Illustrating the Luminaire Comparison Method

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***Abstract*—The Mine Safety and Health Administration (MSHA) enforces underground coal mining lighting regulations in the United States and issues approvals for electrical devices and machines. Companies submit standard test and evaluation (ST&E) documentation to MSHA when seeking approval on a machine-mounted lighting system. Subsequent machine modifications, such as changing the type of light lamp from incandescent to light-emitting diode (LED), will require an update via the revised approval modification program (RAMP). Older incandescent and fluorescent lamps are being replaced by LED technology which has many advantages. Today, thousands of obsolete compact fluorescent lamps are used in underground coal mines. Replacing these with LED lamps requires RAMP documentation for each ST&E. This could require MSHA to review virtually thousands of RAMPS that would require an exorbitant amount of resources and would create backlogs that would take MSHA potentially years to process. This problem is addressed by the luminaire comparison method (LCM) that determines if the luminous intensity from a luminaire with a replacement lamp meets or exceeds the luminous intensity of the luminaire with a legacy lamp. If it does, then the replacement lamp is determined as equivalent and can be used as a replacement. One RAMP can then replace multiple RAMPs that would be required without the LCM. One company estimates over $700,000 USD in savings; another company has saved about $200,000 USD using the LCM. It is projected that the LCM will save millions of dollars. This article provides several examples to illustrate the LCM.**

***Index Terms*—Luminance, mine lighting, underground mining.**

I. Definitions

COLOR rendering index (CRI) indicates the color appearance of an object illuminated by a light source with respect to a 2700-K correlated color temperature, incandescent light source (CRI = 100) that serves as a reference. A light source CRI greater than 90 enables excellent color rendering for tasks that require accurate color discrimination.

Correlated color temperature (CCT) indicates a white light's dominant color appearance. CCT is expressed in kelvin (k) where CCTs below 3200 K are considered "warm white" and CCTs above 4000 K are generally considered "cool white."

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Foot-candle (fc) is the non-SI unit used to describe illuminance when the unit for area is measured in square feet (lm/ft^2). When the area is measured by square meters, the unit lux is used instead (lm/m^2). One fc equals approximately 10.76 lux.

Foot-lambert (fL) is the common English unit of measurement used for luminance, and candelas per square meter, or nits (cd/m^2), is the metric unit. It is defined such that the luminance of a perfect diffuser is 1 fL when illuminated at 1 foot-candle (fc) or $\frac{1}{\pi}$ cd/m^2 when illuminated at 1 lux in SI units [1]. A candela (cd) is a measure of the luminous intensity or the light given off in a certain direction. One fL equals approximately 3.43 cd/m^2.

IES file is a data format for the electronic transfer of photometric data of the distribution of light (intensity). The data are stored in ASCII format. The IES file format is used in North America and is documented by an ANSI/IES standard [2].

Illuminance is the amount of light illuminating a surface. The SI unit is lux that is equal to one lumen per square meter. The foot-candle is a non-SI unit that is also used for illuminance.

Luminaire is defined by the illuminating engineering society of North America (IESNA) as "a device to produce, control and distribute light. It is a complete lighting unit consisting of one or more lamps and some or all of the following components: Optical control devices designed to distribute the light; sockets or mountings to position and protect the lamps, and to connect the lamps to a supply of electrical power; the mechanical components required to support or to attach the luminaire, and various electrical and electronic components …" [3].

Luminance is defined by the Illuminating Engineering Society of North America (IESNA) as the quotient of the luminous flux at an element of the surface surrounding the point and propagated in directions defined by an elementary cone containing the given direction, by the product of the angle of the cone and the area of the orthogonal projection of the element of the surface on a plane perpendicular to the given direction [3]. It is generally considered to be what people see when light is reflected off an object or, in other words, the human perception of brightness. The measurement of luminance is dependent on both the surface area and reflectance of the area [4]. As luminance is the amount of light returning from a surface and measured from a fixed angle, the measurement value does not change with distance from the surface since the area increases along with the distance [5]. However, this generally assumes that the surface area being measured is small.

Luminous intensity is measured in lumens per steradian or candela. It defines the lumens in a given direction per solid angle.

Spectral power distribution (SPD) is the radiant power emitted at each wavelength in the visible region of light.

II. Introduction

Underground mine illumination technology has changed significantly over the years. Illumination was first achieved using open flames from oil lamps and candles. Electric lighting did not occur until 1915 when the U.S. Bureau of Mines approved an electric cap lamp for use in underground coal mines. Since then, the simple incandescent lamp was improved to use a halogen incandescent lamp; other lighting technologies were developed that include fluorescent lamps and light-emitting diode (LED) lamps. More recently, LED lamps are being used in mining given the many advantages that include: more design flexibility, physical robustness given that LEDs are solid-state devices that do not have filaments or glass, less energy usage, and longer useful life. For instance, the U.S. Department of Energy determined that LED lamps can use 75% less energy and have a useful life of 25 times that of an incandescent lamp [6].

Maintaining proper illumination is critical for miners to work safely and effectively; unfortunately, underground mines are considered one of the most difficult places to light [7]. Typically, there are few places in an underground coal mine that have permanent lighting installed. Most of the mine illumination is provided by machine-mounted lighting. Underground coal mine lighting is regulated in the United States. A key element of the regulations is defined in provision 75.1719-l(d) of the code of federal regulations, which states: "The luminous intensity (surface brightness) of surfaces that are in a miner's normal field of vision of areas in working places that are required to be lighted shall be not less than 0.06 foot-lamberts …". This minimum luminance level pertains to mining machines used in by the last open crosscut, and the luminance source is machine-mounted lighting. The Mine Safety and Health Administration (MSHA) is responsible for enforcing these regulations. Companies submit standard test and evaluation (ST&E) documentation when seeking approval on a machine with mounted lighting. The ST&E documentation includes lighting compliance data, lighting and machine layouts, electrical schematics, etc. The luminance compliance data are obtained via a software program named the Crewstation Analysis Program (CAP) that was originally developed by the U.S. Bureau of Mines [8] as a practical alternative to creating a physical mockup of the machine with lighting inside a dark room, and then using a photometer to take illuminance measurements. The CAP software uses a luminaire's illuminance data obtained by measurements conducted by UL Verification Services Laboratory in Allentown, PA that has a custom-designed optical rail used for generating mining-specific photometric files. The photometric file data are obtained in compliance with MSHA ASTP 2050 ST&E ISO Intensity Curves. The CAP software enables users to import a model of a mining machine and the photometric data files. CAP enables the positioning of the machine's luminaires such that the 0.06 foot-lamberts is achieved in the required areas around the machine. CAP also provides reporting documentation that is submitted to MSHA.

The ST&E program documentation is evaluated by MSHA's Approval and Certification Center that approves products and systems for use in underground mines. ST&Es are submitted for MSHA to grant acceptances of ST&Es in lieu of MSHA conducting on-site luminance measurements by inspectors to determine if a machine complies with the luminance requirements. Accurate and repeatable on-site measurement of luminance is difficult because measurements are affected by environmental, photometer, and measurement method factors. For instance, empirical data indicated luminance measurements decreased by −42.9% when the same section of dry coal rib was wetted and up to a 76% luminance change when the photometer perpendicularity to the rib was offset by 5°; hence, field measurement of illuminance is likely to be impractical [9]. Subsequent machine modifications, such as changing the type of lamp, requires an update to an existing ST&E acceptance from MSHA. This can be achieved by submitting documentation to MSHA via the revised approval modification program (RAMP). A RAMP enables MSHA acceptance-holders to request changes to the design of their product that was previously approved via an ST&E. For mining machines, the acceptance is given for a specific machine model as equipped with the machine-mounted lighting.

Today, there are thousands of obsolete compact fluorescent lamps (CFLs) used in underground coal mines. Replacing the CFL with an LED lamp would require the machine and the lighting manufacturers to submit RAMP documentation to MSHA for each MSHA-approved machine. MSHA would then need to review potentially thousands of RAMPS and issue acceptances if warranted. The process would require an exorbitant amount of resources which would create a backlog that would take potentially years to address. An alternate method to allow for replacing the CFL bulbs with approved LEDs would be to remove the ST&E certification tag from the machine and then allow the machine to be subjected to in-mine luminance measurements to verify the 0.06 fL requirement was met. This could be an undesirable option for the mine given the uncertainties and difficulties associated with conducting accurate luminance measurements with a hand-held photometer in a mine [9], [10].

An earlier paper discusses a luminaire comparison method (LCM) devised by NIOSH to address this problem and provides an example that determines if a luminaire with a replacement lamp is equivalent to a legacy lamp by meeting or exceeding the luminous intensity of a luminaire with the legacy lamp [11]. The present article gives a broader view of the LCM by providing three examples. The first concerns the luminaire's mounting fixture. The second is an example of determining if a luminaire with an LED lamp meets or exceeds the luminous intensity of a luminaire using an obsolete, legacy CFL lamp. If the luminaire with the replacement lamp is equivalent, then just one RAMP can be used for up to 15 ST&Es as currently permitted by MSHA for machines in the mine using the luminaire with the legacy lamp. The last example illustrates an LCM limitation. Currently, this method is in use by MSHA and mining machine manufacturers in a limited capacity.

III. Methods

A. Luminaire Comparison Method (LCM)

The LCM uses a luminaire's luminous intensity data as a basis for comparison. Luminous intensity is expressed in terms of a solid angle that defines a three-dimensional angular span; hence, the luminous intensity does not change with distance. This contrasts with CAP, which uses a set of regression equations unique to each luminaire, to calculate illuminance along a vector. Note that illuminance varies with distance. This distinction is important to understand because the luminaire placement among various machines becomes irrelevant when considering luminous intensity as used by the LCM. The following hypothetical example serves to illustrate the difference between CAP and the LCM if you were to use the two methods to compare luminaires mounted on a machine. Machine A has a single luminaire located 15.2 cm (6 in) from the machine's edge on one side of the machine. Machine B is identical to machine A, except the same luminaire is mounted at 40.6 cm (16 in) from the machine's edge. The luminance provided from that luminaire on both machines will be equal, assuming there are no obstructions for either luminaire, because luminous intensity does not change with distance. The result is that if the machine A luminaire has the CFL replaced with an equivalent LED lamp that provides the required 0.6 fL needed for MSHA compliance, then the luminaire for machine B would also comply. This would not be true if the comparison was based upon illuminance as used by CAP because illuminance changes with distance. Therefore, it would be impractical to use the CAP software to compare luminaires because CAP uses illuminance that changes inversely proportional to the distance. So, it is possible that the CAP program could determine that the luminaire with the LED lamp complies; however, the CAP program would need to be used to evaluate machine B because the illuminance has decreased due to the luminaire's distance of 40.6 cm (16 in) from the machine's edge.

Basically, the LCM enables the ability to determine if the luminous intensity of one luminaire is equivalent to or exceeds the luminous intensity of another luminaire. The method accounts for measurement uncertainties (an interval around the measured value where the actual value lies with some probability) and uses the Zeta (Z) score (a measurement used in statistics to determine a value's relationship to the mean of a group of values). This method is superior to a simple greater-than or equal-to comparison between legacy and replacement lamp. For instance, a replacement lamp would not be equivalent if some of the data were less than the original lamp; however, if the Z-scores for that data oriented to a certain range of acceptable values, then the replacement lamp would be determined as equivalent.

The basic steps for the comparison method are as follows.

1) Generate IES files for the luminaire with the legacy lamp and the replacement lamp.
2) Open each IES file by using the Photometric Toolbox software or similar software and export the data to separate Excel files. Photometric Toolbox enables viewing, editing, visualizing, and analysis of IES files.
3) Use the Microsoft Spreadsheet Compare Tool to compare the two Excel files. The tool can compare two Excel workbooks and depict differences that are highlighted by color depending upon the type of difference. Results can be exported to a single Excel file that is simpler to read and more amenable to analysis.
4) Import the comparison results into an Excel file to determine equivalency per the following algorithm:
   a) If $X_i \geq X_{ref}$, then "equivalent"
   b) else if the absolute value of $Z_i < 3$, then "equivalent"
   c) else fail

where:

X_i = luminous intensity of the luminaire with the replacement lamp where *i* indicates values for each angle.

X_{ref} = luminous intensity of the luminaire with the legacy lamp.

Z_i = the Z-score that is a statistical measure that enables the comparison of measurements with uncertainty [12].

$$Z_i = \frac{X_i - X_{ref}}{\sqrt{u_x^2 + u_{ref}^2}} \tag{1}$$

where:

u_x = uncertainty of X_i

u_{ref} = uncertainty X_{ref}

The Z-score indicates the number of standard deviations away from the mean; thus, it is an indication of the difference between two measurements. A Z-score of 1 indicates one standard deviation, which can be interpreted that the difference between the two measurements is less than the measurement uncertainty. A Z-score ≥ 3 indicates the difference between the two measurements is three times the uncertainty or, in other words, the two measurements are not in agreement [12].

Note that X_{ref} = luminous intensity of the luminaire with the legacy lamp and not the mean from a population of legacy lamps. Mean values were not available because a population of CFLs were not available given the CFL was obsolete. Also, note that IES files for X_{ref} and X_i can be obtained from an independent photometric testing laboratory that can also provide uncertainty data needed for U_x and U_{ref}.

B. LCM Examples

The following examples use IES files. The IES files can be obtained from an independent photometric testing laboratory that can conduct goniophotometry to measure the angular distribution of light (candela per angle) from a luminaire. The IES files were obtained from testing done by the UL Verification Services Laboratory. A Lighting Sciences Inc. Model 6440T high-speed Type C moving mirror goniophotometer was used to measure the luminous intensity data for the IES files. The goniophotometer measurements have a $\pm$ 2.3% expanded uncertainty (k = 2, 95% confidence). Expanded uncertainty establishes a confidence interval for which a measurement result will exist. K is the coverage factor that is chosen to establish the desired level of confidence. A k value of two establishes a confidence level of approximately 95%.

After obtaining the IES files for examples 1, 2, and 3, steps 2 through 4 were conducted that enabled the extraction of candela data from the IES files (step 2), the comparison of candela data between the legacy luminaire and the luminaire with the changes (step 3), and the determination of equivalency (step 4).

1) Example 1: The intent of this brief example is to stress the importance of obtaining IES files for the complete luminaire

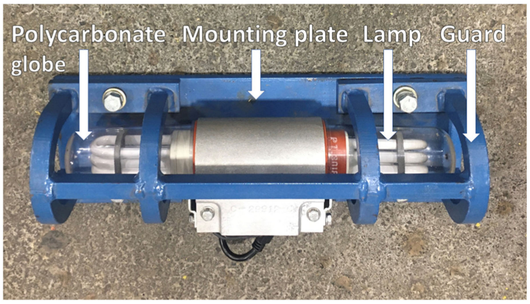


Fig. 1. Dual-lamp luminaire with clear polycarbonate globes, CFL lamps, the guard to protect the lamps, and the mounting plate used to attach the luminaire to the machine.

Fig. 2. Replacement LED lamp (left) and the legacy CFL lamp (right) used for Example 2.

that includes the mechanical components required to protect the lamp and the components to support or attach the luminaire to the mining machine (Fig. 1). MSHA-approved dual-lamp luminaires have had the approval conducted without the guard, which will alter the luminous intensity. This example uses the LCM to compare a CFL single-lamp luminaire with and without the mounting plate that will significantly alter the luminous intensity. The LCM results indicate that there were 228 instances where the luminous intensity was lower and failed the LCM benchmark.

2) Example 2: This detailed example pertains to an MSHA-approved dual-lamp luminaire with the legacy CFL (Fig. 1) that is to be replaced with an LED lamp (Fig. 2). This example uses the data from a company that manufactures mine luminaires. The company used the LCM to request MSHA RAMP approvals.

The luminaire consists of an aluminum housing, two clear polycarbonate lens enclosures on each side, and two lamps. The luminaire does not have any secondary optics. Amber-colored and frosted polycarbonate lens enclosures are also available. Amber-colored lenses are commonly used for luminaires mounted to roof bolting machines because they are perceived to reduce glare. A steel guard is installed over the luminaire once it is mounted on a mining machine.

The following information, Table I and Figs. 3 and 4, are not required for the LCM but are provided to quantify and visualize the photometric characteristics of the legacy CFL luminaire in comparison to the replacement LED lamp luminaire. Table I lists the photometric parameters; Figs. 3 and 4, respectively,

TABLE I
PHOTOMETRIC PARAMETERS FOR THE LED AND CFL LAMPS AS INSTALLED IN THE MSHA-APPROVED, DUAL-LAMP LUMINAIRE WITH CLEAR POLYCARBONATE LENS ENCLOSURES

Lamp	Total Luminaire Output (lumens)	Maximum Candela	Maximum Candela Angle*	Luminaire Efficacy (lumens/watt)
LED	4090	413	-29°H, 0°V	128.1
CFL	3087	382	-47.5°H, 0°V	59.8

*Horizontal (H); Vertical (V)

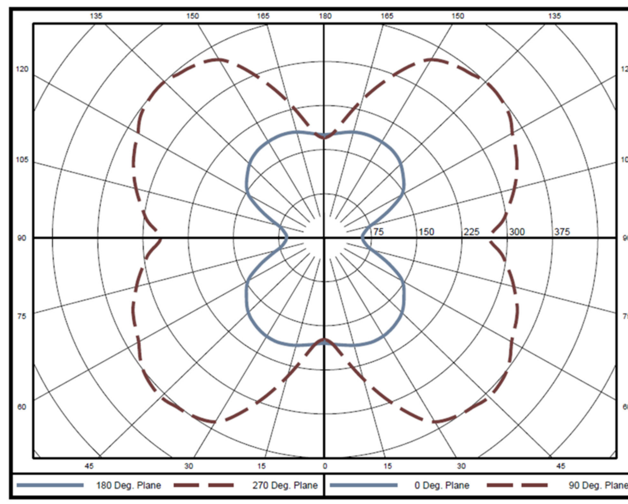


Fig. 3. Polar luminous intensity diagram of the luminaire with clear globes and the CFL lamp. The solid blue line is the "C" slice at the 0° and 180° horizontal angles and the dashed red line is the "C" slice at 90° and 270°. The "C" slice is conceptualized by "standing" at 0° horizontal and looking at the fixture. The vertical measurements from 180° down to 0° make a "C" shape. Image used with permission from Elgin Power Solutions.

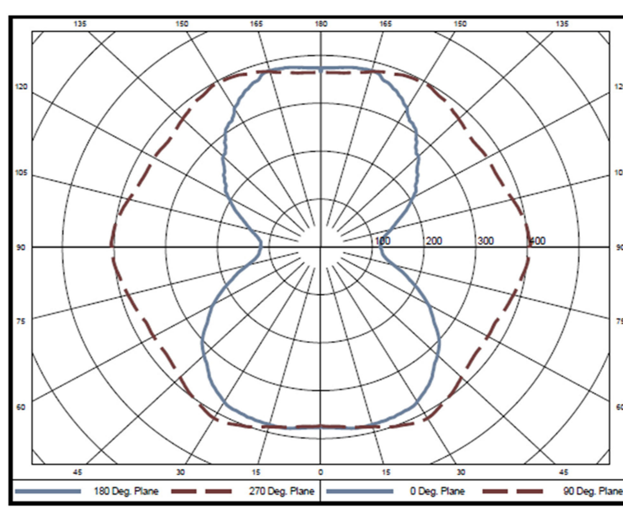


Fig. 4. Polar luminous intensity diagram of the luminaire with clear globes and the LED lamps. Image used with permission from Elgin Power Solutions.

depict the polar luminous intensity diagrams of the luminaire with the CFL and LED lamps. The polar intensity diagrams depict the angular spread of the luminous intensity in candela given a two-dimensional plane. The solid line is the transverse plane (0° and 180°), and the dotted line is the axial plane (90° and 270°).

IV. Results and Discussion

The results indicate that the luminaire with the LED lamps is an acceptable replacement for the CFL because the candela data meets or exceeds the candela data from the luminaire with the CFL lamps. The data resulted in 1805 datum for each IES file. The comparison of data resulted in 29 datum where the luminaire with LED lamps had candela values lower than the CFL; however, the Z-scores were below 3, so these differences were determined to be acceptable. The differences ranged from a 1.0% difference of 3.6 cd (Z-score of 0.298) to 0.1% difference of 0.2 cd (Z-score of .0160). There were many instances where the luminaire with LED lamps exceeded the CFL by about a 53% difference of about 194 cd.

The LCM was used by a company that manufactures mine luminaires, and multiple RAMPs were submitted. MSHA conducted an analysis of the RAMP and issued a RAMP acceptance to replace obsolete 20, 23 and 25-watt CFLs with a replacement LED lamp assembly that can be used in a single-lamp area light luminaire and a dual-lamp area light luminaire, both with clear, frosted, and amber globes. Without the LCM, 438 RAMPs would need to be generated and submitted instead of submitting a much smaller number of RAMPs for the area light luminaires. Currently, MSHA is allowing one RAMP using the LCM to be submitted for up to 15 ST&Es. The company will also be using the LCM for a headlight luminaire that would involve 280 RAMPs. The lighting company projects it will have about $700,000 USD of cost savings using the LCM in comparison to the costs to submit 718 RAMPS individually for the area light and headlight luminaires. A roof bolter manufacturer estimates it has saved $200,000 as of September 2019 because of the LCM. Cost savings are unknown for other mining product companies. Overall, projections are that the use of LCM will save millions of dollars.

The LCM is based on a comparison of the luminous intensity, so it is independent of the lamp technology (LED, incandescent, fluorescent, etc.). Second, the example provided by this article concerns a lamp replacement; however, there are other applications. For instance, a luminaire may have a lamp with a secondary optic. Changing the secondary optic will change the luminous intensity, so that it is possible to use the method to compare a given lamp with a different secondary optic or any combination of lamp and secondary optic changes. Example 1 illustrates that the LCM can also be used to determine if changes to the lighting fixture components results in a luminaire with a luminous intensity that meets or exceeds the legacy luminaire's luminous intensity.

Lastly, the LCM can be generalized to the use of EULUMDAT (also known as LDT) photometric data files having the ldt filename extension rather than IES files. EULUMDAT files are commonly used in Europe, although the file definition is not recognized by a standards organization.

A. Limitations

The LCM does not take into account lamp-to-lamp variations because the CFL lamps are no longer available to evaluate, and the manufacturer of the CFL lamps no longer had lamp variation data. Only luminous intensity data are evaluated and not data concerning the light spectrum characteristics that include the SPD, CRI, and CCT. The light spectrum can affect luminance measurement accuracy; for instance, there was a luminance error of −16% and −19% for an LED luminaire and a CFL luminance when using a photometer being evaluated by MSHA for use in the field to verify luminance compliance [10]. Second, the measurements in this study were conducted in a controlled laboratory environment; so, the measurements might differ from measurements taken in the field. Next, the LCM does not determine glare, which could be greater if the replacement lamp's luminous intensity is greater than the legacy luminaire. Glare can result in visual discomfort, a reduction or loss in visibility that could impede a miner's ability to work safely, or both [13]. Lastly, if a replacement lamp is determined not to be an equivalent substitute with respect to the luminous intensity, that does not mean that it cannot provide the luminance required by MSHA. One would need to use the CAP software to conduct an analysis to make that determination. A third example is provided to illustrate this situation where a LED lamp has the luminous intensity decreased by 10%. Using the LCM, there were 41 instances (2.3% of the data) where the 10% reduced intensity LED lamp failed to meet or exceed the intensity afforded by the legacy CFL.

The CAP software was used to determine if the 10% luminous intensity reduction for the LED luminaires mounted on a roof bolting machine was significant enough to prevent the minimum luminance required by MSHA. The CAP software was modified so that a multiplier can be applied to the light output of the LED luminaires. This modified version was then used with a multiplier of 0.9 to analyze an example roof bolter machine with LED luminaires to determine compliance with MSHA requirements.

The results from the CAP software indicate that even with the 10% reduction in light, the required minimum luminance was achieved for this specific machine and LED luminaires on that machine at the tested locations as depicted by Fig. 5. Each square of Fig. 5 depicts a 0.61 m x 0.61 m (2 ft x 2 ft) measurement area, and green indicates that the MSHA requirement has been achieved. This example does not infer that the same LED luminaires mounted on a different machine will provide the minimum luminance required by MSHA.

B. Future Work

The LCM does not evaluate discomfort and disability glare; therefore, the next steps to take are to address both types of glare using a consistent and systematic method to quantify each type of glare, and then establish glare acceptability benchmarks. Prior NIOSH glare research could be expanded for the next steps [13].

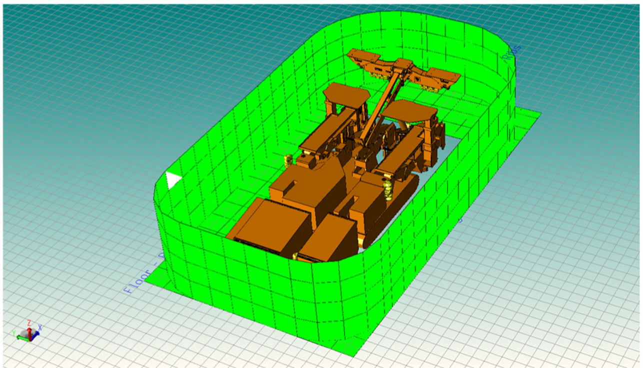


Fig. 5. CAP analysis test panel locations and results with 10% light reduction from the LED luminaires.

V. Conclusion

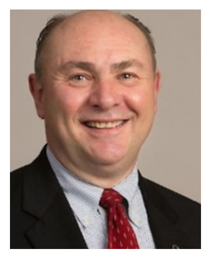
The LCM solves an industry problem concerning the replacement of thousands of obsolete CFLs. Using the NIOSH method of luminaire equivalency reduces the burden for MSHA and companies submitting lighting approvals. Without the LCM method, a great burden would be placed on everyone involved in the replacement of lighting, and this method is projected to save millions of dollars. The LCM also enables MSHA to more readily approve new lighting technologies that could result in better lighting to improve safety given that LCM is independent of the lamp technology.

Acknowledgment

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

References

[1] C. DeCusatis, *Handbook of Applied Photometry*. Washington, D.C., USA: Optical Society of America, 1998.
[2] IES. *Standard File Format For Electronic Transfer of Photometric Data*. New York, NY, USA: Illum. Eng. Soc., 2008, p. 17.
[3] D. L. DiLaura *et al.*, *The Lighting Handbook, Reference and Application*. 10th ed. New York, NY, USA: Illum. Eng. Soc., 2011.
[4] D. A. Trotter, *The Lighting of Underground Mines*. CRC Press, 1988.
[5] A. D. Ryer, *The Light Measurement Handbook*. Peabody, MA, USA: International Light Technologies, 2013.
[6] Energy Saver, Office of Energy Efficiency & Renewable Energy. Washington, DC, USA: Dept. Energy, LED Lighting, 2018. Accessed: Nov. 15, 2019. [Online]. Available: https://www.energy.gov/energysaver/saveelectricity-and-fuel/lighting-choices-save-you-money/led-lighting
[7] M. S. Rea, *Lighting Handbook: References & Application*. 8th ed. New York, NY, USA: Illuminating Engineering Society of North America, 1993.
[8] S. Gallagher *et al.*, "Computer design and evaluation tool for illuminating underground coal-mining equipment," *J Illum. Eng. Soc.*, vol. 25, no. 1, pp. 3–12, 1996..
[9] M. Martell and J. Sammarco, "Luminance measurement for underground mine lighting," in *Proc. IEEE IAS Annu. Meet.*, 2017, pp. 1–9.
[10] M. Martell and J. Sammarco, "Light source spectral power effect on luminance measurements in underground coal mines," in *Proc. IEEE Ind. Appl. Soc. Mining Committee*, 2018. Portland, OR, USA.
[11] J. J. Sammarco, "A luminaire comparison method," in *Proc. IEEE Ind. Appl. Soc. Annu. Meet.*, 2020, pp. 1–6.
[12] ISO 13528:2015, *Statistical Methods for Use in Proficiency Testing by Interlaboratory Comparisons*, Geneva, Switzerland: International Organization for Standardization, 2015.
[13] J. J. Sammarco, A. G. Mayton, and E. N. Rubinstein, "LED area lighting to reduce glare for roof bolter operators," *Mining, Metall. Exploration*, 2020, doi: 10.1007/s42461-020-00193-x.



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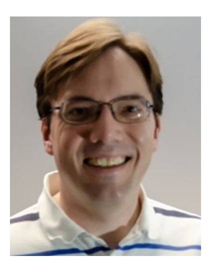

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