# A Centennial of Mine Explosion Prevention Research

**Michael J. Sapko**
Sapko Consulting Services, Finleyville, PA, USA

**Eric S. Weiss**
National Institute for Occupational Safety and Health (NIOSH), Pittsburgh, PA, USA

**Marcia L. Harris**
NIOSH, Pittsburgh, PA, USA

**Chi-Keung Man**
NIOSH, Pittsburgh, PA, USA

**Samuel P. Harteis**
NIOSH, Pittsburgh, PA, USA

**ABSTRACT:** A mere 100 years ago the mining industry, scientific investigators, and a concerned public struggled with the notion that coal dust could lead to mine explosions. A succession of disasters in 1907 left the U.S. mining industry desperately seeking answers. The pioneering work of Taffanel in France and Rice in the U.S. convinced the mining industry of the dangers of coal dust. By 1911, the United States Bureau of Mines (USBM) was conducting full-scale studies of mine explosions at the experimental mine at Bruceton, Pennsylvania. While this work has dramatically improved mine safety since the early days, methane and coal dust remains a threat for miners even now.

This paper provides a brief historical overview of full-scale mine explosion research conducted primarily at the USBM, now the National Institute for Occupational Safety and Health (NIOSH). The paper will evaluate the factors common to explosion disasters over the last century and identify some of the new safety challenges created by modern mining methods. This report reviews the Federal Mine Health and Safety Acts that have been passed over the last century and discusses how explosion research and enforcement of safety regulations have led to a significant reduction in the number of fatalities and disasters.

## PROVING TO THE WORLD THAT COAL DUST IS EXPLOSIVE (1900-1930)

"The coal dust question in this country cannot be said to have awakened widespread interest in mining men until the terrible disasters of December 1907…While it is probable that for several years the leading mining men in the country have believed in the explosibility of coal dust without the presence of firedamp, yet until the public demonstrations were given at the testing station in Pittsburg [sic] during 1908-09…a large proportion disbelieved. These tests were so convincing…that it is exceptional to find a mining man who does not accept the explosibility of coal dust."

- George Samuel Rice, 1910

Coal had become a chief source of energy in the second half of the 1800s as underground coal mining emerged as an important industry in England and the rest of Europe. The explosion dangers of firedamp (methane), hydrogen, and other combustible gases were quickly recognized by the scientific and industrial community. It was strongly and widely believed that when a mine explosion occurred, a flammable atmosphere of firedamp must be present. Unfortunately in the early years of coal mining, few scholars considered the possibility and hazard of a dust explosion, an oversight that led to the loss of hundreds of lives.

Perhaps the first major impetus to conduct more thorough investigations into the cause and prevention of mine explosions came from the 1906 Courrières mine disaster in France. This horrific mining disaster killed 1,099 men and brought the issue of coal dust explosibility to the forefront of public attention. Soon after the Courrières disaster, many countries began extensive experimental investigations of coal dust explosions. In 1907, Taffanel began his seminal experiments in a small surface gallery at Liévin, France and within a year had reproduced and expanded the work in a full-sized gallery. Taffanel devoted much of his attention to the chemistry of dust explosions, including the effect of volatile matter on coal dust explosibility. His pioneering work would serve as the foundation for research into the newly identified danger of dust in mine explosions that continues to this day.

The early history of dust explosions in the U.S. was quite similar to European experiences in that the explosion hazard of coal dust was not widely considered in the U.S. mining industry until the U.S. suffered a number of its own disasters. The coal mine disasters of 1907, especially the Monongah explosion in West Virginia and the Darr explosion in Pennsylvania which caused a combined total of 601 deaths, led the U.S. Congress to appropriate funds for an investigation of mine explosions.

U.S. research on the explosibility of coal dust began at the Federal Geological Survey during the latter part of 1908. Preliminary tests were made in a 6.3-ft. (1.9-m.) diameter, 100-ft. (30.5-m.) long steel gallery erected in Pittsburgh. In 1910, the work was transferred to the newly created United States Bureau of Mines (USBM) in the Department of the Interior. The first director of this new bureau, Dr. Joseph Holmes, would prove to be a crusader for mine safety. Because of the continued reluctance of the mining industry to acknowledge the explosive dangers of coal dust, Holmes determined that experimental testing must be performed in a real mine so results from the tests would not only be valid, but would be accepted as conclusive. Using the newly chartered Bruceton Experimental Mine (BEM), the original USBM scientists demonstrated that coal dust alone was capable of propagating an explosion in the absence of any methane gas. Demonstrations of the hazards of coal dust within the BEM conclusively proved that many practices such as using loose coal dust in mines to pack explosives in boreholes were too hazardous to continue. Shown in Figure 1 is a demonstration of a coal dust explosion conducted in the BEM.

**Figure 1. Bruceton Experimental Mine coal dust explosion demonstration**

The widespread use of rock dusting in U.S. coal mines has been in use for nearly a century as a precautionary measure against the dust explosion hazard. George S. Rice of the USBM recommended the use of rock dusting to prevent or limit coal dust explosions as early as 1911 (Rice 1911) and referenced experiments being conducted in Great Britain. Experiments at the USBM confirmed that ignitions could not be obtained with mixtures of Pittsburgh seam coal dust and rock dust having an incombustible content of 64 percent. In 1927 (Rice, Paul, and Greenwald 1927) and again in 1937 (Mine Safety Board 1937), the USBM recommended that a total incombustible content of 65 percent should be required in all bituminous coal mines.

The effectiveness of rock dusting in preventing mine explosions is illustrated by the decline in fatalities associated with mine explosions. In the U.S., mine explosions declined from 33 per year in the late 1920s to about 20 per year in the late 1960s with further decreases in later decades.

## FOCUS ON EXPLOSIONS AND COMBUSTION (1930s and 1940s)

One of the original missions of the USBM was to provide the mining industry with information on blasting materials and techniques that could be used safely in the presence of flammable mine gases and dust. This meant identifying both the useful and dangerous chemical and physical characteristics of explosives. At the USBM, work focused on identifying the processes associated with initiation, growth, and eventual extinguishment of mine explosions. Scientists discovered that weak methane explosions can initiate violent coal dust explosions and that rock dust and other quenching agents can arrest these explosions. The USBM became a vocal advocate for the use of permissible explosives and denounced the use of black powder through demonstrational and educational programs, as well as research. By listening to the requests of the mining industry and through extensive experimentation, the USBM approved an increase in the permissible charge limit which greatly improved productivity while maintaining safety. In 1941, a year after 257 miners died in four separate mine explosions, Congress passed the Coal Mine Health and Safety Act. Under that law, the government was authorized to conduct safety inspections in mines for the first time. Unfortunately, safety regulations remained advisory during this era of mining.

## TOWARD SAFER EXPLOSIVES (1950s and 1960s)

U.S. mines were becoming safer through voluntary efforts on the part of the mining industry and safety research pioneered by the USBM. In 1951, however, the Orient No. 2 Mine in Illinois suffered a massive coal explosion killing 119 miners. One year later, an updated Federal Coal Mine Health and Safety Act was passed which called for the elimination of black powder and set requirements for rock dusting along with other regulations. During this era, scientists discovered that a small amount of sodium chloride—table salt—added to explosives would greatly reduce the occurrence of methane gas explosions. This advance in permissible explosives gave the mining industry a safe and effective alternative to black powder. Since the start of the USBM explosives testing program, there has been no mine disaster linked to proper use of permissible explosives. After decades of education and research, black powder use in mines was finally outlawed in 1966.

## USBM CONTRIBUTIONS TRANSCEND COAL MINES

In addition to practical advancements in mining safety, the USBM produced an important and extensive body of information on the flammability and explosibility of numerous gases, liquids, and dusts, as well as on the toxicity of the subsequent combustion products. USBM scientists developed methods for determining flammability hazards of combustible materials. Standard tests, developed by USBM personnel, to determine auto-ignition temperatures, flammability limits, and minimum ignition energies were adopted by the American Society for Testing and Materials (now ASTM International). Fundamental and highly innovative research into the manner in which flames and explosions originate, propagate, and are quenched assured the USBM and the United States an authoritative place in the international scientific community. In addition, early research at the BEM supported the growing infrastructure of the country. Technology initially developed for the coal mining industry was extended to meet the needs of many other government agencies, including the Department of Defense (DoD), the Department of Transportation (DOT), and the National Aeronautics and Space Administration (NASA). Over the last 100 years, the USBM and later NIOSH have provided technology, research data, and analysis to various government and civilian organizations (Table 1).

## THE FEDERAL COAL MINE HEALTH AND SAFETY ACT OF 1969

Despite volumes of research on proper explosives use and mine safety, regulations were simply advisory and, as such, variably implemented in actual mines. It would take the death of 78 miners in an explosion at the Consolidation Coal No. 9 Mine in Farmington, West Virginia to permanently change the attitude of the mining industry toward mine safety regulations. Congress passed the Federal Coal Mine Health and Safety Act of 1969 (Public Law 91-173), which, for the first time, provided the mandate for federal mine safety enforcement. This act instituted procedures for developing *mandatory* standards and called for expanded health and safety research. As a consequence, the USBM conducted the research necessary to identify and eliminate coal mining hazards and to reduce the risk of health impairment, injury, or death.

This legislation also redefined and expanded the mission and responsibilities of the USBM at the Pittsburgh Research Center. To the traditional work on fires, explosions, and explosives were added the responsibilities of addressing health, safety, and productivity problems associated with mechanized mining, longwall mining, and the pursuit of deeper, less accessible resources. The Act increased the number of coal mine inspectors and the frequency of inspection. Also during this period, training programs expanded rapidly. In 1971, the Coal Mine and Safety Academy was established in Beckley, West Virginia.

| **Table 1. Partial list of the USBM/NIOSH contributions to various fields** | |
|---|---|
| Medicine | Virtually eliminated the risk of explosions in hospital operating rooms after extensive investigation into the spark ignition of anesthetic gases |
| Transportation | Supported the construction of the Holland Tunnel between New York and New Jersey and the Liberty Tunnel in Pittsburgh through safety research |
| | Established ventilation requirements for car tunnels to maintain carbon monoxide at safe levels |
| | Developed storage and transport systems for liquid natural gas, hydrogen, and chlorine |
| | Established methods for the safe handling of hazardous materials |
| Utilities | Improved burner designs capable of maintaining stable gas flames |
| Aviation | Provided for the safe use of fuels and fluids for conventional aircraft and jet engines |
| Military | Made major contributions to the formulation of new military explosives |
| | Contributed to the development of the trigger for the atomic bomb—the first experimental work on cylindrical implosions |
| NASA | Studied the effect of extraterrestrial atmospheres on the performance of explosives |
| | Apollo mission support and accident investigation |
| | Safe fuel ejection techniques at high altitude |

Numerous techniques, devices, and systems were generated during this time of renewed national emphasis on health and safety. Rescue apparatus for application in mines became more sophisticated. Before the 1970s, a USBM-approved self-rescuer protected the wearer against carbon monoxide for about 30 minutes. However, lessons learned from the Sunshine Mine disaster on May 2, 1972 heralded the era of self-rescuer development that supplied the wearer with oxygen and protection from toxic gases. On June 21, 1981, U.S. mine operators were required (30 CFR 75.1714) to make available to each underground coal miner a self-contained self-rescuer (SCSR) that provided respiratory protection with an oxygen source for at least 1 hour. This advancement proved to be a crucial component to post-disaster survival and rescue efforts in subsequent years.

The extensive experience of the personnel at the Pittsburgh Research Center in mine fires and explosions research was applied to generating new and more quantitative knowledge on the burning behavior of a wide variety of dusts, gases, fluids, and solids, and on the relative merits of flame inhibitors, quenching agents, and high-expansion foam. Large-scale research in the BEM produced basic information on the origin, growth, and suppression of fires and explosions. Passive barriers designed to disperse a quenching agent under the action of an oncoming explosion were successfully deployed in a working mine. Improved cutting bits and directed water sprays were developed to combat the growing problem of frictional methane ignitions associated with modern, mechanized coal-cutting equipment. In the 10 years following the Coal Mine Health and Safety Act of 1969, the number of major explosions was only one-third of that in the previous 10 years, and there were two 4-year periods with no major explosions.

**EXPLOSION HAZARDS IN OIL SHALE MINES (1970s)**

While dependence on foreign oil is now recognized as a threat to national security, the 1973 oil embargo by the major oil exporting nations was the first time the nation became acutely aware of the scope of the problem. It was during this period that the U.S. began to develop more efficient techniques to extract oil from shale rock.

Historically, the mining operations in oil shale were regulated under the standards developed for metal and non-metal mines; however, in the late 1970s the USBM and the newly formed Mine Safety and Health Administration (MSHA) raised concerns regarding the adequacy of these regulations for oil shale mining. This surge in commercial oil shale mining and the unique dangers associated with it led the USBM to study the explosibility of oil shale dust and the effects of blasting in large diameter holes in the presence of methane. This research continued through the early 1990's (Richmond, Sapko, and Miller 1982; Weiss et al. 1996).

Even though oil shale dust had been shown to be explosible in experimental mine tests (see Figure 2), sampling of dust depositions following blasting in oil shale mines had shown that the dust generated during blasting was an order of magnitude below the concentrations required to propagate an explosion in the large headings of typical oil shale operations. However, cameras monitoring these same full-scale blasts recorded high concentration dust clouds generated by the detonation of the blast holes. The ignition of these dust clouds can result in localized secondary explosions near the face (Figure 3). Further, the presence of methane in many of the deep oil shale formations posed a significant hazard to underground blasting operations. Tests within the BEM had shown that even a small amount of methane can significantly reduce the lower explosible concentration for pre-dispersed oil shale dusts. To verify these findings, the USBM developed and installed a tube bundle gas sampling system at the White River Shale Project in Utah and at the Horse Draw mine in Colorado to measure the methane emission rates following blasting operations.

**Figure 2. Bruceton Experimental Mine oil shale dust explosion**

**Figure 3. Frames from a high-speed movie during an oil shale face blast showing the non-electric explosive initiation (left photo) and subsequent flame and dust generation (right photo)**

Similar to coal and oil shale dusts, sulfide ore dusts exhibit a higher degree of explosibility as particle size decreases. Also, explosibility increases as sulfur content increases. Numerous documented sulfide dust ignitions occurred following blasting operations and had resulted in personnel injuries in addition to production and equipment losses.

The USBM research in laboratory, gallery (Figure 4), BEM tests, and through numerous full-scale blasts in operating oil shale and sulfide ore mines contributed to the better understanding of the fire and explosion hazards associated with blasting in these commercial-scale underground mining operations. Through careful analysis of dust depositions, full-scale blasting studies, and the determination of methane accumulations in deep oil shale reserves, researchers at the USBM were able to demonstrate the specific dangers posed by this mining. The use of inert gelled water stemming was shown to reduce the dust generated from blasting and to also cut air blast overpressures in half. The use of low-incendive explosives also reduced the blast-induced explosion hazards in oil shale and sulfide ore mines.

**Figure 4. Coal dust ignited by explosives at the Lake Lynn Laboratory Cannon Gallery**

## FEDERAL MINE SAFETY AND HEALTH AMENDMENTS ACT OF 1977

In 1977, Congress passed the Federal Mine Safety and Health Amendments Act (Public Law 95-164). For the first time, this document provided a single piece of comprehensive legislation for coal, metal and nonmetal mining operations and extended the research mandates of prior legislation to all segments of the mining industry. The Act required four annual inspections at each underground coal mine other mines and two annual inspections at each surface mine. The Secretary of the Interior was authorized to institute civil action for relief, including injunctions, for violations or interferences by operators with enforcement of this Act. Penalties were increased for violations. Provision was made for mandatory health and safety training of miners using both initial and refresher courses. In addition, the Mining and Enforcement Safety Administration (MESA) became the Mine Safety and Health Administration (MSHA) and was later transferred to the U.S. Department of Labor, headed by an Assistant Secretary of Labor.

**ACQUISITION OF LAKE LYNN LABORATORY (1980)**

In keeping with the philosophy of Joseph Holmes that there is no perfect substitute for explosions research performed in a full-scale mine environment, the Lake Lynn Laboratory was acquired in 1979 and became operational in 1982. This 400-acre facility near Fairchance, Fayette County, Pennsylvania was constructed in a limestone bed adjacent to an abandoned limestone mine. Lake Lynn is a highly sophisticated laboratory that provides an unparalleled research venue for mine disaster prevention and response. The Lake Lynn Experimental Mine (LLEM) can be adapted to simulate virtually any modern coal mine geometry while tightly controlling ventilation and humidity. The surface facilities provide an isolated environment in which large-scale research and testing can be done in a realistic, yet environmentally controlled manner. For nearly 30 years, the complex has been used for numerous and significant explosion, fire, and explosives research projects as well as research efforts of national and international interest.

**MINE SEALS AND STOPPINGS**

In research programs dating back to the early 1930s, the USBM (Rice, Greenwald, and Howarth 1930; Mitchell 1971; Nagy 1981) conducted research on mine seal and stopping performance to address the many issues associated with the design and installation of these structures. Seals are barriers constructed in underground mines throughout the U.S. to separate abandoned workings from the active workings. Stoppings are designed to direct the flow of fresh air to the working faces and remove the contaminated air from the mine while minimizing air leakages. Seals must be resistant to specified explosion overpressures while stoppings need only resist very small overpressures (39 $lb/ft^2$). Until the tragic explosion in early 2006 at the Sago Mine in West Virginia, the general consensus was that seals would most likely be subjected to an explosion initiated within the active workings of the mine well away from the seal location. Therefore seals were primarily designed to prevent an explosion from entering the methane-rich sealed areas. Prior to the 1992 regulations, seal designs were based on that of a fully-mortared, solid-concrete-block seal keyed into the ribs and floor as built and explosion tested within the BEM (Mitchell 1971).

In the early 1990s, MSHA requested that the USBM evaluate alternative seal designs to that of the solid-concrete-block seal. Over the next 15 years, many different full-scale designs of seals were evaluated within the LLEM for strength characteristics and air-leakage resistance, and those designs that met the requirements of the 1992 regulations were deemed suitable by MSHA for use in underground coal mines.

NIOSH developed and recommended a new, preferred approach for evaluating seals under static load conditions to address the limitations of the explosion test program within the LLEM entries. This method allowed for the determination of the ultimate strength of the seal by evaluating the seal to failure under a controlled static load using water pressure (Sapko, Weiss, and Harteis 2005).

Likewise, mine stopping designs have also been evaluated under USBM (Kawenski et al. 1965) and NIOSH (Weiss et al. 2008) research studies to evaluate the strength characteristics and air leakage resistance of many typical and innovative stopping designs that can perform their intended function under the requirements of the regulations. The LLEM explosion data on stoppings, coupled with the use of predictive wall strength models have assisted investigators to more accurately determine the range of explosion pressures that destroy or damage stoppings during actual coal mine explosions and can lead to the development of enhanced stopping designs.

**CLOSURE OF THE USBM AND TRANSFER TO NIOSH (1995-1997)**

USBM research played a fundamental role in reducing accidents, fatalities, and health-related problems in the U.S. coal mining industry by providing innovative technology and groundbreaking research. In September 1995, Congress recommended the closure of the USBM; this both surprised and angered many in the industry. The closure resulted in the dismissal of many federal employees and threatened to quiet some of the leading voices in mining research, including the experts of explosion prevention and safety. After restructuring and reorganization, the Mining Health and Safety Research Program at the Pittsburgh and Spokane Research Centers was assigned on an interim basis to the U.S. Department of Energy and, in 1996, it was permanently transferred to NIOSH. Under NIOSH, the Pittsburgh and Spokane Research "Centers" were renamed the Pittsburgh Research Laboratory (PRL) and Spokane Research Laboratory (SRL), respectively. Despite a brief period of challenge and uncertainty at that time, cutting edge, life-saving research continued at both facilities.

**THE MINER ACT OF 2006**

Tragedies at the Sago Mine, the Aracoma Alma Mine No. 1, and Darby Mine No. 1 in early 2006 once again raised serious concerns about underground coal mine explosion safety. These events led to sweeping federal and state legislation, including the Mine Improvement and New Emergency Response (MINER) Act in 2006. Some of the major areas addressed in the Act were enhanced oxygen supply, refuge chambers, and communications and worker tracking.

Post-Sago seals research by NIOSH focused on developing explosion pressure design criteria for new seal designs (Zipf, Sapko, and Brune 2007) and retrofit techniques (Weiss and Harteis 2008) for *in situ* strengthening of thousands of existing 20-psi seals to meet the new, temporary seal strength standard of 50 psi. Zipf, Sapko, and Brune (2007) examined seal design criteria and practices used in the U.S., Europe, and Australia and then classified seals by their various applications. They then considered various kinds of explosive atmospheres that can accumulate within sealed areas and used thermodynamic calculations and simple gas explosion models to estimate worst-case explosion pressures that could impact seals. Three design pressure-time curves were developed for the dynamic structural analyses of new seals under the conditions in which those seals may be used: 1) unmonitored seals where there is a possibility of methane-air detonation or high-pressure nonreactive shock waves and subsequent reflections behind the seal; 2) unmonitored seals with little likelihood of detonation or high-pressure nonreactive shock waves and subsequent reflections; and 3) monitored seals where the methane-air is strictly limited and controlled. The recommended design pressure-time curves for the three scenarios described above are 1) 640 psi falling back to a constant volume explosion overpressure of 120 psi, 2) a constant volume explosion overpressure of 120 psi, and 3) a 50 psi design that requires monitoring and active management of the sealed area atmosphere, respectively. Shown in Figure 5 is the proposed flowchart by NIOSH for selecting design pressure-time curve for new seals.

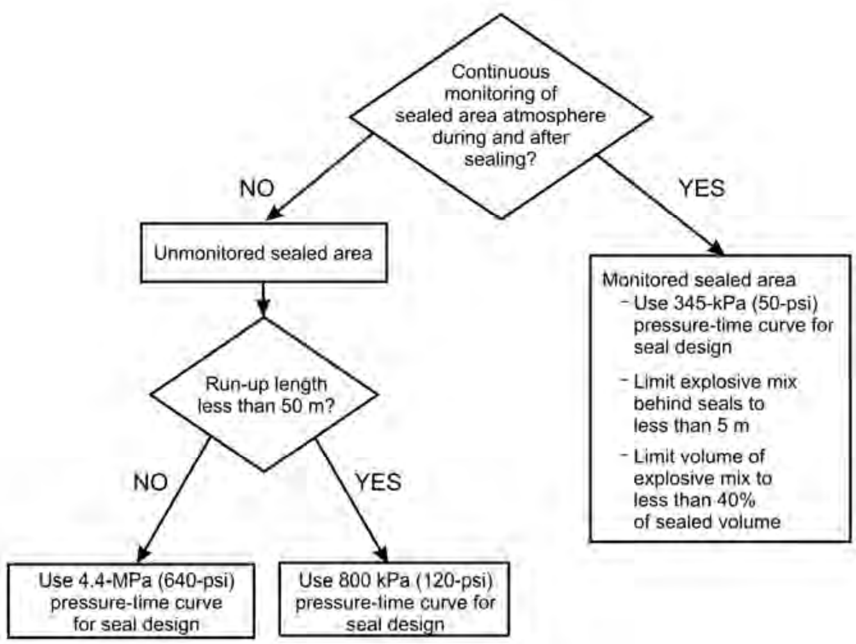


**Figure 5. Flowchart for selecting design pressure-time curve for new seals**

Subsequently, MSHA promulgated the Final Rule on “Sealing of Abandoned Areas” in April 2008 which included requirements for seal strength, design, and construction of seals. In this Final Rule, seals must either

1. Withstand 50 psi if the sealed area is monitored and maintained inert, or
2. Withstand 120 psi if the sealed area is not monitored, or
3. Withstand greater than 120 psi if the area is not monitored and certain conditions exist that might lead to higher explosion pressure.

**NEW MINING METHODS HAVE CHANGED THE NATURE OF HAZARDS**

Mining of coal by explosives has diminished significantly over the years, and the dust or gas ignition hazards associated with properly used permissible explosives has essentially been eliminated. However, the increased use of continuous miner and longwall mining practices produce other hazards. These techniques tend to produce finer dust and an increased incidence in frictional ignitions of methane when cutting bits strike sandstone or pyrites. Also, as deeper seams are mined, the methane content tends to increase, as does the explosion hazard. These modern mining techniques continue to demand innovative research approaches to meet new safety challenges. Improved methods are needed to optimize mine ventilation systems to better manage flammable methane accumulations in mines. Further, improved explosion-resistant ventilation controls that continue to perform their intended function after an explosion will play a key role in future post explosion survival and rescue operations.

Even though rock dusting has been the primary means of defense against coal dust explosions for the past century, there is still room to improve rock dusting procedures and overall miner safety. The most promising method for improving the quality of rock dusting practices combines the results of theoretical and experimental work with practical hardware development, all of which have been developed in large part by the USBM and later NIOSH. The explosibility of thin deposits of “float” coal dust (Figure 6) is well documented and in fact, the most severe experimental dust explosion conducted by the USBM involved float coal dust (Nagy 1981). There is little data regarding the rate of float dust deposition in mechanized mines, but there is no doubt that it correlates with production rates. Experiments indicate that only the top layer (2 to 4 mm) of floor dust participates in a weak to moderate float dust explosion (Sapko, Weiss, and Watson 1987).

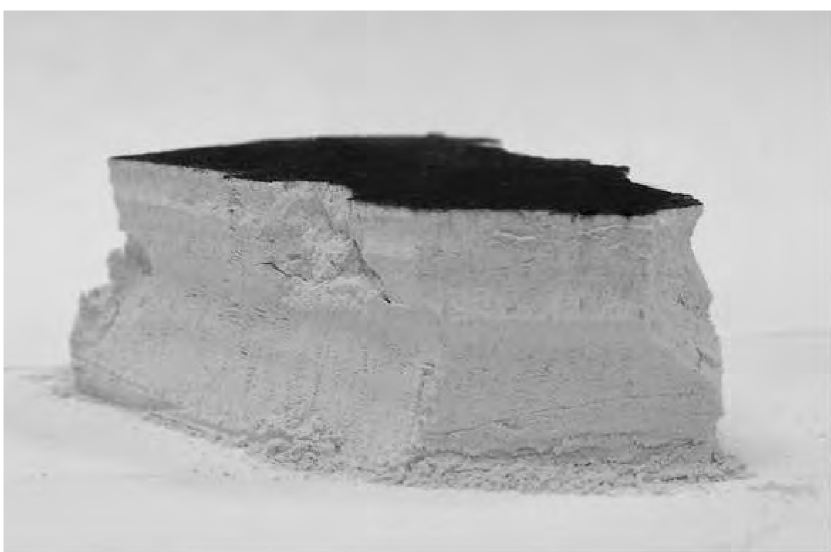

**Figure 6. Cross-section of thin 0.25 mm (0.01 inch) float coal dust layer deposited on top of a 20 mm (0.75 inch) thick layer of rock dust. This amount of float coal dust will propagate an explosion**

The present practice of gathering dust samples then sending the samples to an outside laboratory does not allow for the immediate correction of potentially dangerous situations. Moreover, if the collected samples do not represent the top layer of dust this may misrepresent the actual risk. Further, the current sampling and testing methods do not take into account variations of coal particle size when assessing the local level of protection afforded by rock dusting. In 2006, NIOSH won a prestigious award (R&D Magazine’s selection as one the 100 most technological significant new products of year) for the development of a hand-held Coal Dust Explosibility Meter (CDEM) shown in Figure 7, which rapidly determines the explosibility of a mixture of coal and rock dust *in situ*. The CDEM addresses a long standing problem in our underground coal mines by providing a rapid technique for evaluating the explosibility of coal and rock dust mixtures taking into account particle size in the topmost layers of mine dust. The general use of the CDEM will no doubt lead to more effective rock dusting practices and greatly improved mine safety (Sapko and Verakis 2006).


**Figure 7. Coal Dust Explosibility Meter**

Over the past 2 years, NIOSH in cooperation with MSHA conducted a comprehensive survey on the coal dust particle size in numerous mines representing 10 of the 11 MSHA coal mine safety districts (not anthracite). The data revealed that coal dust in the intake airways of mines today is much finer than that on which the existing rock dusting regulations were based (Sapko, Cashdollar, and Green 2007). Full-scale explosion tests within the LLEM determined that a higher total incombustible content than the current 65% regulation is necessary to render this finer dust inert. Figure 8 shows the effect of coal dust particle size on the explosibility of Pittsburgh seam bituminous coal; finer dust requires more incombustible to inert. The primary difference between the BEM and LLEM data curves in Figure 8 is that explosions in the larger entries of the LLEM (which are typical of mines today) behave more adiabatic than in the smaller BEM entries (Richmond, Liebman, and Miller 1975). NIOSH has recommended that the total incombustible content for intake airway be 80% (Cashdollar et al. 2009).

The next hundred years of mine explosion research will hopefully see an even further decline in mine explosion disasters. While full-scale tests are an invaluable source of information for testing and validating concepts, future work will also likely focus on computer modeling techniques. Development of computer hydrocode and advanced reactive flow models for reconstructing gas and dust explosions will provide the ability to completely reconstruct complicated explosion dynamics. These tools will allow government and independent investigators to unravel complicated blast patterns and chemical reactions of participating gas and coal dust. These models may even facilitate the development of new techniques for explosion mitigation.

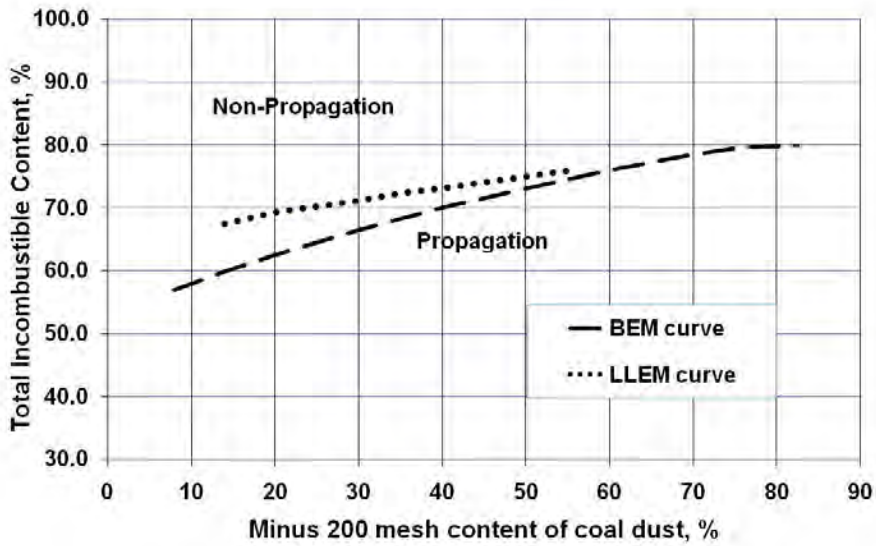


**Figure 8. Effect of particle size of coal dust on the explosibility of Pittsburgh seam bituminous coal**

## SUMMARY

Mining disasters have been the major driving force of mine explosion research. From the seminal work of Taffanel after the Courrières disaster in France in 1906 to the Sago Mine disaster in the U.S. in 2006, mine explosion researchers have responded to these incidents by conducting research and making recommendations that improve the safety of underground personnel. The USBM was and NIOSH continues to be at the forefront of proactive mine explosion research, producing many of the innovations and breakthroughs in the field over the last century. Just as early researchers proved that coal dust represents a significant explosion hazard that is separate from methane gas, NIOSH continues to make major contributions to mine safety in its world-class research laboratory at Lake Lynn Laboratory and in Pittsburgh and Spokane. Some of the early U.S. investigators who studied explosion hazards are listed in the Bibliography. A more extensive bibliography of early investigators that studied coal dust explosions is presented in USBM Bulletins 20 and 167 (Rice 1911; Rice et al. 1922).

After reviewing the past century of mining practices in the U.S., we observe that the major milestones in explosions safety have come from legislation and enforcement supported by extensive research efforts. Each of the Federal Coal Mine Health and Safety Acts and major amendments were passed soon after a major mining disaster. Mine operators and miners must continue to maintain their vigilance through compliance with the mandates of these Acts and regulations to mitigate the explosion hazards. Notwithstanding the effort devoted to prevention, coal mine gas and dust ignitions and explosions continue to occur with unsettling frequency. The increased utilization of high production, mechanized mining methods in deeper and gassier coal seams place additional demands on those responsible for mine safety, particularly in the area of explosion prevention. Despite the vast amount of knowledge gathered and painfully learned over the past century, much more can be discovered through high quality forensic investigations of mine disasters and by identifying ways to prevent future occurrences. Compliance and enforcement along with the development and implementation of affordable, practical, and useful technologies can eliminate deadly mine explosions in the next century and beyond.

## REFERENCES


Federal Coal Mine Health and Safety Act of 1969, United States Public Law 91-173.

Cashdollar, K.L., Sapko, M.J., Weiss, E.S., Harris, M.L., Man, C.K., and Harteis, S.P. 2009. *Recent Coal Dust Particle Size Survey and the Implications for Mine Explosions.* Pittsburgh, PA: U.S. Department of Health and Human Services, National Institute for Occupational Safety and Health, RI *in press*.

Kawenski, E.M., Mitchell, D.W., Bercik, G.R., and Frances, A. 1965. *Stoppings for Ventilating Coal Mines.* Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, RI 6710.

Mine Improvement and New Emergency Response Act of 2006 ("MINER Act"), United States Public Law 109-236.

Mitchell, D.W. 1971. *Explosion-Proof Bulkheads: Present Practices*. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, RI 7581.

Nagy, J., 1981. *The Explosion Hazard in Mining.* Washington, D.C.: U.S. Department of Labor, Mine Safety and Health Administration, Informational Report 1119.

Rice, G.S., Greenwald, H.P., Howarth, H.C., and Avins, S. 1931. *Concrete Stoppings in Coal Mines for Resisting Explosions: Detailed Tests of Typical Stoppings and Strength of Coal as a Buttress.* Pittsburgh, PA: U.S. Department of Commerce, Bureau of Mines, Bulletin 345.

Rice, G.S. 1911. *The Explosibility of Coal Dust.* Washington, D.C.: U.S. Bureau of Mines, Bulletin 20.

Rice, G.S., Paul, J.W., and Greenwald, H.P. 1927. *Coal-Dust Explosion Tests in the Experimental Mine, 1919-24, Inclusive*. Washington, D.C.: U.S. Bureau of Mines, Bulletin 268.

Rice, G.S., Greenwald, H.P., and Howarth, H.C. 1930. *Explosion Tests of Pittsburgh Coal Dust in the Experimental Mine, 1925 to 1932, Inclusive.* Washington, D.C.: U.S. Bureau of Mines, Bulletin 369.

Richmond, J.K., Liebman, I., and Miller, L.F. 1975. *Effect of Rock Dust on Explosibility of Coal Dust.* Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, RI 8077.

Richmond, J.K., Sapko, M.J., and Miller, L.F. 1982. *Fire and Explosion Properties of Oil Shale.* Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, RI 8726.

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

Sapko, M.J., Weiss, E.S., and Watson, R.W. 1987. *Explosibility of Float Coal Dust Distributed Over a Coal-Rock Dust Substratum*. In Proceedings of the 22nd International Conference of Safety in Mines Research Institutes (Beijing, China, November 2-6, 1987). Beijing, China: China Coal Industry Publishing House, pp. 459-468.

Sapko, M.J., and Verakis, H. 2006. *Technical evaluation of the coal dust explosibility meter.* In Transactions of the 2006 Society for Mining, Metallurgy and Exploration (SME) Annual Meeting, St. Louis, MO, March 26-29, 2006.

Sapko, M.J., Weiss, E.S., and Harteis S.P. 2005. *Methods for Evaluating Explosion Resistant Structures*. In Proceedings of the 8th International Mine Ventilation Congress, Brisbane, Australia, July 6-8, 2005.

Weiss, E.S., Cashdollar, K.L., Sapko, M.J., and Bazala, E.M. 1996. *Secondary Explosion Hazards During Blasting in Oil Shale and Sulfide Ore Mines.* Pittsburgh, PA: U.S. Department of Energy, Pittsburgh Research Center, ISSN 1066-5552, RI 9632.

Weiss, E.S., and Harteis, S.P. 2008. *Strengthening Existing 20-psi Mine Ventilation Seals with Carbon Fiber-Reinforced Polymer Reinforcement.* Pittsburgh, PA: U.S. Department of Health and Human Services, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2008-106, RI 9673.

Weiss, E.S., Cashdollar, K.L., Harteis, S.P., Shemon, G.J., Beiter, D.A., and Urosek, J.E. 2008. *Explosion Effects on Mine Ventilation Stoppings.* Pittsburgh, PA: U.S. Department of Health and Human Services, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2009-102, RI 9676.

Zipf, R.K., Sapko, M.J., and Brune, J.F. 2007. *Explosion Pressure Design Criteria for New Seals in U.S. Coal Mines.* Pittsburgh, PA: U.S. Department of Health and Human Services, National Institute for Occupational Safety and Health, IC 9500.

## BIBLIOGRAPHY

Dobroski, H.Jr, Stephan, C.R., and Conti, R.S. 1996. *Historical Summary of Coal Mine Explosions in the United States, 1981-94*. Washington, D.C.: U.S. Bureau of Mines, Information Circular 9440.

Humphrey, H.B. 1960. *Historical Summary of Coal-Mine Explosions in the United States, 1810-1958*. Washington, D.C.: U.S. Bureau of Mines, Bulletin 586.

Nagy, J. 1981. *The Explosion Hazard in Mining*. Washington, D.C.: U. S. Department of Labor, Mine Safety and Health Administration, Informational Report 1119.

Rice, G.S., and Greenwald, H.P. 1929. *Coal-Dust Explosibility Factors Indicated by Experimental Mine Investigations, 1911 to 1929.* Washington, D.C.: U. S. Bureau of Mines, Technical Paper 464.

Rice, G.S., Greenwald, H.P., and Howarth, H.C. 1933. *The Experimental Mine of the United States Bureau of Mines*. Washington, D.C.: U. S. Bureau of Mines, Information Circular 6755.

Rice, G.S., Jones, L.M., Clement, J.K., and Egy, W.L. 1913. *First Series of Coal Dust Explosion Tests in the Experimental Mine.* Washington, D.C.: U. S. Bureau of Mines, Bulletin 56.

Rice, G.S., Jones, L.M., Egy, W.L., and Greenwald, H.P. 1922. *Coal Dust Explosions Tests in Experimental Mine 1913 to 1918, Inclusive.* Washington, D.C.: U. S. Bureau of Mines, Bulletin 167.

Richmond, J.K., Price, G.C., Sapko, M.J. and Kawenski, E.M. 1983. *Historical Summary of Coal Mine Explosions in the United States, 1959-81.* Washington, D.C.: U.S. Bureau of Mines, Information Circular 8909.

Sapko, M.J., Greninger, N.B. and Watson, R.W. 1989. *Review Paper: Prevention and Suppression of Coal Mine Explosions.* In Proceeding of 23rd International Conference of Safety in Mines Research Institutes, Washington, D.C., September 11-15, 1989.

Verakis, H.C. and Nagy, J. 1987. A Brief History of Dust Explosions. In *Industrial Dust Explosions*, American Society for Testing and Materials, ASTM STP 958. Edited by K.L. Cashdollar and M. Hertzberg. Philadelphia, PA: ASTM, pp.342-350.