NIOSH Mining Program

Evidence package for 2008–2018

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Centers for Disease Control
and Prevention
National Institute for Occupational
Safety and Health

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Acronyms and Abbreviations

ABMS	Automated Breathing and Metabolic Simulator
ACARP	Australian Coal Association Research Program
ADRS	Analysis and Design of Rib Support
AFS	Annual Fire School
AIME	American Institute of Mining, Metallurgical, and Petroleum Engineers
ALPS	Analysis of Longwall Pillar Systems
AMSS	Analysis of Multiple Seam Stability
ANSI	American National Standards Institute
ARMPS	Analysis of Retreat Mining Pillar Stability
ART	Annual Refresher Training
ASABE	American Society of Agricultural and Biological Engineers
BAA	Broad Agency Announcement
BAS	breathing air supply
BELT	Belt Evaluation Laboratory Test
BIP	built-in-place
CCBA	closed-circuit breathing apparatus
CCER	closed-circuit escape respirator
CDEM	Coal Dust Explosibility Meter
CERDEC	Communications-Electronics Research, Development and Engineering Center
CFD	computational fluid dynamics
CFR	Code of Federal Regulations
CMDPSU	Coal Mine Dust Personal Sampling Unit
CO	carbon monoxide
CPB	cement paste backfill
CPDM	continuous personal dust monitor
CRADA	Cooperative Research and Development Agreement
CRF	cemented rockfill
CT	communications and tracking
CWHSP	Coal Workers’ Health Surveillance Program
CWP	coal workers’ pneumoconiosis
DEEP	Diesel Emissions Evaluation Program
DMRO	Division of Mining Research Operations
DMST	Division of Mining Science and Technology
DOT	Department of Transportation
DPM	diesel particulate matter
DRDS	Division of Respiratory Disease Studies
DSOV	docking and switch-over valve

EC	elemental carbon
EDS	energy dispersive spectrometry
EM	Experimental Mine
ERP	emergency response plan
ESA	Emergency Supplemental Appropriations
ESP	electrostatic precipitator
ETS	Emergency Temporary Standard
EVADE	Enhanced Video Analysis of Dust Exposures
FAME	fatty acid methyl esters
FAST	Field Analysis of Silica Tool
FCD	float coal dust
FDNY	Fire Department of New York
FTIR	Fourier-transform infrared spectroscopy
FY	fiscal year
GAO	Government Accountability Office
GGV	gob gas venthole
HC	hydrocarbon
HEHD	High-Energy High-Displacement
HRSA	Health Resources and Services Administration
HVAC	heating, ventilation, and air-conditioning
HVORD	hydrotreated vegetable oil renewable diesel
IARC	International Agency for Research on Cancer
IC	Information Circular
ICAMPS	Integrated Computer Aided Mine Planning Software
IDLH	Immediately Dangerous to Life and Health
IEC	International Electrotechnical Commission
ILO	International Labour Office
IMA-NA	Industrial Minerals Association–North America
IMSN	Inter-Mountain Seismic Network
IMU	inertial measurement unit
ISO	International Organization for Standardization
IWT	Innovative Wireless Technologies
JM	Johnson-Matthey
KSAs	knowledge, skills, and abilities
LHD	load-haul-dump
LIAM	Longwall Instrumented Aerodynamic Model
li-ion	lithium-ion
LLEM	Lake Lynn Laboratory Experimental Mine
MCP	Methane Control and Prediction

MECP	Mine Emergency Communications Partnership
MEET	Mine Emergency Escape Training
MEMS	microelectromechanical
MEO	Mine Emergency Operations
MF	medium frequency
MIDAS	Miniature Data Acquisition System
MINER Act	Mine Improvement and New Emergency Response Act
MIS	mining-induced seismicity
MNM	metal/nonmetal
MOU	memorandum of understanding
MRS	Mine Roof Simulator
MSHA	Mine Safety and Health Administration
MSHRAC	Mine Safety and Health Research Advisory Committee
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NFPA	National Fire Protection Association
NIHL	noise-induced hearing loss
NIOSH	National Institute for Occupational Safety and Health
NISA	National Industrial Sand Association
NIST	National Institutes of Standards and Technology
NORA	National Occupational Research Agenda
NPPTL	National Personal Protective Technology Laboratory
NSSGA	National Stone, Sand & Gravel Association
NSW	New South Wales
OC	organic carbon
OEM	original equipment manufacturer
OEP	Office of Extramural Programs
OMSHR	Office of Mine Safety and Health Research
OSHA	Occupational Safety and Health Administration
OWCP	Office of Workers’ Compensation Program
PADEP	Pennsylvania Department of Environmental Protection
PEL	permissible exposure limit
PIB	Program Information Bulletin
PIL	Procedure Instruction Letter
PMF	progressive massive fibrosis
PMR	proportionate mortality ratio
PMRD	Pittsburgh Mining Research Division
POV	Pattern of Violations
PPE	personal protective equipment

PROP	Preventive Roof/Rib Outreach Program
psi	pounds per square inch
R&P	Rupprecht & Patashnick
RA	refuge alternative
RCMD	respirable coal mine dust
RCS	respirable crystalline silica
RD	rock dust
RDPT	Round Determinate Panel Test
RFI	Request for Information
RFID	radio frequency identification
RFP	Request for Proposal
RHD	Respiratory Health Division
RI	Report of Investigations
SCSR	self-contained self-rescuer
SIMTARS	Safety in Mines Testing and Research Station
SME	Society for Mining, Metallurgy & Exploration
SMRD	Spokane Mining Research Division
SP	Special Permit
SRCM	Safety Research Coal Mine
STEP	Student Temporary Employment Program
STOP	Support Technology Optimization Program
TC	total carbon
TEM	transmission electron microscopy
TGD	Technical Guidance Document
TIC	total incombustible content
TTE	through-the-earth
U of Utah	University of Utah
UA	University of Arizona
UHF	ultra-high radio frequency
UL	Underwriters Laboratories
ULSD	ultralow sulfur diesel
USBM	U.S. Bureau of Mines
VHPC	very high-pressure cylinder
VISLab	Virtual Immersion and Simulation Laboratory
VR	virtual reality
WVU	West Virginia University

Contents

Executive Summary

Mining, which comprises underground, surface, coal, and metal/nonmetal mines, is a fundamentally dangerous and closely regulated industry, with mine workers facing health and safety challenges on a daily basis. In 2017, the Mine Safety and Health Administration (MSHA)—which develops and enforces health and safety regulations for all U.S. mines—reported that the mining sector included 321,280 total employees (223,380 operator employees and 97,900 contractor employees) [MSHA 2017].

Although these numbers represent a low percentage of the U.S. workforce, and despite substantial advances in mine health and safety over the years, mine workers remain at risk due to infrequent but high-severity events, which include explosions, fires, roof collapses, flooding, and potential entrapment underground following one or more of these events. Because of the physical requirements inherent to mining, cumulative and traumatic musculoskeletal injuries plague the industry, and underground mining has one of the highest fatal injury rates of any U.S. industry. Further, nonfatal injuries from such events as ground failures also tend to be severe, resulting in a high percentage of lost-time injuries.

When these events do occur, workers need to be knowledgeable in the best practices for self-escape and decision-making. In addition, to ensure their survivability and rescue if self-escape is not immediately possible, they require an understanding of and access to the best available technologies related to communications and tracking, breathing air supplies, and taking refuge. Finally, because of the nature of their work, which involves cutting or excavation of rocks, minerals, and unconsolidated sediment followed by conveying, transporting, and processing of the mined products, workers can develop chronic respiratory diseases that lead to health impairment and death.

The National Institute for Occupational Safety and Health (NIOSH) Mining Program and its predecessor the U. S. Bureau of Mines have been addressing the nation's occupational health and safety challenges for more than a century. NIOSH's subject matter experts, most recent research and outputs, and available burden and need information have been guided by six of the eight strategic objectives established by the National Occupational Research Agenda at the start of its second decade (2006–2016). NIOSH has also been guided by regular discussions with the Mine Safety and Health Research Advisory Committee and commissioned reports that resulted in recommendations from the National Academy of Sciences.

Based on these inputs, NIOSH has prioritized and focused its mission to eliminate mining fatalities, injuries, and illnesses through relevant research and impactful solutions. To that end, researchers collaborate with many national and international partners, including mining companies, industry associations, enforcement agencies, labor unions, equipment manufacturers, product suppliers, and academic institutions. To complement the intramural research component, under the direction of the Office of Mine Safety and Health Research and with support from the Office of Extramural Programs, the Mining Program also sponsors research and training extramurally.

During the 2008–2018 review period, NIOSH activities reflected intramural research conducted at laboratories based in Pittsburgh, PA, Spokane, WA, and Morgantown, WV, as well as extramural research conducted at more than 28 academic institutions and 49 companies. The intramural component of the Mining Program topics described in this evidence package invested an annual average of approximately $28.9 million, and the extramural component received an annual average of approximately $8.8 million.

In selecting topics for this evidence package, NIOSH developed a list of possible topics that was eventually winnowed to three. This selective, iterative process considered criteria including alignment with Mining Program strategic goals; priority research following NIOSH's burden, need, and impact method; and research and science mature enough to have a demonstrable impact on the health and safety of mine workers grounded in concrete, credible evidence. Based on these and other criteria detailed in this evidence package, NIOSH chose to highlight work in three topic areas: disaster prevention and response, ground control, and respirable hazards.

Disaster Prevention and Response

Historically, mine disasters such as fires, explosions, and flooding have driven federal and state governments to enact laws that will protect miners as well as allocate investments in health and safety research. Despite mine disasters being infrequent, fatalities have occurred when miners who survived the initiating event have become entrapped, could not self-escape, or were unable to survive long enough for rescuers to reach them in the toxic atmosphere present in the mine after an event. In particular, disasters that occurred in 2006 highlighted the need for improved disaster prevention and response in mining, and drove the legislation of the Mine Improvement and New Emergency Response Act (MINER Act) of 2006. Among its mandates, the MINER Act called for technical study on the use of belt air and the composition and fire-retardant properties of belt materials, improvements to post-accident breathing air supplies, stringent sealing requirements for abandoned mine areas, evaluation of refuge alternatives, enhancements to communications and tracking technologies, and improved training in and better coordination of emergency procedures to empower both operators and rescuers to respond to an event.

Through multi-stakeholder partnerships devoted to studying and sharing information on breathing air supplies, refuge alternatives, and rock dust, along with detailed analysis of MSHA surveillance data and MSHA narratives resulting from mine accidents and disasters, NIOSH has developed and provided critical activities and outputs to the industry on disaster prevention and response. For disaster prevention, these activities and outputs include monitoring of mine conditions to assess and avoid fire and explosion risk, developing technologies to reduce float coal dust and assess the explosibility of mine dust, published recommendations for a new rock dusting standard, and development of an anti-caking rock dust. Other research and contracts devoted to disaster prevention include improved ventilation practices to control accumulations of toxic gases, training of graduate students with advanced degrees specializing in ventilation science, development of predictive models and software, and advanced understanding of seal designs and fire prevention. Among other measures of impact, NIOSH research in these areas has led to formulation of improved standards in two MSHA final rules that were published during the review period.

For disaster response, NIOSH research efforts have focused on development and testing of critical emergency response communications and tracking systems; effective response procedures, rugged infrastructure, and training of mine personnel and rescue personnel; adequate and practical breathing air supply technology; a better understanding of habitability, survivability, and occupancy standards for refuge alternatives; and technologies to improve the ability of mine rescue teams to safely reach miners who are trapped underground. These efforts have resulted in training materials in the form of guidance documents and software, references to NIOSH research in MSHA final rules, improved design concepts and products related to breathing air supplies, and development of prototype technologies to aid MSHA in its rescue operations. Stakeholders have adopted NIOSH-developed disaster prevention and response materials and practices, bolstered through NIOSH translational activities, including peer-reviewed publications, conference presentations, training, field assessments, and well-attended tutorials and webinars. As evidence of potential impact resulting from these activities, during the review period, ignitions at the mining face fell significantly, with a high of 51 in 2008 and a low of 10 in 2014 [MSHA

2018a], as did MSHA violations due to accumulations of combustible material, with some years including no reportable fires in underground coal mines.

Ground Control

Underground mines pose specialized ground control challenges due to their distinctive geologic settings. For example, in metal mines, ore is extracted from deposits ranging from high-grade veins layered in strong brittle rock to low-grade material imbedded in weak fractured ground. In coal mines, lithology and overburden vary widely, from thin seams at shallow depths to thick seams under deep cover. Underground limestone mines typically use tall pillars to support the overlying roof, which undergoes a high degree of horizontal stress, and these pillars can suddenly fail in a violent manner if they are under-designed. With accelerating depletion of near-surface deposits, operators are mining deeper deposits under increasingly complex geologic structures and stresses. As a result, underground openings can be impacted by failed rock and ground support, creating severe hazards for mine workers.

NIOSH researchers address these issues through both sophisticated laboratory studies and collaborative field studies. Based on NIOSH-developed criteria, lab testing involves analyzing rock stress and fracture by way of facilities and methods that replicate extreme loading and deformation conditions. During field studies, NIOSH researchers install instrumentation to monitor stress and strain over the long term, provide technical assistance to mines to determine the potential for ground control failures based on past cases and predictive modeling software, and provide expertise in improving design practices after an event such as a rib collapse, roof fall, or pillar failure. NIOSH also collaborates with companies and universities through contracts and grants, allowing effective transfer of results by way of peer-reviewed publications, presentations, webinars, industry briefings, and shared problem solving.

As a result of this work, NIOSH has created a suite of widely distributed ground control software; developed procedures and built devices for rigorous, large-scale testing of support systems used in mines; and contributed to the commercialization of support products offered by companies to enhance mine safety. NIOSH provides research briefings and valuable input to state and federal agencies charged with enforcing mining regulations, including MSHA and the West Virginia Office of Miners' Health, Safety and Training. Most recently, NIOSH ground control experts participated in project research to determine whether gas well pillars satisfied the current Pennsylvania Gas Well Pillar Regulation and the MSHA regulation for oil and gas wells.

Further, with the mining industry losing expertise and knowledgeable personnel in ground control due to retirements and the dwindling number of academic programs devoted to ground control studies, NIOSH has provided capacity-building contracts to increase the number of graduates with higher degrees in this area. Based on a review by NIOSH of MSHA data for 2008–2017, there has been a 33% decrease in ground fall fatalities and a 48% decrease in lost-time injuries [MSHA 2018a].

Respirable Hazards

During extraction, transport, and processing of materials from the earth, mining has the potential to release airborne dust and particulates due to fracture and breakage of materials, emissions of residual dusts from disturbances of air or movement of equipment, and combustion of diesel fuel used in diesel-powered equipment. When present in a miner's breathing zone, dust in the respirable-sized range can penetrate deeply into the lungs, potentially causing extensive damage including coal workers' pneumoconiosis (CWP), silicosis, cardiovascular disease, chronic obstructive pulmonary disease, and lung cancer. Exposure to respirable crystalline silica—a common component of respirable dusts encountered at varying levels in virtually all mining sectors—is associated with the development of silicosis, lung cancer, autoimmune disorders, chronic renal disease, and other respiratory ailments [Dockery et al. 1993].

Despite proven successes in reducing respirable hazards and worker exposures, NIOSH's Coal Workers' Health Surveillance Program (CWHSP) continues to identify CWP in the coal mining workforce in both newer and longer-tenured miners. In response to the ongoing incidence of this preventable disease, in 2014, MSHA published a final rule that reduced the permissible exposure limit (PEL) for coal mine dust, changed monitoring procedures and equipment, and expanded CWP surveillance.

To address these issues, NIOSH focuses on key research gaps to improve the understanding of miners' respirable exposures and health outcomes and to develop effective engineering solutions. NIOSH's activities have included sharing expertise in response to an MSHA Request for Information about exposure of underground miners to diesel exhaust; analyzing data from the CWHSP and MSHA to inform research directions and developing technologies to reduce miners' exposure to respirable hazards, sample the air to determine exposure risk, and avoid areas and tasks where accumulations of dust and particulates place them at higher risk.

The outcomes of this research have led to more stringent MSHA standards; identification and adoption of best practices by coal, surface, and metal/nonmetal mine operators; and partnerships to provide input on technologies. Importantly, mine workers and operators can now monitor respirable hazards in real time or near-real time, empowering them to apply administrative and engineering controls that have demonstrably reduced their exposures to respirable coal mine dust, silica dust, and diesel particulate matter over the course of the review period. As one example, industry average respirable dust concentrations from compliance samples taken by MSHA inspectors and mine operators for all occupations in underground coal dropped 20% from 0.77 mg/m^3 in 2008 to 0.62 mg/m^3 in 2017 [MSHA 2018b].

Outlook for the Next Decade

Based on multiple sources of input and collaborations with stakeholders, the NIOSH Mining Program has developed a strategic plan for fiscal years 2019–2023 that fits within the context of the larger NIOSH Strategic Plan. The Program's strategic plan takes a subsector approach that includes coal and subdivides metal/nonmetal into crushed stone, sand and gravel, metal, and industrial minerals, allowing for a focus that better addresses the health and safety challenges unique to each subsector.

To address future disaster prevention and response needs, NIOSH will further investigate mine monitoring to better understand fire safety issues; will continue partnerships with manufacturers to develop improved prototypes, products, and test procedures; and will continue to focus on human systems integration-based research on post-disaster technologies to improve mine worker and mine rescue team survival in the event of an emergency.

Future research directions in ground control will address the challenges of mining deeper reserves and understanding the attendant geological conditions of highly stressed or incompetent rock mass, the need for updated support designs and procedures to better match ground support to the prevailing geotechnical conditions, the analysis and display of geomechanical data for semiautomated or fully automated mining systems, and the currently unanswered questions that will arise about the interaction of new gas wells with existing underground workings.

Future respirable hazards research will further develop and assess effective interventions for control of respirable hazards, explore solutions specific to high-risk job tasks and job types, and develop methodologies for real time and near-real time exposures to respirable crystalline silica at the mine site.

Research will also focus on identifying and addressing barriers to participation in the CWHSP and revising NIOSH training materials for physicians who classify digital radiographs.

References for Executive Summary

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Chapter 1: Mining Program Overview

Program History

U.S. Bureau of Mines

The history of the National Institute for Occupational Safety and Health (NIOSH) Mining Program stretches back more than 100 years, when the U.S. Bureau of Mines (USBM) was established in 1910. The USBM provided the mining industry with information on blasting materials and techniques that could be used safely in the presence of flammable mine gases and dust. The USBM's initial research and development principally targeted the development of safer blasting materials for underground coal mines and the prevention of underground mine gas and dust explosions. For that purpose, a site called the Experimental Mine, dedicated in 1910, was opened in Bruceton, PA, south of Pittsburgh. That location, which now spans 180 acres, remains the site of the current Mining Program's Pittsburgh Mining Research Division (PMRD) as well as other government offices.

By 1936, the USBM research grew to include fuels, metallurgy, and mine roof stability. In 1951, in addition to the Bruceton, PA, location, the USBM established a Northwest Mining Division in Spokane, WA—now called the Spokane Mining Research Division (SMRD). Developing safer explosives remained a key focus of the USBM, but over the course of several decades the USBM mission grew to include fundamental research into electronic instruments; high-temperature, high-pressure chemical reactions; respirable dust and ventilation; noise; industrial hygiene; fire prevention; ground, rib, and roof control; and post-disaster survival and rescue—all as they related to studying and improving the health and safety of the nation's mine workers.

As residential development encroached on the Bruceton area, limiting full-scale underground explosion testing, in 1982 the USBM leased the Lake Lynn Laboratory Experimental Mine (LLEM)—a 400-acre property including an abandoned limestone mine near Fairchance, PA, about 50 miles south of Pittsburgh, PA (Figure 1). Engineers constructed the LLEM by driving new underground entries adjacent to the existing workings of the limestone mine. The new entries simulated the configurations found in modern underground coal mines. Initially, the LLEM served as a new experimental mine for mine explosion testing, but it came to be used for experimental work on such problems as belt fires and seal construction and as a training ground for mine rescue teams. The facility provided an isolated environment, which allowed for large-scale testing in an environmentally controlled manner, and many successful research projects took place at the LLEM over the years.

Photo by NIOSH

Figure 1. Portal to the Lake Lynn Laboratory Experimental Mine.

The last full-scale underground explosion tests at the LLEM were conducted in July, 2008. In October, 2008, a major roof collapse closed one of the two main passageways that provided entrance to and exit from the mine and damaged other surrounding areas within the research mine. Following this, the government could not come to terms with the lessor for fully rehabilitating and purchasing the facility, and the lease was relinquished in 2012.

The NIOSH Mining Program

In 1996, the USBM was closed and some of its functions were transferred to other federal agencies. The occupational health and safety research function was transferred to NIOSH and became what is currently the Mining Program. Further, in 1967, the U.S. Public Health Service established what is now the NIOSH Respiratory Health Division (RHD), whose mission is to prevent work-related respiratory disease and improve workers' respiratory health. In the subsequent few decades, as technologies and knowledge related to health and safety evolved substantially, NIOSH research likewise expanded in both breadth and depth. Today, Mining Program research areas include dust control, ventilation, electrical systems, fires and explosions, workplace health, machine safety, and exposure and assessment monitoring.

During this 2008–2018 review period, the NIOSH Mining Program included the following three research focus areas.

> *Disaster Prevention and Response*. Research in this area seeks a better understanding of float coal dust and rock dust in mines, improved ventilation practices to control harmful gases in the underground atmosphere, mine fire prevention, safety of refuge alternatives, improvement of breathing air supply technology, development of improved emergency communications, and best practices for self-escape and self-escape training.
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> *Ground Control.* The overall goal of ground control research is to reduce the number and severity of rock fall-related injuries and fatalities. With advances in mining technology and the depletion of near surface deposits, researchers must develop appropriate research goals and practical solutions to mine operators as they encounter increasingly complex geologic structures and stresses that accompany mining-induced deformation underground.
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> *Respirable Hazards.* Respirable hazards research targets the reduction of respirable dust and diesel exposures, including exposure assessment and monitoring, and assessing surveillance data related to coal miners to identify the prevalence of lung diseases. This includes tracking the burden of work-related respiratory disease through partnerships with states and communicating results and providing recommendations through various types of NIOSH publications.

Activities in these three research areas are detailed throughout this evidence package.

The Mining Program's Relationship to the Mine Safety and Health Administration

The Mining Program's history has direct ties to governmental responses to mine accidents, disasters, and regulation of both ongoing and newly emerging safety and health challenges. Over the course of the last century, numerous legislative Acts supplied detailed mandates for mining health and safety, with some of the Acts amending previous ones. In the context of this review, the Federal Mine Safety and Health Act of 1977 in particular served as an important piece of legislation. This legislation transferred enforcement responsibilities—which up to that time were under the USBM in the Department of the Interior—to the Department of Labor, and renaming the previously established Mine Enforcement and Safety Administration to the Mine Safety and Health Administration (MSHA) [MSHA 2018]. MSHA's mission is to prevent death, illness, and injury from mining and to promote safe and healthful workplaces for U.S. miners. MSHA develops and enforces safety and health rules for all mines, regardless of method, size, or commodity mined; and the agency conducts investigations after mine disasters.

NIOSH collaborates closely with MSHA to determine research areas with knowledge gaps and to establish partnerships with industry, labor, and government that will lead to the best approaches to addressing these gaps. NIOSH also uses MSHA's Accident, Illness, and Injury database, as well as other surveillance data sources, to analyze trends, inform research areas, and report information to the mining industry. MSHA turns to NIOSH to perform critical health and safety research in common areas of interest.

Importantly, MSHA and NIOSH have different roles in achieving the common goal of protecting miner health and safety. NIOSH primarily conducts scientific research and translates the knowledge gained into products and services. MSHA establishes and enforces workplace regulations, collects important injury and fatality data used by NIOSH as described above, and provides technical and educational assistance to mine operators. Though NIOSH and MSHA have two different roles, the common goal necessitates significant past and ongoing collaborations. As one example, as NIOSH project proposals are drafted, if their content could relate to MSHA regulations and policy, then experts at MSHA review those proposals. Likewise, as new research is finalized for dissemination, MSHA again often provides technical review and feedback. These frequent interactions improve the quality of both NIOSH research and outputs.

The MSHA rulemaking process also affects Mining Program research priorities, with NIOSH and MSHA communicating on a regular basis both informally and formally. One mechanism for formal communication between the agencies is through a Request for Information (RFI) through the Federal Register. An RFI describes a problem or an issue for which MSHA requests data, comments, and other information from the public relevant to the problem presented. When relevant scientific research is available, NIOSH submits a formal response to the RFI based on the Program's scientific expertise. NIOSH's responses to an RFI help MSHA to determine an appropriate course of action to address a particular issue, including whether to develop or enact a rule based on this information. Through this process, NIOSH proactively provides scientific evidence to MSHA for developing and implementing new rules that protect miner health and safety.

Review of NIOSH's Occupational Safety and Health Research by the National Academy of Sciences

In 2005, NIOSH commissioned the National Academy of Sciences (NAS) to conduct reviews of eight of its research programs, including Mining, recruiting a committee of subject matter and program evaluation experts. Each committee received an evidence package of written materials from the managers of the NIOSH program under study. Program managers also gave presentations to their respective committees and answered follow-up questions as requested. Once the committee drafted its report, a second independent committee of experts reviewed it.

Upon completion of its review of the Mining Program in 2007, the NAS committee published its report, *Mining Safety and Health Research at NIOSH* [NAS 2007]. Quantitatively, on a 5-point scale (with 5 being the highest), the committee assigned the Mining Program a rating of 4 for relevance and 4 for impact. Qualitatively, the NAS report found that good progress had been made in the improvement of mine worker health and safety, with decreases in the incidence and severity of diseases, disasters, and fatal and nonfatal accidents in mines. The report concluded that Mining Program research focused on high-priority areas and adequately connected to improvements in the workplace, and that the Program was moderately engaged in technology transfer activities.

After the Academy presented its findings to NIOSH in April 2007, the Program prepared a formal response to the Academy detailing its action plan. This action plan was subsequently reviewed and accepted by the Mine Safety and Health Research Advisory Committee (MSHRAC) on January 23, 2008, and MSHRAC further supported NIOSH's response to each of the 18 recommendations made in the report. For a summary of those recommendations and the responses relevant to this review, see Appendix A.

Two new rounds of performance scoring were completed by MSHRAC in 2012 and 2014, with each round addressing one-third of NIOSH's responses to the 18 recommendations. The 2012 review and Mining Program responses as well as the 2014 review and Mining Program responses are available online. For these two rounds, MSHRAC used the same scoring rubric—achievement, sustainability, and impact—to assess the success of the Program's response to the recommendation, with a score of 5 being the highest. Based on these two new rounds of performance scoring, the Program received a score of 5 for each recommendation, with the exception of one score of 4.5. A final round to review the last third of recommendations was planned for 2016, but was not completed because of other committee priorities.

Program Resources

The Mining Program consists of work done under the Office of Mine Safety and Health Research (OMSHR), which includes PMRD and SMRD. Support for NIOSH research is also provided by RHD, which manages the Coal Workers' Health Surveillance Program (CWHSP), and the National Personal Protective Technology Laboratory (NPPTL), which tests and certifies new closed-circuit escape respirators (CCERs) and self-contained self-rescuers (SCSRs) used in mining. NIOSH also includes extramural research and training related to mining awarded by OMSHR (contracts) and the Office of Extramural Programs (OEP) (grants). These resources all work together to support the Mining Program's mission to eliminate mining fatalities, injuries, and illnesses through research and prevention.

For the review period, Mining Program resources can be described by summarizing the following:

- the Mine Improvement and New Emergency Response Act (MINER Act) of 2006 and its relationship to the extramural grants and contracts program;
- staff and funding;
- primary facilities that conduct research to support the Mining Program's mission.

MINER Act of 2006

The Mine Improvement and New Emergency Response Act (MINER Act) was passed after three separate tragedies in 2006 at the Sago, Aracoma, and Darby mines claimed the lives of 19 miners [MSHA 2016]. The MINER Act amended the Federal Mine Safety and Health Act of 1977 to require mine-specific emergency response plans in underground coal mines, added new regulations related to mine rescue teams and sealing of abandoned areas, required mines to provide prompt notification of mine accidents, and enhanced civil penalties for violations. The MINER Act further established the Office of Mine Safety and Health [MINER Act 2006], which is now OMSHR, with the purpose of enhancing the development of new mine safety technology and technological applications and expediting the commercial availability and implementation of such technology in mining environments. To carry out these functions, OMSHR has the authority to:

(A) award competitive grants to institutions and private entities to encourage the development and manufacture of mine safety equipment; and

(B) award contracts to educational institutions or private laboratories for the performance of product testing or related work with respect to new mine technology and equipment.

The MINER Act and its mandates play an important part in NIOSH's operations and funding priorities.

Extramural Funding

While extramural contracts existed prior to 2006, their administration became an integral part of the Mining Program after the passage of the MINER Act. Extramural funding supports research designed to complement NIOSH's intramural work in an effort to most efficiently and effectively pursue the accomplishment of the Program's strategic goals. One mechanism for providing extramural funding is through contracts awarded and managed by OMSHR. These contracts are developed primarily through Broad Agency Announcement (BAA) solicitations advertised on the Mining Program website as well as through normal government solicitation channels. These solicitations aim to foster innovative solutions to key health and safety issues. Other extramural funding for the Program comes from grants administered by the NIOSH OEP, which awards investigator-initiated (R-01/03/21), small-business innovation (R43/44), and collaborative (U60) research grants under a highly competitive process.

Staff

In the context of this review, the key staff for the NIOSH Mining Program and OMSHR as of 2018 are listed in the following table.

Name	Position	Division
John Howard	Director	NIOSH Office of the Director
Jessica Kogel	Associate Director for Mining, OMSHR Director	NIOSH Office of the Director
George Luxbacher	Deputy Associate Director for Mining	NIOSH Office of the Director
RJ Matetic	Director	Pittsburgh Mining Research Division
Adam Smith	Deputy Director	Pittsburgh Mining Research Division
Todd Ruff	Director	Spokane Mining Research Division
Pamela Drake	Deputy Director	Spokane Mining Research Division
David Weissman	Director	Respiratory Health Division
Mary Ann D'Alessandro	Director	National Personal Protective Technology Laboratory

Figure 2 is a simplified organizational chart for OMSHR, RHD, NPPTL, and other NIOSH divisions (listed, but not detailed for the purposes of this evidence package). Collectively, OMSHR, RHD, and NPPTL are made up of more than 30 teams that support the Mining Program mission.

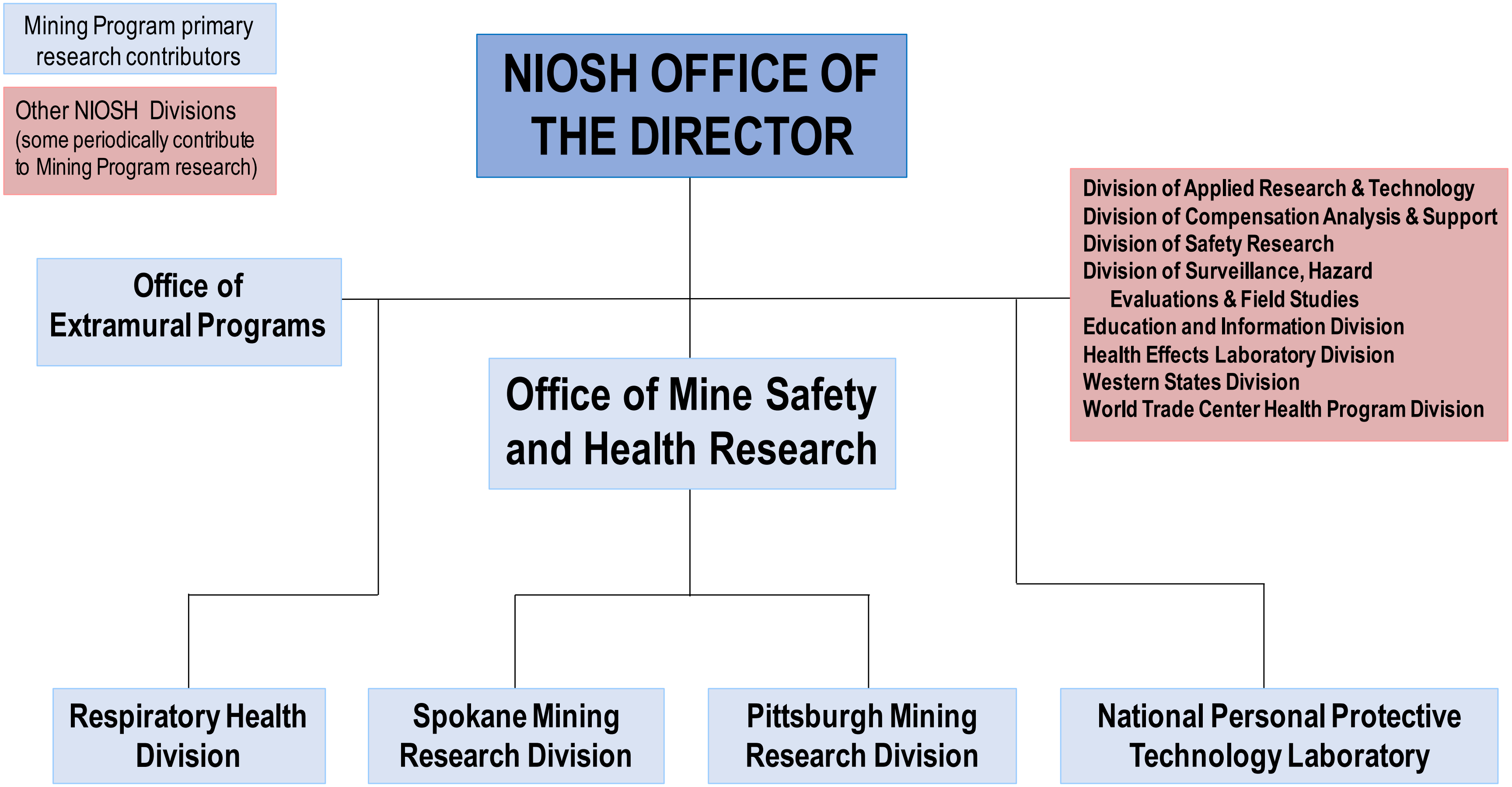

Figure 2. Simplified organizational chart for OMSHR, RHD, NPPTL, and other NIOSH divisions.

Funding

NIOSH distributes funding for mining-related occupational safety and health research across a combination of intramural and extramural activities. Table 1 summarizes the annual funding by fiscal year (FY) for 2008–2018 for the topics described in this evidence package—disaster prevention and response, ground control, and respirable hazards—as well as the number of full-time equivalent (FTE) NIOSH staff for the Mining Program working in these three topic areas. To improve the accuracy of quantifying specific investments, NIOSH implemented a more detailed system for attributing individual projects to strategic goals in FY 2009. Therefore, comparable data are not available for FY 2008.

Table 1. Mining Program funding (in millions) and staff for fiscal years 2008–2018 for disaster prevention and response, ground control, and respirable hazards*

Fiscal Year	Intramural	Extramural	Total	FTE
2008	NA	NA	NA	NA
2009	$26.1	$9.1	$35.2	174
2010	$22.8	$7.5	$30.3	163
2011	$25.4	$8.7	$34.1	153
2012	$30.7	$11.9	$42.6	204
2013	$26.3	$10.1	$36.4	166
2014	$30.0	$10.3	$40.3	174
2015	$31.4	$8.3	$39.7	169
2016	$33.2	$7.8	$41.0	184
2017	$32.5	$6.3	$38.8	185
2018	$30.5	$8.1	$38.6	175
Average	**$28.9**	**$8.8**	**$37.7**	**175**

*Amounts in Table 1 are based on project percentages attributed to three topic areas discussed in this evidence package.

Facilities

From 2008 to 2018, a number of NIOSH divisions, labs, and offices from across the Institute supported the work of the Mining Program, including facilities in Pittsburgh, PA, Spokane, WA, and Morgantown, WV. The key contributors to Program research are described below.

Pittsburgh Mining Research Division, Pittsburgh, Pennsylvania

NIOSH's PMRD site occupies a significant portion of a 180-acre federal campus and is situated in Bruceton, PA, south of Pittsburgh. Programmatic areas at PMRD include dust (coal, respirable crystalline silica, elongate mineral particles) monitoring and control, mine ventilation, hearing loss prevention and engineering noise controls, diesel particulate monitoring and controls, emergency response and rescue, fire-fighting and fire prevention, training research, ergonomics and machine safety, mine ground control, electrical safety, explosives safety, surveillance, and technology transfer. PMRD includes over a dozen specialized laboratories designed for studying work physiology, motion analysis, noise assessment, diesel emissions sampling and monitoring, assessing and improving the performance of dust samplers and monitors, proximity detection, mine electrical systems, and virtual immersion and simulation. The site also includes two underground mines where experiments are performed on critical health and safety issues such as underground illumination and habitability of refuge alternatives.

Spokane Mining Research Division, Spokane, Washington

While SMRD research programs touch most mining sectors, the major program focus of SMRD is on metal mining. Major areas of study include catastrophic failure detection and prevention, mining injury and disease prevention, and mining surveillance data and statistical support. Project research related to underground mining includes developing durable roof support, monitoring seismicity to improve mine stability, preventing rockbursts, and controlling airborne pollutants and physical stressors. Facilities at SMRD include a soil/rock properties laboratory that provides space and equipment for preparing, characterizing, and testing consolidated and unconsolidated materials. Researchers test consolidated or cemented materials and rock for various engineering properties using a suite of test frames in the laboratory. SMRD also conducts research at a 21-acre site near Reardan, Washington, which is a former Atlas missile installation acquired by the USBM and currently maintained by NIOSH. Current research at the Reardon site includes testing a new underground core drilling system for coal mine dynamic failure research, preparing shotcrete panels to replicate in situ ground support, and blasting tests to determine radial damage from fully coupled charges similar to those used in underground metal/nonmetal mine drifting.

Respiratory Health Division, Morgantown, West Virginia

NIOSH’s RHD in Morgantown conducts research and administers service programs to prevent work-related respiratory disease caused by hazardous occupational agents and to improve workers’ respiratory health. The Division conducts multidisciplinary research to identify work-related respiratory hazards, assess workplace exposures, characterize health risks, and develop and disseminate effective interventions. The RHD also oversees the CWHSP, which has the goal of detecting early indications of coal workers’ pneumoconiosis (CWP), also known as “black lung,” and preventing it from progressing to a disabling disease. The CWHSP offers free, confidential health screenings to coal miners to monitor their respiratory health by way of mobile testing units at both local community and mine locations. The CWHSP also provides periodic lung function testing, administers respiratory health assessment questionnaires, and provides extended health surveillance data to workers at surface coal mines. The data collected allow NIOSH to estimate the burden of coal mine dust lung disease in the U.S. and provide miners with information about their respiratory health status, which can be used to inform decisions relating to their right to transfer to a less dusty work environment when indicated.

National Personal Protective Technology Laboratory, Pittsburgh, Pennsylvania

NPPTL is part of the 180-acre Pittsburgh site as described earlier, which houses PMRD and other government offices. NPPTL's research is devoted to advancing the technical methods (e.g., fit testing methods), processes, techniques, tools, and materials that support the development and use of personal protective equipment (PPE) worn by individuals to reduce the effects of their exposure to a hazard. NPPTL tests and certifies new CCERs and SCSRs before they enter the mining market, conducts post-market activities for long-term evaluation and certified product investigation, and conducts research on new technologies, emerging hazards, and PPE test methods to evaluate and improve equipment worn by workers. The primary facility where NPPTL's work on CCER and SCSR testing and certification takes place is the Automated Breathing and Metabolic Simulator (ABMS) lab, pictured and described in the Disaster Prevention and Response chapter, p. 32.

Program Planning

Program planning takes place through a carefully developed Strategic Plan, which focuses research and prevention activities on the areas of greatest need. The Mining Program's efforts to advance communication and collaboration across the mining health and safety community also include the NIOSH-facilitated National Occupational Research Agenda (NORA) Mining Sector Council. This Council comprises representatives from across the occupational health and safety spectrum, including public- and private-sector researchers, professionals, consultants, practitioners, and manufacturers. Unlike MSHRAC, the Council is not an advisory board but instead serves as a means to foster partnerships among stakeholders and share information. The Council works to identify the most salient needs of this large and diverse global sector, facilitate the most important research, articulate the most effective intervention strategies, and understand how to implement those strategies to achieve sustained improvements in workplace practice.

Mining Program Strategic Plan

For the time period covered in this evidence package, the Mining Program's first Strategic Plan was developed in 2004, revised in 2008 after the NAS review, and then reviewed by MSHRAC in 2010. To develop the Plan, NIOSH combined a number of priorities—as established from surveillance data, MSHRAC advice, and stakeholder requests—to establish a set of strategic research priorities. With the top-level goal being to improve mining safety and health by eliminating fatalities, injuries, and illnesses, NIOSH defined six strategic goals:

> Strategic Goal 1: Eliminate respiratory diseases in mine workers by reducing exposure to airborne contaminants.
>
> Strategic Goal 2: Reduce noise-induced hearing loss (NIHL) in the mining industry.
>
> Strategic Goal 3: Reduce the risk of musculoskeletal disorders in mine workers.
>
> Strategic Goal 4: Reduce the risk of traumatic injuries in the mining workplace.
>
> Strategic Goal 5: Reduce the risk of mine disasters (fires, explosions, inundations), improve the post-accident survivability of miners and critical mine systems, and enhance the safety and effectiveness of emergency responders.
>
> Strategic Goal 6: Reduce ground failure fatalities and injuries in the mining industry.

The seventh goal addressed the MINER Act directive for OMSHR to expedite the commercialization and implementation of new technologies originating outside the U.S. mining industry as solutions to pressing mining health and safety concerns:

> Strategic Goal 7: Reduce adverse health and safety consequences in the industry through effective interventions with new technology.

As part of the development process, researchers identified many of the barriers, knowledge gaps, or technology gaps that needed to be addressed to effect a desired change at the strategic goal level. These were articulated as intermediate goals, presented for each strategic goal. The intermediate goals selected were assessed to be on the critical path to achieving the strategic goal, and were deemed to be potentially achievable given the available staff, facilities, and funds at the time. Just after the review period for this evidence package, the Mining Program published a substantially updated new Strategic Plan in the context of a five-year horizon (2019–2023), available on the NIOSH Mining website.

The National Occupational Research Agenda and Mining Sector Council

The National Occupational Research Agenda (NORA) runs in ten-year cycles and is now in its third decade (2016–2026). During its second decade—which is the one most relevant to this review period—the

Mining Sector Council developed the National Mining Agenda for Occupational Safety and Health Research and Practice in the U.S. Mining Sector (the Agenda). Through a series of meetings and discussions between 2010 and 2015, the NORA Mining Sector Council set forth objectives for a national mining health and safety research program and recommended objectives in eight major areas, including disaster prevention, disaster response, health hazards, ventilation, work organization, systems operation and management, human factors, and surveillance.

While research to address many of these objectives was already underway in the NIOSH Mining Program, the Agenda was meant to encourage independent organizations or collaborative partnerships to tackle objectives that NIOSH was not able to pursue. The goals in the Agenda are broader and longer-term than goals in the NIOSH Mining Program Strategic Plan, but the two plans are nevertheless complementary.

The NORA Mining Sector Council meets at the annual conference and expo of the Society for Mining, Metallurgy & Exploration (SME), typically holding a roundtable discussion after brief presentations, in addition to conference calls throughout the year. With the completion of the Agenda, the Council is focused on advancing the Agenda through Council activities, including exchanging information, forming partnerships, and enhancing dissemination and implementation.

Future Plans

As mining practices evolve, NIOSH will continue to conduct research for the coal, metal, industrial mineral, and stone, sand, and gravel industries to develop evidence-based guidelines focusing on high-priority needs. Brief summaries of future plans in the three research areas described in this evidence package—disaster prevention and response, ground control, and respirable hazards—follow.

In relation to disaster prevention and response, future research on mine monitoring will help to address the industry’s major fire safety issues, specifically focusing on sensor deployment strategies that will ensure detection of a mine fire or a hazardous condition in a timely and effective manner. Research on refuge alternatives will inform manufacturer guidelines about survivability, while development of new concepts and materials for breathing air supply will advance technology in that critical area of self-escape and mine rescue. Research and training materials on post-disaster response associated with escape and rescue technologies will help to improve mine worker survival in the event of an emergency, and NIOSH will increasingly apply its virtual simulation research to emergency response and preparedness and will develop interventions on mine emergency response decision-making that integrate with an organization’s overall risk management system.

From a ground control perspective, looking forward, the future of mining will involve working in deeper mines, mines that are less accessible, and ores that are lower grade. In addition, economic pressures will require companies to increase their efficiencies to remain competitive. Mechanization and automation are possible solutions to reducing health and safety risks by removing miners from hazardous conditions, and new mining methods can eliminate the need for drilling and blasting in metal mines.

To address respirable hazards, NIOSH will continue stakeholder collaborations to develop and assess effective interventions for hazard control, including coal mine dust, crystalline silica, diesel emissions, and elongate mineral particles. MSHA compliance data will be used to identify high-risk occupations within each mining sector. Future monitoring research will develop methods for determining crystalline silica concentrations in mine environments on a near-real time basis to minimize overexposures between sampling and to facilitate rapid assessment of control interventions. The CWHSP will also address barriers and develop acceptable International Labour Office classifications for the use of digital radiographs.

External Factors

NIOSH has made great strides to promote safe and healthy workplaces in all sectors of the mining industry. Continued efforts to expand and improve the body of knowledge in this area are subject to changes in funding, research priorities, Congressional directives, and the availability of knowledgeable and experienced researchers. NIOSH also investigates issues and unplanned opportunities as they emerge.

Organization of this Document

Each topic selected in this evidence package details research conducted by the NIOSH Mining Program intramurally or through funded contracts or grants for 2008–2018. The Program considered a number of criteria and developed a list of topics that were eventually winnowed to three. This selective, iterative process was based on the following criteria:

- Topics that align with Mining Program strategic goals and the National Mining Agenda written by the NORA Sector Council.
- Priority research that follows NIOSH’s burden, need, and impact method and also meets stakeholder needs and interests.

- Research that represents significant and ongoing investment of program resources during the review period of 2008–2018.
- Research and science mature enough to have a demonstrable impact on the health and safety of mine workers.
- Measurable impact based on concrete, credible evidence.
- Topics that represent all aspects of the scope of the NIOSH Mining Program, including intramural and extramural research.

Based on the above criteria, for the purposes of this review, the panel will be asked to consider only NIOSH's work in the following areas, organized by chapter: disaster prevention and response, ground control, and respirable hazards. Based on these areas, in the context of this evidence package, Strategic Goals 1, 5, 6, and 7, along with their associated intermediate goals, are discussed.

References for Chapter 1: Mining Program Overview

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Chapter 2: Disaster Prevention and Response

Photo by NIOSH

Introduction

Historically, underground mine disasters such as fires, explosions, floods, and roof falls have driven both the enactment of mining laws and regulations and government investment in mining health and safety research. Fatalities have occurred as a direct result of these events, but have also occurred when workers were unable to successfully escape, to isolate themselves from toxic atmospheres to await rescue, or when rescuers perished during a rescue attempt. Although mine disasters—defined in the U.S. as events resulting in more than five fatalities—have become less frequent, 11 miners who barricaded themselves at the Sago mine following the 2006 explosion suffocated in the toxic atmosphere; the Crandall Canyon pillar collapse in 2007 took the lives of 6 miners and 3 rescuers; and 29 miners perished in the Upper Big Branch explosion in 2010.

While it is difficult to quantify or predict the economic and human costs associated with mine disasters, the resulting fatalities serve as a reminder of the critical need to balance investments in resources to prevent the likelihood of high-probability but low-severity events, with investments focusing on response to low-probability but high-severity events. NIOSH disaster prevention research contributes to helping to reduce the human toll of mine disasters by removing or limiting the conditions under which a disaster might occur. Lives are saved through improved technologies and practices to limit, and help to prevent, the occurrence of mine disasters. These technologies and practices include the following:

- in coal mines, more effective applications of rock dust and improved control of float coal dust to limit accumulations of this explosible fuel source that can lead to explosions;
- in coal mines, more effective bleeder designs to limit accumulations of methane gas in bleeder entries and to maintain the proper split of ventilation airflow at longwall tailgate corners;
- in all mines, improved techniques to identify the incipient stages of a mine fire and the spread of toxic contaminants throughout active workings.

NIOSH is a leader in the development and testing of emergency response systems. NIOSH provides the mining industry with critical guidance on evaluations and future modifications of these systems. Fatalities are reduced through improved solutions for mine worker self-escape and for survivability of those who fail to escape from an underground mine fire, explosion, or flood. Because of its past research in disaster response areas such as self-escape, mine rescue, and post-disaster survivability, NIOSH is well-positioned to make critical advances in these areas to support underground mine workers who could be endangered in future events. Success depends on monitoring systems, which accurately provide information on contaminated underground atmospheres after a mine disaster; communications systems that allow miners to communicate with surface personnel; tracking systems that help to identify the location of miners; technologies that provide a safe location for refuge with a breathable atmosphere where trapped miners can wait for rescue; breathing air supplies that sustain miners as they attempt to escape in an atmosphere with toxic gases; miners who evaluate their situations correctly and take appropriate self-protective actions; and mine rescuers who make decisions so they can safely assist miners during emergency events.

Logic Model

The logic model (Figure 3) illustrates the characteristics of NIOSH research and other activities to prevent underground mining disasters and respond to them when they do occur. Elements of the logic model are Inputs, Activities, Outputs, Transfer and Translation, Intermediate Outcomes, and End Outcomes. The sections that follow describe each element in detail.

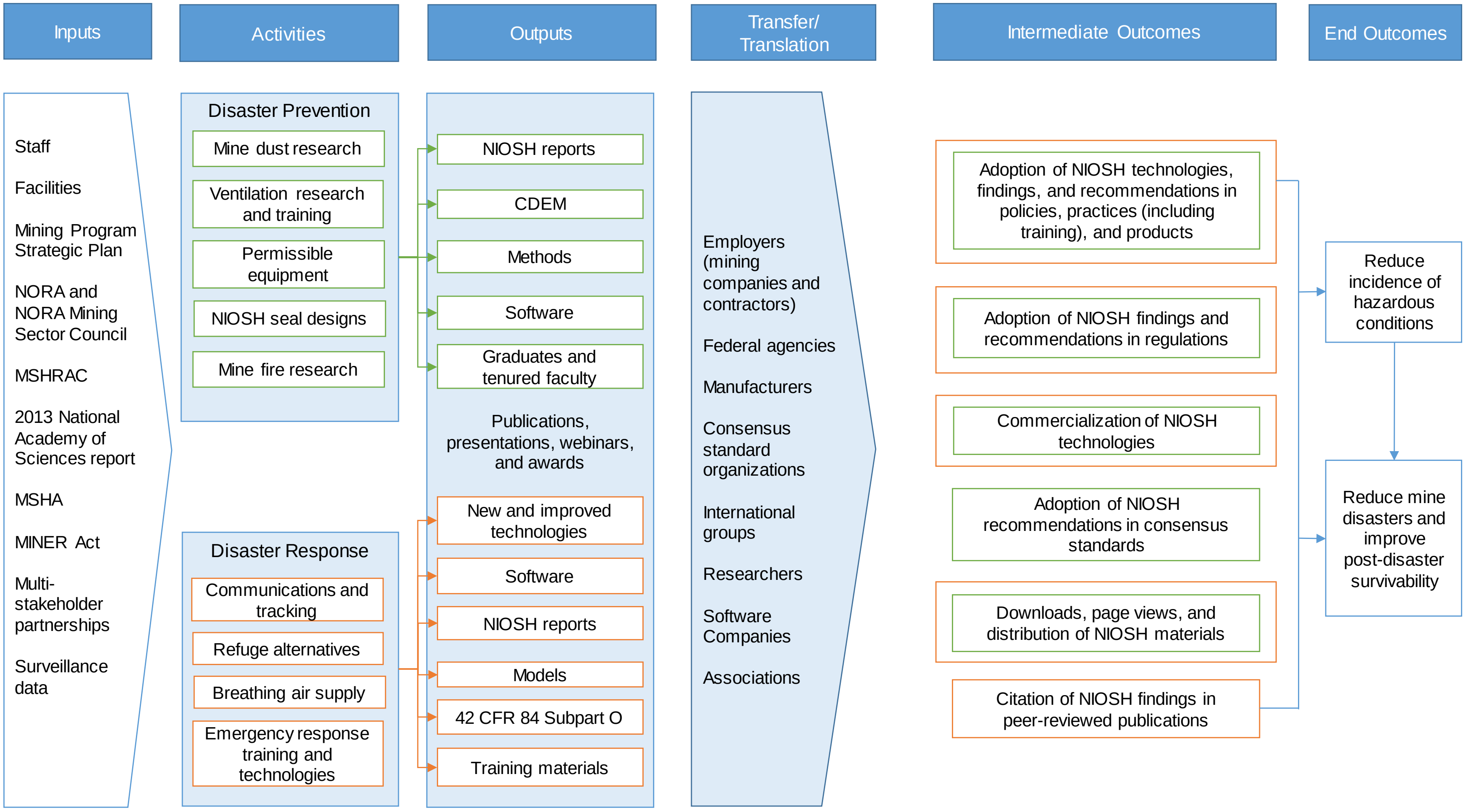


Figure 3. Logic model for disaster prevention and response.

Inputs

Staff

To ensure disaster preparedness, prevention, and response, multi-disciplinary teams of scientists, engineers, and technicians are charged with conducting critical research to aid in the prevention of, preparation for, and response to potential disasters in underground mines. Staff members represented the Pittsburgh Mining Research Division (PMRD), the Spokane Mining Research Division (SMRD), and the National Personal Protective Technology Laboratory (NPPTL). Expertise among staff ranged from mechanical engineering to electrical engineering to behavioral science. During the 2008–2018 review period, the individuals listed in Appendix B were instrumental in advancing NIOSH research in disaster prevention and response.

Facilities

Lake Lynn Laboratory Experimental Mine

The Lake Lynn Laboratory Experimental Mine (LLEM), described and pictured in the Overview chapter (pp. 9–10), was an important facility for several research efforts in disaster prevention and response. Researchers conducted a series of large-scale explosion tests in LLEM entries using different dust sizes. Full-scale flammability tests for conveyor belts of different widths were also completed. Metabolic heat and moisture generated by simulated miners were measured through a four-day test in the LLEM. Results from these tests were considered by MSHA when making recommendations and by manufacturers when determining the technical specifications used by manufacturers for refuge alternatives (RAs), as described later in this chapter.

Safety Research Coal Mine and Experimental Mine

The Safety Research Coal Mine (SRCM) and Experimental Mine (EM) complex (Figure 4) in Pittsburgh, PA, is a multi-purpose underground mine facility used to support research for the development and evaluation of new health and safety interventions for underground mine workers. The EM consists of two drift entries driven into the Pittsburgh coal seam and developed to support full-scale mine explosion tests. The SRCM is a room-and-pillar operation approximately the size of a working section and is used for research in areas including ventilation, fires, heat and humidity buildup, and environmental monitoring. Two full-time miners, supplemented by contract staff as required, provide technical and physical assistance to in-house and contract researchers.

Photos by NIOSH

Figure 4. Portals to the Safety Research Coal Mine and Experimental Mine in Pittsburgh, PA.

Virtual Immersion and Simulation Laboratory

The Virtual Immersion and Simulation Laboratory (VISLab) (Figure 5) in Pittsburgh, PA, uses state-of-the-art 3D display technology to create virtual environments for research studies and to train mine workers. Stereoscopic projection systems allow the creation of zero-consequence research environments that simulate mine emergencies that would be unsafe or impossible to replicate in the real world. By using different interaction devices, researchers capture and analyze data within the research simulations to determine faults or flaws that need further evaluation and discussion.

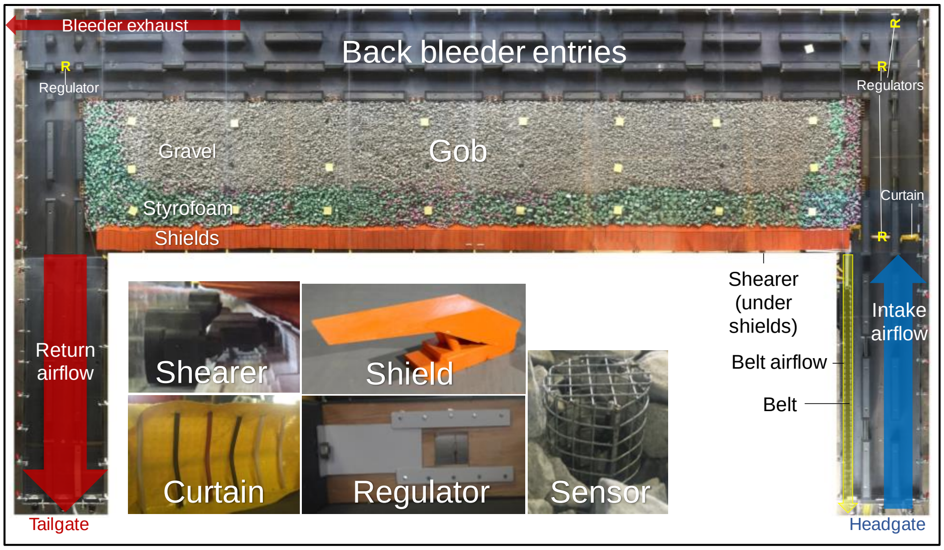
The facility includes a unique, state-of-the-art, 360-degree cylindrical projection system that uses stereoscopic 3D technology to enhance the immersion and experience of the users. It has the capability of putting an entire group into a virtual environment that they can interact with, providing an intuitive immersive experience. An adjacent virtual reality (VR) theater with a 10-ft-tall screen and high-resolution projector acts as a classroom environment for instructor-driven sessions and as a post-simulation debriefing environment following the sessions run in the 360-degree environment.

Photo by NIOSH

Figure 5. Visitors to the VISLab participating in a training exercise.

Longwall Instrumented Aerodynamic Model

In order to study longwall ventilation in a controlled environment, researchers built a unique physical model called the Longwall Instrumented Aerodynamic Model (LIAM) in Pittsburgh, PA. LIAM is a 1:30th scale physical model (Figure 6) geometrically designed to simulate a single longwall panel with a three-entry headgate and tailgate configuration, along with three back bleeder entries. LIAM is built with critical details of the face (area where mining occurs), gob (the mined-out area), and mining machinery. It is instrumented with pressure gauges, flow anemometers, temperature probes, fan, and data acquisition system. LIAM has been used to analyze a variety of ventilation configurations along with a number of roof caving characteristics for their impact on longwall ventilation.



Photos and illustration by NIOSH

Figure 6. Overhead view of the Longwall Instrumented Aerodynamic Model (LIAM) used to analyze ventilation configurations, with expanded and labeled views of some of the key components of a longwall operation.

Apart from its research applications, LIAM also serves as a dynamic tool for in-person demonstrations of longwall ventilation to mining industry stakeholders and the research community. Since it opened in January 2016, over 40 groups have toured LIAM for ventilation simulation demonstrations. These groups have included university students, MSHA personnel, representatives from the Queensland Department of Natural Resources and Mines—Simtars, the Director of the Finnish Institute of Occupational Health, and MSHRAC committee members. A virtual tour of LIAM is also available on the NIOSH Mining website (Figure 7.)

Figure 7. Screenshot of the LIAM, which provides an online virtual tour of varying ventilation configurations. When clicked, each yellow circle offers detailed ventilation information specific to that area of the model.

Automated Breathing and Metabolic Simulator Laboratory

To test and certify closed-circuit escape respirators (CCERs) and self-contained self-rescuers (SCSRs), NPPTL uses its Automated Breathing and Metabolic Simulator (ABMS) Lab. In this lab, researchers conduct certification tests through evaluation of stressors including inspired oxygen, inspired carbon dioxide, breathing resistance, and wet bulb temperature. Human subject testing involves wearing the apparatus under different types of work and physical orientations to ensure that they perform properly under stress (Figure 8).

Photos by NIOSH

Figure 8. Equipment used to test CCERs in the ABMS Lab (left).
Human subject testing in the ABMS Lab of an SCSR (center) and a CCER (right)

Mining Program Strategic Plan

All NIOSH Mining Program research efforts align with goals established in the 2010 Strategic Plan reviewed and accepted by the Mine Safety and Health Research Advisory Committee (MSHRAC), as described in the Overview chapter, pp. 19–20. Strategic Goal 5 and Strategic Goal 7 and their related intermediate goals defined specific needs for research in disaster prevention and response. These goals, listed below, have guided NIOSH research activities described in this evidence package.

Strategic Goal 5: Reduce the risk of mine disasters (fires, explosions, floods), improve the post-accident survivability of miners and critical mine systems, and enhance the safety and effectiveness of emergency responders.

Intermediate Goal 5.1: Prevent or reduce the hazards of mine fires in U.S. coal and metal/nonmetal mines by applying recent technological advances in the areas of fire-resistant and fireproof materials, fire suppression systems, and atmospheric monitoring systems to mining fire hazards.

Intermediate Goal 5.2: Reduce the risk and consequence of mine fires through effective design of mine ventilation and spontaneous combustion control systems based on an improved understanding of mine fire behaviors and their impact from incipient stages through full development.

Intermediate Goal 5.3: Develop competencies, practices, and outputs to improve ventilation effectiveness for underground mining operations.

Intermediate Goal 5.4: Prevent underground coal mine dust explosions by integrating NIOSH-developed technologies, rock dusting practices, and instrumentation into accepted industry practice.

Intermediate Goal 5.5: Decrease the likelihood of explosions within sealed and unsealed abandoned areas of coal mines that can affect the active working areas.

Intermediate Goal 5.6: Improve the potential for self-escape from mine fires and explosions through development of improved escape strategies, effective training materials and methods, and the development and implementation of new or existing technologies.

Intermediate Goal 5.7: Improve the potential for safe and successful mine rescue operations through development of alternative approaches to mine emergency incident pre-event planning, incident management, and implementation of new or existing technologies to aid post-event exploration and mine rescue operations.

Intermediate Goal 5.8: Improve the effectiveness of Critical Systems and the ability of these systems to survive and operate post disaster for use in emergency situations. Critical Systems currently include mine-wide atmospheric monitoring and communication and tracking systems, but they may include other systems that are required to remain operational post-disaster.

Strategic Goal 7: Reduce adverse health and safety consequences in the mining industry through effective interventions with new technology.

Intermediate Goal 7.1: Identify, develop, test, and expedite commercialization of new technologies that contribute to the health and safety of mine workers, as mandated by the MINER Act.

Intermediate Goal 7.2: Eliminate or minimize any adverse side effects that may occur with the introduction of new technology.

Intermediate Goal 7.3: Develop an ongoing demographic surveillance program for the U.S. mining industry.

Intermediate Goal 7.4: Develop a more rigorous evaluation program to assess the effectiveness of NIOSH-developed safety and health interventions for the U.S. mining industry.

The National Occupational Research Agenda and Mining Sector Council

The National Occupational Research Agenda (NORA), described in the Overview chapter, pp. 20–21, includes eight strategic objectives. From these, this chapter addresses the following objectives and sub-objectives:

- Objective 1: *Reduce the Likelihood of Disasters in Mines*
    - 1.4.1: Reduce the risk of methane ignitions in continuous miner development and production faces
    - 1.4.2: Reduce the risk of methane ignitions in longwall production sections
    - 1.4.3: Reduce the risk of ignitions in gob areas
    - 1.4.4: Reduce the risk of coal-dust explosions
- Objective 2: *Improve Mine Disaster Response*
    - 2.2.1: Create comprehensive operational protocols for emergency responses
    - 2.2.2: Determine the benefits and effectiveness of comprehensive operation protocols
    - 2.2.3: Develop the Responsible Persons’ training needed for emergency responders
    - 2.2.4: Identify the best methods for transferring decisions to rescue teams and keeping real-time records of these messages
    - 2.2.5: Determine if electronic telephony can be used effectively in breathing apparatuses
    - 2.2.6: Improve the location and tracking of mine structures and the personnel within them to provide for rapid response during an emergency
    - 2.2.7: Determine how emergency response drills can be enhanced by virtual reality technology
    - 2.2.10: Create guidelines for preparing comprehensive mine emergency response plans

Mine Safety and Health Research Advisory Committee

As described in the MSHRAC Charter, MSHRAC advises NIOSH on conducting mine safety and health research to achieve scientific excellence, address currently relevant needs, and produce the intended results. Meetings with MSHRAC provide opportunities for NIOSH to share progress on current disaster prevention and response research and seek input on future research directions with committee members. These interactions have led to successful collaborations with stakeholders and development of intramural project proposals that address stakeholder needs. In committee meetings on January 22–23, 2008 and on November 15, 2017, NIOSH provided information on its disaster prevention and response research and future plans; and in a meeting on November 29–30, 2018, NIOSH updated MSHRAC with information related to its fires and explosions research. In the 2017 meeting, NIOSH also provided detailed updates on its related Broad Agency Announcements, described in the Overview chapter, p. 15. NIOSH received positive feedback on the relevance and potential success of its ongoing efforts, described later in this chapter.

2013 National Academy of Sciences Report

In 2013, the National Academy of Sciences (NAS) report, *Improving Self-Escape from Underground Coal Mines*, [NRC 2013], which was commissioned by NIOSH to examine the essential components of self-escape, made several recommendations to the Mine Safety and Health Administration (MSHA) and NIOSH to improve post-disaster survivability of underground coal miners. Specifically, the report called for NIOSH to conduct or sponsor a formal task analysis to identify the critical tasks required for effective self-escape, and to identify existing gaps in the training and preparation of underground coal miners. Additionally, the report recommended that NIOSH use current decision science research to inform the development of self-escape training, protocols, and training materials on effective decision-making during a mine emergency. Finally, after the identification of best practices within emergency response training, the report encouraged MSHA and NIOSH to revise or develop training flows to bring all underground coal miners to mastery in critical self-escape tasks.

Mine Safety and Health Administration

The MSHA rulemaking process affects Mining Program research priorities, with NIOSH and MSHA communicating on a regular basis to determine ways to achieve effective collaboration. If the enactment of a regulation is pending, NIOSH has redirected its research to bring the best science possible to the mining community before the rule is in place or during the rulemaking process. During the review period, NIOSH provided research findings that informed MSHA rulemaking on topics related to:

- Incombustible content of rock dust
- Mine seal design
- Belt entry sensor placement
- Communications and tracking (CT)
- Refuge alternatives
- Closed-circuit escape respirators

NIOSH's specific contributions in each of these areas are discussed throughout this chapter.

Mine Improvement and New Emergency Response Act (MINER Act)

The MINER Act of 2006 mandates guided Mining Program research, and the Act's time frames for ongoing tasks or their completion stretched into the review period. Therefore, the MINER Act served as a critical input to Program research. The MINER Act outlined numerous mandates related to emergency preparedness and disaster response, including the following:

- A formal technical study on the use of belt air and the composition and fire-retardant properties of belt materials in underground coal mining.
- Improvements to post-accident breathable air for individuals trapped underground to sustain them for extended periods of time in a potentially toxic atmosphere.
- More stringent sealing requirements for abandoned areas of underground coal mines to enhance safety.
- Evaluation of refuge alternatives, where miners might take refuge in an emergency when immediate self-escape is not possible.
- Enhancements to CT technologies, specifically to provide reliable communications between miners underground and surface personnel, and to track the location of miners.
- Flame-resistant directional lifelines in escapeways to help enable evacuation.
- Training programs for emergency procedures and coordination among operators, mine rescue teams, and local response personnel.

NIOSH's specific responses to these mandates are detailed throughout this chapter.

Multi-stakeholder Partnerships

NIOSH engages in multi-stakeholder partnerships made up of industry, manufacturers, labor, government, and academia to share information on technically complex health and safety topics and to improve the transfer of knowledge to the industry. Partnerships serve as a forum to share research findings, discuss design and testing of novel concepts, and share industry experience with currently employed technologies. NIOSH partnerships create a collaborative environment for resource and knowledge sharing, resulting in guidance documents that address stakeholder needs and enable partners to apply research solutions. NIOSH's three partnerships devoted to disaster prevention and response research are the Breathing Air Supply (BAS) Partnership, Refuge Alternative (RA) Partnership, and Rock Dust (RD) Partnership. As one example of the nature of such partnerships, see Appendix C for a table representing details about the RA Partnership.

Breathing Air Supply Partnership

The BAS Partnership provides research findings to MSHA, labor organizations, and other partners with the goal of addressing implementation of MSHA regulations, and in response to the MINER Act guidelines for a maintenance schedule to check the reliability of self-rescuers and introduce new self-rescuer technology. The regulations relevant to BAS are in the Code of Federal Regulations (CFR), 42 CFR 84 Subpart O, "Closed-Circuit Escape Respirators" (CCERs). These respirators enable users to escape from atmospheres that could be immediately dangerous to life and health. BAS Partnership meetings have focused on oxygen delivery systems for mine escape respirators, respirator wearability issues and engineering development, industry trends in the use of self-contained self-rescuers (SCSRs) and CCERs, the effects of oxygen demand on utilization of SCSRs during mine escape, and next-generation research considerations. These exchanges helped NIOSH to understand BAS-related stakeholder concerns and technology needs. During the review period, BAS Partnership meetings took place in 2012, 2014, and 2017.

Refuge Alternative Partnership

The RA Partnership provides research findings to MSHA, labor organizations, subject matter experts from academia, cooperating mines, and RA manufacturers. Partnership discussions have focused on heat and humidity testing, heat mitigation strategies, thermal simulation modeling, communications with underground miners in an occupied RA, occupancy derating based on mine temperature, built-in-place (BIP) RA contamination ingress testing, BIP RA purging, and BIP RA pressure relief valves. The regular engagement between partnership members helped to focus research technology development efforts to improve timely and effective implementation. During the review period, RA Partnership meetings took place annually from 2015 to 2018.

Rock Dust Partnership

The RD Partnership provides research findings to mining industry stakeholders including industry trade groups representing mine operators, rock dust producers and suppliers, labor organizations, and MSHA regulatory personnel. Partnership discussions have focused on the impact of rock dust on respirable dust exposure and toxicity, rock dust performance, and evaluation of essential rock dust properties, which include dispersibility, caking tendency, and inerting effectiveness—i.e., the quality of rock dust needed to render inert the combustible coal dust generated during mining. Given the risks associated with non-dispersible rock dust, these discussions led NIOSH to award a contract to develop a rock dust treated to resist caking when wetted and dried. Discussions were also helpful in NIOSH's successful efforts to commercialize the Coal Dust Explosibility Meter (CDEM) as a means to obtain rapid measurements of incombustible content. During the review period, RD Partnership meetings took place at least once annually from 2011 to 2014 and from 2016 to 2018.

Surveillance Data

NIOSH researchers regularly analyze MSHA surveillance data and MSHA citation data to determine research priorities—particularly the classification categories, causes of accidents or fatalities, or the language used in the narratives to describe incidents. The results of this analysis are disseminated to the mining community principally by way of peer-reviewed and trade journal articles.

Analysis of MSHA data showed that since 2001, incidents involving fires or explosions with fatalities in underground coal mines led to the deaths of 65 U.S. mine workers and injury to 19 workers [MSHA 2018a]. According to these same data, from 2008 to 2016, roughly 250 methane ignitions occurred during coal mining, generally during longwall mining, and approximately 87 fires were reported that resulted in two fatalities.

When these events occur, ventilation challenges arise when methane is liberated by mine development, and miners may be required to self-escape or make use of RAs. An analysis of 38 mine accidents, completed under a NIOSH contract, showed that RAs could have saved 74 of 252 miners who were killed, including 57 of 67 miners who died while trying to escape, and could have saved 7 to 19 miners from two disasters that involved the use of barricades [Ounanian 2008]. Based on an analysis by NIOSH researchers of MSHA surveillance data, since 2006, there were over 500 incidents that required some level of evacuation [MSHA 2018a]. The uniqueness and complexity of each disaster informs NIOSH researchers on strategies to improve prevention, rescue and response technologies, and best practices to help protect the mining workforce.

Activities, Outputs, Transfer and Translation, and Intermediate Outcomes

Driven by the inputs described above, NIOSH research during the review period focused on two overarching areas: *disaster prevention* and *disaster response*. Given the distinctive nature of each of these research efforts, the two areas are described separately in two major sections below.

Disaster Prevention

Fundamental to disaster prevention efforts in underground mines is the proactive avoidance of fires and explosions, which represent the greatest dangers to the underground mining workforce. For a fire to be able to burn, three requirements must be met simultaneously—commonly referred to as the “fire triangle” (Figure 9, left). An ignition source must be present to start the fire, which can arise from the heat generated by the strike of a cutting bit on rock, welding arcs, stray electrical currents, batteries, hot spots on a conveyor belt, and so on. Secondly, a fuel source must be available to combust, which can include methane liberated from the cutting of coal, coal dust generated during the mining process, conveyor belt material, and the coal itself. Thirdly, oxygen must be available to sustain the combustion. Removal of any one of the three sides of the triangle prevents a fire from starting.

For a dust explosion to occur, two additional factors must be present: The dust cloud must be dispersed or suspended in air to allow rapid combustion of the dust, and that cloud must be confined to allow pressure increases sufficient to result in an explosion. With these two factors added to the fire triangle, the result is commonly referred to as the “dust explosion pentagon” (Figure 9, right). Again, removal of any one of the sides of the pentagon removes the risk of a dust explosion.

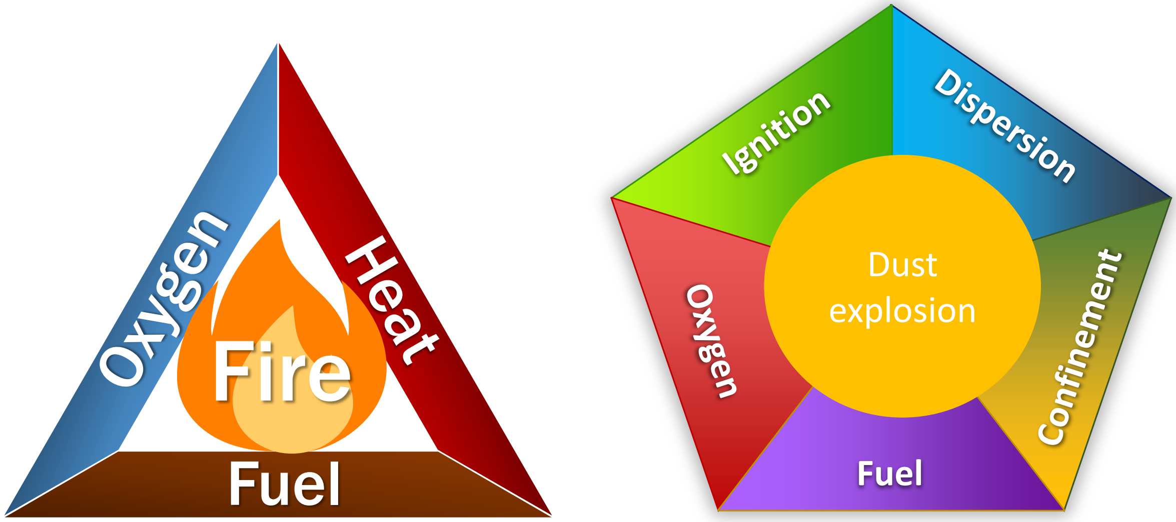


Figure 9. Basic illustration of the fire triangle and the dust explosion pentagon.

With underground mine entries providing confinement for dust clouds, dust dispersion occurs when an initial ignition (typically of methane) provides a shock wave of pressure. This shock wave lifts or disperses dust ahead of the combustion flame, creating the potential for a dust explosion, which can rapidly propagate through the mine.

Key to NIOSH's disaster prevention efforts is addressing all components of the fire triangle and dust explosion pentagon. To this end, NIOSH has performed research in the areas of float coal dust, rock dust, ventilation, permissible equipment, seal design, and mine fire prevention. Float coal dust liberated by mining and dispersed by ventilating air poses an explosion hazard, while effective rock dust mixtures are needed to inert the coal dust in the event of an explosion. Methane levels must be effectively controlled at both the face and in the gob to prevent explosions. Further, removal of the ignition source through the use of equipment that can safely be operated underground reduces the risk of fires and explosions. Effective designs to seal off mined-out areas were an important MINER Act-mandated MSHA requirement, while mine monitoring of atmospheric conditions helps operators to make better decisions about fire-fighting strategies, underground personnel evacuation and escape, and mine rescue.

Float Coal Dust

Float coal dust (FCD, with a diameter < 75 micrometers [μm] or 200 mesh) liberated by mining activities and dispersed by ventilating air poses an explosion hazard to all underground coal mine workers. Coal dust explosions occur when an initial ignition, typically of a methane-air mixture, produces a pressure wave that causes FCD on mine surfaces (i.e. roof, ribs, belt) to lift and disperse. Past research by Nagy

[1981] in the NIOSH EM showed that FCD could be entrained from wet surfaces and even lifted from standing water by an explosion. Once dispersed, the dust cloud is then ignited by the primary explosion flame. The coal dust burns rapidly, releasing more gasses and propagating the pressure wave. In the confined area of an underground coal mine, this cycle continues, growing until there is a break in the fuel source.

Given the serious ramifications of buildup of combustible material combined with inadequate rock dusting practices, additional controls that reduce accumulations of FCD throughout mine airways would provide another layer of protection against the occurrence of disasters of this kind.

To help address this issue, NIOSH researchers responded to a request from Irwin Mine and Tunneling Supply, Beckley, WV, to evaluate a prototype in-line auxiliary scrubber (a wetted scrubber attached to an auxiliary fan) for its potential at float dust control. In keeping with the MINER Act directive to enhance the development of new mine safety technology in the mine environment, NIOSH evaluated the prototype scrubber in the return of a continuous miner section (Figure 10). The published results of this research [Patts 2016] showed over a 90% reduction in float coal dust in the returns, greatly reducing the need to continually reapply rock dust. The in-line auxiliary scrubber tested has been commercially available since 2016 from Western Precision Manufacturing, SMJ Fans, Grand Junction, Colorado.

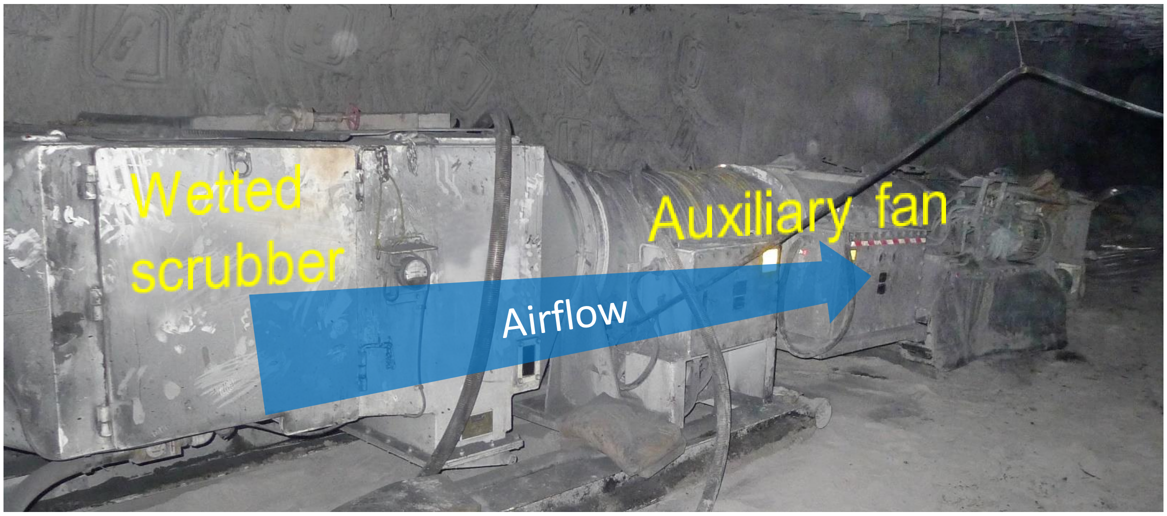


Photo by NIOSH

Figure 10. A wetted scrubber attached to an auxiliary fan to control float coal dust.

Intermediate Outcome:

- Based on the reduction in float dust demonstrated during NIOSH testing, a mine purchased and used four in-line wet scrubbers to reduce float coal dust in the mine's return [Patts 2018]. The purchased scrubbers were observed in action by NIOSH researchers during a site visit in August 2017.

Rock Dust

National and international research conducted over the past century has proven the use of rock dust as an effective inerting method to prevent explosions and explosion propagation. Its effectiveness as an inerting agent is a function of mine dust particle size and dispersibility. However, over time, mine dust particle size has decreased, largely due to the advent of mechanization in the mining process. To address this problem, based on NIOSH research, changes were made to MSHA's incombustible content rule, the CDEM was introduced, a protocol was rewritten for mine dust sampling, and anti-caking rock dust treatments were developed for use in underground coal mines. These changes are discussed below in greater detail.

Incombustible Content Rule

Prior to September 2010, U.S. Federal regulation 30 CFR 75.403, "Maintenance of Incombustible Content of Rock Dust," mandated that the nation's coal mines maintain a total incombustible content (TIC) of at least 65% in nonreturn entries and at least 80% in the return airways. The 65% TIC requirement was based on an average particle size termed "mine-size dust," which was based on an average of representative dust samples collected from mines in the 1920s.

A series of large-scale explosions were conducted by NIOSH using coarse (20% minus 200 mesh or 75 microns), medium (38% minus 200 mesh), and fine (80% minus 200 mesh) coal dust to determine inerting levels. These experiments were completed at the LLEM, which had entry geometries similar to those of modern underground coal mines. LLEM inerting studies using a medium-sized coal dust showed that at least 76.4% total incombustible content is required to prevent explosion propagation. If the finest size dust (80% minus 200 mesh) was considered, approximately 80% total incombustible content would be required to prevent an explosion propagation. As a result, NIOSH testing determined that more incombustible material (rock dust) was required to inert the finer coal dusts found in U.S. coal mines and that a 65% total incombustible content was not sufficient. In its Report of Investigations (RI), *Recommendations for a New Rock Dusting Standard to Prevent Coal Dust Explosions in Intake Airways*

[NIOSH 2010] (Figure 11), NIOSH recommended that the total incombustible content requirement be raised to 80% in all entries.

Figure 11. NIOSH Report of Investigations referenced by MSHA in 30 CFR 75.403 as part of its final rule on maintenance of incombustible content of rock dust.

Intermediate Outcome:

- Upon publication of the NIOSH RI, *Recommendations for a New Rock Dusting Standard to Prevent Coal Dust Explosions in Intake Airways*, MSHA enacted an emergency temporary standard in September 2010 requiring 80% total incombustible content in all underground coal mine entries. MSHA's final rule, 30 CFR 75.403, "Maintenance of Incombustible Content of Rock Dust," referenced this RI when it was published in 2011.

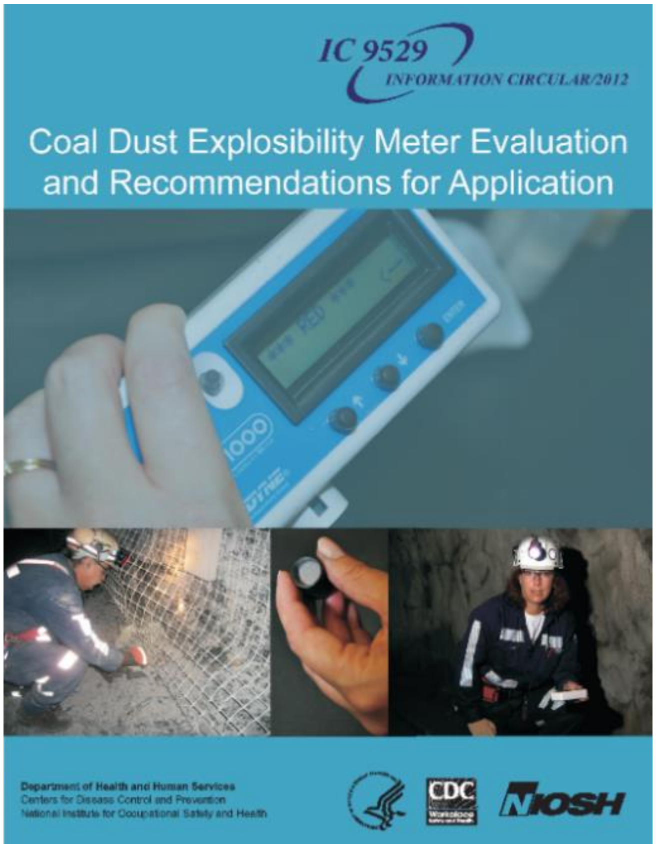
Coal Dust Explosibility Meter

Standards regulating the use of rock dust for explosion prevention are set forth in 30 CFR 75 Subpart E, 75.400, "Accumulation of Combustible Materials," which prohibits accumulations of combustible materials in underground coal mines. From 2008 to 2018, analysis of MSHA violation data showed a total of 69,227 citations issued for violation of this standard [MSHA 2018a]. In 2017, this was the most cited violation in underground coal mining—indicating frequent accumulations of combustible material, mainly float coal dust. 30 CFR 75.403 requires that 80% total incombustible content be maintained in intake and return airways of underground coal mines. There were 15,550 violations of 75.403 for the same time period indicating insufficient rock dust in these samples. These two standards have been in the top 10 most frequently cited violations for the last 10 years.

MSHA inspectors routinely collect samples of rock dust and coal dust to assess compliance with incombustible content in 30 CFR 75.403. These survey samples are sent to the MSHA Mt. Hope laboratory for moisture and low temperature ash analysis (a four-hour procedure) to determine percent incombustible content [NIOSH 2012a]. Citations for insufficient incombustible content are then issued based upon the number of samples out of compliance. The analysis process could take up to four weeks. This could result in an unmitigated hazard in the interim, by permitting areas of inadequate incombustible content to exist for many weeks.

Following up on research by the U.S. Bureau of Mines, NIOSH researchers developed the Coal Dust Explosibility Meter (CDEM) so that mine operators and regulatory personnel could assess explosibility of a mine dust mixture in situ, allow for immediate determination of the explosible reactivity of a coal and rock dust mixture, and allow for correction of any detected deficiencies in incombustible content [Harris et al. 2008]. The CDEM operates based on optical reflectance of the coal and rock dust. A mine operator or inspector collects a sample and the CDEM measures the optical reflectance, compares it to the calibration values, and displays a red or green measurement, indicating whether the sample is explosible or not.

MSHA worked cooperatively with NIOSH on the development and field testing of the CDEM. During 2009–2010, NIOSH and MSHA conducted an extensive joint study to contrast explosibility assessments as determined by the CDEM and results determined by laboratory thermo-gravimetric analysis. Results of that study were published in a NIOSH Information Circular (IC) [NIOSH 2012a] (Figure 12), *Coal Dust Explosibility Meter Evaluation and Recommendations for Application.* This study determined that the CDEM agreed with the MSHA laboratory thermo-gravimetric analysis 97% of the time. In the disagreeing 3%, the samples contained coarser coal material that is not as reactive or explosible.



IC 9529

INFORMATION CIRCULAR/2012

Coal Dust Explosibility Meter Evaluation and Recommendations for Application

Department of Health and Human Services
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health

Figure 12. NIOSH Information Circular investigating the ability of the CDEM to accurately predict the explosibility of samples of coal and rock dust mixtures collected from underground coal mines in the U.S.

Intermediate Outcomes:

- The CDEM was commercialized as the CDEM-1000 by Sensidyne in 2011.
- MSHA issued a Program Information Bulletin (PIB) on the CDEM and its use [MSHA 2013].
- The CDEM began to be used by MSHA in routine dust compliance surveys conducted under final rule 30 CFR 75.403, “Maintenance of Incombustible Content of Rock Dust.”
- In its *Coal Mine Safety and Health General Inspection Procedures Handbook*, MSHA permits its inspectorate to use the CDEM to terminate a citation issued for violation of insufficient incombustible content in underground mine workings [MSHA 2016].
- According to coal district reports from MSHA, as of the end of 2018, U.S. coal mine operators are using 53 CDEM units. MSHA is using 15 CDEM units [Goodman 2019].

Protocol for Mine Dust Sampling

MSHA inspectors collect dust samples according to established procedures [MSHA 2008]. These procedures dictate that the band or perimeter method be used to collect dust samples from the roof, ribs, and floor, creating one “band” sample. This band sample includes 25-mm-deep (1-inch-deep) material from the floor. Once collected, the sample is thoroughly mixed, coned, and quartered to take a portion for analysis. This sampling essentially assumes a homogeneous mixture of coal, rock, and other dust on all surfaces. Underlying this assumption is that in the event of an explosion, the aerodynamic disturbance ahead of the flame front will scour dust from all surfaces and will tend to either enhance or inhibit propagation depending on the incombustible content percentage [BOM 1940].

Research was conducted by NIOSH to examine the sampling procedure and to determine if it provided a representative mine dust sample. NIOSH researchers summarized data collected from nine mines of varying coal seams, depths, and mining methods. The samples were collected so that the roof, rib, and floor samples were maintained separately, and floor samples were collected at varying depths (Figure 13). Previous research indicated that the top one-quarter-inch of floor dust was scoured in an explosion [Harris et al. 2009, 2010]. Study findings indicated that the roof, rib, and floor samples should be maintained and analyzed separately as opposed to sampling a one-inch depth [Harris et al. 2015].

Photo by NIOSH

Figure 13. NIOSH researcher collecting dust sample from mine floor.

Intermediate Outcome:

- As a result of NIOSH research, the protocol for mine dust sampling was rewritten in the MSHA Mine Inspectors Handbook so that samples from the roof and rib should be segregated from the floor sample for analysis [MSHA 2016].

Treated Rock Dust

Rock dust on the mine floor is incorrectly thought to prevent the ignition of pure coal dust clouds. To quench a propagating coal dust explosion, rock dust must be dispersed (or thrown into suspension) as separate particles in a 4:1 ratio to that of the suspended coal dust particles. Further, high humidity and wet entries do not stop a propagating coal dust explosion. Proper rock dusting is therefore still important in these areas to encapsulate the accumulation of float coal dust. Greenwald [1938] noted that rock dust absorbs moisture when in contact with wet surfaces or if moisture is applied directly. He also noted that a thin layer of coal dust may become bound to this wet rock dust, but further applications of additional fine coal dust would remain dispersible. Nagy [1981] also showed that float coal dust could be entrained from wet surfaces and/or standing water to participate in an explosion. Early research conducted by Cybulski [1975] showed that the use of hydrophobic agents in conjunction with conventional limestone-based rock dusts lessened their tendency to cake when exposed to moisture and enabled their dispersibility even in wet mining conditions. These additives permit rock dust to be dispersible and, therefore, effective even in the presence of high moisture levels.

As of 2012, no commercially available rock dust in the U.S. met the dispersibility requirements of 30 CFR 75.2(2), "Rock Dust," which calls for a rock dust, "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." Consequently, NIOSH awarded a contract to Imerys Carbonates, a rock dust manufacturer and supplier, to develop an anti-caking rock dust. The technology and approach used in this contract were successful in developing an anti-caking rock dust blend that would meet the specifications of the 30 CFR 75.2(2) rock dust definition [Imerys 2019]. As part of the contract, the manufacturer also assessed particle size and particle packing density characteristics of a rock dust as a function of the concentration of the added anti-caking agent. This contract resulted in the production-scale development of a stearic acid base anti-caking rock dust. NIOSH determined that 0.5% stearic acid was sufficient to coat the rock dust and prevent it from wetting and caking. Although stearic acid is explosible in large quantities, inerting experiments conducted in NIOSH's 20-L explosibility chamber (Figure 14) showed that a rock dust coated with calcium stearate was as effective as uncoated rock dust in inerting coal dust.

Through yearly partnership meetings with the Industrial Minerals Association–North America (IMA-NA), NIOSH was able to engage with rock dust suppliers to produce a chemically treated rock dust. Interactions with the IMA-NA led to investigations yielding the optimum amount of chemical additive with which to treat rock dust to maximize dispersibility.

Photo by NIOSH

Figure 14. Testing being performed in NIOSH's 20-L explosibility chamber.

Intermediate Outcomes:

- Several companies—Huber, Greer Industries, and Carmeuse—have developed anti-caking treatment options for their rock dust products. Carmeuse specifically cites collaborative exchanges with MSHA and NIOSH in development of its treated rock dust [Coal Age 2014].
- A treated rock dust is currently being used in an underground coal mine in Alabama [JA Holmes Safety Association 2019].

Ventilation

Longwall mining presents a particularly complex ventilation challenge—not only are large quantities of methane gas liberated during mining, but large methane reservoirs can be created simultaneously within the gob area and fractured mine strata. This necessitates constant vigilance on the part of mine operators to maintain ventilation. Incomplete caving may allow face air to flow behind the shield line, resulting in a decrease of airflow on the face. To help operators address this problem, a NIOSH project on ventilation of longwall faces, begun in 2014, is (1) identifying flow paths for ventilation airflow along longwall panels with variations in roof caving characteristics and longwall face lengths, and (2) specifying locations and protocols for implementing continuous ventilation monitoring along the shield line to provide early detection of gas exchanges between the face and the gob.

The methane that originates and accumulates in the gob above the mined-out panel is the main source of methane emissions during longwall mining. Prior monitoring studies directed at longwall face emissions indicate that only a small portion of the overall methane emission and gas production is emitted at the face. It has been reported that methane contributions from the subsided strata generally account for 80% to 94% of the methane present in the ventilation system of an operating longwall [Schatzel et al. 1992]. These research findings suggest that typical longwall face emissions account for no more than 20% of longwall emissions, as little as 6% of the total emissions at one site, and potentially less at very gassy mines. However, this particular emissions source is critical in relation to underground safety. Face areas on longwall mining sections present specific challenges for methane control techniques where high production rates can cause relatively high methane emission rates, making it difficult to meet statutory limits on methane concentrations at face and tailgate sampling locations [NIOSH 2008]. Face areas are also where the greatest number of potential ignition sources exist (bit sparking, metal-to-metal contact, hot surfaces, etc.).

One common technique to control high methane levels at the face and in the gob is the use of gob gas ventholes (GGVs) to remove methane gas from the gob as it collapses during mining. NIOSH researchers conducted field studies using tracer gas and gas monitoring methods to measure gas transport parameters in longwall gobs. Modeling of reservoir parameters and analyses of the collected data showed that the operating GGVs had extensive influence at helping to remove methane gas [Schatzel et al. 2012; Karacan and Goodman 2011]. Research further showed that ventilation airflow impacted the effectiveness of the GGVs by diluting methane gas accumulating in the gob. As a result, NIOSH recommended that GGVs be completed in the fractured rock above the caved zone to minimize interaction with ventilation airflow, thus improving their performance.

In another example of the influence of GGVs, NIOSH collaborated with a mine operator that was considering a face increase, reflecting an industry trend of increasing panel dimensions. Increases of this nature can create ventilation and methane control challenges by increasing the size of the gob and, hence, the amount of methane residing in the gob. NIOSH researchers conducted studies to predict methane emission rates on the longer face using two separate methods [Schatzel et al. 2008]. The first method distinguished methane sources on the face in terms of four emission contributors and analyzed the data using linear equations. The second method split the face into equal-length segments, averaging emissions in the segments and combining them with least-square trend lines. Through analysis of the GGV data set, NIOSH recommended that the mine operator move its GGVs from their existing locations on the center axis of the longwall panel to positions on both the tailgate and headgate sides of the longwall panel. These additional boreholes improved gas extraction and capture for the mine operation [Schatzel et al. 2008; Karacan and Goodman 2011; Karacan et al. 2012].

NIOSH also developed the Methane Control and Prediction (MCP) software (Figure 15) for anticipating methane emissions in underground coal mines and predicting the effectiveness of methane control techniques. Decreasing staff at many mining companies has led to the loss of ventilation and methane control personnel. The MCP software, made available to the public in July 2009, assists mine operators and methane control personnel in ventilation planning and anticipating technologies for methane control to supplement the existing mine ventilation system.

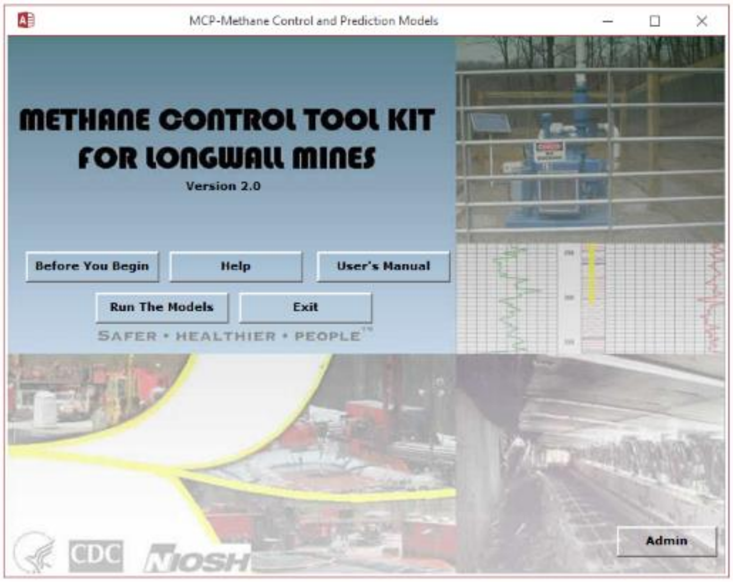


Figure 15. Screenshot from the NIOSH-developed Methane Control and Prediction software, used to address methane and methane control issues in longwall coal mines in the U.S. and internationally.

Intermediate Outcome:

- Between 2015 and 2018, NIOSH recorded 92 downloads of the MCP software from the NIOSH Mining website [NIOSH Web Statistics 2018].

Ventilation Training

Ventilation is a cornerstone in the maintenance of worker health and safety in underground mining. However, NIOSH analysis of MSHA statistics revealed that improper or inadequate ventilation has been cited as a root cause of a number of fatal incidents since 2001 involving fires or explosions that resulted in 65 fatalities and 19 injuries to the workforce [MSHA 2018a]. Education in the mining ventilation sciences rests with programs offering mining engineering degrees that are accredited by the Accreditation Board for Engineering and Technology in the United States. However, retirements and departures of tenured instructional staff left some of the major mining departments without experienced faculty to teach ventilation theory and application. Responsibility for such instruction was given to newly hired faculty who typically did not possess the necessary breadth of knowledge.

To address this deficiency, NIOSH issued five-year capacity-building contracts to seven universities in 2009 and six universities in 2014 (14 contracts in total, with two to the same university) to produce graduate students with advanced degrees in mining engineering with a specialization in the ventilation sciences. This funding also helped to develop tenure-track faculty performing research in this critical area. NIOSH provided capacity-building funding in ventilation to nine different universities and 12 separate faculty members. During the review period, funding through capacity-building contracts resulted in the awarding of 28 PhD degrees and 42 master of science degrees. As of 2018, 20 students were still working toward their PhD degrees and 14 toward their master of science degrees. This funding also assisted five faculty at Virginia Tech, the South Dakota School of Mines and Technology, the Colorado School of Mines, and the University of Nevada-Reno in receiving tenure at their respective institutions. While it is difficult to track students after graduation, five students (three PhD and two MS) who participated in this capacity-building program have been hired by NIOSH. Other graduates have likely gone to work in industry (mining and underground construction), academia, and consulting, internationally as well as domestically.

Permissible Equipment

Permissible equipment is required in certain locations of underground coal mines where there is a risk of exposure to flammable gas or dust. The term “permissible” refers to equipment that is designed, constructed, and installed to ensure that it will not be an ignition source for a flammable or explosible mixture. Removal of the ignition source through use of permissible equipment is one approach for reducing the risk of fires and explosions.

On September 20, 2007, a fire involving a permissible lithium-ion (li-ion) battery-powered cap lamp was instrumental in the establishment of an International Electrotechnical Commission (IEC) working group to promote battery safety research for the purpose of revising international standards for explosive atmosphere equipment. NIOSH researchers assessed the ignition hazards of li-ion batteries, previously considered to be intrinsically safe, and ultimately identified potentially safer lithium battery chemistries [Dubaniewicz and DuCarme 2013, 2014, 2016].

Emerging laser technologies also pose a potential risk of igniting explosive atmospheres. Lasers are used for measuring concentrations of methane gas and for monitoring coal dust levels in silos. To explore this technology, NIOSH researchers conducted over 1,000 optical ignition experiments with powerful lasers, studying several variables that contribute to the explosion of hydrocarbon gases or coal dust. Researchers measured optical ignition power thresholds for methane and coal dust. They observed that the amount of laser power needed to create explosions was proportional to the optical beam diameter. This suggests that explosions could be prevented even for relatively powerful beams by ensuring that the beam diameter is large enough to reduce the beam intensity. Researchers also measured the time delays for producing optical ignitions, which can be used for designing automatic safety shutoffs [Dubaniewicz et al. 2003; Dubaniewicz 2006a; Dubaniewicz 2006b]. From 2011 to 2015, NIOSH awarded a contract to develop a remote fiber optic methane monitor that uses a laser beam to sense the methane gas. The remote fiber optic methane monitor developed under this contract was designed to meet the standard IEC 60079-28 2015, "Explosive Atmospheres—Part 28: Protection of Equipment and Transmission Systems using Optical Radiation." The prototype system, four methane sensors, and 1,000 feet of temperature sensing were installed in an active underground coal mine for extended system testing and evaluation. As reported in 2015 in a technical paper by RSL Fiber Systems, during the field trial, the system performed as designed, verifying that it was unaffected by common mine conditions including high humidity, anaerobic conditions, and the presence of non-target gases.

A NIOSH researcher participates with international and U.S. safety standards committees to translate permissible equipment research findings to equipment safety standards. This researcher is a NIOSH representative on the U.S. Technical Advisory Group to the IEC Technical Committee 31, "Electrical

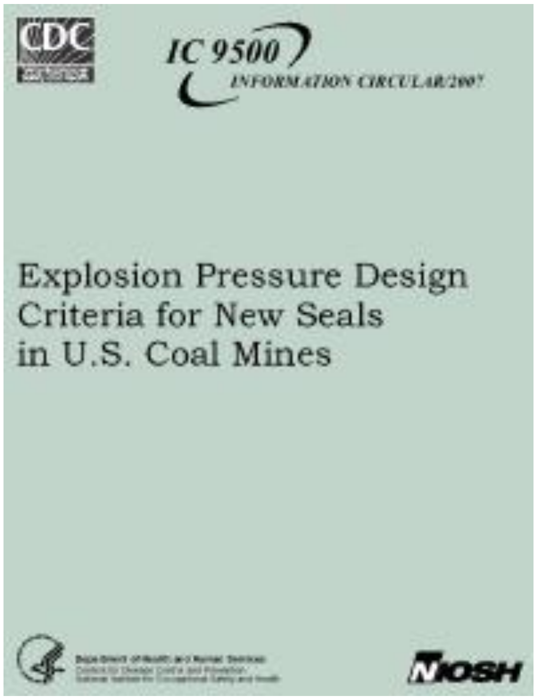
Apparatus for Explosive Atmospheres," and the Underwriters Laboratories (UL) Standards Technical Panel (STP) 60079, "Electrical Equipment for Hazardous Locations." The UL STP 60079 publishes American National Standards Institute (ANSI) U.S. national standards either harmonized with or with U.S. differences to corresponding IEC standards. IEC 60079-28:2015, cited in the paragraph above, references several journal articles authored by the NIOSH researcher [Dubaniewicz 2006a, 2006b].

Intermediate Outcomes:

- Based in part on NIOSH research findings on safe optical powers in explosive atmospheres, IEC 60079-28:2015, "Explosive Atmospheres—Part 28: Protection of Equipment and Transmission Systems using Optical Radiation," was adopted in 2015, with the standard citing three NIOSH journal articles. Over 500 products have been certified to the standard since publication in 2015 per the IECEx website. Underwriters Laboratories published the standard as an ANSI U.S. National Standard in 2017.
- IEC 60079-0:2017, "Explosive atmospheres—Part 0: Equipment—General requirements*,"* was revised to identify ignition hazards associated with li-ion batteries based on NIOSH research findings, referencing three NIOSH-authored journal articles [Dubaniewicz and DuCarme 2013, 2014, 2016]. Over 200 products have been certified to the standard in the eight months since publication per the IECEx website. The UL STP 60079 reached consensus in August 2018 to adopt the standard as an ANSI U.S. national standard.

NIOSH Seal Designs

Abandoned areas of mines must be sealed, and the atmosphere behind the seal monitored to reduce risk of explosions. In response to the 2006 explosions at the Sago and Darby Mines that caused the death of 17 miners, MSHA increased the seal design standard from 20 to 120 psi. However, no specific guidance was provided on how the new seals should be designed and constructed to meet the new requirement. To assist MSHA with the MINER Act mandate pertaining to seals, NIOSH researchers conducted a study of the worst-case explosion pressures that could develop within sealed areas of coal mines, publishing the findings in the NIOSH IC, *Explosion Pressure Design Criteria for New Seals in U.S. Coal Mines* [NIOSH 2007a] (Figure 16). Instead of assuming that sealed areas were inert, this study recognized that sealed areas could develop the critical methane-air mixture ratio during the transition from an inert low ratio after sealing to an inert high ratio as the methane level increased (an air-methane mixture is explosive within a range of 5% to 15% methane). The mixture could also return to a critical ratio if the seals leaked air into the sealed area at a later time, posing a potential explosion threat.



IC 9500

INFORMATION CIRCULAR/2007

Explosion Pressure Design
Criteria for New Seals
in U.S. Coal Mines

NIOSH

Figure 16. NIOSH Information Circular detailing research results related to three design pressure-time curves for seal design.

To address this problem, NIOSH researchers first examined seal design criteria and practices used in the United States, Europe, and Australia and classified seals into their various applications. Next, NIOSH considered various kinds of explosive atmospheres that could accumulate within sealed areas, provided an in-depth phenomenological review of explosion processes, and used thermodynamic calculations and simple gas explosion models to estimate worst-case explosion pressures that could impact seals. The resulting review of methane explosion research cited several studies that recorded methane explosion pressures at or above the detonation pressure, which for a stoichiometric mixture of methane-air is 256 psi. Based on the worst-case explosion pressures that might have to be resisted, NIOSH researchers developed three design pressure-time curves for the dynamic structural analysis of new seals [NIOSH 2007a]. The three curves were keyed to the conditions under which those seals might be used—i.e., (1) unmonitored seals where there is a possibility of a methane-air detonation, (2) unmonitored seals with little likelihood of a detonation, and (3) monitored seals where the amount of potentially explosive methane-air is strictly limited and controlled.

Intermediate Outcome:

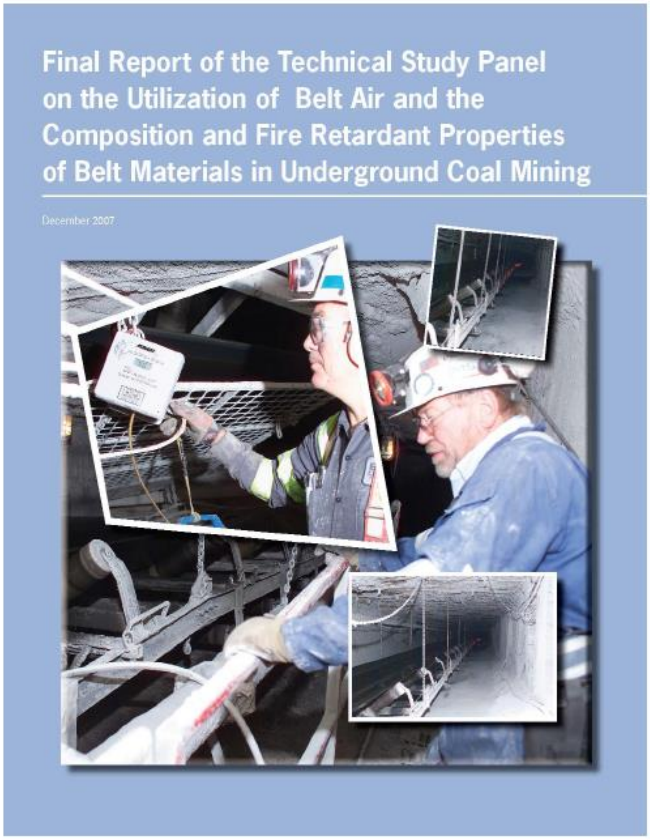
- Based on the three design pressure-time curves developed by NIOSH researchers, MSHA now requires in its final rule, 30 CFR 75, "Sealing of Abandoned Areas," a three-tiered explosion pressure design criterion for new seals in coal mines per 30 CFR Part 75.335b, "Seal Strengths, Design Applications, and Installation." The final rule cites the NIOSH IC, *Explosion Pressure Design Criteria for New Seals in U.S. Coal Mines*, several times [NIOSH 2007a].

Mine Fire Prevention

Mine fires continue to be a serious hazard to the safety of the mining workforce. Mine equipment fires frequently occur in metal/nonmetal mines when combustible liquids (diesel fuel, engine oil, antifreeze, hydraulic fluids) come into contact with hot engine components such as exhaust manifolds, turbo chargers, etc. In addition, issues have arisen with the increased use of emerging li-ion battery technologies. The potential failure modes, intensities, and toxicities of large-format li-ion battery fires are not well understood. Further, standard fire control measures are generally ineffective for fires involving such batteries.

To reduce the fire hazard in underground mines, it is vital to ensure that combustible materials such as conveyor belts are properly fire-retarded, that innovative suppression techniques are developed for underground fires, and that reliable information be available to mine and rescue personnel on the spread of smoke and toxic gases during a mine fire emergency.

To help address this issue, the MINER Act established a Technical Study Panel to provide independent scientific and engineering review and recommendations with respect to the utilization of belt air and the composition and fire-retardant properties of belt materials in underground coal mining. The panel's final report (Figure 17) contained 20 recommendations to increase safety in mines using conveyor belts. One of those recommendations requested that MSHA adopt the BELT method for conveyor belt flammability to significantly reduce the frequency and hazard of conveyor belt fires in mines that course belt air to the working face. The effectiveness of the BELT method had previously been verified and accepted by MSHA as described above, and NIOSH's large-scale belt fire flammability tests used 36- to 60-in-wide conveyor belts. As wider 72-inch conveyor belts became more commonly used in U.S. underground mines, NIOSH researchers conducted many full-scale conveyor belt flammability tests at the LLEM. The results indicated that the BELT method was also valid for the 72-inch belts [Rowland and Smith 2010].



Final Report of the Technical Study Panel on the Utilization of Belt Air and the Composition and Fire Retardant Properties of Belt Materials in Underground Coal Mining

December 2007

Figure 17. Final Report of the Technical Study Panel recommending improved flammability standards for belt materials.

Findings such as those in the final report of the technical study panel are of special interest to the National Fire Protection Association (NFPA), which is a global nonprofit organization dedicated to eliminating death, injury, and economic loss due to fire and its related hazards. The NFPA delivers information and knowledge through more than 300 consensus codes and standards. Currently, there is one mine fire-related NFPA standard: "NFPA 120: Standard for Fire Prevention and Control in Coal Mines." To maintain their relevance and suitability, NFPA standards are constantly revised. To revise NFPA standard 120 for the 2015 edition, the NFPA Technical Committee on Mining Facilities required experimental fire data provided by the Technical Study.

Intermediate Outcome:

- NIOSH research on mine equipment fires, automatic fire sprinkler systems, and smoke control during underground mine fires was cited in "NFPA 120: Standard for Fire Prevention and Control in Coal Mines," 2015 Edition.

Conveyor belts are a major fire source in underground coal mines, as demonstrated by the 2006 Aracoma Alma No. 1 mine conveyor belt fire accident in which two miners were fatally injured from carbon monoxide poisoning [MSHA 2007]. Although the conveyor belt used in that mine passed the MSHA belt flammability test using the 2G method, which was the method used for acceptance of fire-resistant belting since 1955, and was designated as fire-resistant, the belt still caught fire and the flame spread quickly. This indicated that requirements for the testing and approval of flame-resistant conveyor belts using the 2G method were outdated and inadequate. Previously, NIOSH had developed the Belt Evaluation Laboratory Test (BELT) method in cooperation with the MSHA Approval and Certification Center in 1990. The BELT method tests a belt sample 1.52 m long by 0.23 m wide in a ventilated test chamber 1.8 m long by 0.46 m square. This approach more closely resembles real in-mine conditions as compared to the belt sample 15.2 cm long by 1.27 cm wide used in the 2G method. NIOSH conducted a new study to determine if the BELT will also qualify wider belts as fire-resistant for use in underground coal mines. The BELT method proved to be a better testing option compared to the previously used 2G method for flame-resistant conveyor belts used in U.S. underground coal mines.

Intermediate Outcome:

- ❖ The BELT test method was incorporated into 30 CFR Part 75 as the approved method for conveyor belt flammability testing in U.S. coal mines by MSHA. The final rule, "Flame-resistant Conveyor Belt, Fire Prevention and Detection, and Use of Air from the Belt Entry," was published on December 31, 2008, and on the MSHA website. The final rule requires that, at each underground mine using atmospheric monitoring systems, sensors be located along the belt entry so that the spacing between them does not exceed 1,000 feet, and where air velocities are less than 50 feet per minute, spacing must not exceed 350 feet. As noted in the rule, the "350-foot spacing requirement has been shown in NIOSH research to provide effective early warning of a fire in the belt entry when the air velocity is 50 feet per minute or less." Other instances of NIOSH research and recommendations are also cited throughout the rule.

Mine Fire Simulation and Testing

Prediction of smoke and gas spread from an underground mine fire helps operations to identify those escapeways that are free of or less contaminated with toxic products of combustion. Computer simulation technology is well suited to this challenge, in that it offers a strong calculating ability, simulation conditions that can be altered, and high repeatability. Currently, only two mine fire simulation programs are available: MFIRE from NIOSH and VentGraph from Poland. MFIRE was originally developed in Germany in the 1950s, then refined further in the 1970s by Michigan Technological University in work funded by the U.S. Bureau of Mines (the predecessor agency of the NIOSH Mining

Program), and it became a mainstay in the modeling of fire contaminants. In 2010, MFIRE was redesigned and restructured with an object-oriented language and released as MFIRE 3.0. MFIRE 3.0 included a Windows-based front end to facilitate input of mine data. In addition, a common memory dynamic link library was added to allow vendors to easily incorporate the new MFIRE into their mine ventilation codes. MFIRE 3.0 was most recently updated in 2016 to version 3.0.50.

Intermediate Outcomes:

- Ohio Automation contacted NIOSH for assistance to incorporate MFIRE into ICAMPS (Integrated Computer Aided Mine Planning Software), an AutoCAD application. The ICAMPS website states that NIOSH MFIRE 3.0 was incorporated into ICAMPS as ICAMPS MineFire.
- Bluhm Burton Engineering of South Africa incorporated MFIRE into its ventilation simulation software, VUMA. The VUMA Underground Fire Simulation video published on October 23, 2014, demonstrates an example of fume spread simulation using VUMA-3D and the MFIRE module from NIOSH.
- NIOSH results on smoke rollback characterization in mine fires were incorporated into VentSim. The chief developer of VentSim stated in a conference proceedings presentation that NIOSH research on smoke rollback was used by VentSim for underground smoke rollback simulation [Stewart et al. 2015].
- MFIRE 3.0 has been downloaded from the NIOSH Mining website over 200 times since 2015 [NIOSH Web Statistics 2018].

In 2009, MSHA revised CFR 75.350, "Belt Air Course Ventilation," to require a minimum ventilation air velocity of 100 feet per minute and a maximum of 1,000 feet per minute in belt entries ventilating any working section. Furthermore, the ventilation air velocity was required to be compatible with the fire suppression system being used in that higher air velocities would adversely impact the performance of dry powder fire suppression systems. To address this issue, NIOSH researchers collaborated with MSHA to conduct a series of large-scale conveyor belt fire suppression tests at the LLEM. The research tested four different types of fire suppression systems: water sprinkler, deluge-type water spray, and two different types of dry chemical fire suppression systems.

The large-scale testing indicated that air velocity does, in fact, have a significant effect on the detection, activation, and suppression capabilities of a fire suppression system. The two tested water-based fire suppression systems each performed well under both sets of air velocity conditions, but required more time than the 10-minute requirement in 30 CFR 75.1101-8(c), "Water Sprinkler Systems; Arrangement of Sprinklers." The dry chemical systems did not perform as well, and resulted in failure to extinguish the test fires in some experiments.

Intermediate Outcome:

- NIOSH research results were used by MSHA to assess ventilation air velocity compliance with fire suppression systems in the belt entry [Rowland et al. 2009; Verakis and Hockenberry 2008].

Awards Related to Disaster Prevention Research

During the review period, the following honors were awarded to NIOSH researchers demonstrating the quality and significance of NIOSH research in the area of disaster prevention and response.

2012—Secretary's Pick, U.S. Department of Health and Human Services, CDC Innovates Award, for development of the Coal Dust Explosibility Meter. (M Harris, E Weiss, M Sapko, F Varley, C Hollerich)

2014—Robert C. Williams Engineer Literary Award, U.S. Public Health Service, Engineer Professional Advisory Committee, for best paper, "Further Study of the Intrinsic Safety of Internally Shorted Lithium and Lithium-ion Cells within Methane-air." (T Dubaniewicz, J DuCarme)

2017—Robert C. Williams Engineer Literary Award, U.S. Public Health Service, Engineer Professional Advisory Committee, for best peer-reviewed paper, "Design and Development of a Dust Dispersion Chamber." (E Perera)

Disaster Response

In addition to NIOSH's disaster prevention efforts as outlined in the first half of this chapter, the Mining Program also devotes significant resources to disaster response research. In the event that a large-scale underground mine emergency cannot be averted through prevention and mitigation efforts, effective mine emergency response procedures and infrastructure must be in place and all mine personnel adequately prepared. Given the inputs described and the timing of this 10-year review, the activities, outputs, and outcomes described herein reflect the clear temporal relationship between the passage of the MINER Act of 2006 and the focus of NIOSH's emergency response research portfolio. This legislation required that all mine operators develop and maintain emergency response plans (ERPs), which outline specific requirements related to the installation and maintenance of redundant two-way communications, personnel tracking, adequate breathable air supply, and standard tactile lifelines in both the primary and secondary escapeways. In addition to these mandated technological and structural emergency response features and apparatus, the MINER Act also included provisions related to improved training in mine rescue and self-escape knowledge, skills, and abilities (KSAs), while the NAS report, *Improving Self-Escape from Underground Coal Mines*, provided recommendations on how to assess KSAs.

In response to this renewed emphasis on emergency response, NIOSH embarked on several research activities designed to improve the post-accident survivability of underground mine workers. NIOSH developed and tested new technologies representing state-of-the-art communications and tracking for underground use, completed extensive intramural and contract research devoted to refuge alternatives and their habitability, and worked with contractors and regulators to develop technologies toward next-generation breathing air supplies. The establishment of dedicated behavioral interventions and training research and development teams enabled NIOSH to provide the industry with a strong and regular supply of new emergency response training content and materials.

Communications and Tracking

In the event of an underground emergency, mine workers should have a way to communicate with and be tracked by personnel on the surface to ensure their safety. The MINER Act requires that mine operators adopt two-way wireless underground communications and electronic tracking systems that allow personnel on the surface to communicate with and locate workers underground. The systems should be survivable and remain operational following a disaster to aid in self-escape and rescue operations. In concert with the MINER Act, Congress passed an Emergency Supplemental Appropriations (ESA), allocating funds for NIOSH to support development of CT (communications and tracking) prototypes that would lead to commercial products.

When the MINER Act was signed, a number of potential communication technologies existed that could be used in underground coal mines, each working in different frequency bands. Depending on their operating frequency, these communication technologies could be categorized as ultra-high radio frequency (UHF) systems, medium frequency (MF) systems, and through-the-earth (TTE) systems. However, these technologies had not been fully tested or adapted to meet the rigorous safety and survivability requirements of underground mines in the event of an emergency. Through a five-year intramural research project on CT modeling and performance, NIOSH greatly enhanced the understanding of underground mining CT system performance through the development and validation of radio signal propagation models. These models met four objectives, as follows.

- Assessed the performance characteristics of existing radio frequency identification (RFID) tracking devices.
- Determined the signal path loss for low radio frequency propagation in which electromagnetic waves can propagate directly through the earth, linking a miner underground to personnel on the surface.

- Determined the signal path loss for radio frequency propagation at very-high, ultra-high, and super-high frequencies in an underground coal mine.
- Determined the signal path-loss for radio frequency propagation at medium frequencies through parasitic coupling within an underground coal mine.

In order to meet the technical challenges and CT performance expectations established by the MINER Act, NIOSH determined that, in addition to its intramural research, the best approach to fast-track development was through funding contract research from the ESA. For this purpose, NIOSH established an interagency working group that included MSHA and several research laboratories and other agencies, including the U.S. Army and the Department of Energy. The goal was to facilitate the adaptation and movement of CT technologies from other industries or from the prototype stage to commercialization and into the mine as rapidly as possible. This was achieved through a Request for Proposal (RFP) process, by which NIOSH established the technical specifications needed for CT systems underground, assessed the most promising CT technologies by rigorously vetting the RFP responses, and funded contracts through the ESA to further develop these technologies.

In assessing these existing communication technologies, NIOSH determined that some major knowledge gaps existed that limited their ultimate usefulness and capability. Manufacturers typically have a great understanding of their equipments' transmitter power, transmit and receive antenna gains, and receiver sensitivity, but little understanding of the path loss and how it varies depending on the underground mine environment. Therefore, it was vital for NIOSH to understand the environmental factors that control and limit the path loss to be able to optimize system performance, enhance radio service coverage, improve the quality of the communications, and increase the system performance reliability.

Concurrently with this intramural project research and based on stakeholder interactions and the RFP process, NIOSH targeted technology improvements through contract research in four areas: RFID tracking, UHF path-loss modeling and validation, TTE communication system performance, and leaky feeder system survivability.

Radio Frequency Identification (RFID) Tracking

As of September 30, 2010, all electronic tracking systems approved by MSHA were based on RFID technology. The accuracy of these systems can be highly dependent on the spacing of the readers or tags and the accuracy of their placement. Technology developed under a contract with Extreme Endeavors, in partnership with the U.S. Army, Communications-Electronics Research, Development and Engineering Center (CERDEC), explored the use of a "reverse" RFID technology. A reverse RFID system uses stationary tags encoded with an exact location and a mobile transceiver attached to the miner. Theoretically, this system would allow mine rescue teams to move faster, more safely, and more efficiently by way of a microelectromechanical (MEMS) inertial measurement unit (IMU) worn by the miner. Another RFID-related contract with InSeT Systems, LLC, beta tested the installation of an inertial sensor tracking and communication system in a working underground mine to determine the accuracy, communication capability, and suitability for use in a working coal mine. The promise of the technology was that the position of the miner could be determined more accurately than if the tracking system were based on conventional RFID technology alone. The noise and drift performance of the selected IMU was such that it did not appreciably increase the accuracy of the tested system over that of a traditional RFID tracking system; however, NIOSH researchers did successfully demonstrate the accuracy of radio frequency identification (RFID) and other tracking technologies in underground mines [Virginia Polytechnic Institute 2010; InSeT Systems 2010].

UHF Path-loss Modeling and Validation

To adapt existing UHF technologies and novel concepts for CT applications in mining environments, NIOSH awarded numerous contracts. NIOSH researchers worked collaboratively with major CT equipment manufacturers in the mining industry and researchers in academia to develop commercially available CT systems for underground coal mines (Figure 18). For example, a contract with the L-3 Global Security & Engineering Solutions (now Innovative Wireless Technologies [IWT]) developed the first UHF wireless mesh mine communication system. This mesh system provided untethered voice and text communications and miner location tracking through handsets issued to each miner. Another UHF-based contract with Kutta Radios enhanced the performance of MF communications in underground mines. As a result of the research findings, Kutta successfully designed and built an inductive clamp coupler for use with MF conductive cables, produced a software program that controls the functionality of a DRUM 100 MF radio over a serial link, and demonstrated the operation of the improved features in NIOSH's SRCM.

Photo by NIOSH

Figure 18. Underground testing of a communications and tracking system.

Intermediate Outcomes:

- A mining industry survey on UHF technologies conducted by NIOSH in 2014 [Damiano et al. 2014] showed that 54 of 306 (18%) of the installed communication systems in U.S. underground coal mines were the wireless mesh systems made by IWT. IWT acknowledged on its published web news that this mesh system was originally developed under a NIOSH research contract in response to the MINER Act of 2006 [Carrier 2008]. This system has been adapted as a mine rescue communication system, housed at MSHA's five mine emergency operations locations, and used by MSHA mine rescue teams [IWT 2018].
- The 2014 industry survey showed that the DRUM communication and tracking systems were installed in eight U.S. coal mines [Damiano et al. 2014; Savoca 2011]. Kutta Radios acknowledged on its company website that the DRUM communication systems were developed by Kutta Radios in partnership with NIOSH [Kutta 2018].

Through-the earth Communication System Performance

To enhance TTE communication system performance, NIOSH-awarded contracts to determine the factors that most affect signal transmission and reception for TTE communication systems; developed advanced software for TTE communications; extended the operational range of TTE systems, while maintaining the portability and permissibility of the subsurface unit; and developed and tested enhanced magnetics-based communications waveforms with increased ability to provide TTE communication in the presence of ambient noise and interference. Collectively, the results from these contracts significantly improved the reliability of TTE links in the working areas of coal mines and extended their communication range. As a result of these contract findings, NIOSH researchers published dozens of journal articles and conference papers in the area of TTE system performance.

Intermediate Outcomes:

- Four commercially available TTE systems have incorporated NIOSH research findings [MSHA 2018c; Lockheed Martin Corporation 2011; E-Spectrum Technologies 2008; Ultra Electronics Canada Defence, Inc. 2009; Vital Alert Communications, Inc., 2013].
- NIOSH publications on TTE system performance have been referenced by researchers from all over the world, including both national and global stakeholders. Examples include:
    - One journal article published in *IEEE Antennas and Wireless Propagation Letters* received 403 full text views and 16 paper citations [Zhou and Waynert 2014]. The research was used by the National Institute of Technology in India for studying wireless communication networks in underground mine environments [Ranjan et al. 2017].
    - A published paper [Zhou et al. 2015b] that was used by the University of Queensland Australia for exploring the idea of improving wireless communications in underground mines using reconfigurable antennas [Kunsei 2018], and by Cardinality Ltd, UK, for Modelling of UHF television band radio signal propagation in the underground mine environment [Vujić and Ćertić 2018].

Leaky Feeder System Survivability

To address issues of the survivability of CT communications in the event of an accident, NIOSH awarded a contract with Pillar Innovations, LLC, to investigate techniques to increase the survivability of leaky feeder communication systems. Leaky feeders are two-way radio systems that feature a base station on the surface that communicates with underground radio units, such as walkie-talkie radios. To allow radio frequencies to function underground, a special cable network is installed underground that is designed to “leak” a signal. This allows two-way radio transmissions from underground to the surface. The contractor used a Becker Mining Systems UHF leaky-feeder communications system and, through lessons learned from research and in-mine tests, improved its post-accident survivability. The system was installed on a mine-wide basis at the Consol Energy Loveridge Mine, Fairview, WV, for long-term evaluation, spanning an underground distance of eight miles from the belt slope to the mining sections. Based on test results, the Becker leaky feeder system was modified to be permissible so that it could remain operational post-accident as required by the MINER Act.

Intermediate Outcome:

- NIOSH’s 2014 industry survey showed that 53 out of 306 (17%) active U.S. underground coal mines had installed the leaky feeder system from Becker Varis [Damiano et al. 2014].

Communications and Tracking Webinars

To disseminate the findings from the research and contracts detailed above, NIOSH organized annual webinars from 2012 to 2015 through which findings, recommendations, and status of CT work were summarized and presented to mining community stakeholders. Per a request from the Turkish Ministry of Energy and Natural Resources, NIOSH conducted a webinar on communication and tracking research on Jan. 29, 2015. The webinar provided information on the advantages and disadvantages of the different types of CT technologies with respect to longwall mining operations [Zhou et al. 2015a]. Researchers also presented at the Society for Mining, Metallurgy & Exploration (SME) Annual Meetings and participated in working meetings with MSHA representatives to keep them apprised of the research results and recommendations. Tutorial pages on wireless communications and tracking were also added to the Mining Program website (Figure 19). To determine what CT systems had been installed in U.S. underground coal mines, NIOSH researchers visited each MSHA district management office in 2014 and acquired the mine ERPs, analyzing the data and publishing the results in *Coal Age* magazine [Damiano et al. 2014].

Basic Tutorial on Wireless Communication and Electronic Tracking: Technology Overview

1.0 Introduction

The Mine Improvement and New Emergency Response Act of 2006 (MINER Act) requires mine operators to adopt underground communications and electronic tracking (CT) systems that meet specific performance goals. The MINER Act was signed into law on June 15, 2006. It amends the Federal Mine Safety and Health Act of 1977 and is intended to improve the safety of miners. Among other things, it provides updated requirements for emergency response, incident command and control, mine rescue teams, and incident notification.

The MINER Act provides two sets of requirements for communications and tracking:

On This Page

- 1.0 Introduction
- 2.0 CT Technology Overview
- 2.1 Communications Basics
- 2.2 Communications Systems Principles of Operation
- 2.3 Tracking Systems Principles of Operation
- 2.4 Network Options
- 2.5 Mine Operations Center
- 3.0 Acronyms

Figure 19. Screenshot from Mining Program website tutorial on wireless communications and tracking.

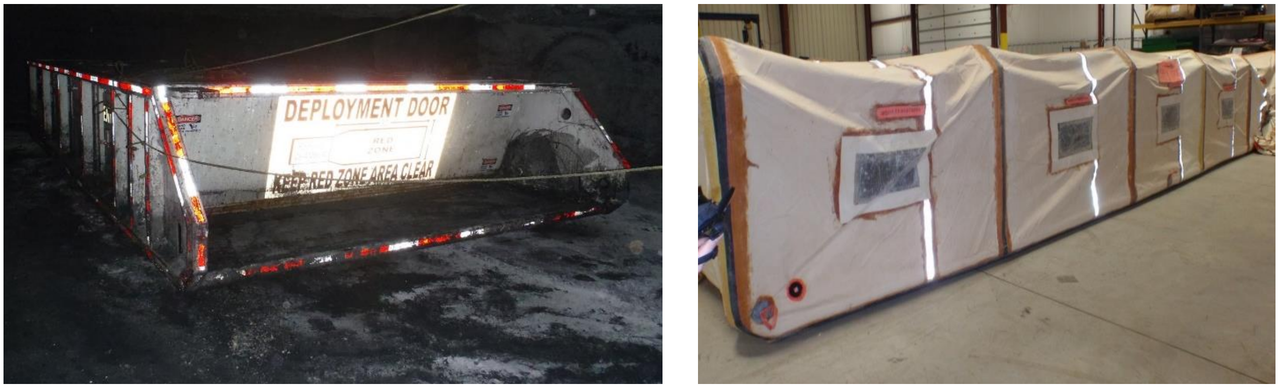
Intermediate Outcome:

- NIOSH’s CT tutorial webpages received more than 10,000 page views from 2015 to 2018. They have also been used by MSHA to make the information available to labor, industry, regulators, and academia [MSHA 2018b].

Refuge Alternatives

Refuge alternatives are structures designed to provide miners with a life-sustaining environment in case of a mine emergency if escape is not possible. RAs must provide a breathable atmosphere, food, water, and waste removal. RAs are either portable structures that can be moved within a mine or fixed-location built-in-place (BIP) structures that are created by building a stopping to enclose a mined-out area.

Two types of commercially available portable RAs are tent-type RAs (Figure 20) and rigid RAs (Figure 21). Portable tent-type RAs consist of a metal box that contains a roll-out tent and uses air cylinders to inflate support tubes that hold up the tent. Tent-type RAs allow for a smaller package to be moved around a mine because the tent is rolled up in the metal box until it is needed. Due to their hard walls, rigid RAs offer occupants additional protection when compared to tent-type RAs. However, the maximum occupancy of rigid RAs is limited when compared to tent-type because as the occupancy increases, the size of the rigid RA makes it impractical to move the structure through a mine. Typically, portable RAs use air cylinders to purge contaminated air from an airlock and oxygen cylinders to provide a breathable atmosphere within the RA.



Photos by NIOSH

Figure 20. Non-deployed portable tent-type RA being moved in an underground coal mine (left) and a deployed portable tent-type RA in a warehouse facility (right).

Photos by NIOSH

Figure 21. External view of a portable rigid RA (left) and internal view of a portable rigid RA (right).

Compared to portable RAs, built-in-place (BIP) RAs offer superior protection and can be sized to offer more space and volume for occupants. Although federal RA regulations allow BIP RAs to use oxygen cylinders to provide a breathable atmosphere, all currently existing BIP RAs use either the mine's compressed air system connected to the BIP RA via piping, or they use an air source, such as a rotary screw compressor or centrifugal fan, connected to the BIP RA via a borehole to the surface.

NIOSH Refuge Alternative Research Immediately Following the MINER Act, 2006–2009

Although the related NIOSH refuge alternative research pre-dates the review period, the resultant efforts directly informed a report to Congress and an MSHA final rule that was enacted during the review period, so research from 2006 forward is described here. The MINER Act called upon NIOSH to "provide for the conduct of research, including field tests, concerning the utility, practicality, survivability, and cost of various refuge alternatives in an underground coal mine environment, including commercially-available portable refuge chambers." The MINER Act required NIOSH to use the gathered information to prepare and submit a report on refuge alternatives 18 months after its passage. The results of this work were published in a December 2007 report to Congress [NIOSH 2007b]. The report included information related to survivability including RA location and position, structural integrity, breathable air, and basic human needs such as food, water, and waste removal.

NIOSH was also concerned about the information needed to approve RAs for use and whether it could be obtained from RA manufacturers without experimental testing. For practical and safety reasons, a decision was made to simulate human occupancy in these RA tests and a peer-reviewed protocol was developed and implemented in collaboration with the NIOSH National Personal Protective Technology

Laboratory. The protocol defined the means of simulating human occupancy to facilitate the evaluation of the chamber. As a surrogate for an RA's ability to provide sufficient oxygen levels, the oxygen flow rate into the chamber was adjusted based on the RA's occupancy and measured to ensure sufficient oxygen would be provided, and carbon dioxide was injected into the chamber according to the oxygen flow rate. To determine the resulting apparent temperature in the RA, the metabolic heat (heat created within the body through chemical processes and digestion) and moisture generated by actual miners was simulated using incandescent light bulbs and humidifiers. The resulting temperature and relative humidity were measured and used to calculate the apparent temperature. These tests were conducted for a period of 96 hours at the LLEM [NIOSH 2007b].

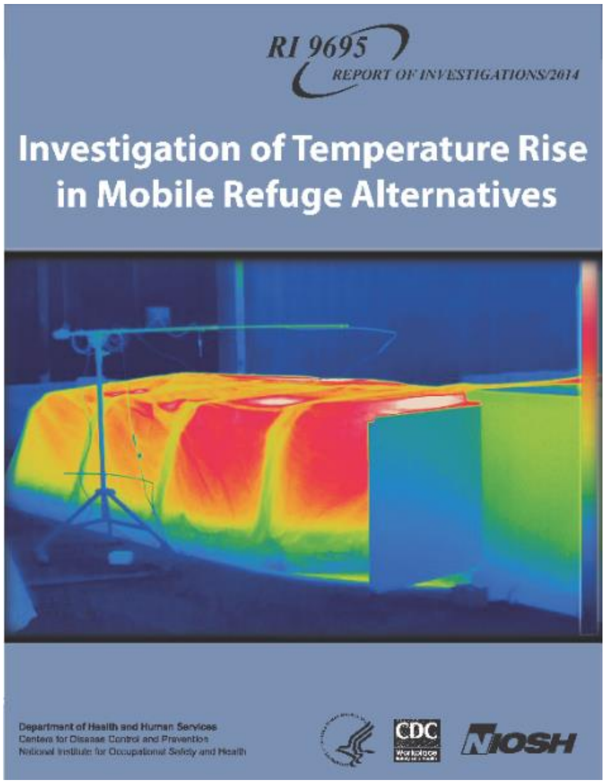
Intermediate Outcomes:

- The information from the 2007 NIOSH report [NIOSH 2007b] was used by MSHA in the formulation of its final rule, "Refuge Alternatives for Underground Coal Mines," published on December 31, 2008. This final rule addresses the following RA areas: structural, breathable air, harmful gas removal, air monitoring, and provisions for sanitation, food, water, and first aid. The thermal environment of RAs is addressed within the structural component of the regulation. NIOSH is cited frequently throughout the final rule, and results from the 2007 NIOSH report are prominently acknowledged as follows: "In developing this final rule, MSHA relied on the NIOSH report on refuge alternatives; research studies on various refuge alternatives; accident investigation reports, especially those for the 2006 Sago and Darby mine explosions; as well as public comments, hearing transcripts, and supporting documentation from all segments of the mining community, including States that already require refuge alternatives."
- NIOSH's LLEM testing revealed areas where the tested RAs were not meeting the standards set by West Virginia legislation in the "Emergency Shelters/Chambers" section. These shortcomings were serious enough to require three of the four manufacturers to modify their RAs with minor technical changes, the addition of clear instructions, and/or improved engineering. Two of these manufacturers redesigned parts of their RAs and NIOSH performed repeat evaluations of their modifications. The third manufacturer conducted an independent evaluation and sent the results to NIOSH for verification [Bauer and Kohler 2009].

NIOSH Refuge Alternative Research, 2009–2018

From 2009 to 2018, NIOSH completed significant RA research related to both portable and built-in-place RA heat and humidity buildup. Because the tests at the LLEM showed that the apparent temperature could approach or exceed the 95°F apparent temperature limit set by MSHA regulations in 30 CFR 7.504 (b)(1), "Refuge Alternatives and Components; General Requirements." NIOSH conducted a broad study of RA heat and humidity with the goal of understanding how RA occupancy and mine temperature affect the final apparent temperature of an RA. The ultimate objective was to ensure that miners who must seek shelter within an RA are not subjected to heat stress.

Because testing an occupied RA in a real mine with real miners for 96 hours is not practical and could put individuals at a health risk, NIOSH developed simulated miners to input the metabolic heat and humidity of actual miners for testing purposes (see YouTube video, "NIOSH Research on Refuge Alternatives for Underground Coal Mines"). One objective of this series of tests was to learn how the mine air and mine strata respond to heat input from an occupied RA. Another objective was to examine the differences between the results for "dry" tests conducted without moisture input and "wet" tests conducted with moisture input (an exhaled breath contains approximately 95% humidity). Finally, the extensive engineering data collected during these tests were collected for validating a thermal simulation model of an RA. The study results indicated that the mine air and mine strata temperatures increased by several degrees, and the "dry" tests resulted in dry-bulb air temperatures that were a few degrees Fahrenheit higher than dry-bulb temperatures from the "wet" tests. Based on these study results, in the RI, *Investigation of Temperature Rise in Mobile Refuge Alternatives* [NIOSH 2014b] (Figure 22), NIOSH provided evidence that mine temperatures increase due to an RA being occupied—a fact that was debated prior to this publication.



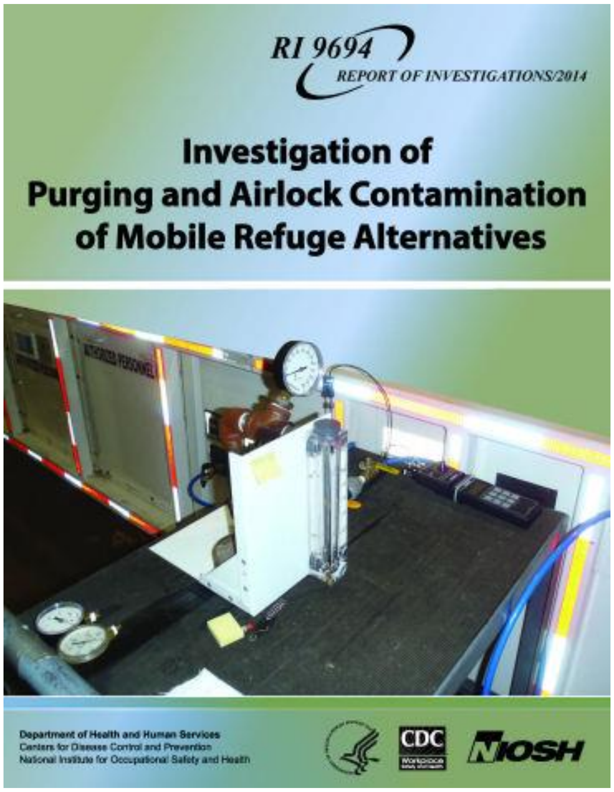
RI 9695
REPORT OF INVESTIGATIONS/2014

Investigation of Temperature Rise in Mobile Refuge Alternatives

Department of Health and Human Services
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health

Figure 22. NIOSH RI investigating the temperature-humidity metric adopted by MSHA in 30 CFR 7.504 (b)(1), and establishing evidence that mine temperatures increase due to an RA being occupied.

NIOSH has also conducted extensive portable RA research related to breathable air and the thermal environment in portable RAs. In the RI, *Investigation of Purging and Airlock Contamination of Mobile Refuge Alternatives* [NIOSH 2014a] (Figure 23), NIOSH published results of contamination ingress and airlock purging tests on portable RAs. These findings were used to provide RA manufacturers and MSHA with guidance on how to ensure that portable RA airlock purging systems provide a safe environment free of carbon monoxide.



RI 9694
REPORT OF INVESTIGATIONS/2014

Investigation of
Purging and Airlock Contamination
of Mobile Refuge Alternatives

Department of Health and Human Services
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health

Figure 23. NIOSH RI investigating contamination ingress and airlock purging on portable RAs and providing RA manufacturers and MSHA with guidance to ensure that purging systems offer a safe, breathable atmosphere.

To inform stakeholders of the important information related to these two RIs, NIOSH held meetings with all major portable RA manufacturers, members of the West Virginia Mine Safety Technology Task Force, and MSHA. To complement these results, NIOSH contracted with ThermoAnalytics, Inc., to create and validate a thermal simulation model of the 10-person tent-type RA training unit [Yantek and Schall 2017]. This model was used to examine how the initial mine air temperature and the initial mine strata temperature affect the final apparent temperature inside an RA. In addition, the effects of the space between an RA and the mine roof and rib, and the effects of mine thermal conductivity on the final apparent temperature, were examined. The results showed the following:

(1) The initial mine strata temperature has a much greater impact on the final apparent temperature than the initial mine air temperature.

(2) As the distance between the RA and the mine strata roof and rib decreases, the final apparent temperature increases.

(3) For the range of expected mine strata thermal conductivities across the U.S., the final apparent temperature varies by a few degrees Fahrenheit.

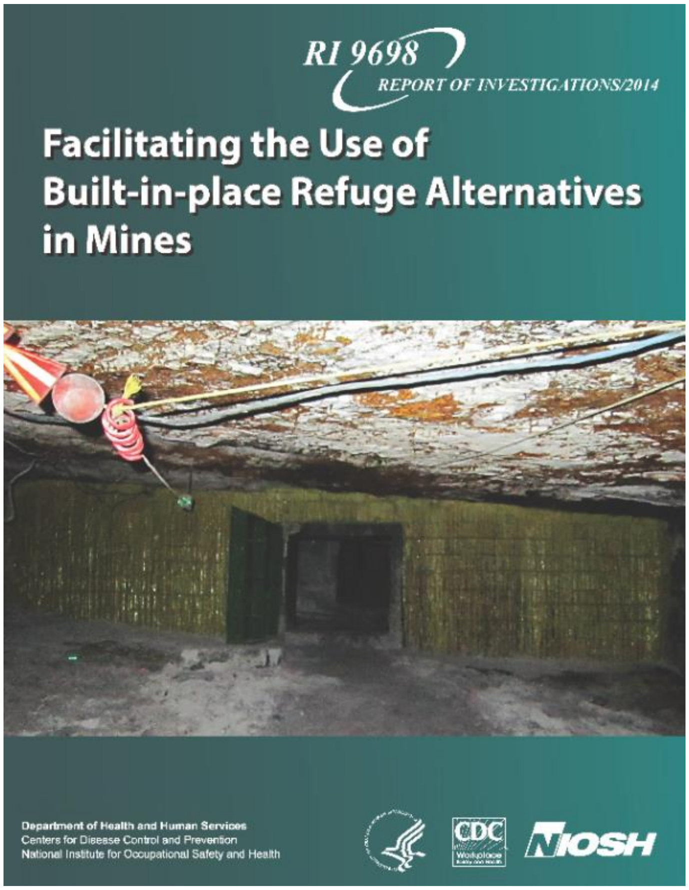
(4) If the mine strata temperature is assumed to remain fixed, the resulting final temperature in an RA could be under-predicted by more than 10°F.

To address concerns about how the above findings for a training unit RA would apply to production RAs, mine entry widths, and built-in-place RAs with portable air supplies, NIOSH developed an RA test facility within its Pittsburgh EM. Over a five-year period, this facility grew to encompass a portable tent-type RA test area, a portable rigid RA test area, a 60-person BIP RA test facility, and a separate BIP-RA-like facility for studying harmful gas movement into a BIP RA. In this facility, NIOSH conducted more than 30 heat and humidity tests on seven different RAs of various capacities and types (Figure 24).

Photo by NIOSH

Figure 24. Underground heat and humidity testing with simulated miners in a tent-type RA in NIOSH's Experimental Mine.

In 2015, NIOSH published recommendations for BIP RAs in the RI, *Facilitating the Use of Built-in-place Refuge Alternatives in Mines*, [NIOSH 2015] (Figure 25), detailing guidelines for how far the BIP RAs could be located from the working face based on seam height, designs for BIP RA stoppings that would meet MSHA approval, and approaches for delivering clean, breathable air to the BIP RA by way of a borehole to the surface or a protected compressed air line system.



RI 9698

REPORT OF INVESTIGATIONS/2014

Facilitating the Use of
Built-in-place Refuge Alternatives
in Mines

Department of Health and Human Services
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health

Figure 25. NIOSH RI detailing recommendations for locating BIP RAs further from the face, design and approval of RA stoppings, and delivering a supply of clean, breathable air to a BIP RA.

To meet the 95°F apparent temperature limit, one strategy is to derate—i.e., lower the capacity of—the maximum occupancy of an RA based on underground mine temperature. In order to explore this possibility, NIOSH used a combination of validated thermal simulation models and field data on mine temperatures. NIOSH contracted with ThermoAnalytics, Inc. to develop and validate additional thermal simulation models of a portable 23-person tent-type RA and a portable 6-person rigid RA. Data collected from NIOSH RA heat and humidity testing were used to benchmark these models. NIOSH also worked with five mines across the U.S. to measure mine air and mine strata temperatures for an entire year.

NIOSH used “worst-case” temperatures and estimates of the mine strata composition as inputs to the thermal simulation model to carry out simulations for 96 hours.

After a year of testing, the results showed that, depending on the mine strata temperatures and RA type, some RAs would have to be derated. As one example, in the Midwestern mine tested with a worst-case mine temperature of 69°F, the RA occupancy would have to be reduced to 21 miners for the 23-person tent-type RA. Even more concerning, for a Southern mine with a worst-case mine temperature of 81°F, the six-person rigid RA would exceed the apparent temperature limit even with just one miner occupying it [Yantek and Schall 2017]. These results highlight the critical need for RA cooling strategies for warm mines. To date, NIOSH has funded development of and conducted tests on two types of RA cooling strategies: a battery-powered air conditioner and a cryogenic air supply. Throughout this research, NIOSH has held regular meetings with the MSHA Approval & Certification Center’s Applied Engineering Division to update MSHA on all findings and offer suggestions related to predicting the final apparent temperature of RAs that accounts for specific characteristics of mines and the area of the country where they are located. In 2017, NIOSH also assisted one of the major RA manufacturers in conducting apparent temperature tests according to the MSHA-developed procedure ACRI 6001, Apparent Temperature Testing.

Intermediate Outcomes:

- As a result of NIOSH research on refuge alternatives, MSHA developed an apparent temperature test procedure, ACRI 6001, for manufacturers to follow to receive MSHA approval. This procedure cites NIOSH research, indicating that the temperature increase in an occupied RA is dependent on the initial mine air temperature and the temperature of the surrounding strata. Based on input from NIOSH, the procedure instructs RA manufacturers on how to increase the air temperature of the test facility throughout a 96-hour test to account for the temperature increase that would be observed in an actual mine; how to use “dry” test results in lieu of “wet” test results; and how to position temperature and relative humidity sensors during these tests [MSHA 2017; Yantek 2017].
- In 2016, San Juan Coal Company, Waterflow, New Mexico, filed a petition with MSHA (docket number M-2016-037) for modification of the existing standard based on findings reported in the NIOSH RI, *Facilitating the Use of Built-in-place Refuge Alternatives in Mines.* Specifically, the petition cites NIOSH findings from this RI about how to reduce the contamination concentration that can enter the BIP RA, the benefit of providing continuous airflow via a borehole to address that risk, the spacing of the BIP RA from the face, and the use of the borehole to provide a protected communications pathway to the surface.

Breathing Air Supply

During the review period, NIOSH activities related to breathing air supplies involved standards development and subsequent respirator approval activities, evaluation and investigation, and research on CCERs. A CCER is an apparatus in which the wearer's exhalation is rebreathed after the carbon dioxide in the exhaled breath has been removed and a suitable oxygen supply has been restored from a source within the device. In the mining industry, CCERs are knowns as SCSRs, and are used by underground miners to escape dangerous atmospheres. SCSRs used in mines are jointly approved by NIOSH and MSHA.

Breathing Air Supply Regulations

In 30 CFR Part 75.1714-1, "Approved Self-rescue Devices," MSHA requires SCSRs for use underground to have at least 60 minutes of breathing air, and 30 CFR Part 75.1714-2, "Self-rescue Devices; Use and Location Requirements," requires that these SCSRs be within 25 feet of a mine worker. Because many miners are mobile, SCSRs need to be of a size and weight so as to be wearable. Further, because SCSRs are single-use devices, there is no way to demonstrate performance for a specific unit prior to use.

Today, several devices approved under NIOSH approval regulation 42 CFR 84 Subpart H, "Self-contained Breathing Apparatus," continue to be used in underground coal mines (Figure 26). However, in December 2008, NIOSH initiated rulemaking to codify a standard for CCERs based upon automated breathing metabolic simulator (ABMS) testing. After extensive stakeholder input and review, on March 8, 2012, NIOSH adopted a new rating system based on volume capacity and improved reliability and codified the new requirements at 42 CFR 84 Subpart O, "Closed-circuit Escape Respirators." Subpart O classified escape respirators based on the quantity of oxygen in liters that would be available, incorporated requirements to evaluate the service life reliability of the devices, and named the devices CCERs (a subset of self-contained breathing apparatus [SCBAs]). Manufacturers have developed and NIOSH has approved three Subpart O devices for use in underground mines to date. NIOSH has developed a strategy to evaluate these newly deployed units to ensure that they continue to conform to the conditions of the approval.

Photo by NIOSH

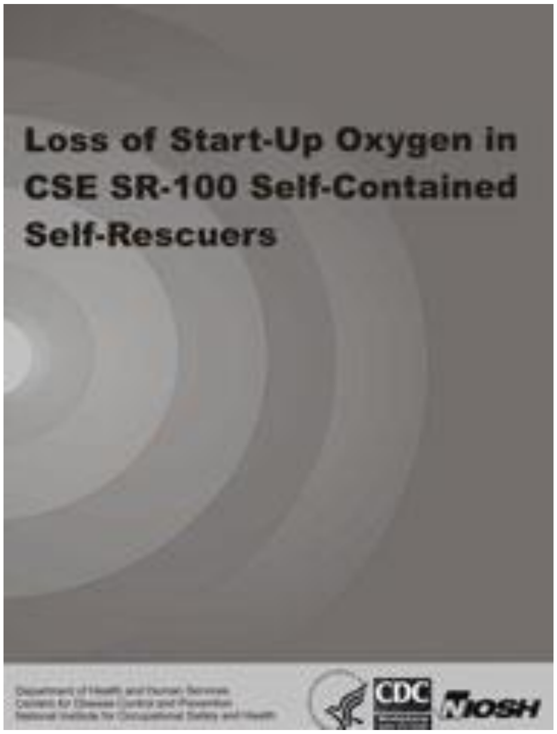
Figure 26. Four of the most common 42 CFR 84 Subpart H-approved SCSRs used in the mining industry in the U.S. The smallest unit in the foreground is an oxygen supply unit rated for 10 minutes. The next two units are 60-minute chemical oxygen generation units, and the largest unit in the back is a cached 60-minute gaseous oxygen supply unit.

As demonstrated by a 1999 publication, NIOSH had long argued for improvements in CCER wearability, capacity, and performance [NIOSH 1999]. Manufacturers were permitted to manufacture, label, and sell Subpart H SCSRs only until April 9, 2015. After that date, Subpart H SCSRs would no longer be manufactured or offered for sale and would eventually be phased out as in-service units reached the end of their service lives. This phase-out date was extended several times, partly because of continuing MSHA and industry concerns about device wearability, documented as far back as 1997 in a draft policy change and request for comments by MSHA. NIOSH has recently proposed a removal of the compliance deadline rather than further extensions due to the significant technical challenges involved in advancing SCSR development.

CSE SR-100 Respirators

NIOSH conducts post-market activities and has published four evaluation and investigation reports since 2009 on BAS-related issues. Most notably, in 2010, NIOSH and MSHA became aware of a problem with the CSE SR-100 after observing that two SR-100s exhibited little or no start-up oxygen during NIOSH post-market testing. Subsequently, CSE reported an additional failure during an in-process quality control check. CSE then voluntarily stopped production of the CSE SR-100. While the investigation was underway, NIOSH and MSHA emphasized to underground mine operators and miners that they should obtain another SCSR if they encountered operational difficulties, and that miners needed to be trained in appropriate actions to take if they encountered difficulty in operating the device [MSHA 2012; NIOSH 2012b].

NIOSH and MSHA designed and implemented a plan to test field-deployed CSE SR-100s to determine the extent of oxygen cylinder failures in the population of approximately 70,000 units in underground coal mines. NIOSH and MSHA collected and tested the oxygen cylinders from 500 field-deployed units to determine if the defect rate among the deployed units was less than 1%. To have 95% confidence that the defect rate is less than 1%, no more than three units in the 500-unit sample could fail the test. Five units failed the test. The results were published in the NIOSH report, *Loss of Start-Up Oxygen in CSE SR-100 Self-Contained Self-Rescuers* [NIOSH 2012b] (Figure 27).



Loss of Start-Up Oxygen in CSE SR-100 Self-Contained Self-Rescuers

Figure 27. NIOSH report describing the results of a joint investigation by NIOSH and MSHA to assess the prevalence of a lack of sufficient start-up oxygen in CSE SR-100 SCSR devices.

NIOSH SCSR testing of other models has continued since 2013, and very little degradation in SCSR performance due to deployment time in the mines has been observed. All SCSRs tested demonstrated the expected life support capacity over the course of the manufacturer’s service time. Through collaboration among NIOSH, manufacturers, MSHA, and underground coal mines across the country, these evaluations ensure the continued reliability of respirators used to escape from underground coal mines in the event of a disaster.

Intermediate Outcome:

- On March 26, 2012, MSHA issued PIB No. 12-09 describing the phase-out schedule for removing CSE SR-100 SCSRs from mines. As noted in an NPPTL NIOSH Respirator User Notice, this schedule was developed in collaboration with MSHA, and the User Notice summarizes and cites findings from the NIOSH report, *Loss of Start-Up Oxygen in CSE SR-100 Self-Contained Self-Rescuers* [NIOSH 2012b].

Next-generation Escape Respirators

Since 2015, NIOSH has conducted BAS intramural research to develop the next-generation escape respirator to meet the requirements of 42 CFR 84 Subpart O, “Closed-Circuit Escape Respirators.” Through the BAS Partnership described earlier on p. 37, NIOSH collaborated with stakeholders to define and develop needed critical escape respirator components. NIOSH-funded contract research has focused on developing the new components and their engineering configurations for integration into existing and future SCSRs [Fernando 2016; Murray 2017; Moore 2018], as follows.

- Docking and switch-over valves (DSOVs) to transition between escape devices without doffing to extend breathing air capacity.
- Oxygen delivery system enhancement using very high-pressure cylinders (VHPCs) and small-sized pressure managing components that extend breathing air capacity.
- Novel chemicals and shapes for carbon dioxide absorption, oxygen generation, and carbon monoxide conversion, and impregnated breathing bags for carbon dioxide absorption.
- Configurations to enhance wearability through component distribution.
- Cryogenics for open- and closed-circuit breathing apparatus and refill stations.
- Hybrid filtering and open-circuit devices that use oxygen concentrations in the mine environment.
- Facepieces with enhanced verbal communications (Figure 28), which facilitate donning without the removal of a helmet.

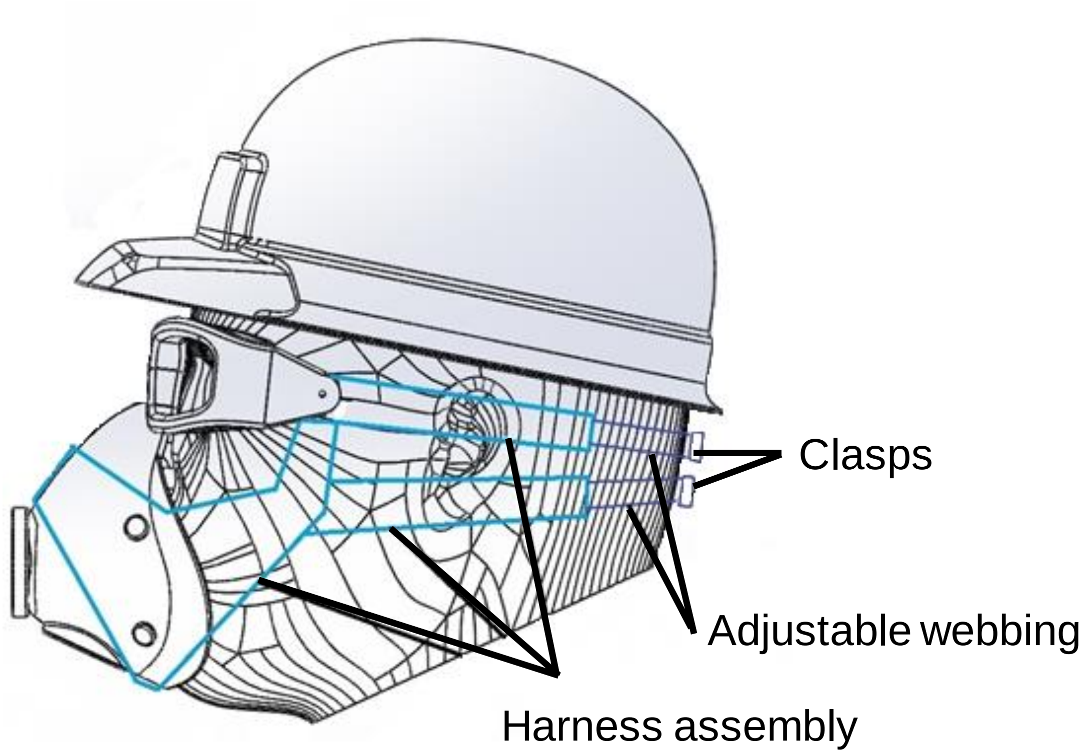


Figure 28. Conceptual drawing of quick-donning facepiece with an integrated speech diaphragm. The facepiece is made up of detachable goggles, an oral nasal cup, a speech diaphragm, and internal bite bit. The components are integrated with a harness assembly and straps that facilitate donning without the removal of a helmet.

Although the BAS project and contract research during the review period resulted in concept designs and prototypes that have not yet reached commercialization, NIOSH researchers at National Personal Protective Technology Laboratory are continuing to work with partners to ensure that the best BAS technologies are available to the mining industry.

A NIOSH contract to develop technology that could reduce the size of escape respirators for the mining environment led Carleton Inc. to create two 10,000 psi oxygen cylinders. These newly designed VHPCs included technical specifications for the cylinders, enabled manufacturers to reduce the overall size and weight of future SCSR units by incorporating these cylinders in their designs. Using the cylinders singularly or in combination allowed for different oxygen capacities and therefore different operational durations for future SCSR designs. Two cylinder sizes are available for manufacturers to use in their respirator designs.

Intermediate Outcome:

- The VHPC 10,000 psi oxygen cylinders developed under a NIOSH contract were approved by the Department of Transportation (DOT) under Special Permit (SP) 20579 [DOT 2018]. This is the first time that the DOT has approved a carbon composite cylinder with an aluminum liner for oxygen service in excess of 3,280 psi.

Emergency Response Training and Technologies

NIOSH's emergency response research focuses on developing practical and testable mine rescue and escape training tools and technologies to be used both by miners and response teams to prepare for an emergency. As described below, these technologies have been developed through the following efforts.

- Intramural work when NIOSH was best equipped to undertake targeted long-term research.
- Use of NIOSH's state-of-the-art training facilities on the Pittsburgh campus.
- Contracts with external subject matter experts.
- Contracts with manufacturers who could produce prototypes to support mine rescue.

Training for Emergency Preparedness and Response

Since 2008, NIOSH has developed and disseminated 14 new emergency preparedness and response training products in the form of written guidance documents, VR training software, or both. A number of NIOSH-developed products have generated notable interest among stakeholders, as described below.

- Lifeline Tactile Signal Flashcards [NIOSH 2011a] are available for easy reference and practice during annual refresher trainings, pre-shift meetings, and toolbox talks to reinforce knowledge of both visual and tactile dimensions of critical lifeline indicators. These flashcards are printable and facilitate a simple way for trainers to help miners recognize lifeline tactile signals.
- The RI *Nonverbal Communication for Mine Emergencies* [NIOSH 2011b] (Figure 29) was developed as an alternative form of communication for times when verbal communication is difficult or impossible due to SCSR use. This training program teaches miners a series of nonverbal hand signals to use in the event of an emergency. These hand signals can be used by miners if they have donned an SCSR and are unable to communicate verbally. The training program includes a Microsoft PowerPoint instructional presentation, several partner/group training activities, and a Microsoft PowerPoint retention test.

RI 9688

REPORT OF INVESTIGATIONS/2012

NONVERBAL COMMUNICATION

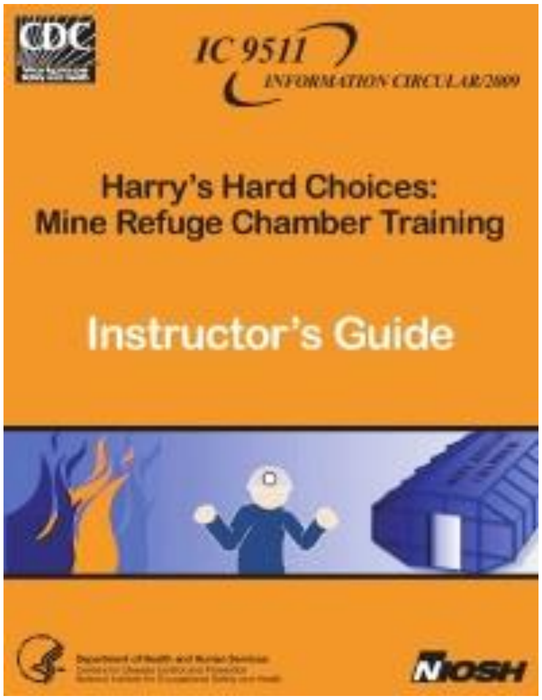
FOR MINE EMERGENCIES

CDC

NIOSH

Figure 29. NIOSH RI training tool teaching miners a series of nonverbal hand signals to use in the event of an emergency when an alternative form of communication when verbal communication is difficult or impossible.

- The IC *Harry's Hard Choices: Mine Refuge Chamber Training* [NIOSH 2009b] (Figure 30) is a paper and pencil simulation designed to help new miners, experienced miners, trainers, and others to prepare for the stressors associated with issues of self-escape and decision-making. In 2015, as part of an Office of Extramural Programs grant (see Overview chapter, p. 14) to the University of Arizona (UA) and the associated Lowell Institute for Mineral Resources developed and evaluated the interactive learning game, “Harry’s Hard Choices,” based on this IC. UA investigators trained 338 mine workers using this serious game [NIOSH 2018].



IC 9511

INFORMATION CIRCULAR/2009

Harry's Hard Choices:
Mine Refuge Chamber Training

Instructor's Guide

NIOSH

Figure 30. NIOSH IC presenting a scenario in which Harry Hamilton, a foreman on a longwall setup section, must decide what to do when he learns there is a fire in his mine. The story is based on real-life incidents.

Underground Coal Mine Map Reading training is one of the early VR-based training products developed during this review period. Released in 2009, this desktop application includes various components designed to train and teach map reading basics and provide opportunities to practice map reading skills while navigating through a simulated mine environment. Also produced in 2009, the NIOSH training video, Escape from Farmington No. 9: An Oral History, recounts the experiences of two survivors of the 1968 Farmington No. 9 coal mine disaster. The target audience for this video is all underground mine workers, regardless of commodity, and is intended to help safety instructors better prepare miners for mine emergencies by offering valuable insights from the perspective of surviving mine workers themselves. Using excerpts from these interviews, NIOSH also developed a companion training module and instructor's guide [NIOSH 2009a] (Figure 31) to educate both inexperienced and veteran miners on important issues related to self-rescue and escape procedures.

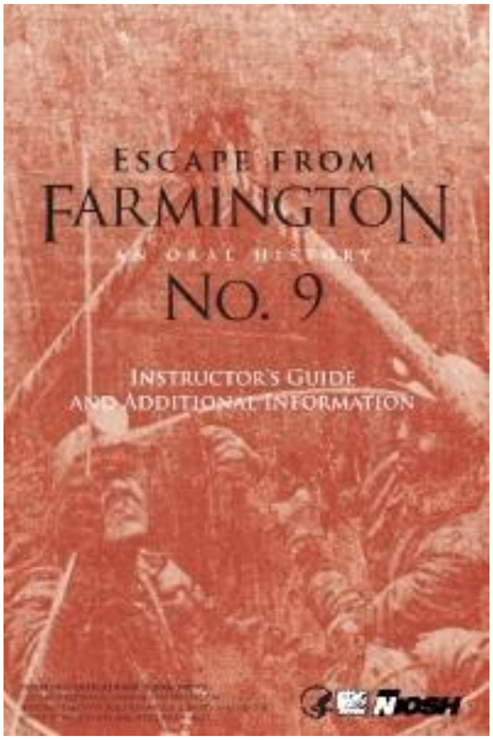


Figure 31. A NIOSH-developed training module to help safety instructors better prepare miners for situations they could encounter should they have to escape an underground mine following an explosion or fire.

Intermediate Outcomes:

- The “Harry’s Hard Choices Interactive” serious game is featured on the Western Mining Safety and Health Training Resource Center website. As of March 2017, this serious game was licensed through TechLaunch Arizona (Invention Disclosure UA14-160) for commercial distribution with a startup company, Desert Saber, LLC.
- In 2016, UA and the Lowell Institute for Mineral Resources utilized *Nonverbal Communication for Mine Emergencies* and *Harry's Hard Choices: Mine Refuge Chamber Training*, for a workshop at MSHA’s 12th Annual Mine Safety & Health Conference in Las Vegas, NV [Granillo et al. 2016].
- The IC *Harry's Hard Choices: Mine Refuge Chamber Training* was downloaded 88 times from the NIOSH Mining website between January 2016 and December 2018 [NIOSH Web Statistics 2018].
- The RI *Nonverbal Communication for Mine Emergencies* was downloaded 54 times from the NIOSH Mining website between January 2016 and December 2018 [NIOSH Web Statistics 2018].
- NIOSH’s Lifeline Tactile Signal Flashcards were downloaded 125 times from the NIOSH Mining website between June 2015 and October 2018 [NIOSH Web Statistics 2018].
- The desktop application Underground Coal Mine Map Reading Training was downloaded over 1,500 times between 2011 and 2016.
- Initial distribution of the Escape from Farmington No. 9: An Oral History DVD numbered 2,000 copies. Since its publication on YouTube in 2015, the video has recorded over 13,000 views.

BG 4 Benching Trainer

The BG 4 benching trainer is the most popular closed-circuit breathing apparatus (CCBA) with mine rescue teams. The process of "benching"—visually inspecting, assembling, and testing the apparatus—is critical to ensuring its proper function in the immediately dangerous to life or health (IDHL) atmosphere that can be present in a mine in an emergency. The BG 4 breathing apparatus and other CCBAs provide emergency responders with respiratory protection during entry into hazardous IDLH environments. Like other CCBAs, once donned by the wearer, the BG 4 operates by removing carbon dioxide, recycling unused oxygen, and supplying the wearer with a fresh oxygen supply from a cylinder. Knowledge of critical benching skills related to the BG 4 helps users to maintain the integrity of the breathing apparatus and helps keep mine rescue team members safe during mine emergencies.

The BG 4 Benching Trainer software was developed by NIOSH researchers as a "proof of concept" to demonstrate the practical utility of mentally practicing between formal training sessions. Although not a substitute for hands-on training, this type of training can serve as a training supplement and is particularly useful when hands-on training is difficult, dangerous, or costly. The cost of CCBAs can be prohibitive to underground mine operators with limited resources. Therefore, giving trainers and rescue team members access for hands-on practice allows mine rescue benchmen and other team members to visually inspect, assemble, and test a BG 4 breathing apparatus in a virtual environment [Bauerle et al. 2016a]. Benching is necessary to ensure that CCBAs are in good working order for mine rescue teams and is required "at intervals not exceeding 30 days" (CFR 49.6b1). The BG 4 Benching Trainer software was developed for benchmen and other mine rescue team members to mentally practice benching the apparatus during or between regular training sessions. It can be used by mine rescue instructors to introduce new team members to the apparatus, and to provide targeted training to team members who may have difficulty with one or more segments of the BG 4 benching process.

Prior to the release of the BG 4 Benching Trainer software, 30 mine rescue team members were trained on its use on-site at the NIOSH Pittsburgh VISLab as part of an evaluation of the effectiveness of VR training interventions [Bauerle et al. 2016] (Figure 32). According to recent CDC Internet download activity reports, the BG 4 Benching Trainer has been among the most popular NIOSH Mining Program outputs since its release in 2015.

Photo by NIOSH

Figure 32. NIOSH researcher demonstrating the BG 4 Benching Trainer software.

Intermediate Outcomes:

- The manufacturer of the BG 4 apparatus (Dräger, Inc.) linked the BG 4 Benching Trainer to its website in the "Application Tools" section.
- In addition to the distribution of 900 BG 4 Benching Trainer CDs, its webpage has been viewed more than 3,500 times and supplemental materials have been downloaded over 1,300 times. The software package has been downloaded 616 times, placing it among the five most frequently downloaded files across the program since its release in June of 2015 [NIOSH Web Statistics 2018].

Mine Emergency Escape Training (MEET)

As a way to study underground mine emergency escape behavior, user interaction, and to provide an optional supplement to required quarterly escape training, NIOSH researchers developed the Mine Emergency Escape Training (MEET) software. MEET uses a virtual immersive environment to create a first-person underground coal mine escape experience focusing on knowledge of escape procedures and requiring judgment and decision-making skills (Figure 33). By invitation, NIOSH researchers provided technical support on the use of MEET to supplement Annual Fire School (AFS) training for over 700 miners in 2014 and roughly 1,500 miners in 2015 [Connor et al. 2016; Bauerle et al. 2016b]. NIOSH researchers visited annual safety trainings to collect a sample of MEET reaction survey data from 64 mine workers in 2014 as part of their annual Fire School training. In 2015, researchers returned to collect a sample of observational data from 500 mine workers engaged in the training [Connor et al. 2016] and examined 922 “avatar escape paths” from system-generated data related to wayfinding and performance [Bauerle et al. 2016b]. Based on feedback from this fieldwork, NIOSH researchers refined the application and supporting documents for release to the public in 2016.

Figure 33. Screenshot from NIOSH-developed MEET software, which uses a virtual immersive environment to create a first-person underground coal mine escape experience and provide training in judgment and decision-making.

Intermediate Outcomes:

- The non-profit Northern Appalachian Coal Mining Heritage Association uses the NIOSH Map Reading Basics and MEET software as part of an interactive exhibit in its museum in Fairmont, West Virginia. Museum visitors can use the Map Reading Basics software to maneuver through a virtual mine. The museum receives several thousand visitors a year [Orr 2019].

- MEET has been downloaded from the NIOSH Science Blog 215 times since May 12, 2016, and has generated modest interest (a dozen comments) from the training and software developer community.

Mine Rescue Team Training and Self-escape Training

A NIOSH intramural research project initiated in 2014 on optimal use of virtual reality technologies was developed for and conducted primarily in the VISLab theater. As part of this project, 70 mine rescue team members from 10 teams with a wide range of experience visited the VISLab to voluntarily participate in a VR mine rescue training exercise similar to that used in required annual mine rescue contests. The 10 mine rescue teams represented underground coal (6) and limestone (1), MSHA (1), and university programs (2). Among these teams, one performed under full apparatus, one used hardwire, and one conducted simulated team checks. All used wireless communication. Participation in the exercise was shown to increase the sense of efficacy among teams [Hoebbel et al. 2015, 2016], thereby reinforcing the value of participation in activities such as these. Importantly, team efficacy has been shown to be positively predictive of training performance outcomes [e.g., Ford et al. 1998, Kozlowski et al. 2001].

For all three training exercises outlined above (BG 4, MEET, and mine rescue team), NIOSH researchers administered pre- and post-training surveys—immediately following the training in the VISLab theater in the case of BG 4 and mine rescue, and through field visits in the case of MEET. Survey respondents reported increases in KSAs, motivation, and confidence, as evidenced in Table 2. MEET, BG 4, and mine rescue team training survey respondents reported increases in KSAs, motivation, and confidence [Bauerle et al. 2016a; Bauerle et al. 2016b]. The 10 mine rescue teams participating in immersive VISLab mine rescue team training reported a greater sense of team efficacy as a result of their participation in the exercise [Hoebbel et al. 2015; Hoebbel et al. 2016].

Table 2. Percentage of respondents who agreed or strongly agreed with each statement, based on NIOSH survey responses to BG 4 (30 participants), MEET (64 participants), and mine rescue team training (70 participants)

This exercise . . .	BG 4 (N = 30)	MEET (N = 64)	Mine Rescue (N = 70)
Included content relevant to (this task)	97	97	100
I would recommend this training to anyone who has a genuine interest in (this task)	93	96	99
Covered knowledge and skills needed during a real mine emergency	90	96	99
Reinforced knowledge and skills I learned during previous training	87	93	99
This simulation is a good supplement to existing training	93	97	97
Motivated me to be generally more prepared for mine emergencies	90	93	95
Helped me learn something that could be helpful during a real mine emergency	90	91	95
Made me more confident that I could correctly respond to a real mine emergency	83	91	95
Motivated me to learn more about (this task)	93	90	92
I would recommend this training to other miners who I work with	63	97	91
Helped prepare me to handle a real mine emergency	67	84	91
Gave me new ways to think about (this task)	90	91	86
Helped prepare me for a competition or drill	70	96	80

Past NIOSH research has helped trainers and mine personnel to be prepared for self-escape. An intramural research project on improvements to mine escape training ensured that suitable information existed for properly training underground coal miners on the appropriate procedures for escape from dangerous situations such as fires, explosions, and inundations. This project assessed how miners could be taught to communicate without removing their SCSR mouthpiece, what they needed to know to use wireless mine emergency communication systems effectively, the types of guidance they needed to comply with new regulations requiring quarterly emergency evacuation training, and methods that could be used to evaluate their escape competencies.

Further guiding NIOSH research priorities, almost seven years after the passing of the MINER Act, in 2013, the NAS report *Improving Self-Escape from Underground Coal Mines* [NRC 2013] identified a compelling set of recommendations for NIOSH and others who are committed to improving the effectiveness of self-escape from underground coal mines. In relation to self-escape competency training, the authors of this report concluded that, “Regulations relevant to training for self-escape appear to emphasize training duration and frequency rather than training to mastery. To ensure that miners can function effectively in an emergency, a train-to-mastery system with competency standards is needed, not time in class" [NRC 2013].

In response to the report recommendations, in 2014, NIOSH initiated a research project on self-escape from underground coal mines to characterize the essential components of the mine emergency escape system and develop recommendations to improve system preparedness and self-escape training of underground coal mining personnel. This ongoing project has identified and prioritized critical self-escape KSAs to improve understanding of the components of the mine emergency escape system; explored current levels of miner competence in the critical KSAs; identified gaps in currently available methods to train and assess those KSAs, and developed strategies to fill the identified gaps. Based on this research, NIOSH has provided evidence-based self-escape competency training and assessment guidelines to the mining industry. NIOSH also funded a contract with the Group for Organizational Effectiveness to perform a hierarchical and cognitive task analysis and to conduct thorough reviews of current decision science and best practices in emergency response training and assessment. Reports generated from this contract were used by NIOSH researchers to develop recommendations for the training and assessment of core self-escape competencies.

Based on the contract findings, NAS report recommendations, and the findings from the above intramural projects, NIOSH researchers developed a mine worker self-report survey that was used to characterize gaps in mine worker competence in 28 critical self-escape tasks. In relation to gap identification, NIOSH has provided mine-specific unpublished and confidential feedback reports to eight different mining operations for their use in targeting emergency response training activities. The aggregate sample data (N = 895) reveal surprising deficiencies in mine worker confidence as it relates to self-escape KSAs [Hoebbel et al. 2018], and a comprehensive data report will be disseminated to the industry along with guidelines in the form of a NIOSH numbered publication, planned for completion in 2019.

Finally, in 2016, NIOSH hosted a Self-escape and Rescue Webinar to highlight self-escape and mine rescue accomplishments and outline the Program's future directions in this area of study. A diverse group of 45 stakeholders representing multiple commodities from 13 states and three other countries participated in this webinar.

Intermediate Outcome:

- Based on mine-specific feedback reports provided by NIOSH on mine worker competence in 28 critical self-escape tasks that revealed gaps in the company's self-escape KSAs, CONSOL Energy revised its Annual Refresher Training (ART) and AFS training curricula for roughly 1,500 miners across three mining operations. Revisions included the addition of assessment and remediation activities, increased hands-on fire-fighting and SCSR training, and incorporation of additional map reading and lifeline symbol training to address specific deficiencies in critical self-escape KSAs [Ryan et al. 2018].

Mine Rescue Technologies for Self-escape

The MINER Act requires that a mine's ERP "be technologically feasible, make use of current commercially available technology, and account for the specific physical characteristics of the mine." One challenge for gassy mines, such as coal mines, is the application of technology for use by rescue teams in support of rescue operations. Any equipment used inby (the area between the last open crosscut and the active face) or in the return airways must be certified as permissible by MSHA, which often requires a custom design. Therefore, NIOSH has taken the approach of evaluating technologies used in other industries that may be able to be applied to mine rescue operations. Specifically, technologies in the areas of robotics and high-speed drilling have been the focus of contract research. This approach has proven to be valuable in helping NIOSH to meet the MINER Act mandate "to enhance the development of new mine safety technology and technological applications and to expedite the commercial availability and implementation of such technology in mining environments."

These technologies were developed and tested through several contracts as described below.

- Based on specifications provided by NIOSH, Raytheon Sarcos modified its tandem-track snake robot to make it suitable for operations in underground mines. The performance of the prototype was evaluated in Pittsburgh's EM, and successfully passed navigation testing by being operated by remote control and navigating obstacle courses designed to simulate post-event debris (Figure 34, left).
- As part of an interagency agreement with NIOSH, Sandia Laboratories developed prototypes of three specialized track-mounted robots to be used as scouts to explore mine workings (Figure 34, right), providing training and technical support on their operation to NIOSH Mining researchers and MSHA's Mine Emergency Operations Branch.
- In the two successful rescues at the Quecreek Mine (Somerset, PA) in July, 2002, and the San José Mine (Copiapó, Chile) in October, 2010, mine workers were reached by way of rescuers drilling a large-diameter borehole from the surface to the area where they were trapped. Based on these successes, NIOSH contracted with a Pennsylvania-based drilling company to develop a process and the equipment necessary for a rapid response drilling system for future mine rescue operations (unnumbered figure, p. 25).

Photos by NIOSH

Figure 34. Prototypes of snake robot (left) and scout robot (right) being tested for use in underground mines.

In conjunction with NIOSH, MSHA has formally trained its Mine Emergency Operations (MEO) staff on the use of these robots and has access to them if needed in the event of an emergency. These robots will help reduce the risk to rescue teams during underground mine exploration involved with locating trapped miners [TribLive 2018].

In order to lessen the physical demand on mine rescue professionals, support their mission, and increase their safety as they help miners with self-escape, NIOSH funded a contract with ROHMAC, which manufactures mine-duty utility equipment and attachments, including equipment that can be operated via remote control, under extreme conditions, and in confined spaces. The self-escape support vehicle resulting from this contract (Figure 35) was designed based on input from mine rescue teams and was successfully demonstrated in several mine rescue training exercises.

Photo by NIOSH

Figure 35. Testing of the mine rescue support vehicle prototype at the Academy for Mine Training and Energy Technologies near Morgantown, WV.

As a result of the NIOSH-awarded contract with ROHMAC, a prototype mine rescue vehicle was successfully tested at NIOSH's Pittsburgh campus, the National Mine Health and Safety Academy near Beckley, WV, the West Virginia University (WVU) Academy for Mine Training and Energy Technologies (Doll's Run) near Morgantown, WV, and at an underground coal mine in the Illinois basin as part of a mine rescue training exercise. The vehicle is currently undergoing modifications to make it permissible for use in underground coal mines prior to being transferred to MSHA's Mine Emergency Operations Branch [Patts et al. 2018].

Intermediate Outcome:

- In 2014, NIOSH transferred the specialized rapid response drilling equipment to the MSHA National Mine Health and Safety Academy in Beckley, WV. The equipment transferred was a 12-inch-diameter bit for drilling an initial pilot hole, a 28-inch-diameter bit able to drill a hole large enough for a rescue capsule, and 200 feet of can-rods necessary for drilling such a large hole through the earth. When a rescue borehole is needed, the equipment can be deployed by MSHA immediately after an accident is reported [NIOSH 2014c].

Awards Related to Disaster Response Research

During the review period, the following honors were awarded to NIOSH researchers demonstrating the quality and significance of NIOSH research in the area of disaster prevention and response.

2012—Alice Hamilton Award, for excellence in occupational safety and health, for leadership through science by publishing in education and guidance, for the NIOSH Report of Investigation 9682: *When Do You Take Refuge? Decisionmaking During Mine Emergency Escape*."
(C Kosmoski, K Margolis, K McNelis, M Brnich, Jr., L Mallett, P Lenart)

2015—Interservice/Industry Training Simulation, and Education Conference, for best paper, honorable mention, for "Assessing the Effects of Virtual Emergency Training on Mine Rescue Team Dynamics." (C Hoebbel, T Bauerle, L Mallett, B Macdonald)

2016—CDC Honor Awards, nominee for Plain Writing award, for "Assessing the Effects of Virtual Emergency Training on Mine Rescue Team Dynamics." (C Hoebbel, T Bauerle, L Mallett, B Macdonald)

2016–Alice Hamilton Award, for excellence in occupational safety and health, and by contributing leadership through science by publishing in education and guidance, for the "BG4 Benching Trainer." (J Navoyski, M MacDonald, W Helfrich, L Mallet, M Brnich, P Roth)

2018—The Bullard-Sherwood R2P Award, for transferring knowledge into effective prevention practices and products, and fostering their adoption in workplaces, for the advancement of refuge alternatives for underground coal mines research. (D Yantek, J Srednicki, L Yan, T Lutz, B Whisner, M Reyes, J Bickson, N Damiano, J Yonkey, P McElhinney)

2018—The Keogh Award for Outstanding Service in Occupational Safety and Health field, for contributions related to mine communication and the advancement of refuge alternatives for underground coal mines, and for crafting a strategic plan to ensure that research conducted within the Mining Program is relevant, impactful, timely, and scientifically sound. (P Kovalchik)

End Outcomes

While the last major coal mine explosion occurred in 2010 at the Upper Big Branch mine, the number of reportable fires has also dropped. Reportable fires in non-coal operations showed a decreasing trend from 2008 to 2017, with a high of 16 in 2010 and a low of two in 2012 [MSHA 2018a]. The number of yearly face ignitions showed a decreasing trend from 2008 to 2017, with a high of 51 in 2008 and a low of 10 in 2014 [MSHA 2018a] (Figure 36).

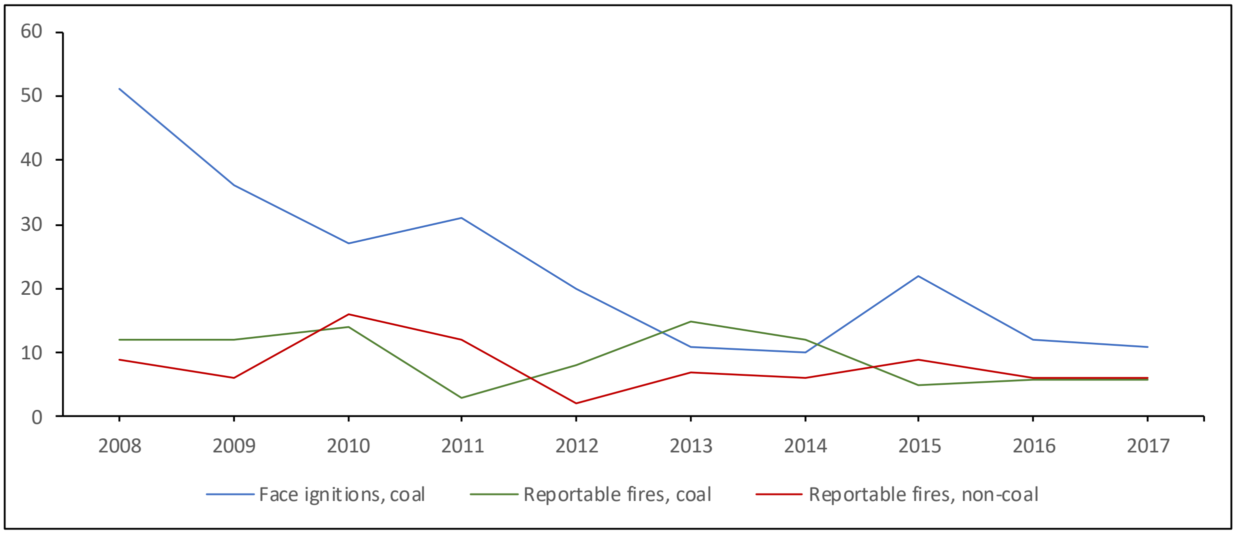


Figure 36. Trends in face ignitions for coal operations, reportable fires for coal operations, and reportable fires for non-coal operations for 2008–2017.

Although these decreases cannot be specifically or solely attributed to NIOSH research, it is likely that NIOSH efforts, as evidenced by the intermediate outcomes described in this chapter, have contributed to this decrease.

Alternative Explanations

Alpha Foundation

The Alpha Foundation for the Improvement of Mine Safety and Health seeks participation from outstanding researchers and organizations to propose and carry out research that explores innovative ideas and concepts, complement existing research efforts, and address knowledge gaps in mine safety and health research. In the area of Mine Escape, Rescue and Training, the Foundation focuses on the following research priorities:

- *Communications and Tracking*: Providing the capability to know where all miners are at all times and to be able to communicate with them during any emergency.
- *Training and Decision-making*: Ensuring that miners are properly trained to recognize the onset of emergency situations and to manage decision-making to facilitate effective escape.
- *Sheltering and Escape Strategies*: Developing escape strategies and technologies to aid in escape, including systems that provide for sheltering when escape is not immediately attainable.
- *Rescue Strategies and Technologies*: Developing procedures and technologies to assist in managing incident command and rescue operations during and following a mine emergency.

The Foundation has funded six grants to five different organizations as of June 2018 related to Communications and Tracking (three awards), Training and Decision-making (one award), Sheltering and Escape Strategies (one award), and Rescue Strategies and Technologies (one award). In addition, the Foundation has sought out NIOSH subject matter experts to assess the validity and merit of research proposals submitted through its process. Furthermore, the Foundation confers with NIOSH to establish alignment between the two research portfolios.

Mine Safety and Health Administration

Since 2008, MSHA has been proactive in supporting improvement for training and regulation. MSHA provided $7.8 million in grants through the Brookwood-Sago Mine Safety Grants program. This competitive grant program funds education and training programs to better identify, avoid, and prevent unsafe working conditions in and around mines. MSHA also provided more than $10 million in grants annually to states through the State Grants Program, with grants made to the state agency program responsible for miners' health and safety, and with most funds used to support health and safety training courses and programs designed to reduce mining accidents, injuries, and illnesses. In addition, MSHA has revised and updated instruction classes at the MSHA Academy to align with the latest research and findings to improve training. MSHA also takes advantage of knowledge and products provided by NIOSH grant recipients under the Miner Safety and Health Training Program–Western United States. These grant recipients have developed training programs and provided training in the Western U.S. in a role similar to that of MSHA's National Mine Health and Safety Academy in Beckley, WV. Finally, MSHA has had a regulatory focus in all areas cited in this chapter, especially combustibles.

Additional alternative explanations include the fact that there has been a reduction in number of underground mines since 2008, specifically in the coal sector, where numbers fell from a high of over 665 underground operations in 2008 to 306 in 2017, with the numbers reflecting those mines reporting employment [MSHA 2018a]. Coupled with this decrease is a general reduction in the number of MSHA inspections of underground coal operations from over 9,375 in 2008 to 9,009 in 2017 [MSHA 2018e]. However, MSHA activity in coal mining operations increased from 14.1 to 29.4 inspections per operation over the same time period [MSHA 2018e]—perhaps in part because of the Upper Big Branch mine disaster in West Virginia in 2010—suggesting higher MSHA visibility to limit occurrence of hazardous conditions that could lead to a mine disaster. Similar data exist for stone, sand, and gravel and metal/nonmetal operations, where the number of inspections per operation increased from 2008 to 2017 [MSHA 2018e], indicating increased MSHA enforcement activity.

MSHA also organized special initiatives focusing on key areas of concern in the mining industry. For instance, MSHA's Faster, Safer Mine Rescue with Cutting Edge Technology webpage focused on the availability of technology to help mine rescuers and responders. MSHA also maintains a rock dusting resources page to provide a single location for information on this topic.

Finally, MSHA launched its Rules to Live By initiative in 2010 to focus industry attention on the most commonly cited standards that caused or led to fatal accidents. One aspect of this four-part initiative focused on the prevention of catastrophic accidents from poor mining methods, explosions, mine emergency escape, and inadequate preshift examinations. That same year, MSHA began a monthly impact inspection program targeting operations with a poor history of compliance. In 2013, MSHA revised its Pattern of Violations (POV) regulation to improve focus on mine operators who demonstrated a disregard for the health and safety of miners through a recurring pattern of serious violations at their mines. Operators with a POV notice face increased MSHA inspections and other punitive measures such as a withdrawal of workers from affected areas of the mine until cited violations are corrected.

Future Plans

NIOSH researchers will continue to analyze data, publish findings, work with industry stakeholders, and translate research related to disaster prevention and response into practice. In particular, future research on underground mine monitoring will help to address the industry's major fire safety issues. The development of sensor deployment strategies will help mine operators to install those sensors appropriately to detect a mine fire or a hazardous condition in a timely and effective manner, thus reducing injuries or fatalities from the fire or toxic byproducts. Improved sensor deployment strategies will be performance-based, permitting early detection of fires and heatings in the incipient stages of combustion. Li-ion battery safety research will advance fire-related knowledge in this area, improving responses to fires caused by such batteries. In both BAS and RA research, NIOSH will continue to partner with manufacturers and stakeholders to ensure that the latest research findings are shared, both to help develop prototypes for BAS manufacturers and to ensure habitability of RAs in the event of their deployment. NIOSH will continue to make use of its virtual simulation research for emergency response and preparedness, and will develop interventions related to mine emergency response decision-making that integrate with an organization’s overall risk management system. Finally, additional human systems integration based research on technologies associated with post-disaster response will help to improve mine worker and mine rescue team survival in the event of an emergency.

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Chapter 3: Ground Control


Photo by NIOSH

Introduction

Most underground mines pose unique ground control challenges because their geologic settings are distinct from other mines, even within the same coal basin or mining district. Western metal mines extract ore from many types of deposits, varying from narrow high-grade veins in strong brittle rock to massive areas of low-grade material in weak fractured ground. Coal seam lithology and overburden also vary widely, from thin seams at shallow depths to thick seams under deep cover.

As near surface deposits are depleted, mine operators encounter increasingly complex geologic structures and stresses that accompany mining-induced deformation underground. Therefore, current mining practices must accommodate more challenging conditions in deeper mines. Ground control issues in deep mines have become a primary hazard for underground miners and are among the most difficult problems to address. The most serious problems involve "coal bumps" or "rock bursts" that can collapse underground openings by dynamically dislodging rock and ground support from the walls and back or ribs, creating severe hazards for mine workers.

Underground mining has one of the highest fatal injury rates of any U.S. industry—more than five times the national average for worker fatalities. According to Mine Safety and Health Administration (MSHA) data analyzed by NIOSH, in 2015 there were 657 active underground mining operations in the U.S., employing 43,747 workers [NIOSH 2015b]. MSHA data show that from 2008 to 2017, ground failures were the largest source of underground mine fatalities (Figure 37).

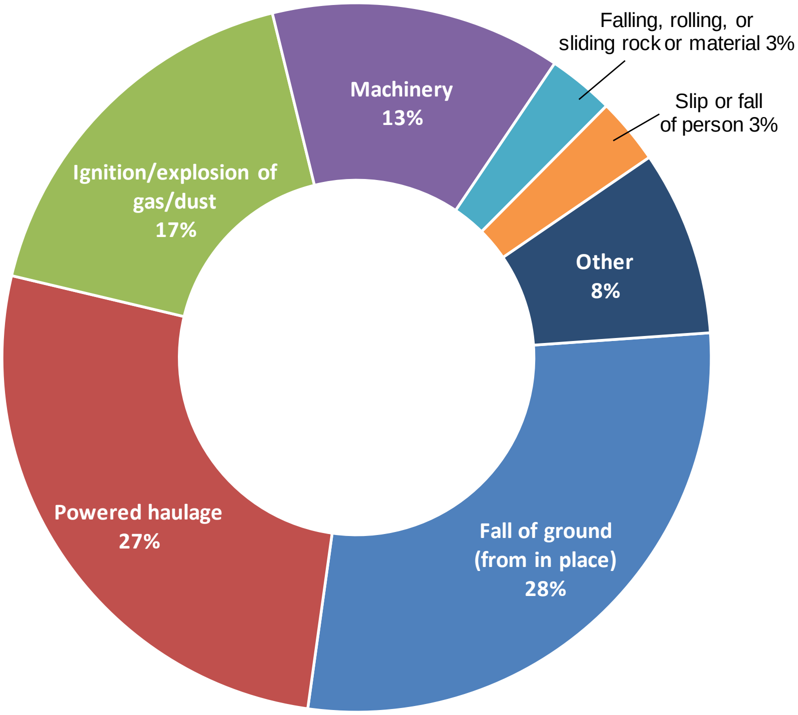


Figure 37. Percentage distribution of occupational underground fatalities by classification, 2008–2017. Excludes office employees. The sum of percentages does not equal 100 due to independent rounding.

For the same period of 2008–2017, Figure 38 shows a breakdown of the causes of ground fall fatalities—roof falls, rib or face collapses, bumps or bursts, and massive collapses—for the underground coal sector.

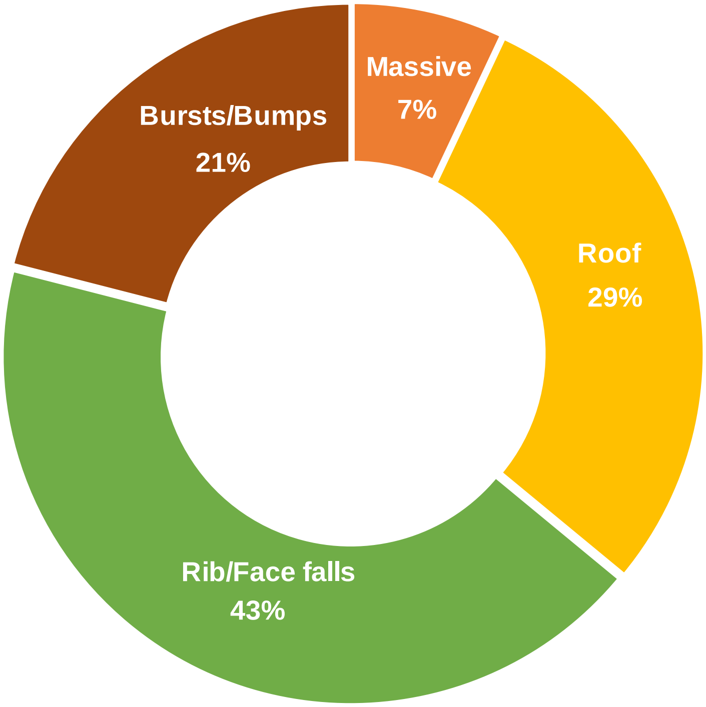


Figure 38. Causes of ground fall fatalities for underground coal, 2008–2017.

To put these fatalities and their causes into context, ground failures most often claim the lives of one or two at a time, but also can result in multiple fatalities. Most recently, in the Crandall Canyon disaster on August 6, 2007 [MSHA 2007], six miners died in a catastrophic coal outburst when pillars failed, violently ejecting coal over a half-mile area. Ten days later, two mine employees and an MSHA inspector were also killed by a second coal outburst during a rescue effort [MSHA 2008].

Nonfatal injuries from ground failures also tend to be severe, resulting in a high percentage of lost-time injuries. In addition to ground failures resulting in injuries, since reporting standards were adjusted in 2012 [MSHA 2012]—which reduced the number of reportable roof falls going forward, with a new definition given to the extent of the "working area"—an average of 366 non-injury, unplanned roof collapses have been reported to MSHA each year. Collectively, these injury and non-injury events represent a significant hazard in underground mines.

Controlling the ground that surrounds a mine excavation is especially complex because mine designers have no control over the variable strength and deformation characteristics of the rock mass, which result in unexpected failures and instabilities. In addition, mining redistributes ground stress in a way that can damage the rock. Unfavorable stress concentrations can also result in dynamic failures with local seismic magnitudes of up to 4.0 on the Richter scale.

Mining-induced larger seismic events, as in the Crandall Canyon coal mine disaster, can cause underground excavations to collapse. In underground metal mines, dynamic failures have resulted in two fatalities in the last 20 years, along with numerous injuries, infrastructure damage, and near misses. As one example, a magnitude 2.2 rockburst occurred at the Lucky Friday mine near Mullan, ID, in 2011, which injured six miners and caused major damage to the underground infrastructure [The Spokesman-Review 2011].

NIOSH researchers address these ground control issues through a mix of laboratory and field studies. Lab-based research generates information about rock and support systems in a controlled environment. The extreme loading and deformation imposed on the rock and support systems require unique laboratory facilities where meaningful tests on these systems can be conducted. Studying the response of the rock in the failed state is particularly important because in deep coal and metal mines the rock stress can fracture the surrounding rocks. Further, knowledge of the rock response in a fractured state is necessary to design effective support systems. Unlike in other branches of engineering, material response beyond initial failure is also important in mining. Therefore, lab tests of support systems are conducted well beyond initial yielding, with the focus on large deformations under both static and dynamic loading.

Field-based studies are also critical because it is not possible to create full-scale underground mining conditions in the lab. At mine sites, direct monitoring of rock deformation and support system response may extend over several years, with instrumentation installed to collect essential data as mining advances. Results provide insight into the full-scale mechanics of ground instability and support performance. These data are required for predictive modeling and engineering-based design. Further, collecting field data on the past performance of support systems and ground control strategies allows researchers to develop empirically based ground control solutions.

Because of the regular contact with operating mines through field studies, NIOSH ground control researchers are highly familiar with the safety issues faced by miners. This close collaboration ensures development of appropriate research goals and practical solutions, facilitates technology transfer, and offers opportunities for technical assistance related to ongoing safety issues. Collaboration with mine operators also allows for effective transfer of research products through presentations, webinars, industry briefings, and shared problem solving.

The ground control research presented in this chapter is organized by coal, metal, and nonmetal commodity types. This is necessary because, while the underlying science is similar, ground control solutions are very different given the unique nature of the geologic environments and the specialized mining methods encountered in each commodity type.

Logic Model

The logic model (Figure 39) illustrates the characteristics of NIOSH’s research and other activities to reduce ground control-related injuries and fatalities. Elements of the logic model—Inputs, Activities, Outputs, Transfer and Translation, Intermediate Outcomes, and End Outcomes—are described in further detail in the following sections.

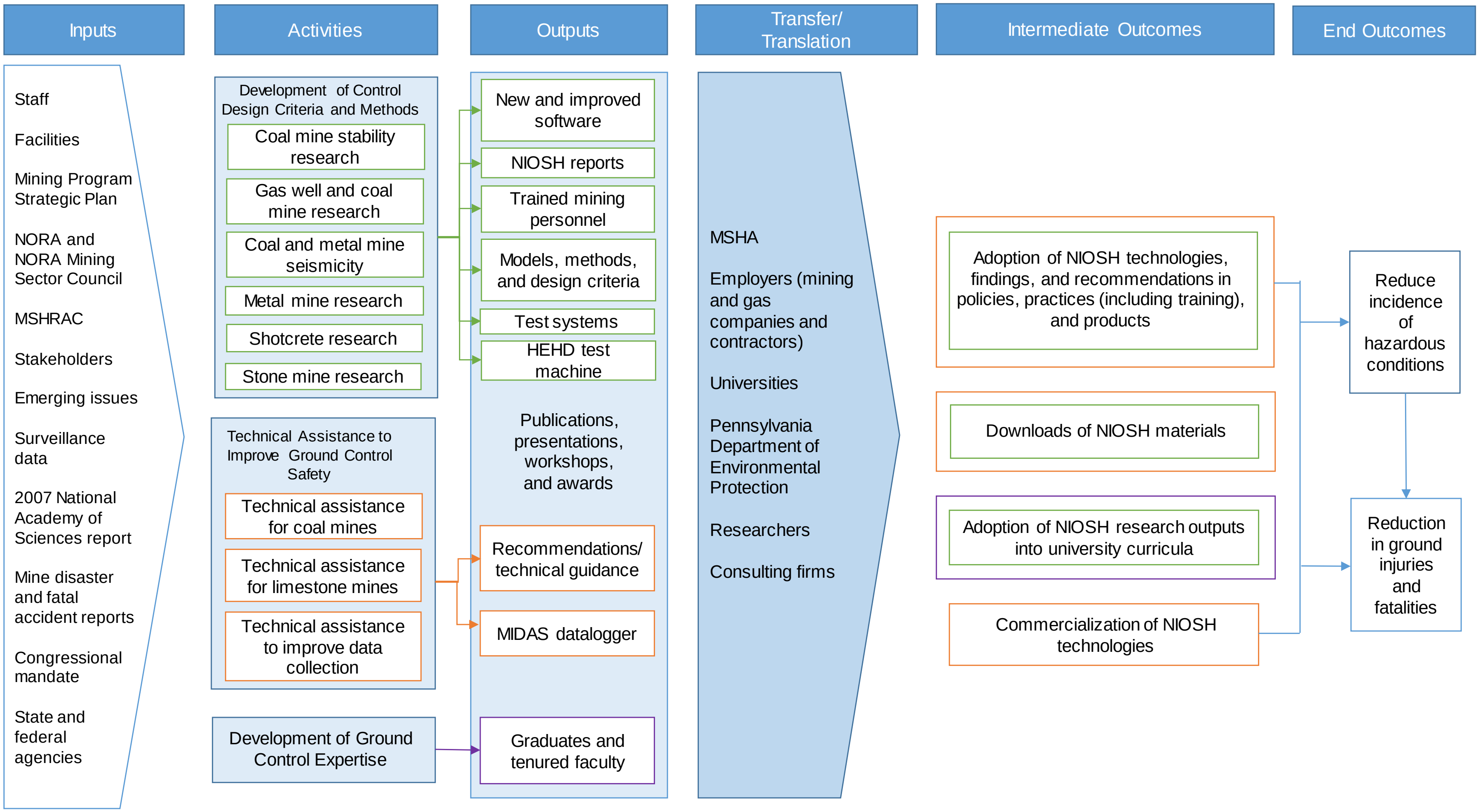


Figure 39. Logic model for ground control.

Inputs

Staff

Reflecting the complex and interdisciplinary nature of ground control research, NIOSH staff have expertise in mining engineering, rock mechanics, seismology, geology, geotechnical engineering, and other engineering disciplines, including electrical, mechanical, chemical, metallurgical, and civil. Staff members represented the Pittsburgh Mining Research Division (PMRD) and the Spokane Mining Research Division (SMRD). In ground control, the level of collaboration between NIOSH personnel and cooperating mines was extensive, as opportunities arose for field studies and technology transfer during the course of a project. During the 2008–2018 review period, the individuals listed in Appendix D were instrumental in advancing NIOSH research in ground control.

Facilities

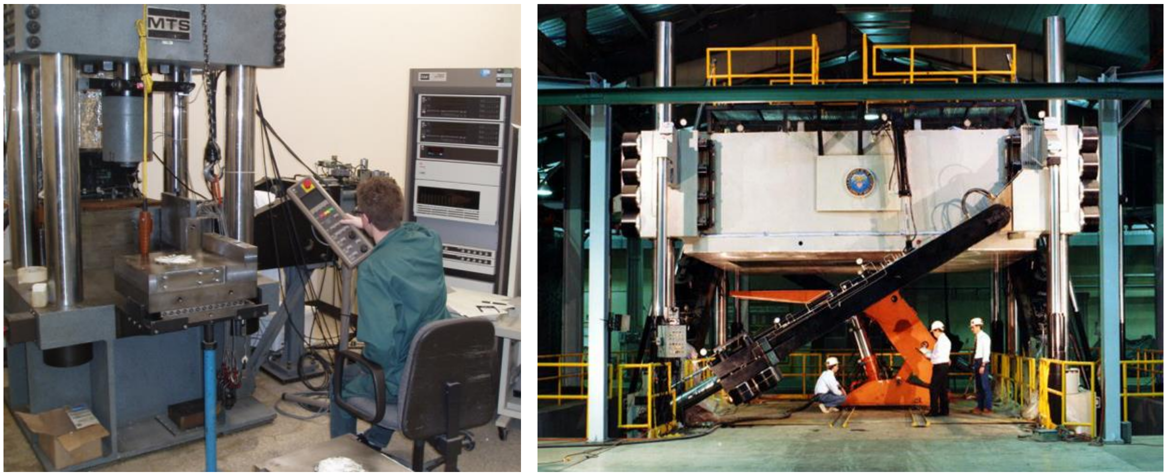
NIOSH Mining Program facilities are located in Pittsburgh, PA, and Spokane, WA, with unique testing systems related to ground control at both campuses, as summarized below.

NIOSH Facilities

Major laboratory equipment and facilities used by ground control researchers are described below.

- *Mine Roof Simulator* (MRS). The MRS is a sophisticated load frame for testing full-scale mine support systems (Figure 40, right). The load frame can apply loads up to 1,500 tons in the vertical (compressive) direction and a horizontal load of 750 tons that can be applied independently or simultaneously. The maximum test area measures 20 feet X 20 feet X 16 feet high. The MRS has been used for decades to develop safe, efficient standing supports.
- *Rock Sample Testing Laboratories*. These labs are used to prepare rock samples for strength and mechanical property testing (Figure 40, left). The labs contain rock sample cutting and grinding equipment as well as a servo-controlled rock testing frame with advanced testing capabilities.
- *Numerical Modeling Workstations*. These high-end workstations can run several large numerical software packages, including Itasca Consulting Group's FLAC3D, UDEC, 3DEC, and PFCSuite; LaModel stress analysis software; and finite element codes RS2 and RS3 from Rocscience.
- *MTS IMPAC 3636 Drop Test Machine*. This free fall shock machine is used to conduct dynamic impact tests with ground support elements.
- *High-Energy High-Displacement* (HEHD) *Frame*. The stiff frame loading structure is used to test large-scale reinforced composite shotcrete panels simulating in-mine support systems (Figure 41).
- *Microseismic/Geophysics Laboratory*. This lab is equipped with hardware and software for conducting lab and field experiments to measure active and passive seismic vibration.

- *Structural Testing Floo*r. This 24-inch-thick, reinforced concrete structure provides a 30-foot by 45-foot by 20-foot high work area with a total reaction load capacity of 12,960,000 pounds of force.



Photos by NIOSH

Figure 40. Rock sample testing in the Spokane laboratory (left). The MRS at the Pittsburgh campus (right).

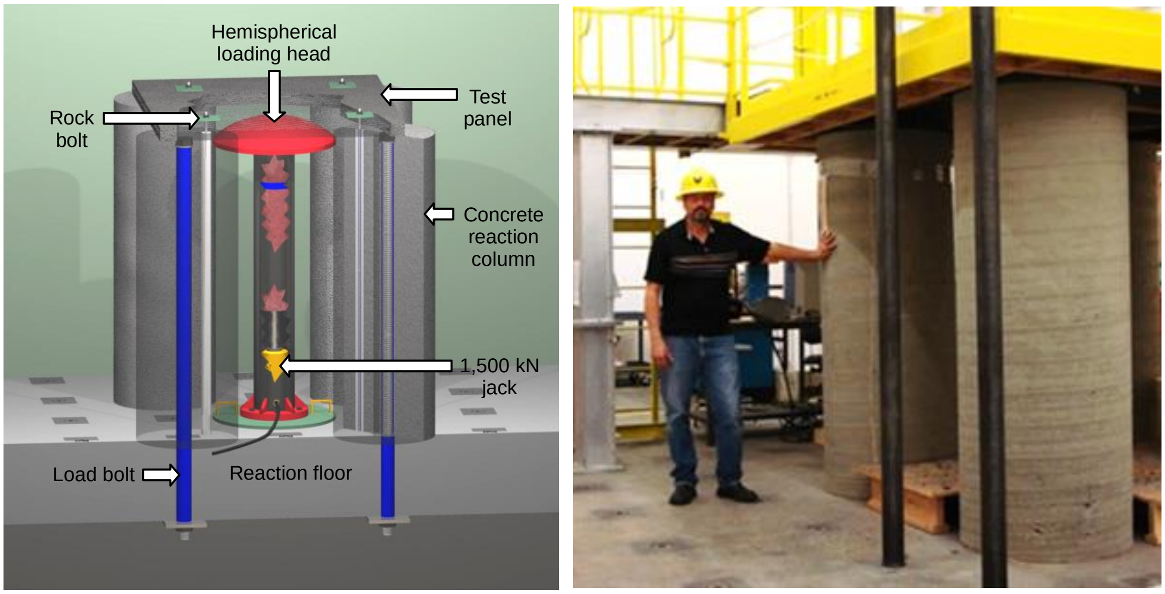


Photo by NIOSH

Figure 41. HEHD test frame schematic (left) and HEHD test frame at the Spokane campus (right).

Mining Program Strategic Plan

All NIOSH Mining Program research efforts align with goals established in the 2010 Strategic Plan reviewed and accepted by MSHRAC, as described in the Overview chapter, pp. 19–20. In the context of ground control, NIOSH research was conducted under the following strategic goals and associated intermediate goals.

Strategic Research Goal 6: Eliminate ground failure fatalities and injuries in the mining industry.

Intermediate Goal 6.1: Develop mine and pillar design strategies to prevent catastrophic roof collapses and pillar failures and excessive stress-related damage that degrades global stability.

Intermediate Goal 6.2: Develop ground support strategies to prevent local instabilities that lead to roof and rib falls.

Intermediate Goal 6.3: Develop surface control of roof and rib structures to prevent injuries from rock falls between supports.

Intermediate Goal 6.4: Reduce injuries associated with the application of ground control technologies through improved ground control practices and support design.

The National Occupational Research Agenda and Mining Sector Council

The National Occupational Research Agenda (NORA), described in the Overview chapter, pp. 20–21, includes eight strategic objectives. From these, this chapter addresses the following objectives and sub-objectives:

- Objective 6: *Improve Mine Design, Systems Operations, and Management Performance to Enhance Mine Health and Safety*
    - 6.6.1: Continue to develop numerical models that exceed the current empirical systems in efficacy
    - 6.6.2: Improve methods for determining the rock mass characteristics that form one of the critical independent datasets for a numerical model
    - 6.6.3: Develop “smart” roof-control drills for continuous detection of roof stability data
    - 6.6.4: Develop methods for rib reinforcement and reliable rib-roll warning devices
    - 6.6.5: Conduct investigations to discover relevant predictive seismic signals
    - 6.6.6: Search for rib-control technologies that reduce the incidence and impact of bumps and bursts
    - 6.6.7: Improve seismic monitoring systems for mine safety and to guide mine design
    - 6.6.8: Develop easy-to-use surface-mine drilling systems that include automated guidance to drill parallel holes in a single plane

Mine Safety and Health Research Advisory Committee

The Mine Safety and Health Research Advisory Committee (MSHRAC) advises NIOSH on the intramural mine health and safety research portfolio and extramural grants and contracts. During the review period, MSHRAC made recommendations on seven major ground control projects as part of annual meetings with NIOSH researchers. During the 2008 annual meeting, researchers gave three presentations on ground control topics, including one detailing a planned study of ground fall hazards involving room-and-pillar coal mining. This study was particularly important because NIOSH was responding to a Congressional mandate for research into safety during deep cover pillar recovery, per the FY 2008 Appropriations Bill (Public Law 110-161). During extensive discussions after the presentation, the committee made recommendations concerning the scope, research methods, and the outputs needed for a successful project that were subsequently incorporated into the research. Progress on this research was presented to the committee at the 2010 MSHRAC meeting to demonstrate how the committee's recommendations were implemented.

Stakeholders

Conferences and meetings held by stakeholders such as the National Mining Association (NMA) and the American Exploration & Mining Association (AEMA) provide forums for feedback from mine operators to ground control researchers. Since mine operators seldom publish papers related to their ground control issues, interactions at these meetings are important for assessing the impact of NIOSH research and for suggesting avenues for further development. Thus, many issues addressed by ground control research are brought to NIOSH directly by mine operators. For example, operators having difficulty with solving stability problems with conventional methods often approach NIOSH for help either to understand the failure mechanism causing an instability or to find a specialized support solution for specific mine conditions. Through research and translational activities, NIOSH also maintains regular contacts with mine operators and engineers that look to NIOSH for ground control expertise. Examples are provided later in this chapter by way of cases and their associated intermediate outcomes.

Emerging Issues

NIOSH ground control staff stay abreast of domestic and international mining practices, pioneering technologies, and the safety and health challenges that come with the introduction of new mining equipment and advanced mining methods specific to ground control. By participating in professional societies, maintaining a familiarity with the published literature, and engaging in fieldwork, NIOSH researchers anticipate trends that can influence health and safety. In addition, close collaboration with foreign mining research organizations alerts researchers to emerging practices and problems related to ground control in mines outside of the U.S. and facilitates the sharing of solutions.

One example of an emerging issue is mining at extended depths. In metal mines, Rio Tinto's Resolution copper mine in Southeast Arizona, Freeport-McMoRan's Henderson molybdenum mine near Denver, CO, and Hecla's Lucky Friday silver mine in Northern Idaho have extended mining to depths of 7,000 feet, 7,700 feet, and 9,000 feet, respectively. Conditions found at these depths challenge the limits of current ground support practices. In underground limestone mines, depths are also increasing as shallower deposits are mined out. Current procedures for limestone room-and-pillar workings are only applicable up to depths of 1,000 feet [NIOSH 2011d].

Periodically, NIOSH also undertakes formal studies to examine the mine health and safety implications of trends in advanced mining methods and technologies. A recent example is an internal NIOSH report, *Mine of the Future: Disruptive Technologies that Impact our Future Mine Worker Health & Safety Research Focus*, which examined the introduction of smart mine technologies that promise to someday achieve completely autonomous mining [Sammarco et al. 2018]. The emergence of the technologies associated with automation and robotics will require new smart sensors and the interconnectivity of devices and data analytics, particularly in the area of situational awareness related to ground control.

Surveillance Data

NIOSH's surveillance and statistics staff gather MSHA data on accidents, injuries, and fatalities and summary statistics; economic analyses; production statistics; and demographics specific to falls of ground. Analyses are performed to identify the sectors, tasks, machinery and equipment, activities, and other factors that are responsible for the greatest risk of injury in order to guide ground control research.

As one example of how these data are used to guide research for the metal/nonmetal (MNM) sector, NIOSH researchers reviewed MSHA data for a five-year period (2007–2011) for a deep vein mine in Northern Idaho, supplemented with investigation reports, interviews, mine records and design information, and underground site visits [Whyatt 2013]. This accident analysis identified the need to develop and implement a method for anticipating the size of mining-induced seismic events; develop design criteria to ensure adequate dynamic support for particular site characteristics; and improve protection of miners by modifying support installation procedures, tools, and components. This led to intermediate outcomes detailed later in this report related to metal mine seismicity, backfill, and shotcrete support for deep metal mines.

Other examples where ground control researchers used surveillance data include:

- A comparison of surface mining versus underground mining fatalities and injuries led to a focus on underground mining. MSHA data show that for all underground mining in the U.S. from 2008 to 2012, the average annual fatality rate and the average non-fatal, lost-time injury rates for those related to falls of ground were higher than the same rates for all of surface mining.
- An analysis of coal mine fatalities/injuries related to mining-induced seismic events revealed the need to conduct research to improve monitoring capabilities and develop dynamic supports.
- An analysis of ground falls that occurred in longwall sections of coal mines from 2008 to 2012 showed that half of the fatalities/injuries were caused by falls of the rib or face.
- In 2005, NIOSH identified an increase in stone mines injury fatality rates. This led to research to develop pillar design criteria for limestone mines.
- MSHA data on injuries and entry blockages resulting from ground falls on longwall gateroads pointed out the need to investigate the support capacity of standing supports.

2007 National Academy of Sciences Report

As noted in the Overview chapter, pp. 12–13, the National Academy of Sciences (NAS) was commissioned to conduct a review of the NIOSH Mining Program in 2005. The NAS recommendations pertaining to ground control research in the committee's follow-up report in 2007 [National Research Council and Institute of Medicine 2007] guided the Program's direction over the ensuing years. Some recommendations encouraged research in ground control-related areas, such as the following:

- Developing a more proactive approach to identifying and controlling hazards.
- Developing more robust methods of monitoring in-situ safety conditions.
- Being prepared to deal with issues associated with increased remote control and automation.
- Evaluating environmental and occupational hazards of deeper mines.

In addition to these major recommendations, the report also suggested the following:

> Because of challenges posed by mining in increasingly severe geologic environments and in closer proximity to existing and abandoned mines, the Mining Program needs to expand its new research to include developing more robust numerical techniques for modeling mine openings in complex geologic materials; better void detection technologies; and strategies to improve design and safety in deep (> 600 m) coal deposits.

When using numerical modeling techniques, in situ conditions need to be modeled more accurately for excavations in discontinuous and heterogeneous materials and further development of the fundamental design methodology with an evaluation of the sensitivity to variability in the input parameters should be considered.

The program should investigate the applicability of current or newly developed technology in detecting voids, especially those containing water, and should consider the benefits of developing routine procedures to improve mining in the vicinity of old mines and at-risk geologic conditions.

For underground mining at great depths, the potential for violent dynamic failure could be reduced by appropriate mine layout and mining sequencing. Research into the relative merits of various mine design scenarios would likely reduce hazards and optimize resource recovery.

Where explosives are used to drive openings for underground metal mines and for some stone mines, research is needed to improve understanding of the fracturing process and to develop better design methods to limit collateral damage. Research is also needed to remove blast-damaged rock through better scaling methods and protection of workers by improved surface treatments.

Mine Disaster and Fatal Accident Reports

Historically, mine disasters such as fires, explosions, inundations, and roof falls have been a driving force behind both enactment of mining laws and regulations and government investment in mining health and safety research. For example, after the Crandall Canyon disaster, MSHA concluded in its Fatal Accident Report that the initial event was caused by a flawed mine design that led to a massive pillar failure. In response, NIOSH initiated research on pillar instability in deep underground coal mines and an initiative to adapt seismic monitoring strategies to monitor deep coal mines.

MSHA Fatal Accident Reports are also examined to determine the root cause of ground fall events. These case studies give insight into specific geologic and other circumstances that led to a ground fall accident that statistical analyses can overlook.

As one example, MSHA accident statistics from Fatal Accident Reports from Jan. 1, 2002, to Oct. 30, 2008, for MNM mines showed that rib falls, falls of roof or back, and sliding rock and material caused 24 fatalities, which represented 13% of the total MNM fatalities for this period. To better understand the related prospective research issues, NIOSH researchers analyzed narratives of all the ground control incidents (n=260) in MNM mines from January 1, 2005, to October 30, 2008. Most of these incidents (97%) occurred in underground mines. Rock bursts caused 24 (9.5%) of the underground incidents and resulted in six injuries. Most of these rock bursts (83%) were large rock failures and 80% of the large falls were in gold and silver mines, with gold mines in Nevada accounting for 41%. Of the 56 large falls, 49 had no injuries, because in most cases miners were not in the area when the fall occurred; however, two resulted in fatalities. Therefore, NIOSH researchers determined that these large falls present a disaster potential similar to rock bursts with the risk of multiple fatalities. This deeper analysis of narratives from accident data for MNM ground control failures supported the need for overall improvement in the design, implementation, and management of ground control in underground MNM mines.

Congressional Mandate

The MINER Act of 2006 established a competitive grants program for new mine safety technology to be administered by NIOSH, with the aim of enhancing the development of new mine safety technology and technological applications and expediting the commercial availability of such technologies in mining. As noted earlier, in the FY 2008 Appropriations Bill, Congress directed NIOSH to conduct, in collaboration with the University of Utah and West Virginia University (WVU), a study of the recovery of coal pillars through retreat room-and-pillar mining practices in underground coal mines at depths greater than 1,500 feet. A primary objective of the study was to identify means of adapting any practical technology to the mining environment to improve miner protections and to undertake research needed to develop improved technology when mining at such depths. The ground control outcomes related to this Congressional mandate are discussed later in this chapter.

State and Federal Agencies

NIOSH ground control researchers receive input and exchange ideas with state and federal agencies both informally and formally. Informal exchanges usually occur when other agencies are addressing a common ground control problem and researchers collaborate on finding solutions. Researchers in Pittsburgh are located on the same campus as the MSHA Technical Support Roof Control Division, which facilitates input from MSHA on current and emerging ground support issues. MSHA's input derives from the wide-ranging exposure that MSHA staff have to ground control incidents around the U.S. In addition, NIOSH researchers regularly attend the annual MSHA Ground Control Specialists Meeting at the MSHA National Mine Health and Safety Academy in West Virginia to learn about ground control issues and trends reported by the different MSHA districts. Informal exchanges of ideas also occur during conference attendance and other professional activities.

More formal input on NIOSH activities is gained through participation in working groups assembled to address specific ground control issues. As an example, NIOSH and MSHA exchanged information about instability at underground limestone mines with the Pennsylvania Department of Environmental Protection (PADEP) as part of the Limestone Mine Pillar Stability Task Force in 2015. Another working group with representatives from NIOSH, MSHA, the PADEP, and the natural gas industry actively addresses the interaction between unconventional gas wells and coal longwall mining operations. This group meets monthly to discuss issues and concerns that guides related NIOSH ground control research.

Activities, Outputs, Transfer and Translation, and Intermediate Outcomes

Based on the analysis of inputs described in the previous section, NIOSH developed an approach to ground control research that integrates field studies, laboratory testing, numerical modeling, and software development to prevent injuries and fatalities in underground mines. NIOSH also worked closely with operating mines and suppliers of ground support components to provide technical assistance as needed. This section describes these activities that took place from 2008 to 2018 under three major headings:

(1) Development of Ground Control Design Criteria and Methodologies.
(2) Technical Assistance to Improve Ground Control Safety.
(3) Development of Ground Control Expertise.

Development of Ground Control Design Criteria and Methodologies

Ground stability at operating mines can be improved significantly by modifying the mine layout and installing appropriate support systems. Different ground support systems are required for different geologic settings and mine geometries. For instance, standing support systems found in wide coal mine entries (i.e., 16 to 20 ft) are not practical for much narrower entries found in deep metal mines in that they would restrict ventilation that is critical to reducing the buildup of harmful gases and providing necessary cooling. Therefore, effective engineering designs need to ensure stability in variable geological conditions, different depths of cover, and varying excavation dimensions.

The core of NIOSH ground control research is to develop ground control design criteria and methodologies that allow mine operators to design safe mine excavations for themselves. Operating mines, consultants, MSHA, and state and local governments use these design criteria and methodologies to evaluate existing ground control systems or design new ones. In some cases, NIOSH has developed specialized software packages to allow mining engineers to perform their own ground control design and to develop more efficient mine layout.

Coal Mine Pillar and Longwall Stability

Pillar instability in underground coal mines can result in the catastrophic collapse of the overburden if the pillars are under-designed. Overloaded coal pillars may also burst violently if unfavorable geologic conditions or mining configurations exist. The implementation of pillar design procedures initially developed by the U.S. Bureau of Mines largely eliminated uncontrolled pillar failures from underground coal mines in the U.S. These procedures are outlined in the software programs, Analysis of Longwall Pillar Systems (ALPS) [Mark 1987], for determining chain pillar sizes in longwall mines, and Analysis of Retreat Mining Systems (ARMPS) [Mark and Chase 1997], for determining pillar size in both development and retreat mining in room-and-pillar mines. These methods can also be used with the LaModel software, which evaluates stress and deformation of coal pillars and surface subsidence for both development and retreat mining [Heasley 1998].

In spite of the success of the pillar design procedures in preventing pillar instabilities, in the Crandall Canyon mine in 2007, significant pillar failure occurred, with pillars failing and violently ejecting coal over a half-mile area of the mine workings [MSHA 2008]. Subsequently, at the request of Congress, NIOSH conducted research into pillar recovery practices in deep coal mines and developed recommendations to prevent similar disasters from occurring. NIOSH researchers focused on collecting new case history data to improve the ARMPS empirical design procedures, including both field data and statistical analysis of retreat mining pillar stability. A new loading model was developed for estimating pillar loads and stability factors, and NIOSH used these findings to improve and update the ARMPS software [Mark 2010] and develop new guidance for safe pillar recovery. Under NIOSH contracts, the University of Utah conducted research to improve seismic monitoring in coal mines while WVU was tasked with improving stress analysis procedures for deep cover coal mining. The major output associated with this work was a report to the U.S. Congress, *Research Report on Coal Pillar Recovery under Deep Cover* [NIOSH 2010a], which included practical recommendations for the safe recovery of pillars under deep cover.

As an extension to this work, NIOSH researchers conducted a field study and evaluated various numerical modeling methods to estimate the overburden load redistribution around longwall panels in Western mines [Larson and Whyatt 2012]. This work showed that the load redistribution could be significantly affected by the presence of a semi-massive or massive member (lithologic unit) in the overburden encountered in Western coal mines. Therefore, NIOSH recommended expanding the MSHA procedure for evaluating layout design [MSHA 2009] with numerical models and observations of conditions to include measurements of instruments and quantifying observations as much as possible. Additionally, NIOSH research showed that, in the case of long load transfer distance, the displacement discontinuity code, MulsimNL, originally developed by the United States Bureau of Mines, was better able to simulate realistic pillar and gob loading than a laminated displacement discontinuity model such as LaModel [Larson and Whyatt 2013; Larson 2015]. Recognizing the limitations of LaModel in simulating stress distribution where their mine had long load transfer distances, design engineers from Bowie Resources requested training on how to use an expanded, beta version of MulsimNL, called MulsimNL/Large, and NIOSH researchers provided that training to two engineers on site at Bowie Resources, Paonia, CO [Larson 2013].

Intermediate Outcomes:

- MSHA adopted the recommendations of the NIOSH 2010 report, *Research Report on Coal Pillar Recovery under Deep Cover*, by prohibiting all pillar recovery operations at a depth of cover exceeding 2,000 feet [MSHA 2010]. In 2013, MSHA issued a directive that all operating coal mines should use the NIOSH ARMPS and ALPS pillar design procedures or equivalent methods to design their pillars [MSHA 2013].
- The company Alpha Natural Resources developed an internal training document entitled "Alpha Pillar Design Standards" [Alpha Natural Resources 2013], which references both the ARMPS and ALPS design procedures. This document was used to train mining engineers at Alpha Natural Resources in using pillar design principles and NIOSH pillar design software to optimize pillar sizes and panel layout, to improve mining efficiency and productivity, and to enhance ground control-related safety in Alpha mines.
- The University of Kentucky, working with MSHA, developed a web-based application called ACPS that provides easy access to the NIOSH ground control software. The conference paper detailing the development of ACPS specifically describes how it integrated three NIOSH-developed software packages and cites the appropriateness of design criteria by NIOSH to calculate pillar load-bearing capacity [Mark and Agioutantis 2018].
- Since 2008, ARMPS and ALPS have been downloaded from the NIOSH website over 2,000 times [NIOSH Web Statistics 2018]. Created in 2005, the NIOSH Ground Control Software Toolbar, which provides access to seven NIOSH ground control software packages, has been downloaded 595 times since 2008 [NIOSH Web Statistics 2018].

Coal Mine Entry Roof and Rib Stability

Coal mine entries (tunnels) are typically developed within the coal seam being mined. Because the immediate roof strata are often thinly laminated layers that tend to bend and buckle when exposed in the excavation, they are seldom ideal for creating a stable roof. A weakened roof can deform over time and can suddenly collapse without supplementary supports. The coal material forming the ribs (sidewalls) of an entry is weaker than the surrounding rock; therefore, rib failures contribute significantly to ground fall injuries and fatalities in deep coal mines [Mark et al. 2011]. The increasing rock loads imposed on the coal ribs as mining progresses result in fracturing of the coal behind the rib surface. The coal rib can fail suddenly, without apparent warning, trapping miners or pinning them against mine equipment [Mark and Gauna 2016].

Modern support systems provide internal reinforcement to the roof and ribs with steel bolts or cables placed in the roof or coal rib. However, when deformations become excessive, external supports, called standing supports, may be required, along with internal reinforcement using steel bolts or fiber-reinforced bolts and supplemented with screen to hold spalled material in place (Figure 42).

Photo by NIOSH

Figure 42. Coal mine entry with standing supports installed, including cribs, roof bolts, steel straps, cable bolts, and roof screen.

Support solutions created by NIOSH research relied heavily on installing instruments and collecting monitoring data at underground mine sites [Esterhuizen et al. 2018], and the monitoring data were supplemented by laboratory testing of rock and coal samples. Lab testing of full-scale standing support systems at the MRS determined the mechanical characteristics of the supports.

Roof support design is typically conducted through empirical experimentation in mines, but results from numerical modeling can help mines to build effective roof support. Through project research, NIOSH developed methods to evaluate support performance based on numerical models, enabling mining engineers to better match support systems to the local ground conditions [Esterhuizen and Tulu 2016b]. Additionally, NIOSH researchers detailed a rapid assessment procedure that allows mine engineers to conduct support assessments without the need for advanced numerical modeling expertise [Esterhuizen et al. 2016]. Numerical modeling played an important part in designing solutions for the large variety of geological conditions encountered in the different coal basins [Mohammed et al. 2015; Tulu et al. 2017].Therefore, NIOSH also developed advanced numerical models to replicate the complex response of coal material when overloaded in the rib of an entry [Mohamed et al. 2015].

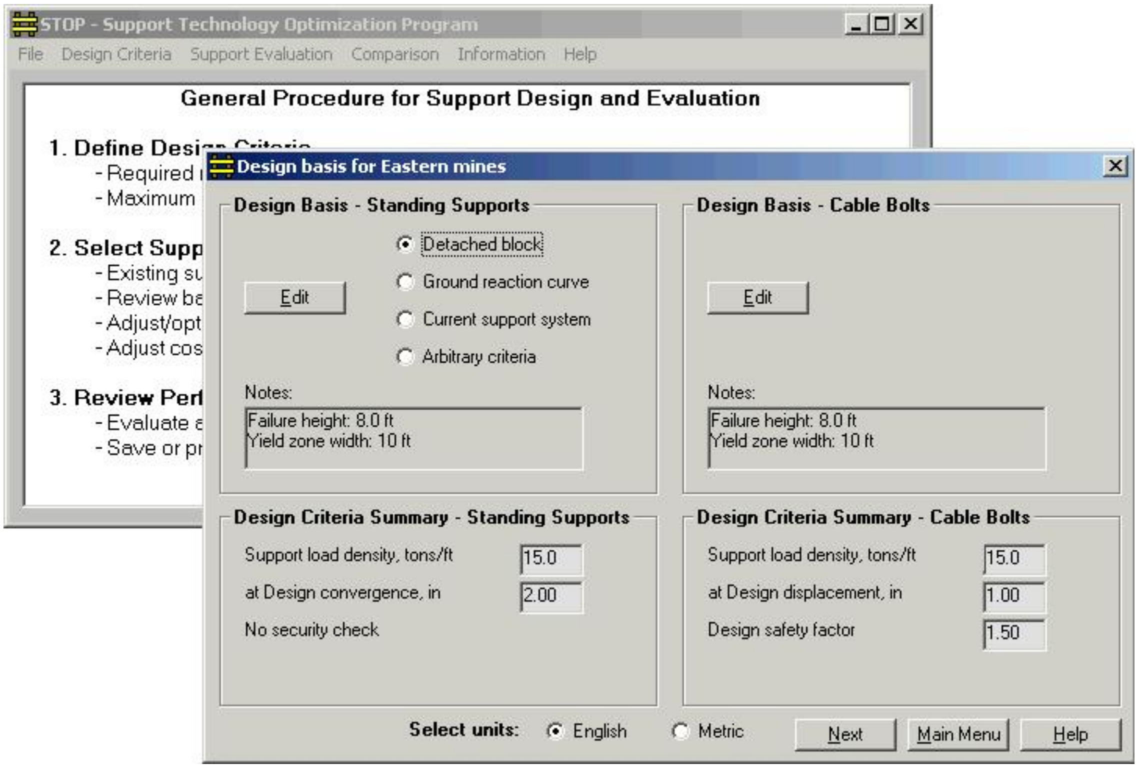
Intermediate Outcomes:

- As part of research funded by the Alpha Foundation, researchers at WVU have adopted the numerical modeling techniques developed by NIOSH to investigate longwall panel loading under various geologic conditions [Alpha Foundation 2018].
- Alpha Natural Resources adopted NIOSH standing support criteria and MRS testing results to develop performance requirements for standing supports used at its longwall operations [Zhang et al. 2012].
- MSHA's Safety and Health Technology Center applied NIOSH rib bolt research outcomes to evaluate new rib support products before they are introduced to mining operations [Mohammed 2018].
- Rosebud Mining Company applied NIOSH-developed support analysis methods to assess support alternatives at two of its low-seam coal mines [Esterhuizen et al. 2016a; Esterhuizen 2019b].

Standing support design poses difficult challenges because of the requirement to control the roof while it is subject to excessive deformation. To help address this challenge, NIOSH researchers conduct in-mine monitoring studies and testing of support units in the MRS. The MRS plays a very important role in the development of standing support technologies for these extreme conditions through full-scale testing of support units. NIOSH researchers use this facility to better understand support loading characteristics and to develop support performance expectations by considering the field monitoring results and the full-scale laboratory test.

Standing support vendors also make use of the MRS facility and NIOSH research outcomes to develop new and innovative standing support products. Appendix E lists the vendors and support products that were tested during the review period. The findings of the research and performance expectations of new standing support technologies are regularly communicated by NIOSH to the MSHA Technical Support Roof Control Division. This information is then communicated internally by MSHA to Roof Control Specialists at their training meetings.

NIOSH researchers published criteria for designing standing supports [Barczak et al. 2008], and these criteria formed the basis for developing standing supports for U.S. coal mines. NIOSH also developed the Support Technology Optimization Program (STOP) design software package (Figure 43) to enable mining engineers to determine optimal standing support when using such materials as timbers, steel posts, wood cribs, concrete cribs, and pumpable cribs [NIOSH 2010b].



General Procedure for Support Design and Evaluation

Design basis for Eastern mines

Design Basis - Standing Supports

● Detached block
○ Ground reaction curve
○ Current support system
○ Arbitrary criteria

Notes:
Failure height: 8.0 ft
Yield zone width: 10 ft

Design Basis - Cable Bolts

Notes:
Failure height: 8.0 ft
Yield zone width: 10 ft

Design Criteria Summary - Standing Supports

Support load density, tons/ft 15.0
at Design convergence, in 2.00
No security check

Design Criteria Summary - Cable Bolts

Support load density, tons/ft 15.0
at Design displacement, in 1.00
Design safety factor 1.50

Select units: ● English ○ Metric

Figure 43. Screenshot from the STOP design software package.

Intermediate Outcomes:

- Engineers from Strata Worldwide, a major supplier of support systems to the mining industry, used NIOSH research and MRS testing outcomes to determine required support capacities, performance ratings, and support design specifications. These outcomes were also communicated by Strata Worldwide engineers to mines to inform them about performance capabilities of their standing support products [Batchler 2018a].
- Members of MSHA's Technical Support Group Roof Control Division apply NIOSH research and MRS testing outcomes when evaluating support systems at operating mines. The NIOSH research outcomes are disseminated by the Technical Support Group to Roof Control Specialists at MSHA training meetings [Batchler 2018b].
- The STOP software has been downloaded from the NIOSH website over 248 times since its introduction in 2010 [NIOSH Web Statistics 2018].

Criteria for Gas Well and Coal Mine Interaction

Due to the shale gas boom that began in 2008 [Brown and Yücel 2013], more than 1,400 unconventional shale gas wells have been drilled through current and future coal reserves in Pennsylvania, West Virginia, and Ohio [Su 2016]. These shale gas wells penetrated many coal seams encountered in Pennsylvania such as the Sewickley, Pittsburgh, Freeport, and Kittanning seams, which are either currently mined or will be mined in the near future. The mechanical integrity of these shale gas wells can be compromised by longwall-induced deformations and stresses, resulting in unexpected, dangerous inflow of high-pressure gas into underground mine workings.

To explore this issue, NIOSH was invited to participate in monthly Pennsylvania Gas Well Workgroup meetings, consisting of representatives from MSHA, the PADEP, the coal industry, and gas industries. These discussions led to project research to evaluate the stability of active gas wells in longwall abutment pillars, even if those gas well pillars satisfied the current Pennsylvania Gas Well Pillar Regulation or the MSHA Code of Federal Regulations (CFR) 75.1700, "Oil and Gas Wells." The research objective was to quantify subsurface overburden deformations in longwall abutment pillars under shallow (<500 feet) and deep (>900 feet) overburden depths, and to employ field instrumentation results and 3D numerical modeling to identify critical parameters affecting subsurface overburden deformations. As a result of this research, NIOSH published four technical papers on longwall-induced stresses and deformations and their effect on gas well casing stability [Su et al. 2018; Su 2018]. This research began in 2016 and has influenced mine procedures to avoid potentially hazardous mine/gas well interactions.

Intermediate Outcomes:

- The PADEP made use of NIOSH recommendations to develop a Technical Guidance Document to assist mines in planning for coal extraction near unconventional gas wells [PADEP 2017a].
- MSHA District 2 used NIOSH gas well stability research results to develop a Risk Evaluation Matrix for Pennsylvania coal mines operating near unconventional gas wells [MSHA 2018].
- CONSOL Energy and Murray Energy implemented NIOSH technical guidance in assessing risk levels of unconventional gas well pads adjacent to current and future longwall panels [NIOSH 2018].
- Gas companies applied NIOSH-developed procedures for cementing gas well casings to minimize potential damage [Scovazzo 2018].

Coal and Metal Mine Seismicity

Mining-induced seismicity (MIS), or micro-earthquakes caused by mining, occur in all types of mining environments, but especially when underground caving methods are used (as in longwall coal mining) and in deep hardrock mines. While dynamic failure events do pose a direct hazard to mine workers, the vast majority of observed MIS does not pose a risk to miners due to the source-distance from active workings or small amounts of energy radiated. In fact, these non-hazardous events can help researchers understand the ground response to mining in order to detect emerging hazardous conditions and to evaluate mine designs. Analyses of seismic datasets can provide information on the geomechanical state of the overall mine, including areas that are not accessible to other instrumentation. Thus, the monitoring and interpretation of MIS data provides the only means currently available to understand mine-wide responses to loading. While seismic monitoring has been employed as an effective ground control tool in deep hardrock mines for several decades, many technical challenges must be overcome to improve the safety value that monitoring can provide. These technical challenges are especially pronounced when applying seismic monitoring to environments other than deep hardrock mining where the technology was initially developed.

NIOSH has cultivated partnerships with mines in the two primary seismically active mining regions in the U.S.: the Coeur d’Alene mining district in Northern Idaho and the North Fork Valley of Western Colorado. During the review period, NIOSH worked with partners to apply seismic monitoring strategies to several deep coal and hardrock mines and undertook a variety of research efforts to address existing technical challenges, improve data collection and processing methodologies, and use seismicity to evaluate the rock mass response to mining. As examples of partnerships, after NIOSH successfully demonstrated and used microseismic arrays over the Elk Creek and Bowie mines in North Fork Valley, Colorado, Memorandums of Understanding between NIOSH and Arch Coal and NIOSH and an unnamed mining company were signed to continue monitoring ground stability over the West Elk Mine and another mine west of the Mississippi River [Swanson et al. 2008; NIOSH 2016]. As another example of Mining Program cooperative research, NIOSH provided raw data for a study by Virginia Tech through the National Science Foundation CAREER Program to conduct a study to use seismic tomography, or the determination of seismic velocities, to evaluate changes in overburden stresses over the course of mining a longwall panel [Westman et al. 2008; King 2012; Westman et al. 2012].

More recently, NIOSH researchers have developed technologies for measuring in-situ seismic velocity models, refined methodologies for event location, and tested them at several mine sites. Event location for MIS is more complex than for traditional tectonic seismology and can have major implications for calculating accurate source parameters used in hazard assessment [Lurka and Swanson 2009; King 2012; Swanson et al. 2014; Chambers and Boltz, 2017; Boltz et al. 2016]. Based on these NIOSH developments a Python extension package for seismic interpretation, called ObsPlus, is nearing release on GitHub for open source code access.

To transfer these developments to the industry, NIOSH presented strategies for monitoring MIS and case histories to coal and metal mine operators [Swanson 2014; Chambers 2018] and to the international MIS community [Swanson 2012; Swanson 2016]. Additionally, NIOSH worked to educate ground control students and professionals on the potential uses and safety benefits afforded by monitoring MIS.

Intermediate Outcomes:

- In December 2012, the Troy silver/copper mine in Northwestern Montana began encountering dynamic failures. After discussions and site visits, NIOSH recommended that the operator, Revett Minerals Inc., install a seismic monitoring system at the mine. NIOSH assistance and guidance on methods to evaluate the seismic response of the mine enabled the mine to make critical decisions concerning measures to stabilize the mine [Farbridge 2014].
- The University of Utah provided a course based on NIOSH research entitled “Introduction to Mining Induced Seismicity” in the fall of 2016, which covered topics related to mining-induced seismicity as they pertain to ground control safety. By invitation, several NIOSH researchers gave lectures on their areas of expertise as they relate to MIS [Boltz and Chambers 2016] as well as on case studies of significant dynamic failure events [Boltz 2016; Chambers 2016].
- Lucky Friday Mine in Northern Idaho used surface seismic monitoring data from NIOSH’s Inter-Mountain Seismic Network (IMSN) as well as improved NIOSH data collection and processing methodologies. The data and methods were used in conjunction with instrumentation arrays

installed underground to provide additional understanding of the rock mass response and backfill performance exposed to MIS [Seymour et al. 2017].

- In 2018, ESG Solutions and the Institute of Mine Seismology used seismic data based on NIOSH outputs to provide training via two workshops to industry personnel and academia on the benefits of seismic monitoring, routine processing, and research applications [ESG Solutions 2018; IMS 2018]. The training was well-attended and included personnel from Hecla, Newmont Mining, U.S. Silver Corporation, Barrick Gold Corporation, Rio Tinto, University of Utah, and University of Nevada–Reno.

Metal Mines Blasting

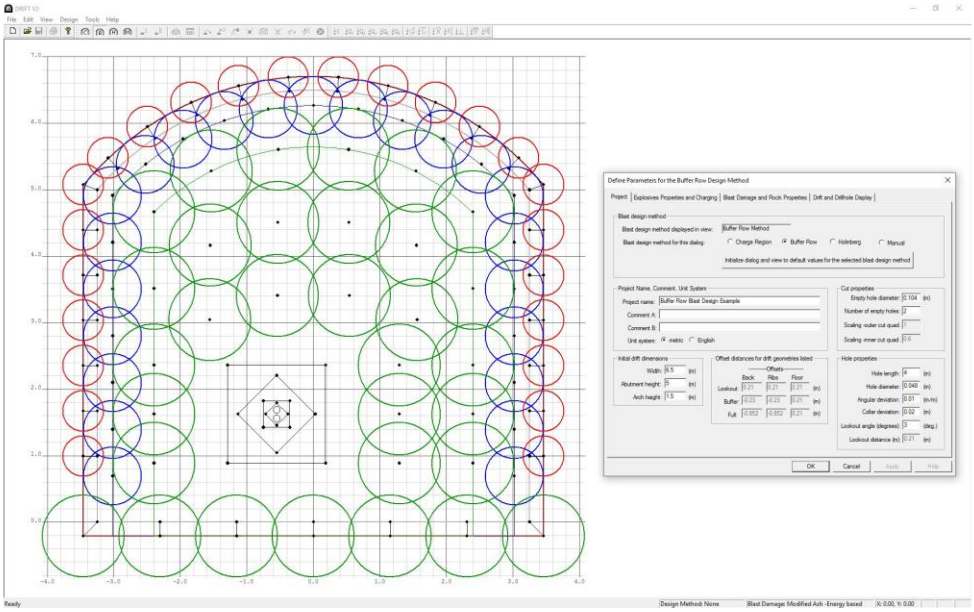
In underground MNM mines, the centerpiece of modern drifting is the drill jumbo. The ability of the drill operator to drill complex blasting patterns and complete the drilling (and in some cases the loading) of blast holes very quickly and easily opened new opportunities for improved ground control. Although drilling improved, controlled blasting was not widely practiced in the mining community. Controlled blasting reduces perimeter damage, which lowers the risk of ground falls, especially during scaling and roof support installation.

As the name implies, controlled blasting adheres to much stricter specifications than past practices. Perimeter control designs require additional blast holes along and near the perimeter. Blasting techniques are also optimized and changes in the types of explosives used are required. The benefits of perimeter control are both safety and cost. A well-blasted drift requires less scaling time and less troublesome ground support installation. The reduced exposure time during these tasks reduces the risk of ground fall injury.

In 2006, NIOSH began a five-year project to validate and improve existing blast damage models through laboratory and field experiments and computer modeling, with the ultimate goal of developing a user-friendly controlled blast design software package. Although much of the work was completed, the software, called DRIFT, was not fully developed, primarily due to a shift in program priorities. Then in 2017, NIOSH contracted with Dr. Mark Kuchta, Associate Professor at the Colorado School of Mines, and Dr. William Hustrulid, of Hustrulid Mining Services, to assist with completing the development of the DRIFT software (Figure 44). The fully developed software provided the blast design engineer with a tool for creating an initial conceptual blast design intended to meet design objectives. DRIFT uses both empirical and first-principle equations to calculate practical damage limits. The DRIFT blast design software package, including a user's guide, is available as a beta download on the NIOSH Mining website and will be published as production software in 2019 after completing the NIOSH approval process.

Intermediate Outcome:

- Since the DRIFT software became available on the NIOSH Mining website in January 2018, it has been downloaded nearly 100 times [NIOSH Web Statistics 2018].



Define Parameters for the Buffer Row Design Method

Blast design method

Blast design method displayed in view: Buffer Row Method

Blast design method for this dialog: ○ Charge Region ● Buffer Row ○ Holmberg ○ Manual

Project Name, Comment, Unit System

Project name: Buffer Row Blast Design Example

Comment A:

Comment B:

Unit system: ● metric ○ English

Cut properties

Empty hole diameter: 0.104 (m)

Number of empty holes: 2

Scaling -outer cut quad: 1

Scaling -inner cut quad: 0.6

Initial drift dimensions

Width: 6.5 (m)

Abutment height: 5 (m)

Arch height: 1.5 (m)

Offset distances for drift geometries listed

	Offsets Back	Ribs	Floor	
Lookout:	0.21	0.21	0.21	(m)
Buffer:	-0.23	-0.23	0.21	(m)
Full:	-0.852	-0.852	0.21	(m)

Hole properties

Hole length: 4 (m)

Hole diameter: 0.048 (m)

Angular deviation: 0.01 (m/m)

Collar deviation: 0.02 (m)

Lookout angle (degrees): 3 (deg.)

Lookout distance (m): 0.21 (m)

Ready

Design Method: None

Blast Damage: Modified Ash -Energy based

X: 0.00, Y: 0.00

Figure 44: Screenshot of the DRIFT software. Based on the user's conceptual blast design chosen, the color-coded circles represent damage for the buffer holes, perimeter holes, lifter holes, and stoping holes.

Metal Mines Backfill

Underground metal mines use backfill to provide both local and regional ground support, usually in the form of a cemented waste product—either mill tailings, referred to as cement paste backfill (CPB), or cemented waste rock, called cemented rockfill (CRF). Mines commonly use CRF in conjunction with underhand cut-and-fill mining methods in mines with a weak host rock, particularly in the gold mines in Nevada [Seymour et al. 2013]. CRF supports the overlying material in the mine roof and confines the surfaces of rock pillars and abutments, enhancing their ground support capabilities.

Although backfilling is very effective as a support tool, its application is not without risk and requires technical oversight. Backfill failures do not occur frequently, but these accidents typically result in a higher proportion of fatalities and lost-time injuries than ground falls in underground metal mines using backfill [Seymour et al. 2013]. Falling backfill is especially hazardous in underhand cut-and-fill mining operations where employees work directly beneath cemented backfill. Most of these backfill failures are attributed to inadequate backfill strength, insufficient or inconsistent quality control measures, or larger-than-expected mining spans [Seymour et al. 2013].

At Hecla's Lucky Friday Mine in Northern Idaho, the use of CPB in conjunction with mechanized underhand cut-and-fill mining methods has reduced the number of injuries and fatalities caused by mining in deep, high-stress, rockburst-prone ground conditions [Peppin et al. 2001]. However, following a large backfill fall on April 27, 2014, Hecla requested that NIOSH conduct a cooperative study to independently confirm the strength properties of the CPB that collapsed. Conventional strength property tests confirmed that the fill met design requirements [Johnson et al. 2015; Seymour et al. 2016]. In addition, a systematic instrumentation approach was developed using robust and reliable closure meters and pressure cells to monitor the geomechanical behavior and stability of the CPB in response to stope closure during undercut mining [Seymour et al. 2016, 2017]. Measurements from these instruments confirmed that the backfill performed as intended and helped to confirm long-standing assumptions about the role of backfill in ground support [Raffaldi et al. 2018b; Seymour et al. 2017] (Figure 45).

Photo by NIOSH

Figure 45. Backfill instruments installed for a NIOSH cooperative study at the Lucky Friday Mine, Northern Idaho.

A NIOSH study of laboratory compressive and tensile strengths tests of CRF samples collected during a backfill span study at the Turquoise Ridge Mine, Nevada, and later for an analysis of the flexural stability of a constructed CRF sill concluded (1) that the long-term compressive strength gain for CRF is similar to that of concrete, and (2) that the tensile-to-compressive strength ratio for CRF is about 1/6 rather than the 1/10 value typically used for backfill design [Seymour et al. 2018]. This information provided a better understanding of the long-term strength properties of CRF, and was used to design safe undercut spans beneath CRF for permanent mine infrastructure at the host mine.

The laboratory test results were supplemented by data collected from instruments previously installed at the Turquoise Ridge Mine to monitor the geomechanical behavior and stability of a typical CRF sill and the surrounding host rock during test mining of a large undercut span. These instruments indicated that the mine roof or back remained stable on an upper level, allowing a majority of the mining-induced stress to be transferred to the host rock abutments rather than to the backfilled drifts. Although only slight loads were measured in the backfill, the CRF confined the abutment ribs and mine roof, thereby improving their long-term stability. During retreat mining of an undercut span on a lower level, the CRF sill remained stable and was not adversely affected by vertical cold joints between adjacent backfill drifts. Additional instrument readings intermittently collected after the completion of undercut mining showed that, while vertical stress continued to increase in the abutments, displacements in the mine roof and abutments stabilized, and vertical stress and deformation within the CRF decreased. The most recent readings from these instruments in 2017 indicated that the backfill span is still intact and in stable condition. Conclusions from this instrumented case study were used to justify the placement of permanent mine infrastructure in CRF undercut spans at the Turquoise Ridge Mine.

Intermediate Outcomes:

- Based on the results of a cooperative study with NIOSH, Hecla redesigned its CPB mix and improved its QA/QC (Quality Assurance/Quality Control) procedures for pumping and placing its backfill [Johnson et al. 2015; Seymour et al. 2016, 2017].
- The Turquoise Ridge Mine in Nevada used design criteria developed from NIOSH’s long-term backfill study to design safe undercut spans beneath CRF for permanent mine infrastructure [Seymour et al. 2018].
- NIOSH test results with large-sized samples of CRF were used at the Stillwater, Cortez Hills UG, and Turquoise Ridge mines to better assess the safety of their backfill mix designs and the stability of their in-place backfill [Seymour et al. 2018; Warren et al. 2018a; Warren et al. 2018b].
- In several cases, instruments installed by NIOSH researchers continue to be monitored by mine personnel and the resulting data have been used to understand ground control issues and enhance safety at underground mines that use backfill for ground support, including the Lucky Friday, Turquoise Ridge, Buick, and Fletcher mines [Raffaldi et al. 2018b; Seymour et al. 2016, 2017; Tesarik et al. 2009].

- The results of NIOSH backfill studies at several underground metal mines have been incorporated in the training materials for Mine Backfill Workshops provided by MineFill Services, Inc. [Johnson et al. 2015; Seymour et al. 2013; Tesarik et al. 2009].

Shotcrete Support Systems for Deep Metal Mines

Underground metal mines extract ore from many types of deposits, varying from narrow high-grade veins in strong brittle rock to massive areas of low-grade material in weak fractured ground. A common factor is the complexity of the geologic structure and high stresses that accompany mining-induced deformation. Primary support of underground entryways in metal mines is typically provided by rockbolts or cables, which support the relaxed zone of rock around the excavation. However, ground control safety often depends on supporting, or at least containing, the ground between rockbolts. This secondary support is typically provided by adding steel mesh and/or shotcrete to the support system. High-energy loading environments encountered in weak or highly stressed rock, which include squeezing and bursting ground, require ground support systems with well-connected components that can yield through large displacements while maintaining support capacity.

When shotcrete or sprayed concrete is used as part of a multicomponent ground support system, it is critical to know the primary performance characteristics of the material [Martin et al. 2015a; Pakalnis et al. 2010], as follows.

> *Early strength*. When the shotcrete has developed enough strength to be self-supporting, allowing for reentry and emplacement of the remaining support elements that require drilling of the shotcrete layer without degradation.
>
> *Bond strength*. The quantified ability of the shotcrete to adhere to rock.
>
> *Load capacity and toughness*. The 28-day and long-term strength that determines when openings are considered to be supporting ground according to the mine's ground control plans.

Early Strength

Determining the early-strength development of as-sprayed shotcrete can improve mine safety by identifying appropriate re-entry times and providing a convenient means of quality control during application. The typical range of early threshold strengths of green shotcrete has been reported in the literature for North American mines [Clark et al. 2012], but these data were taken from cored samples after 24 hours. After conducting extensive laboratory tests using methods typically used by industry, NIOSH concluded that obtaining drill cores and cylinders does not provide a reliable testing medium. These indirect tests are not practical for the one- to six-hour period following application when unconfined compressive strengths of the curing shotcrete are very low and therefore give inconsistent test results [Clark et al. 2010, 2012; NIOSH 2011b].

To address the need for better data on early strength, NIOSH designed a portable partial beam test machine for use onsite at mines. The apparatus applies a compressive load at a fixed displacement rate to conduct the partial-beam strength determination test. The test machine and a field testing protocol also developed by NIOSH adhere to the ASTM C116 (1990) standards and are practical for use at a mine site. NIOSH's Field-Use, Early-Strength Shotcrete Test System provided industry with an accurate method of measuring shotcrete early strength on site in the first six hours after application using the partial beam test standard.

Intermediate Outcome:

- The Turquoise Ridge Joint Venture, Nevada, used the NIOSH early-strength shotcrete test system to measure wet shotcrete strength properties as a quick testing method for establishing the time needed for the shotcrete to reach the desired strength threshold for miners to determine safe re-entry practices for shotcreted areas without other support [Sandbak and Rai 2013].

Bond Strength

Bond strength indicates not only the adhesion strength of shotcrete to the rock, but also important information about the quality of the shotcrete and the competency of the underlying rock [NIOSH 2011a; Seymour et al. 2010, 2011]. To test for bond strength, NIOSH developed a Field-Expedient Shotcrete Adhesion Test System that consists of a small stand-mounted core drill and a pulling unit equipped with a precision pressure gauge. The design criteria for the apparatus included the ability to provide accurate, repeatable data from a rugged and portable system. The test method that was developed applies a direct tensile load to a core drilled through the shotcrete into the underlying rock. As this load is gradually increased, the test core typically breaks or fails in tension. This tensile failure can occur in the shotcrete, at the bond surface (interface), in the rock, or at some combination of these locations. NIOSH first bench tested the system to compare test results with those from laboratory equipment, followed by field trials in an underground mine to verify test procedures, confirm the equipment was suitable for use in underground mining conditions, and validate the practicality of use by mine personnel.

Intermediate Outcome:

- NIOSH shotcrete design criteria and results from bond strength testing were used at the Lucky Friday mine, in conjunction with field experience, to design safer chain-link mesh and shotcrete ground support systems [Golden 2015].

Load Capacity and Toughness

Ultimately, the performance of shotcrete depends on its load capacity and toughness as it cures, developing strength over time. Flexural load capacity is the peak or breaking load when the shotcrete is subjected to bending forces and toughness is a measure of the amount of energy that the shotcrete can absorb for a given displacement and still retain some load capacity. NIOSH developed a Field-Use Round Determinate Panel Test (RDPT) system to measure these properties using ASTM-1550-05 round determinate panel standards. NIOSH researchers designed the system to apply a compressive load at a fixed displacement rate and be used on site at mines.

The apparatus is made up of a self-contained, servo-controlled, stiff-frame press with advanced load-rate and load-collection capability. The portable, field-use system can obtain shotcrete toughness strengths required for determining support requirements [Caceres et al. 2010a, 2010b; NIOSH 2011c]. The tension cracks produced by the RDPT represent the failure type observed in underground tunneling and mining. The two design values obtained from the RDPT—the load profile and the energy—are used when designing ground control for underground openings.

While many methods have been tested for measuring strengths, RDPT is the preferred method for directly measuring determinate breaks and providing resultant toughness [Martin et al. 2010, 2015; NIOSH 2011c]. NIOSH researchers conducted field trials to verify the system's performance at multiple mine sites, one tunnel site, and one shotcrete producer's site. When used in underground mine environments and operated by mine personnel, the field trials demonstrated that the RDPT produced repeatable and accurate test results consistent with the results obtained by NIOSH from fixed laboratory-based test equipment.

Intermediate Outcome:

- Based on NIOSH testing on shotcrete load capacity and toughness, in 2015, Dr. Rimas Pakalnis, formerly a professor specializing in mine stability at the University of British Columbia and later with Pakalnis and Associates, began using the NIOSH shotcrete testing and design methods to design support systems for underground metal mines throughout the world, including the U.S. This was highlighted in a keynote paper at the Deep Mines Conference in Santiago, Chile [Pakalnis 2015].

Methodologies for Shotcrete Testing

Based on the extensive knowledge acquired from shotcrete testing, at the request of the Montana Department of Environmental Quality, NIOSH organized and presented a special session at the SME 2010 Annual Meeting and Exhibit in Phoenix, AZ, to provide shotcrete support recommendations to industry and academia [Caceres et al. 2010a; Clark et al. 2010; Martin et al. 2010; Pakalnis et al. 2010; Seymour et al. 2010]. To further advance its research on shotcrete testing, NIOSH designed and built the HEHD panel test machine (Figure 41, p. 110) [Martin et al. 2015b]. The HEHD machine allows NIOSH researchers to evaluate surface support as a system, taking into account the influence of the rockbolts and providing strengths representative of in-mine support. Rockbolt plates, bolt resin, and other details can be matched to an in-mine system. The jack pressure and ram displacement are recorded continuously during a test to determine the force displacement response.

HEHD testing focused on shotcrete panels constructed with various reinforcement products, including macro-synthetic fibers, chain-link fence, welded-wire mesh, and other products. Each type of reinforced system was tested with four rock bolts tying down the corners of the shotcrete panel. The average force-displacement response for each panel was measured and used to derive an estimate of the energy absorption for each support system. Engineers use energy absorption to assess the ability of the ground support to yield and absorb the kinetic energy of ejecting rock during a rockburst, and it is estimated by integration of the force-displacement curve. NIOSH published the force-displacement curves developed by the HEHD tests on shotcrete panel systems in several national and international industry conference proceedings [Martin et al. 2015b; Raffaldi et al. 2016], and the results drew considerable interest from mine operators.

The installation sequence of ground support elements can also affect support system performance, particularly in weak rock mass conditions. To study this issue, NIOSH worked with Barrick's Turquoise Ridge Mine and a consulting ground control engineer [Raffaldi et al. 2018a] to develop a method of constructing panels to imitate the ground support installation sequence. Different installation sequences for mesh, bolts, and shotcrete were tested in the HEHD machine to measure the relative performance of each. Additionally, post-bolted macro-synthetic fiber-reinforced shotcrete was tested for comparison with the wire-mesh alternatives; lastly, the influence of external wire-mesh was measured. The results demonstrated the importance of shotcrete in the overall support system and the benefit of post-bolting, and they provided a direct comparison between mesh and macro-synthetic fiber reinforcement. The test results were then coupled with empirical shotcrete design guidelines to provide general guidelines for selecting appropriate surface support. The findings were published as part of the proceedings of the 52nd U.S. Rock Mechanics/Geomechanics Symposium [Raffaldi et al. 2018a].

Intermediate Outcomes:

- Results of HEHD testing of commercial mesh materials (welded-wire mesh, cyclone fence, and macro-fibers) that are commonly incorporated in shotcrete mine support systems were used to assist in ground support selection at several mines [Raffaldi 2016, 2017; Raffaldi et al. 2018a].
- Shotcrete suppliers—Thiessen Team USA, Elko, NV, and BASF, Master Builders, Elko, NV—incorporated the results of HEHD shotcrete panel testing into their product lines and their installation recommendations to customers [Clark et al. 2010].
- Barrick Gold Corporation’s Turquoise Ridge Mine incorporated NIOSH recommendations for early strength re-entry for shotcreted excavations into its mining sequence, and QA/QC methods based on the NIOSH designs for the round determinate panel testing, shotcrete early strength testing, and shotcrete adhesion testing [NIOSH 2015a; Martin 2017b].
- Recommendations developed from NIOSH research of in-cycle shotcrete with post-bolting have been implemented at the Turquoise Ridge Mine [Raffaldi et al. 2018a].

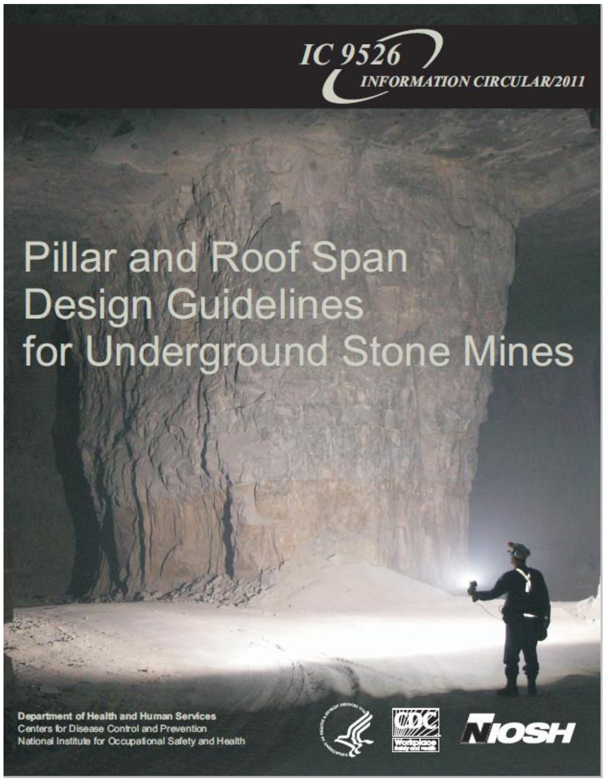
Stone Mine Pillar and Roof Stability

Underground limestone mines generally make use of the room-and-pillar method of mining. In this method, pillars of unmined limestone are used to support the overlying roof. Because of the relatively large opening size, the pillars may be over 60 feet tall (Figure 46). Such tall slender pillars can suddenly fail in a violent manner if they are under-designed. In 2005, NIOSH researchers identified the need for a procedure for designing stable limestone pillars and embarked on research to develop pillar design criteria for limestone mines. NIOSH researchers visited 33 operating limestone mines around the U.S. over three years to collect data on pillar dimensions, depth of cover, rock mass rating, and information on current pillar performance. These data were supplemented by rock strength testing, numerical modeling, and statistical analysis to produce a pillar strength equation that could be used for effective design.

Photo by NIOSH

Figure 46. NIOSH researchers investigating roof and pillar conditions in a limestone mine.

NIOSH published its research findings in the Information Circular, *Pillar and Roof Span Design for Underground Stone Mines* [NIOSH 2011d] (Figure 47). The pillar strength equation and NIOSH-recommended design criteria were incorporated into a software program called S-Pillar [NIOSH 2011b], which allows mine operators to easily calculate safe pillar dimensions using appropriate geological data. Figure 48 represents a screenshot of the S-Pillar data entry screen, showing the inputs and results plotted on a chart. The S-Pillar software has been demonstrated to mine personnel at safety meetings, training workshops provided by NIOSH engineers at the Underground Stone Safety Seminar, and through two webinars presented in 2011 and 2012 [Esterhuizen and Murphy 2011, 2012].



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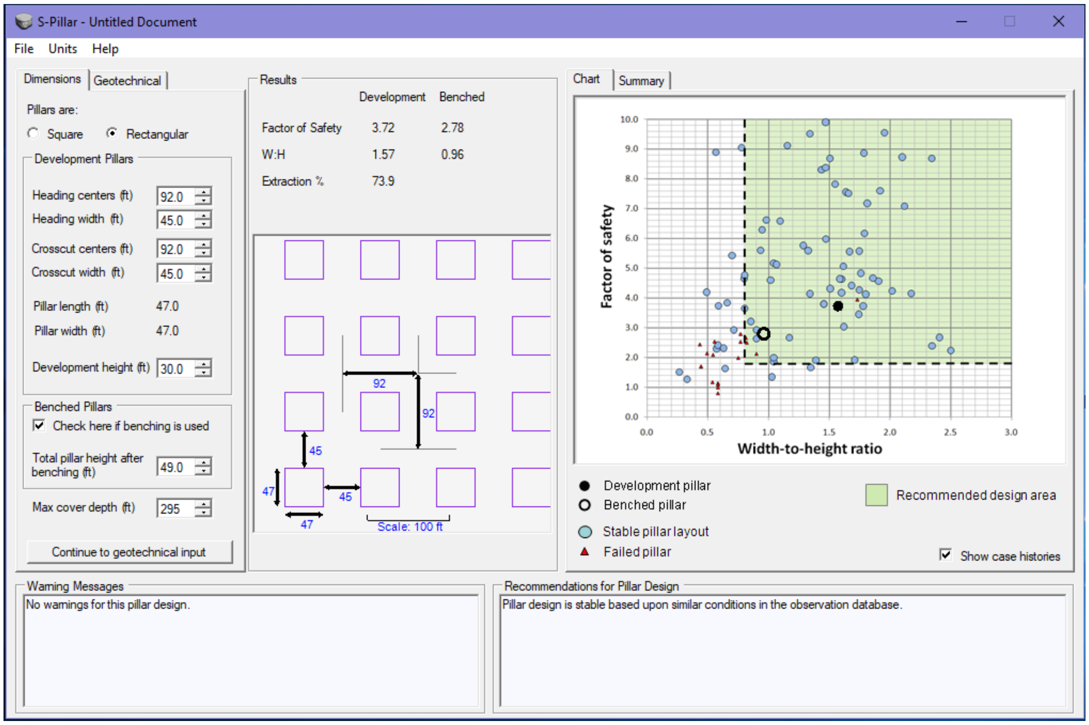
INFORMATION CIRCULAR/2011

Pillar and Roof Span Design Guidelines for Underground Stone Mines

Department of Health and Human Services
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health

NIOSH

Figure 47. A NIOSH Information Circular detailing pillar design guidelines for underground stone mines.



S-Pillar - Untitled Document

Pillars are:
○ Square ● Rectangular

Development Pillars

Heading centers (ft) 92.0
Heading width (ft) 45.0
Crosscut centers (ft) 92.0
Crosscut width (ft) 45.0
Pillar length (ft) 47.0
Pillar width (ft) 47.0
Development height (ft) 30.0

Benched Pillars

☑ Check here if benching is used

Total pillar height after benching (ft) 49.0

Max cover depth (ft) 295

Results

	Development	Benched
Factor of Safety	3.72	2.78
W:H	1.57	0.96
Extraction %	73.9	

● Development pillar
○ Benched pillar
● Stable pillar layout
▲ Failed pillar
🟩 Recommended design area
☑ Show case histories

Warning Messages

No warnings for this pillar design.

Recommendations for Pillar Design

Pillar design is stable based upon similar conditions in the observation database.

Figure 48. Screenshot of the S-Pillar software used for pillar design in limestone mines.

In February 2015, about four acres of room-and-pillar workings that had been mined in the 1990s violently collapsed at a limestone mine in Pennsylvania [Esterhuizen et al. 2018]. The collapse resulted in an air blast that severely injured three mine workers who were standing just outside the mine portal and waiting to enter the mine for the morning shift. Following this unexpected collapse, MSHA and the PADEP invited NIOSH to participate in a task force to evaluate the potential for similar pillar collapses to occur in old workings of limestone mines in the PADEP Northeastern District. NIOSH engineers worked closely with engineers from the MSHA Technical Support Group Roof Control Division to assess current pillar stability using the NIOSH-developed pillar strength criteria. NIOSH presented its findings to upper management of MSHA and the PADEP.

In addition to pillar design, roof stability can be problematic at limestone mines, leading to an increasing trend in roof and rib fall incidents in these types of mines. Horizontal stress in the earth's crust can be sufficient to cause damage in the roof and floor of stone mines in spite of their relatively shallow depth of cover. NIOSH observations of stress-related damage at operating mines, together with an understanding of horizontal stress issues that develop in coal mines, resulted in a set of design procedures that can be applied to alleviate the effect of horizontal stress in limestone mines [NIOSH 2011]. These design procedures are simple to apply and have been implemented at several mines to improve roof stability and mine worker safety.

Intermediate Outcomes:

- Since 2015, the Bureau of Mine Safety of the Pennsylvania Department of Environmental Protection (PADEP) has used the NIOSH-developed S-Pillar software to evaluate pillar stability at operating stone mines and for new stone mine permit applications [Esterhuizen 2018a].
- Members of the MSHA Safety and Health Technology Center regularly apply the NIOSH-developed pillar design criteria to evaluate pillar stability at limestone mines. They also encourage the use of the S-Pillar software by mining companies, and have provided training to mine personnel in the correct use of the software [Esterhuizen 2018b].
- Engineers at the MSHA Safety and Health Technology Center applied the NIOSH-developed pillar design criteria to back-analyze a collapse at a marble mine in Georgia [Phillipson 2012].
- MSHA and the PADEP made use of the results of S-Pillar analyses in a review of the potential for collapse of old workings at six limestone mines in the PADEP Northeastern District [Esterhuizen 2015]. As a result, remedial measures were implemented at one of the mines where a potential risk of collapse was identified.
- The S-Pillar software has been downloaded from the NIOSH website over 180 times since it was published in 2011 [NIOSH Web Statistics 2018].

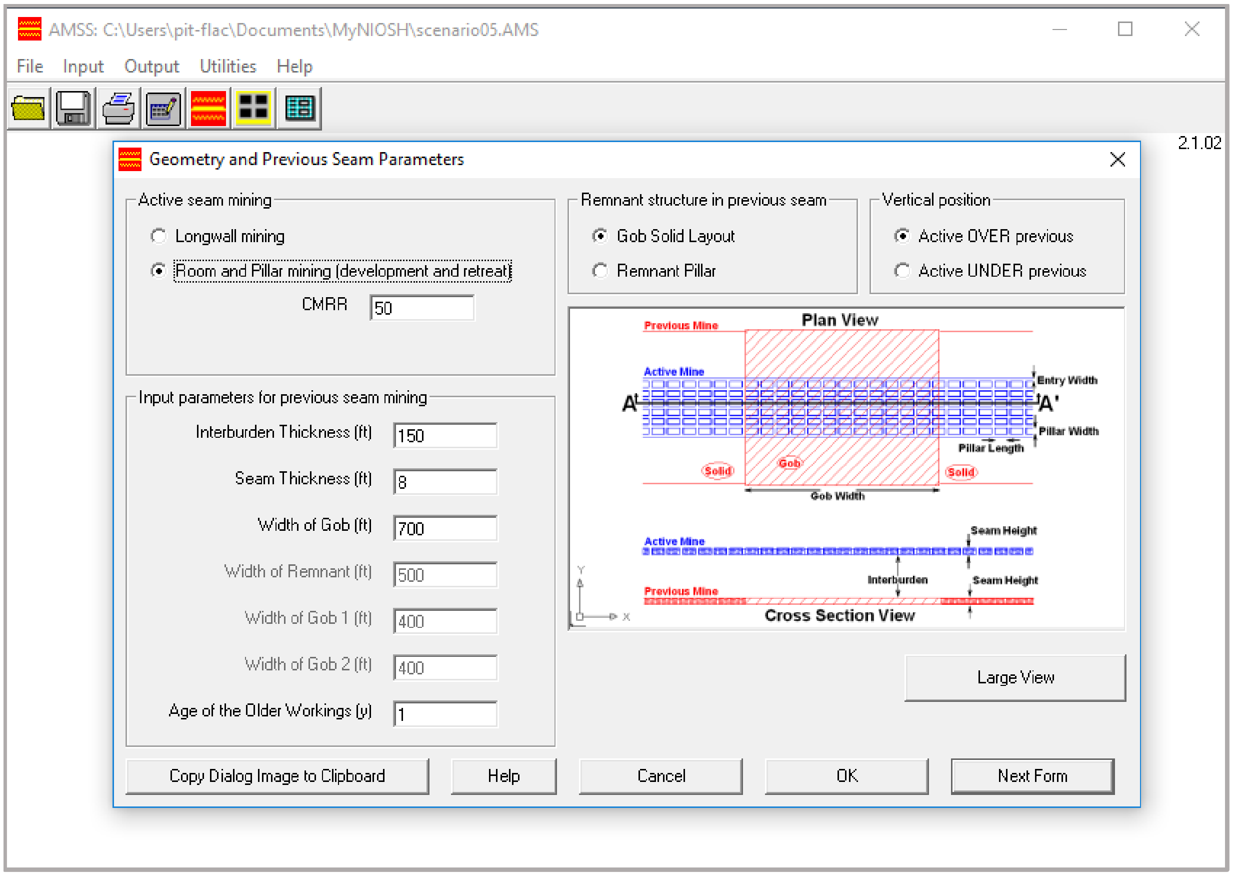
Technical Assistance to Improve Ground Control Safety

Another aspect of NIOSH ground control research is providing assistance to mines experiencing specific problems. During regular research activities at mine sites, opportunities may arise for NIOSH researchers to help improve the safety of the collaborating mines by providing technical assistance. This serves two purposes: It provides NIOSH researchers with insight into emerging stability issues and it facilitates the transfer of solutions that have already been developed.

Technical assistance may also be requested by federal or state agencies where the expert knowledge of NIOSH researchers is required. In these situations, technical assistance to mines leads to direct impacts on safety at the affected mines, facilitating technology transfer and further research that improves ground control in other mines experiencing similar problems.

Support Methods for Multi-Seam Coal Mines

Coal mines that operate in multiple coal seams need to consider the impact of previous mining on current mining operations. Many mines with multiple-seam conditions also practice retreat pillar extraction. These mining practices can result in complex interactions between the workings on the different coal seams. For example, pillars of coal left behind during initial mining on one seam may cause unfavorable stress concentrations on the second seam. These interactions can result in difficult ground conditions and have been responsible for coal bump or burst events, such as the Brody No. 1 Mine accident that claimed two lives in 2014 [MSHA 2014a, MSHA 2014b]. To evaluate simplified multi-seam geometries, the NIOSH-developed Analysis of Multiple Seam Stability (AMSS) software (Figure 49) can be used by mine personnel. However, complex geometries require advanced stress analysis to identify potentially hazardous conditions.



AMSS: C:\Users\pit-flac\Documents\MyNIOSH\scenario05.AMS

2.1.02

Geometry and Previous Seam Parameters

Active seam mining

○ Longwall mining

● Room and Pillar mining (development and retreat)

CMRR 50

Remnant structure in previous seam

● Gob Solid Layout

○ Remnant Pillar

Vertical position

● Active OVER previous

○ Active UNDER previous

Input parameters for previous seam mining

Interburden Thickness (ft)	150
Seam Thickness (ft)	8
Width of Gob (ft)	700
Width of Remnant (ft)	500
Width of Gob 1 (ft)	400
Width of Gob 2 (ft)	400
Age of the Older Workings (y)	1

Figure 49. Screenshot of NIOSH-developed AMSS software for designing longwall or room-and-pillar workings for multiple seam mining operations.

To address this need, NIOSH researchers provided technical assistance to several mines with complex multiple-seam interactions to improve the safety of the operations, including the Darby Fork mine in Harlan, Kentucky. In this case, the mine was extracting coal in a multiple-seam operation and inexplicable stress-related damage occurred along the edge of the panels being extracted. Changes to the layout worsened the problem and MSHA Technical Support Group Roof Control Division requested that NIOSH engineers investigate the issue. After conducting field observations and numerical stress analysis, NIOSH engineers concluded that the problem was most likely related to the severe surface topography causing unusual changes to the stress field [Tulu et al. 2016]. In a second case at the same mine, a need arose to identify the possibility of elevated bump risk during pillar extraction. NIOSH researchers identified four critical parameters affecting the ground stability at this mine: topography-related rotation of the major stress, elevated stress near the gob/solid boundary, significant stress relief underneath pervious gob, and geology-related stress concentrations.

Intermediate Outcome:

- Based on technical assistance from NIOSH researchers, the Darby Fork Mine successfully changed its multi-seam pillar extraction layout to avoid topography-related stress, and also changed all future planning of retreat mining to improve ground stability [Tulu et al. 2014, 2016; Klemetti et al. 2017a].

Gateroad Layout and Support Design for Longwall Coal Mines

In longwall mines, the gateroad entries that provide ventilation and access to the working face are subject to significant stress changes that can result in roof, floor, and rib instability. Gateroad entry and pillar design requires consideration of many complex operational, ventilation, and ground control issues. Besides the obvious hazard of ground fall injuries or fatalities, a ground fall in a gateroad entry can cause ventilation blockages that impact methane control, potentially resulting in an explosion hazard. Evaluating the safety of gateroad systems at a longwall mine requires a broad perspective of industry experience as well as an in-depth review of local geological and stress-related issues at the mine.

Through a combination of geologic analysis, advanced stress analysis, and knowledge of practical solutions implemented at other mines, NIOSH researchers provided technical assistance to several longwall operations to improve the safety of their gateroad layouts, pillar design, and support systems. Two examples represent some of the cases where NIOSH provided such technical assistance.

> *Longwall Mine in Pennsylvania.* A longwall mine operated by Contura Energy was experiencing headgate and bleeder roof control issues associated with changing geology and entry loading conditions. The mine used a traditional longwall pillar layout with equal pillar dimensions. Technical assistance provided by NIOSH engineers resulted in a change in the layout so that the pillars were unequal in size to alleviate headgate loading conditions and improve bleeder stability.
>
> *Three Alpha Natural Resources Mines*. Three Alpha Natural Resources mines operated under deep cover with multi-seam conditions. These conditions can lead to complex interactions between coal pillars and coal remnants on the different mining horizons. Because of the NIOSH-developed design tools LaModel and AMSS, which assess the stability of multiple seam workings, Alpha engineers requested NIOSH assistance in the appropriate application of NIOSH recommendations to their particular conditions.

Intermediate Outcomes:

- Contura Energy applied recommendations based on NIOSH research to improve gateroad roof stability at an operating longwall mine by modifying the pillar layout to alleviate roof control issues [Trackemas 2018].
- Three Alpha Natural Resources mines operating under deep cover with multi-seam conditions implemented NIOSH recommendations on pillar design [Zhang 2018].

Bleeder Entry Design for Longwall Coal Mines

Longwall mines use bleeder entries to route return air from the operating longwall panels to a "bleeder shaft" that extracts the air from the mine. As the result of MSHA concerns about the long-term stability of bleeder entries at their mines, several longwall mine operations requested technical assistance from NIOSH on bleeder stability. Previously no data were available to determine how the distance from the startup line of a longwall panel to the bleeders affects the loading and support response. Engineers at various longwall operations approached NIOSH researchers to assist in the layout and design of support for long-term bleeder entries that connect operating longwall panels to a ventilation shaft. The dilemma faced by mine engineers is that it is less expensive (in relation to development cost and reserve loss) to locate the system of bleeder entries close to the longwall panels; however, the redistribution of overburden stress caused by longwall mining can negatively impact the stability of these entries. The loss of bleeder ventilation would represent a major safety hazard to the mine.

Currently, there are no widely accepted procedures for locating the bleeder entries at an appropriate distance from the edge of the longwall panels. To meet this need, a NIOSH research project into stress redistribution around longwall panels was modified to also include bleeder entry stability. As a result, bleeder stability studies were conducted at five mines around the U.S., and NIOSH researchers provided advice to the collaborating mines on the performance of bleeder entries under long-term loading and offered suggestions for the layout of future bleeder entries [Klemetti et al. 2017b].

Intermediate Outcome:

- Contura Energy applied recommendations based on NIOSH research in the design and support of future bleeder entries at an operating mine [Trackemas 2018].

Longwall Shield Design and Operation at Coal Mines

Longwall shields are used to control the roof at the retreating longwall face, where the shields provide a safe work area for personnel and equipment. Initial shield design to accommodate the ground pressure during longwall mining and shield reliability during operations are two critical issues. The local geological conditions play a significant role in designing shield capacity and operational procedures. With their broad experience related to longwall shield performance in the different coal basins of the U.S., NIOSH engineers were asked to provide technical assistance to shield manufacturers and mine operators on shield design and operation to prevent ground instabilities at the longwall face. Also, while modern longwall shields are too large to test in NIOSH's MRS, the device was used to test older shields to assist a mine operation in deciding whether the shields would be safe for continued use [NIOSH 2013].

Intermediate Outcome:

- A longwall mine in Alabama made use of NIOSH technical assistance and MRS test results to identify potential mechanical issues with its longwall shields. The mine used the test outcomes to make decisions about the continued use of the shields [NIOSH 2013].

Support Design for Limestone Mines

Underground limestone mines rely on the inherent stability of the strong limestone rock to remain stable with a minimum of support. However, geologic structures and tectonic stress in the rock can produce unstable roof and pillar conditions that require additional support or a change in the mine layout. In past cases, NIOSH researchers installed instruments to measure rock deformation and conducted rock strength testing to help operators better understand and address these issues. NIOSH communicated findings of these investigations directly to mine staff. Photogrammetry studies by NIOSH are also used to assess changes in ground conditions as mining progresses.

Three cases where NIOSH provided technical assistance to mines actively seeking advice for support design follow.

> *Petersburg Mine, OH*. At the Petersburg room-and-pillar limestone mine of the East Fairfield Coal Company in Ohio, pillars deteriorated and gradually failed with associated surface subsidence. NIOSH researchers assisted the mine by first identifying the issue as a floor weakness problem rather than a pillar failure problem. Researchers recommended methods of stabilizing the area where weak floor had been identified, and as a result the extent of floor-induced pillar yield was controlled.
>
> *Crab Orchard Mine, TN*. The Crab Orchard Mine in Tennessee mines limestone in a dipping formation that results in very tall excavations in which even minor roof instability can represent a safety hazard. NIOSH engineers assisted the mine geologists in applying NIOSH-developed procedures for assessing ground conditions and in tracking changes in ground conditions to manage better ground control practices.
>
> *Subtropolis Mine, OH*. The Subtropolis mine in Ohio experienced horizontal stress-induced damage to the roof of the room-and-pillar workings despite the shallow depth of cover. NIOSH researchers documented and recommended a method of changing the orientation of the mine workings to alleviate horizontal stress effects [NIOSH 2011d]. The mine implemented the change in mine layout and experienced improved roof conditions.

Intermediate Outcomes:

- The East Fairfield Coal Company in Ohio applied NIOSH-recommended solutions to prevent pillar deterioration at its underground limestone mining operations [Murphy et al. 2015].
- The Crab Orchard Mine in Tennessee implemented the NIOSH-developed Roof Fall Risk Index to enable visual observations of ground defects, rate the hazard of the ground defects, and determine guidelines for ground control interventions [Disney 2017].
- Based on NIOSH input, the Subtropolis Mine in Ohio re-oriented its mine layout to improve ground conditions related to excessive horizontal stress causing damage to the roof rocks [Iannacchione 2018, Murphy et al. 2016; Miller et al. 2018].

Technical Assistance to Improve Data Collection

To advance its work in offering technical assistance to mines in the field, in 2003, NIOSH began to develop the Miniature Data Acquisition System (MIDAS) datalogger to collect geotechnical data from instruments installed in the harsh underground mine environment. MIDAS consists of multiple equipment components working together to provide a high-precision analogue-to-digital datalogging system capable of wired or wireless operation. MIDAS replaces older technology data acquisition systems that are no longer being manufactured. The MIDAS datalogger received MSHA approval and certification for permissibility in 2010. The availability of MIDAS allowed NIOSH ground control engineers and researchers to continue conducting field monitoring in mines that required permissible instrumentation.

Intermediate Outcomes:

- The MIDAS datalogger was licensed to Golder Associates, Ltd., for commercialization in 2013 [Golder Associates 2013].
- MIDAS was used by the Jennmar Corporation to measure standing support response in a longwall tailgate [Mirable and Westman 2018].

Awards Related to Ground Control Research

During the review period, the following were some of the honors awarded to NIOSH researchers, demonstrating the quality and significance of NIOSH research in the area of ground control in mining.

2010—Society of Mining Metallurgy and Exploration, Best of Ground Control Award for technical merit and originality of a paper delivered at the International Ground Control Conference, for “The Ground Response Curve, Pillar Loading and Pillar Failure in Coal Mines.” (G Esterhuizen, C Mark, M Murphy, I Tulu)

2010—Henry Crumb Lecture Series Award, Society For Mining, Metallurgy, and Exploration, SME, 2010 Annual Meeting and Exhibit, for best paper at the Shotcrete Session, “Ground

Support Methodology Employing Shotcrete for Underground Mines.” (R Pakalnis, M Roworth, C Caceres, LA Martin, JB Seymour, P Lourance)

2012—Society of Mining Metallurgy and Exploration, Best of Ground Control Award for technical merit and originality of a paper delivered at the International Ground Control Conference, for “A Stability Factor for Supported Mine Entries Based on Numerical Model Analysis.” (G Esterhuizen)

2013—Best of Ground Control Award, 32d International Conference for Ground Control in Mining (ICGCM), based on the technical originality and merits and quality of presentation, for “Investigation of Pillar Loading Considerations in Determination of Pillar Stability Factors in Longwall Gateroad Design.” (H Lawson, J Whyatt, M Larson)

2014—Best of Ground Control Award, 33rd International Conference on Ground Control in Mining (ICGCM), based on the technical originality and merits and quality of presentation, for “Photogrammetric Monitoring of Rock Mass Behavior in Deep Vein Mining.” (D Benton, S Iverson, J Johnson, L Martin)

2015—South African Institute of Mining and Metallurgy, Silver Medal for a journal paper making a significant impact in rock engineering, for “Extending Empirical Evidence through Numerical Modelling in Rock Engineering Design.” (G Esterhuizen)

2016—Society of Mining Metallurgy and Exploration, Best of Ground Control Award for technical merit and originality of a paper delivered at the International Ground Control Conference, for “Design Concerns for Room and Pillar Retreat Panels in an Eastern Kentucky Mine.” (T Klemetti, I Tulu, M Sears)

2017—Society of Mining Metallurgy and Exploration, Best of Ground Control Award for technical merit and originality of a paper delivered at the International Ground Control Conference, for “Evaluation of Seismic Potential in a Longwall Mine with Massive Sandstone Roof Under Deep Overburden.” (M Van Dyke, W Su, J Wickline)

2018—Society of Mining Metallurgy and Exploration, Coal and Energy Division, Stefanko Best Paper Award for technical quality and quality of presentation, for “Calibration of Coal-mass Model Using In-Situ Coal Pillar Strength Study.” (K Mohammed, G Rashed, M Sears, M van Dyke)

2018—Best Paper Award, American Rock Mechanics Association, Technical Program Committee for the 52nd US Rock Mechanics/Geomechanics Symposium, for best technical quality of the paper and presentation at the 2018 ARMA Seattle symposium, for “Cemented Paste Backfill Geomechanics at the Lucky Friday Mine.” (MJ Raffaldi, JB Seymour, H Abraham, E Zahl, M Board)

2018—Best Paper Award, American Rock Mechanics Association, Technical Program Committee for the 52nd US Rock Mechanics / Geomechanics Symposium, for best technical quality of the paper and presentation at the 2018 ARMA Seattle symposium, for “Long-term Stability of a Large Undercut Span Beneath Cemented Rockfill at the Turquoise Ridge Mine.” (JB Seymour, MJ Raffaldi, SN Warren, LA Martin, LA Sandbak)

Development of Ground Control Expertise

Ground failure incidents could be reduced or eliminated by providing the appropriate experience and expertise in ground control throughout the mining industry. The industry continues to lose expertise and knowledgeable personnel in this area due to a reduction in the number of mines, the need for profitability, the elimination of mining engineering programs at universities, mass retirements, a declining number of graduates in ground control, and a lack of research funds to support training [SME 2013]. The number of trained geotechnical experts available and working in the mining industry significantly decreased over the past three decades [Fairhurst and Furtney 2018]. The decline began with modernization and mechanization of mines and the reduction of universities in the U.S. that maintained a mining engineering program [Fairhurst and Furtney 2018]. Today, very few geotechnical experts work directly for mining companies, with the majority of available expertise limited to a handful of consultants, mining university programs, and government research organizations.

To help address this critical health and safety problem, in FY 2008, NIOSH began awarding capacity-building contracts devoted to building ground control expertise in our nation's workforce. Capacity-building contracts help to produce graduates with advanced degrees in mining and minerals engineering and to develop tenure-track faculty performing research in these areas. Between 2011 and 2018, universities supported by the capacity-building contracts graduated 19 PhD and 28 MS students with expertise in ground control. As of 2018, NIOSH capacity-building contracts were supporting 11 PhD and nine MS students at the Colorado School of Mines, University of Utah, Pennsylvania State University, Virginia Polytechnic Institute and State University, and West Virginia University. This funding also assisted two faculty at the University of Nevada-Reno and at West Virginia University in receiving tenure. While it is difficult to track students after graduation, seven students (four PhD and three MS) who participated in this capacity-building program have been hired by NIOSH. Other graduates have likely gone on to work in industry (mining and underground construction), academia, and consulting, internationally as well as domestically.

As part of their education, these students—as well as other undergraduate and graduate students at their institutions—have developed ground control expertise through exposure to NIOSH publications, software, and design guidelines. They have also been educated by way of conferences and workshops organized by NIOSH researchers which students or their instructors have attended.

Intermediate Outcomes:

- The NIOSH Information Circular, *Pillar and Roof Span Design Guidelines for Underground Stone Mines*, was used as a text for undergraduate students at the University of Pittsburgh and West Virginia University [Esterhuizen 2019a].

- West Virginia University developed modules within several courses that teach students about NIOSH-developed ground control software—specifically ALPS, ARMPS, and S-Pillar [Klemetti 2016].

End Outcomes

A review of MSHA injury data from 2008 to 2017 for underground mines reveals the following trends, shown in Figures 50 and 51 by four-year moving averages. In summary, a total of 45 ground fall fatalities were reported to MSHA in this time period. The four-year average of fatalities at the beginning of this period was 10, while at the end of the period the average was 3.5—a decrease of 65%. Over the same period, the averages for lost-time injuries decreased by 59%. However, it is also important to consider fatality and injury rates to account for changes in employment numbers in this analysis. The average fatality rate started at 19.2 and decreased to 7.6 per 100,000 full time employees—a 60% decrease. For the same period, there was a 52% decrease in injury rates.

Although these decreases cannot be specifically or solely attributed to NIOSH research, it is likely that NIOSH efforts, as evidenced by the intermediate outcomes described in this chapter, have contributed to this decrease.

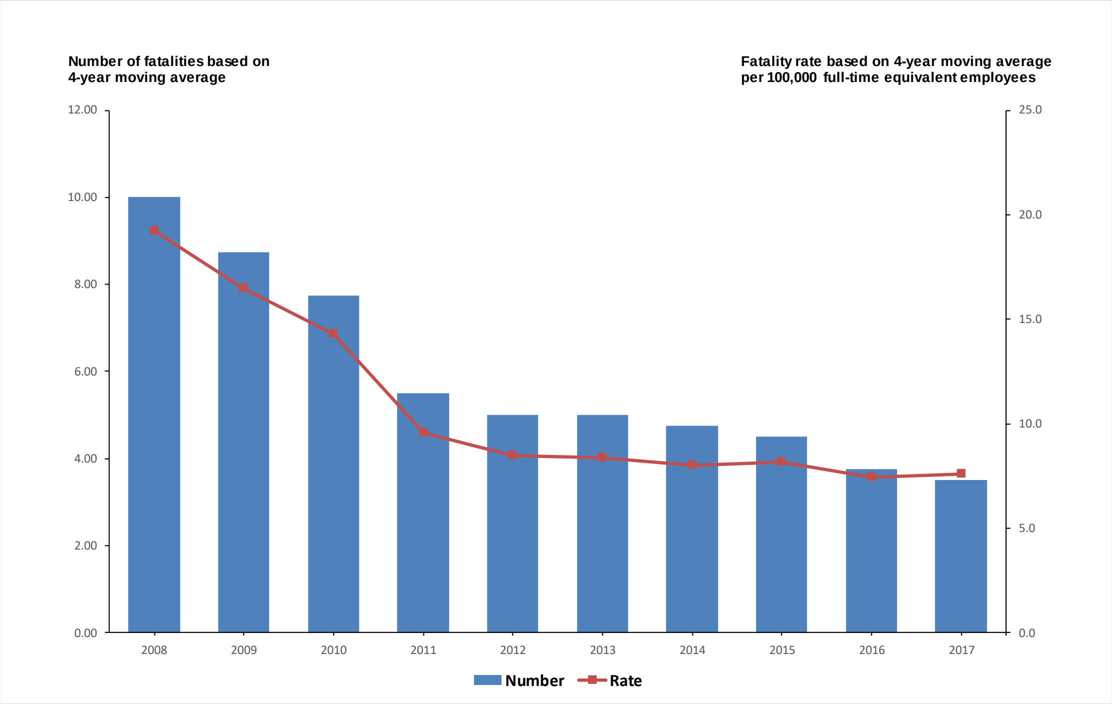


Figure 50. Number and rate of ground fall occupational fatalities for underground mines, 2008-2017. Graphed data from MSHA represent the end years of four-year moving averages. Excludes office employees.

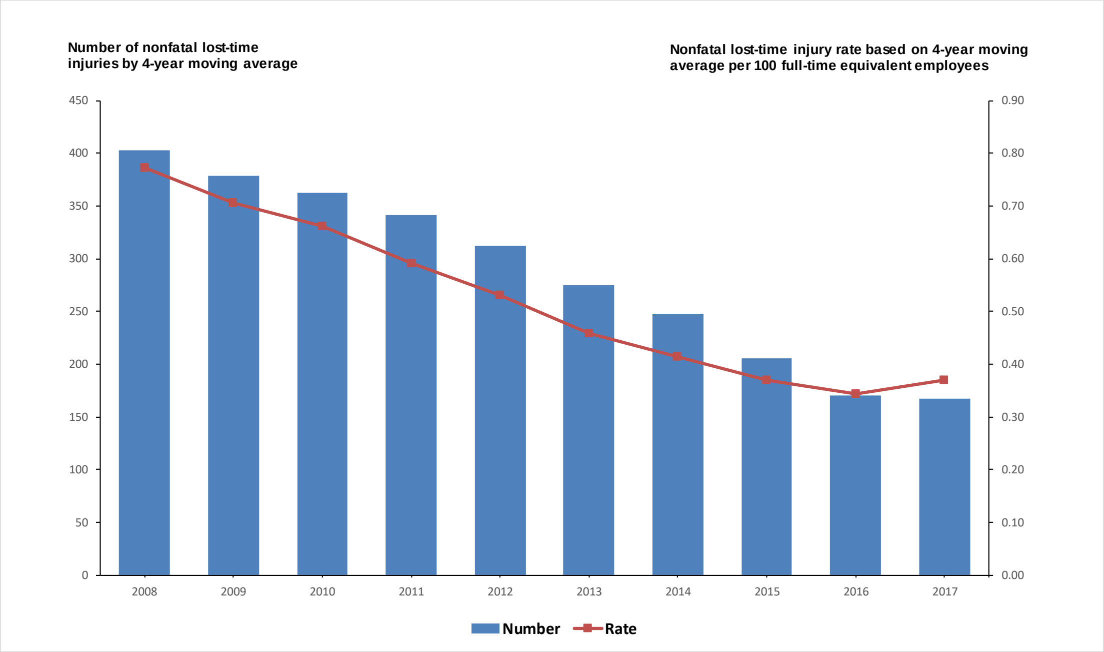


Figure 51. Number and rate of ground fall nonfatal lost-time injuries for underground mines, 2008-2017. Graphed data from MSHA represent the end years of four-year moving averages. Excludes office employees.

Alternative Explanations

While the number and rate of ground fall accidents and injuries within the mining industry have shown a general downward trend from 2006 to 2015 [NIOSH 2015b], and NIOSH efforts have likely contributed to that decline, contributions from other potential sources must also be recognized. Alternative explanations for fatality and injury decreases are grouped into four main categories:

(1) Ground control research and applications outside the NIOSH Mining Program.

(2) New regulations, enforcement initiatives, policies, and programs initiated by MSHA or state regulatory agencies.

(3) Improved mining industry health and safety training.

(4) Changes in the industry, mining methods, or technology.

Ground Control Research and Applications outside the NIOSH Mining Program

During the review period, several significant outputs produced by entities other than NIOSH were adopted by the mining industry. For example, Pariseau [2007] and Pariseau et al. [2008] of the University of Utah studied the design of inter-panel barrier pillars under deep cover in longwall coal mines. As a result, MSHA noted that inter-panel barrier pillars have reduced risk when the depth of cover is greater than 2,000 feet. MSHA further noted that longwall mines should use yield, abutment-yield, or inter-panel barrier pillars appropriate for depth and geology [MSHA 2015a]. These steps resulted in modified designs based on external results that have been accepted by MSHA for use in longwall mines.

In collaboration with NIOSH, in 2004, the Australian Coal Association Research Program (ACARP) developed a comprehensive rib design methodology known as Analysis and Design of Rib Support (ADRS) for Australian underground coal mines. These ADRS procedures are also available to other countries. As an empirical technique, ADRS recognizes that several geotechnical and design factors affect coal rib performance [Colwell and Mark 2004]. In 2009, ACARP published a reference source for the design of ground control measures in coal mine roadways using analytical methods [Seedsman et al. 2009]. The concepts presented in this Australian report also apply to designing rib supports in U.S. coal mines. Thus, new methods and software design products developed internationally may be influencing U.S. designs independently of NIOSH efforts.

In 2009, Foundation Coal developed a Pumpable Crib Standard. The standard specified the requirements for pumpable cribs used in longwall tailgates. In lab testing, it was determined that a 72-inch-high and 30-inch-diameter crib should take at least 150 tons of peak load at about 1-inch initial displacement with a deviation no more than 0.3 inches, and 100 tons of residual load for up to a 6-inch displacement. The standard also specified that new types of cribs should be tested by NIOSH before being used initially and that six cribs be tested annually or bi-annually thereafter.

Finally, from the late 1990s to the present, several private consulting companies have developed and applied various ground control technologies based on geophysical sensing techniques. These technologies have been adopted in both mining and civil engineering ground characterization by companies that include Stolar Global, Amberg, NSA Engineering, Geonics, and Geometrics, to name a few [Dickmann and Krueger 2013; Dickmann 2012; Descour et al. 2012; Duncan and Stolarczyk 2014; Hatherly 2013]. Application of these techniques provides information on the properties and condition of material around mine openings, and so provides better data for input to various design programs along with supplying information on ground stability, thus potentially reducing ground control risks.

New Regulations, Enforcement Initiatives, Polices, and Programs Implemented by MSHA or State Regulatory Agencies

During the review period, regulators implemented new regulations and initiatives due to a number of factors affecting ground control safety in mines. These changes, detailed below, likely contributed to a reduction in ground control-related injuries.

In 2005, MSHA launched the Preventive Roof/Rib Outreach Program (PROP), focusing on roof and rib fall accidents occurring in supported areas. This program emphasized safety procedures and best practices to employ around coal mine roof and ribs. Improvements in roof control technology in underground coal mines have significantly reduced accidents involving roof and rib falls or coal bursts, but such accidents remain a leading cause of injuries. Therefore, MSHA launched PROP to raise awareness of potential risks due to roof and rib falls.

Over the course of several years, MSHA instituted several regulations and policies designed to reduce accidents. While it is difficult to directly attribute accident reduction to any one of these, in aggregate they likely reduced the overall accident rate. These include:

- MSHA Technical Support created a Risk Evaluation Matrix for MSHA District Managers to evaluate the risk levels of unconventional gas wells in a longwall mine [MSHA 2018].
- MSHA instituted a revised rule for Pattern of Violations [MSHA 2013].
- MSHA began a special enforcement initiative targeting mines that have poor compliance histories with “impact inspections” [MSHA 2010].
- MSHA increased mandatory inspections to include 100% compliance for metal/nonmetal mines from 2008 to 2015 [MSHA 2010].
- MSHA created a Rules to Live By Initiative that began in 2010 [MSHA 2017].
- MSHA issued an Examination of Working Places program policy letter No. P15-IV-01 [MSHA 2015b].
- MSHA issued a Reporting of Unplanned Roof Falls program policy letter No. P12-V-03 [MSHA 2012].

Other MSHA regulatory and policy initiatives included MSHA District 9 sending a letter in August 2014 [MSHA 2014c] to mine operators requiring that roof control plans be amended (where depth of cover exceeded 1,200 feet) to include additional training, monitoring, communication, MSHA notification, and required actions for safety in relation to coal or rock outbursts. Also, in August 2015, MSHA launched aggressive enforcement and outreach actions in response to events in 2014 and 2015, when three miners died in separate accidents in Nevada, North Dakota, and Virginia. The campaign ultimately helped to reduce fatalities to an all-time low of three in the seven months that followed. Falling materials was highlighted as a leading cause of fatalities during the campaign [MSHA 2010].

Finally, in November 2017, the Pennsylvania and West Virginia Departments of Environmental Protection, MSHA, and the coal and gas industries created a Technical Guidance Document (TGD) for chain pillar development and longwall mining adjacent to unconventional wells [PADEP 2017].

Improved Mining Industry Health and Safety Training

Improved safety in any industry, not just mining, requires constant vigilance, training, and commitment from staff and management to maintain a safe working environment. During the review period, various programs were initiated or continued to provide miners with updated training. Some programs addressed specific examples of safe and unsafe conditions, and others addressed changes in the culture of safety awareness. Both of these approaches can contribute to overall accident reduction.

In 2007, MSHA awarded the Pennsylvania State University $50,000 to develop education and training materials for MSHA instructors and new underground stone miners. Mine instructors use the updated and improved training materials during 40-hour new miner training to help miners better understand the hazards posed by the mining process [Schmidt 2007].

The CORESafety program instituted by National Mining Association has attempted to teach and create a culture of safety management to reduce accidents and fatalities in the mining industry [NMA 2014]. Safety culture standards from other countries are being introduced into U.S. mines as they are acquired by international companies located in countries such as Australia, Canada, and Sweden. In addition, mining companies have changed internal protocols and standards for training and reporting to receive certifications from the International Organization for Standardization (ISO) that result in decreased insurance rates, better credit ratings, and improved stock prices.

Safety in mining is also becoming a more common topic addressed at various conferences and seminars. This provides another ongoing venue for safety training that can have an impact on accident rates. As an example, the Kentucky Blasting Conference is an annual meeting for blasters to review the basics of blasting methods, learn about the latest techniques, and earn continuing education hours for the renewal of their blaster's license. Proper blasting is the start of good ground conditions in underground stone mines. Another example is the annual Underground Stone Safety Seminar, where NIOSH researchers give technical presentations and support manufacturers such as Minova and Strata typically give an update on the latest ground control solutions for underground stone mines. These companies also routinely visit operations to teach proper bolting installation techniques and to evaluate unique ground control issues.

Changes in the Industry, Mining Methods, or Technology

While changes in regulations, training, and ground control research may have reduced accident rates and risks to miner health and safety, changes in the way mining is conducted and fundamental changes in the industry itself may also have contributed to the observed decrease in accidents. In addition, when smaller operators are purchased by larger corporations, the larger companies typically have more robust safety programs in place and employ a senior mining engineer or senior geologist that can evaluate ground control issues at the mine.

Replacement of the handheld jackleg drill—so named because workers used a hydraulic leg to change the drill height—with mechanical bolters has removed workers from unsupported ground near the face. Mechanized bolting has also facilitated installation of inflatable rock bolts in weak rock masses [Sandbak

2014; Kendall and Ferster 2014]. Another possible explanation for reduction in rock fall-related accidents is that automation reduces the requirements for miners to work at the active face where loose rock exposure occurs. One example of automation is the use of rock cutting rather than blasting, while another is the growing use of automated stopers in hard rock applications.

Numerous changes took place in the mining industry between 2008 and 2018, including improvements in ground control techniques, advanced blasting techniques, improved monitoring, changes in regulation and policies, and an overall decrease in the number of operating mines.

Future Activities

As surface and near-surface mining deposits are depleted, future mining will take place deep underground in challenging environments. Conditions likely to be found in these mines will stretch the limits of current mining practices. New technologies to manage environmental factors and to stabilize highly stressed or incompetent rock mass will be needed. Mechanization and automation can offer solutions that reduce many health and safety risks by removing miners from hazardous conditions. New mining methods using mechanical excavation, such as that found in coal mines, can eliminate the need for drilling and blasting in metal mines, opening the possibilities for new mining geometries that improve ground control.

NIOSH researchers will continue to explore both fundamental and practical ground control questions and to work with existing and seek new collaborating mine partners on the design and evaluation of engineered support that is compatible with automated mining techniques and equipment. To gain a better understanding of the root causes of mine corrosion and the sensors most applicable for its measurement, NIOSH will investigate new techniques that offer wider-scale volumetric information to provide more cost-effective, accurate, and informative data to mine personnel. Through continued research, NIOSH will provide operators with a method for quantifying the innate risk of dynamic failure of underground mine structures in the context of the overall rock mass excavated, so that they can plan pre-emptive and preventative strategies accordingly.

Finally, as the mining industry necessarily expands its utilization of big data, sensor integration, and automation, NIOSH plans new research that will create a blueprint for filling technology gaps in the collection, analysis, and display of pertinent geomechanical and ground control data for automated mining systems. As miners are removed from the active mining areas by automated and instrumented equipment, the need for sensor systems and data integration that can provide rapid, actionable data will grow exponentially. The mining industry will rely on NIOSH research in order to exploit automated hardware with ground control sensor packages that can remove miners from the most hazardous location in the mine—the working face.

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Chapter 4: Respirable Hazards

Photos by NIOSH

Introduction

Mining processes release airborne particulate due to fracture of in situ materials; breakage of minerals and ores during extraction, transport, and processing; emissions of residual dusts due to disturbances by air or equipment movement; and combustion of diesel fuel. When present in a miner's breathing zone, the respirable-sized dust is able to penetrate deeply into the lungs, potentially causing extensive damage [Kennedy 2007] and health consequences, including coal workers' pneumoconiosis (CWP), silicosis, cardiovascular disease, chronic obstructive pulmonary disease, and lung cancer [Dockery et al. 1993].

CWP is a result of overexposure to respirable coal mine dust (RCMD). NIOSH reports that CWP has been an underlying or contributing cause of death for 78,620 U.S. miners from 1968 to 2016 [NIOSH 2018a]. The NIOSH Coal Workers' Health Surveillance Program (CWHSP) continues to identify CWP in the coal mining workforce. From 2010 to 2015, 12.7% of all new CWP cases involved miners with less than 15 years of experience [Smith 2015]. The Central Appalachian region, including KY, VA, and WV, is experiencing a resurgence in the disease, especially among longer-tenured miners, with one of every five workers with more than 25 years of experience having CWP [Blackley et al. 2018a]. Nationally, the prevalence of CWP in this same age segment now exceeds 10% for the first time in a generation. CWP presents a significant economic burden, with federal compensation paid to miners and survivors exceeding USD 46 billion since 1968 [NIOSH 2018a]. In response to the ongoing incidence of this preventable disease, on May 1, 2014, the U.S. Mine Safety and Health Administration (MSHA) published a final rule, "Lowering Miners' Exposure to Respirable Coal Mine Dust, Including Continuous Personal Dust Monitors," that reduced the permissible exposure limit (PEL) for coal mine dust, changed sampling procedures and equipment, and expanded CWP surveillance.

Crystalline silica is a common component of respirable dusts encountered in all mining sectors. Exposure to respirable crystalline silica (RCS) is associated with the development of silicosis, lung cancer, pulmonary tuberculosis, chronic obstructive pulmonary disease, autoimmune disorders, and chronic renal disease [Stayner 2007]. The International Agency for Research on Cancer (IARC) has classified RCS as a Group 1 human carcinogen, which further emphasizes the importance of the health hazards associated with exposure [IARC 2012]. NIOSH researchers found that from 2001 to 2010, silicosis resulted in 1,437 deaths in the U.S. as either an underlying or contributing cause [NIOSH 2014a]. During a similar time (2003–2010), among selected states that report industry and occupation information for decedents, mining and mineral production was the most frequently cited industry on death certificates where silicosis was listed as a multiple cause of death, accounting for 21.75% of silicosis deaths [NIOSH 2018b].

All U.S. mining sectors use diesel-powered equipment extensively. Over 5,000 diesel engines provide power to production, maintenance, and transportation equipment in 185 underground coal mines [Bugarski and Barone 2016]. An additional 7,700 diesel-powered units are employed in 177 underground metal/nonmetal (MNM) mines. As a result, underground miners in the U.S. are exposed to aerosols and gases emitted by diesel engines. Exposure to diesel particulate matter (DPM) can result in the development of several adverse health effects, including lung cancer [IARC 2014].

NIOSH observed 327 deaths in the coal mining sector due to lung cancer in 1999 [NIOSH 2008a]. This resulted in a statistically significant (95%) proportionate mortality ratio (PMR) of 1.3, indicating an elevated risk of death compared to the population at-large. In addition, a cohort mortality study of U.S. underground coal miners documented excess lung cancer mortality [Graber et al. 2014]. Exposure of underground miners to diesel aerosols is higher than in all other industries and occupations [Pronk et al. 2009]. Although the average exposure, as determined from MSHA compliance sampling for the period between 2009 and 2016, is below the existing standard, over 20% of the compliance samples exceeded the standard [MSHA 2018a]. These exposures are predicted to result in numerous deaths due to lung cancer. Peters et al. [2016] estimated that exposure to DPM at levels of 14 and 44 µg/m^3, which is lower than the average exposure level in U.S. mines, could cause 55 and 380 extra lung cancer deaths per 10,000 males, respectively.

In consideration of the above facts, NIOSH continues to address key research gaps to improve the understanding of miners' respirable exposures and health outcomes and to develop effective engineering solutions. The focus of these efforts over the last decade has been on lowering exposures to RCMD, RCS, and DPM.

Logic Models

The logic models in Figures 52 and 53 illustrate the progression from primary inputs to ultimate outcomes, describing NIOSH's research and other activities to reduce respirable dust and diesel exposures in the Mining Sector. The components of the logic model are Inputs, Activities, Outputs, Transfer and Translation, Intermediate Outcomes, and End Outcomes. The sections that follow describe each element in detail.

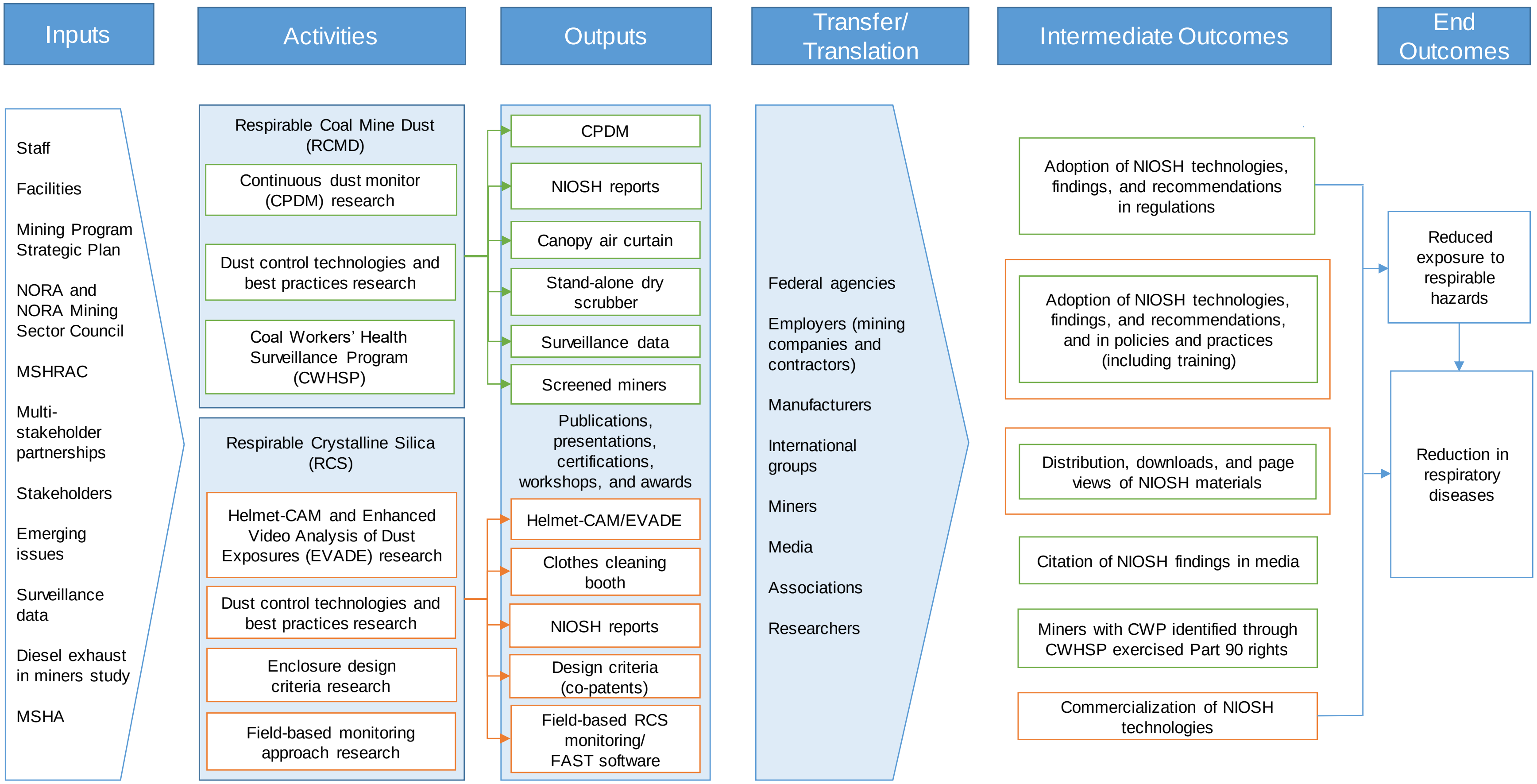


Figure 52. Logic model for respirable coal mine dust and respirable crystalline silica.

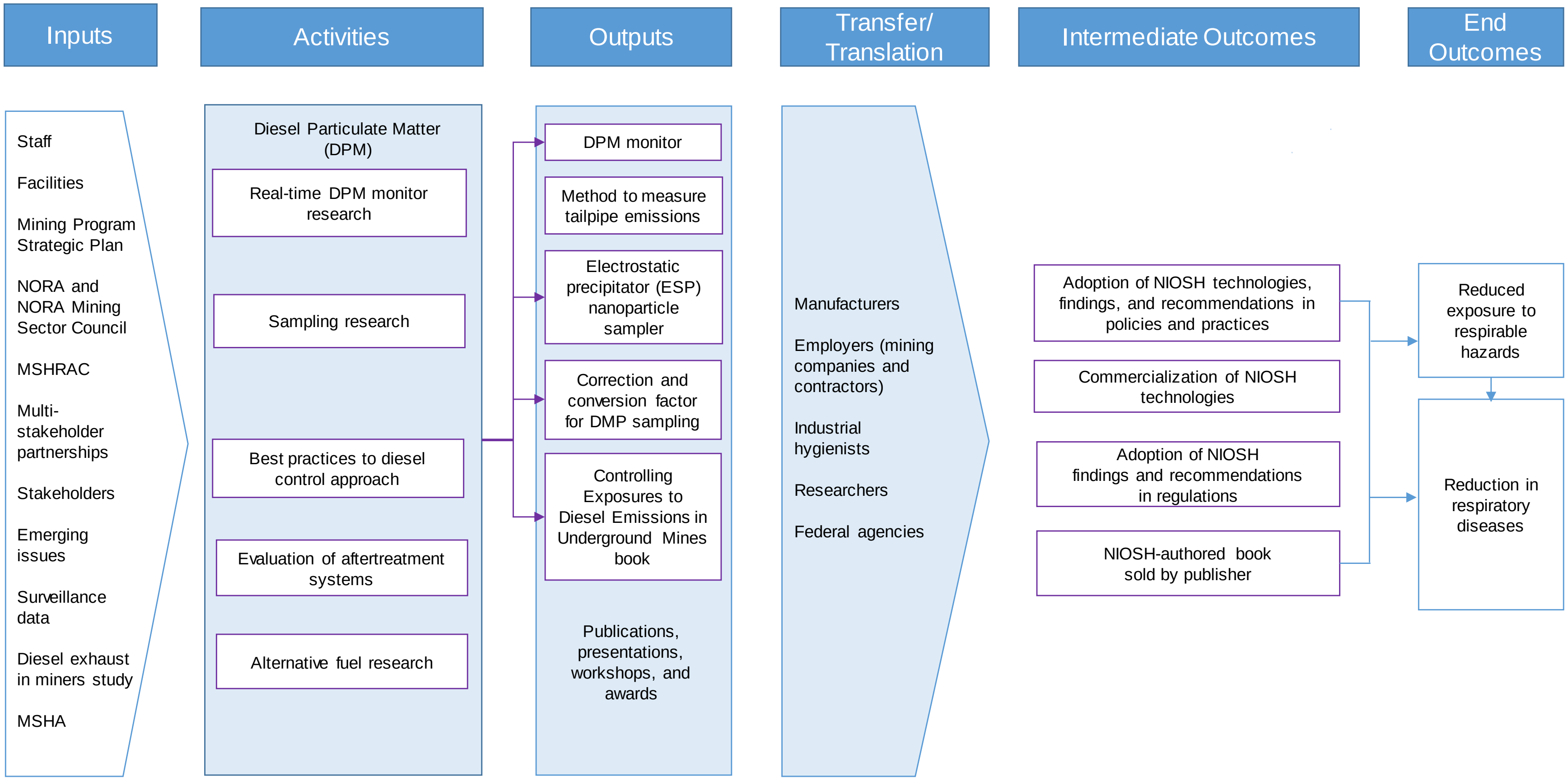


Figure 53. Logic model for diesel particulate matter.

Inputs

Staff

NIOSH staff conduct respiratory hazard monitoring and control research for mining in both field and laboratory settings as well as epidemiological research using respiratory health surveillance and health indicator databases. Field research is closely coordinated with industry stakeholders and requires active participation by mine operators and employees. Staff members represented the Pittsburgh Mining Research Division (PMRD), the Spokane Mining Research Division (SMRD), and the Respiratory Health Division (RHD). Expertise by staff included mechanical engineering, epidemiology, and industrial hygiene. During the 2008–2018 review period, the individuals listed in Appendix F were instrumental in advancing NIOSH research in respirable hazards.

Facilities

Lake Lynn Laboratory Experimental Mine

The Lake Lynn Laboratory Experimental Mine (LLEM), described and pictured in the Overview chapter, pp. 9–10, was an important facility for respirable hazards research. To assist the mining industry in choosing catalytic converters, diesel particulate filters, and exhaust aftertreatment systems that would be mine-worthy candidates, NIOSH researchers evaluated a number of commercially available products at the LLEM. In this facility, researchers also evaluated the potential for using specialized fuels as a control strategy to reduce exposures of underground miners to DPM. Test results and actions taken by manufacturers based on LLEM work are described later in this chapter.

Laboratories

NIOSH has unique, state-of-the-art respiratory hazards research facilities. Industrial and analytical laboratory spaces allow researchers to simulate actual mining environments while using precision instrumentation unable to be deployed in underground settings. Controls and equipment tested in these laboratories have a greater chance of success when transfered to surface or underground mine environments.

Reproducing underground coal production areas and activities, NIOSH’s full-scale continuous miner and longwall mining galleries (CM Gallery and LW Gallery, respectively) are essential to testing and developing effective coal mine dust controls. Likewise, a diesel research laboratory (Diesel Lab), consisting of engine dynamometers and state-of-the-art exhaust characterization instrumentation and equipment, supports research on alternative fuels, advanced engine technologies, and exhaust aftertreatment technologies. Tests performed in stable environments provided by Marple aerosol test chambers (Aerosol Lab) facilitate advancements in exposure monitoring and sample analysis. Supporting these research activities is an environmentally controlled gravimetric measurement laboratory. This laboratory employs the LabX management platform for automatic data handling and standardized process control. Figure 54 presents a collage of these four test laboratories.

Photos by NIOSH

Figure 54. NIOSH respiratory hazards research facilities. Clockwise from top left: LW Gallery, Aerosol Lab, Diesel Lab, and CM Gallery.

CWHSP Mobile Respiratory Health Screening Unit

The CWHSP mobile respiratory health screening unit (Figure 55) provides a mobile facility that offers respiratory health screening to coal miners at the coal mine site and in mining community locations at no cost in coal mining states within the United States. The unit travels to different mining regions starting each spring and continues through the summer.

Photos by NIOSH

Figure 55. The CWHSP mobile health screening unit, which makes annual visits to mines and mining communities throughout the U.S.

Mining Program Strategic Plan

All NIOSH Mining Program research efforts align with goals established in the 2010 Strategic Plan reviewed and accepted by Mine Safety and Health Research Advisory Committee (MSHRAC), as described in the Overview chapter, pp. 19–20. In the context of respirable hazards, NIOSH health research is conducted under the following strategic goals and associated intermediate goals.

Strategic Research Goal 1: Eliminate respiratory diseases in mine workers by reducing exposure to airborne contaminants.

Intermediate Goal 1.1: Develop field-ready instrumentation and utilization software to improve the monitoring of airborne contaminants in mining operations.

Intermediate Goal 1.2: Reduce exposure to respirable coal dust for longwall miners, especially shearer operators and jacksetters, by developing control technologies that optimize face ventilation.

Intermediate Goal 1.3: Reduce coal miner exposure to respirable silica dust by developing control technologies that reduce exposures for the highest risk occupations.

Intermediate Goal 1.4: Reduce the respirable silica dust exposure of workers in MNM mines and mills by developing improved control technologies to reduce exposure in high-risk occupations.

Intermediate Goal 1.5: Reduce miner exposure to diesel emissions in underground mines by identifying effective control technologies and control strategies.

Intermediate Goal 1.6: Characterize the physical, chemical, and toxicological properties of aerosols emitted by diesel engines and aftertreatment systems.

The National Occupational Research Agenda and Mining Sector Council

The National Occupational Research Agenda (NORA), described in the Overview chapter, pp. 20–21, includes eight strategic objectives. From these, this chapter addresses the following objectives and sub-objectives:

- Objective 3: *Prevent Illness from Occupational Health Hazards*
    - 3.1: Eliminate exposures that lead to respiratory diseases
    - 3.6: Improve health surveillance in mining
    - 3.7: Correlate dust-exposure levels with dust-control technologies
    - 3.8: Diesel particulates researchers working with diesel particulates should review the current diesel particulate standard against values used in other countries
- Objective 4: *Improve Atmospheric Control (Ventilation) in Mines*
    - 4.1: Improve air quality and quantity in mines: The threshold values for safe and healthy mining
    - 4.6: Improve the performance of face ventilation and scrubbers
- Objective 8: *Surveillance*
    - 8.3: Trends and data gaps in miners’ health
    - 8.5: Dust data in metal/nonmetal mines

Mine Safety and Health Research Advisory Committee

Mine Safety and Health Research Advisory Committee meetings provide an opportunity for NIOSH to share progress on current respirable hazards research and discuss future research directions with committee members. These interactions have led to successful collaborations with stakeholders; development of project proposals and research that address stakeholder needs; and increased adoption of control interventions demonstrated by NIOSH research. In a committee meeting on May 9-10, 2017, NIOSH provided an in-depth review of respiratory hazard control research and received positive feedback on the relevance and potential success of ongoing dust control technology developments.

Multi-stakeholder Partnerships

Partnerships are a key input to the success of the NIOSH Mining Program. By providing relevant and real-world insight, stakeholder groups help to improve the success and impact of NIOSH research priorities. Key partnerships and stakeholders relevant to respirable hazards research are detailed below.

Coal Diesel Partnership and Metal/Nonmetal Diesel Partnership

In 1999, in anticipation of MSHA rules limiting DPM exposure of underground coal miners, "Diesel Particulate Matter Exposure of Underground Coal Miners," and MNM miners, "Diesel Particulate Matter Exposure of Underground Metal and Nonmetal Miners," underground mining stakeholders formed the Coal Diesel Partnership. A Metal/Nonmetal Diesel Partnership followed in 2001. Each Partnership had the objective of addressing issues related to the exposure of underground miners to DPM and gaseous emissions. These initiatives resulted in many favorable interactions and led to numerous NIOSH field studies. Though these two partnerships are no longer active, they laid the foundation for NIOSH coal and metal/nonmetal research which continues to create usable outcomes in many areas described later in this chapter.

Diesel Exhaust Health Effects Partnership

Following a 2016 MSHA Request for Information (RFI) in the Federal Register, "Exposure of Underground Miners to Diesel Exhaust," NIOSH and MSHA formed a Diesel Exhaust Health Effects Partnership to provide a forum for the dissemination of information, discussion of best industry practices, and input for diesel research and further analysis. This Partnership organized a series of annual public meetings, with the most recent during the review period being held on July 27, 2018. At this meeting, NIOSH presented information on the current exposure level trends and existing technologies and strategies that are available to industry to curtail diesel emissions and exposures. This partnership improved the quality of a current NIOSH diesel control project and has offered a mechanism to effectively transfer research results.

Stakeholders

Industrial Minerals Association–North America

The Industrial Minerals Association–North America (IMA-NA) is a trade association representing companies that mine or process industrial minerals, including bentonite, calcium carbonate, industrial sand, mica, soda ash and talc. On an annual basis, NIOSH attends and presents research findings at the IMA-NA Industrial Minerals Technology Workshop. Interactions with members of the association at these workshops help to refine product outputs and identify gaps in NIOSH's research portfolio. The development of a dust control handbook for industrial minerals mining and processing operations—discussed in more detail later—is one example of a product that resulted from these regular interactions between NIOSH and the IMA-NA.

National Stone, Sand & Gravel Association

The National Stone, Sand & Gravel Association (NSSGA) is the leading industrial association for aggregates producers. In June 2014, NSSGA met with NIOSH leadership to partner in the development of technologies to reduce worker injuries and illnesses. At the meeting, NIOSH researchers shared progress on respirable hazard control efforts. Feedback from NSSGA representatives about their needs helped in the development of the NIOSH Helmet-CAM and field-based silica monitoring. As a continuation of this initiative, NSSGA hosted a January 2018 webinar on NIOSH RCS measurement efforts and video exposure monitoring—each described later in this chapter.

Trade Unions

Trade unions typically provide input to NIOSH through participation in MSHRAC meetings as well as through partnerships, as discussed in more detail in the next section. The current MSHRAC Charter requires three labor appointees to serve on the 10-member committee. Current representation includes the International Representative for the United Mine Workers of America (UMWA); the Director of Health, Safety and Environment for the United Steelworkers (USW); and the Director of Health and Safety for the International Union of Operating Engineers (IUOE).

Emerging Issues

NIOSH identifies emerging issues through surveillance activities (detailed in the Surveillance Data section); interactions with MSHRAC and other stakeholders; actions by other government agencies; toxicology research; and through field-based research. The following emerging issues have driven research during the review period.

- MSHA published a final rule, “Lowering Miners’ Exposure to Respirable Coal Mine Dust, Including Continuous Personal Dust Monitors,” that reduced the PEL for coal mine dust.
- There was an ongoing increase in the prevalence of CWP nationally, with marked increases in prevalence and severity in Central Appalachia [Blackley 2016; Blackley et al. 2018a; Blackley et al. 2018b].
- In 2008, under MSHA’s notice of enforcement of DPM, “Diesel Particulate Matter Exposure of Underground Metal and Nonmetal Miners,” the reduced MSHA PEL for DPM of 160 µg/m^3 of total carbon became effective.
- Diesel exhaust was classified as a Group 1 human carcinogen by the IARC [IARC 2012].

Surveillance Data

Several surveillance data resources inform NIOSH’s efforts to mitigate the incidence of lung disease in the mining workforce. Coal worker respiratory disease surveillance and miner exposure data inform research targeting key occupations and activities within the coal industry. In the MNM industry, although no comprehensive health surveillance system is in place to monitor health outcomes amongst workers [Yeoman et al. 2016], exposure data and extensive studies have allowed focused measures to better monitor and prevent exposures. The information gained from these sources has additionally provided a better understanding of the work conditions that resulted in certain health outcomes. These surveillance data sources include five major inputs, as detailed below.

CDC, National Center for Health Statistics, National Death Index

The National Death Index is a centralized and standardized health outcome database containing death records, including underlying cause of death information for individuals across the U.S. Coded by medical professionals, these health outcomes may be associated with a work history in a particular industry or industry sector. NIOSH frequently uses this resource to estimate mortality rates and years of potential life lost due to occupational lung disease, especially CWP [Mazurek et al. 2018].

NIOSH Coal Workers' Health Surveillance Program

Respiratory health screening acquired through the NIOSH CWHSP continues to inform NIOSH research. While eligible miners may seek screenings at approved health facilities, NIOSH also offers screenings through its mobile facility pictured in Figure 55, p. 172. Miners participating in screening provide a detailed work history and answer respiratory health assessment questions, after which they receive a chest radiograph, blood pressure screening, and a spirometry (lung function) test. A visit to the mobile facility typically takes 30 minutes. NIOSH subsequently provides individual miners with the results of their own screenings. By law, each person's results are confidential, and no individual information is publicly disclosed.

Through this program, eligible coal miners can receive periodic chest radiographs and lung function testing. This information forms the basis for much of NIOSH's coal miner health surveillance, with many publications produced since the CWHSP was initiated in 1970 [Halldin et al. 2017; Halldin et al. 2016; Reynolds et al. 2018; Reynolds et al. 2017; Blackley et al. 2018a; Laney et al. 2017].

Department of Labor, Office of Worker's Compensation Programs, Black Lung Benefits Program

Claims data from the Department of Labor's Office of Worker's Compensation Programs Black Lung Benefits Program [DOL 2018] are used in conjunction with data gathered by NIOSH to identify possible risk factors and concentrated geographic areas of Black Lung Benefits recipients [Almberg et al. 2017]. This administrative database contains almost 1 million records from over 300,000 former coal miners who have applied for federal benefits since 1970. NIOSH has used this compensation data to confirm the resurgence of progressive massive fibrosis, the most severe form of CWP, in U.S. coal miners [Almberg et al. 2018].

Health Resources and Services Administration, Black Lung Clinics Program

The Health Resources and Services Administration (HRSA), Federal Office of Rural Health Policy, operates a Black Lung Clinics Program to support medical clinics in seeking out and providing services to coal miners, whether they are currently involved in mining or not [Program Grants for Black Lung Clinics 2007]. As of 2018, according to an HRSA database, there were 15 clinics operating in 11 states. These clinics regularly collect medical, occupational, and demographic data from patients. NIOSH has used this information on a clinic-level basis to evaluate patient populations and better understand the demographics and characteristics of these former miners who would not be evaluated through the

CWHSP, which has a mandate that only covers active miners [Blackley 2016; Blackley et al. 2018b; Reynolds et al. 2018].

MSHA Compliance Data Sets

Within the U.S. mining industry, mine operators and MSHA inspectors collect occupational dust samples for compliance and enforcement purposes. These form the basis of a database containing respirable dust and RCS concentrations by mining occupation. NIOSH frequently references this information to select research priorities, targeting those mining occupations with the highest rate of overexposure. For example, high rates of respirable coal dust overexposure for longwall face occupations have led to ongoing research on the use of foams for longwall dust control [Reed et al. 2017; Reed et al. 2018]. Additionally, using MSHA's data on mine-level compliance with health regulations, NIOSH researchers observed a correlation between mine compliance with health regulations and fewer mine-level counts of occupational respiratory diseases [Yorio et al. 2018].

Diesel Exhaust in Miners Study

NIOSH and the National Cancer Institute collaborated to complete a retrospective study on the risk of lung cancer by investigating exposures and mortality in the mining industry. Completed in 2012, the Diesel Exhaust in Miners Study identified elevated rates of mortality due to lung cancer. This study was a contributor to the action by the IARC, classifying diesel particulate matter as a known carcinogen, and reinforced NIOSH's determination to develop improved diesel emissions control strategies and technologies.

Mine Safety and Health Administration

In order to mitigate the risk of occupational lung disease, MSHA regulates respirable dust and diesel particulate matter exposures in U.S. mines. PELs are established through the MSHA rulemaking process and vary based on mining sector and aerosol of concern. For coal mines, in the Code of Federal Regulations (CFR) 30 CFR 70.100, "Respirable Dust Standards," MSHA has established a PEL of 1.5 mg per cubic meter (1.5 mg/m^3) of air for RCMD. In 30 CFR 70.101, "Respirable Dust Standard when Quartz is Present," the standard further specifies that the RCS concentration be maintained under 100 µg/m^3. If RCS exposure exceeds 100 µg/m^3, a reduced dust standard is calculated by dividing 10 mg/m^3 by the % RCS in the sample. However, the applicable standard can never exceed 1.5 mg/m^3.

In the MNM industry, MSHA also regulates such that RCS dust exposure remains below 100 µg/m^3. When the RCS in a sample is greater than 1%, an applicable respirable dust standard is calculated by dividing 10 mg/m^3 by (% RCS + 2) [MSHA 2018b].

In 30 CFR 57.5060(b)3, "Limit on Exposure to Diesel Particulate Matter," MSHA's MNM standards further require a miner's personal exposure to DPM to not exceed an average eight-hour full-shift equivalent of 160 micrograms of total carbon (TC) per cubic meter of air (160_{tc}µg/m^3). Diesel particulate matter has no similar mass concentration limit in coal mines because regulators felt that respirable coal dust would interfere with the measurement of organic carbon. However, MSHA requires that tailpipe emissions meet standards for gases and particulate matter in 30 CFR 75.322, "Harmful Quantities of Noxious Gases"; 30 CFR 72.500, "Emission Limits for Permissible Diesel-powered Equipment," and 30 CFR 72.501, "Emission Limits for Nonpermissible Heavy-duty Diesel-powered Equipment, Generators and Compressors"; and 30 CFR 72.502, "Requirements for Nonpermissible Light-duty Diesel-powered Equipment other than Generators and Compressors."

Activities, Outputs, Transfer and Translation, and Intermediate Outcomes

Based on the inputs described above, NIOSH Mining Program research during the review period focused on three overarching areas: *respirable coal mine dust*, *respirable crystalline silica*, and *diesel particulate matter*. Because of the distinctive nature of each of these research efforts, these areas will be described separately in three major sections below.

Respirable Coal Mine Dust

This research area focuses on identifying interventions that successfully reduce RCMD dust exposures and promoting implementation of these interventions within the mining industry—interventions that reduce RCMD include technologies, work practices, training approaches, and timely and accurate monitoring of the mine environment that empowers workers to identify and correct conditions that lead to overexposures.

Personal Dust Monitor (PDM) / Continuous Personal Dust Monitor (CPDM)

Commercialization of the PDM

In 1995, the Secretary of Labor established an Advisory Committee on the Elimination of Pneumoconiosis Among Coal Mine Workers to examine how to eliminate CWP. The committee issued a report [MSHA 1996] with numerous recommendations related to respirable dust control and sampling. Recommendation No. 8 called for the development of instrumentation to achieve continuous monitoring of dust levels and for MSHA to consider using these data directly for compliance sampling. NIOSH collaborated with Rupprecht & Patashnick (later Thermo Fisher Scientific) to develop a person-wearable, continuous respirable dust monitor—the PDM3600. NIOSH also formed a PDM partnership with industry and labor to assist in the development and evaluation of the PDM3600. A design goal for this monitor was to replace the gravimetric sampler used since 1970 for compliance sampling and the belt-worn battery cap lamp, Figure 56 (left), by combining a PDM and cap lamp into one unit [Volkwein et al. 2004], Figure 56 (right). The PDM provides the wearer with a continuous readout of the sampled RCMD concentrations and records the information in a data file that can be downloaded and analyzed for periods of high dust exposure. NIOSH collected side-by-side dust samples with the PDM and gravimetric dust samplers at 180 U.S. coal mines. Analysis of this data indicated that a multiplier of 1.05 for PDM data [Page et al. 2008] results in dust concentration measurements equivalent to the gravimetric sampler used to collect compliance dust samples for MSHA.

Photo by NIOSH

Figure 56. Previously used gravimetric sampler and cap lamp (left) and the PDM3600 (right), developed to replace the sampler.

With the subsequent development of new LED lighting technologies by the coal mining industry, belt-worn cap lamp batteries were replaced with self-contained cap lamps. To reduce the weight of the PDM and take advantage of new lighting technologies, mining industry stakeholders requested that the cap lamp and associated battery be removed from the device. NIOSH issued a contract to remove these items and to incorporate a new lapel-worn sampling inlet, with the new inlet shown in Figure 57 (left) along with the new PDM3700 (right) [Thermo 2018]. Because the inlet configuration was changed and became a permanent part of the PDM3700 (Figure 57, right), NIOSH conducted laboratory testing to compare the performance of the PDM3700 to the PDM3600 for equivalency.

The development of the personal dust monitor spanned two decades, in a process that included the awarding of contracts to develop and refine the technology, intramural research, collaborations with industry and MSHA, publication of related NIOSH Report of Investigations and peer-reviewed journal articles, certification of the device and promulgation of related rules by MSHA, and partnership meetings to disseminate findings and facilitate implementation into the mining industry. This technology development process represents one example of how NIOSH responds to knowledge gaps and industry needs and collaborates with stakeholders to bring a needed product from concept to commercialization. Milestones associated with the development of the PDM technology are listed in Appendix G.

Photos by NIOSH

Figure 57. New inlet design (left) and PDM3700 (right).

Intermediate Outcome:

- MSHA certified the PDM3600 (for intrinsic safety and performance, respectively) for use in underground coal mines in 2011. Since then, 362 of these instruments were sold in the U.S. [Mischler 2018a]. After development of the PDM3700, the sale of the PDM3600 was discontinued.

Compliant Use of the PDM

On May 1, 2014, MSHA published a new dust rule, “Lowering Miners’ Exposure to Respirable Coal Mine Dust, Including Continuous Personal Dust Monitors.” Among changes to the respirable dust standard and sampling procedures, this rule required underground coal mine operators to utilize a CPDM for compliance sampling. Currently, the PDM3700 is the only instrument that meets the performance criteria to qualify as a CPDM. The PDM3700 sampler firmware is capable of transmitting an encrypted data file from the instrument to MSHA in order for MSHA to determine compliance with the applicable dust standard. It also monitors instrument operating parameters and records these parameters along with respirable dust concentrations every minute. MSHA reviews these operating parameters to ensure that the collected sample is valid.

Although the PDM and CPDM have different histories as developed technologies, the terms are often used interchangeably. Because the PDM3700 is the only instrument to meet the compliance criteria defined by MSHA to qualify as a continuous personal dust monitor, the PDM3700 is now commonly referred to as the CPDM by stakeholders.

Intermediate Outcome:

- Beginning on February 1, 2016, underground coal mine operators were required to use the PDM3700 to collect respirable dust compliance samples. Since promulgation of this new rule, 2,504 PDM3700 units have been sold [Mischler 2018a]. Over 250,000 valid CPDM compliance samples were collected by mine operators and submitted to MSHA as of the end of October 2018 [MSHA 2018a].

Changes in Organizational Practices and Policies related to the CPDM

Once the CPDM was established as a compliance tool, NIOSH began to study how mines adapted and integrated the CPDM into job tasks while complying with the lower regulatory RCMD exposure standard. In these studies, NIOSH sought to identify what individual miners learned about their dust exposure based on CPDM use, corrective actions taken, and miners’ responsive, behavioral changes to reduce personal exposures. During 2016 and 2017, five mines were included in NIOSH longitudinal research studies. About 50 miners shared their feedback, including 35 who, based on their designated occupations, were required by MSHA to wear the CPDM. Corrective actions were identified through interviews and focus groups with individuals at these five mines as well as through supervisory-related feedback and support to maintain reduced exposure to RCMD, affecting approximately 750 miners. Follow-up visits conducted for the NIOSH CPDM longitudinal study at approximately six weeks and three months found an increase in awareness of leadership and support among the organizations to maintain reduced RCMD exposures through increased autonomy, competence, and communication [Haas 2018; Haas and Colinet 2018; Haas and Helton 2017; Haas et al. 2016a].

Intermediate Outcomes:

- Based on feedback from the CPDM, a small mining company made changes to its roof bolters' work practices, including how they initiated drilling in order to reduce dust plume spurts, drilling downwind of the continuous miner, and changing dust collecting bags. These changes were made to reduce this occupation's dust exposure, positively affecting a dozen roof bolters within this company and 50 employees overall [Haas and Helton, 2017; Haas and Colinet, 2018].
- Based on feedback from the CPDM, a large mining company identified improved housekeeping practices that were completed every morning to significantly reduce workers' exposure to RCMD, positively affecting all continuous mining machine operators and the surrounding workers. The housekeeping practices identified at the case study mine have been incorporated into the company's nine mining complexes across three states [Haas et al. 2016a].

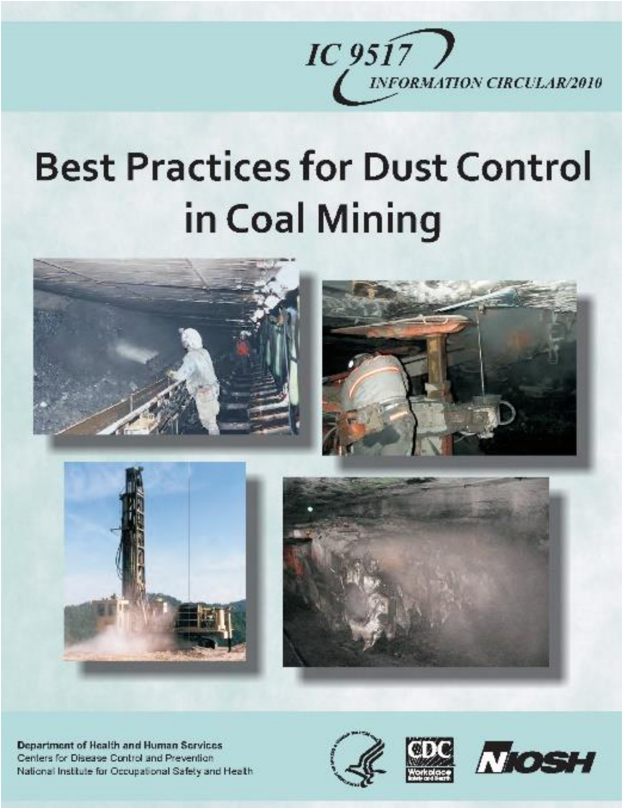
Dust Control Technologies and Best Practices

Dissemination of Best Practices for Dust Control in Coal Mining Handbook

The U.S. Bureau of Mines (USBM) and later NIOSH (as described in the Overview chapter, pp. 9–11) conducted laboratory research as well as in the field to identify and evaluate potential RCMD control technologies for use in coal mining operations. Many of these controls were proven to be both effective in reducing RCMD and feasible for implementation. In 2010, in an effort to promote and facilitate technology transfer to the mining industry, NIOSH summarized these control technologies in the NIOSH Information Circular 9517, *Best Practices for Dust Control in Coal Mining*, (Figure 58) [NIOSH 2010].

Intermediate Outcome:

- Over 1,500 printed copies of NIOSH IC 9517—*Best Practices for Dust Control in Coal Mining*—have been distributed to stakeholders. In addition, from June 1, 2015, to June 27, 2018, 695 PDF copies of this handbook were downloaded from the NIOSH mining website. MSHA referred to this publication frequently during discussion of dust control technologies in the preamble of the final dust rule, "Lowering Miners' Exposure to Respirable Coal Mine Dust, Including Continuous Personal Dust Monitors."



IC 9517

INFORMATION CIRCULAR/2010

Best Practices for Dust Control in Coal Mining

Department of Health and Human Services
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health

Figure 58. NIOSH Information Circular detailing best practices for dust control in coal mining based on research studies.

In addition to developing control interventions, NIOSH also conducts third-party research to investigate the dust reduction potential of products developed by others. Industry relies on unbiased research and evaluation to inform adoption of intervention technology. One example of this follows.

The majority of roof bolting machines in the U.S. are equipped with dry vacuum dust collection systems that capture dust at the drill bit and deposit this dust in a collector box mounted on the roof bolter. Roof bolter operators must clean this collected dust, often containing elevated levels of RCS, from the collector box multiple times each shift. Historically, this unconsolidated dust was pulled from the collection box by hand and was allowed to dump on the mine floor as shown in the left photo of Figure 59. Miners pulling this dust from the box were exposed to plumes of dust in their breathing zones and it contaminated their work clothes, creating a potential source of exposure throughout the work day [USBM 1986].

To address this issue, a collector bag system was developed to be retrofitted into these collector boxes with the goal of containing the dust in the bag (Figure 59, right). NIOSH evaluated the performance of these commercially available collector bags in the laboratory and at mine sites and published information showing that the bags improved dust capture within the collector, reduced dust release during cleaning, eliminated dust piles in the mine entry, and shortened the cleaning time [NIOSH 2007a; Listak 2008]. J.H. Fletcher & Co., the leading manufacturer of roof bolters in the U.S., subsequently offered these collector bags for its roof bolters [Rowland 2014].

Photos by NIOSH

Figure 59. Miner cleaning collector box (left) and collector bag containing dust (right).

Intermediate Outcome:

- The manufacturer J.H. Fletcher & Co. indicated that the largest increase in dust collector bag sales occurred in 2009 and 2010, climbing to a peak in 2013 [Colinet 2018a]. In addition, it became the policy of that manufacturer to ship each roof bolter with the collector bag system installed. It is plausible that the results of the research influenced the industry to purchase the dust collector bags.

Commercialization of Roof Bolter Canopy Air Curtain and Stand-alone Dry Scrubber

Research conducted by the USBM led to the development and testing of a “canopy air curtain” that could be mounted to the underside of the canopy in the operator’s cab on continuous miners [Donaldson 1975]. This system consisted of a blower pulling air through a filter and supplying the filtered air to a manifold that discharged cleaned air down over the continuous miner operator.

Dust sampling data have indicated that roof bolter operators can be exposed to elevated dust levels when working downwind of continuous miners in addition to dust generated by the bolter. NIOSH researchers adapted the USBM canopy air curtain concept and designed a system that could be installed under the uniquely shaped drilling canopies found on roof bolting machines. As shown in Figure 60, NIOSH conducted CM Gallery and in-mine tests, with results showing this technology could reduce dust levels under the canopy by up to 75% [Listak and Beck 2012]. The canopy air curtain concept was commercialized by J.H. Fletcher & Co., citing dust reductions from a NIOSH study [Rowland 2014].

Photos by NIOSH

Figure 60. Canopy air curtain being tested in laboratory (left) and underground (right).

Intermediate Outcome:

- The canopy air curtain is now offered as a standard option on all new machine quotes, with approximately 50 dual-boom roof bolting machines currently operating with canopy air curtains installed [Colinet 2018a]. Assuming these bolters are operating two shifts per day, which is the common industry practice, approximately 200 miners are experiencing lower dust exposures.

As another option for protecting roof bolter operators when working downwind of the continuous miner, NIOSH funded a research contract with J.H. Fletcher to design and fabricate a stand-alone mobile dust collector, Figure 61 (left). This collector can be positioned near the roof bolting machine when working downwind of the miner and uses dry filter technology, Figure 61 (right), to remove dust from ambient mine air. The collector then blows clean air to the bolter work area [Rowland 2014]. A key component of this system is a variable-frequency-drive fan that can deliver up to 10,000 cubic feet per minute of cleaned air to the bolter operators [Fletcher 2018]. The unit continuously monitors the desired airflow quantity set by the operator and, as a dust cake builds on the filters and the pressure drop increases, automatically adjusts the fan to maintain the desired airflow.

NIOSH tested the mobile dry scrubber in the CM Gallery and found that it exhibited a 95% dust removal efficiency for air passing through the scrubber [Organiscak et al. 2017]. In subsequent testing at an underground mine, results showed RCMD reductions of 50% in the bolter entry.

J.H. Fletcher & Co. utilized the experienced gained from NIOSH testing to modify the original dry scrubber design, obtaining MSHA safety approval in 2014 for its use in underground coal mines. Fletcher now offers this equipment as a commercial product [Colinet 2018a; Fletcher 2018]. No units have been sold to date; however, the technology provides mines with a tool for protecting roof bolter operators from upwind dust sources.

Photos by NIOSH

Figure 61. Mobile dry scrubber (left) and filter cartridges (right).

Changes in Organizational Practices and Policies

NIOSH has successfully conducted research to identify control technologies that are effective in reducing RCMD levels in coal mining operations. Stakeholders can then use the results of this research to guide their decision-making with regard to operational practices, regulations, and policies.

On June 3, 2008, MSHA issued a Procedure Instruction Letter (PIL No. I08-V-3) providing guidance for evaluating requests from the mining industry for approval to take extended cuts, which are cuts deeper than 20 feet. In addition, if a mining operation exceeded compliance dust levels in the extended cut, MSHA was requiring operators to revert to taking 20-foot cuts and would not consider reinstating the extended cut before the operator demonstrated acceptable dust control in 20-foot cuts [Kuykendall 2012]. One consequence of this action is that mine operators could no longer run flooded-bed scrubbers because they require a curtain setback variance that accompanies approval to take deep cuts. This inability to operate flooded-bed scrubbers results in elevated RCMD levels downwind of the continuous mining machine [Colinet et al. 2013] and may result in higher exposures for occupations such as roof bolters, shuttle car operators, mechanics, foremen, and scoop operators.

In order to comply with MSHA's requirements, various industry stakeholders requested information from NIOSH that quantified dust levels in different portions of extended cuts. NIOSH initiated surveys at six mines to compare dust levels in the first 20 feet of an extended cut to dust levels in the last 20 feet of the extended cut. Results indicated no statistically significant difference in dust levels between the first and second halves of extended cuts [Potts et al. 2011]. MSHA then asked if data were available that compared dust levels in 20-foot cuts with and without a flooded-bed scrubber operating. NIOSH conducted surveys at three mines to evaluate these operating conditions. NIOSH found no significant difference in face dust levels, but found statistically significant reductions in dust levels downwind of the continuous mining machine when the scrubber was being operated [Colinet et al. 2013].

Intermediate Outcome:

- The data generated in the two NIOSH Reports of Investigations on extended cuts [Potts et al. 2011; Colinet et al. 2013] were used by MSHA when evaluating applications for extended cuts [Colinet 2019].

As previously noted, NIOSH has evaluated numerous control technologies that were shown to successfully reduce RCMD levels. Further, NIOSH has also evaluated control technologies that *did not* substantially reduce dust levels. One example was the wet-head spray system for continuous miners. This system places water spray nozzles directly behind the bits on the cutting head of the miner, as shown in Figure 62, instead of at the typical frame-mounted spray location. When this approach was first introduced in the mid-2000s, the manufacturer indicated that this system would improve mine safety by reducing the potential for frictional ignitions and further reduce RCMD levels [Mining Weekly 2007]. Previous research had indicated that sprays located behind the cutting bits are beneficial for controlling frictional ignitions [Courtney 1990]. Therefore, NIOSH researchers had anticipated that this spray location might also be beneficial for dust levels, but sought data to quantify this potential impact.

NIOSH conducted evaluations of the wet-head spray systems on five different continuous miners [Listak et al. 2010], four of which were equipped with flooded-bed scrubbers. Mixed performance was observed with two miners, including the miner without a scrubber, showing dust reductions when using the wet-head sprays of approximately 30%. However, for three miners equipped with scrubbers, essentially no change in dust levels was observed. It appeared that the flooded-bed scrubber was the dominant control technology at these operations, making the addition of the expensive (over $200,000) wet-head system questionable from a dust control standpoint based on NIOSH research findings.

Photos by NIOSH

Figure 62. Spray nozzle located behind cutting bit (left) on wet-head continuous miner (right).

Intermediate Outcome:

- At peak levels from 2008 to 2010, approximately 125 continuous miners were equipped with wet-head spray systems. Today, less than 20 continuous miners are still equipped with the wet-head system. The leading continuous miner manufacturer indicates that 90% of continuous miners are equipped with flooded bed scrubbers [Colinet 2018b]. It is plausible that the results of the research influenced the industry to decrease its use of wet-head spray systems while still using flooded bed scrubbers as a dominant control technology.

NIOSH research has also had an international influence on organizational practices and policies. In Queensland, Australia, no new cases of CWP had been reported in the country's coal mining workforce since the mid-1980s [Queensland Parliament 2017]. However, beginning in 2015, new cases of CWP were found with a total of 25 new cases identified by 2017 [Williams 2017]. In 2016, the Queensland Parliament appointed the Coal Workers' Pneumoconiosis Select Committee to investigate and report on the re-emergence of CWP in Queensland. Members of this committee visited NIOSH in February 2017 to gather information on dust control technologies, sampling instrumentation and practices, and miner medical surveillance programs. In addition to the visit, the Queensland Government Department of Natural Resources, Mines, and Energy requested technical assistance from NIOSH to train physicians in classifying chest radiographs for pneumoconiosis. A training course and exam were held in Brisbane, Australia, in December 2017, where 12 physicians were certified, enabling proper classification of CWP in Australia and aiding Queensland in becoming more self-sufficient at accurately classifying chest radiographs.

Intermediate Outcomes:

- The Queensland committee issued a report [Queensland Parliament 2017] detailing findings and providing recommendations for changes in the Queensland coal mining industry, including two recommendations directly related to NIOSH dust research:
    - Recommendation 24—"The Mine Safety and Health Authority should research and review new dust techniques and technologies being used in jurisdictions such as New South Wales (NSW) and the USA and publish its findings to ensure all those involved in coal mining in Queensland may be aware of world-leading dust mitigation practices."
    - Recommendation 25—"Real time personal dust monitors, such as the PDM3700, should be assessed having regard to the scientific information already available world-wide, and if possible certified for use in underground coal mines as soon as possible."
- Following consultation with many organizations, including NIOSH, the Queensland Parliament passed the Workers' Compensation and Rehabilitation (Coal Workers' Pneumoconiosis) and Other Legislation Amendment Act 2017, which, among many provisions, extended screening and surveillance to former and retired coal miners, and established a requirement for physicians reading chest radiographs to formally demonstrate competence in the International Labour Office (ILO) International Classification of Radiographs of Pneumoconiosis.

Activities Under the Coal Workers' Health Surveillance Program

The CWHSP was established following enactment of the Federal Coal Mine Health and Safety Act of 1969 (Coal Act). Actively working coal miners can receive a chest radiograph about every five years throughout their career. Between calendar years 2008 and 2017, 41,938 unique miners participated in the CWHSP—17,443 of these through the CWHSP mobile health screening unit as listed in Table 3 and the rest through a health facility certified by the RHD to receive the screenings. Miners received a chest radiograph classification (as well as spirometry lung function results depending on participation date and place) via written communication from NIOSH within 8–10 weeks of their test. During this time period, a total of 1,322 miners received a radiographic classification of pneumoconiosis. Upon request, miners can receive a copy of their radiograph and any supporting medical documentation that is collected as part of the CWHSP. A total of 7,891 medical records requests were processed by NIOSH during 2008–2017.

Table 3. Data gathered from CWHSP mobile health screening unit mine site visits from 2008 to 2018

Calendar year	Number of days available	Numbers of counties visited	Number of miners screened
2008	68	35	1,698
2009	71	67	1,548
2010	82	57	1,570
2011	82	103	1,615
2012	81	64	1,666
2013	82	49	2,015
2014	64	35	1,404
2015	49	60	1,402
2016	64	45	1,843
2017	80	66	2,682
2018	91	66	2,794

According to MSHA regulations, underground or surface coal miners who have received screening through the CWHSP that demonstrated evidence of pneumoconiosis can exercise the right to work in an area of a mine where the average RCMD concentration is maintained at or below 0.5 mg/m^3. Eligible miners are notified in writing by NIOSH through the CWHSP of these rights. Miners that exercise these rights are called Part 90 miners. They must be transferred to an existing position at the same mine and shift unless the miner agrees in writing to a different mine, shift, or newly created position. Part 90 miners retain their regular rate of pay and receive subsequent wage increases. The miner may accept or waive these rights by notifying the Chief, Division of Health, Coal Mine Safety and Health, MSHA.

NIOSH has used observations in the health surveillance data from the CWHSP to inform intervention efforts. In the early to mid-2000s, the increasing prevalence and severity of CWP was just starting to be documented among “hot spots” in the Central Appalachian region [Antao et al. 2005]. In response to this, NIOSH pursued research that targets interventions applicable to this region [Pollock et al. 2009]. These interventions are described later in this chapter, and they provided support for changes in MSHA regulatory requirements. The most recent update of prevalence data indicated that over 20% of longer-tenured (>25 years) active underground coal miners in the central Appalachia have CWP [Blackley et al. 2018a]. Further, recent NIOSH reports have described unprecedented numbers of the most severe form of CWP, among mainly former miners in Central Appalachia [Blackley 2016; Blackley et al. 2018b; Reynolds et al. 2018].

In another example of CWHSP data informing research, the Program identified severe lung disease in surface coal miners with no underground mining experience [Halldin et al. 2015a; CDC 2012]. This unexpected result led to the conclusion that overexposure to RCS was a likely cause and warranted further NIOSH research into RCS control in surface mining, particularly drilling and overburden handling.

In addition to reporting on the prevalence of disease, over the last 10 years NIOSH research has described factors that are associated with disease and demonstrated associations with small mine employment size, lower coal seam heights [Suarthana 2011; Laney and Attfield 2010; Blackley et al. 2014], and observed radiographic features suggestive of crystalline silica exposure [Laney et al. 2010]. Greater prevalence and severity of disease have been observed in miners located in Central Appalachia [Blackley 2016] as well as among former miners [Halldin et al. 2015b]. This recognized increase in disease prevalence has drawn the public's attention to the issue of U.S. coal miner respiratory health through a variety of outlets.

NIOSH strives to make the most current information about CWHSP activities and CWP surveillance data as accessible to the public and stakeholders as possible. Much of this information is available on the NIOSH CWHSP website, which received 13,780 visitors in 2017. Aggregated de-identified data collected by the CWHSP are available to the public in the form of an online Data Query System where interested parties outside of NIOSH submit a specific data query request to learn more about the number and severity of CWP identified via chest radiography in the U.S. or within a specific state/region. The Data Query System produces tables and maps organized by disease severity level and prevalence, with the tables and maps showing demographic and geographical criteria based on the total number of underground miners examined in the CWHSP since 1970. Users can produce outputs based on such variables as geographic location, programs and employment, age and tenure, and time interval. Figure 63 shows a sample map generated by the Data Query System, which has received more than 7,000 query submissions since 2011.

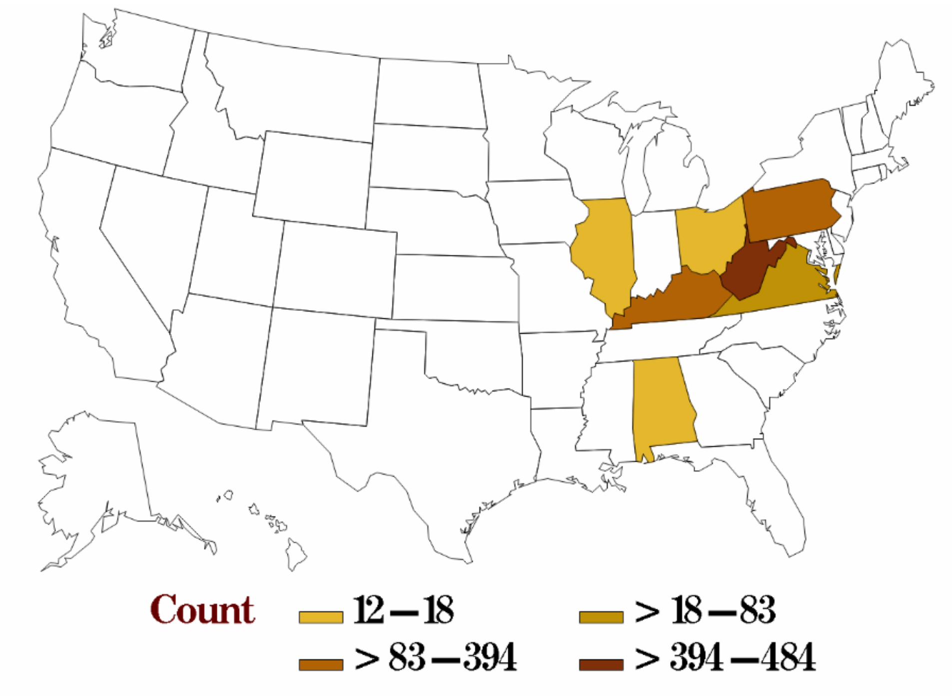


Figure 63. Screenshot from the CWHSP data query system representing number of miners with a CWP severity of category +3 based on x-rays for active miners ages 40 to 59 at underground coal mines, by state, from 1970 to 2009.

Intermediate Outcomes:

- According to data collected through the CWHSP, from 2007 to 2016, 173 miners, who were previously informed that they had CWP through participation in the CWHSP, exercised their Part 90 rights, which required that they be placed in low RCMD environments.
- NIOSH research and researchers were cited in a year-long investigative journalism project by the Center for Public Integrity titled "Breathless and Burdened" in 2013 [Center for Public Integrity 2013].
- NIOSH research and researchers were cited in numerous articles highlighting the black lung epidemic published by the National Public Radio (radio and webstories) Special Series, "Black Lung Returns to Coal Country" [NPR 2012].

Actions by other Governmental Organizations

The resurgence of CWP, demonstrated using CWHSP surveillance data, has brought attention to NIOSH's expertise in respiratory disease surveillance among coal miners. NIOSH research has been used by other federal agencies as well as international sister agencies to guide federal regulations and determine the best paths forward in conducting respiratory health screening for coal miners. Additionally, because of NIOSH's expertise, in a 2016 letter, two Congressional Committees requested that NIOSH work with the HRSA and the Department of Labor's Office of Workers' Compensation Program (OWCP) to estimate the number of cases of severe black lung following a NIOSH-coauthored publication describing 60 severe cases of pneumoconiosis in Kentucky [Blackley 2016]. NIOSH and OWCP entered into a formal MOU to link data from miners who participated in CWHSP with data from miners who applied for Federal Black Lung benefits for specific periods. NIOSH also signed a letter of intent with MSHA and HRSA to explore ways to share, analyze, and apply data to better understand disease burden in coal miners. In February 2017, the director of a network of federally funded black lung clinics in Virginia requested NIOSH's assistance in determining the burden of progressive massive fibrosis (PMF) in patients served by the clinics. This partnership identified and reported the largest cluster of severe black lung disease ever described in the scientific literature [Blackley et al. 2018b].

Intermediate Outcome:

- In 2014, MSHA announced a new final rule to lower miners' exposure to respirable coal mine dust, "Lowering Miners' Exposure to Respirable Coal Mine Dust, Including Continuous Personal Dust Monitors." As a basis for improving protections, MSHA cited more than 20 years of NIOSH research focusing on changes in prevalence of pneumoconiosis, risk factors associated with pneumoconiosis and other occupational respiratory diseases, pulmonary function testing and respiratory symptoms, estimations of and associations with dust exposure, and pneumoconiosis morbidity and mortality among U.S. coal miners. These NIOSH citations included prominent discussions of recommendations from a 1995 NIOSH criteria document, MSHA and NIOSH jointly publishing a proposed rule in 2000 and a final rule in 2010, and multiple references to NIOSH research findings on the pre-commercial CPDM from both laboratory and underground studies.

Respirable Coal Mine Dust Workshops

NIOSH encourages stakeholder adoption of control interventions through collaborations, presentations, publications, and workshops. During the review period, NIOSH conducted two series of regional workshops (2009–2010 and 2014–2015) in cooperation with MSHA to transfer information on successful control interventions to the mining industry. NIOSH presentations from the workshop were uploaded to the MSHA website and remain available.

Eight workshops were held with a total of nearly 700 attendees. Workshops were held in the east (Beckley, WV), south (Birmingham, AL), Midwest (Evansville, IN), and west (Grand Junction, CO). Over 600 copies of *Best Practices for Dust Control in Coal Mining* (Figure 58, p. 184) were distributed to workshop attendees. Four additional workshops were conducted due to direct requests from stakeholders with over 200 total attendees.

Awards Related to RCMD Research

During the review period, the following awards were received from external organizations, demonstrating the quality and significance of NIOSH research in the area of respirable coal mine dust.

> 2010—Robert J. Stefanko Award, Society of Mining, Metallurgy and Exploration (SME) Coal & Energy Division, for best technical quality of the paper and presentation at the SME Annual Meeting and Exhibit, for "Evaluation of a Wet Head Miner to Reduce Respirable Dust in Underground Coal Mines." (J Listak, G Goodman, T Beck)
>
> 2013—American Institute of Mining, Metallurgical, and Petroleum Engineers (AIME) Rossiter W. Raymond Memorial Award for the best paper published by an AIME Member Society where the lead author is a member under 35 years of age, for the paper, "Dust Capture Performance of a Water Exhaust Conditioner for Roof Bolting Machines." (T Beck)
>
> 2013—Howard N. Eavenson Award, SME Coal & Energy Division, for distinguished contributions to the advancement of coal mining and for contributions to mine safety through outstanding personal research and development of dust control methods in underground coal mining. (J Colinet)
>
> 2016—Robert J. Stefanko Award, SME Coal & Energy Division, for best technical quality of the paper and presentation at the SME Annual Conference & Expo, for "Examination of a Newly Developed Mobile Dry Scrubber for Coal Mine Dust Applications." (J Organiscak, J Noll, D Yantek, W Kendall, Jr.)
>
> 2018—SME Robert E. Murray Innovation Award for leadership in the application of new and innovative technologies in mining for the benefit of miner health and safety: CPDM and Helmet-CAM. (NIOSH)

Respirable Crystalline Silica

This research area is focused upon identifying interventions that successfully reduce RCS exposures and promoting implementation within the mining industry. Interventions that reduce dust exposures include technologies, work practices, training approaches, and timely and accurate monitoring of the mine environment—all of which empower workers to identify and correct conditions that lead to overexposures.

Helmet-CAM/EVADE software

Often times, the information provided by a single cumulative exposure is not rich enough to provide guidance on implementation of control interventions that will be most effective. This led to NIOSH's development of Helmet-CAM and the Enhanced Video Analysis of Dust Exposures (EVADE) software in 2010, which combines real-time exposure monitoring data with video that documents work activities. With this information, mine personnel can quickly determine where application of control interventions will produce the greatest effect on lowering exposures. The Helmet-CAM technology uses a lightweight video recording system simultaneously with a real-time, data-logging personal respirable dust monitor—in this case the Thermo Fisher Scientific pDR-1500 (Figure 64). To ensure the usefulness of Helmet-CAM and apply it to stakeholder needs, NIOSH collaborated with Unimin Corporation (now Covia Corporation) to refine the concept and functionality of the technology.

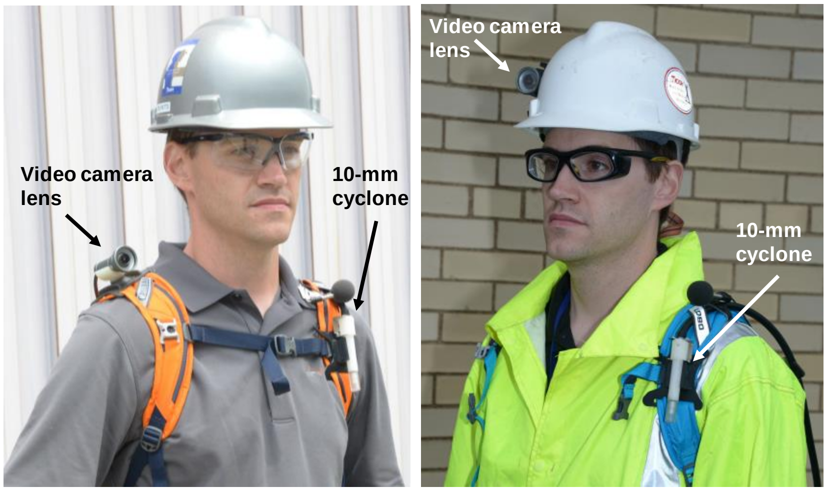


Figure 64. Video camera mounted on worker's shoulder (left) or hardhat (right), with a dust cyclone mounted on the left shoulder in each photo.

After being worn by a miner for a few hours, the video and logged dust data are downloaded to a computer. The NIOSH-created EVADE software synchronizes playback of the recorded video and dust exposure data, providing insight into how, when, and where workers are exposed to contaminants [NIOSH 2014b]. The harmonization of Helmet-CAM exposure data and video footage allows for simultaneous review by both workers and management personnel. In addition to providing training to mine operators in the field about the use of the EVADE software, NIOSH created a "How to Use EVADE 2.0" YouTube Video to help industry professionals learn how to use the EVADE software independently. This video tutorial shows where to access and download this free software from NIOSH, and then how to create, save, and perform a basic exposure assessment using the software.

From April 2011 to July 2012, NIOSH researchers performed 12 different studies at mining operations to evaluate the effectiveness of the Helmet-CAM technology in assessing miners' exposure to respirable dust [Cecala and O'Brien 2014; Cecala et al. 2013; Joy 2013; Cecala et al. 2015]. From April 2015 to September 2016, NIOSH researchers also performed longitudinal studies with 48 workers and 18 managers at seven mines to evaluate the potential impact of Helmet-CAM on worker and organizational practices [Haas and Cecala 2015a; Haas and Cecala 2015b; Cecala et al. 2017; Haas and Cecala 2017]. As demonstrated by these studies, buy-in from management and the workers is critical [Haas et al., 2016b].

Throughout the longitudinal studies, approximately 34 engineering-based and 48 behavioral-based considerations were developed. Follow-up assessments with participating mines revealed that, six months later, approximately 65% of these considerations were being utilized and management made organizational changes or workers made specific changes to their work practices to reduce personal exposure to RCS [Haas and Cecala 2017].

NIOSH's longitudinal research studies also improved workers' safety climate perceptions and proactive behaviors to reduce exposure to RCS [Haas et al. 2019]. The results of a two-tailed t-test using pre- and post-survey results illustrated the positive impact that the intervention had on worker proactivity. Workers' average scores increased by 0.27 and rendered a large effect size. This showed that the Helmet-CAM technology, when integrated and supported by management, can increase workers' health performance. The vast majority of mines that participated in both studies continued to use the Helmet-CAM system and EVADE software to monitor and assess their workers' RCS exposures after completion of the study.

Throughout NIOSH's Helmet-CAM research studies, engineering controls were identified that have allowed operations to reduce or eliminate dust sources. As an example, NIOSH created four infographics representing quick fixes to reduce workers' exposure to RCS resulting from dirty clothing, dust-laden seats, using high-velocity sprays to clean floors, and improperly tying bulk and mini-bulk bags.

Intermediate Outcomes:

- A major industrial sand producer, Unimin Corporation, incorporated a yearly performance standard task for plant managers based upon the use of Helmet-CAM assessment technology at its facilities. This corporate initiative involved approximately 40 managers at 34 industrial sand processing sites with approximately 350 salaried and 1,300 hourly miners. Helmet-CAM is also used to document and monitor ergonomic improvements (7 projects), welding fume studies (6 projects), and noise reduction studies (3 projects). In 2018, Unimin Corporation merged with the Fairmount Santrol Corporation to form Covia Corporation. The Helmet-CAM requirement will now also include the former Fairmount Santrol facilities, nearly doubling the values listed above [Cecala 2018a].
- Organizations have become more aware of the fact that dust can be liberated from cloth chairs due to the results of Helmet-CAM studies. Multiple companies have reported replacing or covering cloth chairs in breakrooms and mobile equipment with vinyl to prevent dust absorption and liberation during worker movement [Haas and Cecala 2017].
- Organizations have used Helmet-CAM to determine which spray nozzles are most appropriate for lowering entrainment of settled respirable dust during housekeeping activities [Haas and Cecala 2017].

- Organizations have developed better storage methods for items including screens, bags, and pallets based on Helmet-CAM footage [Haas and Cecala 2017].
- In response to all of the minor changes that workers can make to reduce exposure to respirable dust, Unimin Corporation updated its 30 CFR Part 46 annual refresher training to incorporate the interventions. Every mineworker must receive Part 46 annual refresher training each year, impacting almost 1,300 hourly workers [Cecala 2016].
- Since tracking was enabled on NIOSH's mining website in June 2015, EVADE has been downloaded approximately 553 times. In addition, for those users who opt-in to report their usage to NIOSH, 108 users have completed 915 sessions—524 in the United States; 230 in Australia; 22 in Belgium; 1 in Brazil; 5 in Canada; 2 in Chile; 6 in Denmark; 12 in France; 6 in Indonesia; 6 in Iran; 30 in Japan; 1 in Norway; 5 in Peru; 32 in Singapore; 15 in Taiwan; 2 in Turkey; and 16 in the United Kingdom [EVADE Metrics 2018; NIOSH 2014b]. In Figure 65, red indicates heavy use of EVADE and green indicates some but not prevalent use of EVADE.
- The "How to Use EVADE 2.0" video has been viewed over 500 times on YouTube since being published in January 2018.
- As of October 2018, NIOSH's four dust exposure infographics have been downloaded 318 times since January 2018, distributed at dozens of exhibition booths to stakeholders, and are included in mine packets provided to health and safety professionals at MNM mines when researchers travel to perform field research [NIOSH Web Statistics, 2018].

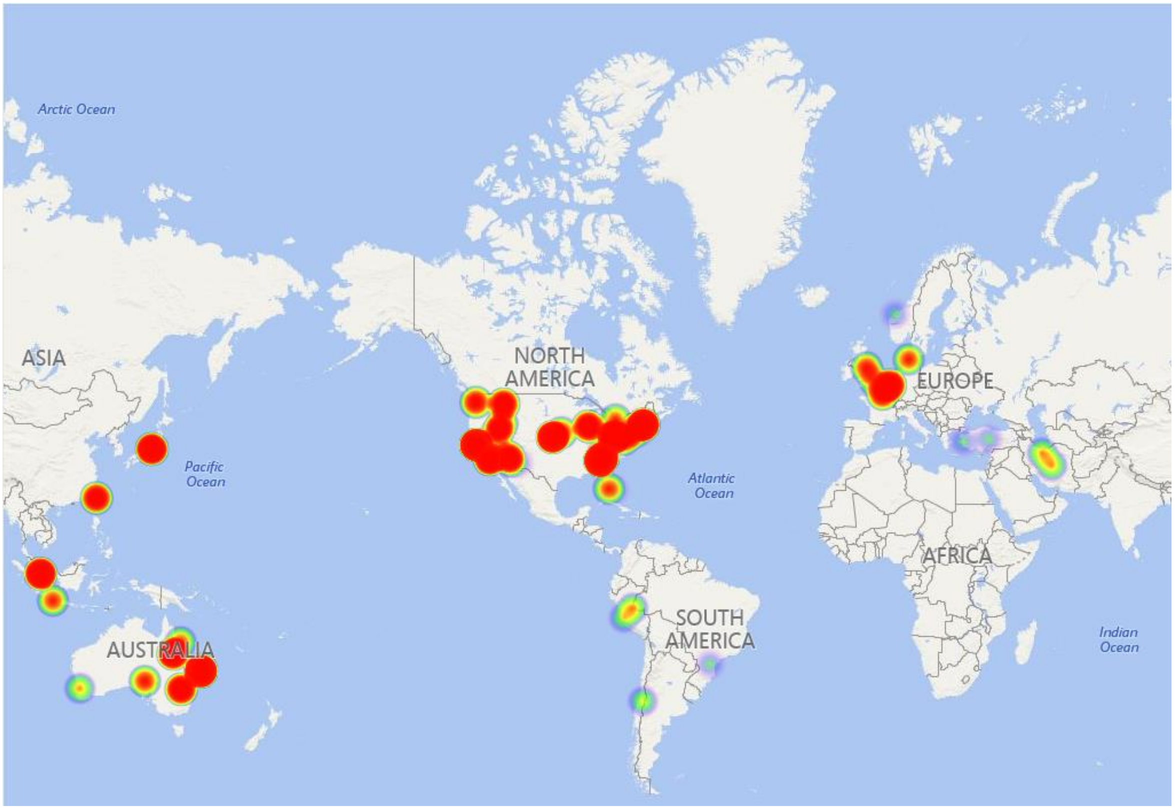


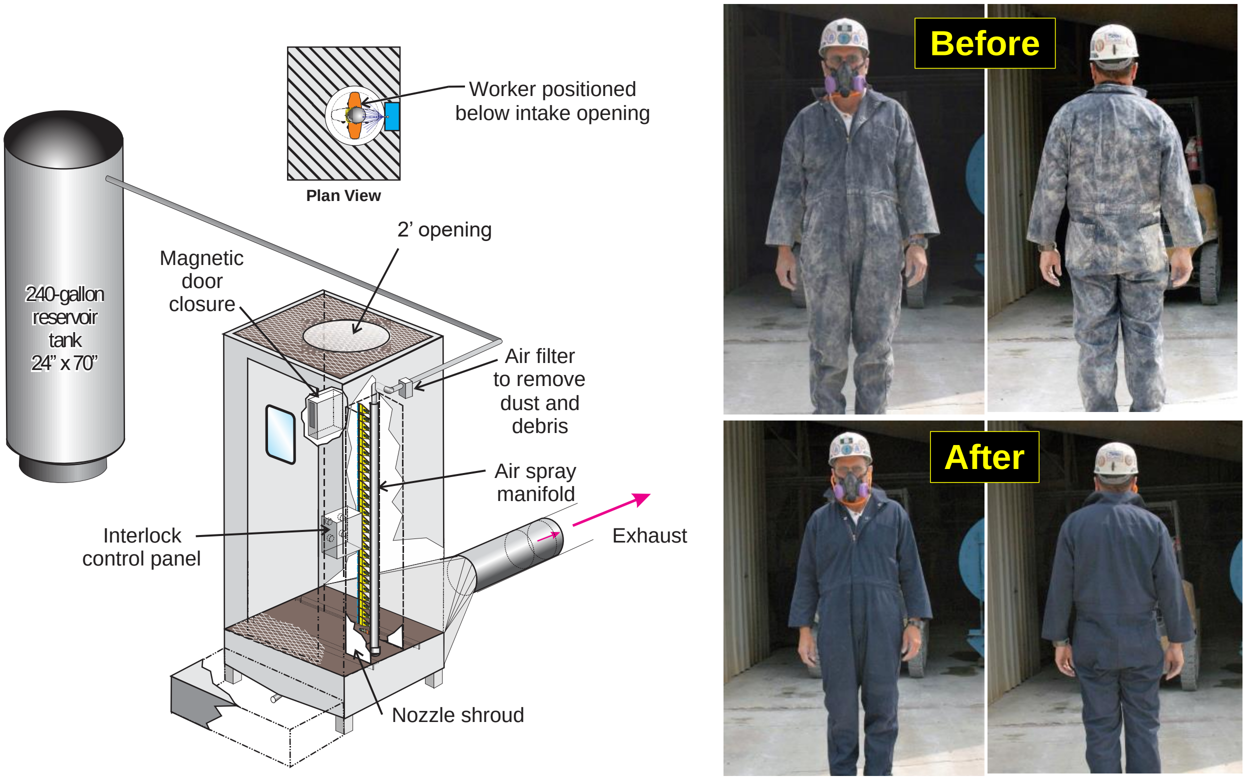
Figure 65. Map illustrating extensive use of the EVADE software.

Dust Control Technologies and Best Practices

Clothes Cleaning Booth Technology

One known source of high respirable dust exposure is contaminated work clothing [Cohen and Positano 1986; Fogh et al. 1999]. A USBM study documented a number of cases of high worker exposure from background dust sources in the minerals processing industry. A report from this study highlighted two cases of a 10-fold increase in respirable dust from contaminated work clothing [Cecala and Thimons 1986]. To address this issue, a clothes cleaning booth technology was developed, with Unimin Corporation (now Covia Corporation) approaching NIOSH with a concept and NIOSH researchers designing the technology. This technology was not intended to eliminate the need to launder work clothing, but to provide an interim solution to allow workers to safely remove dust from their work clothing periodically throughout the day, until laundering could be performed after the work shift.

The clothes cleaning system is made up of four major components: (1) a cleaning booth, (2) an air reservoir, (3) an air spray manifold, and (4) an exhaust ventilation system. The schematic on the left in Figure 66 represents the design of the clothes cleaning system. To perform the clothes cleaning process with this system, a worker rotates in front of the air spray manifold while dust is blown from the clothing via compressed air while wearing required personal protective equipment (i.e., safety glasses, respirator, hearing protection). In less than 20 seconds, the cleaning is completed and the worker can exit the booth with significantly cleaner work clothing (Figure 66, bottom right).



Photos by NIOSH

Figure 66. Schematic of clothes cleaning booth design (left) and test subject before and after using the clothes cleaning booth (right).

During development, in several NIOSH studies, the clothes cleaning technology was compared to both the MSHA-approved vacuuming approach and a single handheld compressed air hose. Results showed that the cleaning booth was 40% more effective in removing dust than vacuuming and 50% more effective than a compressed air hose, while only requiring a fraction of the cleaning time [Cecala et al. 2007b; Cecala et al. 2008; NIOSH 2005; Pollock et al. 2005; Pollock et al. 2006].

Because MSHA prohibits the use of compressed air directed at workers and the Occupational Safety and Health Administration (OSHA) restricts compressed air for cleaning to 30 pounds per square inch (psi), a petition for modification must be obtained from MSHA prior to using the clothes cleaning booth, and the air pressure within the cleaning booth must be regulated to 30 psi. After meeting with NIOSH and the IMA-NA and learning of the NIOSH study results, MSHA agreed to streamline the petition for modification process for cleaning booths using the NIOSH-developed system.

Intermediate Outcomes:

- The company Clothes Cleaning Systems commercialized the NIOSH-developed clothes cleaning booth technology. The company sells the Tempest WindDraft models I and II and mobile versions of each system [NIOSH 2019].
- Mideco, an Australian-based manufacturer and distributor of environmental technology, began manufacturing a clothes cleaning booth technology in 2014 called the "Bat Booth" (Figure 67), basing the design on the NIOSH-developed technology. Since 2014, Mideco has sold 50 units of the Bat Booth to clean workers' clothing in various industrial environments. At one installation of the Bat Booth, which is equipped with an internal counter, there were over 10,000 clothes cleaning cycles in one year [Cecala 2019b].

Photo by Mideco

Figure 67. A clothes cleaning booth based on NIOSH-developed technology located in Narangba, Australia, at a thoroughfare between the quarry and workshop.

Identification of Best Practices

Numerous engineering control technologies and interventions have been developed and identified to successfully lower MNM miners' dust exposures during the decade covered by this review period. In almost all cases, these engineering control technologies were tested in a working mining operation using a pre- and post-control evaluation that highlighted significant reductions in RCS exposures. In 2010, NIOSH summarized these engineering control technologies in a "best practices" publication to effectively transfer this information to the MNM mining industry [NIOSH 2010] (Figure 68).

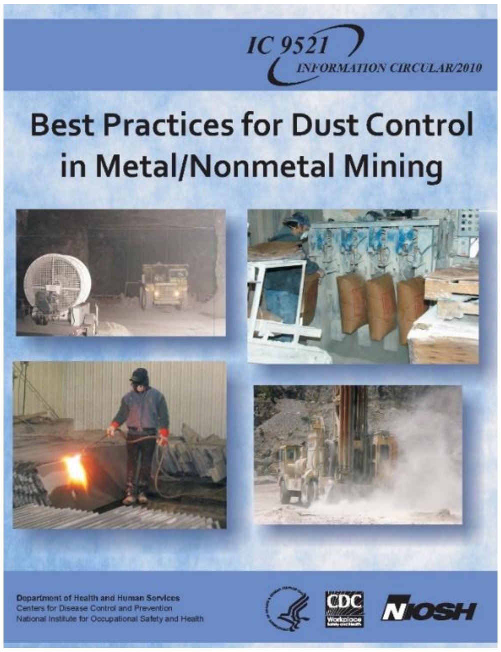
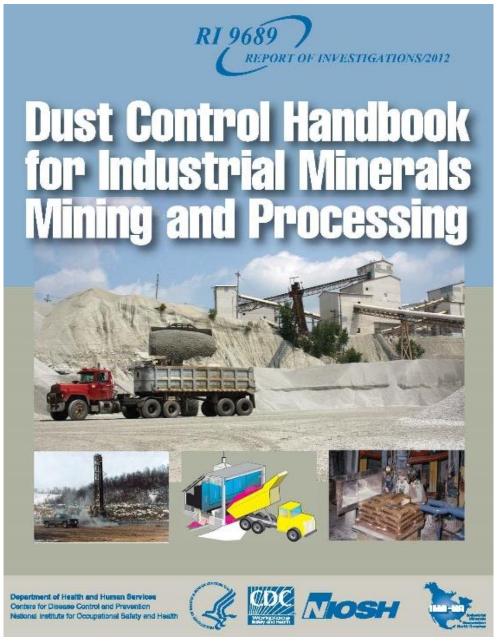


Figure 68. A NIOSH Information Circular detailing guidelines for controlling dust at metal/nonmetal mines.

Shortly after the completion of this publication, NIOSH established a collaborative effort with the IMA-NA to produce a dust control handbook for industrial minerals mining and processing operations that was much more comprehensive in providing detailed information on control technologies to address all stages of the minerals handling process, including drilling, crushing, screening, conveyance, bagging, loadout, and transport. This handbook was written by a task force of safety and health specialists, industrial hygienists, engineers from industry, manufacturers, and government regulatory and research personnel. The first handbook was published in January 2012 [NIOSH 2012a] (Figure 69). A substantially updated second edition was published in March 2019, with distribution at the 2019 IMA-NA Industrial Minerals Technology Workshop.

Intermediate Outcomes:

- At the request of stakeholders, NIOSH has distributed over 500 printed copies of the NIOSH IC 9521, *Best Practices for Dust Control in Metal/Nonmetal Mining* handbook [NIOSH 2010]. From June 1, 2015, to July 27, 2018, 675 PDF copies of the handbook were downloaded from the NIOSH Mining website.
- At the request of stakeholders, 2,600 printed copies of the *Dust Control Handbook for Industrial Minerals Mining and Processing* have been distributed, with 7,700 views on the NIOSH website and 3,700 PDF copies downloaded [NIOSH 2012a]. The Society of Mining, Metallurgy & Exploration (SME) has reproduced and sold copies of this handbook at its meetings.



RI 9689
REPORT OF INVESTIGATIONS/2012

Dust Control Handbook for Industrial Minerals Mining and Processing

Department of Health and Human Services
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health

Figure 69. A NIOSH Report of Investigations detailing guidelines for controlling dust at industrial minerals and mining operations.

Environmental Enclosure Design Criteria

Environmental enclosures such as operator booths, control rooms, and enclosed cabs have been used for many years to isolate workers in the mining industry for health and safety reasons. These enclosures create a microenvironment for miners where they can be either more protected or more vulnerable to contaminants, depending on the effectiveness of their design and maintenance practices [Cecala et al. 2001; Cecala et al. 2007a; Cecala and Zimmer 2004a; Cecala and Zimmer 2004b; NIOSH 2001a, 2001b, 2001c; Whalen et al. 2009]. NIOSH has performed substantial research to improve the air quality inside these environmental enclosures in both underground and surface mining operations, partnering synergistically with mining companies, original equipment manufacturers (OEMs), and manufacturers of filtration and pressurization systems. Over time, various field studies have shown an array of results ranging from protection factors (outside concentration divided by inside cab concentration) of 3 to 89, with the higher protection factor numbers being the most desirable [Cecala et al. 2004; Cecala et al. 2005; Cecala et al. 2009; Chekan and Colinet 2003; Noll et al. 2015a; Organiscak et al. 2004; Organiscak et al. 2016].

Concurrent with the fieldwork, NIOSH performed a comprehensive laboratory study to evaluate all the factors involved in enclosure filtration and pressurization systems and identified those factors that were most important to ensuring an effective system [Organiscak and Schmitz 2006; NIOSH 2007b; Noll et al.

2010]. NIOSH researchers used mathematical modeling of enclosure filtration systems to examine the key design parameters influencing system performance. The first mathematical model, developed in 2008, was derived in conjunction with the laboratory testing (Figure 70). From both the laboratory study and various field tests, key filtration and pressurization parameters identified included intake filter efficiency, air leakage around the intake filter, intake filter loading, recirculation filter usage, and wind infiltration [NIOSH 2008b, 2008c; Organiscak and Cecala 2008; Organiscak and Cecala 2009]. With additional field research, the mathematical model was expanded to simulate the use and positive effects of additional filters [Organiscak et al. 2013; Organiscak et al. 2014]. The engineering and scientific knowledge gained from this extensive research led to the development of published design criteria for effective filtration and pressurization systems [Cecala et al. 2014; Organiscak et al. 2018].

NIOSH has worked directly with the following aftermarket filtration and pressurization manufacturers to improve and test their units at mining operations: Sy-Klone International (Sy-Klone), Polar Mobility Research LTD, Clean Air Filter Company, MI Air Systems LLC, Red Dot Corporation, Bergstrom Climate Control Systems and Sigma Air Filters. In 2010, J.H. Fletcher contacted NIOSH and requested assistance in evaluating a new filtration and pressurization system designed for its MNM underground mining equipment based on NIOSH research and recommendations. Researchers met with the MNM Engineering Department personnel on many occasions and performed testing in the company’s shop (Huntington, WV), as well as visited numerous mining sites to validate the design. A long-term field study demonstrated that both a face drill and roof-bolter machine that use NIOSH design criteria offered average protection factors of over 1,000 [Cecala et al. 2012]. In 2014, NIOSH researchers were invited to give a presentation to staff at Caterpillar’s Cab Summit meeting in Peoria, Illinois. This visit also provided the opportunity to meet with Caterpillar’s Cab Climate Control Engineer Team to discuss NIOSH design criteria for optimizing filtration and pressurization systems for enclosed cabs on mobile equipment.

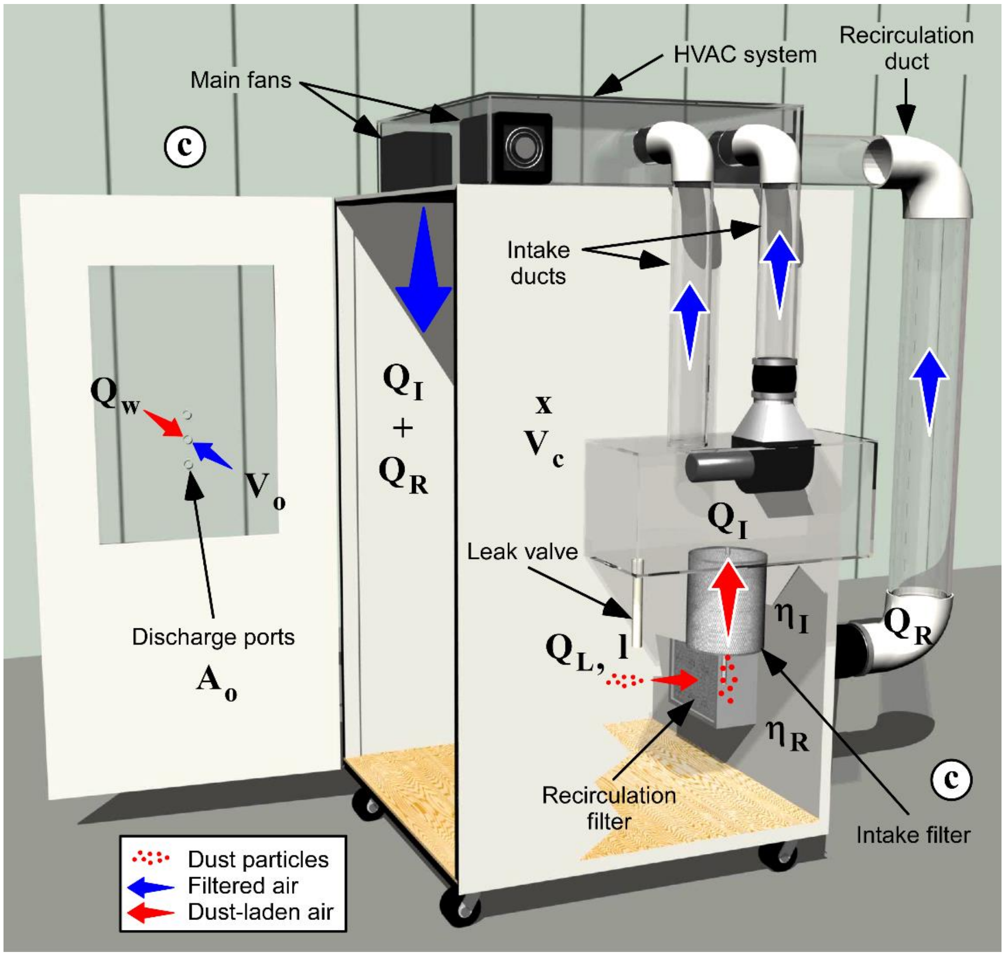


Figure 70. Simulated enclosure test chamber used in laboratory testing to identify test components and parameters for an effective filtration and pressurization system.

Intermediate Outcomes:

- NIOSH collaborated with Sy-Klone to do research into the cause of poor air quality in operator cabs. Sy-Klone adapted its powered precleaning, high-efficiency filtration, and electronic monitoring technologies to improve cab performance. NIOSH research provided the necessary data required for a successful solution. Today, some or all of Sy-Klone's powered precleaning, high-efficiency filtration, and electronic monitoring technologies are used by eight of the 10 largest heavy equipment manufacturers in the world [Cecala 2019a].
- An Engineering Manager from Caterpillar's Earth Moving Division, which offers advanced operator cab filtration systems across many of its product lines, has noted that these filtration systems were heavily influenced by NIOSH, both by way of technical papers published and regular interactions with NIOSH engineers. This influence includes improvements to the powered intake filtration component, optimal efficiencies for both intake and recirculation filters, and the use of an enclosed cab pressure monitor to evaluate system performance. [Cecala 2018b].
- OSHA adopted NIOSH research on recommendations for enclosed cabs, including proper housekeeping, maintaining gaskets and seals, positive pressure maintained through continuous

delivery of filtered air, and intake air that is filtered through a pre-filter that is 95% efficient in the 0.3–10.0 µm range (e.g., MERV-16 or better) [OSHA 2017].

- The American Society of Agricultural and Biological Engineers (ASABE) adopted many design practices, filter efficiency testing, and particle counting measurement methods researched by NIOSH into its enclosed cab consensus standards [ASABE 2013a, 2013b, 2017].

Once an effective filtration system has been designed, it must be maintained and periodically field tested to ensure that operators are protected against respirable hazards. Monitoring cab pressure is a simple way to ensure performance and can alert operators to such things as the need to replace a filter or a breach in the cab seal. NIOSH researchers have tested and identified several commercially available pressure gauges that are suitable for this task [Patts et al. 2018]. Further, NIOSH entered into a Cooperative Research and Development Agreement (CRADA) with Clean Air Filter [Organiscak and Schmitz 2006], which resulted in four co-patents associated with in-field testing to determine cab leakage. This leak testing methodology uses the ambient carbon dioxide in the atmosphere as a tracer gas in conjunction with a highly efficient absorbent gas filter to detect and quantify leakage around the filtration system in cabs [Organiscak and Schmitz 2006; NIOSH 2012a, 2012b]. Clean Air Company now uses the in-field leak testing method developed under the CRADA to ensure that its filtration pressurizer systems are airtight for use on environmentally controlled enclosures (cabs, booths, rooms, etc.) [Organiscak et al. 2018; NIOSH 2012b,c].

Field-based Respirable Crystalline Silica Monitoring / FAST Software

Field-based RCS monitoring is a novel methodology, based on work by the USBM [USBM 1992] and further refined by NIOSH, that is in an advanced stage of development. The monitoring approach entails the use of a portable analyzer, based on a transmission infra-red technology called Fourier-transform infrared spectroscopy (FTIR), for the quantification of RCS in dust samples collected at a mine site. By implementing this approach, health and safety professionals are able to generate RCS exposure data at the end of the same shift, potentially allowing them to remediate issues before the next shift instead of waiting for results from an external analytical laboratory, which take days to weeks to receive. Compared to the traditional monitoring approaches, the new monitoring solution meets the following goals: (1) generation of results within minutes, (2) similar or improved accuracy compared to current methods, (3) use of off-shelf components, and (4) simplified sampling and analytical procedures.

Using this RCS monitoring approach, health and safety professionals can collect respirable dust samples using equipment common to occupational hygiene practices. This approach is not compatible with filters collected with the CPDM due to the design of the stem/filter holder as well as the composition and thickness of the filter media. However, all of the equipment needed to conduct the approach can be purchased for the approximate cost of one CPDM. After the collection, the dust samples can be analyzed in the field using a direct-on-filter technique and commercially available FTIR units (as illustrated in Figure 71). The technique does not require any pre-treatment of the sample and is non-destructive, allowing periodic verification of results by an external laboratory. The raw data generated by any portable FTIR are processed by a NIOSH-developed software that calculates the RCS amount using established mathematical models.

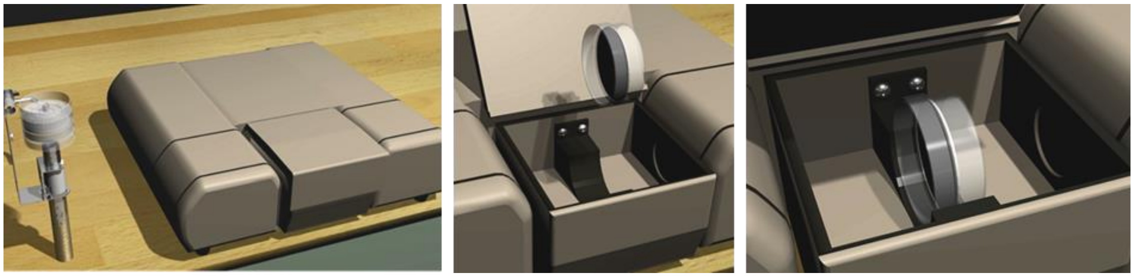


Figure 71. Rendition of portable FTIR unit and placement of cassette for sample analysis.

To refine this novel monitoring approach, NIOSH had initially assessed the performance of a portable FTIR to estimate RCS in coal mine dust samples [Miller et al. 2013; Cauda et al. 2016a; Miller et al. 2016]. The approach was then conceptualized and presented to the health and safety community by way of published peer-reviewed results [Cauda et al. 2016b].

In addition to providing an accurate analytical technique, the approach requires user-friendly components to facilitate field implementation. For this reason, NIOSH established a CRADA agreement with Zefon International for the development of a sampling cassette that minimizes filter handling and allows simple insertion into the analyzer. The cassette became commercially available in August 2018. In addition, new NIOSH software—Field Analysis of Silica Tool (FAST)—was developed and released to the public as a beta version in October 2018. The software can be used to: (1) transform raw data obtained by any FTIR into RCS exposure information, (2) organize results for different samples using tags and identification codes, and (3) integrate data from laboratory analyses to verify and improve the estimation.

NIOSH is also exploring the use of the field-based RCS monitoring approach in non-coal mines. The presence of complex mineralogy in the dust samples from non-coal mines poses an analytical challenge for accurate estimation of RCS without the availability of an expert analyst in the field. Therefore, NIOSH has proposed the use of mine-specific quantification models to generate a relative estimation of RCS in the samples [Cauda et al. 2018; Hart et al. 2018]. NIOSH has also conducted research to identify higher-volume respirable dust sampling equipment that may be necessary to accurately quantify crystalline silica concentrations below the PEL or for periods of time less than 8 hours [Coggins et al. 2014].

Intermediate Outcomes:

- In 2016, a U.S. coal mine company in West Virginia—Blackhawk Mining, LLC—used the field-based RCS monitoring approach to assess the effectiveness of using surfactants to control dust on a continuous miner section [Cauda 2019a].
- In 2017, a large U.S. metal mining company—Freeport-McMoRan, Inc.—used the field-based RCS monitoring approach to assess the RCS levels in seven mines. The company was able to identify gaps in the use of control technologies and new areas where interventions were needed [Cauda 2017a].
- In 2018, a health and safety consultant in South Africa began using the field-based RCS monitoring approach in conjunction with a real-time respirable dust monitor to assess exposures at large metal mines. The use of the combined technologies identified activities that resulted in elevated RCS exposures [Cauda 2018].

Respirable Crystalline Silica Workshops

NIOSH facilitates stakeholder adoption of RCS control interventions through collaborations, presentations, publications, and workshops. During the review period, NIOSH conducted 10 different workshops related to RCS from 2010 to 2018 in cooperation with different mining organizations and associations, including the National Industrial Sand Association, Nevada Mining Association, 3M, Caterpillar and the American Industrial Hygiene Association (AIHA). The combined attendance of these workshops was approximately 550 individuals. They were conducted in the U.S. (Starved Rock, IL; Elko, NV; Wausau, WI; Las Vegas, NV; Orlando, FL; Peoria, IL; Washington DC) and Australia (Queensland). A questionnaire was administered after the AIHA event with the workshop receiving over 95% positive responses related to pace of course, organization of material, usefulness of information, course materials, and achievement of learning objectives. All participants that filled out the survey answered yes to the course increasing understanding of the topics and that the course should be offered in the future. A new series of workshops is planned for the future based on the release of the second edition of a dust control handbook for industrial minerals mining and processing operations, discussed earlier (p. 202).

Awards Related to RCS Research

During the review period, the following awards were received from external organizations, demonstrating the quality and significance of NIOSH research in the area of respirable crystalline silica.

> 2012—Robert J. Stefanko Award, SME Coal & Energy Division, for best technical quality of the paper and presentation at the SME Annual Meeting and Exhibit, for “Long-Term Evaluation of Cab Particulate Filtration and Pressurization Performance.” (J Organiscak, A Cecala, J Noll)
>
> 2013—National Industrial Sand Association (NISA) Recognition of Excellence Award. This is NISA’s highest honor and it recognizes a lifetime of achievement for extraordinary contributions to the industrial sand industry. A NIOSH researcher was the first recipient of the award not employed by the industrial sand industry. (A Cecala)
>
> 2017—Research and Educational Excellence Award–SME Health & Safety Division, for “applied research to produce such technological innovations as a clothes cleaning booth, Helmet-CAM, and a continuous personal dust monitor.” (J Archer, A Cecala, J Colinet, E Haas, S Mischler, J Patts, R Reed, D Tuchman)
>
> 2018—Arthur S. Flemming Award for Social Science Clinical Trials and Translational Research, George Washington University, for “examination of workplace perceptions of safety, what miners’ behaviors tell us about their acceptance of new safety technology, and how adoption of risk management practices by leadership filters down to frontline workers.” This award honors outstanding federal employees who have made significant and extraordinary contributions to the federal government. (E Haas)

Diesel Particulate Matter

This research area is focused upon identifying interventions that successfully reduce exposure to diesel emissions and promoting implementation within the mining industry. Interventions that reduce DPM exposures include technologies, work practices, training approaches, and timely and accurate monitoring of the mine environment that empowers workers to identify and correct conditions that lead to overexposures.

Development and Commercialization of a Wearable Real-time DPM Monitor

The standard method for determining DPM exposures in mines is to collect the particulate onto a quartz fiber filter for an entire shift using a gravimetric sampler and then analyze for elemental carbon (EC) and total carbon (TC) using NIOSH Analytical Method 5040 [NIOSH 2017]. Although NIOSH 5040 is an accurate method for determining DPM exposures, it only provides the average concentration over an extended sampling period—typically an 8-hour or longer work shift—and does not provide timely information that could be critical to protecting miners’ health. Further, this approach can be problematic because, while it reports that an overexposure has occurred, it fails to provide critical information about cause. Conversely, real-time measurement of DPM concentrations provide miners with information to identify the major factors contributing to overexposures, allowing engineering controls to be deployed in a timely manner.

For the above reasons, NIOSH developed an instrument to measure near real-time EC exposure via laser absorption [Noll et al. 2013a]. The accuracy of the instrument was found to be within 10% of the standard method in the laboratory and equivalent to the standard method for field sampling. NIOSH licensed the technology to a manufacturer of thermal imaging infrared cameras, FLIR, and worked with FLIR to develop the Airtec diesel sampling commercial unit as shown in Figure 72.

Photos by NIOSH

Figure 72. Airtec diesel sampler (left) and being worn on a miner's belt (right).

Intermediate Outcomes:

- The manufacturer FLIR used results from NIOSH laboratory and field studies on a prototype instrument to develop a commercial version of the Airtec diesel sampler [Noll et al. 2013a]. Since initial commercialization in 2013, FLIR has sold over 200 Airtec monitors worldwide [Noll 2017b].
- Mines have incorporated Airtec into their DPM control strategy for applications such as spot checking to detect the presence of elevated DPM concentrations, identifying the shortcomings

of engineering and administrative controls, and implementing changes to reduce exposure levels [Noll et al. 2014b, Noll et al. 2011, Noll et al. 2015b, Noll et al. 2014a].

Sampling Research

Development of a Technique for Direct Tailpipe Measurement of DPM

Direct tailpipe sampling of diesel vehicles in mines allows for the direct determination of the effectiveness of control measures, including emissions-based maintenance programs, diesel particulate filters, and identifying the highest DPM emitters in a fleet of vehicles. Furthermore, by quickly determining the presence of a leak in a diesel particulate filter, direct tailpipe sampling can be used to evaluate the integrity of control technologies. Therefore, NIOSH developed a method that utilized the Airtec and a PDM to directly measure tailpipe emissions. Due to the heat and humidity of diesel vehicle exhaust, NIOSH created a special probe (see Figure 73) to remove water and cool the exhaust before entering the instrumentation [Noll et al. 2013b].

Photo by BHP

Figure 73. NIOSH-designed probe used for collecting tailpipe measurements.

Intermediate Outcome:

- BHP, a resources company that extracts and processes minerals, oil, and gas, primarily adopted the use of the NIOSH-designed probe to evaluate its diesel fleet at both hydraulic fracturing and mine sites [Noll 2017a].

Handheld Electrostatic Precipitator (ESP) Particle Sampler

As part of the NIOSH diesel research effort, studies were conducted on detailed characterization of airborne DPM. In particular, one research focus was on the role of inorganics (potentially derived from fuel additives or filter matrices) on diesel particle formation [Miller et al. 2007; Tumolva et al. 2010]. During the course of these studies, a need became evident for a device to collect representative samples of airborne nanoparticles for conducting microanalyses such as transmission electron microscopy (TEM) and energy dispersive spectrometry (EDS). NIOSH researchers subsequently collaborated with scientists at the NIOSH Nanotechnology Research Center to develop an electrostatic precipitator (ESP) nanoparticle sampler [Miller et al. 2010]. The ESP sampler was subsequently beta tested in collaboration with aerosol scientists at the University of Massachusetts and the University of California-Davis.

The sampler is a handheld device powered by batteries and encased in a robust enclosure (Figure 74, left). It is capable of collecting particles as large as tens of microns and as small as ten nanometers, providing representative samples over a wide range of particle sizes. The capability of collecting such a wide range of particle sizes makes this device advantageous for research purposes or when doing air quality surveys at field sites. Such a wide size range is often not possible with other techniques, especially ones that are portable and do not require auxiliary power.

The operating principle entails using a high-voltage electrical field to simultaneously charge and collect airborne particles (Figure 74, right). All sizes and types of particles are deposited onto the sampling media by electrostatic deposition. A wide variety of sampling media can be used, making the device more versatile for conducting characterizations that involve multiple different microanalyses. Particles are collected onto the media, which is then sent to a lab for off-line analyses by TEM, EDS, or other microanalytical methods. Extensive research and development resulted in a particle sampler that is optimized to provide high collection efficiency, representative samples, and short sampling times. After completion of beta testing, NIOSH licensed the product to DASH Connector.

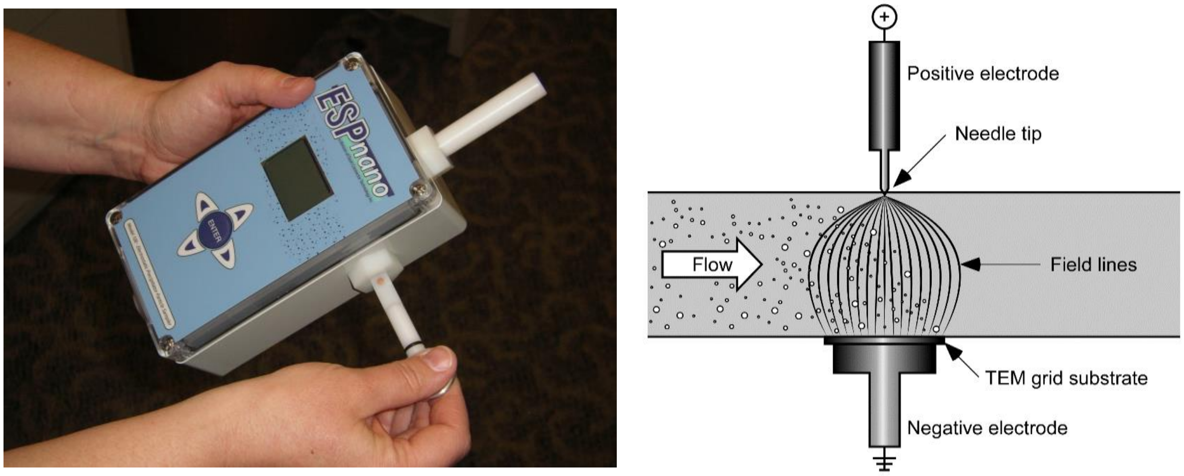


Photo by NIOSH

Figure 74. Handheld ESP sampler (left) and sketch showing principle of operation (right).

Intermediate Outcomes:

- DASH Connector Technology Inc. is selling the ESP particle sampler under the name of ESPnano.
- ESPnano has become a new tool for industrial hygienists and air quality researchers as evidenced by numerous citations of the original work (over 70 to date), as well as published references to its application for the characterization of hazardous airborne particulate matter.
  - Researchers around the world have acquired and used the ESPnano particle sampler to investigate worker exposures to DPM and other airborne hazards [Tumolva et al. 2010; Saffaripour et al. 2015].
  - ESPnano was used in an engine soot morphology study with a focus toward evaluating the toxicity of engine-emitted particles [Saffaripour et al. 2015; Barone et al. 2012; Heejung et al. 2013].
  - ESPnano was used in occupational exposure studies [e.g. O'Shaughnessy et al. 2013].

DPM Sampling Correction

As previously mentioned, the standard method for determining DPM exposures in mines is to collect the particulate onto a quartz fiber filter over a working shift and then analyze the filter for EC and TC using NIOSH Analytical Method 5040. However, during sampling, quartz filters can adsorb gas-phase organic carbon (OC) that is not emitted from diesel engines, thus causing bias in the sampling results. One method of correcting for this sampling artifact is to insert a secondary filter behind the primary or collection filter in the sampling cassette (as seen in Figure 75). Both filters are exposed and adsorb vapor phase OC while only the primary filter collects the particulate. The gas-phase OC mass on the secondary filter can then be subtracted from the OC mass on the primary filter to estimate particle-phase OC. However, the accuracy of this method depends upon several factors that were not well established in the scientific literature. Therefore, NIOSH performed a laboratory study to evaluate this artifact and possible correction methods for DPM mining samples [Noll and Birch 2008]. Based on the results of this study, NIOSH researchers recommended sampling procedures to enable a filter blank correction. When these recommendations were followed, the blank correction was found to minimize the effect of the adsorption artifact on TC samples. Due to these findings, this correction is now a standard practice in the mining industry when determining TC concentrations.

Photo by NIOSH

Figure 75. Two filters in tandem and a stainless steel backing pad to be inserted into a standard three-piece cassette.

Intermediate Outcome:

- ❖ Based upon NIOSH research [Noll and Birch 2008], MSHA began using a dynamic blank for correcting adsorption of vapor phase organic carbon in DPM compliance samples [MSHA 2016c].

Determining a Conversion Factor for Compliance Sampling

TC is used as a surrogate to determine DPM exposures in underground MNM mines because direct DPM measurement lacks both sensitivity and selectivity and because TC represents over 80% of DPM. However, TC can be influenced by non-DPM organic aerosols such as dust, cigarette smoke, vapor phase OC, and oil mist. Therefore, submicron EC was selected as an alternative surrogate since it is a major component of DPM and the analysis is not affected by the presence of OC interferences.

For compliance sampling, MSHA measures a worker's 8-hour TWA exposure level in terms of EC and TC concentrations. MSHA calculates DPM exposures based on both measured TC on personal samples and by calculating the TC from EC concentrations by multiplying the measured EC value with a TC/EC conversion factor. MSHA used NIOSH data from four underground MNM mines and an isolated zone study to develop a conversion factor, based on the NIOSH analysis of the relationship between EC and TC [Noll et al. 2007]. This study concluded that EC and DPM demonstrated a strong correlation (R^2 of 0.99, equation of linear regression: TC=1.12 EC x +39.85) in underground MNM mines for most of the samples collected, but also concluded that an accurate TC/EC ratio for samples at concentrations approaching the PEL could not be recommended. This conclusion was based upon the increased variability of the data nearing the PEL, the limited number of samples in this concentration range, and a concern about the effects of newly implemented control technologies on the relationship between TC and EC.

Intermediate Outcome:

- Based on findings from a NIOSH analysis of the relationship between EC and TC, in 2008, MSHA used this information to determine that a conversion factor should be calculated during each sampling event, developed a methodology for DPM sampling, and incorporated this methodology into the MSHA final rule, "Diesel Particulate Matter Exposure of Underground Metal and Nonmetal Miners."

Multifaceted Best Practices Approach for Diesel Control

Several research projects conducted in the U.S. under the auspices of NIOSH, the Coal Diesel Partnership, the MNM Diesel Partnership [NIOSH 2006a,b], and the Canadian Diesel Emissions Evaluation Program (DEEP) [Conard 2006] provided NIOSH researchers with experiences that were used to develop a multifaceted, integrated approach toward reducing exposure of underground miners to DPM and gases. The approach, based on a hierarchy of viable solutions to reduce diesel emissions and exposures, was detailed in two publications [NIOSH 2011; Bugarski et al. 2012a] and was broadly disseminated to national and international audiences via well-attended one-day workshops. NIOSH also assisted several mine operators on implementation of the various aspects of the approach [Noll et al. 2011; Noll et al. 2014a; Noll et al. 2015b]. Specifically, NIOSH assisted a stone mine with an integrated approach toward reducing exposure of underground miners to DPM and gases. To reduce exposures of its blasters, this mine increased ventilation, installed a diesel particulate filter on the blasters' truck, and used 20% biodiesel, resulting in a 35% reduction in DPM exposure [Noll et al. 2015b].

NIOSH's multifaceted, integrated approach was well accepted by the underground mining industry in the U.S. and abroad [MIAC 2005] and was instrumental to the interventions leading to the gradual reduction in average concentrations of TC and EC in metal and nonmetal mines in the U.S. [MSHA

2017a; MSHA 2017b]. Based on the field and laboratory research, NIOSH produced a book entitled *Controlling Exposures to Diesel Emissions in Underground Mines*, which was published and is being sold by SME [Bugarski et al. 2012a].

Intermediate Outcome:

- To date, over 135 copies of *Controlling Exposures to Diesel Emissions in Underground Mines* have been purchased from the publisher [Mischler 2018b].

Aftertreatment Technologies for Diesel Emission Control

The use of aftertreatment technologies was found to be critical to the curtailment of particulate matter emitted by diesel-powered vehicles in the EPA final rule, "Control of Emissions of Air Pollution from Nonroad Diesel Engines" [Bugarski et al. 2012a; Fiebig et al. 2014]. At the time of promulgation of the MSHA DPM rules ("Diesel Particulate Matter Exposure of Underground Coal Miners," and "Diesel Particulate Matter Exposure of Underground Metal and Nonmetal Miners," cited earlier), diesel particulate filter systems were recognized as the most promising technology for effective curtailment of particulate emissions. However, NIOSH studies [NIOSH 2006a,b] showed that a large number of the diesel particulate filter products available at that time were not suitable for retrofitting to underground mining mobile equipment. The initial efforts to reduce particulate and gaseous emissions from underground mining equipment using retrofitted diesel particulate filter systems were hampered by an increase in secondary emissions of nitrogen dioxide (NO_2) [NIOSH 2006a,b; Cauda et al. 2008; Cauda et al. 2010; MSHA 2011].

In an effort to assist the mining industry in the selection of mine-worthy diesel oxidation catalytic converters, diesel particulate filters, and other exhaust aftertreatment systems, NIOSH researchers evaluated a number of products at NIOSH's LLEM [Bugarski et al. 2008a; Bugarski et al. 2009] and a NIOSH laboratory at the Pittsburgh site [Bugarski et al. 2016a]. Those evaluations showed that the diesel particulate filter systems based on wall flow monolith filtration elements and sintered metal elements are the most effective technology for curtailment of DPM emissions. They also showed that some catalyst formulations in diesel oxidation catalytic converters and diesel particulate filters do not promote secondary emissions of NO_2 (referred to as NO_2 slip).

Due to issues related to the regeneration of the filtration elements, the implementation of diesel particulate filter systems was found to be particularly challenging for light-duty vehicles in underground mines. NIOSH's evaluations at LLEM showed that sintered metal filter systems, fitted with onboard dosing additive systems that facilitate passive regeneration of the filter, or fitted with an electrical heater used to actively regenerate the filter, might be suitable for light-duty applications. Encouraged by the positive results of the NIOSH evaluation, Inco (currently Vale) collaborated with NIOSH to establish a long-term evaluation of the sintered metal filter system on two light-duty vehicles at the Creighton Mine. This series of field and laboratory studies were used to evaluate both the mine-worthiness of this system and to quantify the reduction and characterize the effects on diesel emissions [Bugarski et al. 2011; Bugarski et al. 2013; Bugarski et al. 2016a].

The continuously regenerating trap diesel particulate filter system, developed by Johnson-Matthey (JM), is extensively used to curtail DPM emissions from diesel-powered city buses. Due to NO_2 slip (secondary emissions of NO_2), the initial versions of this system were found to be unsuitable for use in the underground mining industry. JM developed a modified version of the system that was evaluated at the University of Minnesota [Zarling et al. 2006] under a NIOSH contract. After encouraging results, NIOSH and Vale collaborated to conduct a long-term evaluation of the system at the Totten surface mine [Bugarski et al. 2012b] and the Copper Cliff underground mine [Bugarski et al. 2015a; Stachulak 2017].

Some of the diesel oxidation catalytic converters that are extensively used to curtail carbon monoxide (CO) and hydrocarbon (HC) emissions from diesel-powered underground mining equipment were also found to produce secondary NO_2 emissions [Cauda et al. 2008; Cauda et al. 2010; Stachulak and Allan 2014]. Therefore, NIOSH researchers worked with the AirFlow Catalyst Systems, Inc., on an evaluation of catalyst formulations for diesel oxidation catalytic converters that would be effective in controlling CO and HC emissions from contemporary diesel engines and that would not generate additional NO_2 emissions. The evaluation results showed that certain catalyst formulations can provide the desired reductions in CO and HC without increasing NO_2 emissions [Bugarski et al. 2015b].

Intermediate Outcomes:

- Based on NIOSH research, Vale installed 30 sintered metal filter systems on light-duty vehicles deployed in its mines [Stachulak 2017]. Since 2013, the distributors sold 378 sintered metal filter systems to underground mining operations in the U.S. and Canada [Bugarski 2018].

- Johnson Matthey Mining Continuously Regenerated Trap was developed and extensively evaluated at Vale's Totten and Copper Cliff mines in a partnership among Johnson Matthey, Vale, and NIOSH [Bugarski et al. 2012b; Bugarski et al. 2015a]. The system was subsequently certified by CANMET [CANMET 2017] and is currently offered to the underground mining industry by Toromont Cat, Concord, Ontario, as a part of the upgrade on the power package for Caterpillar AD45 haulage truck.
- Based on NIOSH research, diesel oxidation catalytic converters and other retrofit diesel particulate filter systems are being used in the underground mining industry in the U.S. [MSHA 2016b]. These aftertreatment systems are currently integrated into the underground mining diesel-power packages offered by major original equipment manufacturers [Stirling et al. 2016].

Alternative Fuel for Diesel Emission Control

Studies conducted at NIOSH's LLEM showed the potential of using fatty acid methyl esters (FAME)-derived bio fuels as a control strategy to reduce exposures of underground miners to DPM [NIOSH 2006b; Bugarski et al. 2008b; Bugarski et al. 2010]. NIOSH collaborated with Newmont USA Limited to conduct an isolated zone study in the Leeville Mine, Elko, Nevada, to evaluate the effects of several biodiesel blends and ultralow sulfur diesel (ULSD) on airborne contaminants in the underground environment [Bugarski et al. 2014]. The results showed that the FAME biodiesel, when compared with ULSD, reduced DPM, TC, and EC mass concentrations. The reductions were found to be directly proportional to biodiesel content in the blends.

Additional follow-up laboratory studies conducted at NIOSH showed that the toxicity of aerosols is higher when engine is fueled with FAME B100 than with ULSD [Yanamala et al. 2013; Kisin et al. 2014]. As a result, Newmont USA Limited decided to investigate replacing biodiesel and ULSD in some of its operations with a blend of hydrotreated vegetable oil renewable diesel (HVORD) supplied by Neste Oil. A collaboration between Newmont, Neste Oil, and NIOSH was established to evaluate HVORD in a laboratory at the Pittsburgh site [Bugarski et al. 2016b]. This study showed that FAME biodiesel and HVORD both reduced DPM, TC, and EC emissions from an older, mechanically controlled, naturally aspirated engine. The magnitude of reductions in total mass concentrations of DPM, TC, and EC in the exhaust was found to be comparable for FAME and HVORD. Use of these alternative fuels was shown to be a viable tool for the underground mining industry to address the issues related to emissions from diesel engines in transition toward more universal solutions provided by advanced engines with integrated exhaust aftertreatment technologies. Based on the above NIOSH research, Newmont operations at its Chukar and Pete Bajo sites in in Nevada are currently using 100% HVORD as a DPM control strategy [Bugarski 2019].

Diesel Particulate Matter Workshops

NIOSH encourages stakeholder adoption of DPM control interventions through collaborations, presentations, publications, and workshops. During the review period, NIOSH conducted 14 diesel control workshops from 2008 to 2017 to transfer information to the mining industry. The combined attendance of these workshops was several hundred individuals. Over half of these workshops were organized by NIOSH as the result of invitations from mining organizations and associations. Most included presentations by researchers, mining companies, regulators, and equipment manufacturers. They were conducted in the U.S. (Beckley, WV; Charleston, WV; Elko, NV; Golden, CO; Louisville, KY; Morgantown, WV; Pittsburgh, PA; Rolla, MS; Salt Lake City, UT; and Sparks, NV), Australia (Sydney, NSW), Canada (Sudbury, ON), China (Xi'an, Shaanxi), and South Africa (Sun City, NW).

Award Related to DPM Research

During the review period, the following award was received from an external organization, demonstrating the quality and significance of NIOSH research in the area of DPM emissions.

> 2012—Safety Award, Northwest Mining Association, for outstanding work in reducing the exposure of underground miners to emissions from diesel equipment. (A Bugarski, E Cauda, J Hummer, S Janisko, S Mischler, J Noll, L Patts)

End Outcomes

Over the review period, industry average respirable dust concentrations from compliance samples taken by MSHA inspectors and mine operators for all occupations in underground coal mines dropped 20% from 0.77 mg/m^3 in 2008 to 0.62 mg/m^3 in 2017 [MSHA 2018a]. During this same time frame, RCS concentrations in MNM mines dropped 21% from 53 micrograms per cubic meter (ug/m^3) to 42 ug/m^3, and TC diesel concentrations in underground MNM mines dropped 54% from 235 ug/m^3 to 108 ug/m^3.

Although these decreases cannot be specifically or solely attributed to NIOSH research, it is likely that NIOSH's efforts, as evidenced by the intermediate outcomes described in this chapter, have contributed to these decreases.

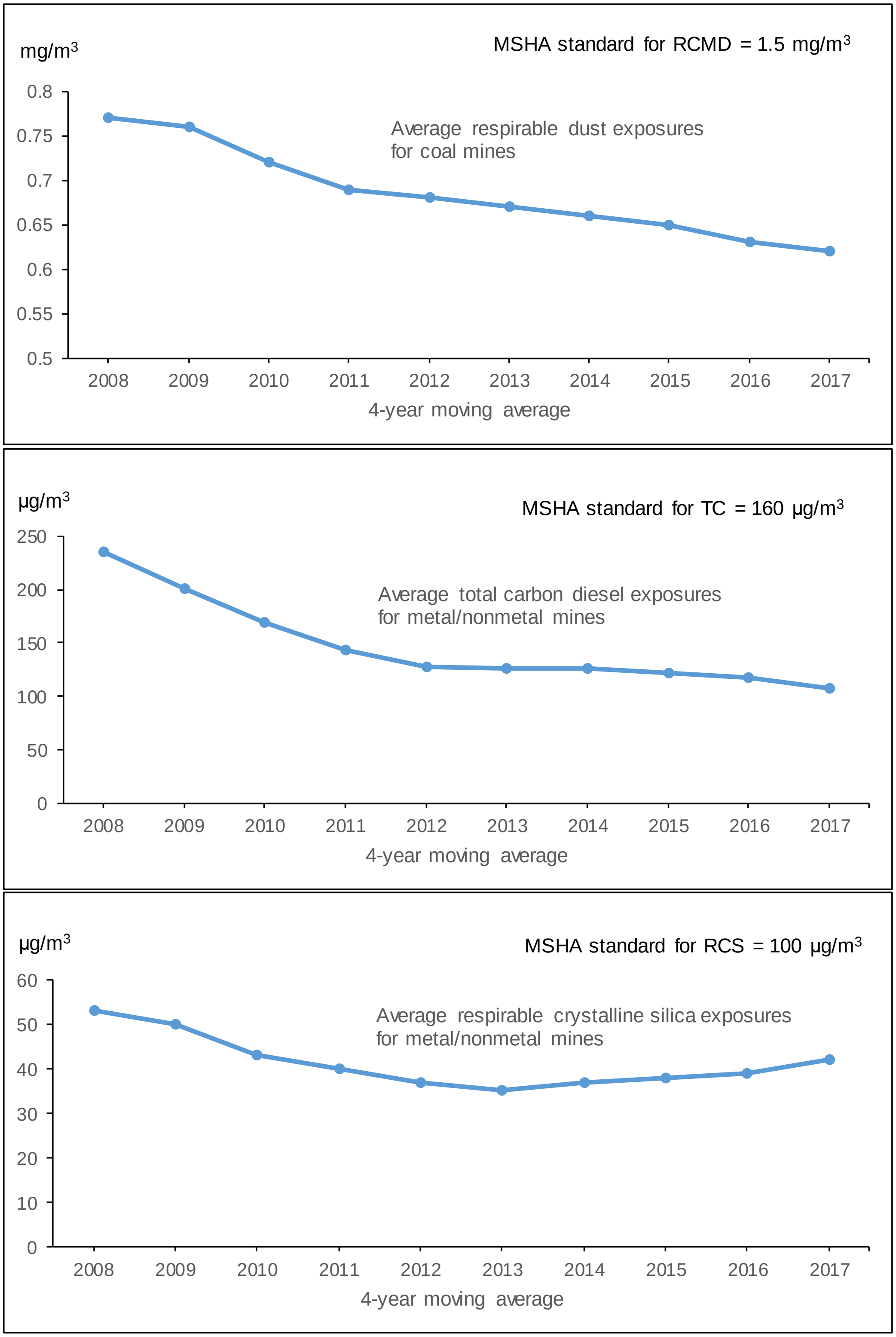


Figure 76. Reductions in average exposures for respirable coal mine dust (top), diesel particulate matter (center), and silica dust (bottom). Graphed data represent the end years of four-year moving averages.

Alternative Explanations

In addition to NIOSH research, the actions and activities of other organizations have also likely contributed to the reductions in concentrations of coal mine dust, crystalline silica, and diesel emissions. These may be broadly characterized as campaigns, enforcement of more stringent regulations, and increased product offerings, as described below.

Respirable Coal Mine Dust

In 2009, then U.S. Department of Labor Assistant Secretary, Joe Main, initiated an “End Black Lung—Act Now” campaign [MSHA 2009] to increase awareness of the disease and the toll taken on miners and the mining industry. The campaign included: (1) education and training for miners, miners’ representatives, supervisors, and operators; (2) enhanced enforcement of respirable dust standards; (3) effective use of available dust control technology; and (4) regulatory improvements to reduce miners’ exposure to respirable coal mine dust. At the request of MSHA, NIOSH presented at a series of dust control workshops that were uploaded to MSHA’s End Black Lung webpage.

In 2014, MSHA published a final rule, “Lowering Miners’ Exposure to Respirable Coal Mine Dust, Including Continuous Personal Dust Monitors,” which changed sampling procedures for respirable coal mine dust, lowered the dust standard from 2.0 mg/m^3 to 1.5 mg/m^3, and required the use of the CPDM for compliance sampling. During 2011 and 2012, the U.S. Government Accountability Office (GAO) [GAO 2012] performed an evaluation of the data cited by MSHA to support lowering the PEL for respirable coal mine dust. The GAO conducted interviews and site visits at government agencies including NIOSH, and reviewed studies cited in supporting documents including the NIOSH 1995 Criteria for a Recommended Standard: Occupational Exposure to Respirable Coal Mine Dust [NIOSH 1995]. The GAO concluded that “the evidence MSHA used supported its conclusion that lowering the exposure limit as proposed would reduce miners’ risk of disease.”

When the price of coal was at its peak, mining operations could extract larger quantities of rock and remain profitable. As power generation increasingly switched to natural gas, coal use and prices dipped, causing marginal and resource-constrained mines to cease operations. Remaining mines were operating in more favorable geologic conditions, which could contribute to a general reduction in dust levels.

Respirable Crystalline Silica

The Occupational Safety and Health Administration promulgated a new rule, "Occupational Exposure to Respirable Crystalline Silica," that lowered the PEL for respirable crystalline silica from 100 ug/m^3 to 50 ug/m^3. The new rule brought significant awareness to the crystalline silica hazard. MSHA had respirable crystalline silica on its spring 2018 semiannual regulatory agenda. It is possible that MSHA will adopt this more stringent standard in the future; therefore, mines may be targeting this level now.

Numerous OEM and aftermarket heating, ventilation, and air-conditioning (HVAC) and filtration and pressurization companies began manufacturing and selling systems to improve the air quality inside enclosed cabs of mobile equipment as well as other environmental enclosures. Many of these aftermarket companies incorporated NIOSH design criteria into their products.

Diesel Particulate Matter

As older higher-emitting diesel engines fail in underground mines, they are being replaced with modern lower-emitting engines. Newer engines must meet more stringent emissions standards as set by the Environmental Protection Agency [EPA 2016].

In 2008, in the MSHA final rule, "Diesel Particulate Matter Exposure of Underground Metal and Nonmetal Miners," the reduced MSHA diesel particulate matter exposure standard of 160 µg/m^3 of total carbon became effective, resulting in mines having to meet the new standard. NIOSH collaborated with mining companies, government agencies, and equipment manufacturers to develop and disseminate effective intervention strategies to address high exposures.

Mine operators may choose to use electrically powered equipment in place of diesel-powered equipment, thus eliminating diesel emission sources [Desrosiers and Willick 2014, Schinkel 2015, Schinkel 2017, Mullally 2017], although this transition has been limited in the U.S. thus far. Options are available for trolley trucks, locomotives, load-haul-dump (LHD) vehicles, jumbo drills, scissor lifts, utility trucks, bolters, tractors, and personnel transporters.

Future Plans

The future plans of NIOSH related to respirable hazards include collaborating with stakeholders to develop and assess effective control interventions, including coal mine dust, crystalline silica, diesel emissions, and elongate mineral particles. MSHA compliance data will be used to identify high-risk occupations within each mining sector. The current research portfolio will explore exposure solutions for the following:

- *Coal*: shearer operators and jacksetters on coal longwall sections; shuttle car operators on continuous miner sections using blowing ventilation.
- *Diesel*: blasters, LHD operators, drillers, truck drivers, and scalers in underground MNM mining operations.
- *Crystalline Silica*: bagging operators.

Future monitoring research will focus on developing methodologies for determining field-based RCS concentrations in MNM mines. This will minimize overexposures between sampling and will facilitate rapid assessment of control interventions. Research will also focus on identifying and addressing barriers to participation in the CWHSP, assisting international partners in developing updated ILO classification standard images for using digital radiographs, and revising NIOSH training materials for physicians who classify digital radiographs.

Finally, NIOSH is analyzing information and preparing a response to the National Academy of Sciences (NAS) consensus study report, *Monitoring and Sampling Approaches to Assess Underground Coal Mine Dust Exposures* [NAS 2018]. This report includes 13 recommendations to address research gaps related to coal miner exposures to RCMD. Work has already begun by way of extramural and intramural resources on four of the recommendations (5, 6, 8 and 11) with the following goals:

- develop a real-time RCS monitor and a less ergonomically stressful CPDM;
- investigate the association among technology, rock extraction, and PMF hotspots to optimize sampling and monitoring strategies; and
- identify and address barriers to participation in the CWHSP.

Recommendation 3—which calls for NIOSH and MSHA to carry out a systematic examination of the content and implementation of training and education programs with respect to RCMD exposure—is included in a proposed project whose outputs will be disseminated to miners, operators, and regulators. To address the recommendations from the NAS report, NIOSH will work with MSHRAC to prioritize research gaps that are not currently being addressed.

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Appendix A: Mining Program Responses to the 2007 National Academy of Sciences Review

Choosing from the 18 recommendations made in the National Academy of Sciences report relevant to this evidence package, those recommendations specifically applicable to disaster prevention and response, ground control, and respirable hazards are listed below. Each recommendation is followed by a summary of how the Mining Program responded over the course of 2008–2018.

Recommendation #1a: *Establish more challenging, innovative goals and attendant objectives.*

> The Program aggressively focused on reducing the potential for coal mine explosions in a number of project areas including lab testing of newly developed rock dusting approaches, the measurement and reduction of float dust, and a significant number of extramural research studies funded through the contracts and grants program. The contracts included technology developments on anti-caking rock dust, improved rock dust application systems, and enhanced monitoring technologies for bleeders and remote workings. The Program's ability to leverage its resources was improved through an expanded number of collaborations with other federal agencies and non-government organizations, including the following: the Naval Research Lab, the U.S. Army Corps of Engineers, the National Aeronautics and Space Administration (NASA), the Los Alamos National Laboratory, Sandia National Laboratories, the National Institutes of Standards and Technology (NIST), and the Safety in Mines Testing and Research Station (SIMTARS) (Australia).

Recommendation #1b: *Take a more proactive approach to identifying and controlling hazards.*

> The Program utilized the available surveillance databases in conjunction with stakeholder input to identify key needs and to set priorities within the research portfolio. The Program identified several issues of concern in the assessment of explosibility hazards in underground coal mines that led to MSHA issuing an Emergency Temporary Standard (ETS) requiring 80% incombustible content in intake airways. Researchers combined a number of numerical methodologies into a single software suite designed to reduce the likelihood of a gas explosion. To address exposure monitoring of hazards, a software program was developed to merge video files and logged data files to allow users to record and assess their exposures to contaminants, and a field-based respirable crystalline silica monitoring approach and software were developed to allow operators to perform filed-based silica monitoring to obtain near real-time results right at the mine site.

Recommendation #3: *Enhance interaction with MSHA where research needs are closely aligned with MSHA's legislative and shorter-term priorities.*

> To deepen its partnership with MSHA, Program signed a new memorandum of understanding (MOU) in January of 2009 that strengthened coordination and consultation on health and safety needs and issues for the mining community, processes for commenting on research and dates for public dissemination, and on research, training, and technical assistance. The Program also responded to an MSHA request to participate in a ground control stability problem at an underground coal mine in Kentucky, developing a mining plan to overcome the high-stress conditions of the property. At MSHA's request, the Mining Program conducted training at the Beckley Academy, Beaver, WV, for mine inspectors and roof control specialists. Finally, in

collaboration with MSHA, the Mining Program developed a number of research collaborations and partnerships with industry, labor, and government organizations in four significant areas: the Mine Emergency Communications Partnership (MECP); the Composition and Fire Retardant Properties of Belt Materials in Underground Coal Mining; Design Criteria for Seals in Coal Mines; and the Breathing Air Supply Partnership.

Recommendation #4: *Fully utilize outside technical expertise through a vibrant extramural and contract research program.*

In particular through MINER Act and OEP funding, the Program developed a much more extensive extramural and contract research program and invested in both new research and in graduate programs at mining universities.

Recommendation #8: *Develop more robust and better methods of monitoring in situ safety conditions in mines.*

Program research included continued development of an in situ personal dust monitor for measuring and displaying, in near-real time, the miner's cumulative dust exposure; the design and testing of a system for measuring the performance of shotcrete applications for roof support in underground metal mines, and development and testing of the Coal Dust Explosibility Meter (CDEM). The CDEM is a technology for real-time measurements of the explosibility of coal dust-rock dust mixtures in underground coal mines, which was successfully transferred to the mining community and is routinely used by the underground coal mining industry.

Recommendation #10: *Develop demonstration projects that show the feasibility and effectiveness of interventions.*

The Program includes a demonstration component in virtually every project that includes an intervention as an output, with some projects specifically structured as demonstration rather than research projects. Relevant to the review areas, the Program's field demonstrations of interventions have included the following: the efficacy of tube-bundle monitoring technology to remotely monitor gas concentrations in an underground coal mine; the use of a real-time, personal dust monitor at over 100 mines located throughout 10 MSHA enforcement districts; and emergency response training procedures at mine rescue contests and mine sites.

Recommendation #11: *Include how small business worker populations will be served.*

NIOSH participates prominently in an annual Underground Stone Mines Safety Seminar sponsored by the Kentucky Crushed Stone Association, which has reached more than 3,000 stone miners representing more than 75 organizations. As one example of a workshop held by the Mining Program to serve small mine worker populations, after developing its S-Pillar software to assist in pillar design at room-and-pillar stone mines, NIOSH trained 15 stone operators, five consultants, and several MSHA specialists on the use of the software in June, 2011, by way of a workshop. Finally, the Program website made this and other past workshops available in video form for those industry members who could not attend the workshops when they were held. The workshop topics included explosibility issues in coal mines and the use of the CDEM, state-of-the-art proximity detection systems, and state-of-the-art practices with communications and tracking systems.

Recommendation #12: *Incorporate training into the strategic goals of all research areas.*

The Program developed over 50 training products between 2008 and 2018, including handbooks on decision-making during an emergency; a suite of ground control analysis software; and downloadable applications including safety and health “toolbox talks” for use during training sessions at mines.

Recommendation #15: *The Mining Program should be prepared to provide recommendations to safeguard health and safety as best strategies for mining deep resources are developed. Environmental and occupational hazards of deeper mines should be evaluated.*

The Mining Program initiated several projects focused on following the changing trends in mining, including mining deeper and more challenging resources. Ground control research was expanded to include an intramural project that developed computational tools for modeling caving mechanisms in deep mining, with revisions made to the Analysis of Retreat Mining Pillar Stability (ARMPS) software program to better reflect the influence of barriers and load transfers in deep mining conditions. Other research projects include building a framework for expanding pillar design criteria into challenging environments by undertaking pillar response investigations in representative conditions at case study mine sites, developing strategies to identify and manage geologic features that increase the risk of dynamic failures in underground coal deposits, and managing a targeted program of case studies to develop engineering solutions for ground control hazards in western underground metal mines.

Recommendation #18: *The Mining Program should seriously attend to workforce replacement issues expected within its own organization in the short term to ensure a supply of capable researchers as its older researchers retire.*

Between 2008 and 2018, the Program sponsored training courses in the elements of coal mining, metal/nonmetal mining, and ventilation engineering for new non-mining recruits; assisted personnel in obtaining advanced degrees in core areas of the Program, expanded its efforts in using the Student Temporary Employment Program (STEP) for attracting and recruiting recent graduates in science and engineering fields; awarded capacity-building contracts to accredited mining engineering programs to increase the available number of mining graduates with higher degrees; and recruited and hired over 100 personnel including engineers, scientists, technicians, and support staff for the Mining Program—11 of whom came from the capacity-building program.

Appendix B: Disaster Prevention and Response Staff

The below table represents key staff who completed disaster prevention and response research for the Mining Program during 2008–2018. The positions listed reflect the status at the time the research was completed, with current retired status also noted. All acronyms used in these tables are defined in the front matter of the evidence package.

NIOSH Mining Program Researchers: Disaster Prevention and Response

Name	Position, NIOSH Division
Michael J. Brnich	Mining Engineer, PMRD (retired)
Thomas Dubaniewicz	Lead General Engineer, PMRD
Rohan Fernando	Associate Service Fellow, NPPTL
Gerrit V.R. Goodman	Branch Chief, PMRD
Marcia L. Harris	Lead General Engineer, PMRD
Cassandra Hoebbel	Behavioral Research Scientist, PMRD
Eranda Perera	Senior Service Fellow, PMRD
Jingcheng Li	Senior Service Fellow, PMRD
Robert H. Peters	Lead Behavioral Research Scientist, PMRD (retired)
Michael Sapko	Contractor, PMRD
Steven J. Schatzel	Research Geologist, PMRD
David P. Snyder	General Engineer, PMRD
Robert Stein	General Engineer, NPPTL
Gary Walbert	General Engineer, NPPTL
Joseph Waynert	Senior Service Fellow, PMRD
Lincan Yan	Associate Service Fellow, PMRD
David Yantek	Mechanical Engineer, PMRD
Liming Yuan	Lead General Engineer, PMRD
Chenming Zhou	General Engineer, PMRD
Lihong Zhou	Senior Service Fellow, PMRD

Appendix C: Refuge Alternative Partnership

The below table represents selective interactions that took place between the NIOSH Mining Program and stakeholders as part of the Refuge Alternative Partnership, 2012 to 2018. As noted, the Partnership involved a mix of stakeholder meetings, personal communications, site visits, and presentations. All acronyms used in the table are defined in the front matter of the evidence package.

Activities	Dates	Interactions
Travel to Strata facility in MD to discuss test details	3/1/2012	Stakeholder meeting
Visit to RA manufacturers ChemBio and A.L. Lee	2/5/–2/7/2013	Stakeholder meeting
Meeting with MSHA A&CC AED	2/20/2013	Stakeholder meeting
RA manufacturer meeting with ChemBio Shelter	6/14/2013	Stakeholder meeting
RA manufacturer ChemBio visit to NIOSH SRCM	6/24/2013	Stakeholder meeting
Meeting with MSHA A&CC AED to discuss portable RAs	9/5/2013	Stakeholder meeting
RA manufacturer meeting with Mine Shield representative	9/10/2013	Stakeholder meeting
RA manufacturer meeting with ChemBio Shelter	9/12/2013	Stakeholder meeting
RA manufacturer meeting with Kennedy representative	9/16/2013	Stakeholder meeting
RA manufacturer meeting with Strata representative	9/17/2013	Stakeholder meeting
RA manufacturer meeting with A.L. Lee representatives	9/19/2013	Stakeholder meeting
Meeting with WV OMHST representatives	9/20/2013	Stakeholder meeting
Meeting with MSHA A&CC AED to discuss portable RAs	11/8/2013	Stakeholder meeting
Conference call with manufacturer Trinity Resources	11/21/2013	Stakeholder meeting
Meeting with WV OMHST/WVU Mining Extension	12/6/2013	Stakeholder meeting
Meeting with MSHA A&CC AED to discuss technical specs	12/30/2013	Stakeholder meeting
Phone call with Mine Ventilation Australia	1/16/2014	Stakeholder discussion
Presentation at MSHRAC to discuss occupancy derating	4/20/2014	Presentation
BCOA/UMWA Joint S&H Committee RA Workshop	5/22/2014	Presentation
Collaboration with 5 mines on temperature measurement	6/2014–8/2016	E-mail communications
Meeting with MSHA A&CC AED to discuss technical specs	8/27/2014	Stakeholder meeting
Meeting with Mine Shield representative	10/8/2014	Stakeholder meeting
Mine Shield collaboration to fabricate special metal RA	10/2014–5/2015	E-mail communications
Meeting with Walter Energy representatives	10/10/2014	Stakeholder meeting
Presentation to visitors from the Turkish government	10/30/2014	Presentation
Meeting with members of WV OMHST	11/7/2014	Stakeholder meeting
Meeting with Jürgen Brune, Colorado School of Mines	11/12/2014	Stakeholder meeting
Visit to ChemBio to discuss portable RA technical specs	11/17/2014	Stakeholder meeting
Meeting with Mine Shield representative to give RA tour	12/12/2014	Stakeholder meeting
Visit to meet with University of Kentucky representatives	1/13/2015	Stakeholder meeting
Visit to UNR to discuss thermal simulation tool	2/3/2015	Stakeholder presentation
Meeting with USF/TAI representatives to discuss models	2/9/2015	Stakeholder meeting
Inaugural RA Partnership Meeting	2/10/2015	Partnership meeting
Conference call with ChemBio on borehole air supply	3/18/2015	Stakeholder meeting

Meeting with MSHA A&CC AED to discuss portable RAs	3/17/2015	Stakeholder meeting
WV Mine Safety Technology Task Force Meeting	3/19/2015	Stakeholder meeting
Phone call with ChemBio and MSHA A&CC AED	3/23/2015	Stakeholder discussion
Meeting with DRS Environmental Systems	5/26/2015	Stakeholder meeting
Meeting with MSHA A&CC AED to discuss research findings	5/28/2015	Stakeholder meeting
Conference call with ChemBio to update on test procedure	6/4/2015	Stakeholder discussion
Presentation at MSHRAC on overview of RA research	6/8/2015	Presentation
Meeting with DRS Environmental Systems to discuss device	6/22–6/23/2015	Stakeholder meeting
Conference call with DRS Environmental and MSHA A&CC	7/1/2015	Stakeholder discussion
Visit to Riverview Mine to see BIP RA and air supplies	8/5/2015	Field site visit
Meeting with MSHA A&CC representatives to discuss specs	1/15/2016	Stakeholder meeting
RFI on Refuge Alternatives for Underground Coal Mines	1/15/2016	Response letter
Meeting with DRS Environmental Systems and MSHA	2/19/2016	Stakeholder meeting
Meeting with MSHA A&CC representatives to discuss BIPs	3/22/2016	Stakeholder meeting
MOU with DRS Environmental Systems on POC system	4/19/2016	Legal agreement
Presentation at MSHRAC on update of research findings	5/10/2016	Presentation
NIOSH PMRD EMSSB visit to MSHA AC&C	5/18/2016	Stakeholder meeting
MSHA/NIOSH Joint Meeting on RAs and BAS devices	6/2/2016	Stakeholder meeting
Refuge Alternative Partnership Webinar	6/23/2016	Stakeholder meeting
Presentation at JAHSA meeting on research findings	6/29/2016	Presentation
Meeting with MSHA representatives to discuss mine air	8/17/2016	Stakeholder meeting
Presentation at MineExpo on thermal simulation software	9/27/2016	Presentation
Refuge Alternatives Partnership Meeting	10/19/2016	Stakeholder meeting
Field data collection at cooperating mine	10–11/2016	Field site visit
Meeting with MSHA to discuss research findings	1/10/2017	Stakeholder meeting
Personal communication with MSHA representative	3/3/2017	Personal communication
NIOSH research cited in MSHA testing document	3/21/2017	Test procedure
Meeting at mine for in-situ heat/humidity test	3/29/2017	Field site visit
NIOSH PMRD EMSSB visit to MSHA AC&C AED	4/13/2017	Stakeholder meeting
Breathing Air Supply and Refuge Alternative Workshop	6/7/2017	Stakeholder meeting
Meeting with RA manufacturer ChemBio on test results	6/27/2017	Stakeholder meeting
NIOSH PMRD EMSSB visit to MSHA to discuss UNR tool	8/28/2017	Stakeholder meeting
Visit to ChemBio to set up for heat/humidity testing	9/12/2017	Stakeholder meeting
Collaboration with MSHA on UNR thermal simulation tool	9/18/–11/7/2017	Personal communications
Meeting with MSHA A&CC to demonstrate simulation	10/17/2017	Stakeholder meeting
Conference call with RA manufacturer ChemBio	10/31/2017	Personal communication
Presentation at MSHRAC to update on research findings	11/15/2017	Presentation
Response to MSHA AC&C AED e-mail request	12/7/2017	Personal communication
Conference call with MSHA AC&C and Chasm Engineering	12/11/2017	Personal communication
Meeting with MSHA A&CC AED to discuss test results	1/11/2018	Stakeholder meeting

Appendix D: Ground Control Staff

The below tables represent key staff who completed ground control research for the Mining Program during 2008–2018. The positions listed reflect the status at the time the research was completed, with current retired status also noted. All acronyms used in these tables are defined in the front matter of the evidence package.

NIOSH Mining Program Researchers—Current Staff: Ground Control

Name	Position, NIOSH Division
Timothy Batchler	Mechanical Engineer, PMRD
Donovan Benton	Mining Engineer, SMRD
Chaparral Berry	Chemical Engineer, SMRD
Shawn Boltz	Mining Engineer, SMRD
Amy Chambers	Metallurgical Engineer, SMRD
Derrick Chambers	Mining Engineer, SMRD
Frank Chase	Mining Engineer, PMRD
Curtis C. Clark	Mechanical Engineer, SMRD
Craig Compton	Technician, PMRD
Kathryn Dehn	Geologist, SMRD
Heather Dougherty	Mining Engineer, PMRD
Gabriel Esterhuizen	Principal Mining Engineer, PMRD
David Gearhart	Electrical Engineer, PMRD
David Hanson	General Engineer, SMRD
Steven R. Iverson	Mining Engineer, SMRD
Ted Klemetti	Mining Engineer, PMRD
Bo-Hyun Kim	Mining Engineer, SMRD
Mark K. Larson	Mining Engineer, SMRD
Heather E. Lawson	Geologist, SMRD
Lewis A. Martin	Mechanical Engineer, SMRD
Tim Matthews	Engineering Technician, PMRD
Daniel McKelhinney	Engineering Technician, PMRD
Todd Minoski	Electronics Technician, PMRD
Khaled Mohamed	Mining Engineer, PMRD
Michael Murphy	Mining Engineer, PMRD
David Oyler	Mechanical Engineer, PMRD
Deno Pappas	Geologist, PMRD
Mark Powers	Engineering Technician, SMRD
Leonard Prosser	Geologist, PMRD
Michael Raffaldi	Mining Engineer, SMRD
Gamal Rashad	Associate Fellow, PMRD
Jerald Richardson	Electronics Technician, SMRD
Morgan Sears	Mining Engineer, PMRD
Joseph B. Seymour	Mining Engineer, SMRD
Brent Slaker	Mining Engineer, PMRD

Richard Sobeck	Engineering Technician, PMRD
Daniel Su	Mining Engineer, PMRD
Carl Sunderman	Electrical Engineer, SMRD
Jack Trackemas	Mining Engineer, PMRD
Mark Van Dyke	Geologist, PMRD
Sean Warren	Mining Engineer, SMRD
Peter Zhang	Mining Engineer, PMRD

NIOSH Mining Program Researchers—Former Staff: Ground Control

Name	Position, NIOSH Division
Tara Bajpayee	Mining Engineer, PMRD (retired)
Thomas Barczak	Mining Engineer, PMRD (retired)
Timothy Barton	Mining Engineer, PMRD (retired)
Suresh Bhatt	Mining Engineer, PMRD (retired)
Gary Buchan	Mining Engineer, PMRD (retired)
Dennis Dolinar	Mining Engineer, PMRD (retired)
David Dwyer	Engineering Technician, PMRD (retired)
John Ellenberger	Mining Engineer, PMRD (retired)
William Hammond	Geologist, SMRD (retired)
William Hustrulid	Mining Engineer, SMRD (retired)
Anthony Iannacchione	Mining Engineer, PMRD (retired)
Nicole Iannacchione	Geologist, PMRD
F. Michael Jenkins	Mining Engineer, SMRD (retired)
Jeffery C. Johnson	Mining Engineer, SMRD
Tristan Jones	Mining Engineer, PMRD
Tex Kubacki	Mining Engineer, SMRD
Andrew King	Seismologist, SMRD
Marc Loken	Geoengineering, SMRD
Nathan T. Lowe	Geologist, SMRD (retired)
Christopher Mark	Mining Engineer, PMRD
John Marshall	Electronics Technician, PMRD (retired)
Sean Martin	Technician, PMRD
Edward McHugh	Geologist, SMRD (retired)
Gregory Molinda	Geologist, PMRD (retired)
Gerald Morrow	Electronics Technician (retired)
Richard Rains	Geologist, SMRD (retired)
John Rusnak	Geologist, PMRD
William Sexton	Engineering Technician, PMRD
Stephen P. Signer	Civil Engineer, SMRD (retired)
Michael A. Stepan	Engineering Technician, SMRD (retired)
Peter L. Swanson	Seismologist, SMRD (retired)
Stephen Tadolini	Mining Engineer, PMRD (retired)
Douglas R. Tesarik	Civil Engineer, SMRD (retired)
Ihsan B. Tulu	Mining Engineer, PMRD
James Urley	Geologist, SMRD (retired)
Floyd D. Varley	Mining Engineer, SMRD

Stephen E. Ward	Technician, SMRD (retired)
Jeffery K. Whyatt	Geological Engineer, SMRD (retired)
Eric G. Zahl	Civil Engineer, SMRD (retired)

Appendix E: List of Manufacturers Using NIOSH Facilities and Expertise to Develop Ground Support Products

Company	**New Product Development**	**Reference**
Strata WorldWide	Sand Props Propsetters Cluster Props Kegs Link-N-Lock Link-N-X RocProps	https://www.strataworldwide.com/roof-supports
*Heintzmann	Ball Buster ACS/Spindle Props Pumpable crib	https://www.jennmar.com/products
Ellis Manufacturing	Jack Post	https://ellismanufacturing.com/collections/mining-and-excavation
Jennmar	J-Pak J-Latch J-Sand J-Sandy J-Crib RIP	https://www.jennmar.com/products
Micon	Pumpable Fabric Crib Armored Stackable Support	http://themicongroup.com/
Tensar	Biaxial BX Geogrid	http://www.tensarcorp.com/Systems-and-Products/Tensar-Biaxial-BX-geogrids
Minova	Mine Mesh (ASW)	https://www.minovaglobal.com/web/guest/mine-mesh
Geobrugg	TECCO Mesh	https://www.geobrugg.com/en/TECCO-SYSTEM-35795,7859.html?markierung=tecco
Huesker	Minegrid	https://www.huesker.us/products/geosynthetics/grids/minegrid.html

Appendix F: Respirable Hazards Staff

The below table represents key staff who completed respirable hazards research for the Mining Program during 2008–2018. The positions listed reflect the status at the time the research was completed, with current retired status also noted. All acronyms used in these tables are defined in the front matter of the evidence package.

NIOSH Mining Program Researchers: Respirable Hazards

Name	Position, NIOSH Division
Teresa L. Barone	Senior Service Fellow, PMRD
Timothy W. Beck	Commissioned Corps, PMRD
David J. Blackley	Lead Research Epidemiologist, RHD
Aleksandar D. Bugarski	Mechanical Engineer, PMRD
Emanuele G. Cauda	Senior Service Fellow, PMRD
Andrew B. Cecala	Principal Mining Engineer, PMRD
Lauren G. Chubb	Physical Scientist, PMRD
Jay F. Colinet	Research General Engineer, PMRD
Emily Haas	Research Behavioral Scientist, PMRD
Cara N. Halldin	Commissioned Corps, RHD
Scott S. Klima	Mining Engineer, PMRD
A. Scott Laney	Epidemiologist, RHD
Taekhee Lee	Senior Service Fellow, PMRD
Jeffrey M. Listak	Mining Engineer, PMRD (retired)
Arthur Miller	Mining Engineer, SMRD
Steven E. Mischler	Mining Engineer, PMRD
James D. Noll	Research Chemist, PMRD
John A. Organiscak	Mining Engineer, PMRD (retired)
Steven J. Page	Physical Scientist, PMRD (retired)
Jason Pampena	Associate Service Fellow, PMRD
Justin R. Patts	Mechanical Engineer, PMRD
Larry D. Patts	Physical Scientist, PMRD
J. Drew Potts	Mining Engineer, PMRD
W. Randy Reed	Mining Engineer, PMRD
James P. Rider	Lead Research Scientist, PMRD
Clara E. Seaman	Mechanical Engineer, PMRD
Michael R. Shahan	Commissioned Corps, PMRD
Donald P. Tuchman	Industrial Hygienist, PMRD
Jon C. Volkwein	Research Physical Scientist, PMRD (retired)
Yi Zheng	Associate Service Fellow, PMRD

Appendix G: Milestones in the Development of the Personal Dust Monitor

- 1996—Secretary of Labor committee recommends improved monitors for coal mine dust.
- 1998—NIOSH establishes a contract with Rupprecht & Patashnick (R&P) to develop the PDM.
- 2000 to 2004—NIOSH collaborates with R&P, the mining industry, and MSHA in making multiple instrument design decisions. NIOSH laboratory and field tests result in several iterations of the PDM, including a two-piece lapel-mounted sampling unit (not wearer-friendly) and a one-piece unit with an inlet attached to a cap lamp.
- 2004—NIOSH RI 9663 is published and documents that the prototype PDM meets NIOSH accuracy criteria for dust sampling instruments.
- 2004—25 pre-commercial PDM units are purchased and testing at 20% of U.S. mines is initiated to evaluate accuracy, precision, durability, wearability, and equivalency to the Coal Mine Dust Personal Sampling Unit (CMDPSU).
- 2006—NIOSH RI 9669 is published and documents that the pre-commercial version of the PDM meets NIOSH accuracy criteria and successfully documents in-mine precision and durability.
- 2007—Thermo Fisher Scientific (Thermo) purchases Rupprecht & Patashnick.
- 2008—A peer-reviewed equivalency paper is published reporting the underground full-shift performance of the PDM compared to the CMDPSU.
- 2009—A commercial version of the PDM—the PDM3600—is made available for purchase.
- 2010—Changes in CFR Part 74 are finalized to define requirements of a continuous personal dust monitor (CPDM) for use as a certified dust sampler.
- 2011—The PDM3600 is certified by MSHA and NIOSH for use in underground coal mines.
- 2012—In response to stakeholder requests, NIOSH initiates efforts to remove the cap lamp and battery from the PDM3600. NIOSH develops three new inlet design candidates and conducts tests in a laboratory at the Pittsburgh site to demonstrate performance.
- 2012—NIOSH establishes a contract with Thermo to remove the cap lamp from the PDM—the new model is called the PDM3700.
- 2013—Thermo manufacturers a prototype inlet and NIOSH tests new inlet performance in the Aerosol Lab.
- 2014—MSHA promulgates a new dust rule requiring the use of a CPDM for compliance sampling by mine operators.
- 2014—The PDM3700 is certified by MSHA and NIOSH for use in underground coal mines.
- 2015—NIOSH has multiple meetings with MSHA to discuss technical aspects of PDM3700 operation and MSHA's utilization of "status codes" for sample invalidation.
- 2016–2017—NIOSH participates in seven dust stakeholder meetings with MSHA, leading coal companies, and Thermo to provide technical input relative to PDM3700 operation and to facilitate implementation of the CPDM by the mining industry.