary spatially and temporally. The intent in using the CPDM is to identify high-exposure periods. If corrections made in response to those readings do not also reduce exposures of the other miners in the same area, the samples collected by the CPDM might underestimate their RCMD exposure.
- *Assurance of process control effectiveness*. Sampling is carried out in support of worker health surveillance for identification and mitigation of potentially hazardous exposures. Plotting and viewing the time-series sampling data on various control charts that show how a process changes over time can help identify causes of departure from normal conditions (usually seen as extreme individual values or series of values). Control effectiveness can be regained by correcting or removing the cause of the departure (Alwan and Roberts, 1988). Area monitoring is a useful means of evaluating dust control equipment and has been used extensively for the evaluation of techniques (Chugh et al., 2006; Goodman et al., 2006).
- *Epidemiologic studie*s. Sampling data are used in future studies to reconstruct miners' exposures to contaminants of interest and compare those exposures with disease risk. Epidemiologic studies can serve as a tool for assessing the adequacy and overall effectiveness of health and safety regulations. However, because of the regulatory nature of the samples being collected in coal mines, the results may not be comparable to studies done under other regulatory regimens. In addition, most available RCMD data were obtained from sampling efforts that targeted worst-case exposures and those data are not reflective of exposures to the general mining workforce. That has limited the extent of understanding relationships between RCMD exposures and risks for adverse health outcomes.

It is important to note that area sampling does not correlate with personal samples. In a study of area monitoring data and personal exposure data along longwall faces, Sun et al. (1997) found no direct relationship between the dust concentration of the shearer operator and the concentration at the tailgate of the face. Kissell and Sacks (2010) calculated the mean ratios of area sampling to personal sampling from five published studies of coal mines in the United States. The highest mean ratio was 30.7 and the lowest was 3.07. Therefore, the current personal sampling routines, by themselves, might not be sufficient to evaluate the processes that are the source of dust in the mines. Area monitoring is a well-established and acceptable method for that evaluation of the dust sources and the engineering controls used to diminish them.

Each of the three kinds of sampling mentioned above has particular needs regarding method, location, frequency, and statistical and chemical analyses of the collected samples. As the CPDM is used primarily for regulatory compliance sampling (and to some extent for engineering studies), a broader range of sampling approaches is needed to assess relationships between exposure and disease. Assumption A4 listed in Table 4-1 (Total RCMD and Silica Only) runs counter to that need.

PROVIDE INFORMATION ON CRYSTALLINE SILICA EXPOSURE FOR DESIGNATED OCCUPATIONS

As indicated in Chapter 1, increased silica exposure appears to explain at least some of the observed cases of rapidly progressive pneumoconiosis in coal miners. The 2014 dust rule requires that the average airborne concentration of respirable quartz (the most common form of crystalline silica) not exceed 0.1 mg/m^3 (100 µg/m^3). When the airborne RCMD concentration in the active workings of a coal mine contains more than 5 percent quartz, a reduced allowable RCMD concentration is computed by dividing 10 by the quartz concentration, expressed as a percentage (30 CFR 70.101).

The CPDM is unable to measure quartz in RCMD samples. As discussed in Chapter 2, MSHA collects RCMD samples using a personal gravimetric sampler (CMDPSU) to monitor respirable quartz. Filters containing dust samples are sent to a laboratory for analysis, using infrared spectroscopy (MSHA, 2013). That entire process can take several days or more to provide the quartz results to the mine operator, starting from when the dust samples had been collected.

In addition to the time lag in getting results, the required analytical techniques might not account for the fraction of occluded (coated) quartz particles in a dust sample. Surface coating might alter the biological availability of the surface area of quartz particles and thus alter their potential for toxic effects. Occluded respirable quartz particles were found less frequently in samples of anthracite dusts compared to all bituminous dust samples (Harrison et al., 1997).

Currently, no device is capable of monitoring respirable quartz or crystalline silica in real time, as indicated by Assumption A5 in Table 4-1 (No Silica Monitor). Assuming that a continuous monitor to provide real-time measurements of crystalline silica is not feasible tends to be inconsistent with the importance of obtaining silica exposure information in a timely manner. Chapter 5 discusses ongoing efforts to develop methods for obtaining silica analytic results more rapidly, including work on a device to provide end-of-shift silica concentrations at the mine site (Cauda et al., 2016). Both x-ray fluorescence (XRF) and Fourier transform infrared spectroscopy (FTIR) have been suggested as post-shift methods of analysis. Apart from the technical challenges inherent in the methods themselves (Reig et al., 2002; Nayak and Singh, 2007) there is the issue of how to use the information in the most efficient manner. The CPDM's intended use is to allow visualization of the potential threat of overexposure while there is time to take action. Not determining the crystalline silica content of the dust in real time would seem to invalidate that tactic. However, an argument could be made for tracking the silica content of the dust on a daily basis with the thought of predicting what that content might be for the next shift (Miller et al., 2012; Tuchman et al., 2008). The success of that approach, however, relies on the intrinsic variability of the silica content of the coal and rock materials (Colinet and Listak, 2012).

CONCLUSIONS

1. Effective monitoring technologies and sampling approaches would provide information on not only on the total RCMD mass concentrations for meeting regulatory requirements, but also the hazardous characteristics of RCMD that are of greatest relevance to disease risk in miners.
2. Continuous personal dust monitors (CPDMs) are being used to comply with the monitoring and sampling requirements of the 2014 dust rule. The ability to measure exposures in near real time by using CPDMs is an important technologic advancement compared to monitoring methods used previously. If a measurement collected during a full shift exceeds allowable limits, operators must take corrective actions immediately. In addition, miners wearing CPDMs receive information about their personal exposures and sometimes can modify their activities or locations within a mine in response to elevated readings.
3. Changes in mining technologies during the past several decades might have led to changes in typical particle-size distributions of RCMD. If so, there might have been a change in the relationship between CPDM measurements of RCMD mass concentrations and the health effects associated with particle type, size, concentration, and deposition in the lung.

4. Training in the use of CPDMs and education concerning important factors that affect exposure-response relationships can enhance workers' ability to take precautions that reduce RCMD exposures. It is important to ensure that training and education programs are implemented in a consistent manner across the coal mining industry. Therefore, in addition to exploring the impetus for change of work habit in the coal mines it will also be necessary to determine if the change persists and for how long.
5. CPDMs worn by individual miners in designated occupations are used to determine whether mine operators maintain RCMD concentrations at or less than the allowable exposure concentration. However, only a small number of miners wear a CPDM on any given shift, and it is possible that those coal miners using the CPDMs are not representative of the dust exposure to other miners who are not using the CPDMs. When miners wearing CPDMs react to high monitor readings to reduce their personal dust exposure (for example, by altering their locations while carrying out their job duties), the required RCMD measurements might no longer be representative of the miners with the highest exposures. Whether demonstrations of compliance with allowable RCMD exposure concentration is being achieved only for those miners wearing the CPDM, or for all personnel in the work area, is unknown.
6. Area monitoring, which involves the use of measurement devices at fixed locations in underground mines, is critical for understanding environmental and operational factors that influence the concentration and particle characteristics of RCMD.
7. The health hazards posed by crystalline silica exposure warrant greater focus on developing improved sampling and monitoring techniques.

REFERENCES

Ajzen, I. 1985. From intentions to actions: A theory of planned behavior. In *Action Control: From Cognition to Behavior*, J. Kuhl and J. Beckman, eds. Heidelberg: Springer, pp. 11-39.

Alwan, L. C., and H. V. Roberts. 1988. Time-series modeling for statistical process control. *Journal of Business & Economic Statistics* 6(1):87-95.

Attfield, M. D. and K. Morring. 1992. An investigation into the relationship between coal workers' pneumoconiosis and dust exposure in US coal miners. American Industrial Hygiene Association Journal 53(8):486-492.

Attfield, M. D. and N. S. Seixas. 1995. Prevalence of pneumoconiosis and its relationship to dust exposure in a cohort of US Bituminous coal miners and ex-miners. American journal of industrial medicine 27(1):137-151.

Bandura, A. 1977. Self-efficacy: Toward a unifying theory of behavioral change. *Psychological Review* 84(2): 191-215.

Bandura, A. 2004. Health promotion by social cognitive means. *Health Education & Behavior* 31(2):143-164.

Bartley, D. L., C. Chen, R. Song, and T. J. Fishbach. 1994. Respirable aerosol sampler performance testing. *American Industrial Hygiene Association Journal* 55(11):1036-1046.

Birch, E., and J. D. Noll. 2004. Submicrometer elemental carbon as a selective measure of diesel particulate matter in coal mines. *Journal of Environmental Monitoring* 6(10):799-806.

Burkhart, J. E., M. A. McCawley, and R. W. Wheeler. 1987. Particle size distributions in underground coal mines. *American Industrial Hygiene Association Journal* 48(2):122-126.

Cauda, E., A. Miller, and P. Drake. 2016. Promoting early exposure monitoring for respirable crystalline silica: Taking the laboratory to the mine site. *Journal of Occupational and Environmental Hygiene* 13(3):D39-D45.

Chugh, Y. P., A. Patwardhan, H. Gurley, A. Moharana, R. Carty. 2006. A field demonstration of an innovative spray system on continuous miners for dust control. In *Proceedings of the 11th US/North American Mine Ventilation Symposium*. Boca Raton, FL: CRC Press. pp. 233-240.

Colinet, J. F. and J. M. Listak. 2012. Silica and respirable content in rock dust samples. *Coal age* 117(12): 48-52.

Corn, M. 1985. Strategies of air sampling. *Scandinavian Journal of Work, Environment and Health* 11(3 Spec. No.):173-180.

Davies, C. N. 1952. Dust sampling and lung disease. Arhiv za higijenu rada i toksikologiju 3(1):54-58.

DePasquale, J. P., E. S. Geller. 1999. Critical success factors for behavior-based safety: A study of twenty industry-wide applications. Journal of Safety Research 30(4):237-249.

Esmen, N. A., and T. A. Hall. 2000. Theoretical investigation of the interrelationship between stationary and personal sampling in exposure estimation. *Applied Occupational and Environmental Hygiene* 15(1):114-119.

Esmen, N. A., D. L. Johnson, and G. M. Agron. 2002. The Variability of Delivered Dose of Aerosols with the Same RespirableConcentration by Different Size Distributions. Annals of Occupational Hygiene 46(4):401-407.

Fisher, D., and M. McCawley. 1997. Lack of correlation between PM10 measurements and upper respiratory tract dose. *Annals of Occupational Hygiene* 41(Suppl 1):14-18.

Frederick, J. and N. Lessin. 2000. Blame the worker: The rise of behavioral-based safety programs. Multinational Monitor 21(11):10-17.

Goodman, G. V. R., T. W. Beck, D. E. Pollock, J. F. Colinet, and J. A. Organiscak. 2006. Emerging technologies control respirable dust exposures for continuous mining and roof bolting personnel. In Proceedings of the 11th US/North American Mine Ventilation Symposium. Boca Raton, FL. pp. 211-216.

Harrison, J. C., P. S. Brower, M. D. Attfield, C. B. Doak, M. J. Keane, R. L. Grayson, and W. E. Wallace. 1997. Surface composition of respirable silica particles in a set of U.S. anthracite and bituminous coal mine dusts. *Journal of Aerosol Science* 28(4):689-696.

Hewett, P. 1991. Limitations in the Use of Particle Size-Selective Sampling Criteria in Occupational Epidemiology. Applied Occupational and Environmental Hygiene 6(4):290-300.

ICRP (International Commission on Radiological Protection). 1994. Human respiratory tract model for radiological protection. ICRP Publication No. 66. *Annals of the ICRP* 24(1-3):1-482.

ISO (International Standards Organization). 1995. Air Quality: Particle Size Fraction Definitions for Health-Related Sampling. Standard 7708. Geneva, Switzerland: ISO.

Janz, N. K., and M. H. Becker. 1984. The health belief model: A decade later. *Health Education Quarterly* 11(1):1-47.

Janz, N. K., V. L. Champion, and V. J. Strecher. 2002. The health belief model. In *Health Behavior and Health Education: Theory, Research and Practice*, 3rd ed., K. Glanz, B. R. Rimer, and F.M. Lewis, eds. San Francisco: Jossey-Bass, pp. 45-66.

Kissell, F. N. and H. K. Sacks. 2002. Inaccuracy of area sampling for measuring the dust exposure of mining machine operators in coal mines, *Mining Engineering*, Vol. 54, No. 2, pp. 17-23.

Kluger, A. N., and A. DeNisi. 1996. The effects of feedback interventions on performance: A historical review, a meta-analysis, and a preliminary feedback intervention theory. *Psychological Bulletin* 119(2):254-284.

Kogut, J., T. F. Tomb, P. S. Parobeck, A. J. Gero, and K. L. Suppers. 1997. Measurement precision with the coal mine dust personal sampler. *Applied Occupational and Environmental Hygiene* 12(12):999-1006.

Krause, T. R., K. J. Seymour, and K. C. M. Sloat. 1999. Long-term evaluation of a behavior-based method for improving safety performance: a meta-analysis of 73 interrupted time-series replications. Safety Science 32(1):1-18.

Leidel, N. A., K. A. Busch, and J. R. Lynch. 1977. Occupational Exposure Sampling Strategy Manual. NIOSH 77-173. National Institute for Occupational Safety and Health, Cincinnati, OH [online]. Available at https://www.cdc.gov/niosh/docs/77-173/pdfs/77-173.pdf (accessed March 16, 2018).

Lippmann, M. 1970. "Respirable" dust sampling. *American Industrial Hygiene Association Journal* 31(2):138-159.

Mark, D., J. H. Vincent, D. C. Stevens, and M. Marshall. 1986. Investigation of the entry characteristics of dust samplers of a type used in the British nuclear industry. *Atmospheric Environment* 20(12):2389-2396.

Miller, A. L., P. L. Drake, N. C. Murphy, J. D. Noll, and J. C. Volkwein. 2012. Evaluating portable infrared spectrometers for measuring the silica content of coal dust. Journal of Environmental Monitoring 14(1):48-55.

MSHA (Mine Safety and Health Administration). 2013. Infrared Determination of Quartz in Respirable Coal Mine Dust [online]. Available at https://arlweb.msha.gov/TECHSUPP/pshtcweb/MSHA%20P7.pdf (accessed March 23, 2018).

MSHA. 2016. Coal Mine Health Inspection Procedures. MSHA Handbook Series. Handbook Number: PH89-V-1 (27). June, 2016.

Nayak, P. S. and B. K. Singh. 2007. Instrumental characterization of clay by XRF, XRD and FTIR. Bulletin of Materials Science 30(3):235-238.

Olson, R., A. Grosshuesch, S. Schmidt, M. Gray, and B. Wipfli. 2009. Observational learning and workplace safety: The effects of viewing the collective behavior of multiple social models on the use of personal protective equipment. *Journal of Safety Research* 40(5):383-387.

Orenstein, A. J. 1960. Proceedings of the Pneumoconiosis Conference held at the University of Witwatersrand, Johannesburg, 9th-24th February, 1959. London: J&A Churchill Ltd.

Page, S. J., J. C. Volkwein, R. P. Vinson, G. J. Joy, S. E. Mischler, D. P. Tuchman, and L. J. McWilliams. 2008. Equivalency of a personal dust monitor to the current United States coal mine respirable dust sampler. *Journal of Environmental Monitoring* 10:96-101.

Patashnick, H., and E. G. Rupprecht. 1991. Continuous PM_{10} measurements using the tapered element oscillating microbalance. *Journal of the Air & Waste Management Association* 41(8):1079-1083.

Patashnick, H., M. Meyer, and B. Rogers. 2002. Tapered element oscillating microbalance technology. In *Mine Ventilation: Proceedings of the North American/Ninth U.S. Mine Ventilation Symposium, June 8-12, 2002, Kingston, Canada*, E. De Souza, ed. Lisse, Netherlands: Balkema, pp. 625-631.

Peluso, R. G. 1996. Continuous monitoring of environmental parameters in underground coal mines. *Applied Occupational and Environmental Hygiene* 11(7):615-617.

Peters, R. H., C. Vaught, E. E. Hall, and J. C. Volkwein. 2008. Miners' Views About Personal Dust Monitors. Information Circular 9501. DHHS (NIOSH) Publication No. 2008-110. National Institute for Occupational Safety and Health, Pittsburgh, PA [online]. Available at https://www.cdc.gov/niosh/mining/UserFiles/works/pdfs/2008-110.pdf (accessed November 21, 2017).

Potts, J. D., M. A. McCawley, and R. A. Jankowski. 1990. Thoracic dust exposures on longwall and continuous mining sections. *Applied Occupational and Environmental Hygiene* 5(7):440-447.

Rando, R. J., R. Shi, J. M. Hughes, H. Weill, A. D. McDonald, and J. C. McDonald. 2001. Cohort mortality study of North American industrial sand workers. III. Estimation of past and present exposures to respirable crystalline silica. The Annals of occupational hygiene 45(3):209-216.

Reig, F. B., J. G. Adelantado, and M. M. Moreno. 2002. FTIR quantitative analysis of calcium carbonate (calcite) and silica (quartz) mixtures using the constant ratio method. Application to geological samples. Talanta 58(4):811-821.

Rodes, C., R. M. Kamens, and R. W. Wiener. 1991. The significance and characteristics of the personal activity cloud on exposure assessment measurements for indoor contaminants. *Indoor Air* 1(2):123-145.

Seixas, N. S., N. J. Heyer, E. A. E. Welp, and H. Checkoway. 1997. Quantification of historical dust exposures in the diatomaceous earth industry. The Annals of occupational hygiene 41(5):591-604.

Souëf, P. L. 1999. The meaning of lung dose. *Allergy* 54(s49):93-96.

Stajkovic, A. D., and F. Luthans. 1997. A meta-analysis of the effects of organizational behavior modification on task performance, 1975-95. *Academy of Management Journal* 40(5):1122-1149.

Sun, G., R. V. Ramani, E. W. Grygiel, and T. E. McNider. 1997. Relationship between Area Concentrations and Personal Exposures along Longwall Faces. Applied Occupational and Environmental Hygiene 12(12):991-998.

Tebbens, B. 1973. Personal dosimetry versus environmental monitoring. *Journal of Occupational and Environmental Medicine* 15(8):639-641.

Thermo Fisher Scientifc. 2016. Model PDM3700. Personal Dust Monitor Users Manual [online]. https://assets.thermofisher.com/TFS-Assets/LSG/manuals/EPM-manual-PDM3700.pdf (accessed June 16, 2018).

Thompson, E. M., H. N. Treaftis, T. F. Tomb, A. J. Beckert, and A. J. Gero. 1981. Laboratory evaluation of instantaneous reading dust monitors. *American Industrial Hygiene Association Journal* 42(3):191-197.

Tomb, T. F., H. N. Treaftis, R. L. Mundell, and P. S. Parobeck. 1973. Comparison of Respirable Dust Concentrations Measured with MRE and Modified Personal Gravimetric Sampling Equipment. Report of Investigations 7772. U.S. Department of Interior, Bureau of Mines, Washington, DC.

Tuchman, D. P., J. C. Volkwein, and R. P. Vinson. 2008. Implementing infrared determination of quartz particulates on novel filters for a prototype dust monitor. Journal of Environmental Monitoring 10(5):671-678.

Volkwein, J. C., R. P. Vinson, L. J. McWilliams, D. P. Tuchman, and S. E. Mischler. 2004. Performance of a New Personal Respirable Dust Monitor for Mine Use. Report of Investigations 9663. DHHS (NIOSH) Publication No. 2004-151 [online]. Available at https://www.cdc.gov/niosh/mining/UserFiles/works/pdfs/ri9663.pdf (accessed November 17, 2017).

5

Optimizing Monitoring and Sampling Strategies

In response to the committee's statement of task (see Appendix A), the preceding chapter of this report discussed the efficacy of current monitoring technologies and sampling approaches for respirable coal mine dust (RCMD) in U.S. mines, which are primarily driven by regulatory requirements. The statement of task also calls for the committee to address optimal monitoring and sampling strategies to aid mine operators' decision making related to lowering RCMD exposures. The alarming increase in disease prevalence and severity—following a historical downward trend after enactment of federal regulations—was a focus of the committee's considerations. Given current uncertainties about the cause of that increase, the committee noted the possibility that high rates of operator compliance with the 2014 dust rule requirements may not guarantee that RCMD exposures will be controlled adequately or that future disease rates will decline.

In the committee's view, optimal strategies would augment or enhance the outcomes expected from compliance with the current regulatory requirements. In presenting guidance on optimal monitoring and sampling strategies that go beyond regulatory compliance, this chapter begins with a discussion of an idealized program. Then, in recognition of practical constraints, it discusses key features of more-realistic strategies that exhibit elements of the idealized program. The chapter also describes specific implementation opportunities in the near term and research and development needs to support the long-term success of the strategies.

AN IDEAL MONITORING AND SAMPLING PROGRAM

One approach to developing an optimal strategy for RCMD monitoring and sampling is to begin by envisioning an ideal program: to start fresh and define the central objectives, resources, and procedures of a program with few practical constraints, such as those related to cost, availability of technology, existing regulatory requirements, or program acceptance by various stakeholders. For the purpose of this discussion, the two primary stakeholders are mine workers and mine operators. However, other stakeholders (for example, government agencies, technology developers, and researchers) can certainly play a role in a RCMD monitoring and sampling program.

Figure 5-1 illustrates a possible development and implementation process for an ideal program. The process is methodical, with a clear sequence of procedural elements and interdependence of human, technical, and information resources. Moreover, the cyclical depiction of the process recognizes that all program drivers are dynamic in nature. As knowledge, needs, and capabilities evolve, so must the program. Such cyclic processes are frequently described for a range of environmental management and other data-driven programs, where iterative feedback is key to the program efficacy (Raymond et al., 2010; Williams and Brown, 2014). That feature is often termed continual or iterative improvement, learning, or assessment.

Program Objectives

Defining objectives is fundamental to establishing a program's boundaries and components. The ultimate goal of any RCMD monitoring and sampling program is to protect worker health via mitigation of disease risk. Thus, there is an underlying assumption that surveillance of some dust metric(s) will facilitate control of exposures within a range that should minimize risk for development of disease. Indeed, the Coal Mine Health and Safety Act of 1969 and the 2014 dust rule (79 Fed. Reg. 24,814, 2014) explicitly connect the RCMD exposure limitation and desired health outcomes. Also, particular RCMD measurements are required to demonstrate that exposure limits are achieved and maintained.

In addition to occupational health protection, other program objectives might include

- Tracking temporal and spatial trends in airborne RCMD concentrations to correlate dust metrics with other metrics (such as production or operational variables, geologic or environmental conditions, and worker behaviors). The trends information may be used for historical or predictive analysis or coordinating smart systems (such as ventilation on demand);
- Evaluation of new RCMD control measures or exposure prevention strategies;
- Enhanced training and education of various stakeholders; and
- Documentation of RCMD metrics to assess accountability (for example, regulatory compliance or other obligations).

It is important to note that, although an ideal RCMD monitoring and sampling program may include demonstration of regulatory compliance as an objective, the goal of worker health protection is the primary impetus.

Exposure Metrics and Tools

In an ideal program, careful consideration is given to selection and prioritization of RCMD metrics that are to be monitored. In the United States and elsewhere, RCMD mass concentration and quartz mass fraction have become the two primary metrics for monitoring. Those are the focus of U.S. regulatory exposure limits and related compliance monitoring and enforcement efforts. The legal impetus for tracking and reducing exposures by using those two metrics has resulted in significant decreases in the incidence of occupational lung disease (Seixas et al., 1992; NIOSH, 2008; Suarthana et al., 2011; Vallyathan et al., 2011). However, recent and unexpected observations of many new and severe cases of coal mine dust lung disease suggest the importance of other characteristics of RCMD particles, which had not been monitored widely in the past. In essence, those recent observations have raised a question about whether the important aspects of exposure are being monitored.

FIGURE 5-1 Process for developing and implementing an ideal RCMD monitoring and sampling program.

As indicated in previous chapters of this report, RCMD can contain a range of constituents (Walton et al., 1977; NIOSH, 1995; IARC, 1997), particle sizes, and shapes (NIOSH, 1995; Seixas et al., 1995; IARC, 1997); other characteristics, such as those associated with coal rank,[1] can also vary (Walton et al., 1977; NIOSH, 1995; IARC, 1997). However, detailed data on such RCMD particle characteristics are limited, and research on associations of specific occupational exposures with disease outcomes is nearly nonexistent. Nonetheless, coupling available RCMD information with what is known in general about coal mine dust lung disease allows for some inferences about RCMD metrics of potential interest:

- Mass fractions of silicate minerals, diesel particulate matter (DPM), and total or specific metals (IARC, 1997; Schatzel, 2009; Laney et al., 2010, Cauda et al., 2015; Cohen et al., 2016; Barrett et al., 2017);
- Distributions of particle size for the RCMD mass and the fibrogenic potential of specific constituents (for example, quartz, silicates, and metal-bearing minerals) (Huggins et al., 1986; Seixas et al., 1995; IARC, 1997; Sapko et al., 2007; Johann-Essex et al., 2017); and
- Distribution of particle surface features and ambient air pollution that have implications for health effects (for example, reactive oxygen species and free radicals) (Wallace et al., 1994, 2002; Castranova et al., 1995; Harrison et al., 1997; Vallyathan et al., 1998; Li et al., 2003; Araujo et al., 2008).

Appropriate sampling and analytical tools are needed for each metric selected for inclusion in a monitoring program. The objective is to collect samples for analysis that are representative of the airborne RCMD to which miners are or may be exposed. Sampling is done on either a personal basis (device is worn by a miner) or an area basis (device is at a fixed location in the mine), as discussed later. Because the tools and methods used to analyze the collected dust samples usually cannot exclude particles outside of the respirable size fraction, the sampling method itself is designed to do so. For that reason, RCMD sampling, like other size-specific particle sampling, is conducted generally with a particle-size selector. The cyclones currently used in RCMD sampling trains (that is, sampling equipment connected in sequence) were chosen originally so that the size distributions of airborne respirable particles sampled in coal mines approximately match the size distribution of particles able to penetrate into the distal airway and gas exchange regions of the lung (such that the cyclone reliably samples the respirable particle-size range, as discussed in Chapter 4). However, it is unclear whether there have been changes in the particle-size distributions of airborne RCMD over time that might have significantly affected that match. If so, RCMD samples may be less representative of particles penetrating into the lung than they were decades ago, when the particular cyclones used for sampling were first adopted.

From an analytical standpoint, all of the RCMD metrics listed above could be included in a monitoring and sampling program, as methods already exist, or could be adapted, for making the desired measurements. Electron microscopy (for example, scanning electron microscopy with energy dispersive x-ray spectroscopy [SEM-EDX]) can be used to estimate particle size, shape, and mineralogy number distributions in filter samples (Sellaro et al., 2015; Johann-Essex et al., 2017). Other methods can be used for determining mass concentrations of specific particle constituents, including x-ray diffraction (Page, 2006; Schatzel, 2009; MSHA, 2013a; Harper et al., 2014); infrared spectroscopy (IR) (Ainsworth, 2013; MSHA, 2013b); Fourier-transform infrared (FTIR) spectroscopy (NIOSH, 2003a; Schatzel, 2009; MSHA, 2013b; Cauda et al., 2016; Miller et al., 2017); x-ray fluorescence (XRF) (Schatzel, 2009; Wang et al., 2015); mass spectrometry (for example, inductively coupled plasma mass spectrometry or high-performance liquid chromatography mass spectrometry (Freedman and Sharkey, 1972; Lintelmann et al., 2006; Buiarelli et al., 2017); thermogravimetric analysis (TGA) (Scaggs et al., 2015; Phillips, 2017; Phillips et al.,

[1]Coal rank is a classification of coal based on fixed carbon, volatile matter, and heating value. It indicates the progressive geological alteration (coalification) from lignite to anthracite.

2017); and thermal-optical analysis (Chow et al., 2001, 2007; Birch, 2003). Analytical methods are also available for determining free radicals (Delal et al., 1989) and other surface characteristics (Harrison et al., 1997) in RCMD.

Most analytical methods for filter samples require considerable processing time because of sample preparation requirements, the analysis itself, or the need for specialized laboratory instrumentation, which is not widely available, or field deployable. The need for processing time effectively means there may be lag times of days to weeks between sample collection and availability of analytic results. However, in some cases, methods and tools may be available to allow relatively quick analysis. For instance, NIOSH has developed a quartz monitor prototype, which is undergoing field testing (Cauda et al., 2015, 2016; Lee et al., 2017). The monitor is intended to provide results from a sample that is collected during a miner's entire shift, which means the quartz mass fraction in a dust sample could be measured immediately after a filter sample is collected. Clearly, the sooner analytic results are available, the more effectively they can be correlated to the conditions under which sampling occurred.

Beyond postcollection filter analysis, the potential exists for continuous measurement of some RCMD metrics (that is, a sample is analyzed during the time it is being collected, as opposed to analysis after collection has occurred). The continuous personal dust monitor (CPDM) provides that capability for measuring the RCMD mass concentration; other instruments might offer capabilities for additional metrics. For example, near-real-time particle counters and size analyzers are being used in other environmental monitoring applications (Hutchins, 2016; Scherließ, 2016), and instruments have been developed or demonstrated for continuous DPM monitoring in metal/nonmetal mines (Barrett et al., 2017; Volkwein et al., 2016, 2017).

Monitoring Protocol

After selecting the RCMD metrics and appropriate tools and methods for sampling and analysis, a monitoring protocol can be designed and implemented. For that, the frequency and location of sample collection are important. In addition, appropriate training and education of miners is a critical component of implementation.

Frequency and Location of Sample Collection

In a truly ideal program, all RCMD metrics could be monitored continuously to allow exposures to be identified and addressed in real time. When and where that capability exists, exposure mitigation is certainly the highest aim. However, given the real-world limitations of analytic methods and instrumentation, continuous monitoring might never be possible for some metrics. When analysis must occur sometime after a sample is collected, sampling would be frequent enough to provide meaningful information about exposure, such that the sampling frequency could change with risk level or uncertainty. For example, changes in mine and operational conditions may lead to changes in the characteristics of RCMD particles that have serious health implications. Likewise, some miners might perform job duties or behave in other ways that cause his or her RCMD exposure to be higher than the exposure of other miners. In both of those examples, frequent sampling could help to identify and reduce RCMD exposures relatively quickly.

Furthermore, an ideal monitoring and sampling program should offer the flexibility and support to integrate additional (or replace outdated) RCMD metrics and tools, as new scientific information and technologies become available. Early on, monitoring of new metrics may occur infrequently, for example, to survey for specific risks. If significant risks are identified, a monitoring protocol that includes more routine measurements may be adopted as an understanding of the risk factors and mitigation strategies evolve. As discussed later, risk management and a commitment to best practices are key features of an *optimal* (as well as an ideal) monitoring and sampling program too.

The two primary monitoring approaches personal monitoring and area monitoring, serve two very different purposes. Personal monitoring serves to track an individual's RCMD exposures and, in the interest of health protection, a monitoring program could ideally include every individual on every work shift. Area monitoring serves to track airborne RCMD trends in particular locations (for example, close to primary dust generation sources and key ventilation splits) can provide feedback data for assessing the performance of process control measures. When a process is controlled to minimize dust generation or aerosolization, workers in the vicinity would likely be exposed to minimal process-related dust, thus receiving an indirect means of health protection. Moreover, comprehensive and frequent (if not continuous) area monitoring can allow for a correlation between RCMD measurements and mine environment or operating conditions. Such correlations are extremely important in developing approaches for forecasting risks of possible RCMD exposures, and for evaluating dust mitigation strategies. It is important to note, however, that area monitoring results should not be conflated with personal exposure measurements.

For reference, the current regulatory approach for U.S. coal mines is monitoring designated occupations (DOs).[2] According to the approach, the exposure of a group of miners is controlled by using data from the personal monitoring of selected members of the groups. The assumption is that the DO's RCMD exposure is the maximum expected exposure of any individual in the mining unit. As discussed in Chapter 4, however, that assumption may not be valid with use of the CPDM or any other direct-reading continuous personal monitor. Since the individual in the DO is provided with near-real-time data on personal exposure (that is, CPDM measurements of RCMD mass concentrations), he or she has the opportunity to take steps to limit personal exposures. That opportunity for reaction is a primary benefit of a CPDM, but it means an individual wearing the CPDM may not reflect exposures to others in that group.

If all RCMD metrics could be measured in real time on every individual, an ideal program might focus first on personal monitoring to support direct protection of individuals. Nevertheless, real-time analysis may be impossible for some metrics, especially using wearable monitors. It is more realistic to expect that continuous or semicontinuous analytic methods for RCMD would be developed and implemented for stationary monitoring locations (for example, using tube bundle or similar systems (Zipf et al., 2013; Brady et al., 2015) to draw air samples for analysis using a centrally located instrument). In that case, area monitoring would provide data for assessing the performance of process control measures thereby indicating changes in RCMD concentrations.

In the absence of continuous instruments, the question of personal versus area monitoring is still important. Personal exposure data can be related more directly to an individual's health outcomes, and such data are more relevant for assessing an individual's health risk, as those data reflect changes in the location and activities of an individual. Area-monitoring data are critical for understanding environmental and operational factors that influence the concentration and particle characteristics of RCMD in underground mines. An ideal monitoring protocol would therefore include both personal and area sampling.

Training and Education

Education and training are critical for achieving a monitoring strategy's goal of providing accurate information on miners' RCMD exposures to inform exposure control decisions. The words *education* and *training* are often used interchangeably, but in the committee's view, they mean two different things. Training teaches the methods and procedures for completing a task or operation. Education conveys a deeper understanding of the task, including its importance and

[2]Designated occupation is the occupation on a mechanized mining unit (MMU) that has been determined by results of RCMD samples to have the greatest respirable dust concentration. In addition, other occupations on an MMU that are designated for sampling are referred to as other designated occupations. Designated areas are specific locations in the mine where samples will be collected to measure sources of airborne RCMD in the active workings (that is, any place in a coal mine where miners are normally required to work or travel) (see 30 CFR 70.2).

context, as well as the circumstances for which the specific training may not apply. In other words, training is about *how* and education addresses *why*.

Training in the proper use of the CPDM is important for the miners who will wear the device. Equally important is education concerning

- Characteristics and risks of coal mine dust lung diseases;
- Components of coal mine dust;
- Respective hazards of coal dust, rock dust, and silica;
- Relevant Mine Safety and Health Administration (MSHA) regulations;
- RCMD and silica control, both industry wide and in their mines;
- Strategies for RCMD monitoring and sampling;
- How to use the CPDM read-outs to identify dusty locations and operations;
- The mine's procedure for addressing hazardous conditions; and
- The miners' right to file a complaint to the mine operator, the miners' representative, or MSHA without fear of retaliation.

Done correctly, that kind of education would lead to better overall understanding and increased motivation to use the CPDM. The monitoring device is heavy and bulky for a miner already laden with heavy equipment, such as the self-contained self-rescuer. Miners will wear the CPDM and use its data more willingly if they perceive the monitor is helping to save their lives and the lives of their co-workers (Lindell, 1994).

How education and training are conducted is also important. Adults learn best when education is hands-on, interactive, based on using newly acquired knowledge to solve problems, and preferably in small groups (OSHA, 2010, 2015; ILO, 2012). Too often, safety and health instruction is delivered through lectures, videos, and slide presentations without accounting for how adults learn best.

As one of the objectives of the program is providing exposure information to the miner wearing the CPDM, that individual miner may be able to move to a less dusty location or otherwise adjust work practices. However, such an action only protects that one miner. CPDM readings could be used to identify the areas and operations where RCMD concentrations are highest, for permanently reducing those concentrations through engineering and work practice controls. Proper education empowers miners to take action, not just for themselves, but also for their fellow miners (Weinstock and Slatin, 2012).

Unfortunately, there is little published research on the effectiveness of mine safety and health training. (There is a more extensive literature on safety and health training in general [Cohen and Colligan, 1998; Sokas et al., 2009; Robson et al., 2010].) One study looked at the impact of MSHA Part 46 of title 30 of the Code of Federal Regulations training in stone, sand, and gravel mines before and after such training was first required in 1999 (Monforton and Windsor, 2010). The authors found a statistically significant decrease in permanently disabling injuries, but not in overall injury rates or other nonfatal injury categories. They concluded that although a causal relationship between the regulatory intervention (MSHA Part 46 training) and the decline in the most-serious injuries was plausible, the existence of such a relationship was called into question by the lack of a decline in other injury rates. In addition, Monforton and Windsor (2010) observed that the Part 46 regulation was written by lawyers, economists, and regulatory specialists instead of experts in adult education; the regulation was grounded more in the need to achieve consensus with the industry and reduce paperwork than in objective evidence; and that many stone, sand, and gravel mine operators were already providing training. The authors also pointed out that training and education alone will not make the workplace safe. Equally important are management commitment, worker involvement, worksite analysis, and hazard recognition. Education and training can facilitate, but not replace, those actions.

Data Management and Decision Making

In the context of an RCMD monitoring and sampling program, data management encompasses all the processes and structures for the collection, storage, processing, dissemination, and use of information. Good data management is a comprehensive and vital element of any monitoring program that provides a foundation for informed decision making. In contrast, poor data management can lead to ineffective, and perhaps counterproductive, decision making—or even a tendency toward nonparticipation of key program stakeholders. Beyond data quality (that is, reliability of measurements), the value of data with respect to program objectives is determined largely by its availability and usability. If data are not available to the appropriate stakeholders in a timely manner, or if their method of collection or presentation format are not easily understood, they would have little value in ensuring worker health protection, supporting process control, or predicting conditions that may result in elevated RCMD exposures.

For the purpose of this discussion, the primary data types of concern are RCMD metrics, which might be collected (semi)continuously (for example, via a CPDM worn by a worker or placed in a stationary location), periodically (for example, measurements of quartz or other constituents on regularly collected filter samples) or intermittently (for example, detailed characterization of RCMD), and related contextual information such as sampling locations and frequencies. Additionally, data related to environmental and operational conditions during RCMD sampling and other periods may be available. These may include measurements related to ventilation (for example, velocity at the mining face or in other locations, curtain positioning), dust control (for example, spray volumes and pressures, loading rate of dust collectors), and mining conditions (for example, total mining height, coal seam thickness, roof rock characteristics, production or advance rate, bit replacement rate); and, again, these data may be collected on range of time bases (that is, from continuously to intermittently) and in various locations. Especially important for continuous measurements, data transmission in coal mines has been a topic of much research, including for personnel tracking and communications and for atmospheric gas monitoring applications (for example, see Dubaniewicz and Chilton, 1995; Novak et al., 2009; Griffin et al., 2011; Sunderman and Waynert, 2012; Damiano et al., 2014; Zhang, 2014; Rowland et al., 2018)—and an optimal RCMD sampling and monitoring program would take advantage of existing data transmission capabilities or develop further capabilities.

For RCMD metrics, data availability is generally related to the sample analysis method. Where continuous measurements are possible, and the user has immediate access to the data, relatively quick, albeit reactive, decision-making is supported. For example, a miner wearing a CPDM might make a decision to change positions in order to limit further dust exposure during a work shift; and based on experience or other data might be able to identify and correct a condition that is allowing an inordinate amount of dust into his work area.

On the other hand, post-collection RCMD sample analysis means there is a lag period before results are available. Lag times also may occur when obtaining other non-continuous data types (such as descriptions of operational conditions), or when continuous data is not immediately transmitted to the user. An example of the latter situation might be post-shift analysis of CPDM data to study how a worker's exposure changed over the shift. Given the dynamic nature of mining and mine environments, consideration of such data availability issues is critical for processing to support further analysis and interpretation. For instance, determining correlations between RCMD metrics and ventilation and/or dust control conditions requires careful accounting of the relevant measurement lag periods, as well as the location of measurements. In such instances, a system would be in place for processing data to match measurements temporally (and, where necessary, spatially). An output of this might be time-series plotting to visualize trends in different data types, identifying when a specific metric crosses a certain threshold, and ultimately correlating RCMD metrics to mine environmental or operating conditions.

In using sophisticated processing that integrates RCMD monitoring data with ventilation, dust control, or other data, a possible eventual outcome is a fully automated smart system that makes or recommends operational changes to optimize the mine environment. Smart systems for environmental monitoring and control have been the topic of research for several decades. As reviewed by Cook and Das (2007), a wide range of applications have been considered and developed to varying degrees, including residential safety, comfort and efficiency; intelligent work and educational spaces; and even health monitoring. But the key elements are common across smart systems: an array of sensors (i.e., data collection instruments), hardware that allows data transmission to a centralized data processor, software to process and analyze data, and feedback controllers to adjust environmental conditions. A host of information on these elements and their integration is available in the literature, including for industrial applications (for example, see Ramamurthy et al., 2007; Pillai et al., 2010; Wang et al., 2010; Bhattacharya et al., 2012; Lee et al., 2014).

Whether or not such smart systems materialize, the ability for real users to see and interpret data is critical. Data usability refers to the meaningfulness of data, as presented, to the intended user, and thus it determines the types of decisions that can be made, and who can make them. Commonly, the purpose of wearable and continuous monitors, such as the CPDM, is to afford individual workers an opportunity to see and react to measurement data in real-time. For this purpose, the CPDM display serves as the primary data presentation and is generally usable by the worker wearing the monitor. Ideally, however, the collected data would also become part of a more extensive database that other workers and mine operators could access and use, which would require an open and understandable presentation format. For instance, brief summaries showing time-series exposures for annotated work shifts could be used to exemplify potentially high-dust activities during training sessions, and exposure comparisons between different job categories might be used to help evaluate dust-specific health risks. Similarly, multiple stakeholders would benefit from access and usability of RCMD measurements gathered from area sampling efforts, and corollary analysis describing relationships between various mine conditions and RCMD metrics.

It is worth noting that, beyond the technological challenges associated with data collection (e.g., measurement of specific RCMD metrics), transmission, processing and analysis, data presentation carries its own challenges, especially in systems where multiple users are intended (Wolfe, 2013; Hoffer, 2014). In an ideal RCMD monitoring and sampling program, design of presentation platforms (such as for instrument displays and reporting) would be thoughtful and flexible. Such platforms have yet to be designed for this specific application, though some examples are available for other mine monitoring applications such as atmospheric monitoring and ventilation on demand systems (for example, Agioutantis et al., 2014; Wallace et al., 2015). Moreover, user training and education would be a top priority, both in terms of how to interpret data and make decisions, and the rights and responsibilities of various stakeholders to do so. The importance of training and education is in ensuring an efficacious program cannot be overstated.

Program Evaluation and Improvement

Periodic evaluation of an RCMD monitoring and sampling program is imperative. Output data need to be reviewed to determine whether objectives are being met, and to identify and prioritize areas for improvement (for example, locations associated with high RCMD exposures). Specific program elements, including analytic tools, monitoring protocols, and data integration systems, also need to be reviewed to assess how each contributes to attainment of objectives. Again, where deficiencies are spotted, improvements are developed (such as modified sampling frequencies and adoption of new tools).

In an ideal RCMD monitoring and sampling program, evaluation and improvement would be explicitly included as procedural elements themselves (Figure 5-1). Target outputs and elements for evaluation, the timeline, and responsible stakeholder(s) would be defined. Also, the necessary resources would be committed for conducting the evaluation and making improvements. Further, the procedures for evaluation and improvement would include consideration of current information concerning RCMD exposures and related disease. The health implications of observations based on monitoring data would be assessed using the latest knowledge of aspects, including factors that contribute to health effects (such as RCMD exposure metrics and nonoccupational factors), mine and operational factors that control RCMD metrics, and specific health outcomes of workers in the mine(s) being monitored. Knowledge of those aspects is woefully incomplete at present.

OPTIMAL MONITORING AND SAMPLING STRATEGIES

The previous discussion envisioned an ideal monitoring and sampling program that would be implemented with few limitations. However, from a real-world perspective, the objectives of an ideal program cannot be achieved fully because of a variety of real-world constraints. This section considers optimal approaches for implementing aspects of an ideal program in the context of practical constraints.

A mathematical approach to optimization could involve the use of techniques (such as linear, dynamic, nonlinear, or goal programming) to develop an objective function that is to be maximized or minimized. After the constraints on the function are specified, a mathematical region is described, where maximum or minimum values for the function can be determined, considering the pertinent variables and parameters (Taha, 2007).

In the case of optimizing monitoring and sampling strategies mathematically, the objective would be to elucidate the most effective real-world strategy for quantifying the critical RCMD exposures causing lung diseases. However, the substantial complexities and uncertainties associated with performing a mathematical optimization in this context would not likely allow for meaningful solutions.

Thus, in the context of this study, an optimal strategy involves monitoring and sampling strategies that enable continued, actual progress to be made toward the elimination of diseases associated with RCMD exposure. In that context, a broad range of conditions and constraints need to be considered in developing optimal monitoring and sampling strategies, including

- Current regulatory requirements;
- The state of monitoring and sampling capabilities, how they are being used, and the feasibility of making improvements;
- The state of dust control approaches, how they are used, and the feasibility of making process improvements that would reduce airborne RCMD concentrations;
- Miners' ability to avoid or reduce exposures;
- Effectiveness of current medical surveillance programs for detecting lung diseases and the feasibility of improving them;
- Ability to identify the relative importance of RCMD exposure characteristics with respect to causes of deleterious health effects; and
- Likelihood that operators and miners would undertake activities that go beyond regulatory requirements.

At present, the CPDM and a gravimetric personal sampler are used to conduct mass-based personal and area monitoring, as prescribed by regulations. Improved strategies would embrace voluntary additional monitoring and sampling to gain information on potentially important aforementioned parameters affecting miners' health as well as temporal and spatial variation of RCMD.

As new scientific evidence links deleterious health effects with specific characteristics of RCMD particles and new monitoring techniques become available, operators may choose to revise the objectives of optimization and institute additional monitoring technologies and sampling protocols based on newly evolved technology. That is, an optimal program would be flexible and improve when constraints are substantially reduced or eliminated. That approach would be consistent with the process diagram shown in Figure 5-1. Various monitoring techniques and their expected capabilities are shown in Table 5-1. For example, new technology for more-rapid measurement of quartz exposure would necessitate changes in an optimal program for which the capability did not exist before. Analysis of monitoring data would provide feedback for the subsequent improvement of the overall monitoring and sampling processes.

While some proactive operators might adopt additional monitoring technologies voluntarily and use a more robust sampling protocol to obtain information aimed at reducing lung disease among their miners, other operators might tend to focus on mitigating exposures only by complying with MSHA regulations. However, the coal mine industry had used beyond-compliance efforts in the past to pursue a goal of zero accidents and injuries. In response to recommendations from the Mine Safety Technology and Training Commission (2006), the industry espoused widespread adoption of a comprehensive safety management systems approach and recognized that regulatory compliance was only a starting point. Several years later in an assessment of five underground coal mines, Kosmoski (2014) found behaviors among the participating mines and their companies that indicated a strong commitment to safety in their operations. Considering industry-wide statistics, the National Institute for Occupational Safety and Health (NIOSH, 2016a,b) observed decreased nonfatal injuries in underground mine workers since 2006; however, the number of fatalities for coal operators at underground work locations varied widely, with 36 deaths in 2006, 6 deaths in 2009, 40 deaths in 2010, 14 deaths in 2013, and 8 deaths in 2015.

Near-Term Opportunities for Implementing Optimal Strategies

A number of near-term opportunities exist for improving the understanding of relationships between RCMD exposures and health effects and providing information to support decision making for exposure control. Table 4-1 in Chapter 4 describes potential outcomes of the monitoring and sampling requirements of the 2014 dust rule for mine operators and underlying assumptions for which there are important uncertainties. Table 5-2 identifies components of optimal monitoring and sampling strategy that could help achieve various potential outcomes from required monitoring and sampling methods.

RCMD Monitoring

RCMD monitoring is expected to ensure that efforts for minimizing the incidence of disease are focused on reducing RCMD exposures to *all* miners in underground coal mines in a maintainable manner, not only those wearing a monitoring instrument. There is a need for monitoring, not only to help prevent high-exposure episodes but also to help reduce long-term exposures of all miners as low as reasonably possible. Evaluations of RCMD sampling data should consider whether results from different sampling locations are sufficiently informative for making decisions for controlling exposures. Maguire (2006) discusses risk-based decision making for achievement of dust exposures as low as reasonably practicable in light of technical and economic constraints.

TABLE 5-1 Monitoring Techniques and Expected Capabilities for RCMD Exposures

RCMD Monitoring	Expected Capability
Mass-based sampling device	Demonstrate regulatory compliance; Characterize airborne RCMD mass spatially and temporally
Particle size distribution devices	Characterize particle mass selectively by size
Faster quartz analysis method	Reduce time for airborne respirable quartz concentration
Diesel particulate matter (DPM) devices	Monitor DPM at low concentrations
Particle counter devices	Characterize numbers of small-sized particles (for example, less than 1 μm)
Devices for monitoring of other specific contaminants	Characterize concentrations of target contaminants

Use of CPDMs for Nonregulatory Purposes

The current CPDM technology represents an innovative step toward better understanding the exposure conditions in coal mines. The stored data provide a time-related record of airborne RCMD concentrations. When compared with operational information, dust sources can be identified and the impact of worker positioning or control technologies can be evaluated.

TABLE 5-2 Potential Outcomes from Required Monitoring and Sampling Methods, Assumptions, and Components of Optimal Monitoring and Sampling Strategies

Potential Outcomes	Assumptions	Optimal-Strategy Component
Determine compliance with the RCMD standards by sampling designated occupations (DOs).[a]	Required dust exposure data are representative of underground coal miners for all periods. When and where RCMD mass and silica content are monitored is sufficient to ensure health protection of miners.	RCMD MONITORING It is not apparent that DOs always represent the highest exposures on a given shift. Additional sampling could be deployed and available data could be used to ensure that DOs are representative of the highest exposures.
Inform workers in DOs of a need to change behavior in response to dust concentration readings while conducting tasks.	Current training and education programs are implemented in a consistent manner across the coal mine industry so that all miners are knowledgeable of RCMD exposures, resulting in behavior modification for dust exposure avoidance in response to CPDM readings.	WORKER BEHAVIOR MODIFICATION It is unclear whether behavior modification occurs for miners not physically wearing a CPDM. It is important to ensure that effective training and education programs are in place throughout the industry.
Provide information to mine operators for addressing airborne dust issues through process control.	Process control of dust is ensured by determining compliance with dust regulations.	PROCESS CONTROL Area sampling could aid operators' decision making related to reducing RCMD exposure through process control.
Determine sample variability for DA and DO.	RCMD mass concentrations (without specifying composition) and silica content are the characteristics of coal mine dust most strongly associated with health effects.	RCMD PARTICLE CHARACTERISTICS Risks associated with other RCMD components need to be characterized.
Provide information on crystalline silica exposure for DOs.	Continuous, real-time measurement of crystalline silica content of RCMD is not achievable.	SILICA MONITORING Continued development of technology for continuous, real-time measurement of crystalline silica content is needed. Currently available data can be used to identify mining characteristics associated with potentially high silica concentrations.
Miners with early evidence of CMDLD (coal mine dust lung disease) which encompasses the spectrum of diseases caused by RCMD.	Medical surveillance programs identify at-risk miners	MEDICAL SURVEILLANCE Increased miner participation in health surveillance programs would be beneficial.

[a]Designated occupation (DO) is the occupation on a mechanized mining unit (MMU) that has been determined by results of RCMD samples to have the greatest respirable dust concentration. In addition, other occupations on an MMU that are designated for sampling are referred to as other designated occupations. Designated areas (DAs) are specific locations in the mine where samples will be collected to measure sources of airborne RCMD in the active workings (that is, any place in a coal mine where miners are normally required to work or travel) (see 30 CFR 70.2).

The use of the available CPDM technology by mine operators has been limited mostly to compliance control purposes. Although the instruments are well suited for such purposes, there are other possible applications. For example, mine operators could apply CPDMs in a stationary role for monitoring certain areas in a mine that have the potential for high RCMD concentrations, depending on technical conditions of machinery, geologic conditions, and the type of RCMD control measures being used. See Box 5-1 for other potential uses of CPDM data.

BOX 5-1 Potential Uses of Monitoring Data to Aid in Mine Operators' Decision Making

Compliance demonstration: The type of monitoring device is specified for most locations, including for personal sampling and area sampling, but the operator may choose to do additional sampling as a check on results used for compliance purposes. Further, the data collected from required sampling may be used for other purposes, for example, to get more granularity in what is happening over a shift. Operators also may choose to use the compliance data in their continuous improvement program, which for example would be designed to track trends possibly leading toward noncompliance. The feedback signaling potential excursions would be useful to personnel at all organizational levels, including to the workforce in the mine.

Immediate, end-of-shift, and cumulative dust exposure monitoring over selected periods: Rather than waiting for compliance feedback from MSHA, the mine operator and the workforce could use monitoring data for making decisions on necessary changes to better control dust generation or dust exposure at a location. CPDM data would be particularly useful for this purpose in the workplaces from the face to the last open crosscut. The miner, in consultation with the foreman, could make immediate changes to dust controls or in the miner's position while working. Also, at the end of a shift, CPDM data provide opportunities for checking the fluctuations of RCMD concentrations during the operating cycles and entire shift.

Using accumulated sampling data from a location over time, the operator could obtain cumulative dust exposure data for employees working at high-risk locations, or for all employees exposed. Further, the fluctuations of RCMD concentrations at virtually any location could be tracked by using a sampling strategy designed for that purpose. That could be used to estimate a cumulative exposure for a miner working in this location. Extending this objective another step, the work locations for any miner over any period, if tracked, could be used to estimate a cumulative exposure for the miner, calculate the standard deviation, and then calculate a probability of exceeding a management-selected maximum cumulative exposure over a selected period.

Routine use of near-real-time data to avoid high dust concentrations: Getting to the point of the routine use of the CPDM to indicate the need for miners to move to a less dusty area would need operator buy-in so that their miners would also buy in. The implication that use of the CPDM for that purpose is tantamount to it being used as personal protective equipment has been suggested.

Analysis of varying RCMD concentrations over single and multiple shifts for miners being sampled: CPDM data can be used for analysis of varying RCMD concentrations for any selected period, whether by mining cycle time, move time, during delay periods, over an entire shift, or over multiple shifts. Any level of data granularity would be possible once commitment is made to pursue more in-depth analyses of the data. Adopting a continuous improvement, or quality assurance and quality control (QA/QC) process allows a range of selected performance targets to be pursued. Such a process would allow management and the workforce to be proactive in pursuing systematic compliance but also in pursuing the reduction of RCMD exposures to a level that is as low as reasonably practicable.

Determine additional sampling for selected jobs and locations on sections and throughout the mine: Whenever the analysis of near-real-time data suggests the potential for samples to indicate regulatory noncompliance, or if the allowable RCMD exposure concentration may be exceeded, management may decide to pursue additional sampling for selected jobs and locations. That would result in more data points for a more robust assessment of variability over time and over shifts. If a continuous improvement process were being used, the tracking of potential excursions would be realized with more confidence in the observed level of variability.

Implement a QA/QC process for continuous improvement of the sampling and monitoring strategies and give feedback to the workforce: Implementation of a QA/QC process could provide much more confidence in pursuing sampling strategy targets. Importantly, the feedback loop in the process would reinforce the performance of management and the workforce in pursuing control of RCMD exposures, including miners removing themselves from high RCMD concentrations.

Under current regulations, these additional applications of the CPDMs would require notification but not the permission of MSHA.[3] That requirement might discourage engineering applications and make them less attractive to mine operators. However, it may be preventing mine operators from purchasing additional instruments for the indicated purposes. Therefore, a first step for improving the application of the CPDMs would be for MSHA to encourage mine operators to use them in scenarios beyond the scope of compliance control measurements with assurances that the additional data will not be used as an enforcement tool.

Less Expensive Direct-Reading Instruments

CPDM cost is one of the major limitations for the use of the device for control and area monitoring purposes. Because CPDMs are relied upon for demonstration of regulatory compliance, they need to be highly reliable and provide data of high quality. Consequently, the cost for a single instrument is high. For many of the area monitoring purposes (see Chapter 4), measurements of very high quality are not of prime consideration, because area monitoring is primarily concerned with trends in the data over longer periods. As analytical chemists have known for centuries, measurements do not need to be as good as possible, just as good as necessary.

As discussed below, it is important to evaluate area monitors for possible use in coal mining environments. Mine operators would need scientific support to identify criteria for determining the successful use of the monitors. It is likely that the use of the lower-cost sensors would not be available for compliance control in the near future.

Worker Behavior Modification

Based on operator sampling data reported to MSHA, it is apparent that miners, who wear a CPDM during a working shift, are adjusting their work behavior (such as positioning in the work area in response to elevated RCMD concentrations) to manage exposure during the shifts when a CPDM is worn. An optimal program would facilitate measurement of these behavioral modifications when the CPDM is not present. In addition, CPDM data can be used by operators to investigate whether dust control measures should be adjusted.

Once an optimal monitoring and sampling strategy is implemented, it needs to be well executed. How well it accomplishes the goals depends on good execution at all organizational levels, including in the mine and particularly at the designated sampling locations. This means that an effective training campaign is necessary to ensure buy-in by all personnel, including miners, as recommended by the report of the Secretary of Labor’s Advisory Committee on the Elimination of Pneumoconiosis among Coal Mine Workers (1996). If the sampling strategy is executed well at all levels, then the data on dust exposures that will be forthcoming can be trusted as accurate and meaningful, as planned. Use of the results to aid the operator and miner in making decisions for reduction of dust exposure will be well founded and robust.

Process Control

An optimal system of dust prevention and control is designed to guarantee sustainably low RCMD exposure concentrations for all miners during their entire time working underground. Current approaches used in various countries tend not to focus on a maintainable strategy of exposure control for the long term. Instead, they tend to obtain short-term measurements within comparably small groups of miners and use those results (or the results of selected stationary measurements) as a surrogate for the exposure of much larger groups of miners.

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[3]An operator is required to provide written notification to the MSHA district manager when a RCMD sample is collected using a CPDM only for engineering purposes (30 CFR 70.210(d),71.207(d), and 90.208(d)). The CPDM must be programmed to indicate that engineering samples are being collected. The samples are not uploaded to the MSHA database.

Efforts to augment that approach would focus on dust measurements, which try to monitor RCMD concentrations and silica concentrations nearly continuously in all relevant sites of the mines. That augmented approach is analogous to current monitoring systems for identifying dangerous concentrations of carbon monoxide and methane in coal mines. Those systems do not rely on a few expensive monitors that provide high-quality individual measurement result. Rather monitoring of those gases involves the use of an array of many lower-cost sensors with an appropriate level of reliability. The monitor readings would not be used for determining regulatory compliance; instead, they would be used for identifying high RCMD concentrations at specific sites that might warrant additional dust control actions.

In order to be useful for assessing process control effectiveness in coal mines, direct-reading instruments do not need to follow the performance specifications of RCMD regulatory monitoring, but one should know how the readings of those monitors relate to readings obtained from compliance monitors. The supplemental monitors need to be reasonably sensitive in the size range of respirable particles (for example, 1-10 µm). They would need not to be too cross sensitive under coal mining conditions (water sprays would be a consideration here). They would not need to give mass concentration results (say in mg/m^3) directly or indirectly after calibration. Instead their electrical signals could be directly used for comparison of “high” or “low” concentrations depending on the situation in a given mine environment. Those instruments would need to be intrinsically safe, such that their use in coal mine environments would not present an explosion hazard and their use in coal mining environments would require additional effort to enable them to withstand dust loading with minimal maintenance and calibration efforts.

Until very recently those types of instruments were not available (Thompson, 2016; Clements et al., 2017; Raj et al., 2017; Crilley et al., 2018). Due to recent demands for RCMD monitoring in environmental settings in recent years, many lower-cost sensors have become available. The sensors almost exclusively use optical principles for measuring airborne RCMD (light scattering of aerosols or single particles). Their electrical signals may not easily be recalculated or translated into mass concentrations of RCMD. Light-scattering signals depend on more airborne particle properties than mass (or number) concentration. Particle size distribution, particle shape, various cross sensitivities, and optical properties of the particles are the most important factors. However, if all these factors for airborne particles are kept constant, the monitors provide cheap, plentiful, simultaneous, and immediately available direct-reading information for assessing process control effectiveness on a *relative* scale. For example, a longwall operation could be equipped before and after the longwall. If signals behind the operation are increasing without a simultaneous increase before it, that would point to problems within the operation itself. Intervention could start immediately. Due to the fact that the sensors themselves are quite inexpensive, numerous units could be installed.

RCMD Characterization

Current regulations require gravimetric sampling and analysis for total mass and silica content. The total mass data are used to confirm results captured by CPDM measurements. As discussed earlier in this chapter, some factors potentially causing lung disease in coal miners have been hypothesized to include submicron-size fractions, number of particles, and DPM.

There may be other factors yet to be recognized. Identifying the presence and concentration of such RCMD-relevant factors is a challenge when using mass-based monitoring and sampling strategies. Other monitoring technology and analytical techniques do exist to seek more information on some of those factors, but they have not been linked causally to lung disease. Without scientific evidence of the contribution of RCMD components to lung disease, regulators and many mine operators are not likely to pursue the development of new technologies. Some operators may desire to monitor a factor or factors to manage their risk for disease progression among their miners, but the cost involved in doing so may be prohibitive at this point in time.

While very frequent and detailed characterization of RCMD on large numbers of samples is perhaps a longer-term aim, some available data and ready or near-ready analytical techniques may offer a better understanding of RCMD compositions in specific regions or mine environments. For example, considering the recent reports of significant numbers of coal workers' pneumoconiosis (CWP) cases in geographic hot spots (Laney et al., 2010) and specific clinics (Blackley et al., 2016, 2018), it seems prudent to correlate basic work history of affected miners with any existing dust records collected as part of regulatory compliance activities. Such an effort could shed light on possible RCMD exposure factors associated with disease development (for example, trends in quartz concentrations, perhaps correlated with particular mining practices).

Furthermore, it is currently possible to survey a range of characteristics of RCMD particles and assess the entire composition of RCMD using available analytical techniques on filter samples. A recent study by Johann-Essex et al. (2017) applied a computer-controlled SEM-EDX routine to determine size, shape, and mineralogical class distributions in RCMD mine samples. XRF can also be used for direct elemental quantification on filter samples (for example, see Harper et al., 2007), as can digestion methods followed by analysis by ICP-MS or other mass spectrometry methods (for example, see ASTM D7439-14 [2014]). A simpler method using TGA has been used to estimate the mass fractions of coal, carbonate, and noncarbonate minerals in RCMD samples (Phillips et al., 2017). For mines with diesel equipment, the mass fraction of DPM in RCMD can be determined using submicron elemental carbon as a surrogate (Birch and Noll, 2004), which can be collected using an appropriate size selector during sampling and measured by the NIOSH 5040 standard method (Birch, 2003). While the time and costs associated with those and other possible methods for RCMD characterization are likely prohibitive for very routine monitoring, they may provide valuable opportunities to gather detailed information for critical questions or decision making (for example, comparing RCMD control strategies and diagnosing specific RCMD sources). Moreover, comprehensive RCMD characterization at discreet time intervals or in different areas of a mine could support monitoring of particular temporal or spatial trends, and surveys across many mines may help identify particular conditions or practices that influence RCMD exposure risks.

Specific to silica (quartz) monitoring, recent work by NIOSH may provide a real opportunity to bridge the gap between the current model of very infrequent quartz monitoring and the long-term goal of continuous monitoring. At present, quartz content in RCMD is measured following collection of filter samples and using the MSHA P-7 standard method (MSHA, 2013b) or the similar NIOSH 7603 standard method (NIOSH, 2003b), both of which use infrared spectroscopy. As mentioned above, due to the complex steps required to prepare samples for analysis and use of centralized laboratories, there is generally a significant lag time between sample collection and results. The need for options that can provide a more timely assessment, either for personal or area sampling, has been well established (NIOSH, 2015).

NIOSH has been working on two methods for this, both of which are aimed at providing an end-of-shift quartz measurement. The first method uses the "fast quartz" monitor mentioned earlier, which is a field FTIR instrument to analyze a dust sample collected on a standard filter using a gravimetric sampler (Miller et al., 2015; Cauda et al., 2016, Lee et al., 2017). The analysis time is short (a few minutes) and, since this method is nondestructive, the filter could be shipped to a laboratory for further analysis if desired. This method is currently in the field-testing stage. The second method NIOSH has been working on more recently is to measure quartz content directly on the CPDM filter, which is facing two primary challenges. Because the filter is attached to a stub, which allows the CPDM's tapered-element oscillating microbalance (TEOM) to work, it is unsuitable for FTIR analysis (Miller et al., 2015). This has prompted NIOSH to consider XRF analysis, but the current CPDM filter media (borosilicate fiberglass) has the potential to cause interference for the quartz analysis. NIOSH identified a novel filter media (polyester-backed nylon fiber) that may allow this method for end-of-shift analysis on CPDM filters to be fully developed (Tuchman et al., 2008). While neither of the two methods currently in development for "fast quartz" analysis is envisioned for real-time monitoring, their availability would significantly improve mine operators abilities to understand RCMD conditions and make informed decisions to reduce hazardous exposures.

Silica Monitoring

As has been stated above, crystalline silica is a highly relevant constituent in RCMD regarding lung disease in miners. At present, no direct-reading instruments are available to monitor crystalline silica that would replace the gravimetric sampling approach that is currently being used. Although the feasibility of continuously monitoring silica content in real time is under debate, progress is being made and prototypes are under development. It is important that efforts to develop a real-time crystalline silica monitor continue, and that NIOSH continue its efforts to develop an end-of-shift quartz monitor, as discussed earlier in this chapter.

Until a real-time silica instrument becomes available for routine monitoring, available data on RCMD composition could be used to gain a better understanding of mining areas with the potential for elevated silica exposures.

Correlation of Dust Surveillance and Medical Surveillance Data

Coupling surveillance information with monitoring and sampling information helps to attain the ultimate goal of disease eradication. Therefore, a system of RCMD exposure prevention needs to be accompanied by a suitable and acceptable system of medical surveillance.

As outlined in previous chapters, mounting evidence from medical surveillance of U.S. coal miners shows a substantial increase in the prevalence of coal mine dust lung diseases, especially the more disabling and rapidly progressive forms of CWP. Also, research on RCMD particle characteristics suggests that particle size, shape, and composition, along with changes in mining production, may be important risk factors for those diseases. Better linkage of medical data with exposure monitoring data to identify specific risk factors that may account for the upswing in pneumoconiosis cases is essential to ensure effective RCMD control and disease prevention.

RCMD sampling for compliance with MSHA-permissible exposure limits is not synonymous with exposure monitoring for epidemiology and prevention purposes. In order to explore ways to improve understanding of exposure-disease linkages, it is useful to consider currently existing data sources, data that have been collected, and where more-comprehensive data collection and integration opportunities exist. It is important to seek exposure data that accurately reflect a range of exposures including, but not limited to, worst-case exposures.

The major source of medical surveillance data on disease trends is the NIOSH Coal Workers' Health Surveillance Program. Participation rates by active miners has been stable over many years, estimated at 40 to 60 percent. The vital information provided by that program would be enhanced by higher miner participation rates. Early cases of silicosis could be identified and progression could be prevented. Investigation into reasons driving miners' reluctance to participate is needed to address disincentives where possible.

Similarly, there is little available information on disincentives for participation in the MSHA Part 90 Program. That program was designed to provide low-exposure mining jobs for miners whose chest radiograph results indicate the presence of early CWP and the risk for disease progression from ongoing exposure. A recent study provided data and analyses on participation rates (Reynolds et al., 2017). Additional exploration is needed on reasons for the low participation rates and the integration of Part 90 Program findings with specific exposure data would likely enhance the understanding of exposure-disease relationships. It is important that Part 90 data collected by MSHA are available to NIOSH researchers for pursuing that information.

Information from the more recently implemented Enhanced Coal Workers' Health Surveillance Program (including details of miners' occupational histories, job duties, specific mine locations, duration of employment, use of personal protective equipment, and other factors that are important for understanding exposure) needs to be integrated with more-comprehensive exposure monitoring data obtained for epidemiologic purposes. Access to dust sampling data or to the mines themselves for sampling purposes would support that goal. Ongoing analysis of findings from chest imaging, lung function testing, arterial blood gas testing, and other factors that may be important in disease pathogenesis (such as smoking and family histories) is essential for linking particular exposures to particular disease outcomes. For example, in-depth characterization of miners' exposures to respirable crystalline silica is likely important in understanding risk for rapidly progressive pneumoconiosis. Analysis of RCMD particle size and shape may be important in understanding dust deposition in a person's airways and risk for chronic obstructive pulmonary disease.

In addition to NIOSH medical surveillance data, other data sources on trends in lung disease, particularly in retired coal miners, may be available through the Department of Labor Office of Black Lung Compensation Programs. Information from the Health Resources and Services Administration-funded Black Lung Clinics Program could also be used for cases of coal mine dust lung disease by integrating it into general medical surveillance data sets for understanding disease trends. Currently, there are few systems in place to collect and integrate those data sources for prevention research. Recent studies (for example, Almberg et al., 2017 and Graber et al., 2017) have begun to link those disparate datasets and provide insight into variable rates of participation in programs that shed light on coal mine dust lung disease prevalence and risk factors. Further such efforts are needed.

TECHNOLOGY DEVELOPMENT NEEDS

Alternative Tools for RCMD Monitoring

While the CPDM represents a significant advancement in RCMD monitoring capabilities, several drawbacks make more widespread use for either personal or area monitoring a real challenge. An ideal monitoring program would provide every individual with a real-time monitoring device, but the cost of the CPDM and the ergonomic issues (see Chapter 4) would be prohibitive. However, that technology is only currently available for coal mine environments as the CPDM device itself, which is now mandated for the determination of regulatory compliance. That circumstance sets up an undesirable situation for mine operators wishing to apply the near-real-time monitoring capability for area monitoring: To use their compliance-designated CPDM units for noncompliance purposes, they must notify MSHA, which could create a perceived additional burden. Alternatively, the mine operator could acquire additional monitors to be designated for engineering (that is, nonregulatory) purposes only. To address both the inherent and procedural challenges to more widespread use of monitors with capabilities similar to the CPDM, alternative technologies for near-real-time RCMD monitoring are a real need.

As a precursor to the CPDM, a machine-mounted continuous RCMD monitor (MMCRDM) was previously developed by NIOSH using the same TEOM sensing technology (NIOSH, 1997). It could continuously monitor, display, and record RCMD concentrations for at least 30 days without servicing. Results from the field testing of the machine-mounted instrument indicated that, to be mine worthy, its reliability needed substantial improvement (Kissell and Thimons, 2001). Reliability was addressed as the TEOM technology was further developed for application in the CPDM, but the MMCRDM was effectively abandoned. Nevertheless, a TEOM device could be used for area monitoring—be it machine mounted or otherwise—particularly if it required only infrequent intervention for filter changing, had a constant power supply (instead of battery power), and could transmit RCMD data for integration into decision-making systems (for example, concerning ventilation and other RCMD control processes).

Another approach to RCMD monitoring is embodied by the respirable dust dosimeter (RDD), also developed by NIOSH in the late 1990s (Volkwein et al., 1999). It utilizes the principle that changes in pressure drop across a filter can provide a measurement of dust mass accumulated on the filter. The device itself consists of two lengths of foam, inside a glass tube, which successively trap oversized, nonrespirable particles, allowing the respirable particles to deposit on the filter. A number of publications describe the development, testing, and applications of several versions of the RDD in laboratory and mine settings (Volkwein et al., 1999; Volkwein and Thimons, 2001; Ramani et al., 2001, 2002; Hall et al., 2006). The initial development was aimed at its use as a personal sampler, and problems identified with the device for this application include the need for calibration to specific environments (that is, given different characteristics of RCMD). However, the device has potential for use in real-time area RCMD monitoring applications, where overall trends in RCMD concentrations may be of great interest. In this case, the RDD might be able to provide sufficiently reliable results at a relatively low cost compared to a TEOM device.

As particulate matter pollution is a major occupational and public health hazard around the world, a considerable amount of research and development is being devoted to the monitoring of this hazard (Koehler and Peters, 2015). Advances are occurring in sensors, batteries, pumps, information storage and telemetry devices, some of which might be transferrable or adaptable for applications in coal mines. For instance, a number of personal and environmental (that is, area) monitoring devices (such as, dust monitors, and particle counters) are currently available that contain suitable technology with respect to analytical needs, but may require modifications to meet the intrinsically safe requirement for operation in permissible areas of a coal mine).

Tools and Techniques for Routine Characterization of RCMD

As discussed earlier, most RCMD sampling, and all compliance sampling in U.S. mines, has focused on the RCMD mass concentration and the mass fraction of quartz in the RCMD. For these, progress has been made to enhance monitoring efforts resulting in the ability to measure RCMD mass concentration in near real time (via the CPDM) and to advance the potential for more timely quartz assessment (via the end-of-shift quartz measurement). However, it is good practice to question not only the adequacy of tools and techniques for the metrics presently in use, but also the adequacy of the metrics themselves to contribute to an optimal monitoring and sampling program of the future. Indeed, as more is learned about the cause-and-effect relationships of RCMD exposure factors and disease outcomes—including what key uncertainties remain—there is a need for routine, and ideally real-time, RCMD characterization as a long-term goal. This section discusses techniques that are currently available or in development for monitoring particle sizes and numbers, quartz, and DPM. Those are among the characteristics of RCMD particles that appear to be of highest concern at present. As more is learned about other RCMD constituents that may be important in a health context, development of monitoring techniques for those constituents would become future needs.

Real-time analysis of airborne mineral particles is of great interest in many fields, including mineral processing and outdoor air quality management. A range of monitors, based on different operating principles, has been demonstrated for particle counting and sizing applications. Optical particle sizers, which use light-scattering techniques, are popular in the range of respirable-sized dust; they are currently used in a variety of environmental monitoring applications to complement measurements of fine dust concentrations (for example, PMR_{10} and $PMR_{2.5}$) (Grimm and Eatough, 2009; Burkart et al., 2010; TSI, 2017a). Those instruments generally have a lower particle-size limit of about 1 μm and relatively fast data collection speeds (for example, one reading per second), but in mixed-dust environments their sizing accuracy can degrade because different mineral or dust types can yield different light scattering because of their refractive indices (Müller et al., 2011). Possible degradation of sizing accuracy for area monitoring in coal mines might represent only a minor shortcoming for use in tracking general trends in particle sizes and numbers over time. For more accurate particle sizing in mixed dust, other options might be available. For example, Liu et al. (2016) have recently demonstrated an alternative particle sizer that uses a microfluidic multichannel Coulter counter. There are also options for monitoring nanoparticles, which is a need that was previously identified (NRC, 2007). Nanoparticle monitoring is commonly carried out by using spectrometers with condensation particle counters, which are now commercially available as field monitors (TSI, 2017b). Perhaps the biggest challenge for using or adapting instruments designed for dust monitoring in noncoal applications is meeting safety and other permissibility requirements for equipment to be used in U.S. coal mines. Another challenge is making relatively sensitive instruments rugged enough to work without inordinate maintenance requirements in tough mining environments.

Beyond the ability to count particles and measure their size distributions, long-term potential also exists for continuous monitoring of specific constituents. While NIOSH has indicated that it is not developing a real-time quartz monitor internally, it issued a research solicitation announcement in November 2017 calling for proposals on this topic. Also, Chalmers and Harb (2017) presented a proof-of-concept demonstration for using a cavity ring-down spectrometer for real-time quartz analysis on airborne RCMD samples collected on a filter. That and other options for quartz monitoring may be challenged by the problem of small sample size relative to the critical mass of sample needed to perform a particular analysis. However, even a semicontinuous approach may be very valuable for either personal or area monitoring applications in coal mines. (As currently designed, the CPDM actually functions as a semicontinuous monitor, providing exposure metric readouts as 15- or 30-minute averages.)

Real-time monitors are also available for tracking DPM. The aethalometer measures black carbon, which is a major component of DPM, using a laser absorbance technique. While it was developed for relatively low-level black carbon monitoring applications (for example, urban air pollution and forest fires), this instrument has been demonstrated several times in non–coal mining environments (Volkwein et al., 2016, 2017; Barret et al., 2017). Using the same principle of measurement, NIOSH developed a personal DPM monitor for metal/nonmetal miners, which is now commercially available (Noll and Janisko, 2013; Noll et al., 2013, 2014; FLIR, 2017). It is calibrated against the NIOSH 5040 standard method to read elemental carbon (EC; effectively analogous to black carbon).[4] NIOSH has shown that coal dust–sourced EC and DPM-sourced EC might generally be differentiated on a size basis (that is, coal dust is frequently supramicron and DPM is mostly submicron) (Birch and Noll, 2004). This means that, with use of an appropriate size selector (for example, an impactor or cyclone) during sampling, the aethalometer or other types of monitors might practically be applied in coal mines to monitor DPM. Again, these technologies would have to be certified as intrinsically safe for permissible environments or be adapted to meet this requirement.

CONCLUSIONS

1. Given current uncertainties about the cause of the increase in coal mine dust lung disease prevalence and severity, the committee noted the possibility that high rates of operator compliance with the 2014 dust rule requirements may not guarantee that RCMD exposures will be controlled adequately or that future disease rates will decline.
2. Optimal strategies would embrace additional voluntary monitoring and sampling to gain information on potentially important factors affecting miners' health as well as the temporal and spatial variation of RCMD within a mine. In the committee's view, optimal strategies would augment or enhance the outcomes expected from compliance with the current regulatory requirements.
3. The primary impetus for optimal sampling and monitoring strategies is the protection of worker health through reduction in disease risk. The strategies are conceived to enhance the reduction of health risks in recognition of practical constraints (such as costs, avail-

[4]It cannot be used to demonstrate regulatory compliance with personal exposure limits since these have been set to limit total carbon (that is, determined by the 5040 method as elemental plus organic carbon). In coal mines, the coal dust itself has the potential to cause interference with measurements of elemental carbon and thus total carbon, and so DPM is regulated on the basis of equipment emissions (that is, measured at the tailpipe) rather than on a personal exposure basis.

ability of technology, existing regulatory requirements, and program acceptance by various stakeholders).

4. Optimal sampling and monitoring strategies manifest as programs that, in principle, exhibit these attributes:

   - Aiding mine operators' decision making related to reducing RCMD exposures in a maintainable manner with data that are representative of high-exposure episodes and cumulative exposures over the long-term for all workers throughout the mine, not only the ones wearing a monitoring instrument.
   - Supporting the decision-making ability of individual mine workers to protect themselves through training in the use of CPDMs and education concerning important factors that affect exposure-response relationships.
   - Monitoring characteristics of RCMD particles that are directly related to the risk of occupational cardiopulmonary disease. Using appropriate tools and methods to collect samples that are representative of the dust to which mine workers are or may be exposed.
   - Applying various monitoring technologies in engineering studies of RCMD exposure variability and exposure mitigation approaches.
   - Integrating RCMD monitoring data with associated contextual information, such as sampling locations and frequencies, environmental and operational conditions during sampling and other periods, and general knowledge of the health risks associated with the RCMD exposure metrics being monitored.
   - Involving a suitable and acceptable system of medical surveillance that provides regular, no-cost medical examinations for all miners to help assess the efficacy of exposure reduction efforts.
   - Making integrated data readily available, accessible, and usable for timely decision making.
   - Striving for continuous improvement in disease risk reduction, including periodic performance review and necessary modifications, and reaction to changes that remove or eliminate previous constraints.

5. Research and development efforts are needed for better understanding of relationships between miners' exposures and disease, including studying effects of changes in mining methods, improving monitoring approaches, and increasing participation in medical surveillance programs. Likewise, enhanced worker education and mine operators' monitoring and sampling efforts would help ensure that all coal miners' exposures are adequately controlled, in addition to those whose individual exposures are being measured for regulatory compliance purposes.

REFERENCES

Advisory Committee on the Elimination of Pneumoconiosis among Coal Mine Workers. 1996. Final Report to the Secretary of Labor, Department of Labor, Mine Safety and Health Administration [online]. Available at https://arlweb.msha.gov/S&HINFO/BlackLung/1996Dust%20AdvisoryReport.pdf (accessed December 13, 2017).

Agioutantis, Z., K. Luxbacher, M. Karmis, and S. Schafrik. 2014. Development of an atmospheric data-management system for underground coal mines. Journal of the Southern African Institute of Mining and Metallurgy 114(12):1059-1063.

Ainsworth, S. M. 2013. Infrared analysis of respirable coal mine dust for quartz: Thirty five years. In *Silica and Associated Respirable Mineral Particles*, 45T M. Harper and L. Taekhee, eds. STP1565.

Almberg K. S., R. A. Cohen, D. J. Blackley, A. S. Laney, E. Storey, and C. N. Halldin. 2017. Linking Compensation and Health Surveillance Data Sets to Improve Knowledge of US Coal Miners' Health. Journal of Occupational Medicine 59(10):930-934.

Araujo, J. A., B. Barajas, M. Kleinman, X. Wang, B. J. Bennett, K. W. Gong, M. Navab, J. Harkema, C. Sioutas, A. J. Lusis, and A. E. Nel. 2008. Ambient particulate pollutants in the ultrafine range promote early atherosclerosis and systemic oxidative stress. *Circulation Research* 102:589-596.

ASTM D7439-14. 2014. Standard Test Method for Determination of Elements in Airborne Particulate Matter by Inductively Coupled Plasma–Mass Spectrometry. West Conshohocken, PA. ASTM International.

Barrett, C., S. Gaillard, and E. Sarver. 2017. Demonstration of continuous monitors for tracking DPM trends over prolonged periods in an underground mine. *Proceedings of the 16th North American Mine Ventilation Symposium, June 17-22, 2017, Golden, CO.* Littleton, CO: Society for Mining, Metallurgy, and Exploration.

Bhattacharya, S., S. Sridevi, and R. Pitchiah. 2012. Indoor air quality monitoring using wireless sensor network. In *Sensing Technology (ICST)*, pp. 422-427.

Birch, M. E. 2003. Elemental Carbon (Diesel Particulate). Method 5040. NIOSH Manual of Analytical Methods (NMAM), 4th Ed. [online]. Available at https://www.cdc.gov/niosh/docs/2003-154/pdfs/5040f3.pdf (accessed May 25, 2018).

Birch, M. E., and J. D. Noll. 2004. Submicrometer elemental carbon as a selective measure of diesel particulate matter in coal mines. *Journal of Environmental Monitoring* 6:799-806.

Blackley, D. J., J. Crum, C. Halldin, E. Storey, and A. Laney. 2016. Resurgence of progressive massive fibrosis in coal miners – Eastern Kentucky, 2016. *Morbidity and Mortality Weekly Report* 65(49):1385-1389. Available at https://www.cdc.gov/mmwr/volumes/65/wr/pdfs/mm6549.pdf (accessed October 23, 2017).

Blackley, D. J., L. E. Reynolds, C. Short, R. Carson, E. Storey, and C. N. Halldin. 2018. Progressive massive fibrosis in coal miners from 3 clinics in Virginia. *JAMA* 319(1):500-501.

Brady, D., M. Watkinson, and P. Harrison. 2015. Best Practice Review of Atmospheric Monitoring Practices for Fire and Explosion Prevention Using Tube Bundle Systems for the National Institute for Occupational Safety and Health (NIOSH), under Contract No. 200-2013-56949.

Buiarelli, F., P. Di Filippo, D. Pomata, and M. Bartocci. 2017. A liquid chromatography tandem mass spectrometry method for simultaneous analysis of 46 atmospheric particulate-phase persistent organic pollutants and comparison with gas chromatography/mass spectrometry. *International Journal of Environmental Analytical Chemistry* 97(9):797-818.

Burkart, J., G. Steiner, G. Reischl, H. Moshammer, M. Neuberger, and R. Hitzenberger. 2010. Characterizing the performance of two optical particle counters (Grimm OPC1.108 and OPC1.109) under urban aerosol conditions. *Journal of Aerosol Science* 41(10):953-962.

Castranova, V., N. S. Dalal, and V. Vallyathan. 1995. Role of surface free radicals in the pathogenicity of silica. In *Silica and Silica-induced Lung Diseases*, V. Castranova, V. Vallyathan, and W. E. Wallace, eds. Boca Raton, FL: CRC Press, pp. 91-105.

Cauda, E., A. Miller, and P. Drake. 2015. A new end-of-shift. Monitoring approach for respirable crystalline silica in coal mine dust. In *15th North American Mine Ventilation Symposium*, E. Jong, E. Sarver, S. Schafrik, and K. Luxbacher, eds. Virginia Tech Department of Mining and Minerals Engineering.

Cauda, E., A. Miller, and P. Drake. 2016. Promoting early exposure monitoring for respirable crystalline silica: Taking the laboratory to the mine site. *Journal of Occupational and Environmental Hygiene* 13(6):D39-D45.

Chalmers, D., and C. Harb. 2017. Pilot study in real time respirable silica measurement. In *Proceedings of the 16th North American Mine Ventilation Symposium, June 17-22, 2017, Golden, CO*, J.F. Brune, ed. Littleton, CO: Society for Mining, Metallurgy, and Exploration, pp. 15-9–15-17.

Chow, J. C., J. G. Watson, D. Crow, D. H. Lowenthal, and T. Merrifield. 2001. Comparison of IMPROVE and NIOSH carbon measurements. *Aerosol Science and Technology* 34(1):23-34.

Chow, J. C., J. G. Watson, L. W. Chen, M. C. Chang, N. F. Robinson, D. Trimble, and S. Kohl. 2007. The IMPROVE-A temperature protocol for thermal/optical carbon analysis: Maintaining consistency with a long-term database. *Journal of the Air & Waste Management Association* 57(9):1014-1023.

Clements, A. L., W. G. Griswold, J. E. Johnston, M. M. Herting, J. Thorson, A. Collier-Oxandale, and M. Hannigan. 2017. Low-Cost Air Quality Monitoring Tools: From Research to Practice (A Workshop Summary). *Sensors* 17(11): 2478.

Cohen, A., and M. J. Colligan. 1998. Assessing Occupational Safety and Health Training: A Literature Review, DHHS (NIOSH) Publication No. 98-145 [online]. Available at https://www.cdc.gov/niosh/docs/98-145/pdfs/98-145.pdf (accessed April 26, 2018).

Cohen, R. A., E. L. Petsonk, C. Rose, B. Young, M. Regier, A. Najmuddin, J. L. Abraham, A. Churg, and F. H. Green. 2016. Lung pathology in U.S. coal workers with rapidly progressive pneumoconiosis implicates silica and silicates. *American Journal of Respiratory and Critical Care Medicine* 193(6):673-680.

Cook, D. J. and S. K. Das. 2007. How smart are our environments? An updated look at the state of the art. *Pervasive and mobile computing* 3(2):53-73.

Crilley, L. R., M. Shaw, R. Pound, L. J. Kramer, R. Price, S. Young, A. C. Lewis, and F. D. Pope. 2018. Evaluation of a low-cost optical particle counter (Alphasense OPC-N2) for ambient air monitoring. *Atmospheric Measurement Techniques* 11(2):709.

Damiano, N., G. Homce, and R. Jacksha. 2014. A review of underground coal mine emergency communications and tracking system installations. *Coal Age magazine*, pp. 34-35.

Delal, N. S., M. M. Suryan, V. Vallyathan, F. H. Green, B. Jafari, and R. Wheeler. 1989. Detection of reactive free radicals in fresh coal mine dust and their implication for pulmonary injury. *Annals of Occupational Hygiene* 33(1):79-84.

Dubaniewicz, T. H., and J. E. Chilton. 1995. Fiber optic powered remote gas monitor. In *Optical Engineering Midwest '95* 2622: 285-292.

FLIR. 2017. Airtec™ Diesel Particulate Monitor [online]. Available at http://www.flir.com/instruments/display/?id=57067 (accessed December 14, 2017).

Freedman, R. W., and A. G. Sharkey, Jr. 1972. Recent advances in the analysis of respirable coal dust for free silica, trace elements, and organic constituents. *Annals of the New York Academy of Sciences* 200(1):7-16.

Graber, J. M., G. Harris, K. S. Almberg , C. S. Rose, E. L. Petsonk, R. A. Cohen. 2017. Increasing Severity of Pneumoconiosis Among Younger Former US Coal Miners Working Exclusively Under Modern Dust-Control Regulations. Journal of Occupational Environmental Medicine 59(6):e105–e111.

Griffin, K. R., E. C. Jong, K. D. Luxbacher, and E. C. Westman. 2011. A review of atmospheric monitoring systems in underground coal mines: implications for explosion prevention. In *SME Annual Meeting and Exhibit and CMA 113th National Western Mining Conference 2011*. 683-686. Society for Mining, Metallurgy, and Exploration.

Grimm, H., and D. J. Eatough. 2009. Aerosol measurement: The use of optical light scattering for the determination of particulate size distribution, and particulate mass, including the semi-volatile fraction. *Journal of the Air & Waste Management Association* 59(1):101-107.

Hall, E. E., R. P. Vinson, and J. C. Volkwein. 2006. Evaluation of SKC Inc. dust detective. In *Proceedings of the 11th U.S./North American Mine Ventilation Symposium 2006*, J. M. Mutmansky and R. V. Ramani, eds. Boca Raton, FL: CRC Press, pp. 175-178.

Harper, M., B. Pacolay, P. Hintz, D. L. Bartley, J. E. Slaven, and M. E. Andrew. 2007. Portable XRF analysis of occupational air filter samples from different workplaces using different samplers: final results, summary and conclusions. Journal of Environmental Monitoring 9(11):1263-1270.

Harper, M., K. Sarkisian, and M. Andrew. 2014. Assessment of respirable crystalline silica analysis using proficiency analytical testing results from 2003–2013. *Journal of Occupational and Environmental Hygiene* 45T46T1146T(10):D157-D163.

Harrison, J., P. Brower, M. Attfield, C. Doak, M. Keane, R. Grayson, and W. E. Wallace. 1997. Surface composition of respirable silica particles in a set of U.S. anthracite and bituminous coal mine dusts. *Journal of Aerosol Science* 28:689-696.

Hoffer, D. 2014. What does big data look like? Visualization is key for humans. Wired.com [online]. Available at https://www.wired.com/insights/2014/01/big-data-look-like-visualization-key-humans/ (accessed December 13, 2017).

Huggins, C. W., S. J. Johnson, J. M. Segreti, and J. G. Snyder. 1986. Comparison of the particle size distribution of alpha quartz found in respirable dust samples collected at underground and surface coal mines with four reference standards. In *Electron Microscopy in Forensic, Occupational, and Environmental Health Sciences*, S. Basu and J. R. Millette, eds. Boston, MA: Springer, pp. 187-202.

Hutchins, P. M. 2016. Real-time viable particle monitoring: Principles and benefits for in-process measurements. *American Pharmaceutical Review* December 1 [online]. Available at http://www.americanpharmaceuticalreview.com/Featured-Articles/331674-Real-Time-Viable-Particle-Monitoring-Principles-and-Benefits-for-In-Process-Measurements/ (accessed December 12, 2017).

IARC (International Agency for Research on Cancer). 1997. Aramid Fibrils. IARC Monographs on Evaluation of Carcinogenic Risks to Humans Vol 68. Lyon, France: IARC Press [online]. Available at http://monographs.iarc.fr/ENG/Monographs/vol68/index.php (accessed October 23, 2017).

ILO (International Labour Organization). 2012. Encyclopedia of Occupational Health and Safety, Chapter 18, Education and Training [online]. Available at http://www.ilocis.org/documents/chpt18e.htm (accessed December 8, 2017).

Johann-Essex, V., C. Keles, M. Rezaee, M. Scaggs-Witte, and E. Sarver. 2017. Respirable coal mine dust characteristics in samples collected in central and northern Appalachia. *International Journal of Coal Geology* 182:85-93.

Kissell, F. N., and E. D. Thimons. 2001. Test report on the machine-mounted continuous respirable dust monitor. In *Proceedings of the 7th International Mine Ventilation Congress, June 17-22, 2001, Krakow, Poland*, S. Wasilewski, ed. Krakow, Poland: Research & Development Center for Electrical Engineering and Automation in Mining (EMAG), pp. 253-260.

Koehler, K. A., and T. M. Peters. 2015. New methods for personal exposure monitoring for airborne particles. *Current Environmental Health Reports* 2(4):399-411.

Kosmoski, C. L. 2014. Assessing the safety culture of underground coal mining: Results and recommendations. Available at https://www.cdc.gov/niosh/mining/UserFiles/works/pdfs/atsco.pdf (accessed February 7, 2018).

Laney, A. S., E. L. Petsonk, and M. D. Attfield. 2010. Pneumoconiosis among underground bituminous coal miners in the United States: Is silicosis becoming more frequent? *Occupational and Environmental Medicine* 67(10):652-656.

Li N., C. Sioutas, A. Cho, D. Schmitz, C. Misra, J. Sempf , M. Wang, T. Oberley, J. Froines, A. Nel. 2003. Ultrafine particulate pollutants induce oxidative stress and mitochondrial damage. Environ Health Perspect. 111:455–460.

Lee, J., H. Kao, and S.Yang. 2014. Service innovation and smart analytics for industry 4.0 and big data environment. *Proceedings of the 6th CIRP Conference on Industrial Product-Service Systems* 16:3-8.

Lee, T., L. Lee, E. Cauda, J. Hummer, and M. Harper. 2017. Respirable size-selective sampler for end-of-shift quartz measurement: Development and performance. *Journal of Occupational and Environmental Hygiene* 14(5):335-342.

Lindell, M. K. 1994. Motivational and organizational factors affecting implementation of worker safety training. *Occupational Medicine* 9(2):211-240.

Lintelmann, J., K. Fischer, and G. Matuschek. 2006. Determination of oxygenated polycyclic aromatic hydrocarbons in particulate matter using high-performance liquid chromatography–tandem mass spectrometry. *Journal of Chromatography A* 1133(1-2):241-247.

Liu, F., Y. Han, L. Du, P. Huang, and J. Zhe. 2016. Airborne mineral dust measurement using an integrated microfluidic device. *Microfluidics and Nanofluidics* 20:27.

Maguire, R. 2006. So how do you make a full ALARP justification? Introducing the accident tetrahedron as a guide for approaching completeness. In *Developments in Risk-based Approaches to Safety: Proceedings of the Fourteenth Safety-critical Systems Symposium, 7-9 February 2006, Bristol, UK*, F. Redmill and T. Anderson, eds. London: Springer, pp. 69-80.

Miller, A. L., N. C. Murphy, S. J. Bayman, Z. P. Briggs, A. D. Kilpatrick, C. A. Quinn, M. R. Wadas, E. G. Cauda, and P. R. Griffiths. 2015. Evaluation of diffuse reflection infrared spectrometry for end-of-shift measurement of α-quartz in coal dust samples. *Journal of Occupational and Environmental Hygiene* 12(7):421-430.

Miller, A. L., A. T. Weakley, P. R. Griffiths, E. G. Cauda, and S. Bayman. 2017. Direct-on-filter α-quartz estimation in respirable coal mine dust using transmission Fourier transform infrared spectrometry and partial least squares regression. *Applied Spectroscopy* 71(5):1014-1024.

Mine Safety Technology and Training Commission. 2006. Improving Mine Safety Technology and Training: Establishing U.S. Global Leadership. December 2006 [online]. Available at http://www.indiaenvironmentportal.org.in/files/mining%20safety_report.pdf (accessed December 13, 2017).

Monforton, C., and R. Windsor. 2010. An impact evaluation of a federal mine safety training regulation on injury rates among U.S. stone, sand, and gravel mine workers: An interrupted time-series analysis. *American Journal of Public Health* 100(7):1334-1340.

MSHA (Mine Safety and Health Administration). 2013a. 45TX-Ray Diffraction Determination of Quartz and Cristobalite in Respirable Mine Dust. Method P-2.45T [online]. Available at https://arlweb.msha.gov/Techsupp/pshtcweb/MSHA%20P2.pdf (accessed December 14, 2017).

MSHA. 2013b. Infrared Determination of Quartz in Respirable Coal Mine Dust. Method No. P-7 [online]. Available at https://arlweb.msha.gov/TECHSUPP/pshtcweb/MSHA%20P7.pdf (accessed December 14, 2017).

Müller, T., A. Schladitz, K. Kandler, and A. Wiedensohler. 2011. Spectral particle absorption coefficients, single scattering albedos and imaginary parts of refractive indices from ground based in situ measurements at Cape Verde Island during SAMUM-2. *Tellus* 63(4):573-588.

NIOSH (National Institute for Occupational Safety and Health). 1995. 16TCriteria for a Recommended Standard-Occupational Exposure to Respirable Coal Mine Dust.16T DHHS (NIOSH) Publ. No. 95-

106. U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, NIOSH, Cincinnati, OH [online]. Available at https://www.cdc.gov/niosh/docs/95-106/pdfs/95-106.pdf (accessed October 20, 2017).

NIOSH. 1997. Machine-mounted continuous respirable dust monitor. *Technology News* 463. July 1997 [online]. Available at https://www.cdc.gov/niosh/mining/UserFiles/works/pdfs/463.pdf (accessed October 25, 2017).

NIOSH. 2003a. Silica Crystalline by IR (KBr pellet). Method 7602 [online]. Available at https://www.cdc.gov/niosh/docs/2003-154/pdfs/7602.pdf (accessed December 14, 2017).

NIOSH. 2003b. Quartz in Coal Mine Dust, by IR (Redeposition). Method 7603 [online]. Available at https://www.cdc.gov/niosh/docs/2003-154/pdfs/7603.pdf (accessed December 14, 2017).

NIOSH. 2008. Work-Related Lung Disease Surveillance System (eWoRLD) 2008-171. U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, Respiratory Health Division, Morgantown, WV [online]. Available at https://wwwn.cdc.gov/eworld/Data/Respirable_coal_mine_dust_Geometric_mean_exposures_and_percent_exceeding_designated_occupational_exposure_limits_by_type_of_mine_MSHA_inspector_and_mine_operator_samples_1979-2003/171 (accessed February 22, 2017).

NIOSH. 2015. Exposure Monitoring of Dust and Toxic Substances [online]. Available at https://www.cdc.gov/niosh/mining/topics/monitoringdust.html (accessed December 14, 2017).

NIOSH. 2016a. Number and rate of occupational mining fatalities for coal operators at underground work locations by year, 2006-2015. Available at https://www.cdc.gov/niosh/mining/UserFiles/statistics/15g09uoc.svg (accessed February 7, 2018).

NIOSH. 2016b. Number and rate of coal mining operator nonfatal lost-time injuries at underground work locations by year, 2006-2015. Available at https://www.cdc.gov/niosh/mining/UserFiles/statistics/15g09uoc.svg (accessed February 7, 2018).

Noll, J. D., and S. Janisko. 2013. Evaluation of a wearable monitor for measuring real-time diesel particulate matter concentrations in several underground mines. *Journal of Occupational and Environmental Hygiene* 10(12):716-722.

Noll, J., S. Janisko, and S. E. Mischler. 2013. Real-time diesel particulate monitor for underground mines. *Analytical Methods* 5(12):2954-2963.

Noll, J., A. Cecala, J. Organiscak, and S. Janisko. 2014. Real-time DPM monitoring. *Engineering & Mining Journal* 215(6):78 [online]. Available at http://www.e-mj.com/features/4217-real-time-dpm-monitoring.html#.WjLKlFWnGHs (accessed December 8, 2017).

Novak, T., D. P. Snyder, and J. L. Kohler. 2010. Post-accident mine communications and tracking systems. *IEEE Transactions on Industry Applications* 46(2):712-719.

NRC and IOM (National Research Council and Institute of Medicine). 2007. *Mining Safety and Health Research at NIOSH: Reviews of Research Programs of the National Institute for Occupational Safety and Health*. Washington, DC: The National Academies Press.

OSHA (Occupational Safety and Health Administration). 2010. Best Practices for the Development, Delivery, and Evaluation of Susan Harwood Training Grants, 2010 [online]. Available at https://www.osha.gov/dte/sharwood/best-practices.html (accessed December 8, 2017).

OSHA. 2015. Resource for the Development and Delivery of Training to Workers [online]. Available at https://www.osha.gov/Publications/osha3824.pdf (accessed December 8, 2017).

Page, S. J. 2006. Crystalline silica analysis: A comparison of calibration materials and recent coal mine dust size distributions. *Journal of ASTM International* 3(1):1-14. https://pdfs.semanticscholar.org/cd01/c36a3a5c261116bf8cd3ce49865f627cef87.pdf (accessed December 8, 2017).

Phillips, K. T. 2017. Applications of Thermal and Laser-Based Methods for Monitoring Airborne Particulates in Coal Mines. M.S. Thesis. Virginia Polytechnic Institute, Blacksburg, VA [online]. Available at https://vtechworks.lib.vt.edu/bitstream/handle/10919/79386/Phillips_KT_T_2017.pdf?sequence=1&isAllowed=y (accessed December 8, 2017).

Phillips, K., C. Keles, M. Scaggs, V. Johann, M. Rezaee, and E. Sarver. 2017. Comparison of coal vs. mineral mass fractions in respirable dust in Appalachian coal mines. In *Proceedings of the* 16th North American Mine Ventilation Symposium, June , 2017, Golden, CO. J. F. Brune, ed. Colorado School of Mines, pp. 7-1 – 7-9.

Pillai, M. A., S. Veerasingam, and D. Y. Sai. 2010. CAN based smart sensor network for indoor air quality monitoring. In *Computer Science and Information Technology (ICCSIT)* 8:456-460.

Rai, A. C., P. Kumar, F. Pilla, A. N. Skouloudis, S. Di Sabatino, C. Ratti, A. Yasar, and D. Rickerby. 2017. End-user perspective of low-cost sensors for outdoor air pollution monitoring. *Science of The Total Environment* 607:691-705.

Ramani, R. V., J. M. Mutmansky, H. He, J. C. Volkwein, V. A. Marple, B. A. Olson, and P. C. Luna. 2001. A comparative evaluation of the differential pressure-based respirable dust dosimeter with the personal gravimetric respirable dust sampler in underground coal mines. In *Proceedings of the 7th International Mine Ventilation Congress, June 17-22, 2001, Krakow, Poland*, S. Wasilewski, ed. Krakow, Poland: Research & Development Center for Electrical Engineering and Automation in Mining (EMAG), pp. 243-251.

Ramani, R. V., V. A. Marple, J. M. Mutmansky, J. C. Volkwein. B. A. Olson, H. He, and P. C. Luna. 2002. Evaluation of the respirable dust dosimeter for real-time assessment of airborne respirable coal mine dust exposures. In *Proceedings of the North American/9th U.S. Mine Ventilation Symposium, June 8-12, 2002, Kingston, Ontario, Canada*, A. A. De Souza, ed. Boca Raton, FL: CRC Press, pp. 579-586.

Ramamurthy, H., B. S. Prabhu, R. Gadh, and A. M. Madni. 2007. Wireless industrial monitoring and control using a smart sensor platform. *IEEE sensors journal* 7(5): 611-618.

Raymond, C. M., I. Fazey, M. S. Reed, and L. C. Stringer. 2010. Integrating local and scientific knowledge for environmental management. *Journal of Environmental Management* 91:1766-1777.

Reynolds L, C. N. Halldin, A. S. Laney AS, D. J. Blackley. 2017. Coal miner participation in a job transfer program designed to prevent progression of pneumoconiosis, United States, 1986–2016. *Arch Environ Occup Health*. November 2017:1-3.

Robson, L., C. Stephenson, P. Schulte, B. Amick, S. Chan, A. Bielecky, A. Wang, T. Heidotting, E. Irvin, D. Eggerth, R. Peters, J. Clarke, K. Cullen, L. Boldt, C. Rotunda, and P. Grubb. 2010. A Systematic Review of the Effectiveness of Training and Education for the Protection of Workers. DHHS (NIOSH) Publication No. 2010-127 [online]. Available at https://www.cdc.gov/niosh/docs/2010-127/pdfs/2010-127.pdf (accessed April 26, 2018).

Rowland III, J. H., S. P. Harteis, and L. Yuan. 2018. A survey of atmospheric monitoring systems in US underground coal mines. *Mining engineering* 70(2):37.

Sapko, M. J., K. L. Cashdollar, and G. M. Green. 2007. Coal dust particle size survey of U.S. mines. *Journal of Loss Prevention in the Process Industries* 20(4-6):616-620.

Scaggs, M., E. Sarver, and C. Keles. 2015. Considerations for TGA of respirable coal mine dust samples. *15th North American Mine Ventilation Symposium*, E. Jong, E. Sarver, S. Schafrik, and K. Luxbacher, eds. Virginia Tech Department of Mining and Minerals Engineering [online]. Available at https://vtechworks.lib.vt.edu/bitstream/handle/10919/73748/Scaggs%20et%20al.%2C%20TGA%2015-48.pdf?sequence=4&isAllowed=y (accessed December 8, 2017).

Schatzel, S. J. 2009. Identifying sources of respirable quartz and silica dust in underground coal mines in southern West Virginia, western Virginia, and eastern Kentucky. *International Journal of Coal Geology* 78(2):110-118.

Scherließ, R. 2016. Particle size measurements in aerosols. In *Analytical Techniques in the Pharmaceutical Sciences*, A. Müllertz, Y. Perrie, and T. Rades, eds. New York: Springer, pp. 701-715.

Seixas, N. S., T. G. Robins, M. D. Attfield, and L. H. Moulton. 1992. Exposure-response relationships for coal mine dust and obstructive lung disease following enactment of the Federal Coal Mine Health and Safety Act of 1969. *American Journal of Industrial Medicine* 21(5):715-734.

Seixas, N. S., P. Hewett, T. G. Robins, and R. Haney. 1995. Variability of particle size-specific fractions of personal coal mine coal dust exposures. *American Industrial Hygiene Association Journal* 56(3):243-250.

Sellaro, R., E. Sarver, and D. Baxter. 2015. A standard characterization methodology for respirable coal mine dust using SEM-EDX. *Resources* 4(4):939-957.

Sokas, R. K., E. J. Nickels, W. Gao, and J. L. Gittleman. 2009. An intervention effectiveness study of hazard awareness training in the construction building trades. *Public Health Reports* 124(Suppl 1):161-168.

Suarthana, E., A. S. Laney, E. Storey, J. M. Hale, and M. D. Attfield. 2011. Coal workers' pneumoconiosis in the United States: Regional differences 40 years after implementation of the 1969 Federal Coal Mine Health and Safety Act. *Occupational and Environmental Medicine* 68(12):908-913.

Sunderman, C. and J. Waynert. 2012. An overview of underground coal miner electronic tracking system technologies. In *Industry Applications Society Annual Meeting (IAS)*, pp. 1-5.

Taha, H. A. 2007. *Operations Research: An Introduction*, 8th ed. Upper Saddle River, NJ: Pearson Prentice Hall.

Thompson, J. E. 2016. Crowd-sourced air quality studies: A review of the literature & portable sensors. *Trends in Environmental Analytical Chemistry* 11:23-34.

TSI. 2017a. Optical Particle Sizer 3330 [online]. Available at http://www.tsi.com/optical-particle-sizer-3330/ (accessed December 14, 2017).

TSI. 2017b. Nanoscan SMPS Nanoparticle Sizer 3910 [online]. Available at http://www.tsi.com/nanoscan_smps_nanoparticle_sizer_3910/ (accessed December 8, 2017).

Tuchman, D. P., J. C. Volkwein, and R. P. Vinson. 2008. Implementing infrared determination of quartz particulates on novel filters for a prototype dust monitor. Journal of Environmental Monitoring 10(5):671-678.

Vallyathan, V., X. Shi, and V. Castranova. 1998. Reactive oxygen species: Their relation to pneumoconiosis and carcinogenesis. Environmental Health Perspectives 106(Suppl 5):1151-1155.

Vallyathan, V., D. P. Landsittel, E. L. Petsonk, J. Kahn, J. E. Parker, K. T. Oslowy, and F. H. Green. 2011. The influence of dust standards on the prevalence and severity of coal worker's pneumoconiosis at autopsy in the United States of America. *Archives of Pathology & Laboratory Medicine* 135(12):1550-1556.

Volkwein, J. C., and E. D. Thimons. 2001. New tools to monitor personal exposure to respirable coal mine dust. In *Proceedings of the 7th International Mine Ventilation Congress, June 17-22, 2001, Krakow, Poland*, S. Wasilewski, ed. Krakow, Poland: Research & Development Center for Electrical Engineering and Automation in Mining (EMAG), pp. 143-150.

Volkwein, J. C., A. L. Schoeneman, and S. J. Page. 1999. Laboratory evaluation of pressure differential based respirable dust tube. In *Proceedings of the 8th U.S. Mine Ventilation Symposium, June 11-17, 1999, Rolla, MO*, J. C. Tien, ed. Rolla, MO: University of Missouri-Rolla Press, pp. 255-261.

Volkwein, C., A. Hansen, and J. Hill. 2016. 16TNew sensor for continuous tracking of diesel particulate matter in mines to optimize mine ventilation systems. In *The Future for Mining in a Data–Driven World: 16TSME Annual Conference & Expo, February 24-26, 2016, Phoenix, AZ.* Red Hook, NY: Curran Associates, Inc., pp. 128-131.

Volkwein, J. C., C. Barrett, E. Sarver, and A. D. A. Hansen. 2017. Application of an environmental 'black carbon' particulate sensor for continuous measurement of DPM in three underground mines. Presentation at the Australian Mine Ventilation Conference, August 27-31, 2017, Brisbane, Australia.

Wallace, W. E., J. C. Harrison, R. L. Graysone, M. J. Keane, P. Bolsaitis, R. D. Kennedy, A. Q. Wearden, and M. D. Attfield. 1994. Aluminosilicate surface contamination of respirable quartz particles from coal mine dusts and from clay works dusts. *Annals of Occupational Hygiene* Special Issue: Inhaled Particles VII 38:439-445.

Wallace, W. E., J. Chen, J. Harrison, V. Hnizdo, W. Chen, J. Nelson, W. Chisholm, E. Hnizdo, M. J. Keane, and W. E. Miller. 2002. Respirable silica particle occlusion by alumino-silicate: Surface properties of dusts with disease risk anomalies. *Med Lav* 93(Suppl):S24.

Wallace, K., B. Prosser, and J. D. Stinnette. 2015. The practice of mine ventilation engineering. *International Journal of Mining Science and Technology* 25(2):165-169.

Walton, W. H., J. Dodgson, G. G. Hadden, and M. Jacobsen. 1977. The effect of quartz and other non-coal dusts in coal workers' pneumoconiosis. In *Inhaled Particles IV Part 2*, W. H. Walton, ed. Oxford: Pergamon Press, pp. 669-689.

Wang, W., Y. Wang, and G. Shi. 2015. Experimental investigation on the infrared refraction and extinction properties of rock dust in tunneling face of coal mine. *Applied Optics* 54(35):10532-10540.

Wang, Z., R. Yang, and L. Wang. 2010. Multi-agent control system with intelligent optimization for smart and energy-efficient buildings. In *IECON 2010-36th Annual Conference on IEEE Industrial Electronics Society*, pp. 1144-1149.

Weinstock, D., and C. Slatin. 2012. Learning to take action: The goals of health and safety training. *New Solutions* 22(3):255-267.

Williams, B. K., and E. D. Brown. 2014. Adaptive management: From more talk to real action. *Environmental Management* 53(2):465-479.

Wolfe, P. J. 2013. Making sense of big data. *Proceedings of the National Academy of Sciences of the United States of America* 110(45):18031-18032.

Zhang, Y., W. Yang, D. Han, and Y. Kim. 2014. An integrated environment monitoring system for underground coal mines—wireless Sensor Network subsystem with multi-parameter monitoring. *Sensors* 14(7):13149-13170.

Zipf, E. K., W. Marchewka, K. Mohamed, J. Addis, and F. Karnack. 2013. Tube bundle system: For monitoring of coal mine atmosphere. *Minerals Engineering* 65(5):57-63.

6

Overall Conclusions and Recommendations

Based on discussions in the previous chapters of this report, this chapter presents overall conclusions for trends in disease epidemiology and mining practices and the specific items listed in the committee's statement of task (see Appendix A). The chapter also recommends research and development activities to address important information gaps regarding monitoring and sampling approaches for controlling mine workers' exposure to respirable coal mine dust (RCMD).

TRENDS IN DISEASE EPIDEMIOLOGY AND MINING PRACTICES

Conclusion 1.1: The purpose of the Federal Coal Mine Health and Safety Act of 1969 was to protect the health and safety of the nation's coal miners. The regulatory focus on controlling the RCMD mass concentration and silica-mass concentration has not changed over the past several decades. That approach has been associated with a substantial decline in rates of coal workers' pneumoconiosis (CWP) from 1970 to 2000 across all coal mining regions in the United States. However, since around the year 2000, an increase in cases of rapidly progressive pneumoconiosis has been observed in various hot-spot geographic areas. *(see Chapter 1)*

Conclusion 1.2: Changes in mining practices and conditions (for example, increases in equipment size and horsepower and mining increasingly thinner coal seams) have resulted in an increased extraction of rock. Crystalline silica, silicates, and other RCMD components contributed by rock extraction likely play an important role in relationships between exposure and health outcomes. *(see Chapter 1)*

Conclusion 1.3: The requirements of the 2014 dust rule that went into effect on February 1, 2016, lowered the allowable airborne RCMD mass concentration in underground mines. However, most miners incurred much of their exposures when previous regulations were in effect. Given that the latency period of CWP disease onset is typically 10 or more years, sufficient time has not elapsed to assess the effect of the 2014 dust rule on disease incidence. It is important to note, that compliance with regulatory requirements by itself is not an adequate indicator of the rule's effectiveness in protecting miners' health. *(see Chapter 1)*

EFFICACY OF CURRENT MONITORING AND SAMPLING IN UNDERGROUND MINES IN THE UNITED STATES

Conclusion 2.1: Continuous personal dust monitors (CPDMs) are being used to comply with the monitoring and sampling requirements of the 2014 dust rule. The ability to measure exposures in near real time by using CPDMs is an important technologic advancement compared to monitoring methods used previously. If a measurement collected over a full shift exceeds allowable limits, mine operators must take corrective actions immediately. In addition, miners wearing CPDMs receive information about their personal exposures and sometimes can modify their activities or locations within a mine in response to elevated readings. *(see Chapters 1 and 4)*

Conclusion 2.2: CPDMs worn by individual miners in designated occupations are used to determine whether mine operators maintain RCMD concentrations at or less than the allowable exposure concentration. However, only a small fraction of coal miners are required to use a CPDM during any given shift, and it is possible that those coal miners using the CPDMs are not representative of the dust exposure to other miners who are not using the CPDMs. When miners wearing CPDMs react to high monitor readings to reduce their personal dust exposure (for example, by altering their locations while carrying out their job duties), the required RCMD measurements might no longer be representative of the miners with the highest exposures. Whether demonstrations of compliance with allowable RCMD exposure concentration are being achieved only for those miners wearing the CPDM, or for all personnel in the work area, is unknown. *(see Chapter 4)*

Conclusion 2.3: Changes in mining technologies during the past several decades might have led to changes in typical particle-size distributions of RCMD. If so, there might have been a change in the relationship between CPDM measurements of RCMD mass concentrations and the health effects associated with particle type, size, concentration, and deposition, in the lung. *(see Chapters 1 and 4)*

OPTIMAL MONITORING AND SAMPLING STRATEGIES TO AID MINE OPERATORS' DECISION MAKING

Conclusion 3.1: The primary impetus for optimal sampling and monitoring strategies is the protection of worker health through reduction in disease risk. The strategies are conceived to enhance the reduction of health risks in recognition of practical constraints (such as costs, availability of technology, existing regulatory requirements, and program acceptance by various stakeholders). *(see Chapter 5)*

Conclusion 3.2: Optimal sampling and monitoring strategies manifest as programs that, in principle, exhibit these attributes:

- Aiding mine operators' decision making related to reducing RCMD exposures in a maintainable manner with data that are representative of high-exposure episodes and cumulative exposures over the long-term for all workers throughout the mine, not only the ones wearing a monitoring instrument.
- Supporting the decision-making ability of individual mine workers to protect themselves through training in the use of CPDMs and education concerning important factors that affect exposure-response relationships.
- Monitoring characteristics of RCMD particles that are directly related to the risk of occupational cardiopulmonary disease. Using appropriate tools and methods to collect samples that are representative of the dust to which mine workers are or may be exposed.
- Applying various monitoring technologies in engineering studies of RCMD exposure variability and exposure mitigation approaches.
- Integrating RCMD monitoring data with associated contextual information, such as sampling locations and frequencies, environmental and operational conditions during sampling and other periods, and general knowledge of the health risks associated with the RCMD exposure metrics being monitored.
- Involving a suitable and acceptable system of medical surveillance that provides regular, no-cost medical examinations for all miners to help assess the efficacy of exposure reduction efforts.
- Making integrated data readily available, accessible, and usable for timely decision making.
- Striving for continuous improvement in disease risk reduction, including periodic performance review and necessary modifications, and reaction to changes that remove or eliminate previous constraints. *(see Chapter 5)*

EFFECTS OF ROCK DUSTING ON RCMD MEASUREMENTS

Conclusion 4.1: Measurements of airborne RCMD concentrations include respirable rock dust particles, by definition. However, it appears that complying with the rock-dusting requirements (30 Code of Federal Regulations [CFR] 75.2 and 30 CFR 75.402-403) has not been a large obstacle to demonstrating compliance with the 2014 dust rule. It is critical that efforts to comply with the rock-dusting requirements and RCMD requirements not compromise the effectiveness of either explosion mitigation or RCMD exposure reduction. *(see Chapter 2)*

SAMPLING AND MONITORING PRACTICES USED IN DIFFERENT INDUSTRIALIZED COUNTRIES

Conclusion 5.1: Differences in exposure monitoring and sampling approaches among major coal-producing countries make it difficult to compare exposure measurements among different countries directly. Despite those differences, there are important commonalities, such as using gravimetric sampling devices to monitor mass concentrations of RCMD and silica. Those commonalities point to potential opportunities for harmonizing monitoring data collected in different countries, including RCMD and silica content. Additionally, a more complete understanding of international approaches to medical surveillance for coal mine dust diseases, including strengths and limitations, would lead to opportunities for improved understanding of the relationships between RCMD exposure and disease prevalence and ensuring that monitoring approaches are targeting the most important aspects of RCMD exposures. *(see Chapter 3)*

Conclusion 5.2: The various approaches to medical surveillance among coal-producing countries warrant an in-depth and appropriately critical analysis, which was beyond the scope of this report. Such an analysis would provide insight into the country-specific prevalence of RCMD-related diseases over time and would inform an understanding of the success of various strategies for monitoring and controlling exposures. *(see Chapter 3)*

RECOMMENDATIONS

The statement of task asked the committee to identify important research gaps regarding monitoring and sampling protocols for controlling miners' RCMD exposures. The recommendations provided in this section include research and development activities to address the gaps identified by the committee. It is important to note, however, that the committee makes no recommendation concerning the requirements of the 2014 dust rule or the implementation of those requirements.

Challenges in Implementing Optimal Monitoring and Sampling Practices

Historically, the primary focus of RCMD sampling and monitoring efforts had been based on compliance with federal regulations. Additional sampling efforts were undertaken by coal mine operators to support improvements in mine ventilation and other dust controls, for instance to resolve noncompliance conditions. Over three decades, the compliance-driven approach led to a significant reduction in the rates of lung diseases associated with occupational exposure to RCMD among U.S. coal miners. However, it has not resulted in attainment of the ultimate goal of the Coal Mine Health and Safety Act of 1969, which is to eliminate such diseases. To continue progress toward reaching this goal, a fundamental shift is needed in the way that coal mine operators approach RCMD control, and thus sampling and monitoring.

Relative to the findings in this report, it is clear that an optimal sampling and monitoring strategy needs to support RCMD control efforts that go beyond compliance with regulations. This report offers a detailed discussion of various components that might comprise such a strategy, and it identifies several possible challenges to implementation. It is important to note that the coal mine industry has faced similar challenges previously in the realm of beyond-compliance efforts. Most notably, the industry has worked for widespread adoption of a comprehensive safety management systems approach for pursuing the goal of zero accidents and injuries. As part of that approach, the industry recognized compliance as only a starting point in an effective process of safety risk management.

> **Recommendation 1:** The National Institute for Occupational Safety and Health (NIOSH) and other organizations, such as the National Mining Association and the unions representing miners, should conduct a comprehensive investigation to identify key challenges that coal mine operators face in implementing an optimal, beyond-compliance approach to RCMD exposure monitoring and sampling for informing exposure control efforts. The organizations conducting the investigation also should recommend practical solutions for overcoming those challenges. *(see Chapter 5)*

Consideration of All Miners' Exposures

RCMD Exposures of Mine Workers Not Wearing CPDMs

> **Recommendation 2:** Conduct studies to evaluate the exposures of miners not wearing CPDMs to ensure that the approach of detecting and mitigating high-exposures for designated occupations reliably results in mitigating high exposures of all workers. *(see Chapters 4 and 5)*

Consistency and Effectiveness of Worker Training and Education Programs Across the Coal Industry Regarding RCMD Exposures

Training in the use of CPDMs and education concerning important factors that affect exposure-response relationships can enhance workers' ability to take precautions that reduce RCMD exposures. It is important to ensure that training and education programs are implemented in a consistent manner across the coal mining industry.

> **Recommendation 3:** NIOSH and MSHA should carry out a systematic examination of the content and implementation of training and education programs with respect to RCMD exposure. The examination should focus not simply on curricula, but also on the way adults learn. It should seek ways of implementing education and training programs in an effective and consistent manner across the coal mining industry. As a part of being effective, the programs should be relevant to all mine workers, not just the ones who wear CPDMs, as well as to operators and regulators. Programs should be assessed after they have been implemented for a few years to determine their overall effectiveness. *(see Chapters 4 and 5)*

Monitoring Devices

Particle Size Distribution Represented by Cyclone Sampler Data

> **Recommendation 4:** NIOSH, in collaboration with the Mine Safety and Health Administration (MSHA), should evaluate whether 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 (CMDLD) is similar to the relationship established decades ago, when the monitoring devices used for sampling were first adopted. In studying the particle-size distribution in modern-mining RCMD samples and their relationship to the particles deposited in the lung, it is important to consider associations with or implications in the development of CMDLD. *(see Chapter 4)*

Real-Time Monitoring of Crystalline Silica

The health hazards posed by crystalline silica exposure warrant greater focus on developing improved sampling and monitoring techniques.

> **Recommendation 5:** Develop a real-time crystalline silica monitor. As an interim measure, NIOSH should continue its efforts to develop an end-of-shift silica monitor. *(see Chapter 5)*

Disincentives for Mine Operators' Use of Personal Monitoring Devices for Engineering Studies

Although CPDMs have the potential to be used by operators for engineering studies of exposure mitigation approaches, the predominant use is for determining regulatory compliance by providing end-of-shift readings. Disincentives for nonregulatory applications include the size and cost of the device, and requirements to notify MSHA in advance of using the CPDM for purposes other than determining compliance.

> **Recommendation 6:** NIOSH should continue to facilitate the development of a less costly and less ergonomically stressful real-time RCMD monitoring device that would facilitate the use of the personal monitors for engineering studies and other purposes in addition to compliance monitoring. As part of that effort, NIOSH should incorporate appropriate filter media that is compatible with an end-of-shift analyzer for respirable crystalline. *(see Chapters 4 and 5)*

RCMD Spatial and Temporal Information

Area monitoring, which involves the use of measurement devices at fixed locations in underground mines, is critical for understanding environmental and operational factors that influence the concentration and particle characteristics of RCMD.

> **Recommendation 7:** Explore the broader use of area monitoring devices for gathering trends information on RCMD concentrations and particle characteristics in underground mines. *(see Chapters 4 and 5)*

RCMD Exposure and Disease Rates

Association of Changes in Mining Technology and Activities with the Occurrence of Disease Hot Spots

> **Recommendation 8:** Conduct a systematic evaluation of changes in mining technology and activities to determine the extent to which those changes have caused increased extraction of rock and the extent to which past rock extraction had been co-located with disease hot spots. The evaluation should identify important focus areas for optimal sampling and monitoring strategies in the future. *(see Chapters 1 and 5)*

Key Characteristics of RCMD Particles to Be Monitored by Future Exposure Studies

> **Recommendation 9:** NIOSH should conduct or facilitate a comprehensive assessment of RCMD particle characteristics, including their variability, to help target future exposure studies, because different particle characteristics (for example, composition and surface area) can pose different health hazards. In addition, the assessment should characterize and quantify important source contributions to airborne RCMD, including rock dusting and extraction of

rock strata adjacent to the mined coal seam. To the extent possible, NIOSH should assess how RCMD characteristics have changed over time and consider making provisions for tracking temporal trends in the future. Further research and development are needed to improve analytic methods for evaluating source contributions of RCMD. *(see Chapter 5)*

Efficacy of Exposure Reduction Efforts in Reducing Disease Risks

No specific medical treatment is effective in reversing coal mine dust lung diseases or in controlling disease progression. Consequently, efforts to minimize RCMD exposure along with medical surveillance for early disease detection and removal from exposure are the mainstays in protecting a miner's health.

Since around the year 2000, an increase in cases of rapidly progressive pneumoconiosis observed in various hot-spot geographic areas points to a need for an in-depth evaluation to identify key risk factors, some of which might be more strongly associated with certain RCMD components rather than RCMD mass concentration.

Medical surveillance of miners that includes comprehensive occupational histories containing details of mining processes and exposures (for example, chronology of specific mine employment, duration of work at the coal face, job titles and duties, and use of respiratory protection) is an important tool for understanding disease trends and risk factors and assessing the efficacy of exposure monitoring and reduction efforts.

Recommendation 10: Link medical surveillance programs directly with exposure monitoring programs and integrate health-related data on active and retired mine workers. *(see Chapters 1 and 5)*

Disincentives for Participation in Voluntary Medical Surveillance

The lack of worker participation in medical surveillance impairs the effectiveness of that tool for assessing the efficacy of exposure reduction efforts.

Recommendation 11: Elucidate factors that act as disincentives for participation in the voluntary portions of the NIOSH medical surveillance programs and in the MSHA Part 90 Program, with the goal of addressing those disincentives and improving participation rates. *(see Chapters 1 and 5)*

Opportunities for Using Data from Coal-Producing Countries for Epidemiologic Research

Recommendation 12: Conduct a comprehensive assessment of the requirements for exposure monitoring, including RCMD and silica mass content, and medical surveillance as well as the implementation of those requirements in major coal-producing countries. The assessment should identify opportunities for data harmonization and the use of that data for improving exposure monitoring approaches and conducting epidemiologic research. *(see Chapter 3)*

Research Capacity and Resources

Reliable information on RCMD exposures in underground coal mines is crucial for predicting, reducing, and preventing miners' disease risks. As the committee has identified a number of important information needs, NIOSH and other organizations clearly will need sufficient capacity and resources to carry out the recommended activities. The committee also recognizes that some of the recommendations may be difficult to undertake, and that sufficient resources may not be available to undertake them all in the near term. For example, an experimental mine, such as the former Lake Lynn facility, is currently not available to conduct full-scale underground mine testing. (*see Chapter 2*)

In addition, implementing the committee's recommendations will require a commitment by all parties to collaborate. A case in point would be the conduct of field testing in working mines to assess RCMD concentration variability caused by different sources within the mines.

> **Recommendation 13:** NIOSH, MSHA, and other organizations should set priorities for addressing the committee's recommendations and develop a strategy for addressing them. Federal agencies should provide the capability for research to be conducted in an experimental underground mine. Federal, academic, and coal mine industry researchers should seek opportunities for conducting collaborative research and development activities.

Appendix A

Statement of Task

Statement of Task: An ad hoc committee will assess monitoring and sampling approaches for informing underground coal mine operators' decision making regarding the control of respirable coal mine dust and mine worker exposure. The committee will

- Compare the monitoring technologies and sampling protocols (including sampling frequency) currently used or required in the United States, and in similarly industrialized countries for the control of respirable coal mine dust exposure in underground coal mines.
- Assess the effects of rock dust mixtures and their application, as required by current U.S. regulations, on respirable coal mine dust measurements.
- Assess the efficacy of current monitoring technologies and sampling approaches and develop science-based conclusions regarding optimal monitoring and sampling strategies to aid mine operators' decision making related to reducing respirable coal mine dust exposure to miners in underground coal mines.

The committee will identify important research gaps regarding monitoring and sampling protocols for controlling miners' exposure to coal mine dust. It will not recommend changes to the requirements of the Mine Safety and Health Administration's final rule for lowering miners' exposure to respirable coal mine dust, as the development of those requirements involves considerations beyond the scientific and technical focus of this study.

Appendix B

Committee Member Biosketches

Thure E. Cerling (NAS), *Chair*, is a Distinguished Professor of Geology and Geophysics and Distinguished Professor of Biology at the University of Utah. His research focuses on near-surface processes and the geological record of ecological change, particularly using geochemical proxies to understand the physiology and paleodiets of mammals, using soils as indicators of climatological and ecological change over geological timescales, landscape evolution over the past several million years, and isotopes as used in forensic studies. Dr. Cerling currently serves on the National Academies Committee on Earth Resources and he previously has served on several National Academies committees, including the Board on Earth Sciences and Resources (BESR), the U.S. Geodynamics Committee, and the U.S. National Committee for the International Union for Quaternary Research. He was a member of the U.S. Nuclear Waste Technical Review Board from 2002 to 2011. Dr. Cerling is a member of the National Academy of Sciences. He is a fellow of the American Association for the Advancement of Science, the American Geophysical Union, the Geological Society of America, and the International Association of Geochemistry. Dr. Cerling received a Ph.D. in geology from the University of California at Berkeley.

Dirk Dahmann has been technical director and head of the Department of Research and Development on dust and aerosols at the Institut für Gefahrstoff-Forschung (IGF) (Institute for Hazardous Substances), formerly Silikose-Forschungsinstitut, until his retirement in October 2017. Dr. Dahmann's research interests include aerosols in working places, nanoparticles/ultrafine particles, exposure measurements, and sampling of dust and aerosols. He has written numerous publications about dust sampling and was actively involved in the German NanoCare project, which focused on the systematic investigation of nanoscaled materials, and several follow-up projects of German and/or European sponsorship. He is also active in research on silica, systematic exposure assessment on a scientific base, and exposure by diesel particles. Additionally, he has participated in several large international and national research programs within the scope of the European Union (EU) coal and steel program from the late 1980s, as well as various national and international standardization committees. Dr. Dahmann has served on the advisory board of the Research Association for Diesel Emission Control Technologies (FAD) since 2003. He is head of the German standardization committee on dust measurement in workplace air and as such German speaker in the European Standardization committee TC 137 WG 3 (Workplace exposure). He has a Ph.D. in silicon phosphorus chemistry from the Ruhr-Universität Bochum.

R. Larry Grayson was the George H., Jr., and Anne B. Deike Chair in Mining Engineering and Professor of Energy & Mineral Engineering at The Pennsylvania State University from July 2007 through June 2013. At Penn State, he oversaw the Mining Engineering program and the graduate program. For 8 years previously, he was the Chair, Department of Mining & Nuclear Engineering at the University of Missouri-Rolla (UMR). During that time, he was the Director of the National Institute for Occupational Safety and Health (NIOSH)-funded Western Mining Safety & Health Training and Translation Center for 5 years. Following the mine tragedies in 2006, Dr. Grayson chaired the Mine Safety Technology & Training Commission, which was established by the National Mining Association to do an independent study on current and future approaches to improve mine safety in the United States. Prior to going to UMR, he served in government as the first permanent Associate Director of the Office for

Mine Safety & Health Research, NIOSH, Centers for Disease Control and Prevention (CDC), and managed the merger of former U.S. Bureau of Mines' mine health and safety research functions into NIOSH. Dr. Grayson also has experience in the Pennsylvania coal mining industry, having worked as a United Mine Workers of America laborer and in various engineering and management positions, including as chief mining engineer and as superintendent of a 500-employee underground coal mine and surface facilities. In academia, he has been a professor, a chair, and a dean, and has published 174 technical articles, reports, and book chapters, including 62 articles in peer-reviewed journals. His publications largely focus on mine health and safety, including on underground coal mines, and mine management applications. Dr. Grayson is a registered professional engineer in Pennsylvania and is a certified Mine Foreman and Mine Examiner in Pennsylvania. He received a Ph.D. in engineering from West Virginia University.

Braden T. Lusk is chair of the Mining and Nuclear Engineering Department at the Missouri University for Science and Technology. Previously, he was a Professor of Mining Engineering at the University of Kentucky. His research interests primarily focus on industrial/mine blasting and blast mitigation, including optimizing blasting operations for fragmentation, productivity, product selection, and environmental effects. His research specialties also include numerical modeling using physics-based models for high-energy events, blast-resistant testing and evaluation, and monitoring and analysis of vibrations for mining and industrial blasting. Dr. Lusk received the UK College of Engineering's Dean's Award for Excellence in Research in 2014 and received the Tau Beta Pi Outstanding Teacher in Mining Engineering Award seven times. Active in the International Society of Explosives Engineers (ISEE), Dr. Lusk has served on the ISEE board of directors since 2013 and currently serves as secretary. He received the ISEE President's Award in 2012. Also in 2012, he received the Society for Mining, Metallurgy and Exploration (SME) Coal and Energy Division J.W. Woomer Award. Dr. Lusk earned a Ph.D. in mining engineering from the Missouri University of Science and Technology.

Michael McCawley is the interim chair in the Department of Occupational and Environmental Health Sciences at West Virginia University. He has taught at that university since 1979, with primary interests in air pollution, aerosols, and occupational health. He has developed air sampling equipment and a pulmonary function test. Recently, he has been working on issues related to Marcellus Shale drilling and mountain top mining. Dr. McCawley serves as a member of the World Trade Center Health Program Scientific/Technical Advisory Committee. He had spent more than 27 years as a Public Health Service Officer with the CDC at the National Institute for Occupational Safety and Health, studying miners' health, occupational respiratory disease, aerosol measurement, and ultrafine particles. There he worked on projects concerning exposure to wood dust, volcanic ash, diesel exhaust, coal mine dust, silica, and beryllium. He retired from the U.S. Public Health Service in 2001. Dr. McCawley has a M.S. in engineering from West Virginia University and a Ph.D. in environmental health from New York University.

Raja V. Ramani (NAE) is an independent consultant, Emeritus Professor of Mining and Geo-Environmental Engineering, and Emeritus George H. Jr. and Anne B. Deike Chair in Mining Engineering at The Pennsylvania State University. Dr. Ramani's research activities include flow mechanisms of air, gas, and dust through mining systems; innovative mining methods; simulation and mathematical programming; equipment selection; management issues of health, safety, productivity, costs, and human resource development; environmental monitoring; resource conservation; mined land reclamation; land use planning; and environmental site planning for underground and surface mining. Dr. Ramani's experience in mineral extension education has spanned more than 45 years including: planning, developing, directing, and conducting short courses for across academia and the public and private sectors. As a part of his research and consulting experiences, Dr. Ramani has visited mining operations in over 35 countries. He is active in several technical and professional societies and was the 1995 president of the SME. He has served on several expert panels for U.S. and state government agencies and as consultant to national and international agencies and mining companies worldwide on health, safety, productivity, and environmental issues. He chaired the National Academies Committee on Underground Mine Disaster Survival and Rescue and the National Academies Committee to Review the NIOSH Mining Safety and Health Research Program. In addition, he has served as a member of the Panel on Technologies for the Mining Industry, Committee on the Study on Preventing Coal Waste Impoundment Failures and Breakthroughs, Committee on the Review of NIOSH Research Programs, and the Committee on Coal Research, Technology, and Resource Assessments to Inform Energy Policy. He is also a member of the Health Research Panel of the National Academies Committee on the Research Programs of the U.S. Bureau of Mines. He is a member of the National Academy of Engineering. A graduate of the Indian School of Mines, Dr. Ramani received a Ph.D. in mining engineering from Pennsylvania State University.

Cecile S. Rose is a Professor of Medicine in the Division of Environmental and Occupational Health Sciences at National Jewish Health and has academic appointments in the Division of Pulmonary Sciences and Critical Care Medicine at the University of Colorado and in the Department of Environmental and Occupational Health at the Colorado School of Public Health. Her research interests focus on mining-related cardiopulmonary diseases and on lung diseases following post-9/11 military deployment. Dr. Rose served between 2014 and 2016 as chair of the NIOSH Research Study Section and for several years as chair of the NIOSH Mine Safety and Health Research Advisory Committee. She has served on the National Academy of Sciences Committee on the Assessment of the Department of Veterans Affairs Airborne Hazards and Open Burn Pit Registry and on the standing Committee on Personal Protective Equipment in the Workplace. Dr. Rose received her M.D. and M.P.H. degrees from the University of Illinois Chicago. She is board certified in internal medicine, pulmonary medicine, and occupational and environmental medicine. She has an active clinical practice in occupational and environmental lung diseases as well as sustained funding for research in that area.

Emily A. Sarver is an associate professor in the Department of Mining and Minerals Engineering at the Virginia Polytechnic Institute and State University (Virginia Tech). She is also an adjunct faculty member in the Department of Civil and Environmental Engineering at Virginia Tech. Her primary research and outreach focuses on monitoring, characterization, and control of mine-generated contaminants that have implications for occupational or environmental health. She has specific expertise in respirable dust and diesel particulate matter in underground mines and has led work on several funded projects to characterize respirable particulates in coal mines. This work has used a variety of analytical techniques, some of which have not been previously applied to mine dusts. Dr. Sarver also has expertise in respirable particulate sampling and real-time monitoring in mine environments. Her other research interests include responsible development of mineral and energy resources, hydrometallurgy, and corrosion. In 2015, Dr. Sarver was named one of the first two recipients of the Freeport-McMoRan, Inc. Career Development Grant, awarded by the SME. She was also the recipient of the 2017 Health & Safety Research and Educational Excellence Award and the 2016 Mineral Processing Division Young Engineer Award from the SME, and the 2015 Outstanding Researcher Award from the Appalachian Research Initiative for Environmental Science. Dr. Sarver holds B.S. and M.S. degrees in mining engineering and a Ph.D. in civil engineering from Virginia Tech.

Joseph A. Sbaffoni is principal for JAS Mine Consulting LLC, offering consulting services to the mining industry. He has more than 47 years of experience in miner health and safety program areas including mine inspection, miner training, miner certification, equipment approval, accident investigation, and emergency response. Mr. Sbaffoni began his career in mining in 1970, was certified as a Pennsylvania Mine Foreman in 1975 and held a range of management positions in Pennsylvania's mines rising to the position of mine superintendent. He was certified as a Pennsylvania Bituminous Mine Inspector and was appointed sequentially to the positions of Bituminous Deep Mine Inspector (1984), Bituminous Division Chief (1988), and Director (2003), in the Pennsylvania Bureau of Mine Safety. During his tenure, Mr. Sbaffoni played a major role in updating and improving all mine health and safety programs in the Commonwealth. Mr. Sbaffoni played a key role in the Quecreek mine rescue of nine trapped miners in 2002. He was instrumental in the enactment of the Mine Families First Act in 2007 and a new Mine Safety Act for Bituminous Coal Mines in 2009, which contributed to the outcome of fatal free years in Pennsylvania's underground mines in 2010, 2011, 2012, 2013, and 2014. He served on NIOSH's Mine Safety and Health Research Advisory Committee from 2004 to 2012. He holds an associate degree in mining technology from Pennsylvania State University and was recognized as a Centennial Fellow in 1996, received a Special Recognition for Sciences and Engineering in Service to Society award in 2002 and the Robert Stefanko Distinguished Achievement Award in Mineral Engineering in 2010. He is a member of the Penn State Mining Engineering Industrial and Professional Advisory Committee and the Eberly Campus Advisory Board and Mining Industry Advisory Board. He is a past president and member of the Joseph A. Holmes Safety Association, National Mine Rescue Association, Mine Rescue Veterans of the Pittsburgh District, Pittsburgh Coal Mining Institute of America, Mine Safety Institute of America, and Pennsylvania Bituminous Safety Association.

Michael J. Wright is the director of Health, Safety and Environment for the United Steel, Paper and Forestry, Rubber, Manufacturing, Energy, Allied Industrial and Service Workers International Union. He is a former member of the Department of Labor's National Advisory Committee on Occupational Safety and Health and EPA's Clean Air Act Advisory Committee. He has worked extensively on international health, safety, and environment issues with the International Labour Organization and the International Trade Union Confederation. He currently serves on the world's first global union-management safety and health committee, established in 2009 by ArcelorMittal Steel. He is a member of NIOSH's Mine Safety and Health Research Advisory Committee. He has taught safety and health, and worked with unions in South Africa, Zimbabwe, India, Brazil, Mexico, Argentina, Poland, Romania, Bosnia-Herzegovina, and Russia. He was a member of an international team that investigated the Bhopal disaster. He is a former member of the Program Advisory Committee of the International Program on Chemical Safety, set up under the ILO, the World Health Organization, and the United Nations Environment Program. He also served on the international coordinating group overseeing the effort to harmonize chemical classification and labeling systems throughout the world, whose work was completed in 2003. Mr. Wright worked on several MSHA rulemakings, most notably on the standard for diesel particulate matter in underground metal and nonmetal mines. In addition, he has worked on safety and health issues in iron, copper, silver, trona, potash, uranium, and nickel mines in the United States and Canada. Mr. Wright received an M.S. degree in industrial hygiene from the Harvard School of Public Health.

Appendix C

Open-Session Meeting Agendas

Committee on the Study of the Control of Respirable Coal Mine Dust Exposure in Underground Mines First Meeting

Open Session: February 8, 2017
National Academies Keck Center, Room 100
500 Fifth Street, NW
Washington, DC 20001

PUBLIC AGENDA

1:00 Opening Remarks and Introduction of Committee Members
Thure Cerling
Chair, Committee on the Study of the Control of Respirable Coal Mine Dust Exposure in Underground Mines

1:10 Perspectives on the Congressional Study Request
Joshua Hoffman, Professional Staff
H.R. Committee on Natural Resources, Subcommittee on Energy and Mineral Resources
Richard Miller, Senior Policy Advisor
H.R. Committee on Education and the Workforce

1:50 MSHA Perspective on the Study Objectives and Background
Kevin Stricklin
Administrator for Coal Mine Safety and Health, and Acting Deputy Assistant Secretary, Mine Safety and Health Administration

2:50 Break

3:05 NIOSH Perspectives on the Study Objectives and Background
RJ Matetic
Director, Pittsburgh Mining Research Division
National Institute for Occupational Safety and Health

4:05 Coal Mining Industry Perspectives
Bruce Watzman
Senior Vice President, Regulatory Affairs,
National Mining Association
Mark Watson
Vice President of Operations
Alliance Coal, LLC

5:00 **Opportunity for Public Comment**

5:30 **United Mine Workers of America Perspectives**
Joshua Roberts
Administrator of the Department of Occupational Health and Safety
United Mine Workers of America

6:00 **End of Open Session**

Committee on the Study of the Control of
Respirable Coal Mine Dust Exposure in Underground Mines
Third Meeting

Open Session: April 13, 2017
Marriott Charleston Town Center
200 Lee Street East; Charleston, WV 25301

OPEN-SESSION AGENDA

1:00 **Opening Remarks and Introduction of Committee Members**
Thure Cerling
Chair, Committee on the Study of the Control of Respirable Coal Mine Dust Exposure in Underground Mines

1:15 **Performance of the Continuous Personal Coal Dust Monitor (CPDM)**
Jay Colinet
Principal Mining Engineer, Pittsburgh Mining Research Division
National Institute for Occupational Safety and Health

1:55 **Production and Characteristics of Rock Dust Applied in Underground Mines**
Steven Phagan
Executive Vice President, Lime and Limestone Divisions
Greer Industries, Inc.

2:30 **Break**

2:50 **United Mine Workers of America (UMWA) Panel Discussion of the Use of CPDMs**
Scottie Cline
Pinnacle Mine
Brad Craddock
Black Oak Mine
Adam McCormick
Black Oak Mine
Eric Taylor
Pinnacle Mine

3:35 **Opportunity for Public Comment**

5:00 **End of Open Session**

Committee on the Study of the Control of Respirable Coal Mine Dust Exposure in Underground Mines Fourth Meeting

Open Session: June 29, 2017
Morgantown Marriott at Waterfront Place
2 Waterfront Place; Morgantown, WV 26501

OPEN-SESSION AGENDA

1:00 **Opening Remarks, Introduction of Committee Members, and Descriptions of Recent Coal Mine Visits**
Thure Cerling
Chair, Committee on the Study of the Control of Respirable Coal Mine Dust Exposure in Underground Mines

1:20 **Emerging Trends in Data Reported by Coal Mine Operators**
Greg Meikle
Chief of Health for Coal Mine Safety and Health, MSHA

2:20 **Research Findings on the Respiratory Health of Coal Mine Workers**
A. Scott Laney
Epidemiologist, Respiratory Health Division, NIOSH

3:20 **Break**

3:40 **Opportunity for Public Comment**

4:30 **End of Open Session**

Committee on the Study of the Control of Respirable Coal Mine Dust Exposure in Underground Mines Sixth Meeting

Open Session: October 5, 2017
National Academies Keck Center, Room 100
500 Fifth Street, NW
Washington, DC 20001

OPEN-SESSION AGENDA

9:00 **Opening Remarks and Introduction**
Thure Cerling
Chair, Committee on the Study of the Control of Respirable Coal Mine Dust Exposure in Underground Mines

9:10 **Panel Discussion**
Derk Brouwer
University of the Witwatersrand
Johannesburg, Republic of South Africa
Bharath Belle

Anglo American Coal (Australia and South Africa)
Brisbane, Australia
Ting Ren
University of Wollongong
Wollongong, Australia

9:50 **Panelist Discussion with Committee**

10:30 **Break**

10:50 **Resume Panelist Discussion with Committee**

11:45 **Opportunity for Public Comment**

12:30 **End of Open Session**

Appendix D

Glossary

Coal mine dust personal sampling unit: A gravimetric sampler used to collect respirable dust samples. Filters containing collected samples must be mailed to a laboratory for analysis, which can take several days.

Coal rank: A classification of coal based on fixed carbon, volatile matter, and heating value. It indicates the progressive geological alteration (coalification) from lignite to anthracite.

Continuous personal dust monitor: Monitoring device worn by a miner that provides a near real-time display of cumulative concentrations of respirable coal mine dust.

Crystalline silica: Crystalline silica is a collective term that refers to quartz, cristobalite, tridymite, and several other rare silica minerals. All of the crystalline silica minerals have the same chemical composition but have different crystal structures and are thus termed polymorphs. Quartz is the most common form of crystalline silica.

Designated area: Areas in an underground mine that are sampled for specific reasons, such as the point where coal is loaded onto a conveyor belt.

Designated occupation: Occupations in an underground mine set by the 2014 respirable coal mine dust rule because they are exposed to the highest concentrations of respirable dust, such as the operator of a continuous mining machine.

Designated work position: Location at the surface area of an underground coal mine that is exposed to the highest concentrations of respirable coal mine dust, such as highwall drill operators and bulldozer operators.

Dose: The amount of material that passes or otherwise has influence across the boundary within an organism; comes into contact with the target system, organ, or cell; and produces an outcome.

Exposure: Contact of a stressor, such as respirable coal mine dust, with a receptor, such as a coal miner, over a defined period.

Mining research establishment instrument: The gravimetric dust sampler with a four-channel horizontal elutriator developed by the Mining Research Establishment of the National Coal Board, London, England. 30 CFR 70.2.

Normal production shift: A shift during which there is at least 80 percent of the average production over the most recent 30 production shifts (or for all shifts if fewer than 30).

Other designated occupation: Additional occupations at underground mines set by the 2014 respirable coal mine dust rule that are frequently exposed to high concentrations of dust, such as the coal hauler or roof bolter operator.

Part 90 Miner: A miner at an underground mine who has evidence of coal workers' pneumoconiosis.

Quartz: Crystalline silicon dioxide (SiO_2) not chemically combined with other substances and having a distinctive physical structure

Respirable coal mine dust: Airborne particulate matter occurring as a result of the extraction or preparation of coal in or around a coal mine. It is the dust collected with a sampling device approved by the Secretary of Labor and the Secretary of Health and Human Services.

Silicate: Any of a large class of chemical compounds composed of silicon, oxygen, and at least one metal. Most rocks and minerals are silicates. Any mineral containing the group SiO_4, either isolated, or joined to other groups in chains, sheets, or three-dimensional groups with metal elements.

Appendix E

Coal Mining in the United States

HISTORICAL PERSPECTIVE

Coal is widely distributed around the world and the United States has approximately 21 percent of the world's coal resources (EIA, 2014). The coal industry in the United States is mature, tracing its origin to the first commercial exploitation of coal in the Manakin area, near Richmond, Virginia, in 1701. By 1760, most of the colonies knew about the existence of coal fields within their borders, but very little had been done to exploit them (Lasson, 1972). Anthracite coal mining started around 1775 in northeastern Pennsylvania and, by the late 1700s, coal was mined in Mount Washington, in Pittsburgh. Soon thereafter, coal mining started in Ohio, Illinois, and other states.

From this modest beginning, U.S. coal mining grew enormously to 26 states and nearly a billion tons of production per year by 2000 (see Figure E-1). Anthracite coal production reached its highest level (more than 100 million tons) in 1917. By 1987, anthracite coal production dropped to about 5 million tons, and only about 600,000 tons were produced from mining anthracite seams.

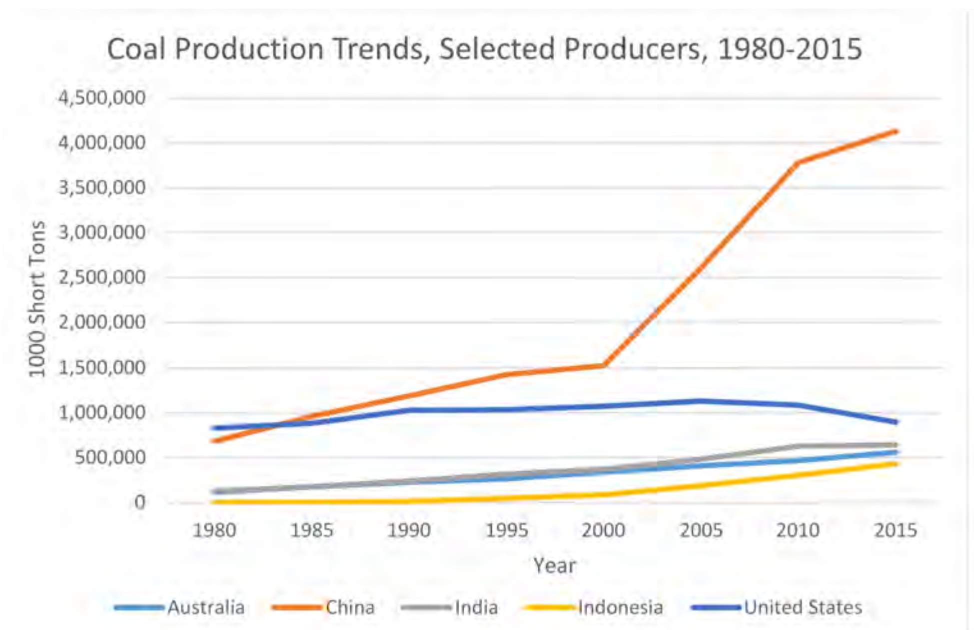

FIGURE E-1 Coal production trends of the five lead producers, 1980-2012. SOURCE: Data from EIA, 2016.

The health and safety regulations of the coal mining industry by the states were introduced almost a century after the start of mining in Pennsylvania, with the enactment of the Pennsylvania [Anthracite] Mine Inspection Act in 1869 (for anthracite coal) and the Pennsylvania Mine Inspection Act in 1877 (for bituminous coal). Mining laws also were proposed in several other states, for example, Illinois in 1872 and Ohio in 1874. Regarding federal health and safety legislation, the Federal Coal Mine Inspection Act was enacted in 1941 and the Federal Coal Mine Safety Act was enacted in 1952. The passage of the Federal Coal Mine Health and Safety Act of 1969 represented a significant departure from tradition in that the enforcement of federal health and safety standards were to be performed by an agency of the federal government, the Mine Safety and Health Administration (MSHA), regardless of the extent and quality of the state programs. The Federal Mine Safety and Health Act was enacted in 1977 and the Mine Improvement and New Emergency Response Act was enacted in 2006.

At the federal level, mine health and safety research was conducted initially by the U.S. Geological Survey and later by the U.S. Bureau of Mines, from the time when the bureau was created in 1910 to 1995 when it was abolished. From 1997 onwards, the National Institute for Occupational Safety and Health has been the federal agency with research responsibility.

PRODUCTION

In 2017, coal was mined in 25 states, both east and west of the Mississippi River. While U.S. production has been rising from about 1960, the production from areas west of the Mississippi exhibited steep growth from the 1970s (Figure E-2). Coal production reached a high of 1,172 million tons in 2008. The production in 2016 was the lowest in recent years, 728 million tons (EIA, 2017).

Historically, the dominant production by state occurred in Kentucky, West Virginia, Pennsylvania, Illinois, Indiana, and Ohio in the eastern United States and in Colorado, Utah, North Dakota, Texas, and, more recently, Wyoming and Montana, in the west. Production from eastern states exhibited a decline that began in the 1990s and grew steeper after the turn of the century.

DISTRIBUTION OF PRODUCTION BY RANK OF COAL

Depending on the duration, temperature, and pressure that the vegetative matter had been subjected to during the coalification process, the rank of mined coal is classified into ranks (categories) of anthracite (97 to 86 percent carbon), bituminous (85 to 46 percent carbon), subbituminous (45 to 34 percent carbon), and lignite (33 to 25 percent carbon). The distribution of U.S. coal production by rank is shown in Figure E-3. Although mines in northeastern Pennsylvania at one time produced about 100 million tons of anthracite coal per year, at the present time, there is very little anthracite coal production. Lignite is mostly produced in Texas and North Dakota and accounts for about 10 percent of coal production. With increasing production from states west of the Mississippi, the production of subbituminous coal has increased greatly and at present just exceeds the production of bituminous coal. Because of their lower energy content, subbituminous and lignite coals represent a smaller proportion of energy production, relative to bituminous coal.

DISTRIBUTION OF PRODUCTION BY METHOD OF MINING

The two major methods of mining coal are surface mining and underground mining. A generalized schematic illustration of the two methods is shown in Figure E-4.

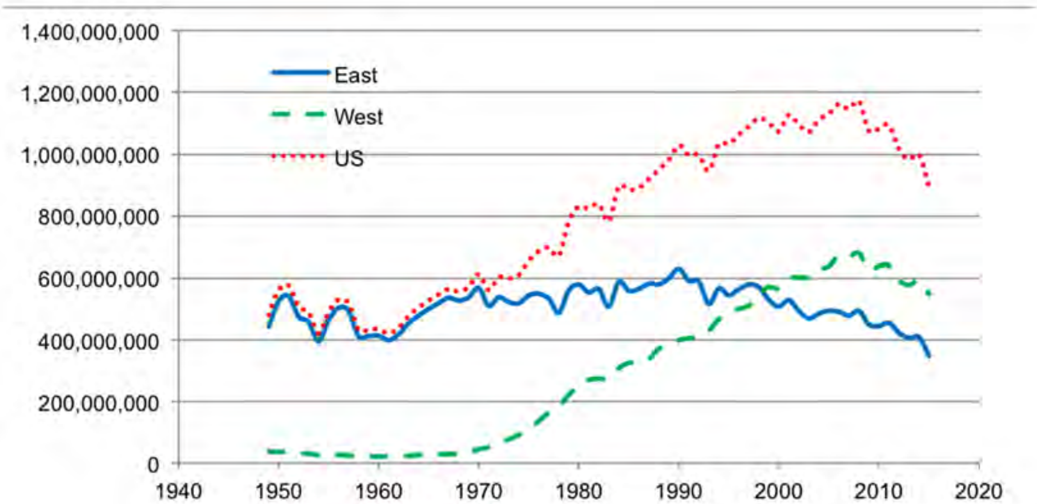

FIGURE E-2 Coal production (tons), east/west demarcation by Mississippi River. SOURCE: Kolstad, 2017. Reprinted with permission; 2017, Stanford Institute for Economic Policy Research.

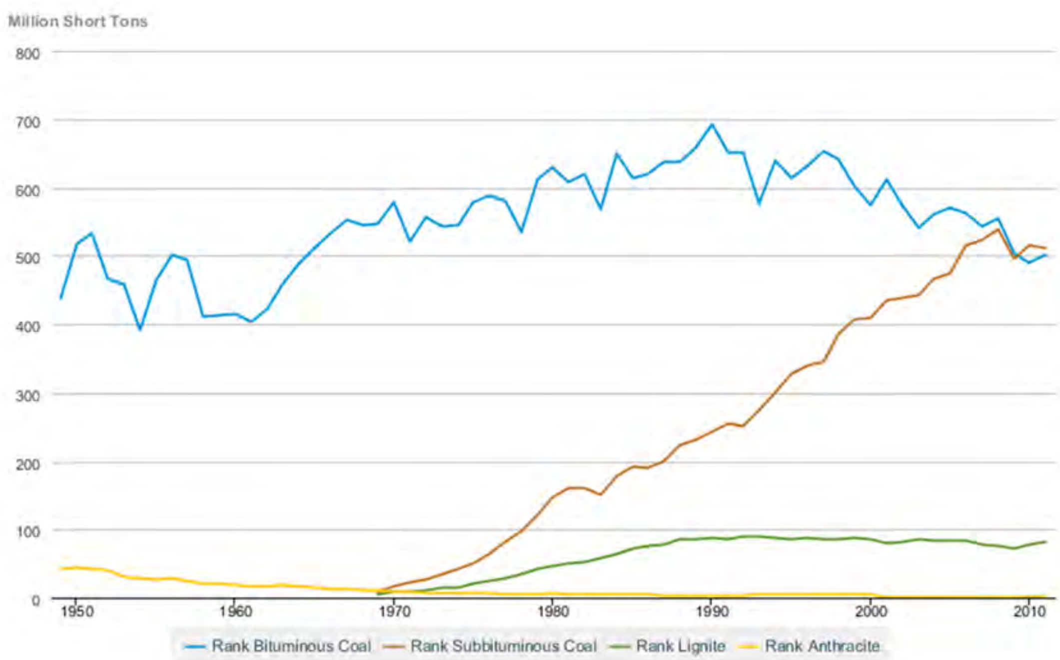

FIGURE E-3 U.S. coal production distribution by rank of coal. SOURCE: EIA, 2012.

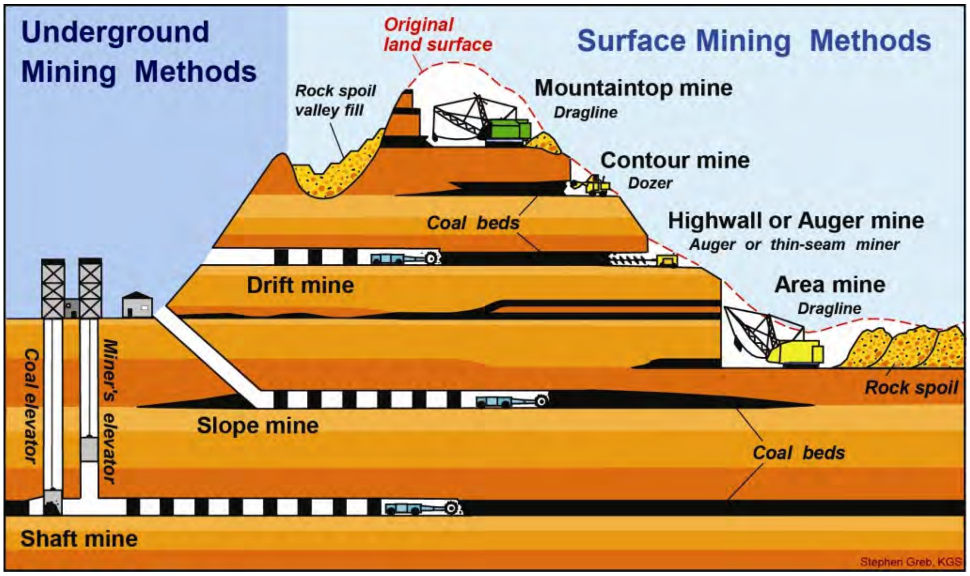

FIGURE E-4 A generalized schematic of methods of mining a coal seam. SOURCE: Kentucky Geological Survey, 2018. Reprinted with permission; 2017, Kentucky Geological Survey.

In surface mining, soil and rock over the coal seam are removed to expose the coal seam. After the coal seam is fragmented and removed, the void can be filled with the previously removed rock and topped with soil and revegetated. The activities of drilling, blasting, loading, and hauling all require detailed planning and design for a safe operation. Depending on the conditions of the coal deposit, a variety of surface mining methods can be used, with regard to type of equipment and how it is deployed for removing the overlying materials and the coal seam.

Where surface mining is not feasible, underground mining of the coal seam is generally conducted. The coal is accessed by suitable openings from the surface (referred to as shafts, slopes, or drifts). From these openings, the seam is developed through a network of roadways (referred to as entries and cross-cuts) separated by blocks of coal pillars. The pillars may be extracted in sequence at a predetermined time.

The infrastructure required for transporting miners, supplies, and mined coal, and for supplying ventilating air and utilities (such as power and water), is a major aspect of mine planning and design to ensure a safe operation. In contrast to surface mining, underground mining is conducted in a confined geologic medium and presents a number of unique challenges arising from factors such as strata pressure, gas liberation, and airborne dust. Often, when mining thin coal seams, the section of strata that is mined can include portions of roof, floor, or both to ensure adequate head room for miners and equipment. In some cases, the coal seam itself will contain partings of shale or clay materials, veins, or dykes, which are mined along with coal.

Surface mining's share of coal production in the United Stateswas about 66 percent in 2015. In absolute terms, the surface coal production in 2015 was 589 million tons, representing greater than a fourfold increase relative to the 139 million tons production in 1950 (EIA, 2012; NMA, 2017). As shown in Figure E-5, in recent years, the decline in production appears to have been similar for the surface and underground sectors.

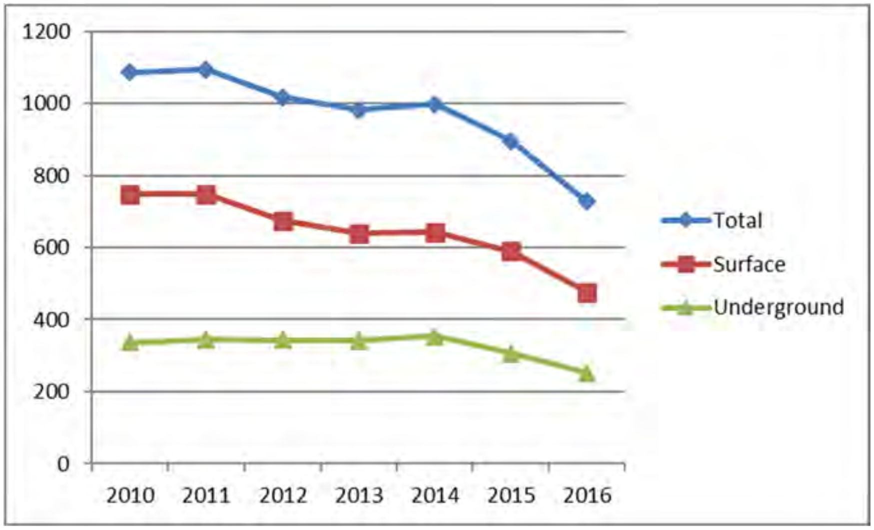

FIGURE E-5 Distribution of U.S. coal production (million tons) by mining method. SOURCE: Data from MSHA, 2017b.

NUMBER OF MINES AND EMPLOYMENT

The trends toward increased surface mining, increased production and productivity using new technology, consolidation of the mining companies, and closure of smaller operations have contributed over the years to a continuous decline in the number of mines and the number of miners employed in those mines. Variations in those statistics are affected by variations in the geologic aspects of coal deposits in different locations in the United States, coal quality, and differences in mining conditions. Those factors also affect the selection of mining methods and their implementation. Historically, the states of Kentucky, West Virginia, Virginia, and Pennsylvania accounted for a large number of small underground and surface mines, while accounting for a small percent of the total production.

In 1980, coal production was 830 million tons, the total number of coal mines was greater than 5,200 (with underground mines numbering more than 2,400 and surface mines more than 2,800), and the total employment in coal mining was about 215,000. In 2005, coal production was more than 1,100 million tons (33 percent higher than in 1980), with 70 percent fewer mines (1,600 mines total, 650 underground mines, and 950 surface mines) and with 50 percent fewer miners (105,000) (MSHA, 2017a). Recent data on number of mines and the number of miners employed in these mines are shown in Figures E-6 and E-7, respectively, for the years 2010 to 2016. The figures show a more dramatic drop in both the number of mines and employment.

NUMBER OF SMALL UNDERGROUND MINES

Mention has been made of the large number of small mines in the states of Kentucky, West Virginia, Virginia, and Pennsylvania. Figures E-8 and E-9 show the distributions of underground coal mines in the United States by the number of miners employed (more than 50 miners, 20-49 miners, and fewer than 20 miners), and in the four states combined.

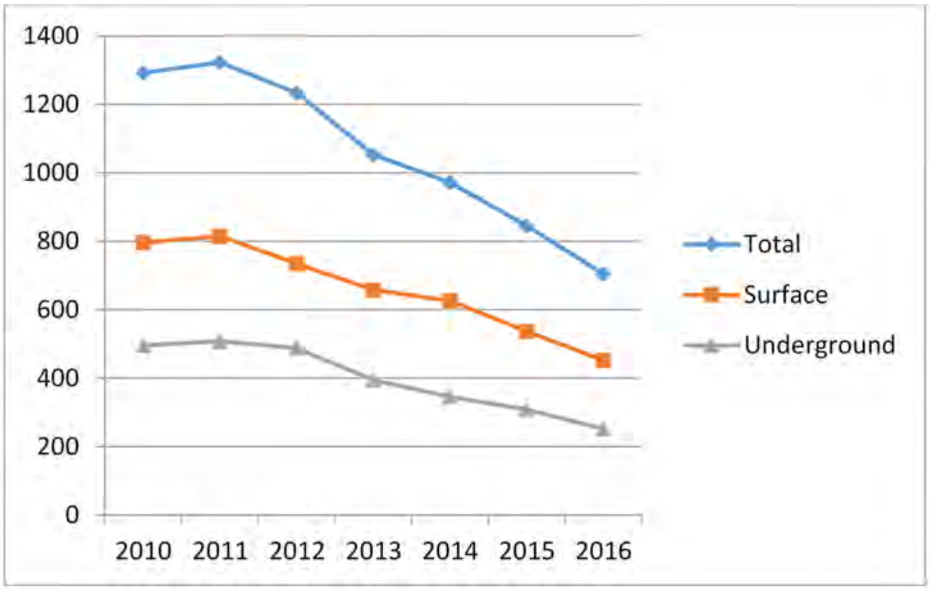

FIGURE E-6 Number of coal mines in the U.S.: total and by mining method, 2010-2016. SOURCE: Data from MSHA, 2017b.

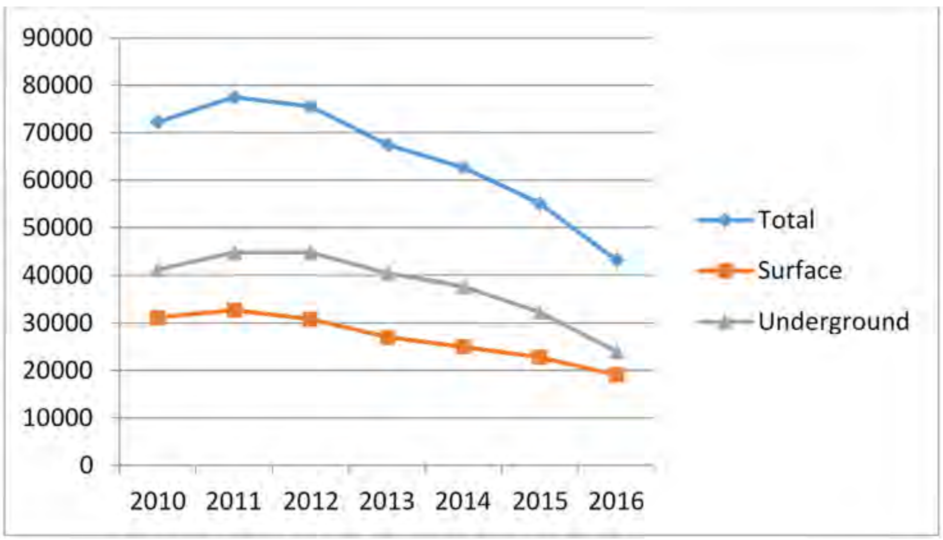

FIGURE E-7 Number of miners employed in coal mines: total and by mining method, 2010-2017. SOURCE: Data from MSHA, 2017b.

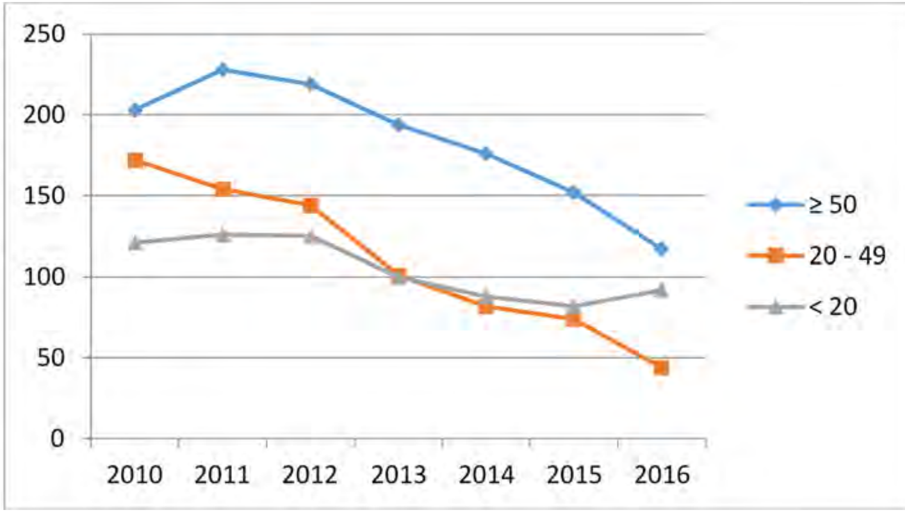

FIGURE E-8 Distribution of U.S. underground coal mines by mine size (number of miners), 2010-2016. SOURCE: Data from MSHA, 2017b.

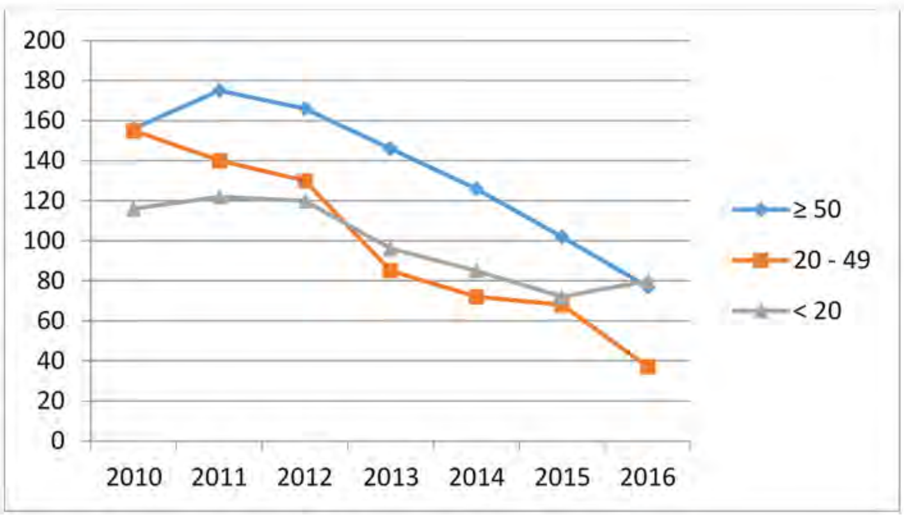

FIGURE E-9 Distribution of underground coal mines in the states of Kentucky, Virginia, West Virginia, and Pennsylvania by mine size (number of miners), 2010-2016. SOURCE: Data from MSHA, 2017b.

SUMMARY

In considering issues concerning the coal industry in the United States, it is important to recognize the diverse and variable nature of the industry in terms of the location of the major operations, distributions of coal production by regions and mining methods, mine size, number of mines, and numbers of miners.

REFERENCES

EIA (U.S. Energy Information Administration). 2012. Annual Energy Review 2011. Table 7.2 Coal Production, 1949-2011 (Million Short Tons) [online]. Available at https://www.eia.gov/totalenergy/data/annual/showtext.php?t=ptb0702 (accessed December 22, 2017).

EIA. 2014. Coal Recoverable Reserves 2014 [online]. Available at https://www.eia.gov/beta/international/rankings/#?cy=2014&aid=6&pid=1 (accessed December 22, 2017).

EIA. 2016. International Energy Statistics [online]. Available at https://www.eia.gov/beta/international/data/broswer (accessed May 15, 2018).

EIA. 2017. U.S. Coal Production by State, 2005-2016 (Thousand Short Tons). National Mining Association [online]. Available at https://nma.org/wp-content/uploads/2016/11/coal_production_by_state_2016p.pdf (accessed July 10, 2017).

KGS (Kentucky Geological Survey). 2018. Coal Mining [online]. Available at http://www.uky.edu/KGS/coal/coal-mining.php# (accessed May 16, 2018).

Kolstad, C. D. 2017. What Is Killing the U.S. Coal Industry? Stanford Institute for Economic Policy Research Policy Brief May 2017 [online]. Available at https://siepr.stanford.edu/research/publications/what-killing-us-coal-industry (accessed July 10, 2017).

Lasson, K. 1972. A history of Appalachian coal mines. In *Legal Problems of Coal Mine Reclamation: A Study in Maryland, Ohio, Pennsylvania and West Virginia*. Washington, DC: U.S. Government Printing Office, pp. 3-18 [online]. Available at http://scholarworks.law.ubalt.edu/all_fac/794/ (accessed November 17, 2017).

MSHA (Mine Safety and Health Administration). 2017a. Coal Mining Data: Average Number of Employees at Coal Mines in the United States, by Primary Activity, 1978-2007 [online]. Available at https://arlweb.msha.gov/STATS/PART50/WQ/1978/wq78cl03.asp (accessed November 17, 2017).

MSHA. 2017b. Employment/Production Data Set. Online. Available at https://arlweb.msha.gov/OpenGovernmentData/OGIMSHA.asp (accessed November 17, 2017).

NMA (National Mining Association). 2017. U.S. Coal Production Trends, 1980-2016 (Million Short Tons). Available at https://nma.org/wp-content/uploads/2017/06/us_coal_production_trends_2016-2.pdf (accessed December 22, 2017).

Appendix F

Underground Coal Mining Methods and Engineering Dust Controls

An underground mine consists of the portals (entrance and exits to the mines), mains, submains, panels, and working faces. The panels are the working sections of the production operation. Depending on the mining method, a working section can have one or more working faces.

The mining activities that traditionally take place to advance a working face further into the coal seam, called unit operations, include cutting, drilling, blasting, loading, and hauling the coal from the current position of the face to the planned advance distance position of the face. Supporting the newly exposed roof and extending the ventilation arrangement and other utilities to the new working face are also considered unit operations. Auxiliary operations deal with activities that support the unit operations, include hauling of the coal from the panel to outside the mine; transporting miners and supplies in and out of the mine; maintaining the structural stability of mine openings, mains, and submains; maintaining the main ventilation system to provide fresh air and to dilute and carry away gases, dusts, and other harmful agents in the mine atmosphere; and ensuring water-handling and power systems are in proper operational condition at all times. The health and safety of the miner anywhere in the mine is very much dependent on the adequate planning, design, and operation of both unit and auxiliary operations.

The two major underground methods are referred to as the room-and-pillar method and the longwall method. In both methods, the coal seam is developed by driving entries and cross-cuts to create blocks or pillars of coal by the room-and-pillar method. In the past, separate machines were used for cutting, drilling, blasting, and loading the coal and the method was called conventional room-and-pillar mining. At the present time, in room-and-pillar mining, a continuous miner mechanically cuts and loads the coal onto a face transport vehicle which is usually a shuttle car. In longwall mining, the longwall shearer does the same job, cutting and loading the coal onto a face conveyor on which it rides. The introduction of modern longwall mining in the United States is comparatively more recent, about 60 years ago.

In a room-and-pillar mine (Figure F-1), a panel consisting of four or more parallel entries is driven to the predetermined boundary of the panel. A continuous miner is used for cutting and loading and shuttle cars to transport coal from the miner to the intermediate haulage. Cross-cuts are driven at suitable intervals to connect the entries, creating pillars. The size of the pillar is often determined by the decision as to whether to recover the pillars (called retreat mining or pillaring) or not. If the mining plan is not to recover the pillars, then the pillar size is more often determined by stability and other safety considerations so as to increase the coal recovery during the development of the pillars itself.

In a longwall mine (Figure F-2), the objective is to develop, in each panel, a wide (600 to 1,200 ft. or more) and long (6,000 to 15,000 ft. or more) pillar in the first stage. This pillar will be recovered by the longwall method in the second stage, allowing the roof to collapse in areas where coal has been recovered. In a typical longwall mine, there may be one or more longwall sections and three or more continuous miner sections that are needed for the development of the mains, submains, and panels (Evans and Ramani, 2006). While the longwall section accounts for the bulk of the production from a longwall mine, the continuous miner sections, depending on mining conditions and practices, can account for up to 40 percent of the total production.

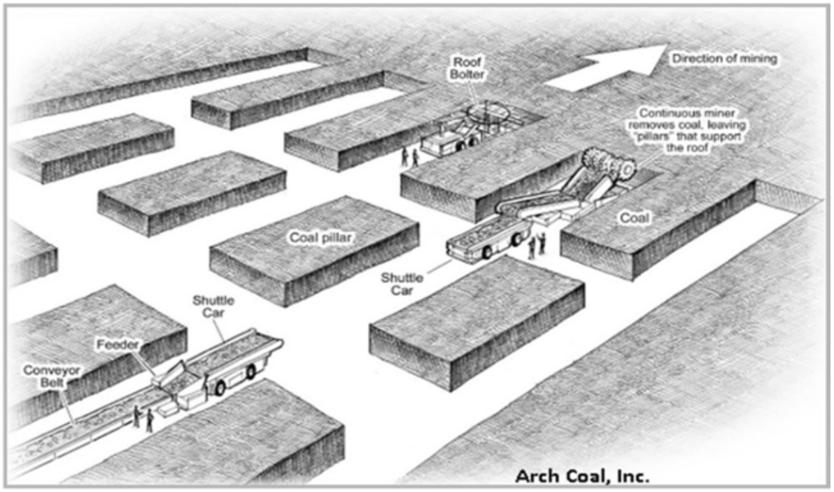

FIGURE F-1 Schematic of a room-and-pillar coal mine section. SOURCE: Arch Coal, Inc., 2012.

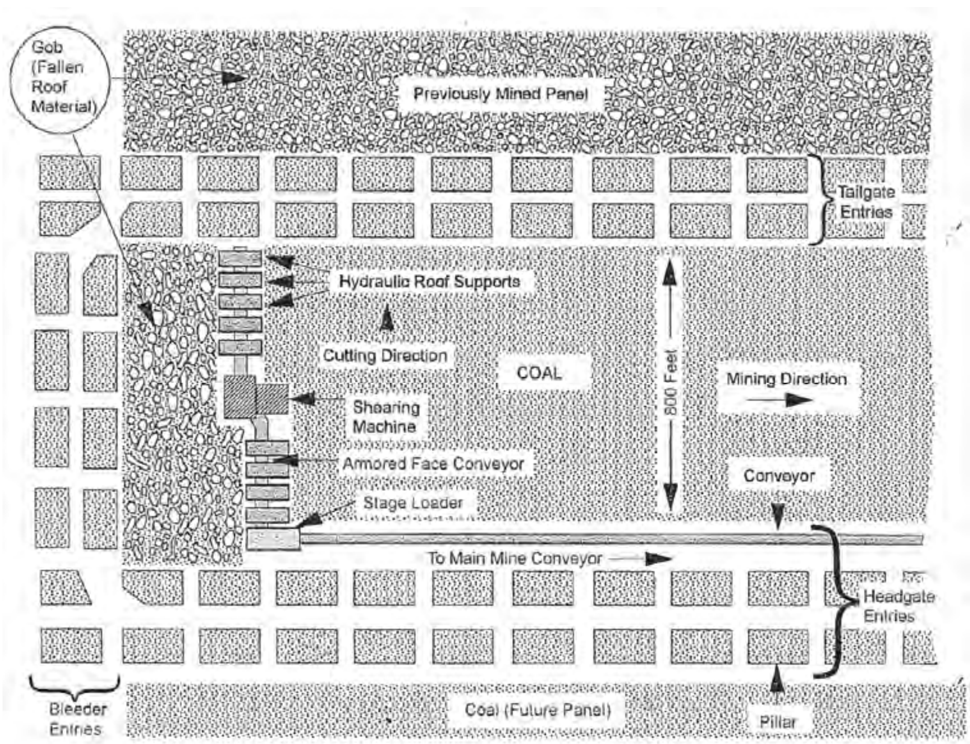

FIGURE F-2 Details of the longwall face. SOURCE: EIA, 1995.

There are several variations of each method. However, ever since the introduction of continuous miners in the late 1940s, room-and-pillar continuous mining has been gaining ground over conventional room-and-pillar mining. In recent years, room-and-pillar continuous mining accounts for more than 38 percent of the underground coal production (EIA, 2017). Room-and-pillar retreat mining currently accounts for a small fraction (less than 10 percent) of this underground production. Longwall mining had a slow growth in the United States in the early years, contributing to less than 1 percent of the underground coal production in 1970 and to about 10 percent in 1980. However, its growth has been phenomenal in the last 30 years. At the present time, about 60 percent of the underground production comes from longwall mines.

ROOM-AND-PILLAR CONTINUOUS MINING SECTION

The schematic view of a room-and-pillar continuous miner section shown in Figure F-1 is a typical five-entry development where the continuous miner is shown working in entry 2 from the right, cutting and loading a shuttle car. The roof bolter is shown working in entry 3 from the right, bolting the roof. After the miner has advanced to the face in entry 2 to the planned extent, the miner will move to the next designated place. The bolter will move into entry 2 to support the newly exposed roof by inserting bolts in a planned sequence.

For a typical dual-split ventilation system, the intake air is brought through entries 2 and 4 and returned through entries 1 and 5 (see Bise, 2013). The continuous miner will advance the entry by 18 ft. or more in each cut. In general, there are two shuttle cars that cycle between the miner and the feeder-breaker at the conveyor belt for transporting coal. The feeder-breaker serves two purposes: it breaks large lumps of the materials and it evens out the load on the belt. After the planned number of cuts have been made, the power centers, belt, ventilation, and other accessories associated with the panel will be moved.

The specifics of a continuous-miner working section or panel—the number of entries, the cut sequence, the ventilation scheme, the haulage system, and particularly the dimensions of the pillars and entries—can vary from mine to mine, and even within a mine depending on whether the panel is a main, submain, or longwall development, or if pillaring is planned. In particular, the thickness of the seam, conditions of the roof and floor strata, and the gassiness of the seam are major considerations in determining the height and width of entries, the distance between crosscuts, and the number of entries. There are also equipment considerations such as remote-operated miners, battery- or diesel-powered shuttle or ram cars, and dual-boom bolters and such, which may be different from one operation to another and offer flexibility in section layout and cut-plan development. Several mines use a supersection, which uses two sets of equipment and one augmented crew in one section (the supersection) to decrease wait/idle time and increase production time. All these determine the production and the number of personnel employed in the face, their duties, and their locations. The number of personnel in the panel may include a continuous-miner operator and possibly a helper, roof bolter operator and helper, two shuttle car operators, a mechanic, a ventilation/utility miner, and a mine foreman.

Continuous-Miner Section Equipment

The major equipment list for a continuous-miner section would include the continuous miner, roof bolter, shuttle cars, feeder-breaker, panel belt, and utility scoop to carry supplies. Depending on the ventilation system and water problems, there may be other equipment such as auxiliary fans, portable water pumps, and rock-duster machines.

Continuous-Mining Dust Sources

The primary source of respirable coal mine dust (RCMD) in a continuous-mining section is the continuous miner. Dust is generated by the miner during the cutting and loading processes and this dust has great potential to be airborne. Miners who can be exposed to the airborne RCMD include not only the continuous-miner operator but also those who may be working downwind of the continuous miner. RCMD is generated during the drilling of the roof for installing roof bolts and roof bolter operators can be exposed to dust from the drilling process. There may be other sources of RCMD, such as dust from conveyors, dust from intake airways (due to reentrainment of settled dust in the floor and sides), and dust from rock dusting.

The designated occupation (DO), the occupation with the highest RCMD exposure, in a continuous-miner section is the continuous-miner operator. DO is sampled both by the operator and by the Mine Safety and Health Administration (MSHA) for compliance purposes. The second major source of RCMD in a continuous-miner section is the roof bolter. Roof bolter operators are also sampled as other designated occupations (ODOs). Designated areas in an underground mine are sampled for specific aspects, such as the point where coal is loaded onto a conveyor belt or transferred from one belt to another

According to MSHA RCMD sample data for the 4-year period 2001 to 2004 (17,000 personal samples), about 11 percent exceeded the 2 mg/m^3 RCMD standard at the continuous miner and roof bolter occupations, and 20 percent exceeded the silica concentration of 100 $\mu g/m^3$ (Colinet and Listak, 2007).

In the MSHA sample data for the 4-year period (2009-2012) shown in Table F-1, additional information is provided on miners working as shuttle car operators. Clearly, control of RCMD from continuous miner, roof bolter, and other sources is important in a miner section.

Basic Strategies for Dust Control

The basic strategies for dust control are generally sorted into three classes: engineering controls, administrative controls, and personal protection. The aim is to achieve the mandated RCMD standard in the atmospheric mine environment through the application of engineering controls and, where required, through administrative and personal protection measures. In another classification, the strategies for RCMD control are

- Prevention of formation;
- Removing the dust, that is, preventing it from entering the air stream;
- Suppressing the dust from becoming airborne (or decreasing the airborne propensity of the dust);
- Isolating the dust from the miners (keep the dust away from miners and the miners away from the dust); and
- Diluting the airborne dust to concentrations below the mandated levels through adequate ventilation.

While prevention of formation and from becoming airborne are two primary means to reduce the problem of airborne dust, the provision of adequate ventilating air to dilute the airborne dust and carry it away from the workers, and keeping the workers on the outby side of the dust sources, are equally important to reduce exposure to RCMD.

The application of those strategies has been greatly aided over the years by a number of developments in equipment design considerations and operating practices. As additional measures, miners may be provided with respirators but it is necessary to recognize that administrative controls and personal protection cannot be in lieu of engineering controls. Further, monitoring technology and sampling strategies for respirable RCMD measurement have evolved to assist miners, mine management, and mine inspectors in their efforts to comply with the prevailing ambient airborne RCMD standards.

TABLE F-1 MSHA RCMD Samples, 2009-2012

Occupation/No. of Samples	RCMD > 2 mg/m^3	RCMD > 1.5 mg/m^3	Quartz Dust > 100 $\mu g/m^3$
CM Operator/15,237	3.7%	8.8%	9.7%
Roof Bolter/16,632	1.1%	3.7%	10.6%
SC Operator/22,294	1.3%	3.7%	0.0%

SOURCE: Organiscak, 2014.

Continuous-Miner Dust Control

In a modern continuous-miner section, combinations of several of the strategies described in the previous section are practiced to control the generation, entrainment, and dispersion of dust. Effective dust control is achieved by control measures that are applied close to the dust sources and are well maintained. Miner education and training is an important part of these measures as well. The ventilation plan for the section needs to ensure adequate air to ensure dilution of the dust and gases to below their mandated concentrations. Major aspects of continuous-miner dust control are associated with

- Design of cutter bits and the cutter head speed;
- Frequent replacement of worn-out bits;
- Use of scrubbers on the machines to capture and remove the dust;
- Appropriate arrangement of water sprays, water flow rate, number of sprays, and the water pressure;
- Use of wetting agents;
- Use of sprays, fans, and other means to course air currents toward dust sources and to conduct dusty air away from miners (Figure F-3 illustrates a water spray arrangement on a continuous miner);
- Face ventilation alternatives, including several auxiliary ventilation systems;
- Modified cutting practices; and
- Remote control of the continuous miner.

Roof Bolter Dust Control

Roof bolting can be done by wet or dry drilling. In coal mines, it is most common to use dry drilling. In most modern roof bolters, the primary dust control mechanism is the dry collection vacuum system. The drill cuttings are drawn into a dust collector box in the roof bolter through the drill bit, drill steel, and drill head by a vacuum pump. A precleaner collects large drill cuttings before they enter the drill box and deposits them in the mine floor. A filter in the dust box prevents the finer particles from passing to the blower. Proper maintenance of this collection system should prevent leaks of the dust-laden air into the mine atmosphere. A potential source of exposure to roof bolter–generated dust arises when the dust box and the filter are cleaned and replaced.

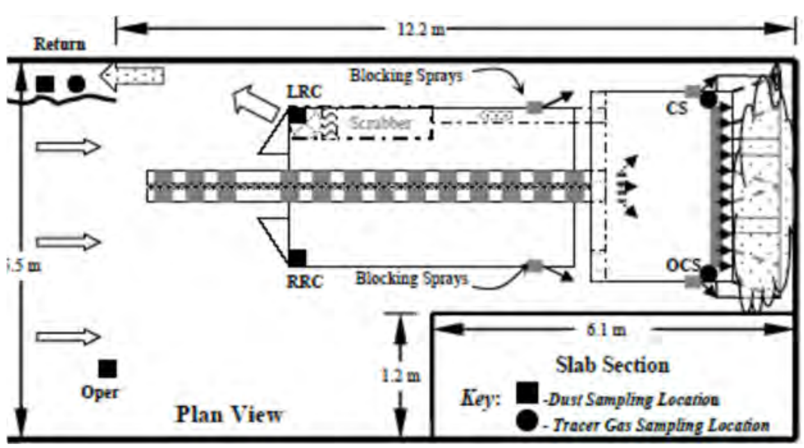

FIGURE F-3 Layout of sprays on a continuous miner with blocking sprays. SOURCE: Organiscak and Beck, 2010.

As with the continuous-mining machine, where worn cutting bits must be replaced, drill bits must also be replaced when worn to prevent excessive generation of respirable-size particles. The frequency of change-out depends on the hardness of the rock through which the bit progresses.

A major source of dust exposure for roof bolter operators is when working downwind of the continuous miner. To avoid such exposures, the canopy of the roof bolter may be so designed with a fan and duct system such that part of the air entering the entry is drawn into it, filtered, and then blown in the breathing zone of the bolter operator.

LONGWALL MINING SECTION

A schematic of a portion of a mine that has been laid out for longwall mining is shown in Figure F-4. As shown in the figure, the first longwall panel has been extracted and the working face is in the second panel. The length of the working face typically ranges from 800 to 1,200 ft. and the length of the panel from about 8,000 to 15,000 ft. In general, the height of extraction is the height required to provide adequate clearance for equipment and personnel. In thin seams and where part of the immediate roof parts from the strata above, this height may include some cutting of the roof strata as well.

Longwall Equipment

The details of the longwall face can be seen in Figure F-2. The major equipment in the longwall system is the longwall shearer, which cuts and loads the coal onto the armored face conveyor (AFC) on which it rides. The shearer slices away about 42 in. of the coal seam every time it travels from one gate to the other. The shearer and the AFC are under a canopy of roof supports, called shields, each either 5.74 ft or 6.56 ft. wide. Shields are self-advancing, powered hydraulic supports that carry the load of the overlying strata that has separated from the main roof. The load-bearing capacity of each of the shields can vary from 800 to 1,300 tons.

In a 1,200-ft.-wide face, there usually will be 209 shields, each equipped to operate either singly or in combination with neighboring shields, or to be activated by the shearer automatically at a predetermined distance after it has cut the coal in front of the shield. After the coal has been cut in front of the shield, the canopy is extended. Then, the shields push the AFC up to the face by fully extending their rams, after which they can pull themselves forward, allowing the broken strata that it was supporting to collapse into the opening behind them. The shearer can travel along the face, cutting and loading the coal, at about 40 to 50 ft. per minute, often limited by both the ability of shields to keep up with it and by the capacity of the outby coal clearance system.

The high production and productivity of a longwall system arise from the truly continuous nature of the mining system and the potential it has for automation. In addition to proper selection of equipment to match the geologic conditions, ventilation planning is critical as the high production demands large quantities of air in the working faces to keep dust and gas concentrations under mandated levels. Shown in Figure F-5 is a ventilation schematic of a longwall mine in southwestern Pennsylvania. As can be seen, two longwall panels have been extracted, the third one is under extraction, and the fourth is under development. The results are from a study conducted by the National Institute for Occupational Safety and Health (NIOSH) to evaluate the performance of ventilation and bleeder system at this mine.

The gob gas ventilation holes to drain methane from the longwall gobs is an indication of the high methane problem in the mine. The bleeder fan, which handles part of the air from the longwall gobs, the active longwall, and longwall development, exhausts about 273,000 cubic feet per minute (cfm). The intake air is brought in through the headgate, where it splits, most entering the face, some returning through the belt, and some returning through the head gate. After ventilating the face, while leaking into the gob all the way through the face, the air again splits at the tailgate, part to the bleeder fan and part to the tailgate returns. The quantity of air entering the section at the release location was 190,000 cfm. The quantity near the headgate end was 150,000 cfm, whereas the quantity at shield 17 was 83,770 cfm, and at shield 186, 73,800 cfm. The quantity in the tailgate entry was 26,000 cfm. While these data represent a point in time, they shows the large quantities of air that are required to adequately ventilate a longwall face. These high quantities in the entrance to the face and along the face lead to high velocities in the face and facilitate entrainment of dust.

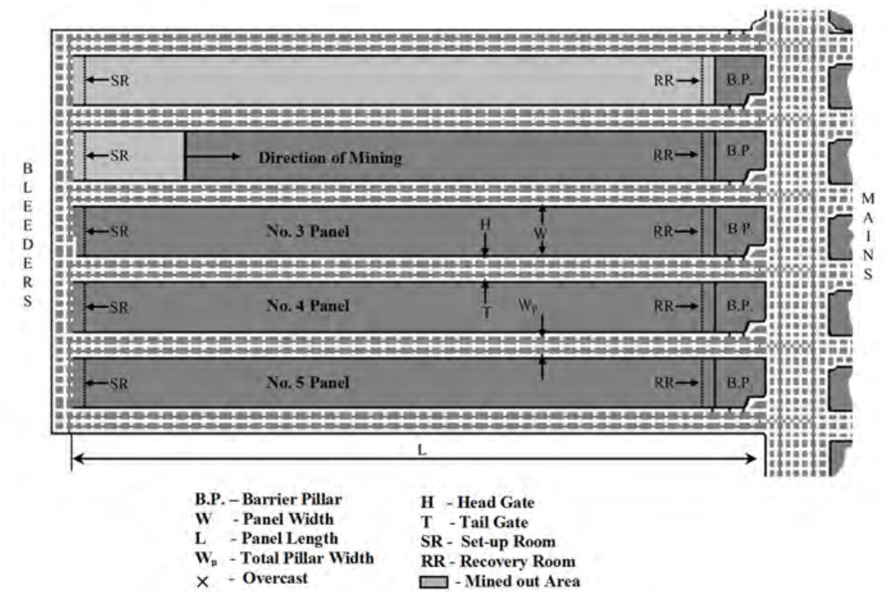

FIGURE F-4 Layout of longwall panels. Transport of miners, supplies, coal, and intake air occurs through the headgate entries. Return air is conducted out of the section through the tailgate entries. Note that the headgate entries on longwall panels become the tailgate entries of the next panels. SOURCE: Peng, 2006. Reprinted with permission; 2006, Syd S. Peng.

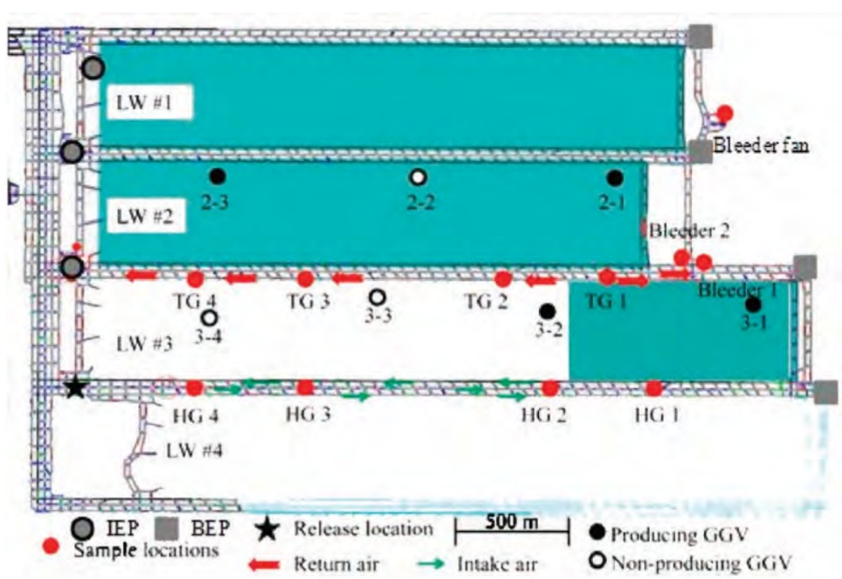

FIGURE F-5 Longwall ventilation plan. Note that intake air enters the headgate, traverses across the face, and returns toward the bleeder fan in the back and the main returns through the tailgate. BEP = bleeder evaluation point; GGV = gob gas vent holes; IEP = intake evaluation point. SOURCE: Schatzel et al., 2012.

The personnel on a longwall face would depend on the length of the face and the level of automatic control and advance. An average face would include two shearer operators, often identified as the headgate operator and tailgate operator, two or more jack setters (shield operators), a mechanic, a headgate miner, and section foreman.

Longwall Dust Sources

The primary source of dust in a longwall face is the longwall shearer. The other sources of dust in a longwall face are shields, the armored face conveyor, and the stage loader. Sources on the intake side of the face include the intake air entry and the belt entry. The longwall shearer cuts in both directions (Figure F-2): with the airflow, when cutting from headgate to tailgate, and against the airflow, when cutting from tailgate to headgate. In either case, part of the shearer-generated dust cloud is entrained into the airstream. As the shields are advanced, broken material from above them falls through the opening between the shields and the dust is entrained into the flowing ventilation stream. The dust that is generated from the components of the material transport system—the AFC, the stage-loader crusher, and the belt—and from the intake airways also traverses from the intake side of the face to the return. In summary, any miner on the longwall face is exposed to dust that emanates from all dust sources that are on the intake side of the miner.

The DOs in a longwall section include the headgate and tailgate shearer. The other occupation sampled generally includes jack setters. Unless required for a very specific reason, such as the shearer operators or jack setters, it is always a good practice to keep all miners upwind of the shearer when it is cutting coal. It is also a good practice to keep the dust that is generated by the shearer confined to the face area and conducted away from migrating into the walkway anywhere near the shearer's length.

While longwall faces had great difficulty in maintaining compliance with the RCMD standard of 2 mg/m^3 initially, the situation improved over the years. During the period 2004-2008, mine operators and mine inspectors collected 6,600 and 1,321 valid samples, respectively, from longwall DOs. About 11 percent of each of these samples exceeded the stated compliance levels (Colinet et al., 2010). In the MSHA sample data for the 4-year period (2009-2012), shown in Table F-2, additional information is provided on miners working jack setters. These data reveal that dust control in a longwall section is more difficult than that in a continuous-miner section.

Basic Strategies for Longwall Dust Control

The basic strategies for dust control discussed earlier are all applicable for longwall dust control. There has been tremendous improvement in the control of dust from every source in the longwall face (Rider, 2016). At the same time, the tremendous increases in production and productivity present great challenges to keep the RCMD concentrations under mandated requirements. The ventilation plan for the longwall section must be so designed to ensure that there is adequate air quantity for ventilating the face—to dilute the dust and gases to below their mandated levels and carry them away.

Shearer Dust Control

The shearer is the major source of dust in a longwall face. The control of dust from the shearer involves a combination of strategies to reduce the production of dust by maintaining the cutting bits and drums in good condition, to capture the dust after it is formed, to suppress it from becoming airborne, and to keep the dust away from the working area or walkway near the shearer where the shearer operators generally position themselves. There are a large number of spray systems associated with the shearer: (1) drum-mounted water sprays, which can number anywhere from 35 to 62, to spray water directly at the point of coal-bit contact, (2) sprays on the top end of ranging arms, directed toward the face, and (3) a directional spray system which splits the intake air into two splits, one that flows through the walkway and the other along the face and which consists of three distinct components, (a) the headgate splitter arm, (b) the shearer-mounted sprays directed toward the face and downwind, and (c) the tailgate splitter arm or spray manifold. The idea of a scrubber for a longwall shearer—much like a flooded bed scrubber for continuous miner—is under research and development. An arrangement of water sprays on the shearer is depicted in Figure F-6.

Shield Dust Control

In most modern longwall mining, the shields' advance is automated and is initiated by the advance of the shearer. In general, the shields are advanced within five shields of the trailing drum. Sprays have been mounted on the canopy of the shield to discharge water on top of shields. Shearer-activated sprays have also been installed under the canopy of the shield to direct water from the shield to the tip and the spill plate of the shearer, creating a moving curtain to suppress the shield dust. The maintenance of these sprays in operational condition is key to their effectiveness. Additional sprays (gob side sprays, side sprays, and washdown sprays) are also employed to reduce the dust generated by the shield movement. Application of foam for longwall shield dust control is also being experimented. An image depicting water sprays mounted on shields is given in Figure F-7.

Other Sources

The stage loader/crusher component at the headgate of a longwall is generally completely enclosed. The dust control from this source is addressed by proper design of the transfer/loader/crusher system sprays, adequate construction to eliminate leakage of dust-laden air from the system, adequate airflow in the entry, and good maintenance around the area where coal transfer to the belt takes place.

When the shearer is cutting out near the headgate entry, there is significant potential for dust exposure due to the high velocity of air and the open area. The control of ventilation and the location of the miners are important operational practices to reduce the exposure.

TABLE F-2 Longwall MSHA RCMD Samples, 2009-2012

Occupation/No. of Samples	RCMD > 2 mg/m^3	RCMD > 1.5 mg/m^3
LW tailgate operator/755	4.9%	14.1%
Jack Setter/1495	7.4%	19.3%

SOURCE: Organiscak, 2017.

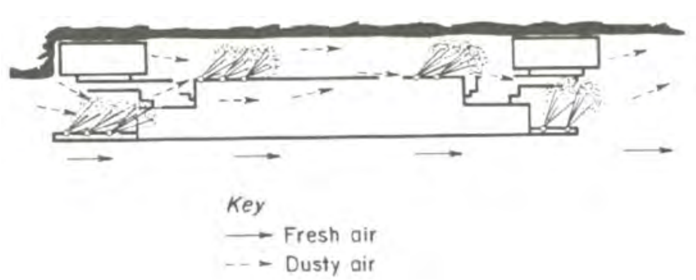

FIGURE F-6 Shearer clearer water spray arrangement. SOURCE: Rider and Colinet, 2001.

FIGURE F-7 Shields equipped with water sprays. SOURCE: Matetic, 2017.

DUST CONTROL PLANS

Every underground coal mining section in the United States operates under a MSHA-approved mine ventilation plan, which contains provisions for methane and dust control, as specified in 30 CFR 75.370 . The dust control portion of the ventilation plan is specifically developed by the mine operator for each section in the mine and approved by the MSHA District Manager. Additional requirements for dust control provisions are specified in 30 CFR 90.300 and 90.301 for Part 90 miners, who have been diagnosed with coal mine dust disease. The dust control plan provides detailed descriptions of dust control measures to control miners' exposures at less than the allowable limit. In addition, it specifies sampling locations for monitoring purposes and serves to assess the performance of the process controls for respirable dust generation, entrainment, dispersion and control. The dust control plan provisions must be measurable and verifiable. Box F-1 provides examples of items included in dust control plans for longwall mining units. Box F-2 provides examples for continuous miner units.

SUMMARY

When the 1969 Coal Mine Health and Safety Act was enacted, U.S. coal production was about 600 million tons with about 60 percent underground mining and 40 percent surface mining. Longwall mining accounted for less than 1 percent of the underground production; room-and-pillar continuous mining accounted for about 50 percent of the underground production. By 2015, underground mining accounted for only 35 percent of U.S. coal production. The amount mined was 300 million tons; longwall mining and room-and-pillar continuous mining accounted for about 60 and 39 percent of that production, respectively. The average RCMD concentration in underground coal mines has been decreasing (Figure F-8), albeit rapidly from the 1970 to 1980 and somewhat less so after that. According to Meikle (2017), the average RCMD concentrations in continuous and longwall mining sections were less than 1.0 mg/m^3.

BOX F-1 Examples of Dust Control Plan Items for Longwall Mining Units in Underground Mines

Shearer Spray System Specifications: details of drum sprays and other sprays such as shearer-clearer including types of sprays, number of sprays, operating pressure, quantity of water flow, and minimum number operating.

Description of the Remote-Control Operation of the Shearer.

Specifications of the Spray Supply System: booster pump, supply lines, pressures and quantities at various points.

Stage loader Dust Control System, including the enclosures and details of the sprays.
Shield Dust Control System: the frequency for the wash down of the shields, hosing down of the shield tips, and any special provisions for the headgate and tailgate shields.

Operational Provisions to Reduce Exposure: shearer cutting sequence, the locations of the shearer and shield operators, maximum amount of time personnel downwind of the shearer or the shield when operating, average production.

Ventilation Controls: specifications of the quantity and velocity of air at specified locations in the face; use of gob curtain and wing curtain; air splitting barriers on the shearer; use of belt air.

Other Dust Control Provisions, if any, such as water infusion, wetting agents, intake air dust control, roadway dust control.

Respiratory Protection: provisions and requirements for the use of respirators. use of personal protection equipment such as powered air purifying respirator by shearer operator or by all miners when working downwind of the shearer.

Any other detail as necessary to fully illustrate the dust control is maintained.

SOURCE: Adapted from Ramani et al., 2003.

BOX F-2 Examples of Dust Control Plan Items for
Continuous Miner Units in Underground Mines

Continuous Miner Dust Control: location, type and number of sprays, pressure and quantity of water flow; machine-mounted scrubbers.

Provision of Hoses: wash down hoses, sprinkler hoses

Roof Bolter Dust Control: dust collection system operation and maintenance

Sprays on belt lines

Ventilation Controls: single or dual-split ventilation, air quantity in the coal face, face ventilation system (line curtain or tubing), belt ventilation.

Float Dust Control.

Cleaning of Dust Accumulations.

Any other detail as necessary to fully illustrate the dust control is maintained.

SOURCE: Adapted from Ramani et al., 2003

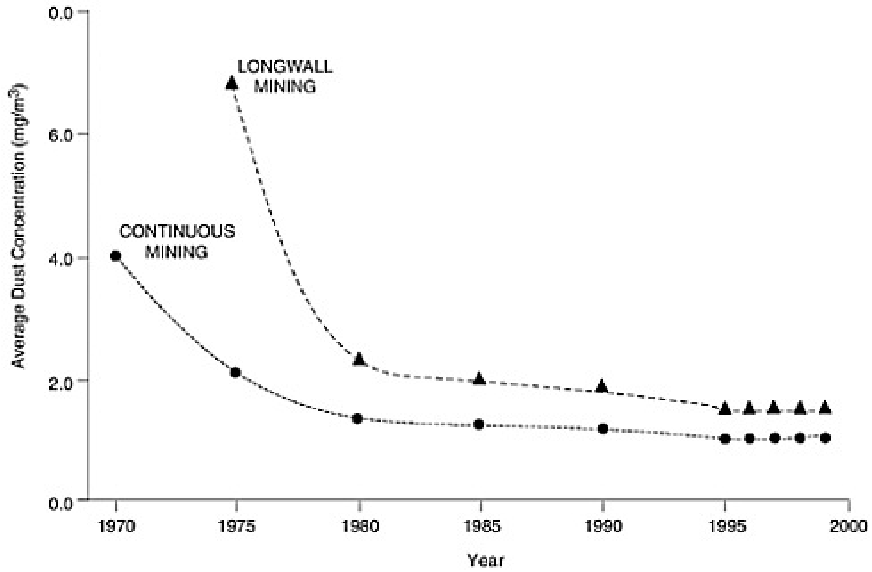

FIGURE F-8 Average dust concentrations for U.S. longwall and continuous mining operations. SOURCE: NRC, 2002.

REFERENCES

Arch Coal, Inc. 2012. Annual Report Pursuant To Section 13 Or 15(D) Of The Securities Exchange Act Of 1934. Washington, DC: U.S. Securities and Exchange Commission. Online. Available at https://www.sec.gov/Archives/edgar/data/1037676/000104746912001909/a2207536z10-k.htm (accessed May 16, 2018).

Bise, C. J. 2013. *Modern American Coal Mining: Methods and Applications*. Englewood, CO: Society for Mining, Metallurgy and Exploration, Inc. p. 563.

Colinet, J. F., and J. M. Listak. 2007. Reducing Dust Generation and Optimum Suppression Techniques. Presentation to Controlling Respirable Coal Mine Dust in Underground Mines National Mine Health and Safety Academy, July 25, 2007, Beckley, WV [online]. Available at https://arlweb.msha.gov/s&hinfo/blacklung/ControlDust2007/NIOSH%20PRL%201-97.pdf (accessed April 26, 2018).

Colinet, J. F., J. P. Rider, J. M. Listak, J. A. Organiscak, and A. L. Wolfe. 2010. Best Practice for Dust Control in Coal Mining. Information Circular 9517. DHHS (NIOSH) Publication No. 2010-110 [online]. Available at https://www.cdc.gov/niosh/mining/userfiles/works/pdfs/2010-110.pdf (accessed November 2017).

EIA (U.S. Energy Information Administration). 1995. Longwall Mining. DOE/EIA-TR-0588 [online]. Available at http://webapp1.dlib.indiana.edu/virtual_disk_library/index.cgi/4265704/FID1578/pdf/coal_nuc/tr0588.pdf (accessed November 2017).

EIA. 2017. Annual Coal Report 2016. [online]. Available at https://www.eia.gov/coal/annual/pdf/acr.pdf (accessed August 2018).

Evans, A. M. and R.V. Ramani. 2006. Coal Mining. Encyclopedia Britannica. Online. Available at https://www.britannica.com/technology/coal-mining (accessed May 16, 2018).

Matetic, R. J. 2017. Presentation from Director of NIOSH Pittsburgh Mining Research Division, NIOSH Information for NAS Committee on Respirable Coal Dust to Committee on the Study of the Control of Respirable Coal Mine Dust Exposure in Underground Mines, Washington, DC, February 8, 2017.

Meikle, G. 2017. Presentation from the Chief of Health for Coal Mine Safety and Health, MSHA to Committee on the Study of the Control of Respirable Coal Mine Dust Exposure in Underground Mines, Morgantown, WV, June 29, 2017.

NRC (National Research Council). 2002. Health and safety risk and benefit. *In Evolutionary and Revolutionary Technologies for Mining*. Washington, DC: National Academy Press, pp. 47-52.

Organiscak, J. 2017. Personal communication.

Organiscak, J. 2014. Controlling Dust on Continuous Mining Operations [online]. Available at https://arlweb.msha.gov/endblacklung/docs/4%20Continuous%20Miner%20Dust%20Control_Beckley%202014.pdf (accessed May 20, 2018).

Organiscak, J., and T. Beck. 2010. Continuous miner spray considerations for optimizing scrubber performance in exhaust ventilation systems. *Minerals Engineering* 62(10):41-46 [online]. Available at https://pdfs.semanticscholar.org/b132/d1ee660fe7916429c857106b3f14ab00537f.pdf (accessed November 20, 2017).

Peng, S. 2006. *Longwall Mining*. Second Editon. pp. 621.

Ramani, R. V., M. C. Radomsky, J. P. Flick. 2003. Control of Airborne Respirable Dust Hazards: A Training Program for Underground Coal Miners," by, The Penn State Miner Training Program. Available at http://miningquiz.com/powerpoints/dust_and_silica.htm (accessed June 17, 2018).

Rider, J. 2016. Sound Practices to Control Respirable Dust on Longwall Operations and Ongoing. Presentation at MSHA Coal Mine Respirable Dust Control Summit, National Mine and Safety Academy, December 6, 2016, Beckley, WV [online]. Available at https://arlweb.msha.gov/endblacklung/docs/niosh-lwdc.pdf (accessed November 17, 2017).

Rider, J. P., and J. F. Colinet. 2001. Reducing worker exposure to dust generated during longwall mining. In *Proceedings of the Seventh International Mine Ventilation Congress, June 17-22, 2001, Krakow, Poland*. S. Wasilewski, ed., Krakow, Poland: Research & Development Center for Electrical Engineering and Automation in Mining (EMAG), pp. 275-282.

Schatzel, S., R. Krog, and H. Dougherty. 2012. Field study of longwall coal mine ventilation and bleeder performance. *Transactions of the Society for Mining, Metallurgy and Exploration* 330:388-396 [online]. Available at https://www.cdc.gov/NIOSH/Mining/UserFiles/works/pdfs/fsolc.pdf (accessed November 17, 2017).

Appendix G

Mandatory Airborne Dust Standards for U.S. Underground Coal Mines

The laws and regulations that are aimed at protecting the miners from the health hazards associated with exposure to airborne respirable coal mine dust (RCMD) also specify monitoring technology and sampling protocols. Prior to 1969, the enforcement of health and safety standards in the coal mining industry was viewed as primarily a state responsibility, even though in 1865 a bill was introduced in Congress to create a Federal Mining Bureau. In July 1910, Congress established the Bureau of Mines in the Department of Interior by enacting the Bureau of Mines Organic Act, but it contained a specific denial of "any right or authority in connection with inspection or suspension of mining" (Committee on Human Resources, 1978). During subsequent decades, the extent of federal agencies' involvement in enforcement of mine health and safety standards in the coal mining industry increased through regulatory changes.

From 1970 to 2012, government inspectors collected 750,000 coal mine dust samples in underground mines, and mine operators collected 4.6 million samples during that same period (GAO, 2012). Those numbers reveal the enormous efforts spent by industry, labor, and government to monitor the airborne dust conditions underground. As shown in Figure F-8 in Appendix F of this report, the average airborne RCMD concentrations in underground longwall and continuous-mining sections have been decreasing. However, disappointingly, there has also been an increase in the prevalence of coal workers' pneumoconiosis in certain mining areas of the country, pointing to the need for further investigations into the effectiveness of the present control strategies.

THE COAL MINE HEALTH AND SAFETY ACT OF 1969

In Title II of the Coal Mine Health and Safety Act of 1969, Congress stated that the purpose of the act is

> "to provide to the greatest extent possible, that the working conditions in each underground coal mine are sufficiently free of respirable dust concentrations in the mine atmosphere to permit each miner the opportunity to work underground during the period of his entire adult working life without incurring any disability from pneumoconiosis or any other occupation-related disease during or at the end of such period."

Specifications in Title II included allowable airborne RCMD concentration in coal mines, sampling technology, procedures determining average RCMD concentrations, allowable quartz content in airborne RCMD, medical examinations (chest x-ray, other tests), and transfer of miners, who show early indications of developing pneumoconiosis, to work areas where the RCMD concentration is lower than the allowable level. In Title IV of the act, Congress created the Black Lung Benefits program to provide benefits to coal miners "who are totally disabled due to pneumoconiosis and to the surviving dependents of miners whose death was due to such disease."

According to the act, which became effective on June 30, 1970, the average concentration of RCMD in the active sections of underground coal mines was to be maintained at or below 3.0 mg/m^3. On December 30, 1972, the standard was reduced to 2.0 mg/m^3. The act further stated that the standard would be reduced further whenever the quartz content in RCMD was greater than 5 percent. The effect of the reduced standard was to keep the quartz concentration at or below 0.1 mg/m^3. The significance of achieving these RCMD standard in mines was substantial, as a U.S. Bureau of Mines survey of 29 mines during the period 1968-1969 found average RCMD concentrations in excess of 6 mg/m^3 (Shepich, 1983).

The rationale for the allowable RCMD concentrations was provided in a Department of Interior report on the causation of pneumoconiosis (Committee on Education and Labor, 1970). According to that report, the probabilities of developing simple pneumoconiosis and progressive massive fibrosis (PMF) decreased with reduced RCMD exposure. Those probabilities were based on British medical data on dose-response relationships extrapolated to various dust concentrations.

Required Instruments

The Isleworth type 113A (MRE) gravimetric dust sampler was the reference dust sampling instrument for measuring RCMD concentrations with respect to the standard. The device uses a four-channel horizontal elutriator for size classification of the dust sample into respirable and nonrespirable fractions (Tomb et al., 1998). The most commonly used sampling instrument was a personal sampling device that utilizes a cyclone to separate a dust sample into respirable and non-respirable size fractions.

Sampling Protocols

Federal regulations issued in 1970 initiated a dust sampling program for mine operators based on the high-risk-occupation concept. Under that concept, individuals in the occupations in the working section of the mine exposed to the highest RCMD concentrations are sampled. The high-risk occupation for each method of mining was identified in the regulation. In addition, Mine Safety and Health Administration (MSHA) inspectors conducted mine inspections and collected RCMD samples to determine compliance with the standards and assess the operator samples. The Government Accountability Office (GAO, 1975) noted the general agreement among the miners, mine operators, union officials, and government agencies that significant reductions had been made in RCMD concentrations in mines. However, the report also identified weaknesses in the dust-sampling program that affect the accuracy and validity of the RCMD results and make it virtually impossible to determine how many mine sections complied with allowable dust concentration. The operator sampling program was revised in 1980 (Raymond et al., 1987) to require mine operators to collect two types of samples during bimonthly sampling periods:

- Designated occupation (DO) samples, which are the same as the previous high-risk-occupation samples, and
- Designated area (DA) samples collected at appropriate locations in the section.

Compliance determinations were based on the average RCMD concentration by five valid RCMD samples taken by the operator during five consecutive normal production shifts or five normal production shifts worked on consecutive days. Compliance was also based on the average of multiple measurements taken by an MSHA inspector over a single shift or on the average of multiple measurements obtained for the same occupation on multiple days. In addition, miners (Part 90 miners) were sampled who had exercised the option to work in areas of mine where the concentration was at or below 1 mg/m^3. The sampling results became available to the miner operator, miners, and MSHA about 1 week after the samples were collected due to the need to analyze the samples off site.

SUBSEQUENT RCMD CONTROL PROGRAMS

In May 1991, the Secretary of Labor directed MSHA to form a task force for conducting a review of the administration's program to control RCMD concentrations and recommend program improvements (MSHA, 1992). The task force examined the developments in the coal industry; explored the roles of labor, industry, and government in the enforcement program; designed and implemented a short-term monitoring program with specific objectives; and explored future technologies for RCMD measurement, monitoring, and control. The review concluded that, even though there were significant reductions in RCMD concentrations since 1969 (Table G-1), MSHA was not conducting the prescribed number of dust sampling inspections nor was it adequately monitoring the operator sampling program.

Recommendations of the task force included the use of continuous monitoring of the mine environment and parameters relevant to control RCMD, development of a personal sampling device capable of measuring short-term exposures and cumulative exposures over a full shift, greater use of more tamper-resistant cassettes, and submission of improved RCMD control plans by operators. Recommendations also addressed topics concerning MSHA inspections, education and training, and the role of miners in improving compliance sampling.

NIOSH Coal Mine Dust Criteria Document

In September 1995, the National Institute for Occupational Safety and Health (NIOSH) published a criteria document (NIOSH, 1995) for occupational exposure to RCMD, which included these recommendations:

- Exposures to RCMD should be limited to 1 mg/m^3 as a time-weighted average (TWA) concentration for up to 10 hours per day during a 40-hour workweek, measured according to current MSHA methods.
- The RCMD allowable concentration represents the upper limit of exposure for each worker during each shift. For single, full-shift samples used to determine compliance, no upward adjustment of the limit should be made to account for measurement uncertainties.
- Exposures to respirable crystalline silica should not exceed 0.05 mg/m^3 as a TWA concentration for up to 10 hours per day during a 40-hour workweek.

The criteria document provided an extensive analysis of the data from the RCMD sampling program and from the x-ray surveillance program. The criteria document indicated that excess prevalence of coal workers' pneumoconiosis, PMF, and decreased lung function is expected to be reduced substantially if lifetime average RCMD exposures are reduced from 2 to 0.5 mg/m^3. The document also indicated that, at exposures to a mean RCMD concentration of 0.5 mg/m^3, miners have a greater than 0.1 percent risk of developing those disease conditions.

Secretary of Labor's Advisory Committee

A 1996 report (MSHA, 1996) of an advisory committee established by the Secretary of Labor recommended separating and lowering the RCMD and silica standards. The advisory committee recognized the potential uses of continuous-monitoring data for hazard surveillance and compliance monitoring. It recommended that MSHA take full responsibility for all compliance sampling and that the operator-sampling program be continued with substantial improvements to increase its credibility. The advisory committee called for an appropriately balanced strategy of personal (individual miner), occupational (such as DO), and environmental (such as DA) for RCMD sampling for compliance. It recommended major emphasis on personal sampling and single full-shift samples for determining compliance. The advisory committee observed miners' low participation rate in the medical surveillance program for respiratory effects and recognized the difficulty in resolving the individual's right to confidentiality and the need for MSHA, NIOSH, operators, and fellow miners to know where and how much disease is occurring.

CURRENT DUST STANDARDS

The development of a continuous personal dust monitor (CPDM) that can measure RCMD continuously and in near real time was seen as a key advancement for exposure assessment and RCMD control (Volkwein et al., 2004). In 2010, MSHA and NIOSH published a final rule for approval requirements for the existing RCMD personal samplers, and new approval requirements for the CPDM.

In October 2010, MSHA proposed a rule titled "Lowering Miners' Exposure to Respirable Coal Mine Dust, Including Continuous Personal Dust Monitors" that included a lowering of the allowable RCMD concentration, full-shift sampling, and redefining "normal production shift," among other requirements.

Following the publication of the proposed rules, public hearings were held, written comments were submitted, and GAO issued reports on lowering the RCMD standard and single-shift sampling procedures (GAO, 2012, 2014).

TABLE G-1 Underground Dust Exposure Concentrations in 1969 and 1991

Occupation	1969[a] (mg/m^3)	1991[b] (mg/m^3)
Cutting Machine Helper	8.4	0.8
Continuous Miner Operator	7.7	1.5
Loading Machine Operator	7.1	1.3
Cutting Machine Operator	6.9	1.9
Coal Drill Operator	6.7	1.3
Continuous Miner Helper	6.5	1.3
Loading Machine Helper	6.0	1.4
Shot Firer	5.9	--[c]
Timberman	4.7	--
Roof Bolter Operator	4.6	1.2
Beltman	3.7	0.9
Section Foreman	3.2	0.8
Scoop Car Operator	--	0.9
Supply Man	3.0	1.0
Shuttle Car Operator	2.7	0.9
Boomboy	2.4	--
Mechanic	2.1	0.6
Longwall Operator (tail)	--	1.7
Longwall Operator (head)	--	1.5
Longwall Jack Setter	--	1.4

[a]Wheeler, 1970.
[b]MSHA's Respirable Dust Spot Inspection Program.
[c]Indicates that the studies did not include these occupations.
SOURCE: MSHA, 1992.

In 2014, MSHA published a final rule that changed the RCMD standards, measurement technology and sampling protocols (79 Fed. Reg. 24,814, 2014). The major changes include the following:

- RCMD airborne concentration limit is 1.5 mg/m^3 for underground mines, and 0.5 mg/m^3 for intake air at underground mines and for Part 90 miners (coal miners who have evidence of the development of pneumoconiosis).
- Mine operators are required to use the CPDM to monitor the exposures of underground coal miners in occupations exposed to the highest RCMD concentrations and the exposures of Part 90 miners. Use of the CPDM is optional for nonproduction areas of underground coal mines.
- Normal production shift is redefined such that coal production must be at least 80 percent of the average production over the last 30 production shifts when RCMD samples are collected in the mechanized mining unit.
- The operator must collect RCMD samples for the full shift that a miner works. If a miner works a 12-hour shift, RCMD samples must be taken with an approved sampling device for the entire work shift.
- MSHA inspectors will use single, full-shift samples to determine noncompliance with the RCMD standards.
- Immediate corrective actions to lower RCMD concentrations are required when a single, full-shift operator sample meets or exceeds the excessive concentration value (ECV) for the RCMD standard. ECV ensures that MSHA is 95 percent confident that the applicable standard has been exceeded and allows for the margin of error when measuring the RCMD concentration with an instrument. ECV tables are provided in the regulations for the applicable standard and device.
- Spirometry testing, occupational history, and symptom assessment have been added to the periodic chest radiographic (x-ray) examinations required to be offered by mine operators to underground miners under NIOSH's existing standards.
- Certified persons who perform RCMD sampling and who maintain and calibrate sampling equipment must complete an MSHA course of instruction and must pass an MSHA examination to demonstrate competency in the tasks needed for RCMD sampling procedures and in maintenance and calibration procedures. MSHA is allowed to revoke a person's certification for failing to carry out the required sampling or maintenance and calibration procedures in a proper manner.

Frequency of Sampling

Operators must collect all samples quarterly on consecutive shifts. The sampling frequency for the DOs and other designated occupations (ODOs) is 15 shifts per quarter, and the frequency for DAs and Part 90 miners is 5 shifts per quarter. DOs and ODOs cannot be sampled concurrently. Corrective action is required when one operator full-shift sample meets or exceeds the ECV. Noncompliance is considered to occur when three samples meet or exceed the ECV or the average of the 15 samples meets or exceeds the ECV. Data from CPDM must be transmitted within 24 hours to MSHA.

When sampling is done by MSHA, the instrument used is the personal gravimetric sampler (CMDPSU). The collected sample is used to determine compliance with the RCMD standard and the allowable limit for quartz concentration in RCMD.

Since February 2016, CPDM must be used for operator sampling and since August 2016, the RCMD concentration limit for underground coal mines has been 1.5 mg/m^3. Tables G-2 and G-3 summarize quarterly operator-sample data from April 2016 to March 2017 for the designated occupation and other designated occupation, respectively (Meikle, 2017). It is evident from the reported data that noncompliance was rare and the average RCMD concentration was well below the mandated level.

TABLE G-2 Designated Occupation Sampling of RCMD Mass Concentrations in Underground Coal Mines by Mining Method for Regulatory Compliance, April 2016 to March 2017

Valid CPDM Dust Sample Counts by Type

Longwall Designated Occupation Sampling Results for a 4 Quarter Period April 2016 - March 2017

Quarter	Total Number of Samples	Number of Samples Non-Compliant	Compliance %	Average Concentration (mg/m^3)
1	639	3	99.5%	0.999
2	626	2	99.7%	0.866
3	581	8	98.6%	0.903
4	628	2	99.7%	0.861
Total	2474	15	99.4%	0.907

Valid CPDM Dust Sample Counts by Type

Continuous Miner Designated Occupation Sampling Results for a 4 Quarter Period April 2016 - March 2017

Quarter	Total Number of Samples	Number of Samples Non-Compliant	Compliance %	Average Concentration (mg/m^3)
1	6553	4	99.9%	0.712
2	6745	11	99.8%	0.664
3	7051	21	99.7%	0.651
4	7409	22	99.7%	0.688
Total	27758	58	99.8%	0.679

SOURCE: Meikle, 2017.

TABLE G-3 Other Designated Occupation Exposures to RCMD in Underground Coal Mines by Mining Method, April 2016 to March 2017

Valid CPDM Dust Sample Counts by Type

Longwall Other-Designated Occupation Sampling Results for a 4 Quarter Period April 2016 - March 2017

Quarter	Total Number of Samples	Number of Samples Non-Compliant	Compliance %	Average Concentration (mg/m^3)
1	518	2	99.6%	0.835
2	503	1	99.8%	0.716
3	505	4	98.8%	0.789
4	635	0	100.0%	0.732
Total	2161	7	99.7%	0.768

Valid CPDM Dust Sample Counts by Type

Continuous Miner Other-Designated Occupation Sampling Results for a 4 Quarter Period April 2016 - March 2017

Quarter	Total Number of Samples	Number of Samples Non-Compliant	Compliance %	Average Concentration (mg/m^3)
1	5402	11	99.8%	0.694
2	6248	8	99.9%	0.610
3	6372	15	99.8%	0.647
4	7226	12	99.8%	0.635
Total	25248	46	99.8%	0.647

SOURCE: Meikle, 2017.

Of the 86,941 CPDM samples submitted to MSHA in 2016, about 24 percent of the samples were voided (or invalidated) (NMA, 2017). About 45 percent of the samples were voided because an insufficient amount of coal production occurred during the shift the sample was taken. CPDM malfunction was responsible for about 55 percent of the voided samples. Some of those problems were associated with temperature selection, battery life, and CPDM software.

SUMMARY

The current monitoring technology and sampling protocols are significantly different from the ones that were specified in the rules and regulations stemming from the 1969 coal act. The CPMD had been under development for more than two decades to address a long-recognized need for the real-time assessment of airborne RCMD underground. The use of the CPDM for personal sampling is demonstrated as being effective for obtaining regulatory compliance data.

REFERENCES

Committee on Education and Labor. 1970. *Legislative History of the Federal Coal Mine Health and Safety Act*. Washington, DC: U.S. Government Printing Office, pp. 14-17.

Committee on Human Resources. 1978. *Legislative History of the Federal Mine Safety and Health Act of 1977*. Washington, DC: U.S. Government Printing Office, pp. 589-591.

GAO (U.S. Government Accountability Office). 1975. Improvements Still Needed in Coal Mine Dust-Sampling Program and Penalty Assessments and Collections [online]. Available at http://www.gao.gov/assets/120/114174.pdf (accessed July 30, 2017).

GAO. 2012. Mine Safety: Reports and Key Studies Support the Scientific Conclusions Underlying the Proposed Exposure Limit for Respirable Coal Mine Dust. GAO-12-832R [online]. Available at http://www.gao.gov/products/GAO-12-832R (accessed November 17, 2017).

GAO. 2014. Mine Safety: Basis for Proposed Exposure Limit on Respirable Coal Mine Dust and Possible Approaches for Lowering Dust Levels. GAO 14-345 [online]. Available at http://www.gao.gov/assets/670/662410.pdf (accessed November 17, 2017).

Meikle, G. 2017. Presentation from the Chief of Health for Coal Mine Safety and Health, MSHA to Committee on the Study of the Control of Respirable Coal Mine Dust Exposure in Underground Mines, Morgantown, WV, June 29, 2017.

MSHA (Mine Safety and Health Administration). 1992. Review of the Program to Control Respirable Coal Mine Dust in the United States. Report of the Coal Mine Respirable Dust Task Group, June 1992 [online]. Available at https://arlweb.msha.gov/s&hinfo/blacklung/Reports/1992ReviewCoalMineDust.pdf (accessed November 17, 2017).

MSHA. 1996. Report of the Secretary of Labor's Advisory Committee on the Elimination of Pneumoconiosis Among Coal Mine Workers [online]. Available at https://arlweb.msha.gov/S&HINFO/BlackLung/1996Dust%20AdvisoryReport.pdf (accessed November 17, 2017).

NIOSH (National Institute for Occupational Safety and Health). 1995. Criteria for a Recommended Standard: Occupational Exposure to Respirable Coal Mine Dust, DHHS (NIOSH) Publication No. 95-106. September 1995 [online]. Available at https://www.cdc.gov/niosh/docs/95-106/pdfs/95-106.pdf (accessed November 17, 2017).

NMA (National Mining Association). 2017. Coal Mining Industry Perspective on Respirable Dust. Presentation to the committee on February 8, 2017.

Raymond, L. D., T. F. Tomb, and P. S. Parobeck. 1987. Respirable Coal Mine Dust Sample Processing. Mine Safety and Health Administration Informational Report 1156.

Shepich, T. J. 1983. Welcome remarks. In *Proceedings of the Symposium on Control of Respirable Coal Mine Dust,* Washington, DC: MSHA, pp. 3-6.

Tomb, T. F., R. G. Peluso, A. J. Gero, and J. P. Seiler. 1998. Study to assess respirable dust exposures in underground U.S. coal mines. Applied Occupational and Environmental Hygiene 13(1):62-72.

Volkwein, J. C., R. P. Vinson, L. J. McWilliams, D. P. Tuchman, and S. E. Mischler. 2004. Performance of a New Personal Respirable Dust Monitor for Mine Use. Report of Investigations 9663 [online]. Available at https://www.cdc.gov/niosh/mining/UserFiles/works/pdfs/ri9663.pdf (accessed November 17, 2017).

Wheeler, H. P., Jr. 1970. The working environment: Statement of the steps and rationale for action taken by the Department of the Interior. Papers and Proceedings of the National Conference on Medicine and the Federal Coal Mine Safety and Health Act of 1969. June 15-18, 1970, pp. 28-34.