Technological Aspects of Solid-State and Incandescent Sources for Miner Cap Lamps

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***Abstract*— Light emitting diodes (LEDs) are emerging as viable replacements for incandescent-based cap lamps used in mining. The photometric and energy characteristics of these light sources differ in important ways. The present paper describes the performance of LED and incandescent sources in cap lamps in terms of correlated color temperature, color rendering, light output, electric power, ambient temperature and airflow, and light source aging. Importantly, these characteristics can influence a miner's ability to spot mining hazards thus impacting safety. Secondly, some of these characteristics interact with the operating life of the cap lamp's battery power, such that differences between LED and incandescent sources can be magnified toward the end of a 10-hour battery discharge cycle. Empirically, we have determined that after 8 hours at an ambient temperature of 25 °C, the average light output of an incandescent cap lamp can decrease to about 69% of its initial value when powered by a lead-acid battery and it can decrease to about 65% of its initial value when powered by a nickel-hydride battery. An LED-based cap lamp using a constant current drive circuit can maintain about 96% of its initial value when powered by a nickel-hydride battery. Real-world tests addressing the effects of ambient temperature and airflow on the light output of an LED and incandescent cap lamp were conducted in the NIOSH Safety Research Coal Mine (SRCM). The LED cap lamp yielded a vertical average illuminance improvement of approximately 9.5% and the INC cap lamp yielded a vertical average illuminance degradation of approximately 4%. The differences between LED and incandescent cap lamps were further quantified by the calculation of "mesopic luminance" data that indicated for the same photopic luminance (i.e., as measured using a conventional light meter) the LED cap lamp could be up to 38 % more efficient than the incandescent cap lamp with a lead-acid battery at the end of the 10-hour driving cycle. Lastly, accelerated life tests were used to empirically determine light output depreciation as the incandescent light source age approached its useful life. There was about a 35% decrease in light output. This is quite considerable, especially given that the light output will decrease an additional 30% to 45% over the period of a 10-hour shift. The implications of the differences between LED and incandescent sources are discussed. This information is crucial in determining how visual performance could be affected for real-world conditions where batteries discharge during the work shift and as the light source ages. To date, only idealized conditions have been used for LED and incandescent cap lamp visual performance research.**

Keywords-mine illumination; visual performance; cap lamps; mine safety

I. INTRODUCTION

The National Institute for Occupational Safety and Health (NIOSH) Pittsburgh Research Laboratory (PRL) has initiated a project to improve mine illumination such that a miner's visual performance improves to better recognize mine hazards. The project's main objective is to determine if solid-state lighting technology (i.e., light emitting diodes (LEDs)) enables visual performance improvements as compared to traditional mine illumination technology (i.e., incandescent (INC) lamps). A miner's visual performance is critical for spotting mine hazards [1]. Typically, 80% of our perception is obtained visually. Human process visual data at about four times the rate of audible information. For mining, important audible data (i.e., verbal communications and audible warning alarms) are less useful given the noisy mine environment.

Prior cap lamp research aimed to improve safety by increasing the light output as defined by quantifying illuminance. Canadian researchers noted dramatic increases in the ability of miners to see loose rock as illuminance increased from 500 to 1500 lux [2]. Indian researchers conducted a comparative study of cap lamp light output verses battery discharge for various battery capacities. The light output increased 20% to 22% during the period of a working shift when batteries increased 35% from 10 ampere hours (Ah) to 13.5 Ah [3].

Other research has focused on the spectral characteristics of light. Lighting research indicates that LEDs with a visible spectrum containing more of the shorter wavelengths can enable significant improvement in peripheral visual performance at mesopic conditions for automotive applications [4]. Recent NIOSH mining research findings indicated that, in comparison to INC lighting for cap lamps, cool-white LEDs do enhance peripheral visual performance from 15% to 20% for high-contrast targets [5]. Cool white LED-based miner cap lamps can also enable visual performance improvements with respect to slip/trip/fall hazard detection [6]. It was inferred in these studies that the light source's spectral distribution was a statistically significant main effect. These NIOSH studies focused on a miner's cap lamp because this is a miner's primary light source [2].

The LED and INC cap lamps used by NIOSH researchers were operated at optimal conditions [5] [6]. New cool-white LEDs and new INC bulbs were used, and the cap lamps were powered at the levels for a fully charged, new cap lamp battery. It would be expected that the visual performance improvements enabled by the LED cap lamps would be even greater under real-world conditions.

The present paper addresses the real-world mining conditions for INC and LED cap lamps. Presented are the results of an analytical study conducted to understand and quantify the photometric and spectral characteristics of INC and LED light sources used in miner cap lamps as a function of battery discharge (i.e., over the length of a day's work shift), ambient temperature and airflow, and as the light source ages. This information is crucial in determining how visual performance could be affected for real-world conditions that would be encountered during a work shift.

II. METHODS

We tested the relative lumen (lm) maintenance curve and spectral power distribution (SPD) of three cap lamp systems: 1) LED cap lamp with an internal heat sink and a 6 volt (V), 8 Ah nickel-hydride battery, 2) INC cap lamp with a 4 V, 13 Ah lead-acid battery; and 3) INC cap lamp with a 6 V, 8 Ah nickel-hydride battery. The light sources of each system were new at the time of test. Each system was tested for two discharge cycles. Each discharge cycle lasted 10 hours without interruption during the discharge period. An automated, computer controlled data acquisition system was set up for the purpose of this test and collected data every minute. A photometrically calibrated photosensor measured the relative light output of each cap lamp for the duration of each test. A three-channel power analyzer measured the electric current, voltage, and power of the light source in each system. After the second discharge cycle was finished, the data between the two cycles were compared. Since the difference between the two cycles in all cases was less than 5%, the data were averaged for the purpose of characterizing each system photometrically. A 152.4 cm photometrically calibrated integrating sphere was used to measure the absolute light output and spectral power distribution of each system. The averaged electric current and voltage were used to power each system under four conditions corresponding to 0, 10, 300, and 600 minutes of battery discharge time.

To understand the changes in spectral composition of INC lamps over time, ten 6 V lamps were subjected to an accelerated life test. For traditional light sources, including INC lamps, life is defined as the median time to failure of a large group of samples under controlled conditions. Accordingly, for this test, "life" was defined as the time to failure of the first five lamps. To reduce the time needed to complete the test the lamps were operated at 7.2 V, which is 20 % higher than nominal voltage. By using empirical relationships between the operating voltage and life [8], the expected life of the samples could be estimated if needed. However, in this case knowing the actual lamp life in hours was not as important as analyzing the spectral shifts at the end of life. In order to characterize spectral changes, the initial light output and spectral power distribution of two new lamps were measured before the life test. After the life test, two out of the five remaining lamps were tested for light output and spectral power distribution. Because of the small differences in light output (less than 4 %) and spectral composition expected among the ten test lamps, it was not necessary to characterize all lamps at the beginning of the life test.

Real-world tests addressing the effects of ambient temperature and airflow on the light output of an LED and INC cap lamp were conducted in the PRL Safety Research Coal Mine (SRCM). The cap lamps were powered by fully charged Ni-MH battery for the purpose of replicating typical cap lamp use. The cap lamps remained on until the temperature stabilized as measured by thermocouples positioned internal (near the LED) and external to the cap lamp. Positioning of the external thermocouples was dictated by the hotspots identified using a thermal imaging camera. Figure 1 depicts a thermal image of the LED cap lamp given an ambient temperature of 23.8 °C and negligible air flow. The thermal image depicts a maximum surface temperature of 44.8°C. Temperature and light output measurements were recorded at 15 minute intervals for the duration of the evaluation period.

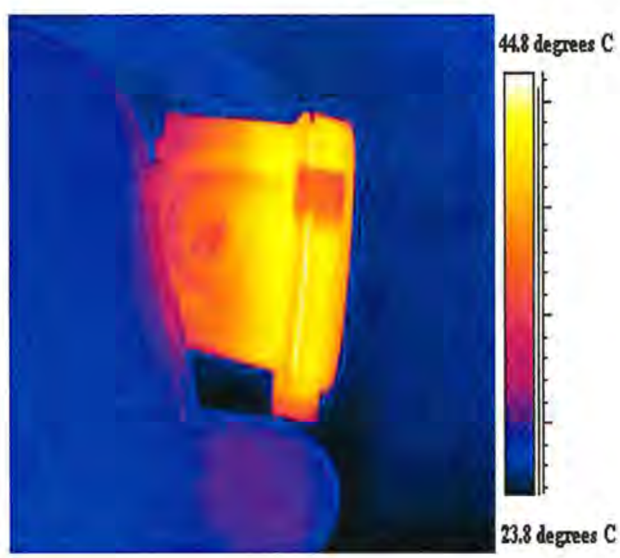

Figure 1. Thermal image of an LED cap lamp at an ambient temperature of 23.8 °C and negligible air flow.

III. Results and Discussion

Figure 2 shows the relative, photopic light output over the 10-hour discharge period for each system. As evidenced in Figure 2, the INC systems show a relatively sharp drop in light output after just a few minutes, particularly with the lead acid battery system. The INC-based cap lamp systems tested do not have any regulation circuitry, thus the light output of the lamps follow the discharge characteristic of the battery used in each case. By the end of the 10-hour cycle, the light output levels of the INC systems were approximately 65 % (nickel-hydride battery) and 56 % (lead-acid battery) of the initial value. In contrast, the LED based system tested uses a current regulating device that compensates for the voltage drop of the battery, resulting in a light output drop of only 4 % over the 10-hour period. This 4% light output drop can be attributed to a typical light reduction experienced as the LED junction temperature (Tj) increases, rather than a light output reduction as a function of battery voltage drain. Once the thermal equilibrium is reached, an LED will experience a relative stable photopic light output % over the 10 hour period.

A second effect of the lack of regulation in the INC systems is the change of spectral composition in the light over the test period. At lower operating voltages, the spectral power distribution of INC lamps shifts toward increased long visible ("yellow") wavelengths that could be considered detrimental to peripheral vision at mesopic light levels [8].

As the light output of the cap lamp drops, the adaptation level of the miner will shift toward the shorter wavelengths, i.e., toward a scotopic adaptation. At these lower light levels (approximately 1 cd/m^2 and lower), the short wavelength content of the light source becomes more useful than the longer wavelengths. In the case of INC lamps, as the voltage drops the content of short wavelength decreases, resulting in potentially lower visibility. It is worth emphasizing that the LED discharge curve of Figure 2 could be representative of the tested system only because there are different current limiting methods that could be used in commercial systems to achieve lower cost or intrinsic safety approvals. For example, it would be reasonable to expect that an LED system regulated with a simple resistor would behave similarly to an INC based system. Such systems would need to be evaluated on a one by one basis in order to compare their relative benefits to INC systems. Although there are some benefits of using a resistor to regulate the current of LED cap lamps, there are significant disadvantages with respect to light output and the potential for thermal runaway conditions that could greatly reduce light output or result in catastrophic failure of the LED cap lamp.

Table I summarizes the electrical and photometric characteristics of the LED based cap lamp and the INC with lead-acid battery cap lamp at the four conditions tested (0, 10, 300, and 600 minutes). Table II shows for reference only the photometric characteristics of the LED based prototype cap lamp developed during the 2006 joint research efforts of LRC and NIOSH.

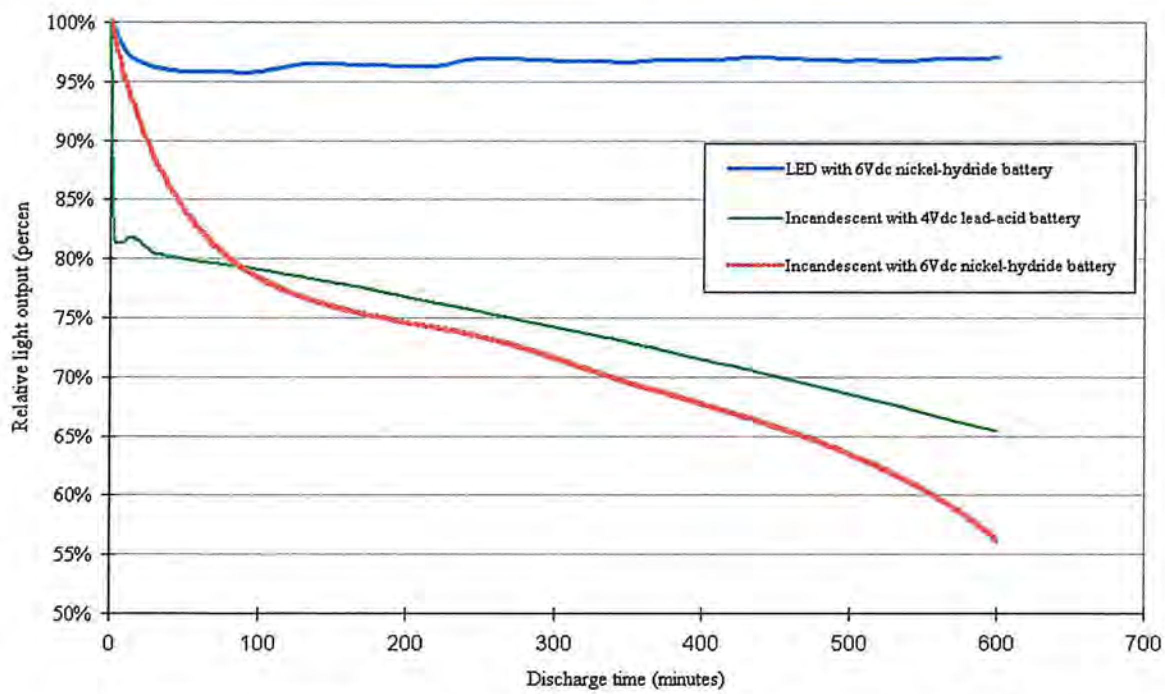

Figure 2. Average relative, photopic, light output of each system tested over a 10-hour discharge period.

TABLE I. ELECTRIC AND PHOTOMETRIC CHARACTERISTICS OF AN LED SYSTEM WITH A NICKEL-HYDRIDE BATTERY AND AN INC SYSTEM WITH LEAD-ACID BATTERY AT 25°C.

Source	Time	Electric characteristics			Photometric characteristics					
		Voltage (V)	*Current (A)*	*Power (W)*	*Luminous flux (lm)*	*Efficacy (lm/W)*	*CIE 1931 chromaticity (x,y)*		*Correlated color temperature (K)*	*General color rendering index (Ra)*
LED	0 min	6.82	0.365	2.49	36	14.5	0.3252	0.3283	5851	73
	10 min	6.66	0.375	2.50	35.7	14.3	0.3251	0.3281	5857	74
	300 min	5.99	0.424	2.54	35.2	13.9	0.3245	0.3272	5890	74
	600 min	5.74	0.444	2.55	35.0	13.7	0.3243	0.3269	5905	74
INC	0 min	3.39	1.088	3.69	38.7	10.5	0.4411	0.4067	2951	100
	10 min	4.28	1.055	4.52	30.8	6.8	0.4463	0.4082	2880	100
	300 min	4.13	1.04	4.3	27.7	6.4	0.4489	0.4089	2847	100
	600 min	4.03	1.025	4.13	24.9	6.0	0.4513	0.4094	2815	100

TABLE II. ELECTRIC AND PHOTOMETRIC CHARACTERISTICS OF THE LED BASED PROTOTYPE CAP LAMP DEVELOPED BY LRC DURING 2006.

Source		Electric characteristics		Photometric characteristics					
		Current (A)	*Power (W)*	*Luminous flux (lm)*	*LED efficacy (lm/W; does not include LED driver)*	*Average CIE 1931 chromaticity (x,y)*		*Average correlated color temperature (K)*	*General color rendering index (Ra)*
LED	Main plus peripheral beam	0.350	3.75	155.3	41.4	0.3134	0.3290	6490	82
		0.700	8.24	255.2	31.0				

All of these measurements were taken at room temperature (nominally 25°C) with negligible airflow. All LED technologies have different sensitivities to temperature, both in the short and the long term. Thus, junction temperature (Tj) is usually the main determinant of life, light output, power, and color shift of LEDs. Note that T_j is partially determined by the forward current and partially by the ambient temperature and airflow of the environment in which the LED is operating. Measurements for an INC cap lamp over a wide ambient temperature of 25°C ±10°C will yield relatively consistent results over this temperature range because for incandescent lamps the effect of ambient temperature is limited. However, ambient temperature can play a major role in LED performance because the temperature at the junction depends in part on the ambient conditions. Thus, measurements over the same ambient temperature range for an LED cap lamp will result in a wide range of performance and inconsistent results across tests. Considering that a typical ambient temperature in a coal mine is 13°C, it would be reasonable to expect a slight increase in the performance of LED systems and almost no change for INC systems [8].

The light output of phosphor-converted white LEDs changes from about -0.25%/°C to -0.33 %/°C depending on the manufacturer [9][10]. Thus, the theoretical estimate of light output increase for a white LED would be of the order of 4 %. This calculation assumes that T_j drops at the same rate as the ambient temperature (i.e., T_j at 25°C ambient is 12°C higher than at 13°C ambient). Following the same assumption, it would be reasonable to expect a benefit in terms of the estimated life of an LED system. Recent research has shown that the depreciation rate of phosphor-converted white LEDs doubles with every 10°C increase in junction temperature [11]. Thus, the projected life of an LED system operating in an environment at 13°C could be significantly longer than that when operating in an environment at 25°C. In reality, the practical implications of a low ambient temperature would include the opportunity to optimize an LED cap lamp in terms of light output, battery discharge time, LED life, and heat sink requirements.

Testing conducted at NIOSH research facilities compared the effects of ambient temperatures and airflow on the performance of both LED and INC lamps. The Mine Illumination Laboratory (MIL), with an ambient temperature of 23.8 °C and negligible air flow, was used for room temperature evaluations. The Safety Research Coal Mine (SRCM), with an ambient temperature of 10.7 °C and a recorded air flow of 178.4 cubic meters per minute, was used for underground coal mining environment evaluations. Cap lamp performance was evaluated by conducting a light survey of the cap lamps' central beam (hot spot). Measurements were made on a vertical illuminance test grid located 1.83 m from the cap lamps. The LED cap lamp yielded a vertical average illuminance increase of approximately 9.5% (MIL: 1520 lx vs. SRCM: 1664 lx) after extended use in cooler ambient conditions whereas the INC cap lamp yielded a vertical average illuminance decrease of approximately 4% (MIL: 1382 lx vs. SRCM: 1327 lx) after extended use in cooler ambient conditions. The results for other LED cap lamps will vary depending on the individual LED cap lamp design, especially as the design relates to thermal management of the LED. For example, a LED cap lamp with an external heat sink yielded a vertical average illuminance increase of approximately 14.4% in the SCRM.

Phosphor converted white LEDs offer an obvious advantage over INC lamps for mesopic vision because, being based on blue LEDs, they have a greater proportion of short-wavelength light than INC lamps. LED SPDs are rich in short-wavelength energy as evidenced by the typically high correlated color temperatures (in the order of 5000 K and higher). Fig. 3 shows the SPD of the phosphor converted white LED and INC lamp tested.

To further quantify the implications of the spectral change as a function of battery discharge, and to compare among the two systems, we conducted mesopic luminance calculations using the SPD of each light source at the beginning and at the end of each test cycle. By using the model of unified photometry described in Rea et al. (2004), the "mesopic" luminance can be estimated for a given SPD and light level. Table III shows the "mesopic" luminance of the LED and INC cap lamps for different photopic luminances relevant to mine conditions. It is worth noting that the luminances of specific objects in a scene will depend upon the illuminance on each object's surface and its reflectance. For the mesopic calculations, several representative luminance (L) values were selected and the respective illuminance levels (E) were calculated considering an average diffuse reflectance of 0.26 for common surfaces found in coal mines. The results are shown in Table IV. As the light level decreases, the relative effectiveness (DL) of the LED system compared to the INC one is more evident. In other words, for the same photopic luminance (i.e., as measured using a conventional light meter) the LED cap lamp could be up to 38 % more efficient than the INC cap lamp with a lead-acid battery at the end of the 10-hour driving cycle. It is also worth noting that these calculations are relevant to peripheral vision, where light levels would be expected to be the lowest due to the typical low intensity of most cap lamps at wide angles.

The implications of these results are that an LED system could be optimized to provide the same visibility at mesopic light levels as an INC system while reducing the battery requirements or, it could be optimized to increase the reducing the battery requirements or, it could be optimized to increase the visibility of miners throughout the duration of a work shift for the same battery discharge time.

Table IV summarizes the electrical and photometric characteristics of the INC lamps at the beginning and at the end of the accelerated life test. The two main points to consider from this test are a large decrease in light output and the spectral shift. In terms of light output depreciation, the observed value was approximately 17%. This depreciation is considerable, especially given that the light

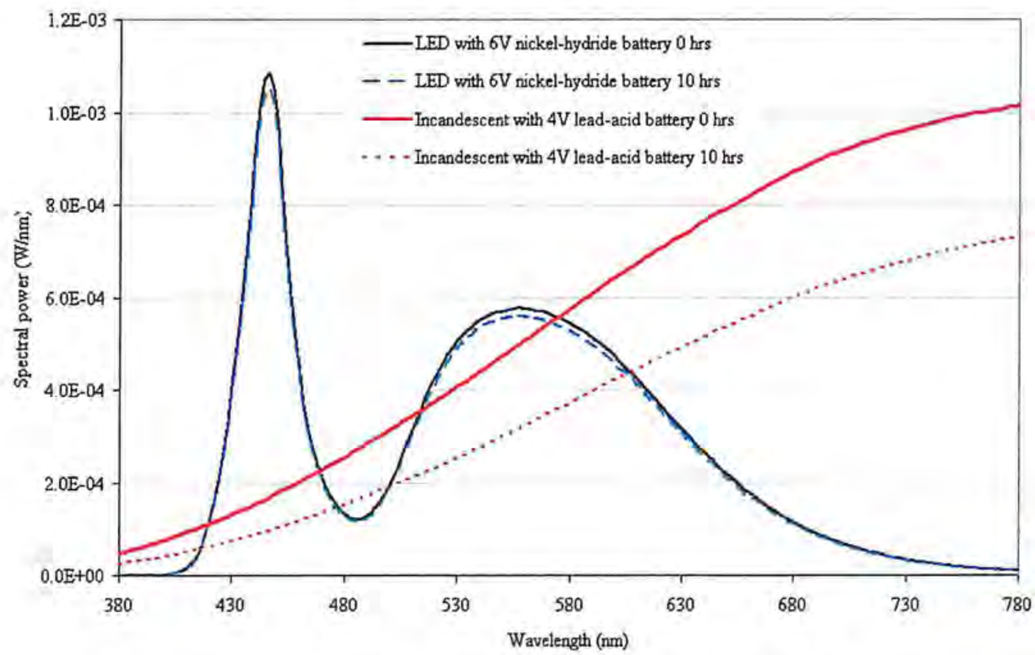

Figure 3. Spectral power distribution of the LED and INC lamp tested.

TABLE III. MESOPIC LUMINANCE CALCULATIONS FOR THE LED AND INC CAP LAMP SYSTEMS.

L (cd/m²)	E (lux)	Mesopic luminance from LED (cd/m²)		Mesopic luminance from INC (cd/m²)		ΔL	
		0 hrs	*10 hrs*	*0 hrs*	*10 hrs*	*0 hrs*	*10 hrs*
1	12.1	1	1	1	1	0%	0%
0.1	1.21	0.149	0.15	0.127	0.123	17%	22%
0.01	0.121	0.0182	0.0184	0.0142	0.0136	28%	35%
0.001	0.0121	0.00188	0.0019	0.00144	0.00138	31%	38%

TABLE IV. COMPARISON OF TWO INC LAMPS AT THE BEGINNING AND END OF LIFE.

	Electric characteristics			Photometric characteristics				
	Voltage (V)	*Current (ma)*	*Power (W)*	*Luminous flux (lm)*	*Luminous efficacy (lm/W)*	*CIE 1931 chromaticity (x,y)*		*Correlated color temperature (K)*
Beginning of life test (samples 1 and 2)	6.0	603.4	3.62	46.06	12.7	0.4403	0.4067	2965
	6.0	614.8	3.69	48.11	13.0	0.4399	0.4063	2969
End of estimate life (samples 1 and 2)	6.0	588.3	3.53	39.81	11.3	0.4448	0.4089	2910
	6.0	588.4	3.53	38.70	11.0	0.4445	0.4087	2914

output will decrease another 30% to 45 % over the period of a 10 hour shift. The main implication of the light output depreciation over the life of an INC lamp is that even when a cap lamp may pass all the photometric tests when new, it is quite possible the minimum intensity requirement of 1 cd [12] would not be met at some point as the lamp ages, resulting in reduced visibility of miners. Again, this problem is compounded by the light output reduction over the length of each shift. In terms of spectral shift, the observed change was in the order of -50 K. Though this value may seem small, it is an indication that in general the relative effectiveness of the LEDs over INC lamps calculated for mesopic conditions (Table III) will only increase as INC lamps age.

In the interest of putting this information in a certain context, it would be necessary to compare these results to LED light output depreciation and spectral shift over time. Different LED technologies have different degradation and failure mechanisms. However, in general terms, phosphor-converted LEDs have a much slower depreciation rates and a smaller spectral shift over time. As an example, it would be reasonable to take 50,000 hours for an LED's light output to decrease 30% in contrast to 1,800 hours for an INC's light output to decrease 30%. Given that an INC cap lamp would be expected to need approximately 10 lamp replacements before an LED system would be considered depreciated, the relative benefits of LED systems over INC ones hold true for each replaced INC lamp.

Lastly, we note the LED cap lamp used in this research was purchased in 2005 at which time LED luminous efficacies were about 20 lm/W. This value does not include the efficiency of the LED driver circuitry. LED luminous efficacies have significantly increased in the past two years for LEDs. Given ideal laboratory test conditions, a LED could have a luminous efficacy of 100 lm/watt.

IV. SUMMARY

Although the performance tests were conducted using relatively dated LED technologies, the results indicate the potential benefits of LED systems over INC systems. LED systems can provide higher system efficacy, resulting in improved lighting conditions for the same battery run time, or equal lighting conditions for a longer battery run time. This can potentially result in more compact system designs encouraged by the use of smaller batteries. Additionally, by using controlling circuitry, the lighting conditions provided by an LED system can remain almost constant over the duration of each shift while providing the evident advantage, from the spectral composition of phosphor-based cool white LEDs, for peripheral vision under mesopic conditions. An LED system's inherent characteristics and design advantages can potentially lead to improvements in miner's safety and productivity.

A. Disclaimer

The findings and conclusions in this report have not been formally disseminated by the National Institute for Occupational Safety and Health and should not be construed to represent any agency determination or policy. Mention of any company or product does not imply endorsement.

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