A Century of Bureau of Mines/NIOSH Explosives Research

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ABSTRACT: The U.S. Bureau of Mines (USBM) was created by an Act of Congress on July 1, 1910. The USBM strove to eliminate the use of black powder in underground coal mines and replace it with safer permissible explosives. The testing and approval of permissible explosives, blasting units, and blasting practices evolved and are now codified in the Code of Federal Regulations Title 30, Part 7, Subpart C and Parts 15 and 75. In subsequent years explosives and blasting safety research expanded from Pittsburgh, PA to include USBM labs in Minneapolis, MN, Denver, CO, Spokane, WA and College Park, MD. Research grew from studies of newer explosives and blasting technology for underground coal mines to include applications for all types of mining. During wartime the USBM applied it's expertise to studies and research that supported national defense. Following World War II, the USBM continued explosives research for industrial applications. Advances were made on vibration from blasting, evaluations of the state-of-art in safer explosives, electronic detonators and blasting devices, and research that supported changes in regulations for blasting in the mining industry.

INTRODUCTION

The history of explosives and blasting research at the U.S. Bureau of Mines (USBM) spans many years, many locations, and wide-ranging applications. This work has been documented in hundreds of publications over the years but there has been no publication that summarizes the totality of the USBM's explosives and blasting research. The authors' goal is to summarize this work.

U. S. BUREAU OF MINES EXPLOSIVES RESEARCH – THE EARLY YEARS

The early history of the U.S. Bureau of Mines (USBM) was closely related to the development of permissible explosives. In the USA, the first blasting-related explosion disaster occurred in the Coulterville coal mine in Illinois in 1883 and resulted in 10 fatalities. It was initiated by a blown-out black blasting powder shot and propagated by coal dust. The worst coal mine explosion disaster in the USA in the 1800's occurred in the Laurel Mine in Virginia on March 13, 1884 and resulted in 112 fatalities. The cause indicated for this disaster was the use of large quantities of black blasting powder to blast coal off-the-solid (Humphrey 1960).

Due to the disastrous coal mine explosions during the 1800's, actions were taken by various states in the USA to enact laws and requirements for mine safety improvements. In 1872, Illinois was the first state to enact a bituminous coal mine safety law. Over the next 45 years, 24 other states enacted mine safety laws. Observance of the laws fell short and often needed revisions because of the subsequent occurrence of coal mine explosion disasters. The view that coal dust without the addition of methane was explosive was not generally accepted by industry. Coal mine explosions continued to occur into the 1900's with more disastrous results.

During the ten-year period, 1901-1910, there were 111 major explosion disasters. A major disaster was defined as resulting in 5 or more fatalities. The 111 major explosion disasters resulted in a total of 3, 316 fatalities. This 10-year period was catastrophic for the US coal mining industry. The details of these disastrous explosions pointed to the use of black powder in shooting overburdened and overloaded blast holes. The flame from blasting the overburdened and overloaded holes was a primary ignition source that caused the explosion of accumulations of methane and coal dust. Blasting constituted about 44 percent of the 111 ignition sources in these disasters (Humphrey 1960). Although the major causes of coal mine explosions were known, particularly since studies were made by Britain and other European countries, many in the U.S. coal mining industry were not convinced. Black blasting powder and dynamite continued to be used and could not be made safe for blasting in underground coal mines. An obvious safety hazard is illustrated in Figure 1 which shows an early miner with an open light on his hat while forming a cartridge of black powder. Instances such as illustrated in Figure 1 continued on a daily basis. It took numerous coal mine explosion disasters to force the changes needed for improvements in blasting safety.

Figure 1. Miner making black powder cartridge for blasting coal.

The worst coal mine explosion disaster in the USA occurred on December 6, 1907 in the Monongah Number 6 and 8 coal mines in Monongah, West Virginia. The explosion resulted in a reported 362 fatalities (Humphrey 1960). However, a recent book indicates that close to 500 men and boys lost their lives in the Monongah coal mine explosion (McAteer 2007). Although the exact cause of the Monongah coal mine explosion was not determined, several theories suggested an electric arc, open lights, or a blown-out shot from blasting with black powder may have been the cause. The second worst coal mine explosion in the USA occurred thirteen days later, on December 19, 1907, at the Darr Mine, Jacobs Creek, Pennsylvania. When the explosion occurred, an awful rumbling was followed by a loud report and a concussion shook the nearby buildings. The underground coal mine explosion was felt within a radius of several miles. This explosion caused 239 fatalities; no miners escaped the explosion. The cause of this explosion was indicated as a blown-out shot or open lights (Humphrey 1960).

The increasing frequency of mine explosions and the tremendous loss of human lives, especially during the latter part of the 1800's and the first decade of the 1900's, greatly aroused public attention. The attention brought about action through federal agencies to find means to control the occurrence of disastrous coal mine explosions and to reduce the loss of life and injuries. The study of explosives as a cause of mine explosions began in 1908 as part of the Technologic Branch in the U.S. Department of Interior's Geologic Survey (USGS). The Technologic Branch of the USGS had been created in 1907 to test fuels and structural materials but its mission expanded in 1908 to include the study of mine explosions in response to the series of disastrous coal mine explosions in December, 1907 (Powell 1922). An act of congress appropriated $150,000 "for the protection of lives of miners in the territories and in the District of Alaska, and for conducting investigations as to the causes of mine explosions with a view to increasing safety in mining." Work began with examinations of explosives, conducted chiefly at the Geological Survey's laboratory in Pittsburgh, PA. This work passed to the Bureau of Mines following its creation in 1910. The initial goal of this work was to replace the black powder used for blasting in underground coal mines with safer explosives.

These were termed permissible explosives and they would produce flame of short duration with relatively low temperature.

Early explosives work by the Bureau of Mines covered a wide range of topics including:

- Publishing information describing the characteristics and chemistry of various explosives (Hall 1912; Hall 1915)
- Promoting the use of permissible explosives (Rutledge, Hall 1912)
- Reporting on tests employed to evaluate the safety of explosives (Hall, Howell 1913)
- Promoting the safe and effective use of explosives (Rutledge, Hall 1912; Hall, Howell 1913; Munroe, Hall 1911)
- Testing of explosives for the U.S. Army and Navy departments prior to and during World War 1.(U.S. Bureau of Mines 1919)

Over the next half century, new and different types of explosives were developed and introduced for commercial use. Prior to 1981, the majority of permissible explosives were nitroglycerin-sensitized granular, semi-gel, or gelled-typed explosives (Verakis, Uraco 1992). However, water-gel explosives accounted for nearly 50 percent of the commercial market within a decade of first being approved in 1970. Water-gels generally consist of about 10 to 20 percent water and contain no nitroglycerin sensitizer. Subsequent to the introduction of water-gels, new emulsion-type explosives were approved and introduced for use in coal mines in 1981. These explosives were in the form of water-in-oil emulsions and utilized artificial microspheres made from glass or other material for sensitizers. The development of water-gel and emulsion explosives improved product safety and made it possible to encompass a wide range of mine blasting requirements.

PERMISSIBLE EXPLOSIVES

The use of permissible explosives has significantly reduced blasting accidents in coal mines. Enactment of legislation, such as the Federal Coal Mine Health and Safety Act of 1969 and enforcement of regulations has also improved blasting safety. In the 1980's, MSHA began a major revision of its regulations for blasting in coal mines. In 1988, MSHA published final rules for the approval and use of permissible explosives and blasting safety requirements in coal mines. The approval requirements for permissible explosives addressed testing and evaluation in which some test changes and additions were made based on technical studies (Verakis, Uraco 1992). The requirements included tests for sheathed explosives, which represented a new technology and permitted unconfined or "open shooting" (See Figure 2). The sheathed explosive basically consists of a permissible explosive surrounded by an inert material. The inert material serves to suppress the flame from the detonation of the permissible explosive. The regulations also provided increased safety protection for miners by including qualifications for blasters, multiple-shot blasting and the use of sheathed explosives (Mainiero 1990).

Today, black blasting powder, which was the primary blasting agent a century ago, peaking in 1917 at about 125,645 metric tons (277 million pounds), is no longer permitted to be taken into underground coal mines and has been replaced by permissible explosives (ISEE 1998). However, the use of permissible explosives has declined significantly from peak sales in 1947 of about 60,328 metric tons (133 million pounds) to about 998 metric tons (2.2 million pounds) in 2007. The 998 metric tons (2.2 million pounds) of permissible explosives represents about 0.03 percent of the total amount of commercial explosives consumed in the United Sates in 2007 (USGS 2008). As a point of interest, about 12,247 metric tons (27 million pounds) of permissible explosives were consumed in 1912 versus about 12,247 metric tons (27 million pounds) consumed in 1988 when the steep decline began to occur in the use of permissible explosives in underground coal mines (ISEE 1998). Over the past several decades continuous and longwall mining have become the dominant methods of extracting coal in underground coal mines; therefore, the demand for permissible explosives has declined.

Figure 2. A miner and an explosives company technical representative preparing to break rock using the commercial version of the sheathed explosive charge, the Rock-Buster.

USBM LABS

Explosives Research Lab (ERL)

The Bureau of Mines explosives program in Bruceton, PA made significant contributions to the war effort during World War II. In the summer of 1940 the National Defense Research Committee (NDRC) was looking for a location to set up a centralized laboratory for testing explosives. They wanted to place this lab in "…the hands of staff which was already familiar with the subject" (Kistiakowsky, Connor 1948). The USBM was selected to operate the laboratory because they had many years of experience testing commercial explosives at their facilities in Bruceton, PA. Following acceptance by USBM the lab, designated the Explosives Research Laboratory (ERL), was set up in Bruceton in the fall of 1940. The USBM explosives scientists contributed generously to operation of the lab but their lack of experience with military explosives and their need to continue working on USBM activities created a need to recruit additional personnel. Initially, recruiting was only moderately successful due to the difficulties of recruiting personnel under the civil service system and only three scientists had been recruited by January, 1941. The NRDC looked for ways around this bottleneck and decided to contract out operation of the Bruceton ERL to Carnegie Institute of Technology (CIT). Under this arrangement research at ERL would continue under the direction of USBM scientists but CIT would recruit and pay new personnel. ERL grew quickly and by the end of the war 90% of the personnel in Bruceton were CIT employees. Growth of ERL activities may be judged from the number of personnel in Bruceton. In January, 1941 there were 5 ERL personnel and the number grew to 162 by 1945 (Kistiakowsky, Connor 1948). During the war, research at the lab included development of shaped charges for anti- armor applications (Walters, 2008), development and production of propellants, and work on cylindrical implosions. Following the war the number of personnel in Bruceton dropped significantly. CIT continued to operate ERL at a reduced level of effort, while USBM research and testing in Bruceton continued as before. During the 1960's CIT discontinued work in Bruceton as ERL was shut down.

Explosives research in Bruceton contributed in a significant way to the successful development of the atomic bomb. During 1943 scientists pursued two techniques for the creation of a nuclear chain reaction. A good chain reaction required that a critical mass of Uranium 235 or Plutonium be created quickly, in a time frame of milliseconds. If the critical mass was assembled too slowly the chain reaction would not release the desired amount of energy. In the gun method a subcritical mass of nuclear material would be fired into another subcritical mass thereby creating a critical mass. Another alternative was to collapse and compress a sphere of nuclear material to the point that it represented a critical mass, resulting in a chain reaction. In 1943 the gun method for forming a critical mass was the first choice because gun technology was well developed and no one knew if a spherical implosion would work. At this time scientists envisioned gun type bombs employing both Uranium 235 and Plutonium. There was some uncertainty whether the technique would function for Plutonium since the timing of the critical mass assembly was more critical than that required for Uranium 235; if assembly of the critical mass of fissionable material didn't occur quickly enough the chain reaction would begin before the critical mass was in its optimum configuration. As research progressed it became apparent that a gun type Plutonium bomb would require Plutonium of a purity previously not obtained. An implosion type bomb would function with a lower purity Plutonium and a smaller quantity would be required. One member of the Los Alamos community, Dr. Neddermeyer, remained optimistic about the possibility of creating an implosion type bomb. In 1943 Dr. Neddermeyer visited ERL in Bruceton. At that time the lab was operated by Dr. Kistiakowsky of Harvard, a renowned explosives scientist. Experiments were conducted in which explosives were formed around steel pipe and initiated at multiple points. These shots demonstrated that a detonation could uniformly compress the pipe, thus demonstrating that an implosion-type atomic bomb was feasible (Hoddeson, Henriksen, Meade, Westfall 1993). From this beginning, research continued in Bruceton and Los Alamos, resulting in sophisticated explosive lenses that made the implosion type bomb possible. An explosive lens was constructed of two explosives of different detonation velocities that would bend a detonation wave much the same way as a glass lens bends light. A new explosion formulation, Baritol, was developed in Bruceton to serve as the slower detonation velocity explosive in explosives lenses. This development was also fortuitous because the scientists learned during 1944 that Plutonium would not function in a gun type bomb.

Eastern Experimental Station/Applied Physics Lab

The Eastern Experimental Station in College Park, MD opened in 1937. The lab was set up to provide a facility where selected experiments could be conducted under the direct supervision of the USBM's headquarters staff. During and after World War II research into the physics of blasting was carried out here by USBM scientists. In 1942 air blast instrumentation was developed and used to study glass breakage by detonating cartridges of dynamite at various distances (Ireland 1942).

Following World War II the study of blasts in rock began. The research is well summarized by the following excerpt from the introduction of a paper published in 1949 (Obert 1949),

> "This report describes the development of a dynamic strain gage and a companion amplifier and recording cameras – an apparatus designed to pick up and record the strain waves produced in rock by a nearby explosion. Also included in the report is a discussion of the relationships connecting the strain with the displacement, velocity, and acceleration for both plane and spherical waves?"

The following year a group of USBM scientists from the Eastern Experimental Station used these strain gauges to measure the strain in rock surrounding a blast hole. This was a simulation of shooting oil and gas wells to increase permeability in rock. Following each shot the permeability of the rock surrounding the borehole was determined by pouring in water and timing how fast the borehole emptied.

Over the following two decades researchers at the USBM Eastern Experimental Station (later renamed the Applied Physics Laboratory) continued to develop instrumentation for measuring ground vibrations from blasting (Duvall 1964), study how detonating explosives in blastholes break rock (Atchison, Duvall, Pugliese 1964), evaluate the application of photography to blasting studies (Petkof, Atchison, Duvall 1961), and study damage to homes caused by blast vibrations (Nicholls, Johnson, Duvall 1971). This was the beginning of blasting science as we know it today. In the mid 1960s the blasting research at the USBM's facilities in College Park, Maryland was discontinued and the work was moved to other USBM laboratories.

Twin Cities Research Center (TCRC), 1959-1996

In 1959 the USBM opened a mining research center in Minneapolis, MN. In 1972 the lab was renamed the Twin Cities Research Center (TCRC). During the 1960's the lab began research on explosives cratering (Johnson, Fischer, 1963), factors affecting blasting performance (Dick, 1970), vibration produced by blasting operations, and effects of blast vibrations on the roof and ribs in underground mines (Snodgrass, Siskind 1974). This work was intended to develop a better understanding of the interaction between detonating explosives and rock so that more efficient blasting methods could be developed, as well as protecting homes around a mine from vibrations produced by a blast. A study was conducted to combine data collected in TCRC research with data from earlier USBM studies to produce two landmark publications on the effects of blasting- related ground vibration and airblast on residential structures (Siskind, Stagg, Kopp, Dowding, 1980; Stachura, Siskind, Engler 1981). During the 1980's additional research was conducted to develop a better understanding of the effects of blast vibrations on structures (Stagg, Siskind, Stevens, Dowding 1984), evaluate techniques for measuring ground vibrations (Siskind, Stagg 1985), and study the effects of underground workings on the blast vibrations from surface mines (Siskind, Crum, Otterness, Kopp 1989). Millisecond delay blasting was studied as a way to yield more stable highwalls (Stachura, Fletcher, and Peltier 1986), and a technique for controlling air blast and ground vibrations (Kopp, Siskind 1986). In 1982 TCRC published the USBM Information Circular 8925, "Explosives and Blasting Procedures Manual" which provided industry with a comprehensive review of current safe, productive blasting practices (Dick, Fletcher, D'Andrea 1982). During its first year of publication, more than 5000 copies of IC8925 were distributed.

TCRC research and publications on airblast and ground vibrations from blasting rank as one of the top USBM contributions to the science of blasting safety. Data generated in the TCRC studies formed the basis for the Office of Surface Mining and Reclamation's (OSMRE) air blast and ground vibration limits published in their 1983 regulations (U.S. Government Printing Office, 1982; U.S. Government Printing Office, 1983). In addition, a majority of the U.S. jurisdictions base their regulations on TCRC data (Eltschlager, 2003; Seismic Regulation Subcommittee, 2000). The publications generally referenced are Bulletin 656 published in 1971 and Report of Investigation 8507 published in 1980 (Eltschlager, 2003; Seismic Regulation Subcommittee, 2000).

USBM Pittsburgh Research Center (PRC) - NIOSH Pittsburgh Research Lab (PRL)

As mentioned earlier, PRC in Bruceton, PA has been involved in explosives and blasting research since the creation of the USBM in 1910. Evaluating permissible explosives and blasting practices was a significant part of the PRC's activities for the entire life of USBM. The early years and work on permissible explosives are described above. This section will discuss PRC's explosives research other than that conducted as a part of ERL and for permissible explosives safety.

Following closure of the Explosives Research Lab in the 1960's, PRC continued to conduct explosives research for the military and other government entities under Interagency Agreements. This work included studies of the effects of hypervelocity projectiles on metallic target plates, a study of the factors affecting the energy transferred from detonating explosives to coupled metal plates, a study of detonation initiation phenomena in liquid explosives, the destruction of earthen tunnels used by the Viet Cong (Tuchman, Brinkley 1990), the development of a test to evaluate the explosive reactivity of solid wastes (Bajpayee, Mainiero 1988), and others. In 1967 PRC's Research Director, Dr. Robert Van Dolah, was awarded the Nitro-Nobel Gold Medal for the theory he developed to explain the accidental initiation of liquid explosives (Person 1999; Tuchman, Brinkley 1990). In 1972 PRC published guidelines for the safe use of ammonium nitrate/fuel oil (ANFO) blasting agents (Damon, Mason, Hanna, Forshey 1972). Beginning about 1980 Richard W. Watson, Research Supervisor for PRC's Explosives Section, participated in a United Nations effort to develop an international classification system for explosives and other hazardous materials. The outcome of this work was the development of the U.N. Recommendations on the Transportation of Dangerous Goods and a manual containing procedures and tests to be used in evaluating the safety of new explosives and explosives devices, and assign them to a hazard class and division. This work involved close work with the U.S. Department of Transportation (USDOT), the agency tasked with coordinating U.S. activities in this international effort (See Figure 3). These close ties lead to PRC's designation as one of two U.S. laboratories authorized to test explosives pursuant to classification by USDOT during the 1980's. This activity continued until 1997 when it was discontinued following closure of the USBM and PRC's transfer to the National Institute for Occupational Safety and Health (NIOSH).

From 1997 to 2005 PRL conducted a research program looking at all aspects of toxic gases produced by blasting. The effort began with the development of a technique for measuring toxic gases produced by blasting agents. The research studied factors controlling the quantity of toxic gases produced and resulted in recommendations surface mines could employ to minimize production of nitrogen oxide by blasts (Sapko, Mainiero, Rowland, Zlochower 2002). Later the work expanded to include toxic fumes produced by high explosives. This work was initiated by concerns that carbon monoxide could migrate from a blast into nearby homes or other confined spaces (Harris 2005). Due to staffing and budget shortfalls, the NIOSH explosives program in Pittsburgh was discontinued in 2005 (Sharpe 2009).

Figure 3. A USBM technician prepares to conduct a test that would eventually become Test 8(d) in the UN Test Manual. If the 45.3 kg (100 lb) of blasting agent loaded explodes when subjected to the fire it will not be approved for bulk transport.

The problem of air blast and noise produced by explosives research at the USBM's Bruceton facility had always been a concern. This became especially true during World War II when the explosives research effort expanded significantly with the opening of ERL. Initially residents of neighboring communities were tolerant of the noise because the research was in support of national defense. However, as the population of the surrounding area increased the public became less tolerant of the noise. During the early 1960's a study was initiated to determine how the noise from research at PRC might be reduced. This study led to enclosing the bombproofs, closing the end of the permissible gallery tube, and monitoring weather reports. Research and testing would be halted on days when a weather inversion would reflect noise down on the neighbors (Van Dolah, Gibson, Hanna 1964). Limitations on explosives research at PRC led to the relocation of large scale explosives research to the USBM's Lake Lynn Laboratory following its opening in 1982.

USBM Spokane Research Center (SRC) – NIOSH Spokane Research Lab (SRL)

The USBM's Spokane Research Center (SRC) began research on blasting safety relatively recently with one exception. During the 1960's researchers at SRC needed to measure differential movement within a borehole as a way to understand the movement of rock formations in and around ore deposits before, during, and after mining operations. The plan was to install an anchor at one end of a drill hole and measure the movement of wire extending from that point to the collar. Wire was threaded through a bolt from the collar to an anchor at the other end of the borehole. Standard expansion-type anchors could not be used because rotating the bolt to tighten the anchor would twist and tangle the wire. To alleviate this problem, SRC developed an explosive-expansion center-hole anchor which did not require turning of the bolt; an explosive charge in the anchor would expand the anchor, locking it firmly in place (Parsons, Osen 1963).

In 2006 the Spokane Research Lab began a 5-year research effort to develop techniques for evaluating damage to a mine's roof and ribs caused by the blasting process and develop blasting techniques that would produce more stable roof and ribs. The program recognized that fall of ground was a significant hazard in underground mines and a leading cause of fatalities. This hazard is increased if the standard drill and blast process leaves the roof and ribs significantly fractured and unstable. The goal of the program is the perfection of perimeter blasting techniques that remove the desired rock but do not produce fractures into the remaining rock (Johnson, Hustrulid, Iverson 2009). The program continues as of the writing of this paper.

CONCLUSION

For the last century the USBM and NIOSH have contributed to explosives and blasting science far more than would be expected for an organization of its size. Prior to World War II the USBM was considered the preeminent explosives research organization, which led to it selection to head up the Department of Defense Explosives Research Lab where explosives research was conducted for application to weapons systems and development of explosive components for the first implosion type atomic bomb. The USBM's reputation continued long after World War II. During the mid sixties the military explosives work was moved to other facilities which could accommodate large-scale explosives testing. The USBM, and later NIOSH, have continued with mining-related explosives and blasting research to the present time.

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