Mine Illumination: A Historical and Technological Perspective

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ABSTRACT: Illumination plays a critical role in mining because miners depend on proper illumination to safely perform their work and to see various mine and machinery-related hazards. Open-flame lamps were used in the early days of mining, but these often caused disastrous mine explosions. During 1914, two engineers from the U.S. Bureau of Mines (USBM) formed a new company, Mine Safety Appliances, and initiated work with Thomas Edison for an electric cap lamp. This electric cap lamp was approved in 1915 by the USBM. The seminal works in mine illumination research were dominated by the USBM. They addressed many issues in permissibility, human factors, and researched new lighting technologies. The current mine regulations and test procedures for mine illumination are based on USBM research. Today, illumination technology is drastically changing with light emitting diodes (LEDs) that could revolutionize mine illumination just as was done by the 1915 electric cap lamp. Researchers at the National Institute for Occupational Safety and Health (NIOSH) are leading the way in the human factors and technological aspects of LED research for mine illumination to improve the safety of miners.

INTRODUCTION

Adequate illumination is crucial in underground coal and metal/nonmetal mine safety because miners depend most heavily on visual cues to detect hazards associated with falls of ground, slips/trips/falls (STFs), moving machinery, and other threats. For as long as underground mining has been performed, illumination has been critical to both safety and to the ability of the miners to perform their work. Open flames were used from the earliest days of mining. The Greeks and Romans used oil lamps, and candles were introduced in about the 1st century AD. In about the 16th century, oil wick lamps became common and were used in some mines even until the 1920's (Trotter 1982). Carbide lamps were developed in the 19th century and were used well into the 20th century. The first attempts to make a safety lamp that would not cause explosions in gassy mines began around the turn of the 19th century. Safety lamps provided a significant improvement over open-flame lighting and were the safest method of lighting gassy mines until electric lighting became feasible in the first half of the 20th century. At the turn of the 20th century, the most commonly used lighting technologies were safety lamps for gassy mines and carbide lamps for non-gassy mines (Trotter 1982).

In 1879, Edison developed the first practical incandescent lamp, with an efficiency of about 1.4 lumens per watt (lm/W). During the early 1900's, the new technology of electric lighting began making its way into underground mines in the United States. Safety was the primary driver of this new technology given the pervasive occurrences of explosions caused by mine gas ignition. These explosions resulted in many mine disasters that claimed the lives of thousands of miners. On May 16, 1910, Congress passed public Law 61-179 that established the USBM. Shortly after, the USBM began research to evaluate the safety of the new technology of electric lighting. In this paper, the seminal works of USBM illumination research are described in conjunction with the development, evolution and spread of electric lighting as well as the technological changes that have taken place since 1910.

ELECTRIC LIGHTING

By the end of the 19th century, electric lighting was widely used in homes and for industrial lighting. Use in mining, however, was delayed several decades. Permanent lighting installations were impractical due to the high cost of wiring the miles of workings and due to the logistics of advancing the lights with the face, and small, efficient batteries did not exist to allow for portable lamps. Additionally, concerns existed about the lamps causing explosions, and efforts to make them explosion proof resulted in heavy cumbersome lamps (Trotter 1982).

There was, however, a pressing demand for safer face lighting as explosions caused by mine gas ignition continued to claim the lives of miners. In 1914, two engineers from the USBM, John Ryan and George Deike, formed the Mine Safety Appliances Company and began work with Thomas Edison to develop personal electric lamps. By this time, more efficient tungsten filaments had replaced the older carbon filaments, drastically improving light output from the bulbs, and Edison was able to design a small-scale, rechargeable battery that could be carried on a miner's belt (Trotter 1982). The Edison electric cap lamp (Fig 1.) was approved by the USBM in 1915 (Clark and Ilsley 1917). Electric lamps gained acceptance and eventually replaced the older technologies.

Figure 1. The Edison Electric Cap Lamp (circa 1915) from the NIOSH collection of mine illumination. Image courtesy of New South Associates.

Permissibility and Ignition of Mine Gases

By the turn of the twentieth century, the safety lamp had drastically improved mine safety. The mining community was hesitant to replace the trusted technology of safety lamps with the new technology of electric lamps until they had been extensively tested and shown to be safe even in gassy environments.

In 1912, a series of tests were conducted by the USBM investigating whether an incandescent lamp bulb with either a carbon or a tungsten filament could ignite mine gases when the glowing filament was exposed (Clark and Ilsley 1913). In these tests miniature and standard bulbs from 8 manufacturers were subjected to four types of tests in which the bulb was smashed, the tip of the bulb was cut off, a hole was punctured in the neck of the bulb and a pre-exposed filament was suddenly subjected to a voltage in a natural gas and air mixture. Ignition was found to occur at mixtures containing as little as 5% natural gas. The probability of ignition for each type of bulb and for each type of test was rated on a scale from "unlikely" to "certain." Based on these results, safety features were built into the cap lamps approved by the USBM. For example, Figure 2 shows a typical method by which breaking the bulb could be made to cause the electrical connection to also be broken using spring-loaded contacts.

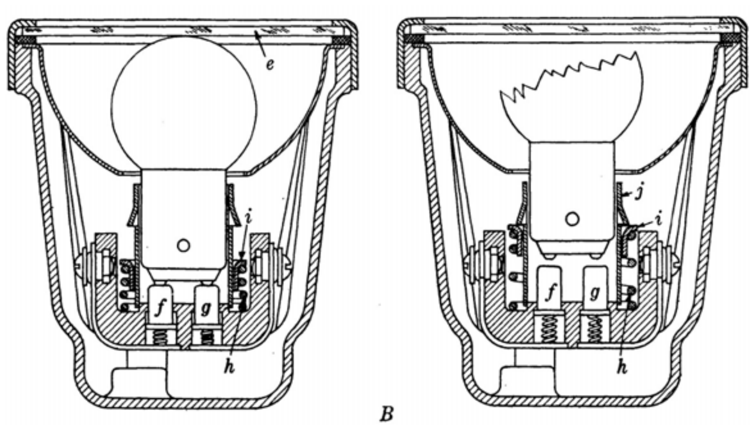

Figure 2. A typical cap lamp head piece design that prevents a burning filament being exposed through the use of spring-loaded contacts (Ilsley and Hooker 1930).

Development and Approval of Early Technologies

The next step in USBM research was to establish the test conditions and requirements for the prevention of gas ignition by electric lamps and for determining suitable attributes of electric lamps for mines. The attributes included period of operation, liability to spill electrolyte, liability to ignite gas, weight, light producing capacity, durability and reliability. The permissibility and suitability requirements were critical for electric lamp approvals conducted by the USBM. The testing process for electric lamp approvals along with results of the tests were published by Clark and Ilsley (Clark 1914; Clark and Ilsley 1917). Figure 3 shows the test equipment developed by the USBM. The first requirements were set forth in Schedule 5, issued in 1913, which focused solely on permissibility. USBM experience necessitated a broader basis of approval so the USBM evaluated several other aspects of electric cap lamps and worked closely with manufacturers during the design and development of early cap lamps. Hence, Schedule 6 was issued in 1914 and the Caeg, Hirsch, and Wico lamp were approved (Clark 1914). Schedule 6 was later revised as Schedule 6A in 1915. Schedule 6A included more requirements for the safety and the practicability of the lamp. The original approvals under Schedule 5 were withdrawn and the lamps were retested in accordance with Schedule 6A [7]. The Edison cap lamp was the first approval under Schedule 6A and by 1917, seven models of lamps had been approved (Clark and Ilsley 1917). By August, 1916, about 70,000 USBM-approved lamps were in use and about 2,000 lamps a week were being installed (Clark and Ilsley 1917). While these cap lamps found great acceptance in the mining industry, their performance (Table 1) pales in comparison to today's modern LED cap lamps that can achieve at least 35 lumens after 10 hours of operation.

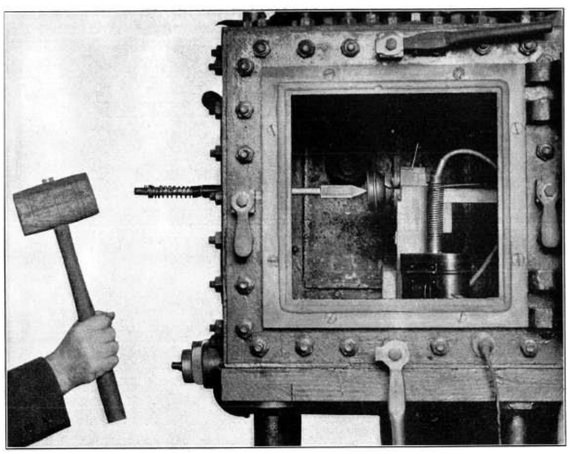

Figure 3. USBM-developed apparatus (circa 1917) for exposed lamp filament ignition testing (Clark and Ilsley 1917).

Table 1. Photometric data for early electric cap lamps (circa 1915-17). ***Source: Clark and Ilsley*** **[2].**

	Average candlepower after burning 1 hour	Average candlepower after burning 12 hours	Total lumens after burning 1 hour	Total lumens after burning 12 hours
Edison cap lamp	1.19	0.83	4.32	3.01
Concordia hand lamp	0.74	0.57	6.92	5.36
GE cap lamp	1.00	0.68	3.63	2.47
WICO cap lamp	0.93	0.69	3.37	2.50
Concordia cap lamp	1.05	0.72	3.80	2.60
Pioneer cap lamp	1.13	0.78	4.10	2.83

The USBM also tested and issued approvals for animal lamps, flood lights, and flashlights (Ilsley, Hooker and Roadstrum 1942). An approval plate was attached to each lamp and a list of approved lamps was periodically published (Howell, Fieldner and Ilsley 1922). The USBM conducted extensive work investigating and reporting on the use of electric lamps at operating mines throughout the country. For example, a survey of the number, location, and type of electric cap and animal lamp installations in the Alabama mining district was conducted in 1935 (Cash

1935). The early work of the USBM provided the industry with confidence in the safety and performance of electric lighting technology thus enabling its acceptance in the mining industry.

Initial Development of Safety Rules and Regulations

In addition to evaluating the new technologies, during the 1910's and afterward, the USBM was charged with developing the safety rules and guidelines that would govern the use of these technologies underground. Safety rules initially developed by USBM covered several aspects of operating electric lamps, but were focused perhaps most heavily on aspects related to permissibility and the prevention of gas and coal dust explosions.

A set of safety rules was published in 1916 for the construction, installation, maintenance and use of several types of electrical equipment including cap lamps underground (Clark and Means 1916), and revised rules were issued in 1926 (USBM 1926) and several times thereafter. The rules for portable lamps were concerned with the enclosure of the bulbs, type and condition of connections, grounding, and type and condition of cords.

In addition to developing the federal standards, the USBM attempted to make state laws known by the industry, and, for example, conducted a review of state mining laws on the use of electricity underground, including the use of stationary, semi-portable and portable electric lamps, in 1920 (Ilsley 1920). In 1935, USBM guidelines were established for the maintenance and inspection of electric cap lamps. An analysis of factors that decrease the efficiency of electric cap lamps was published by the USBM (Hooker and Zellers 1935). Factors decreasing the efficiency of the lamps were attributed to poor lamp house supervision and poor lamp care. The USBM placed responsibility for maintaining proper lamp performance on the mine operators, and provided them with recommendations for inspection and maintenance of batteries, cords, bulbs, lenses and reflectors. The USBM also recommended a procedure for testing lamp performance by using a photometric sphere that the USBM recommended be purchased and used by mine operators. In 1935, guidelines were published on how to maintain permissibility of cap lamps (Zellers and Hooker 1935) which focused on similar types of maintenance and inspection issues.

Through this early work of the USBM in the development and approval of new lamps and in the development of safety rules and guidelines, the industry was provided with a good starting point for the improvement and evolution of underground lighting throughout the 20^{th} and into the 21^{st} century.

FURTHER ADVANCEMENT

Significant advancement was made in the area of mine illumination during the 20^{th} century by both improving existing technologies and developing new technologies. Now in the 21^{st} century, improvements are continuing to be made. In this section, some of the advances in mine illumination since the work of the early 20^{th} century will be discussed.

Advancement of Cap Lamps

The cap lamp steadily became a reliable and trusted piece of equipment used by practically every underground miner. Few major changes in the technology occurred for several years. The major advances for the industry came in the form of new bulb and battery technologies being developed. In the early 1980's, a prototype nickel-cadmium (Ni-Cd) cap lamp battery was developed by the USBM and the Energy Research Corporation. This battery provided about a 48% weight reduction, 15% volume reduction and a useful battery life of 3 to 4 years. A new reflector was designed to accept the new tungsten-halogen type bulbs in the conventional dual-filament incandescent bulbs. The tungsten-halogen lamps were evaluated to replace the conventional incandescent lamps. The tungsten-halogen lamp was shown to be capable of producing the same light output as the conventional lamp while consuming less power. Other improvements to the cap lamp design at this time included elevation adjustment of the lamp, break-away cords, and segmented cords with coiled ends to allow the cord to better conform to the miner's body (Lewis 1982).

In the 1970's fluorescent cap lamps were developed and tested. The USBM generated performance specifications that included light output, battery capacity, charging time, system weight, and compatibility with existing hardware. A fluorescent cap lamp that met the USBM requirements (Figure 4) was developed by Ocean Energy, Inc. (Ocean Energy Inc. 1975). It was shown to provide superior light output with less degradation over a 10-hour shift as compared to an incandescent lamp. Additionally, bulb life was significantly longer. The fluorescent cap lamp never found widespread use in mining, most likely because of the size, weight, and higher initial costs. However, machine-mounted fluorescent lamps became widespread and are still in use today.

Figure 4. The development of a fluorescent cap lamp enabled the evaluation of this new technology. Source: NIOSH mining photo archive.

Machine-Mounted and Area Lighting

In the second half of the 20th century, as mining became increasingly mechanized, a clear advantage was recognized in installing lighting systems on mobile equipment such as continuous miners, bolters and LHDs. During the 1970's and 1980's, the USBM conducted or supported several projects investigating the installation of different lighting technologies on mining machines. In a series of projects conducted or funded by the USBM, lighting hardware was installed and evaluated on conventional, continuous and longwall machinery and for area lighting both in the laboratory and at several low, mid, and high coal and metal/non-metal mining operations throughout the country (Bockosh 1977; Lewis 1982). The USBM evaluated lighting systems for continuous miners and roof bolters (Chironis 1974), longwall faces (Bockosh 1976), conventional mining equipment, and for low coal (Bockosh and Murphy 1976). These evaluations included several types of new lighting technologies such as mercury-vapor and fluorescent systems. In all of these trials, the placement of the lights, the distribution of light, the durability and reliability of the systems, safety concerns, and several other issues were addressed. The USBM also did work with equipment manufacturers investigating the factory integration of lighting systems into equipment as opposed to after-market addition of these lights (Corbitt 1977) and the design and development of permissible DC power supply systems for face lighting systems (Conroy 1976).

Additionally, mining companies, equipment manufacturers and lighting companies independently experimented with the installation of machine mounted lighting systems (Kreutzberger 1977; Patts 1977; Slone 1977). The performance of these systems was scrutinized by the mining companies in terms of durability, light output, ease of installation and maintenance and acceptance by the workers.

Advances using Computers

Evaluation of new illumination systems was a time-consuming and expensive proposition because it often required construction of full-scale machine mockups (Figure 5) in a simulated mine entry. Thus in 1977, the USBM initiated a cooperative project with the Mathematical Applications Group, Inc. to develop numerical models to simulate machine geometry and luminaire characteristics so that computer-based evaluations could be conducted (Novak and Goldstein 1978). This approach required the use of a goniometer to make experimental measurements of representative samples of luminaires. The numeric model ran on a mainframe computer. Users connected to the mainframe via terminals. While the new approach was validated via comparisons of measurements taken at the Pittsburgh Research Lab using machine mockup installations to the new values obtained by simulation, the mainframe-based numerical model did not find widespread use. By the 1990's, the PC-based software Crewstation Analysis Program (CAP) for the design and evaluation of machine lighting systems for underground coal equipment had been developed by the USBM (Gallagher, Mayton, Unger, Hamrick and Sonier 1996). The CAP software added much more functionality, and was much more user-friendly than the earlier mainframe-based software developed in the late 1970s. Figure 6 depicts what a user of the CAP software would see on their PC. The CAP software drastically changed the way in which underground lighting systems are designed and evaluated, thanks to USBM research on computerized evaluation of mine illumination systems. CAP is still in use today by mine lighting manufacturers and by MSHA. The software is specified in MSHA criteria to acquire lighting survey data for MSHA's Statement of Test and Evaluation applications.

Figure 5. Wooden mockups of mining machine were constructed and used to evaluate machine-mounted lighting. The USBM-developed CAPS software eliminated this costly and time-consuming approach. Source: NIOSH mining photo archive.

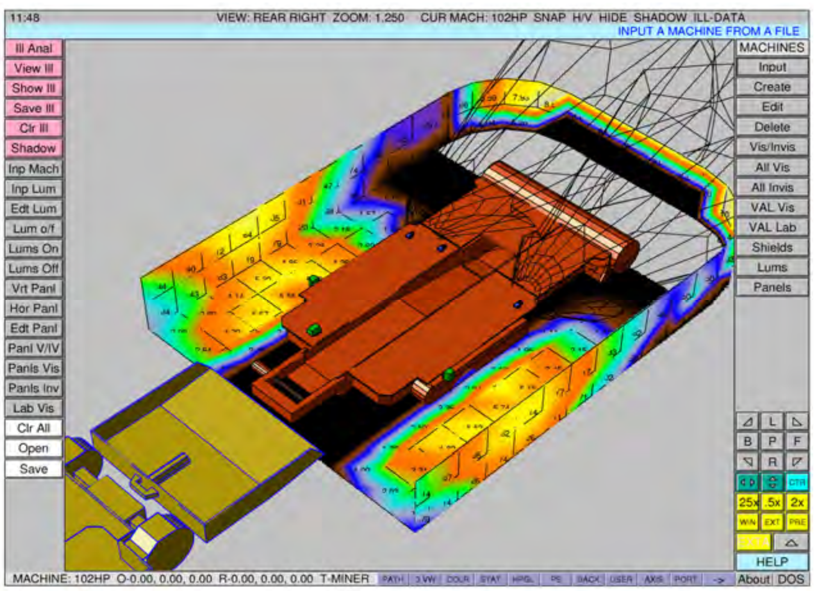

Figure 6. The CAPS software, still in use today, enables a more effective method of evaluating lighting. Source: NIOSH mining photo archive.

Changes in Safety Rules, Regulations and Guidelines

Safety rules, regulations and guidelines were re-evaluated and changed several times throughout the 20th century. These changes were guided by research efforts investigating the minimum light levels needed by workers, the problems of glare, background illumination and other issues. Some of the guiding research was completed by BCR (du Breuil 1977) and Perceptronics (Crooks and Peay 1982) on USBM contracts.

In 1973, the Mining Enforcement and Safety Administration (MESA) was formed as a new agency in the Department of the Interior. MESA assumed the functions of safety and health enforcement that had previously been carried out by the USBM. In 1977, this agency was moved to the Department of Labor and was renamed the Mine Safety and Health Administration (MSHA). Both MESA and MSHA were responsible for officially setting illumination standards, inspecting lighting installations, issuing equipment approvals and determining violation of illumination standards. The efforts of MSHA during the 1970's to provide guidelines for the design of lighting systems on mobile underground equipment are described in (Wright 1982).

The USBM published an Underground Coal Mine Lighting Handbook in 1982 (Lewis 1986; Lewis 1986). This handbook was prepared to act as a complete reference for underground coal mine operators and equipment designers. The handbook includes sections on the history of underground lighting, technical considerations, light physics, light and vision relationships and the issues of glare.

IMPACTS OF LEGISLATION

Two major pieces of legislation were passed during the second half of the 20th century, which impacted mine illumination. These are the Federal Coal Mine Health and Safety Act of 1969 and the Federal Mine Safety and Health Act of 1977.

Federal Coal Mine Health and Safety Act of 1969

Regulations for coal mine illumination were established of the *Coal Mine Health and Safety Act of 1969*, Public Law 91-173, also referred to as the *Coal Act*. Section 317 (e) stated that "Within nine months after the operative date of this title, the Secretary (of the Interior) shall propose the standards under which all working places in a mine shall be illuminated by permissible lighting, within eighteen months after the promulgation of such standards, while persons are working in such places. " Working places were defined as those areas inby the last open crosscut. The USBM was charged with establishing the standards for minimum illumination levels. A notice of proposed rulemaking was published in the Federal Register during December, 1970. This notice prescribed a required minimum illumination of the least 5 foot-candles and no more than 110 foot-candles in all working places. At this time, mine officials and mining equipment manufacturers stated that research and experimentation was needed to scientifically determine if this required minimum illumination was valid, and if the technology existed to achieve it. Numerous public hearings were held in which comments and objections were voiced. Given the concerns and objections of the mining industry, the regulations were temporarily suspended and the USBM and MESA were charged to determine if 5 foot candles was a valid, practical and attainable lighting level. The USBM started two research projects with the National Bureau of Standards (predecessor of the National Institute of Standards and Technology), and the Naval Ammunition Depot to determine minimum levels of illumination (Vines, Klouse, Bockosh, Slone, Evans and Beckett 1977).

In the report by the Naval Ammunition Depot in Crane, Indiana (Hitchcock 1973), 11 jobs (e.g. cutter operator, shuttle car operator, etc.) encompassing the work completed from the working face to the first transfer point were analyzed for both continuous and longwall mining methods. From analysis of these jobs, a total of 114 "visual tasks" were identified and analyzed. Some examples of the visual tasks analyzed include "read dial on methane meter" and "determine position of boom in relation to rib." Data for each task was taken including identification of the item viewed, description of the background, distance to the item viewed, and the time taken to study the item. In addition, the visual properties of several mines were studied to quantify visual parameters such as reflectivity of coal and roof slate, reflectivity of machinery, and light transmission through the mine atmosphere. Based on these measurements and observations, a simulated mine entry and mining equipment models were constructed with similar visual properties. The visual tasks were then evaluated using the Illuminating Engineering Society (IES) method for prescribing illumination using a contrast reducing visibility meter (Visual Task Evaluator). The threshold visibility luminance for each visual task was set to encompass a 99% probability of detecting the task and to encompass 95% of a 55-65 year-old population with 50% of the measurement variation included. The results of this study showed that there is little difference in the light requirements between jobs. Based on the results of this report, a minimum illumination level of 0.06 foot lamberts was recommended.

In October 1976, the regulations were promulgated which required 0.06 foot lamberts and also specified areas to be illuminated , and the industry was given till July, 1978 to come into compliance with these regulations .

Both prior to and following the announcement of these regulations, the USBM and MESA conducted a number of seminars to educate the industry about the standards and how they apply (Blakely 1976; Chironis 1976; Klouse 1976; Lester 1976; Lester 1976; Crawford 1978). About 44 one-day seminars were given to about 1000 people. The regulations prompted several mining companies to take action to insure their operations were in compliance. For example, Westmoreland Coal constructed an illumination laboratory for testing of equipment on site (Slone 1977).

Federal Mine Safety and Health Act of 1977

With respect to the illumination of underground work areas, the Federal Mine Safety and Health Act of 1977, public Law 95-164 was an extension of the 1969 Coal Act to metal and nonmetal mining. Overall, this act of 1977 established a single piece of comprehensive legislation for coal and metal nonmetal mining. The procedures for determining lighting system acceptance according to these regulations are presented in (Huffman 1982). Described are the methods for determining if systems meet the three requirements of being accepted as permissible, providing adequate illumination, and minimizing discomfort and disability glare.

Shortly after the 1977 act was introduced, the USBM began illumination research for metal/nonmetal mines. The focus of this work was on the establishment of minimal luminance requirements. The research was empirically based on human subject detection of hazards common to metal/nonmetal mines (Merritt 1983). Over 13,000 measurements of visual test performance were used for this research. As a result, various ranges of minimum luminance for safety were recommended for common visual tasks encountered in metal and nonmetal mining. The visual tasks included roof crack detection, rock motion detection, floor and rubble detection, peripheral motion detection, and protrusions detection. Recommended lighting practices were also established for cap lamps, machine mounted luminaires, and portable/fixed luminaires.

MINE ILLUMINATION RESEARCH TODAY

NIOSH carries on the tradition of leading mine illumination research to improve the safety of miners. Today, the new lighting technology is the light emitting diode (LED) and it is poised to revolutionize mine illumination. White LEDs are achieving about 110 lm/W in comparison to, in general, about 15 lm/W for an incandescent bulb. They are robust because they do not have a glass envelope or filament that can break, and they can provide useful light in excess of 50,000 hours of operation as compared to about 1000 to 3000 hours for an incandescent bulb.

NIOSH researchers are investigating the human factors issues and technological aspects of LEDs to improve the safety of miners. Human factor issues of age-related visual performance have been investigated for detection of mine hazards. The results of a comparative study using an incandescent cap lamp, a commercially-available LED cap lamp, and a NIOSH prototype LED cap lamp indicated significant improvements for older subjects when using the NIOSH prototype LED cap lamp. Moving hazard detection improved 15.0%, trip hazard detection improved 23.7%, and discomfort glare was reduced 45.0% (Sammarco, Reyes and Gallagher 2009). LED cap lamps have also been investigated to better understand the technology to ensure proper application for mining (Sammarco, Freyssinier, Zhang, Bullough and Reyes 2008). NIOSH research is expanding into machine-mounted LED lighting for metal and nonmetal mines and for coal mines.

SUMMARY

USBM mine illumination research addressed many issues including permissibility, human factors aspects of visual performance, electric lamp power sources, and new lighting technologies as summarized by Table 2. Over the years, the USBM research successfully addressed unresolved issues and enabled significant impacts in the mining industry. Based on the USBM research that established that a lamp’s glowing filament could cause an ignition, the design and construction of incandescent bulbs was modified and improved to minimize the danger of causing an explosion in the event a bulb was broken. The USBM paved the way for acceptance of electric lighting in the mining industry by establishing that electric lighting was safe and reliable. The USBM led research of new lighting technologies such as tungsten-halogen bulbs and fluorescent lighting, as well as lighting hardware for new lighting technologies for machine-mounted luminaires. Cap lamp improvements included Ni-Cd battery technology that reduced battery weight by 48%. Many of the technologies the USBM researched are still in use today as well the computer-based software CAP that is still the de-facto tool used to evaluate mine illumination. The federal regulations for mine illumination we use today are still based on the luminance requirements established by the USBM.

Table 2. Summary of the major milestones and research of the USBM with respect to illumination.

Year (s)	Event or Research Area
1910	U.S. Bureau of Mines
1912-1913	Research proves exposed bulb filaments can ignite mine gas
1913-1917	Electric lamp performance and safety research
1913-1973	USBM conducts approvals of electric lamps
1916-1926	Developed safety rules and guidance for electric lights
1935	Guidance for maintenance and inspection of electric cap lamps
1935	Guidance for maintaining permissibility
1969	Development of mine illumination requirements for coal mines
1976-78	Mine lighting conferences and seminars given to over 1000 people
1980	Prototype cap lamp with NiCd battery and tungsten-halogen bulbs
1982	Guidance developed: Underground coal mining lighting handbook
1983	Development of mine luminance requirements for metal/non metal mines
1995	USBM develops the CAP software for PC-based analysis of lighting
1995	End of USBM

DISCLAIMERS

Mention of any company or product does not constitute endorsement by NIOSH. The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

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