The potential impact of light emitting diode lighting on reducing mining injuries during operation and maintenance of lighting systems

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A B S T R A C T

Research by the US National Institute for Occupational Safety and Health (NIOSH) indicates that light emitting diodes (LEDs) can be used to enhance safety by improving a miner's ability to see mining hazards and reducing glare. This paper investigates if LEDs provide another benefit by reducing miner exposure to hazards during maintenance and operation of LED lighting. LEDs could provide useful lives up to 50 times longer than incandescent lighting commonly used in mining and could enable design changes to reduce certain hazards. The mining accident records compiled by the Mine Safety and Health Administration (MSHA) were examined to determine the extent and nature of accidents involving the maintenance and operation of mine luminaries. A total of 140 relevant accident records were found for the years 2002–2006. These incidents resulted in 3668 days lost from work with an additional 925 days of restricted activity. The injury narratives were studied to determine if the implementation of LED-based luminaries could reduce injury severity and frequency. The greatest near-term potential impacts appear to be related to reducing maintenance and cap lamp redesign. Longer term (5 years), low-power and lightweight auxiliary LED lighting for surface mines could also have potential impact for improving safety.

1. Introduction

Coal is a vital energy source, with coal-fired electrical generation plants providing about 45% of the electricity for the US. The importance of mining is even more evident when one considers that approximately 619,000 people (US Bureau of Labor and Statistics, 2008a) are employed in the mining industry, including those directly employed by mining companies and those in support-related jobs. The hazardous nature of mining is well-known throughout the world. There has been a declining trend of mining accidents during the last century; however, recent mining disasters such as at Sago Mine, West Virginia, quickly remind us of the many dangers encountered by miners.

Miners depend on established safe work practices, safety monitoring systems, safety devices and interlocks, and personal protection equipment to perform their work. Proper lighting plays a significant role in safety; however, lighting is generally overlooked as a safety factor and the risks associated with maintaining lighting systems are often neglected (Driscoll et al., 2007). In underground mining, the quality and quantity of illumination are important factors for miners to safely perform their jobs (Sanders and Peay, 1988). Miners depend heavily on visual cues to spot fall of ground, potential machinery-related pinning and striking incidents, and slipping and tripping hazards (Cornelius et al., 1998). The Illuminating Engineering Society of North America cites the working face of an underground coal mine as the most difficult environment in the world to illuminate (Rea, 2000). It is a dynamic environment that includes dust, confined spaces, low reflective surfaces, low visual contrasts, and glare. This harsh environment poses many hazards encountered during the operation and maintenance of mining equipment.

Miners wear cap lamps on their hard hats to illuminate nearby areas where their vision is directed. Underground lighting installed on mobile machinery is used to illuminate work areas for the machine operators. Headlights are used to improve visibility in the direction of travel, while flood-type lights provide illumination around the machine periphery. For surface mining, lights are used to illuminate mobile surface-mining equipment and the hazardous areas surrounding this equipment, as well as catwalks, walkways, loading and dumping sites, and general work areas. Auxiliary light plants are used to concentrate illumination on specific work areas of interest, such as the entrances of highwall mines.

Recent safety analyses of mining accidents include a study of electrical accidents during 1990–1999 (Cawley, 2003), an investigation of work locations (Karra, 2005), a global risk analysis (Komljenovic et al., 2008), and an analysis of accidents involving mining equipment (Groves et al., 2007). These prior reports did not address lighting-related injuries in mining, nor did they address the extent of maintenance or operational-related accidents. However, other industries have noted maintenance or operational-related accidents. A lighting-related injury study was

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prompted by the high number of serious accidents involving electricians (Wolfman and Capelli-Schellpfeffer, 2002).

Prior safety research involving mine lighting aimed to improve safety by increasing the light output. It was noted that accident rates decreased as much as 60% when the overall illumination was increased (Sanders and Peay, 1988). Other researchers noted dramatic increases in the ability of miners to see loose rock as illuminance increased from 500 to 1500 lux (Trotter and Kopeschny, 1997). Recent NIOSH research has focused on the spectral characteristics of light from miner cap lamps to improve safety. The results indicate significant gains in visual performance that could reduce pinning/striking accidents (Sammarco et al., 2009a), glare-induced accidents (Sammarco et al., 2009b), and slip/trip/fall (STF) accidents (Sammarco and Lutz, 2007). These accidents pose major risk to miners. For instance, our analysis of Mine Safety and Health Administration (MSHA) accident data for 2003–2007 indicates that for underground mining, STFs are the third leading accident class (17.8%, $n = 2441$) of lost-time injuries. For 2007, STFs resulted in 42,716 non-fatal days lost of work for all US coal mining operations (US Mine Safety and Health Administration, 2007).

High brightness, white light emitting diodes (LEDs) are emerging as a viable replacement for traditional (i.e. incandescent and florescent) lighting in mines. LED technology has the potential to improve mine safety in several areas. Illumination from LEDs can potentially improve a miner's visual performance for the detection of mine hazards. LEDs can be used for visually communicating warnings and alerts. LED technology can provide longer service life and require less power than traditional mine lighting technologies. LEDs could provide, depending on the design and ambient conditions, useful lives up to 50 times longer than incandescent lighting technologies commonly used in mining thus greatly reducing exposure to maintenance-related hazards associated with lighting. Reduced power requirements can enable reductions in the size and weight of mine lighting. LEDs can also enable the elimination of power cords that tether miner cap lamps to wearable battery packs. These power cords are known to contribute to accidents when they get caught against equipment or protruding hazards.

Mine lighting safety research has not been conducted to address operational and maintenance-related accidents. MSHA data from 2002 to 2006 indicated that there were a total of 74,154 mining accidents in all of mining, with about 24.5% occurring during maintenance-related activities (US Mine Safety and Health Administration, 2002–2006). This significant number of accidents during maintenance further motivates more detailed analysis. Therefore, the objective of this study is to better understand the nature and extent of these accidents, and determine if LED technology has the potential to reduce operational and maintenance-related accidents of mine lighting systems.

2. Solid-state LED technology

Mine lighting systems, as with other lighting systems, typically consist of a light source (lamp), a lighting fixture, optics, a power source, and drive electronics (ballast). Incandescent and halogen light sources do not require drive electronics because they can operate directly from the power source; however, fluorescent and metal-halide light sources require drive electronics known as ballasts. LEDs usually require drive electronics to regulate current to the LED. The light output efficiency depends on the entire lighting system so caution must be used in looking at the light source efficiency. There are many variations in mine lighting systems, but this paper focuses on the light source and the associated drive electronics, if any, to enable a direct comparison of light source technologies.

The photometric and energy characteristics of LED light sources differ in important ways (Bullough, 2003) (Sammarco et al., 2008). In general, LEDs exhibit longer life and thus require less maintenance with respect to light source replacement. A light source's usable life is important because it will dictate light source replacement requirements, which is a maintenance activity. LED lighting systems could, depending on the design and ambient conditions, have a useful life that exceeds 50,000 h. By comparison, an incandescent cap lamp bulb could last 800–1200 h, and metal-halide light sources could last 7500–20,000 h. LEDs also differ from current mine lighting technology in other ways. LEDs consist of a semiconductor die encapsulated by a clear, solid resin, so they are much more durable than other lighting options. Most importantly, there are no glass envelopes to break such as with incandescent, halogen, fluorescent, and metal-halide lighting sources. In addition, there are no incandescent filaments to break that could result in a catastrophic failure and subsequent replacement of the light source.

LEDs do not typically fail catastrophically such as with incandescent light sources; rather, they gradually decrease in light output over time. LED life is defined by lumen maintenance that is typically reported as the operating time (L) in hours that corresponds to a set reduction in the initial light output. For general lighting, the useful life (lumen maintenance) is denoted by L_{70}, which corresponds to a 30% reduction of the initial light output; this is the approximate threshold considered acceptable by most of the occupants within a space (Alliance for Solid-State Illumination Systems and Technologies, 2005). Note that L_{70} denotes a general threshold for detecting light reduction and is not related to human visual performance required for safety. Fig. 1 depicts lumen maintenance values for various light sources that are commonly used in mining.

LEDs also use less electrical power than conventional incandescent or halogen lighting sources. Energy consumption is especially important for portable lighting applications. As the energy efficiency increases, the portable lighting system power source (battery or generator) can become smaller and lighter. Energy efficiency, the ratio of light output in lumens (lm) to input power in watts (W), is expressed as lm/W. This energy efficiency is typically known in the lighting industry as luminous efficacy because this measure has dimensional units. Efficiency is used to describe dimensionless measures such as the energy efficiency of drive electronics, which is quantified by the ratio of input power to output power. Table 1 lists the typical ranges of luminous efficacies for various light sources, as of October 2007. The Department of Energy's luminous efficacies goal for white LEDs is 160 lm/W in cost-effective, market-ready systems by 2025 (US Department of Energy, 2009a). A luminous efficacy of 139 lm/W for commercially-available, cool-white LEDs was made available during 2009. During early 2010, 208 lm/W was reported achieved for a white LED in a research laboratory (Cree, 2010). LED luminaires could use up to 90% less energy as compared to incandescent light sources commonly used in mining. The reduced energy consumption can enable new designs of miner cap lamps. For instance, the typical incandescent cap lamp requires about 4 W of battery power. The most recent designs of LED cap lamps require less than one watt of battery power, enabling integration of the battery and cap lamp headpiece. This will eliminate the electric cable that connects the headpiece to the battery pack worn on the miner's belt. The electric cable presents a hazard given that it can be caught on an object.

Overall, it appears that luminaires using LEDs have the potential to significantly reduce the frequency of accidents related to the maintenance and repair of lighting systems. The long life of LEDs would enable an exposure reduction to the associated hazards. Consequently, risks would be reduced. Secondly, LEDs use signifi-

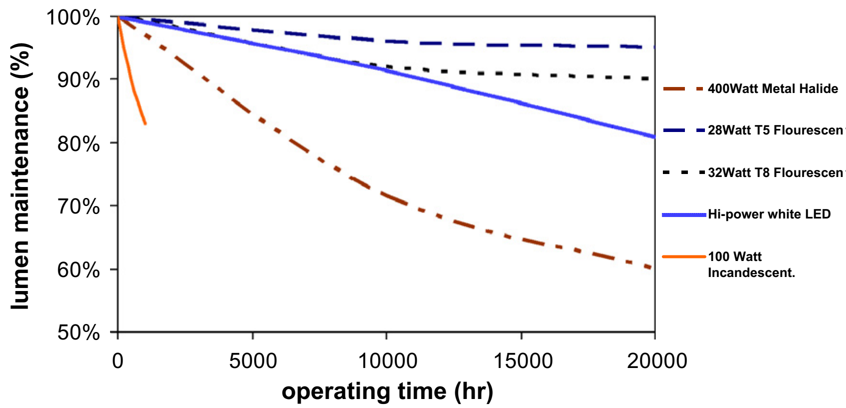

Fig. 1. Typical lumen maintenance values for common light sources. Adapted and used with permission (Bullough, 2003).

Table 1
Luminous efficacies for various light sources as of October 2007. Adapted from the US Department of Energy (2009a).

Light source	Typical luminous efficacy range (lm/W)
Incandescent (no ballast)	10–18
Halogen (no ballast)	15–20
Compact fluorescent (CFL) (includes ballast)	35–60
Linear fluorescent (includes ballast)	50–100
Metal halide (includes ballast)	50–90
Cool white LED 5000 K (w/LED drive circuit)	47–64
Warm-white LED 3300 K (w/LED drive circuit)	25–44

cantly less power compared to other lighting technologies. New designs can be realized that could reduce battery power enabling new cap lamp designs that eliminate hazards associated with the electric cable. Lastly, LEDs could reduce the frequency of accidents related to the loss of light during operation, given they can provide useful light in excess of 50,000 h of operation as compared to about 1000–3000 h for an incandescent bulb.

Note that there is a wide range of "white" available for LEDs; note the "warm" and "cool" LED types in Table 1. The range is dependant on the light source type and wattage rating. A cool-white type of LED is characterized by a correlated color temperature (CCT) between 5000 K and 10,000 K. Warm-white LEDs typically have a CCT from 2600 K to 3700 K. The CCT for warm-white LEDs is similar to that for incandescent lamps. Warm-white LEDs generally have a lower efficacy compared to cool-white LEDs.

3. Methods

The Mine Safety and Health Administration (MSHA) is empowered by statute to collect detailed information on accidents, injuries, and illnesses that occur in the mining industry. MSHA also collects information about mines, employment, and production. MSHA mining accident and illness annual records (US Mine Safety and Health Administration, 2002–2006), maintained as SPSS data documents by the National Institute for Occupational Health and Safety (NIOSH), were used as the basis for this study. A narration section contains a brief description of the accident. Narrative fields for the years 2002–2006 were searched for key words including: 'fixture(s)', 'bulb(s)', 'lamp(s)', 'light(s)', 'lighting', 'luminaire(s)', 'caplamp(s)', and 'caplight(s)'. These records, containing 60 fields of information, were then imported into Excel for further analysis. Non-germane incidents, such as when an employee hit his/her head on a cab dome light while going over a bump, were discarded.

Mine accident reporting requirements are defined by Section 50.20 of Part 50, Title 30 Code of Federal Regulations. The regulations (Section 50-20-6) also define potential causes or contributing factors as categorized by 12 accident/injury codes that pertain to mining equipment, protective items, compliance issues with rules and regulations, and operator issues such as job skills, training, and attitude. These codes are listed on a single page form, MSHA Form 7000-1 *Mine Accident, Injury, and Illness Report*, that is used to report accidents by mine operators and independent contractors working on mine properties. Section C of the form has an area for a narrative to describe contributing conditions and actual cause(s).

The MSHA accident/injury database is one of the most extensive industrial safety databases. It encompasses all types of mining including underground and surface metal, nonmetal, stone, and coal mines. It also covers metal, nonmetal, stone, and coal mills and plants, along with sand and gravel operations. Contractors are also included. The authors note, however, that there are limitations. Mine lighting is not listed as one of the injury classification options on the accident form. Poor illumination is seldom cited as a cause or contributing factor in MSHA accident data. Incidents may be documented by persons with expertise is mining, but not necessarily in accident analysis nor in mine illumination; therefore, it is unlikely that root causes and contributing factors involving the human factors of visual performance or illumination can be discerned. Another limitation is that not all accidents may actually be reported, especially those resulting in very minor injury. Conversely, some events may be reported that result in no injury. The narration texts also may contain misspellings or atypical descriptions of circumstances that may hamper word searches. Finally, the accident narration may be overly brief or somewhat cryptic, which may lead one to misread the rationale for the worker's actions. For instance, the narrative description might simply state that the miner was installing a light fixture when the accident occurred. In this case it is not known whether the installation was being done to enhance a poorly lighted area or to replace a faulty fixture.

4. Accident analysis results and discussion

A total of 140 relevant accident records were found, averaging 28 annually. The leading mine commodity categories were 64 accidents (46%) in bituminous coal mines and 35 accidents (25%) for stone mining as depicted by Fig. 2. Given all commodities, 105 accidents (75%) occurred during surface mining operations with 38 accidents (27%) at mills or preparation plants. Thirty-five accidents (25%) occurred during underground mining operations. For

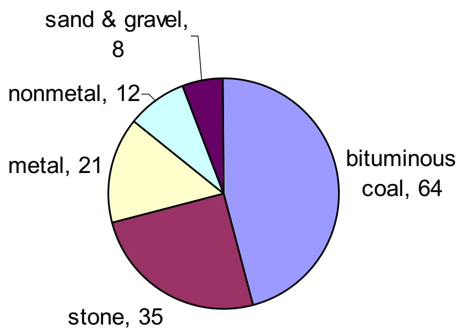

Fig. 2. Lighting accidents by mining classification.

surface mining accidents, the leading injuries were cuts (31), sprains/strains (27), and fractures (10). For underground mining accidents, fractures (12) and sprains (8) predominated.

All of the accidents were non-fatal, but resulted in a total of 3668 days lost with an additional 925 days of restricted activity. The leading injuries were sprains/strains (40), laceration/puncture wounds (39), fractures/chips (18), or contusions/bruises (13). The most common body parts injured were the fingers (26) followed by the back (18), multiple parts (14), and the eyes (10). There was a notable absence of injuries from lighting burn hazards which could be explained by the required guarding around lights to prevent burn accidents. The leading accident classifications were handling materials (34%), followed by slip or fall of person (28%), powered haulage (11%), hand tools (8%), and machinery (7%). The MSHA accident classifications relate to the circumstances that contributed to the accident. Most accidents could be separated into three main groups associated with maintenance, repair, and operation of cap lamps, auxiliary lighting, machine-mounted lighting, and portable or fixed lighting.

The distribution of worker ages in Fig. 3 shows a high percentage occurring in the 45–55 age group with a median of 44 years old. Total mining experience averaged 10.5 years with an average of 7.7 years at the particular mine and job. Fig. 4 shows that, except for the oldest group of workers, experience with a particular job increased with age as expected. The leading job titles of the employees were electricians (31), mechanic/repairman (31), and laborer (20). These job titles account for 59% of the 140 accidents.

4.1. Maintenance, repair, and operation of machine-mounted lighting, and portable or fixed lights

Lighting is used in mines to illuminate workplaces and areas where employees routinely travel. It may consist of machine-mounted lights, portable, or fixed lights. Illumination of work areas is needed both underground and on the surface. The greatest percentage of accidents (53%) occurred when employees were maintaining or repairing light bulbs or light fixtures. Maintenance of lights may involve cleaning or replacement of bulbs. Light fixtures may need to be replaced if subjected to damage. Often, hand tools are also needed to perform their work. Maintenance activities require workers to walk to the area of the mine where the light maintenance is needed, and might involve climbing ladders and placing their bodies in awkward positions. Thus, worker exposure is increased to slip, trip, or fall hazards, moving machinery hazards, and hand-tool related hazards. Lastly, workers are exposed to broken glass hazards if the light has been damaged. Lacerations have occurred even though workers were wearing gloves. The longer life and packaging (no glass envelope) of LEDs would decrease the exposure to these hazards. Thus, the risk, a product of accident frequency and severity, would be decreased.

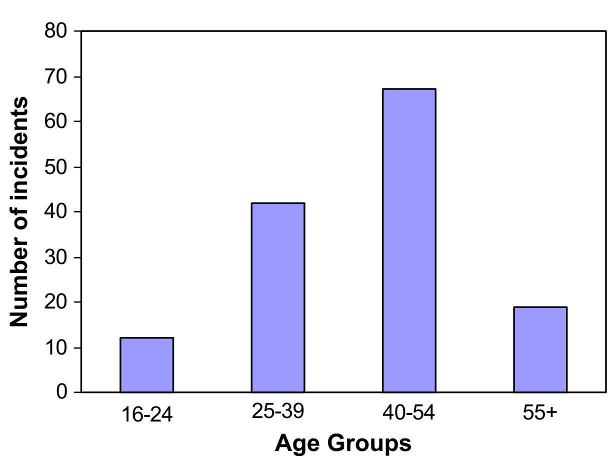

Fig. 3. Age distribution of workers in lighting accidents.

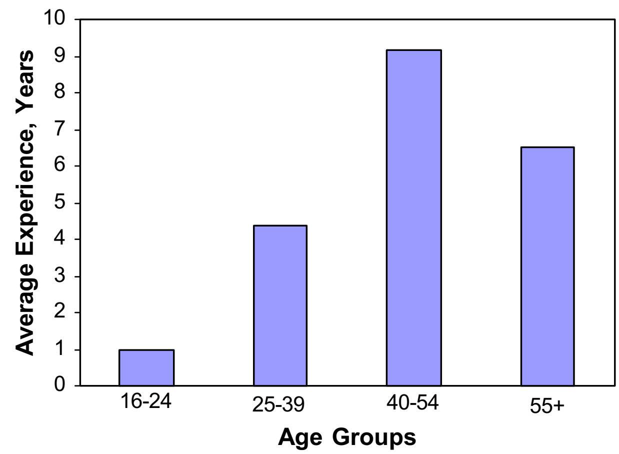

Fig. 4. Average worker experience with a job versus age.

Seventy-four accidents (53%) occurred during lighting maintenance, predominantly while changing light bulbs. The accident severities were significant. Although 37% of the maintenance, and repair accidents resulted in non-fatal days lost injuries, the days away from work averaged 78.4 per incident. The remainder yielded no days lost. Eleven workers were hurt while using a ladder. Many of these occurred when personnel over extended their reach. In five cases, the ladder collapsed and wrist, back, hip, and leg injuries were sustained. Five workers fell from a ladder, while two were hurt positioning it. One worker slipped on a wet surface while dismounting. While standing on vehicles, two workers slipped while changing lights. For the maintenance worker, fixtures must be held in place with one hand while the other hand pulls wire or operates a tool. Four employees sustained lacerations to hands/fingers on the sharp fixture edges while another was cut while splicing wires. There were five instances where employees received cuts when the bulb being removed broke in their hands. Eye injuries resulted when a bulb of the wrong voltage exploded following installation and when dust was put in suspension. Three employees lacerated their hands while popping open light covers with knives, and one injured an eye with a popped cover. One worker was shocked while changing a light bulb.

There were 27 injuries associated with the repair of lights and fixtures. These occurred in a variety of fashions. Among the total, three happened when employees slipped while dismounting vehicles after repairing lights. One employee was struck by a service truck after pulling up to a dozer to repair lights. Three were cut on broken bulbs. Three workers were cut using knives to strip wire. While removing or repositioning fixtures, three were injured when the fixture fell, while another was shocked during fixture removal. Safe work practices concerning ladder safety and eye and hand protection would likely have eliminated or reduced the accident severity. Some workers were wearing gloves but still received hand lacerations. The role LED technology plays in these accidents is in reducing the need for maintenance thus reducing exposure to these maintenance-related hazards.

There were accidents related to the operation of lighting. Thirty accidents occurred while personnel were working or walking in the vicinity of operating lights. Three workers suffered burns to the eyes and skin from a 1000-W mercury vapor flood light operated with a broken outer shell at a gold processing plant. In another incident two employees at a surface coal mine were eating lunch near a metal halide lamp with a broken outer shell and received ultraviolet burns to the eyes. At a copper mine, an unguarded light exploded cutting the eyes of two nearby workers. One worker was cleaning a housing with a solvent and was burned on the face and neck when a halogen work light ignited vapors. Finally a worker suffered burns to the face and neck when he brushed against an unguarded light. The cooler operation temperatures and lack of UV radiation of LED lights would have precluded these injuries. A number of incidents could be tied to catastrophic failures of lighting. One worker tripped over the tongue of a welder in an area where a light had gone out. Two accidents occurred while employees were operating mobile machinery with headlights out. One involved a haulage vehicle that struck the rib at an underground potash mine; the operator suffered neck and back sprains and missed 97 days of work. The other incident involved two vehicles, one without lights, at an underground coal mine.

Overall, it appears that LEDs have the potential to significantly reduce the frequency of accidents related to the maintenance, operation, and repair of lighting systems because the long life of LEDs would enable an exposure reduction to the associated hazards; thus, risks would be reduced. To help facilitate risk assessment, accident severity and frequency categories have been recommended for mining in Table 2 (Komljenovic et al., 2008 Sammarco, 2005) and 3 (Sammarco, 2005), respectively. The frequency categories of Table 2 are based on the total number of hours worked annually for all employees, including contractors but excluding office workers, and for all commodities. Using MSHA data from 2002 to 2006, the average annual work hours are about 609.5 million work hours (US Mine Safety and Health Administration, 2002–2006). A subjective risk assessment can be made by using a risk matrix tool as depicted by Table 4. The potential risk reduction enabled by LEDs could be significant. As an example, 24 accidents (62%) resulted in lost work days that correspond to a severity category of marginal (Table 3). The average frequency of these 24 accidents per work hours per year is less than 0.39E−07 so the frequency category is remote (Table 2). The resulting risk index (Table 4) is "C," which suggests it could be an acceptable risk with management review and approval. However, using the total worked hours for all of mining to determine frequency can yield a misleading result because all the people are not exposed to maintenance-related hazards. According to labor statistics for 2007, about 53,850 people directly employed in mining are in electrician occupations and installation, maintenance, and repair occupations (US Bureau of Labor and Statistics, 2008b). This represents about 24% of all people directly employed in mining. This 24% is conservative given that not all those in installation, maintenance, and repair occupations would be installing or maintaining lighting. Electricians are the most likely workers to be involved in maintaining lighting and they comprise only about 3% of all people directly employed in mining. Taking a conservative approach by using 24%, the frequency is about 1.64E−07 so the category is occasional (Table 2). The resulting risk index (Table 4) is "B," which suggests it could be an undesirable risk. Continuing the example of the potential risk reduction potential of LED-based lighting for maintenance-related accidents, consider the maintenance required for incandescent lighting that could last 750–1000 h before failing catastrophically and resulting in no light output. This typical life can be shortened if the incandescent bulb is exposed to shock, vibration, or voltage fluctuations all of which are common in mining. It could take 50,000 h for an LED's light output to decrease 30% and require replacement. Note that this is not a catastrophic failure that results in no light output. Therefore, an incandescent light source would be expected to need approximately 28 lamp replacements before an LED would need replaced. Translating this factor of 28 to the frequency categories of Table 2 reduces the frequency from occasional to rare with the resulting risk index reduced to C.

Table 2
Frequency category examples. Adapted from (Komljenovic et al., 2008).

Category	Specific individual item	Example frequencies (work h/year)
Frequent	Likely to occur frequently	>1.0E−04
Probable	Occurs several times in the life of an item.	2.5E−06 to 1.0E−04
Occasional	Likely to occur some time in the life of an item	1.0E−07 to 2.5E−06
Remote	Unlikely but possible to occur in the life of an item	1.0E−08 to 1.0E−07
Rare	So unlikely, it can be assumed occurrence may not be experienced	<1.0E−08

Table 3
Severity category examples recommended for mining (Sammarco, 2005).

Category	Example definitions
Catastrophic	Death or multiple deaths
Critical	Severe injury, permanent disability (partial or total)
Marginal	Moderate injury, medical treatment and lost work days
Negligible	Minor injury, first aid treatment and no lost work days

Table 4
Risk assessment matrix.

	Catastrophic	Critical	Marginal	Negligible
Frequent	A	A	A	B
Probable	A	A	B	C
Occasional	A	B	B	C
Remote	B	C	C	D
Rare	B	C	C	D

Risk index suggested criteria.
A – unacceptable risk.
B – undesirable risk.
C – acceptable risk with management review and approval.
D – acceptable risk without review or approval.

4.2. Personal cap lamp cables

Personal illumination in mines is provided by a cap lamp that is typically the primary and most important source of light (Trotter and Kopeschny, 1997). Traditionally, miner cap lamps used an incandescent bulb as the light source and a lead-acid battery. Today, LED light sources and lithium technology batteries are gaining acceptance.

The main parts of a typical cap lamp are the headpiece, battery, and an interconnecting cable. The cap lamp headpiece contains the light source and is mounted on the top of the employee's protective helmet or hard hat. The cap lamp is powered by a battery mounted in a pouch that is worn on the miner's belt. Typically, lead-acid batteries weighing about 2.2 kg (4.8 lbs) have been used.

Newer battery technologies such as lithium ion and nickel-metal hydride are gaining wide usage due to the significant reductions in size and weight. The lithium ion batteries are about one-third the weight of a lead-acid battery. The battery, regardless of the various battery technologies, connects to the cap lamp headpiece by a flexible electrical cable that contains two 18-gauge insulated wires. The cable is firmly attached to the battery and to the cap lamp headpiece. Disconnection requires the removal of mechanical fasteners. The cord diameter range is 0.838–0.884 cm (0.330–0.348 in.) and 1.6 m (63 in.) in length. Some manufacturers provide a longer, 1.7 m (66.9 in.) cable for taller miners. The cable can hang over the front of a miner's torso or over the miner's back or side. Placement of the cable and the battery is a matter of personal preference.

The cap lamp cable can be loosely hanging, thus it can pose a hazard of getting caught on or hitting against an object or a machinery control lever. Consequently, the miner's head could be jerked back and the helmet could be pulled off; the cable could interfere with a control lever and cause the machine to unexpectedly move; the cable could become entangled and the miner could be pulled into moving parts or be dragged by moving machinery (Blake et al., 1980). The hazard potential varies due to cable and battery placement, the miner's physical size and weight, the physical positioning of a miner's body, and the miner's proximity to the mining machine. The height of miners varies considerably when considering the seated height to eyes. The range is 68.5 cm (27 in.) for the 5th percentile female to 84.8 cm (33.4 in.) for the 95th percentile male. There is a 91.44 cm (36 in.) difference in cable length versus height for a 5th percentile female. This excess cable poses a hazard that has a greater likelihood of causing an accident. The analyses of MSHA data reveal that the cord is also a hazard that could result in injury. Coiled cap lamp cables were recommended as a safety intervention that could reduce the risk to miners (Blake et al., 1980). However, this intervention was never implemented in the industry.

During the period 2002–2006, there were 24 incidents in the mining industry involving the miner's cap lamp cable getting caught on an object. Nine resulted in no days lost while the remainder, though non-fatal, averaged 44 days away from work per incident. As expected, 83% (20) occurred underground, with bituminous coal the leading commodity (29 occurrences). Cables were caught in/on diverse items, including the tram levers of roof bolters and a continuous miner, a drill steel rotation lever, a bridge carrier, and a mucker door handle, and a belt splice. The cables caught on machine controls caused unintended machine movements, running over the victims' feet. One worker was struck in the face by a drill steel. Others fell after their cable snagged a roof bolt, a canopy post, a drill steel following a small roof fall, a steering wheel for a material handler, an overcast handrail, or a conveyor belt. A worker tripped over a cable while carrying the cap light and another was sitting on a portion of the cable. Insufficient lighting from a cap lamp was either the direct or indirect cause in two accidents. An employee tripped when his light was going dim. Another twisted a knee by stepping in a hole that was not seen because his cap lamp failed.

Currently, LED technology is being used for cap lamps in the US mining industry. All of these cap lamps use a cable to a battery. The current design of these cap lamps cannot enable the elimination of the cable because the luminous efficacy is too low. In the future, it would be expected that LED cap lamps in the US would be cordless because of the rapid progress in LED efficacy. Cool-white LEDs in 2005 had luminous efficacies of about 20 lm/W. Assuming 80% electronic driver efficiency, the resulting luminous efficacy is 16 lm/W. Today, LED luminous efficacies have significantly increased. Cool-white LEDs are available at 100 lm/W. Assuming 80% electronic driver efficiency, the resulting luminous efficacy is 80 lm/W, which would require about 20% of the electrical power compared to the 2005 example. Thus, the technology for cordless LED cap lamps appears to be viable today.

4.3. Auxiliary lighting

Mobile light plants are used in surface areas of mines to provide concentrated illumination where work is taking place, such as highwalls. They consist of a bank of lights mounted on a tower that can be raised or lowered via a hand winch. These plants can weigh 2000 lb, so they are towed to a needed location by hitching to a vehicle. Power for the lights is typically provided by an onboard generator. These mobile plants typically contain four 1000 W metal-halide light sources, each producing about 110,000 lm.

From 2002 to 2006, there were 12 accidents involving light plants in the mining industry. Eleven of these involved lifting or moving the light plant. All occurred at surface mines with bituminous coal (4), limestone (3), and copper ore (2) as the leading commodities. Six resulted in days lost, averaging 25.3 days per incident. Typically, accidents occurred when employees attempted to hitch the light plant to the truck. The light plant would inadvertently move and a hand or foot injury would result. Others strained their backs or shoulders attempting to lift the light plant. Two injured their hands with the winch handle or crank as they were lowering the light plant tower.

Metal halide lamps produce light in the range of 50–90 lm/W, making them more energy efficient than fluorescent lamps and incandescent lamps (Table 1). Metal halide lamps have an efficacy comparable to commercially-available LEDs. The current state of LED technology would not enable a power reduction for mobile light plants because LED efficacy, measured by lm/W, is approximately equal to the metal halide lamps currently used for portable mine lighting. Thus, the light plant size and weight would remain about the same. However, in the near future this should change given the rate of LED technology advancements. By 2015, if LED efficacy projections are met, cool-white LEDs efficacy will be 188 lm/W (US Department of Energy, 2009b). Assuming a 90% efficiency for the drive electronics and neglecting the fixture, the result is 169 lm/W. This is a 58% energy reduction assuming an average 70 lm/W efficacy for metal halide.

5. Summary and conclusions

From 2002 to 2006, an average of 28 accidents involving lighting occurred annually within the US mining industry. Nearly half occurred in bituminous coal mines. Most the incidents could be separated into three main groups associated with operation and maintenance/repair activities, cap lamps, and auxiliary lighting. The greatest number of accidents occurred when employees were maintaining or repairing lighting. This is also the area of greatest severity as measured by the days away from work.

These 28 accidents a year represent an undesirable level of risk when looking at the exposure to those workers involved in maintaining or repairing lighting in mines. The longer life and robustness of LED lighting systems can potentially reduce the frequency of accidents associated with maintenance, repair, and the catastrophic lamp failures occurring during operation. To a lesser extent, it appears that LEDs could reduce accident severity for the cases of eye injury from an exploding bulb and the eight cases of cuts from broken glass. For these cases, the hazards would be eliminated by the LEDs given the physical construction of this light source.

Elimination of the cap lamp cable could eradicate cable-related accidents. It is anticipated that new LED cap lamp designs will use high efficacy (100 lm/W) cool-white LEDs thus enabling considerable power reductions such that the battery that it will be integrated with the cap lamp headpiece, thus eliminating the cable. Major changes such as reductions in power, size, and weight in mobile light plants do not seam achievable given today's state of LED technology; however, by 2015, LED efficacies could enable such reductions of about 50%. While these reductions could potentially reduce the risks associated with lifting or moving mobile light plants, this is not a major safety benefit for LEDs given that only six accidents involving days lost from work occurred from 2002 to 2006.

Thus it appears that overall, LED technology could provide some added safety benefits in terms of reducing operational and maintenance-related accidents involving lighting. This is primarily through reduced hazard exposure given that LEDs could potentially reduce lamp replacement by a factor of 28 as compared to incandescent bulbs. However, given the risks posed by other accidents the primary benefit of LEDs is likely to be improving the visual performance of miners such that they can better detect mining hazards.

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