U.S. Bureau of Mines/NIOSH Mining Electrical Safety Research: A Legacy of Protection Against Shock, Fires, and Explosions

Michael R. Yenchek
NIOSH, Pittsburgh, Pennsylvania, United States

Gerald T. Homce
NIOSH, Pittsburgh, Pennsylvania, United States

ABSTRACT: This paper reviews the 100-year history of federal electrical safety research in the U.S mining industry, originally by the US Bureau of Mines, and as carried on today by NIOSH. First, there is a brief historical review of the use of electrical power in mining and an examination of the associated shock, fire, and explosion hazards. These hazards were the impetus for government intervention to improve the safety of U.S mineworkers. The evolution of electrical power systems and equipment in mining then serves as a backdrop for a review of continued electrical safety research. The paper concludes with a recap of the contributions made to mine worker electrical safety by federal research efforts, and thoughts on where the future will lead such research under NIOSH.

INTRODUCTION

This paper reviews the 100-year history of federal electrical safety research in the U.S mining industry, originally by the US Bureau of Mines, and as carried on today by NIOSH. First, there is a brief historical review of the use of electrical power in mining and an examination of the associated shock, fire, and explosion hazards. These hazards were the impetus for government intervention to improve the safety of U.S mineworkers. The evolution of electrical power systems and equipment in mining then serves as a backdrop for a review of continued electrical safety research. The paper concludes with a recap of the contributions made to mine worker electrical safety by federal research efforts, and thoughts on where the future will lead such research under NIOSH.

Early in its history, the lack of federal safety regulations forced the Bureau into an advisory role for the mining industry. Since the Bureau had no regulatory powers, it relied principally on publications, such as technical papers and bulletins, to enlighten the industry about potential hazards. These suggestions were to be the precursors for the mandatory rules and regulations that later governed the use of electricity in mining. Many of the “good practices.” were the result of surveys of operators and manufacturers as was the case for the installation of cables in shafts and boreholes (Ilsley and Gleim 1932). At that time, several states had enacted laws governing mining equipment based upon the recommendations of the Bureau of Mines. It was only later, in 1946, that a federal safety code for bituminous coal and lignite mines was enacted. Ultimately, the Federal Coal Mine Safety Act of 1952 provided for annual inspections and gave the Bureau limited enforcement authority. However, it was the passage of the Coal Mine Safety and Health Act of 1969 that greatly influenced and expanded the Bureaus research, with much work being accomplished through grants and contracts. In 1973, the Bureau of Mines electrical safety functions associated with equipment approvals transferred to the Mining Enforcement and Safety Administration (MESA, later MSHA).

The Bureau of Mines was actively involved in electrical safety research since its inception in 1910. An electrical section was organized in 1909 under the technologic branch of the U.S. Geological Survey (Ilsley 1923) and continued under the Bureau. The act establishing the Bureau detailed its scope, which included in part, investigating the methods of mining especially in relation to the use of explosives and electricity (Powell 1922). Technical Paper 4 (Clark 1911), describing the purpose and equipment of the Bureau’s electrical section stated that, “There is a distinct branch of electrical engineering in connection with the equipment of mines. The conditions in mines are very different from those on the surface. Not only is it more difficult to install and properly maintain electrical equipment underground, but, unless suitable precautions are observed, the presence of such equipment in mines adds danger to a calling already hazardous.” The paper also acknowledged the cooperation of various state inspection departments and equipment manufacturers in safeguarding life and property underground.

By 1910, electricity was already being used underground for haulage, lighting, driving pumps, fans, drills, coal cutting machines, and hoists, for detonating explosives, and for signaling. Both direct and alternating current were used, the former much more extensively. Direct current (DC) was distributed at up to 600 volts, while alternating current (AC) at over 2,000 volts was carried a short distance underground to feed motor-generator sets or rotary converters. Explosives could be detonated by batteries, magneto generators, or power circuits. Signals, which may include lights, bells, and telephones, were operated principally from batteries.

Technical Paper 4 (Clark 1911) recognized the temporary nature of electrical service at many points and the fact that many workers did not appreciate its inherent danger. These dangers from electricity were classified as shock, fire, and explosions. Shock hazards included the trolley wire and other bare conductors along with ungrounded equipment. Fires could result from grounds to coal, flashing of motors, and short circuits. Explosions could originate from arcing and sparking that could ignite methane or dust accumulations.

The electrical section of the Bureau was originally a part of the experimental station in Pittsburgh, PA and was initially staffed by an electrical engineer, an assistant electrical engineer, a junior electrical engineer, and an electrical engineering aid (Powell 1922). The section's purpose (Clark 1911) was to "attempt to discover the causes of accidents from the use of electricity in mines and to suggest means for the prevention of such accidents; to make tests of the safety of electrical equipment under conditions most conducive to disaster; and to make such tests of a general nature as bear upon the safety of electricity in mines, accidents attributed to electrical causes, etc." The laboratory, initially at the Government Arsenal at Fortieth and Butler Streets in Pittsburgh, was primarily for testing mining equipment. It featured direct current capability up to 750 volts and alternating current up to 2000 volts for power, and 30,000 volts for high potential tests. Two galleries were used for testing electrical equipment in the presence of explosive gas. The smaller consisted of a boiler-iron box with connections for gas and air, heavy plate-glass observation windows, and pressure-relief vents. Incandescent lamps and other small items were evaluated in this chamber. The larger was a tube designed to represent a short section of a mine entry, thirty feet long and 10 feet in diameter, and was used for tests of larger apparatus such as motors and switches (Clark 1911). This facility can be contrasted with the present-day Mine Electrical Laboratory, which is located at the NIOSH Pittsburgh Research Laboratory. Established in the early 1980s, it can support full-scale testing of mine electrical power system components, and over the years has been used for projects examining mining safety issues such as fuse performance, electric motor failure, trolley system faults, electric motor circuit protection, electrical cable performance, and overhead power line hazards. It is equipped with electrical power supplies capable of delivering voltage up to 100 kV AC or DC, and current up to 50 kA AC, as well as a secure control room from which tests and experiments can be controlled and observed safely. It has also been used to support Mine Safety and Health Administration investigations. A small rail haulageway at Lake Lynn was used for trolley system research.

This research history is organized by major types of electrical apparatus, i.e., explosion-proof enclosures, motors, trailing cables, trolley wires, etc. Within each category, the work is listed chronologically along with mine technological developments. Space limitations precluded inclusion of some related areas such as communications, lasers, and instrumentation as well as research that was applicable mainly to non-mining industries.

PERMISSIBLE EQUIPMENT

Electrical equipment used in potentially methane-laden atmospheres must be housed in explosion-proof (X/P) enclosures or be of intrinsically-safe design, so as to have insufficient energy, under normal or faulted conditions, to ignite a methane-air mixture. The earliest electrical safety investigations involved the explosion hazards associated with various types of electrical apparatus already in use in gaseous underground coal mines. These included portable electric mine lamps, motors, storage-battery locomotives, mine lamp cords, gas detectors, danger signals, and coal-cutting apparatus. A series of schedules, published by the Bureau of Mines, specified the evaluation fees and requirements for the use of such equipment in gaseous mines and further stated that the Bureau would give its seal of approval to acceptable apparatus as being *permissible*. Schedule 2, approved by the Secretary of the Interior, October 26, 1911 was the first schedule issued and covered testing of motors. The Bureau published revised requirements (Schedule 2A) for test and approval of explosion-proof electric motors in 1915 (Clark 1915). This included tests where the motor casing was filled and surrounded with the "the most explosive mixture of Pittsburgh natural gas and air." Subsequent tests would prove that the results obtained with natural gas and pure methane were essentially the same (Leitch, Hooker, and Yent 1925). The motor would be operated at rated speed and the gas mixture ignited by a spark inside the casing. Gas mixtures would be varied and coal dust added in over fifty tests prescribed to determine the greatest internal enclosure pressure.

Occasionally excessive pressures, due to “pressure heaping.” would be recorded especially where two internal compartments were joined via a small interconnecting passage (Gleim 1929). The conditions leading to these excessive pressures were better defined in a subsequent study (Gleim and Marcy 1952). A metallic foam material, investigated for potential use in large volume enclosures as a vent and flame arrestor, performed satisfactorily for methane-air mixtures (Scott and Hudson 1992).

Tests were also conducted on broken incandescent lamps to relate newly introduced tungsten filament temperatures to the “fire damp.” (methane-air) gas ignition threshold (Clark 1912) and to show that broken lamps can ignite methane-air mixtures (Clark and Ilsley 1913). These tests also showed that higher wattage carbon filament lamps were necessary to ignite a given methane-air mixture compared with tungsten filaments. They were followed up by tests of electric lamps for miners for permissibility according to Schedule 5, a key criterion of which was that (Clark, 1914) “under no circumstances can the bulb of a completely assembled lamp be broken while the lamp filament is glowing at a temperature sufficient to ignite explosive mixtures of mine gas and air.” Electric cap lamps were introduced and approved under Schedule 6. Yet in 1935, more than half of the Nation’s miners still used open carbide lights for illumination (Zellers and Hooker 1935).

The first electrically powered coal mining machine, the coal cutter, was seeing widespread use by the 1920s (Morley 1990). Tests to determine the permissibility of cutting machine components were conducted in a new gallery in Pittsburgh (at that time located on Forbes Avenue adjacent to Carnegie Mellon University) which was designed jointly by the Bureau and the Jeffrey Manufacturing Company (Ilsley and Gleim 1920). This chamber shown in Figure 1 (Ilsley, Gleim, and Brunot 1941) consisted of a cylindrical steel tank with an internal diameter of 10 feet and a height of 4½ feet. Four observation windows were spaced equally around the chamber.

The Bureau recognized the potential fire and explosion hazards from batteries used in mine locomotives. Investigations indicated that the safety of the locomotive would depend largely on the proper care of the batteries. Therefore, mechanical endurance tests were devised to prove their adequacy and later were incorporated into Schedule 15 (Ilsley and Brunot 1922). The first storage-battery approval was issued in 1921 (Brunot and Freeman 1923).

Figure 1. Explosion-proof motor testing gallery, Pittsburgh (Ilsley and Gleim 1920)

Permissible equipment and explosives lists were published annually as Technical Papers. Periodically guides, based upon the latest approval schedules, were issued to facilitate the field inspection of permissible equipment (Gleim 1932; Gleim 1954) and, for machine designers (Gleim, James, and Brunot 1955). By 1923, a number of electric apparatus had been listed as approved including: 5 electric cap lamps, 20 coal-cutting machines, 4 electric drills and 5 battery locomotives (Ilsley 1923). Despite the publication of approval requirements, the widespread use of unapproved equipment in underground mines persisted into the 1920s (Ilsley 1922). From 1910 to 1924, there were 499 fatalities in disasters and fires caused by ignitions from electrical apparatus and circuits (Ilsley 1924). However, by the end of the decade there was a noticeable increase in the use of permissible equipment, even though maintaining them in permissible condition was still a problem (Gleim and Freeman 1932). By the mid 1930s rock-dust distributors, air-compressors, pumps, and room hoists were added to the classes of permissible equipment.

In the early 1980s, a guide was prepared for the design of explosion-proof electrical enclosures. It addressed those aspects of design that affected enclosure strength and ruggedness. Materials such as polycarbonates, as well as adhesives and sealants, which may be degraded by the mine environment, were also analyzed (Staff 1982). Research into the by-products of electrical arcing in X/P enclosures found that hydrogen and acetylene can be formed as certain organic insulators decompose. Research produced acceptance criterion for adhesives and sealants and a design guide for explosion-proof enclosures (Cox and Schick 1985). Performance-based design and test recommendations were published for enclosures containing high-voltage components (Berry and Gillenwater 1986). These recommendations were referenced by MSHA to help formulate new regulations governing the use of high-voltage longwall machines in coal mines (Federal Register 2002).

Intrinsic safety research concentrated on basic studies into ignition mechanisms. Factors influencing the minimum igniting current level were identified. Early work focused on capacitive discharges (Lipman and Guest 1959). Later, spark ignition probabilities were defined for various electrode materials and for resistive, inductive, and capacitive circuits under varying temperature, humidity, and atmospheric conditions (Cawley 1988; Peterson 1992).

TRAILING CABLES

Initially most of the inspection, testing, and approval of electrical equipment concentrated on the explosion-proof integrity of enclosures. However, trailing cables had been employed since shortly after the turn of the century and the Bureau of Mines generally accepted the cables that were specified by the manufacturer for a particular machine. One of their first uses was in connection with cable-reeled, rail-mounted locomotives. These cables, featuring a weatherproof braid, had a short life and were largely superseded by rubber-sheathed cables in the 1920s when three types of cables were in general use: a concentric 2-conductor, a flat or twin duplex, and a round triplex (Ilsley, Hooker and Coggeshall 1932). By 1930, a new emphasis was being placed upon the dangers from wiring and connections outside the enclosures (Ilsley and Brunot 1931). Field inspections had shown that the workmanship of splices in concentric cables was typically poor and that they were seldom vulcanized to exclude moisture (Ilsley and Hooker 1929). Schedule 2C, published in 1930, specified a performance test for two-conductor trailing cables subjected to abuse due to being run over by rail-mounted cars and locomotives (Ilsley 1930). The performance of twin cables was found in tests to be far superior to the concentric design. The overheating of rubber-insulated reeled cables was also investigated by electrical loading and measurement of resultant temperature rise. Revised ampacities were established for various cable sizes (Ilsley and Hooker 1931).

The standard procedure for locating faults in trailing cables into the 1970s was to apply a high level of electric power to blow a hole in the cable at the fault site, a crude and unsafe procedure. The Bureau developed safe, portable devices that locate faults accurately and rapidly based upon infrared, electromagnetic, and time domain reflectometer (TDR) techniques. Three manufacturers marketed electromagnetic devices based upon the original Bureau design (Bureau of Mines 1981).

Industry cable splicing practices were studied in a 1960 survey of 440-V and 4,160-V cables at an Indiana surface mine (Douglas 1960). A follow-up survey of industry practices uncovered deficiencies in cable repair and care (Williams and Devett 1962). In the late 1970s, cable-related research concentrated on improved splicing procedures for trailing cables (Staff 1984). Programs were initiated to redesign splice kits to better protect spliced cables from short circuits and moisture intrusion and to increase mechanical strength. Improved crimp connectors and joining sleeves were designed. This work culminated in splicing workshops conducted for industry personnel and the effort saw 12 major kit manufacturers improve their products based upon Bureau work. The operating characteristics of repaired (spliced) portable power cables were later compared with undamaged cables (Yenchek, Schuster, and Hudson 1995) and deficiencies in the thermal rating of splice kit insulating tapes were noted.

In the 1980s, in cooperation with MSHA, the American Mining Congress and the Insulated Cable Engineers Association, the Bureau initiated an extensive investigation into the operational characteristics of trailing cables powering coal mining machinery. Initially a relationship was established between electric current and resulting temperature rise of the cable conductors (Yenchek and Kovalchik 1989; Yenchek and Kovalchik 1991). These extensive laboratory tests were the basis for the subsequent development of a computerized thermal model for cables operating in open air (Yenchek and Cole 1997). Machine designers could apply this interactive program to determine anticipated cable temperatures given the electrical load requirements of new machines. Accelerated life tests of cable insulation and jacket materials were conducted to determine the long-term effects of elevated temperatures (Yenchek and Kovalchik 1989). Arrhenius models were constructed that related cable thermal life to operating temperature for the cable materials. A correspondence was then established between current load and useful thermal life (Yenchek and Kovalchik 1993). Using this methodology and knowing the electrical characteristics of a particular machine, a designer

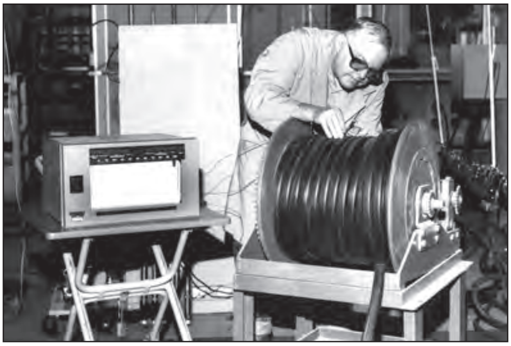

Figure 2. Cable reel thermal test in the Mine Electrical Laboratory

could theoretically predict and compare the available service lives of different cable sizes. Finally, research was conducted to measure the temperature of cables wrapped on shuttle car reels as shown in Figure 2 (Kovalchik, Scott, Dubaniewicz, and Duda 1999). A novel method was devised to measure internal cable temperatures with an imbedded optical fiber. This work allowed for a more accurate calculation of ampacity derating factors for reeled cables, especially under cyclic loads.

ELECTRICAL POWER SYSTEMS

In 1916 in cooperation with professional societies, operators, and equipment manufacturers, the Bureau of Mines published a suggested guide for the installation and use of underground and surface electrical equipment in bituminous coal mines (Clark and Means 1916). In 1923 a suggested guide for electrical safety inspection was published (Ilsley 1923) and in 1926 one for the design of accessories used in permissible equipment (Ilsley and Gleim 1926). A subsequent publication covered surface as well as underground installations and recommended the National Electric Code as a suitable reference (Gleim 1936). Ultimately an electrical safety standard, co-sponsored by the American Mining Congress and the Bureau, was published as a supplement to federal and state regulations (American Standard 1952) and was periodically revised.

Periodically the Bureau would publish warnings to the industry about dangerous electrical system practices. In 1929 a Bureau publication pointed out a hazard associated with equipment use, that of cables and equipment overheating due to low voltage on direct current systems as a result of insufficient copper and poor rail bonding (Ilsley 1929). Incredibly, voltages measured at equipment in some mines were as low as 40 to 80 volts on 250 DC systems! Yet, equipment operating at voltages greater than 250 volts was viewed as potentially more hazardous and difficult to maintain as permissible (Ilsley 1932). Although most mines in the U.S. were still using DC to power machinery in 1960, the use of alternating current was growing due to concerns with fires and voltage regulation on DC systems, concurrent with the lifting of AC distribution voltage limits underground by individual states (Morley 1990). Also current interruption was far easier with AC. The Bureau, recognizing this trend, published recommendations for the use of AC, and endorsed the wye-connected, resistance-grounded neutral transformer secondary configuration due to its inherent safety advantages (Staff 1960). In the 1970s a series of Application Notes (Figure 3) on a variety of aspects of mine power system operation were produced for distribution to the mining community. In 1990, a comprehensive engineering reference was published and was used to instruct university students on the design of mine power systems (Morley 1990). More recently, NIOSH, in an analysis of underground explosions, showed that many were caused by electrical equipment in intake air entries. This led to recommendations to apply the hazardous location provisions of the National Electrical Code in these areas (Dubaniewicz 2007).

GROUNDING

A good grounding system is paramount for the protection of personnel in a mine or mineral processing facility. Prompted by unwillingness on the part of the mining industry to provide adequate grounding of equipment enclosures in the 1920s, a compilation of best practices was published to promote the

Figure 3. Loose-leaf power system handbook

Figure 4. Ground bed design workshop at Pittsburgh Research Laboratory, 1980

importance of grounding mine electrical systems to minimize shock hazards (Ilsley 1930). Bureau of Mines engineers characterized the effectiveness of ground rods, machines in earth contact, and rail through resistance measurements (Griffith and Gleim 1943). The effectiveness of drill-hole casings as a grounding medium was confirmed through field measurements (Griffith and Gleim 1944). A study, conducted out of the Bureau's Birmingham, Alabama office, showed how the impedance offered by moist earth could increase over time when conducting ground fault currents (McCall and Harrison 1952). To assist in mines in complying with the requirements for a low-resistance grounding medium, the Bureau undertook research to systematize the design of ground beds based upon soil and other environmental conditions. This work led to publication of a guide that greatly simplified the design of driven-rod ground beds (King, Hill, Bafana, and Cooley 1979; Staff 1979) along with workshops (Figure 4) for industry personnel. Other ground bed subjects investigated were ground bed measurement, corrosion of ground rods, and composite bed materials (Staff 1985).

The 1969 Act required a device to monitor ground conductor continuity to prevent accidental electrocution resulting from high frame potentials. Bureau research produced such a device, which served as an industry prototype (Staff 1979). Contractual research in the 1970s developed a method to monitor safety grounding diodes on underground DC circuits, quantified earth contact resistance for various electrodes, and devised a prototype device to measure ground return resistance for open-pit mine machines (Bennett, Sima, and King 1978).

ELECTRICAL MAINTENANCE

Accidents associated with the maintenance of electrical equipment, especially troubleshooting and repair, have, over the years, been a major cause of injuries in mines. Design practices, including dead-front construction, voltage segregation, and interlocks, were identified as means to minimize shock during control box maintenance (Staff 1982). Beginning in the 1970s and continuing well into the 1990s the Bureau of Mines sponsored and conducted research into the early prediction of insulation failure in electrical components, focusing primarily on electric motors. Research efforts concentrated on sophisticated computer-based analysis of motor input power measurements during normal operation, and included contract research (Kohler and Trutt 1987), in-house work at the Pittsburgh Research Laboratory's (PRL) Mine Electrical Laboratory (Homce 1989), cooperative work with the Navy, and extensive field data collection (Homce and Thalimer 1996). The serious problem of electrical burns due to arc flash incidents in mining was addressed by identifying and promoting prevention methods used successfully in other industries (Figure 5) (Homce and Cawley 2007). As part of this work, a safety training package, titled "Arc Flash Awareness." was released on DVD. Thousands of copies were distributed directly, and it had extensive promotion, distribution, and use by other agencies and organizations, including translation into Spanish by the Electrical Safety Foundation International (Kowalski-Trakofler, Barrett, Urban, and Homce 2007).

PROTECTION DEVICES

Devices such as fuses, circuit breakers, vacuum interrupters, and relays are use to protect against fire and shock. A 1951 study out of the Bureau of Mine's Birmingham, Alabama office showed that a fuse in combination with a short-circuiting contactor could provide effectively the same protection against short circuits as a more expensive circuit breaker (Harrison 1951). A resettable current-limiting prototype was built and tested to minimize arcing during interruption of DC currents (Hamilton and Strangas 1978). A portable calibrator was developed for on-line use with DC circuit breakers (Bureau of Mines 1981). In the 1980s, in efforts to improve personnel shock protection, the Bureau investigated the application of sensitive ground fault relays (GFR's) to mine power circuits (Trutt, Kohler, Rotithor, Morley, and Novak 1988). Mine-worthy prototype devices with sensitivities in the milliampere range were designed and

Figure 5. Appropriate arc flash personal protective equipment demonstrated by NIOSH researcher

constructed for both AC and DC circuits (Figure 6) (Yenchek and Hudson 1990). NIOSH investigated how the starting of large AC induction motors might cause nuisance tripping of short-circuit protection on coal mine power systems. A method was devised to provide short-circuit protection without intentional time delays to account for motor starts (Yenchek, Cawley, Brautigam, and Peterson 2002). A recent study concluded that the significant capacitance of shielded cables on mine distribution systems can have a detrimental effect on high voltage ground fault relay selectivity (Sottile, Gnapragasam, Novak, and Kohler 2006).

TROLLEY WIRES

The fire and shock dangers associated with the use of bare trolley wires for rail coal haulage had long been recognized by the Bureau of Mines. A 1932 Bureau study showed that of 71 electrical fatalities in one state during a 5-½ year period, 55 were from contact with trolley wires operating at 250 volts or less. The hazards associated with the use of bare trolley wires were tied to poor installation, lack of guarding, inadequate maintenance, and back-poling (Gleim 1932). During a 19-month period, in 1943–44, 101 mining fatalities resulted from four fires that originated on the trolley system, as the coal industry attempted to meet the demands of war production. A contemporary

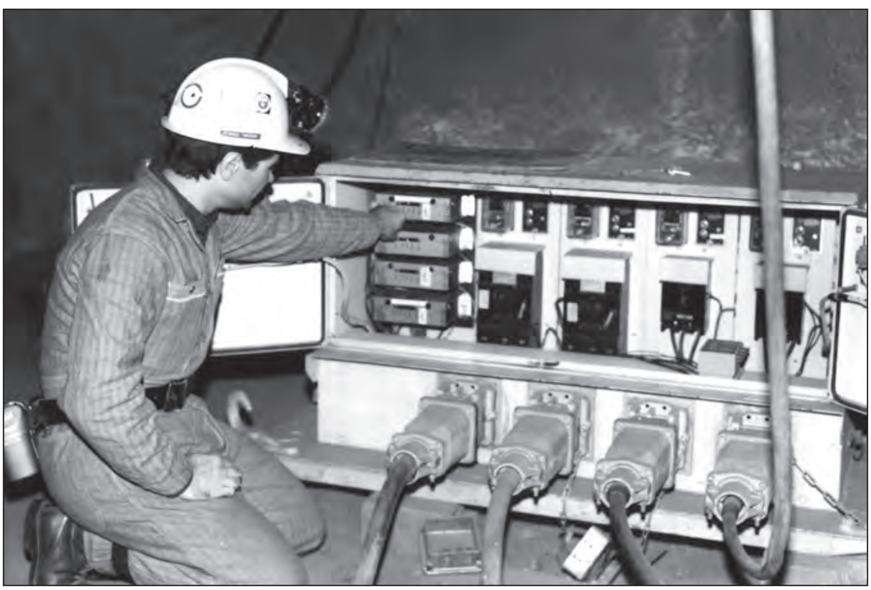

Figure 6. Sensitive AC GFR's installed in Safety Research Coal Mine

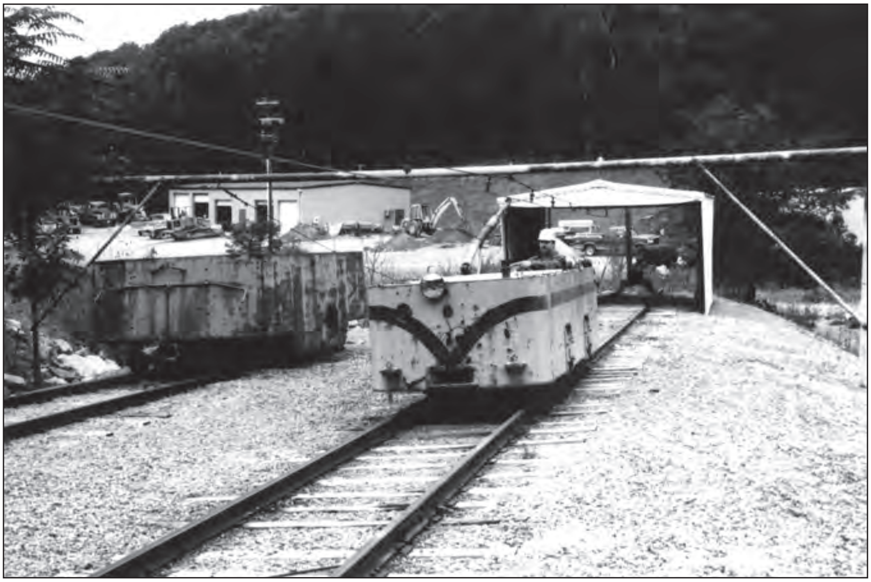

Figure 7. Tests on DC haulageway at Lake Lynn Laboratory

Bureau publication suggested the elimination of bare, single-wire trolley by the application of two-wire overhead systems (eliminating the track as a return), circuit breakers that would discriminate between heavy fault and load currents, and diesel or battery-powered locomotives (Griffith, Gleim, Artz, and Harrington 1944). In the early 1980s the Pittsburgh Research Center demonstrated technology that could detect such faults (Staff 1982). Since this approach required additional wiring along the length of the haulage way, it was never adopted by the industry. A final attempt to develop a 'smart' circuit breaker for trolley haulage involved tests at cooperating mines to develop a neural-network detection algorithm based upon the rectifier current signature (Figure 7) (Peterson and Cole 1997). A simple, low-cost means to detect hot trolley insulators was prototyped (Yenchek and Hudson 2000). Although successful, the smart circuit breaker and hot insulator detector were never deployed due to the industry-wide transition from rail to belt for coal haulage.

SURFACE MINING

The electrification of shovels and draglines began before 1920 (Morley 1990). As horsepower requirements increased, so did distribution and utilization voltages. An area of interest to the Bureau of Mines and later, NIOSH, was the electrical shock hazard from accidental contact of overhead electrical power lines, both at surface mines and the surface facilities of underground mines. Such accidents usually involve high reaching mobile equipment like cranes or other equipment such as scaffolds and ladders and are a leading cause of electrical fatalities at mine sites. Early contract work thoroughly analyzed the problem, and looked at available warning-device solutions (Hipp, Henson, Martin, and Phillips 1982) (Morley, Trutt, and Homce 1982). NIOSH developed and patented (Sacks, Cawley, Homce, and Yenchek 1999) a practical low-cost concept to detect line contact and emit a warning (Sacks, Cawley, Homce, and Yenchek 2001). More recent research has evaluated currently available warning devices (Figure 8) (Homce, Cawley, and Yenchek 2008).

ACCIDENT ANALYSES

Periodically, analyses of accidents were conducted which showed a continued need for research aimed at improving electrical safety in mines. A 1936 analysis of electrical accidents in coal mines showed that electricity ranked fourth as a cause of coal mine fatalities, excluding deaths from fires and explosions of electrical origin (Harrington, Owings, and Maize 1936). Ninety percent of electrocutions were caused by contact with the bare trolley wire. Forty-one percent of the explosions for the period 1928–1935, resulting in 476 deaths, were caused by the electrical ignition of gas or coal dust. These were mainly due to the use of open-type equipment or poorly maintained permissible equipment. From 1930–35,

Figure 8. Full scale power line proximity alarm test at Pittsburgh Research Laboratory

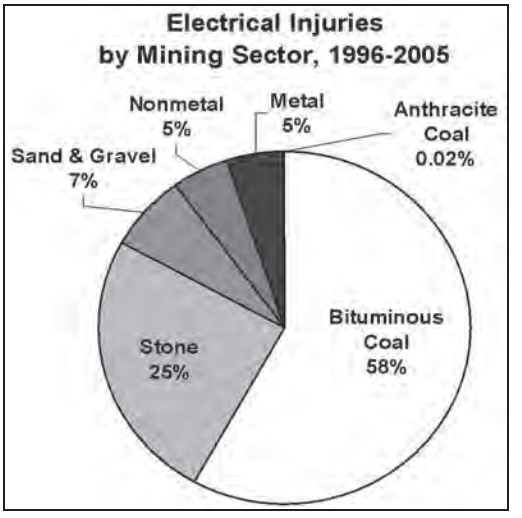

Figure 9. Electrical accident data analysis

fires of electrical origin were the cause in 29% of the fatalities from all mine fires (Harrington, Owings, and Maize 1936). An analysis of electrical accidents in the late 1970s and Bureau research yielded a cost-benefit analysis for electrical safety projects (Tenney, Cooley, and Elrazaz 1982). Recent NIOSH studies of occupational electrical injuries have indicated that, despite dramatic improvements over the years, mining has an electrical injury rate that is still much higher than many other industries. These studies, in addition to highlighting the need for continued improvements in mining electrical safety, were very influential in the broader electrical safety community. The first (Cawley and Homce 2003) was described as a “landmark research study.” and “one of the most, if not the most, comprehensive analyses of occupational electrical injuries ever undertaken.” in the April 2004 *IEEE Industry Application*s magazine. The second was hailed as “seminal research.” in the May/June 2007 edition of the same publication (Cawley and Homce, 2006). Within mining (Figure 9), electricity continued to rank fourth as a cause of death (Cawley 2003). Burns were found to be the leading type of injury, but were rarely fatal. Electrical shock was the overwhelming cause of electrical fatalities.

SUMMARY AND FUTURE DIRECTION

The Bureau of Mines/NIOSH electrical safety research program has focused on a wide variety of topics over its 100-year history. Research has been conducted to address safety issues associated with advancing technology as well as to develop new solutions prompted by regulatory mandates. Future priorities will be driven by surveillance, customer/stakeholder input, and risk analyses and should include overhead power line, electrical maintenance, and lightning hazards. The technical feasibility of an improved power line proximity warning system that does not depend on electric field detection should be studied. There will be a continuing need to provide effective training for both experienced and younger, inexperienced maintenance personnel to increase awareness of electrical shock and burn hazards and the need for, and type of, protections available. The procedures for electrical maintenance can be systematized by developing job hazard methodologies for critical tasks. Finally, further investigation is needed in the future to achieve a better understanding of lightning and develop practical guidelines and recommendations that can help mine operators reduce the chance of ignitions and protect workers from the resulting hazards.

REFERENCES

American Standard M2.1. 1952. *American Standard Safety Code for Installing and Using Electrical Equipment in and about Coal Mines*. Bureau of Mines Bulletin 514. Washington, DC: U.S. Government Printing Office.

Bennett, J.L., G.R. Sima, and R.L. King. 1978. Electric Shock Prevention. Proceedings of the Fourth WVU Conference on Coal Mine Electrotechnology, Morgantown, WV, Aug 2–4, 1978.

Berry, D.R. and B. Gillenwater. 1986. Development of a High-Voltage Permissible Load Center (contract H0308093, Foster Miller, Inc.) BuMines OFR 58-86, 136 pp.: NTIS PB 86-215803.

Brunot, H.B and H.B. Freeman. 1923. *Permissible Electric Drills*. Bureau of Mines Reports of Investigations 2434. Washington, DC: Government Printing Office.

Bureau of Mines. 1981. *Technical Highlights: Health and Safety Research, 1970–1980*. Supt. of Docs. No. I 28.151.

Cawley, J.C. 1988. *The Probability of Spark Ignition in Intrinsically Safe Circuits*. Proceedings of the Ninth WVU Mining Electrotechnology Conference. Morgantown, WV, July 26–29. p. 128.

Cawley, J.C. 2003. *Electrical Accidents in the Mining Industry, 1990–99*. IEEE Trans Ind Appl Nov/Dec 39(6): 1,570–1,577.

Cawley, J.C. and G.T. Homce. 2003. Occupational Electrical Injuries in the U.S., 1992–1998, and Recommendations for Safety Research. *Journal of Safety Research*, Vol. 34 pages 241–248.

Cawley, J.C. and G.T. Homce. 2008. Trends in Electrical Injury, 1992–2002. *IEEE Transactions on Industry Applications*, Vol. 44, No. 4.

Clark, H.H. 1911. *The Electrical Section of the Bureau of Mines, Its Purpose and Equipment*. Bureau of Mines Technical Paper 4. Washington, DC: Government Printing Office.

Clark, H.H. 1912. *Ignition of Gas by Miniature Electric Lamps with Tungsten Filaments*. Bureau of Mines Technical Paper 23. Washington, DC: Government Printing Office.

Clark, H.H. 1914. *Permissible Electric Lamps for Miners*. Bureau of Mines Technical Paper 75. Washington, DC: Government Printing Office.

Clark, H.H. 1915. *Permissible Explosion-Proof Electric Motors for Mines; Conditions and Requirements for Test and Approval*. Bureau of Mines Technical Paper 101. Washington, DC: Government Printing Office.

Clark, H.H., and L.C. Ilsley. 1913. *Ignition of Mine Gases by the Filaments of Incandescent Lamps*. Bureau of Mines Bulletin 52. Washington, DC: Government Printing Office.

Clark, H.H., and C.M. Means. 1916. *Suggested Safety Rules for Installing and Using Electrical Equipment in Bituminous Coal Mines*. Bureau of Mines Technical Paper 138. Washington, DC: Government Printing Office.

Cox, P.A. and W.R. Schick. 1985. *A Design Guide for Explosion-Proof Electrical Enclosures. Part 3-Final Technical Report*. (Contract H0387009, SW res. Inst.). BuMines OFR 47C-86, 353 pp.: NTIS PB 86-209525.

Douglas, S.J. 1960. *Testing and Splicing Electric Cables and Frame-Grounding Pit Equipment*. Bureau of Mines Information Circular 7995. Washington, DC: Government Printing Office.

Dubaniewicz, T.H. 2007. The Brookwood Disaster and Electrical Requirements for Hazardous (Classified) Locations. Proceedings of the IEEE Industry Applications Society Annual Meeting, N. Orleans, LA: 1,353–1,359.

Federal Register. 2002. *Electric Motor-Driven Mine Equipment and Accessories and High-Voltage Longwall Equipment Standards for Underground Coal Mines*. Vol. 67, No. 47, pp. 10,972–11,005.

Gleim, E.J. 1929. *Abnormal Pressures in Explosion-Proof Compartments of Electrical Mining Machines*. Reports of Investigations 2974. Washington, DC: Government Printing Office.

Gleim, E.J. 1932. *Guarding Trolley Wires in Mines*. Bureau of Mines Information Circular 6577. Washington, DC: Government Printing Office.

Gleim, E.J. 1932. *Notes Pertaining to Safety Inspections of Permissible Electric Mine Equipment*. Bureau of Mines Information Circular 6584. Washington, DC: Government Printing Office.

Gleim, E.J. 1936. *Electrical Viewpoint in a Complete Safety Survey of a Coal Mine*. Bureau of Mines Information Circular 6894. Washington, DC: Government Printing Office.

Gleim, E.J. 1954. *United States Bureau of Mines Standard for Inspection and Test of Explosion-Proof Enclosures for Mining Equipment*. Bureau of Mines Report of Investigations 5057. Washington, DC: U.S. Government Printing Office.

Gleim, E.J. and H.B Freeman. 1932. *Maintenance of Electrical Mine Equipment from the Viewpoint of the Safety Inspector*. Bureau of Mines Technical Paper 537. Washington, DC: Government Printing Office.

Gleim, E.J., R.S. James, and H.B. Brunot. 1955. *Explosion-Proof Design and Wiring for Permissible Mining Equipment*. Bureau of Mines Bulletin 541. Washington, DC: U.S. Government Printing Office.

Griffith, F.E. and E.J. Gleim. 1943. *Grounding Electrical Equipment in and about Coal Mines*. Bureau of Mines Report of Investigation 3734. Washington, DC: Government Printing Office.

Griffith, F.E. and E.J. Gleim. 1944. *Ground-Resistance Measurements of Drill-Hole Casings*. Bureau of Mines Report of Investigations 3756. Washington, DC: Government Printing Office.

Griffith, F.E., E.J. Gleim, R.T. Artz, and D. Harrington. 1944. *Prevention of Fires Caused by Electric Arcs and Sparks from Trolley Wires*. Bureau of Mines Information Circular 7302. Washington, DC: Government Printing Office.

Hamilton, H.B. and E. Strangas. 1978. *Implementation of a High-Speed, Heavy Current, DC Switching System*. BuMines OFR 56-78. 77 pp. NTIS: PB 283 388/AS.

Harrington, D., C.W. Owings, and E.R. Maize. 1936. *Some Suggestions on the Prevention of Electrical Accidents in Coal Mines*. Bureau of Mines Information Circular 6919. Washington, DC: Government Printing Office.

Harrison, L.H. 1951. *The Short-Circuiting Contactor as an Electrical Protective Device for Coal Mine Service*. Bureau of Mines Report of Investigation 4759. Washington, DC: Government Printing Office.

Hipp, J.E., F.D. Henson, P.E. Martin, and G.N. Phillips, G.N. 1982. *Evaluation of Proximity Warning Devices*. Bureau of Mines Final Report, Contract JO188082. Washington, DC: Superintendent of Documents.

Homce, G.T. 1989. *Predicting the Failure of Electric Motors*. Bureau of Mines Information Circular 9211. Washington, DC: U.S. Government Printing Office.

Homce, G.T. and J.C. Cawley. 2007. *Understanding and Quantifying Arc Flash Hazards in the Mining Industry*. Proceedings for the 2007 Institute of Electrical and Electronic Engineers Industry Applications Society conference, New Orleans, LA.

Homce, G.T. and J.R. Thalimer. 1996. Reducing Unscheduled Plant Maintenance Delays—Field Test of a New Method to Predict Electric Motor Failure. *IEEE Transactions on Industry Applications*, Vol. 32, No. 3, pp. 689–694.

Homce, G.T., J.C. Cawley, and M.R. Yenchek. 2008. *A Performance Evaluation of Overhead Power Line Proximity Warning Devices*. NIOSH Information Circular 9510. Pittsburgh, PA: DHHS (NIOSH) Publication No. 2009-110.

Ilsley, L.C. 1922. *Ten Reasons Why Permissible Equipments Approved under Schedules 2B and 15 are Safer than Unapproved Types*. Bureau of Mines Reports of Investigations 2398. Washington, DC: Government Printing Office.

Ilsley, L.C. 1923. *Electrical Safety Inspection: Suggestions for Mine-Safety Engineers*. Bureau of Mines Reports of Investigations 2541. Washington, DC: Government Printing Office.

Ilsley, L.C. 1924. *Hazards of Electric Sparks and Arcs in Coal Mines*. Bureau of Mines Reports of Investigations 2626. Washington, DC: Government Printing Office.

Ilsley, L.C. 1929. *Hazards from Low or Under Voltage*. Bureau of Mines Information Circular 6201. Washington, DC: Government Printing Office.

Ilsley, L.C. 1930. *Performance Tests for Trailing Cables*. Bureau of Mines Information Circular 6263. Washington, DC: Government Printing Office.

Ilsley, L.C. 1930. *The Grounding of Electric Systems in and around Mines*. Bureau of Mines Information Circular 6318. Washington, DC: Government Printing Office.

Ilsley, L.C. 1932. *250 versus 500 Volts or More for Circuits in Gassy Mines*. Bureau of Mines Information Circular 6556. Washington, DC: Government Printing Office.

Ilsley, L.C. and H.B. Brunot. 1922. *Endurance Tests of Storage Batteries for Use in Permissible Mine Locomotives*. Bureau of Mines Reports of Investigations 2358. Washington, DC: Government Printing Office.

Ilsley, L.C. and H.B. Brunot. 1931. *Suggestions for Wiring Permissible Equipment*. Bureau of Mines Information Circular 6463. Washington, DC: Government Printing Office.

Ilsley, L.C. and E.J. Gleim. 1920. *Approved Explosion-Proof Coal-Cutting Equipment*. Bureau of Mines Bulletin 78. Washington DC: Government Printing Office.

Ilsley L.C. and E.J. Gleim. 1926. *Suggestions for the Design of Electrical Accessories for Permissible Mining Equipment*. Bureau of Mines Bulletin 258. Washington, DC: Government Printing Office.

Ilsley, L.C. and E.J. Gleim. 1932. *Data in Reference to Installation of Cables in Shafts and Boreholes*. Bureau of Mines Information Circular 6595. Washington, DC: Government Printing Office.

Ilsley, L.C., E.J. Gleim, and H.B. Brunot. 1941. *Inspection and Testing of Mine-Type Electrical Equipment for Permissibility*. Bureau of Mines Information Circular 7185. Washington, DC: Government Printing Office.

Ilsley, L.C. and A.B. Hooker. 1929. *A Preliminary Investigation of Rubber Sheathed Concentric-Type Trailing Cables for Mining Machines*. Bureau of Mines Reports of Investigations 2909. Washington, DC: Government Printing Office.

Ilsley, L.C. and A.B. Hooker. 1931. *The Overheating of Rubber-Sheathed Trailing Cables*. Bureau of Mines Report of Investigations 3104. Washington, DC: Government Printing Office.

Ilsley, L.C., A.B. Hooker and E.J. Coggeshall. 1932. *Rubber-Sheathed Trailing Cables*. Bureau of Mines Bulletin 358. Washington, DC: Government Printing Office.

James, R.S. 1950. *Effect of Temperature on Flame-Arresting Properties of Flat Joints in Explosion-Proof Mine Equipment*. Bureau of Mines Report of Investigations 4639. Washington, DC: Government Printing Office.

King, R.L., H.W. Hill, Jr., R.R. Bafana, and W.L. Cooley. 1979. *Guide for the Construction of Driven-Rod Ground Beds*. Bureau of Mines Information Circular 8767, 26 pp.

Kohler, J.L. and F.C. Trutt. 1987. *Prediction of Incipient Electrical-Component Failures*. Bureau of Mines Final Report, Contract JO338028. Washington, DC: Superintendent of Documents.

Kovalchik, P.G, L.W. Scott, T.H. Dubaniewicz, and F.T. Duda. 1999. Dynamic Temperature Measurement of Overheated Shuttle Car Trailing Cables in Underground Coal Mines. *Trans. Soc. Min. Metal Explor*. 306: 1–4.

Kowalski-Trakofler, K., E. Barrett, C. Urban, and G.T., Homce. 2007. *Arc Flash Awareness*. DVD training package. DHHS (NIOSH) Publication No. 2007-116D

Leitch, R.D., A.B. Hooker, and W.P. Yent. *The Ignition of Firedamp by Exposed Filaments of Electric Mine Cap-Lamp Bulbs*. Bureau of Mines Reports of Investigations 2674. Washington, DC: Government Printing Office.

Lipman, K. and P.G. Guest. 1959. *Measurement of Electrical Waveforms of Low-Energy Spark Discharges*. Bureau of Mines Report of Investigations 5460. Washington, DC: U.S. Government Printing Office.

McCall, M.C. and L.H. Harrison. 1952. *Some Characteristics of the Earth as a Conductor of Electric Current*. Bureau of Mines Report of Investigations 4903. Washington, DC: U.S. Government Printing Office.

Morley, L.A. 1990. *Mine Power Systems*. Bureau of Mines Information Circular 9258. Washington, DC: U.S. Government Printing Office.

Morley, L.A., F.C. Trutt, G.T. Homce. 1982. *Electrical Shock Prevention, Volume IV—Overhead-Line Contact Fatalities*. Bureau of Mines Final Report, Contract JO113009. Washington, DC: Superintendent of Documents.

Peterson, J.S. 1992. Influence of Electrode Material on Spark Ignition Probability. Bureau of Mines Report of Investigation 9416. Washington, DC: U.S. Government Printing Office.

Peterson, J.S. and G.P. Cole. 1997. *Detection on Downed Trolley Lines Using Arc Signature Analysis*. NIOSH Report of Investigations 9639. Pittsburgh, PA: DHHS (NIOSH) Publication No. 97-123.

Powell, F.W. 1922. *The Bureau of Mines, Its History, Activities, and Organization*. The Institute for Government Research Monograph No. 3. New York and London: D. Appleton and Co.

Sacks, H.K., J.C. Cawley, G.T. Homce, and M.R. Yenchek. 1999. Alarm System for Detecting Hazards Due to Power Line Transmission Lines. U.S. Patent No. 6,600,426.

Sacks, H.K., J.C. Cawley, G.T. Homce, and M.R. Yenchek. 2001. Feasibility Study to Reduce Injuries and Fatalities Caused by Contact of Cranes, Drill Rigs, and Haul Trucks with High Tension Lines. *IEEE Trans Ind Appl*, 37(3): 914–919.

Scott, L.W. and A.J. Hudson. 1992. Performance of RETIMET Metal Foam Vents on Explosion-Proof Enclosures. Bureau of Mines Report of Investigations 9410. Washington, DC: Superintendent of Documents.

Sottile, J., S.J. Gnapragasam, T. Novak, and J.L. Kohler. 2006. Detrimental Effects of Capacitance on High-Resistance-Grounded Mine Distribution Systems. IEEE Trans Ind Appl Sep-Oct; 42(5): 1,333–1,339.

Staff, Bureau of Mines. 1982. Underground Coal Mine Power Systems, Proceedings: Bureau of Mines Technology Transfer Seminar, Pittsburgh, Pa. Bureau of Mines Information Circular 8893. Sup. of Docs, 88 pp.

Staff, Bureau of Mines. 1984. *Splicing Mine Cables*. Bureau of Mines Handbook 1-84, 92 pp.

Staff, Bureau of Mines. 1985. *Earth Grounding Beds-Design and Evaluation. Proceedings: Bureau of Mines Technology Transfers, Pittsburgh, PA and Reno, NV*. Bureau of Mines Information Circular 9049, 24 pp.

Staff, Health and Safety. 1960. *Recommended Standards for Alternating Current in Coal Mines*. Bureau of Mines Information Circular 7962. Washington, DC: U.S. Government Printing Office.

Staff, Mining Research. 1979. *Mine Power Systems Research (In Four Parts). 2. Grounding Research.* Bureau of Mines Information Circular 8800, 78 pp.

Staff, Mining Research. 1979. *Mine Power Systems Research (In Four Parts). 3. Circuit Protection.* Bureau of Mines Information Circular 8801, 148 pp.

Tenney, B.S., W.L. Cooley, and Z. Elrazaz. 1982. *Coal Mine Electrical Accident Reduction*. Proceedings of the WVU Conf. on Coal Mine Electrotechnology, Morgantown, WV; July 28–30, 1982, p. 137.

Trutt, F.C., J.L. Kohler, H. Rotithor, L.A. Morley, and T. Novak. 1988. *Sensitive Ground Fault Protection for Mines. Phase III: Coordination-Free GFR's for AC Distribution* (contract J0134025, PA State Univ.). 95 pp.

Williams, F.A. and W.R. Devett. 1962. *Prevailing Practices in Splicing Electric Trailing Cables in Coal Mines.* Bureau of Mines Information Circular 8090. Washington, DC: Government Printing Office.

Yenchek, M.R., J.C. Cawley, A.L. Brautigam, and J.S. Peterson. 2002. Distinguishing Motor Starts from Short Circuits through Phase Angle Measurements. *IEEE IAS Transactions*, Vol. 38, No. 1.

Yenchek, M.R. and G.P. Cole. 1997. Thermal modeling of portable power cables. *IEEE Transactions on Industry Applications* 33(1):72–79.

Yenchek, M.R. and A.J. Hudson. 2000. A Passive Means to Detect Hot Trolley Insulators. *Min Eng* 2000 Jan; 52(1): 43–47.

Yenchek, M.R. and A.J. Hudson. 1990. *The Bureau of Mines Ground-Fault Protection Research Program-A Summary.* Bureau of Mines Information Circular 9260, 23 pp.

Yenchek, M.R. and P.G. Kovalchik. 1989. Thermal characteristics of energized coal mine trailing cables. *IEEE Transactions on Industry Applications* 25(5):824–829.

Yenchek, M.R. and P.G. Kovalchik. 1989. Mechanical performance of thermally-aged trailing cable insulation. *IEEE Transactions on Industry Applications* 25(6):1,000–1,005.

Yenchek, M.R. and P.G. Kovalchik. 1991. Thermal characteristics of energized shielded and an unshielded reeled trailing cable. *IEEE Transactions on Industry Applications*. 27(4):791–796.

Yenchek, M.R. and P.G. Kovalchik. 1993. The impact of current load on mine trailing cable thermal life. *IEEE Transactions on Industry Applications* 29(4):762–767.

Yenchek, M.R., K.C. Schuster, and A.J. Hudson. 1995. *Operational characteristics of trailing cable splices*. Bureau of Mines, Report of Investigations 9540. Pittsburgh, PA: U.S. Department of the Interior

Zellers, D.H. and A.B. Hooker. 1935. *Maintaining the Permissibility of Electric Cap Lamps.* Bureau of Mines Information Circular 6832. Washington, DC: Government Printing Office.