Luminance Measurement for Underground Mine Lighting

Max J. Martell[1], Mining Engineer
National Institute for Occupational Safety and Health (NIOSH)
626 Cochrans Mill Road, PO Box 18070
Pittsburgh, PA 15236
MMartell@cdc.gov

John J. Sammarco, Ph.D., Principal Research Engineer, Senior Member, IEEE
National Institute for Occupational Safety and Health (NIOSH)
626 Cochrans Mill Road, PO Box 18070
Pittsburgh, PA 15236

***Abstract*—Underground mine lighting is critical for the safety of miners and for the ability of miners to perform their jobs. Measuring luminance to determine proper illumination within an underground mine is faced with many challenges because in practice, luminance measurements are affected by the photometer accuracy, measurement method, and condition of the measurement surface. Laboratory experiments and field testing in an underground coal mine were performed at four rib locations in order to quantify various sources of variance, including the variances due to angle offset of the photometer, measurement distance from the coal rib, changing texture of the coal rib, and wetness of the coal. The variations among different locations of coal ribs within the mine were also considered. Results showed a very large variation in the luminance measurements that ranged from a -42.9% luminance change when the coal rib was wetted up to a 67% luminance change when the photometer perpendicularity was offset by 5°. The results indicate that field measurement of luminance is likely impractical given it is affected by multiple factors that are difficult to control in the field.**

***Index Terms*—mine lighting, underground mining, luminance**

I. Definition of Terms

A. *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 [1]. Luminance is generally considered to be what many people see when light is reflected back off of 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 [2]. 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 [3]. However, this generally assumes that the area of surface being measured is small.

B. *Illuminance* is defined by the IESNA as the area density of the luminous flux that is incident at a point on a surface and oriented in a particular direction [1]. In essence, illuminance is the total amount of visible light reaching a unit area of surface. Illuminance is the most commonly used measurement for lighting design [4]. The measurement of illuminance is affected by the distance the reading is taken from the surface according to the inverse square law [5].

C. *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 [6]. A candela (cd) is a measure of the luminous intensity, or the light given off in a certain direction.

D. *Foot-candle* (fc) is the 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).

E. *Reflectance* (ρ) is, in essence, a measure of how well a surface retransmits light, where ρ = 0 indicates all light is absorbed, and ρ = 1 indicates all light is reflected. A surface appears brighter as the reflectance increases given equal surface illumination. Surface reflectance is calculated using the following equation where L = luminance and E = illuminance at the surface [7].

$$\rho = L/E \qquad (1)$$

[1] Corresponding author

F. Specular Reflectance is exhibited from flat, smooth surfaces such as shiny metal or calm water. Reflection is directional where the angle of incoming (incident) light equals the opposite angle of reflected light, thus the brightness will change as the angle of observation changes [7]. Specular reflection reflects the light at one angle.

G. Diffuse Reflectance is exhibited by rough surfaces where the light is scattered at many different angles with respect to the incident light; Lambertian surfaces equally scatter light in many directions, causing the luminance to appear constant as the angle of observation changes [7].

II. Introduction

For as long as underground mining has been performed, illumination has been critical to both safety and to the ability of the miners to perform their work. As mining became increasingly mechanized, a clear advantage was recognized in installing lighting systems on mobile equipment. Each country has its own regulations regarding mine illumination as expressed in terms of illuminance or luminance, both of which can be measured with a photometer. Most countries around the world specify illuminance based upon the location in the mine, with some countries providing illuminance suggestions for their mining industry, and some countries simply stating that lighting must be "sufficient" or "suitable" [8]. Table 1 provides a summary of lighting requirements for various countries.

The United States of America (U.S.A.) is the only country without regulations set for illuminance, instead opting for luminance as the standard [8, 9] . The measure of luminance was preferred over illuminance in mining as it more directly correlates to what the human eye perceives [7]. The Federal Mine Safety and Health Act of 1977 required 0.06 fL (0.21 cd/m^2) in the areas around machinery, as measured by a luminance photometer. This level was considered sufficient to perform most of the tasks conducted by miners and to support proper peripheral vision. The U.S.A. requires lighting during the operation of certain types of mining equipment, including continuous mining machines, coal-loading machines, self-loading haulage equipment, cutting machines and drills, shortwall and longwall equipment, roof bolting machines, and other self-propelled equipment [10]. Particular areas to be illuminated during mining activities include the face, ribs, roof, floor, and exposed surfaces of equipment, though exact locations vary among the different types of machines. When seam heights are above 1.1 m (42 in), the measurement should be done 1.5 m (5 ft) away and perpendicular to the measured surface. It is required that the measurement area be between 0.91m^2 (3 ft^2) and 1.52 m^2 (5 ft^2) [11]. If the actual mining height is less than 1.1 m (42 in), then measurements should be done within a 1.5 m (5 ft) perimeter of the machine [12]. The accepted method for making such measurements is to take an average of the surface luminance measurements at the corners of a 0.37 m^2 area (4 ft^2) with the photometer held no more than 0.6 m (2 ft) from the measurement surface [11]. A "Go/No Go" photometer is used for this purpose [13]. The photometer's green light is illuminated when the luminance equals or exceeds 0.21 cd/m^2 (0.06 fL) and a red light is illuminated for measurements below 0.21 cd/m^2 (0.06 fL). This photometer has a 26° acceptance angle. An alternative to field measurements of luminance is to submit light survey data to receive a Statement of Test and Evaluation (STE) from the Mine Safety and Health Administration (MSHA)[13].

Table I. Summary of the specified illumination levels around machinery for various countries [2].

Country	Illuminance (*lux*)
Belgium	25
Hungary	20-50
Canada (British Columbia) **[5]**	53
Poland	10
West Germany	80
Czechoslovakia	20
United States of America	0.06 fL (Luminance)

Taking proper luminance measurements can be difficult due to the challenges of the mine environment and limitations of the light-measuring devices [2, 8]. For example, the requirements for reflected light area or photometer distance cannot always be met due to the actual size of the mine, which may not allow for enough room to take the measurement as specified by regulations. There is also a high variance in the design of different mining equipment, which means a uniform set of testing protocols may not always be possible. The mine itself can vary significantly as well, with the average reflectance of coal walls ranging from 1% to 10%, with 4% being used as the standard [7]. The way humans perceive light can also differ among individuals, meaning if the measurement taken is incorrect it would be very difficult for a person to tell by visual means alone [2]. Another source of error stems from the photometer, with accuracy of the device depending on the amount, color, and direction of the measured light, as well as physical complications such as vibrations and temperature fluctuations. Other potential factors include the angle of the measurement, the reflectiveness of the clothing and reflective materials the worker is wearing, shadows from the worker or nearby equipment, stray light from other sources including cap lamps, level of wetness of the target area, the type of lighting being considered (halogen, fluorescent, LED, etc.), roughness or smoothness of the surface area, air dust level, and the calibration of the photometer, among others. All of these factors play a role in making luminance measurements in an underground coal mine.

To the authors' knowledge, there has not been a study to investigate the practicality of using a photometer to conduct field measurements of luminance for lighting compliance. Therefore, the primary objective of this exploratory study was to advance the practice of mine lighting measurements by investigating this practicality in terms of quantifying the major factors that could significantly affect luminance measurements.

III. Methods

A. Laboratory Investigations

The laboratory measurements were conducted in the Mine Illumination Laboratory located at the Bruceton, PA NIOSH campus. Laboratory measurements enabled a much more controlled environment compared to a mine that has numerous factors affecting luminance measurements. The luminance measurements were made by using a relatively flat, 0.46 m^2 (4.9 ft^2) reference target painted with a matte paint of 4.7% reflectance. The reference target has a diffuse, specular-reflecting surface such that the luminance would generally not be constant for every angle of measurement. Coal samples can potentially have surface and reflectance irregularities making them unsuitable for laboratory measurements, and therefore were not used in the laboratory experiments.

The field measurements include the condition of wet coal ribs, however it was impractical to wet the reflectance reference target given concerns that the reflectance could be permanently altered, and it was likely that the water would not be evenly distributed given this is a flat painted surface that would be oriented vertically.

1) Luminance Photometer

The photometer used for measuring luminance was the Konica-Minolta LS-100. This photometer has a through-the-lens viewing system that visually indicates the circular area to be measured. It also has the ability to handle color correction factors to adjust the spectral response of the photometer for more accurate measurements for a variety of light sources that have different spectral characteristics. The LS-100 specifications are: luminance measurement range of 0.001 to 87,530 fL; spectral accuracy of 2% at 2800 K; electrical display accuracy of ± 2% of ± 2 digits of the displayed value.

The LS-100 has a 1° acceptance angle. The minimum measuring distance is 1014 mm (3.3 ft) and the maximum measuring distance is infinity. Measurements in the mines were desired as close as 0.6 m (2 ft) so a close-up lens was used for laboratory measurements. Note that the photometer used for the mine measurements was not used in the laboratory given it has a very large acceptance angle of 25°, thus the measurement area would exceed the size of the reflectance target. Additionally, the LS-100 is a much more precise instrument that would give a more accurate measurement of luminance in the laboratory.

A Photo Research model RS-3 reflectance standard was used to check the accuracy of the LS-100. The RS-3 reflectance standard reflectivity ranges from 98% to 100% throughout the visible light spectrum. The LS-100 accuracy was determined by using (1) to calculate the reflectance of the RS-3 reference standard given the luminance measured by the LS-100.

2) Light Source

The source of light used for illumination was the battery-powered GD-929 15 watt LED work light with a 6000 K color temperature. The light was comprised of a 20-LED panel and a reflector, which was then mounted on a tripod and positioned to illuminate the wall to 16.1 lux (1.5 fc). A diffuser filter was added to the work light to more evenly distribute the illumination of the reference target. The light source was located directly behind the photometer and positioned perpendicular to the reference target. The GD-929 was used in both the laboratory experiments and in field tests.

3) Procedures

First, the photometer zero offset was measured and the light source was aligned to provide 16.1 lux (1.5 fc) illumination of the reference target. Then luminance measurements were taken at distances between the photometer and reference target of 1.5 m (5 ft) and 0.6 m (2 ft) with the photometer at various horizontal and vertical angles. The measurement procedures are outlined as follows:

1. Set the measurement distance to 1.5 m (5 ft).
2. Align the photometer position to:
    a. Reference target (0° horizontal, 0° vertical)
    b. 5° horizontal, 0° vertical
    c. 10° horizontal, 0° vertical
    d. 10° horizontal, 5° vertical
    e. 5° horizontal, 5° vertical
    f. 0° horizontal, 0° vertical
3. Set the measurement distance to 0.6 m (2 ft) and repeat step 2.

B. Mine Investigations

1) Experimental Layout

This study was conducted in the NIOSH Safety Research Coal Mine (SRCM) and the Experimental Mine (EM) located on-site at the Bruceton, PA NIOSH campus. These room-and-pillar mines in the Pittsburgh coal seam have been used for decades by researchers to conduct experiments in a realistic coal mine setting. Both mines are inactive in that no coal is mined, however typical mine lighting and ventilation conditions are present. The SRCM coal mine entry dimensions are 6.5 ft by 14 ft, with a seam of 5.5 ft.

Two ribs were measured at the SRCM and two ribs were measured at the EM. The ribs are identified sequentially from SRCM 1 to EM 4. Although the EM ribs measured for this study are located only about 305 m (1000 ft) from the SRCM ribs, they differ in that there are layers of shale present in the EM ribs, and the SRCM ribs are entirely coal. SRCM 1 was about 91.4 m (300 ft) from SRCM 2, and EM 3 was about 9.1 m (30 ft) from EM 4.

Fig. 1 depicts the layout used at both mines. The luminance photometer and light source were placed on tripods. The relative tripod positions were replicated for each rib location. The photometer was affixed to a small platform attached to the tripod. This platform also had a laser to project a crosshair on the coal rib to help verify alignment. The laser was turned off once measurements were ready to begin.

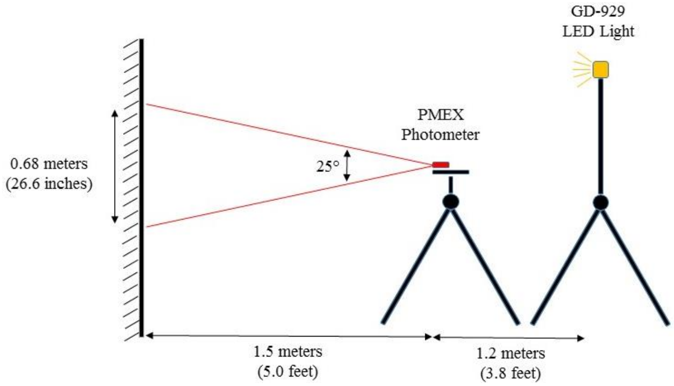

Fig. 1. General layout of the photometer and light source with respect to the mine rib. The light source was placed directly behind the photometer and positioned normal to the coal rib.

2) Luminance Photometer

The photometer used for measuring luminance was the Quantum Instruments Photo Meter PMEX. The photometer was selected because the field of view closely matches the 26° used by MSHA for measuring luminance, and because it is low-cost and simple to use in the field. It has an acceptance angle of 25° when reading luminance. Placing the photometer at a distance of 1.5 m (5 ft) from a rib (Fig. 1) results in a circular measurement area having a radius of 0.33 m (13.3 in). The photometer does not have a viewing system that visually indicates the circular area to be measured. It also does not have the ability to utilize color correction factors that adjust the spectral response of the photometer for more accurate measurements given a variety of light source types. The PMEX specifications are: luminance measurement range of 0.00 – 9.99); spectral accuracy of 7% at 2800 K; electrical display accuracy of ±1% of ±2 digits of the displayed value. A Konica-Minolta T-10A illuminance meter was used to measure rib illuminance. This illuminance meter was designed to measure pulse-width-modulated LED light sources.

3) Procedures

The procedures were designed to measure luminance given different rib surfaces, different measurement distances from the photometer to the rib, different orientations of the photometer to the rib, and different rib conditions of dry and wet.

At each rib location, a measurement of luminance was taken with no lighting in order to determine the photometer zero horizontal. Next, the light source was aligned for a rib illuminance of 16.1 lux (1.5 fc) given that this illuminance at a 4% reflectance will result in 0.21 cd/m^2 (0.06 fL) of luminance.

The following steps outline the measurement procedures at each rib:

1. Set the measurement distance to 1.5 m (5 ft).
2. Align the photometer position to:
    a. Perpendicular to the rib (0° horizontal, 0° vertical)
    b. 5° horizontal, 0° vertical
    c. 10° horizontal, 0° vertical
    d. 10° horizontal, 5° vertical
    e. 5° horizontal, 5° vertical
    f. 0° horizontal, 0° vertical
3. Remove some coal from the rib and repeat step 2.
4. Set the measurement distance to 0.6 m (2 ft) and repeat step 2.
5. Remove some coal from the rib and repeat step 2.
6. Wet the rib and repeat step 2.

Table II depicts a summary of the data sets collected when implementing the measurement procedures at each rib location.

Table II. A summary of conditions for data sets 1 through 5.

Data set	Distance		Surface altered	Surface wet
	1.5 m (5 ft)	0.6 m (2 ft)		
1	✓			
2	✓		✓	
3		✓		
4		✓	✓	
5		✓		✓

IV. Results

The laboratory and mine graphical data of Fig. 2 through 8 are presented as the luminance percentage change for each rib location and photometer positions 1 through 7 as defined by Table III. The range of luminance percentage change is given for each data set, and median data are given as a measure of central tendency as the data are not normally distributed.

Table III. Horizontal and vertical photometer angle for each condition depicted by Fig. 2 through 8.

Position	Horizontal Angle	Vertical Angle
1	0°	0°
2	5°	0°
3	10°	0°
4	10°	5°
5	5°	5°
6	0°	5°
7	0°	0°

A. Laboratory Results

The LS-100 photometer zero offset was 0 cd/m^2 (0 fL). The calculated reflectance of the RS-3 reflectance standard was 98%, using (1) with the measured luminance from the LS-100, thus indicating that the LS-100 luminance measurements are within the photometer's accuracy specifications.

Fig. 2 depicts the laboratory results in terms of the luminance percentage change with respect to position 1 for the various photometer positions and measurement distances. The luminance percentage change maximum was −16.3% at the 1.5 m (5 ft) distance and −8.3% at 0.6 m (2 ft). The median luminance percentage change was −3.3% for both photometer distances of 1.5 m (5 ft) and 0.6 m (2 ft). The Δd of Fig. 2 represents the differences between 1.5 m (5 ft) and 0.6 m (2 ft) where the range was −6.25% at position 1 to 3.7% at position 5.

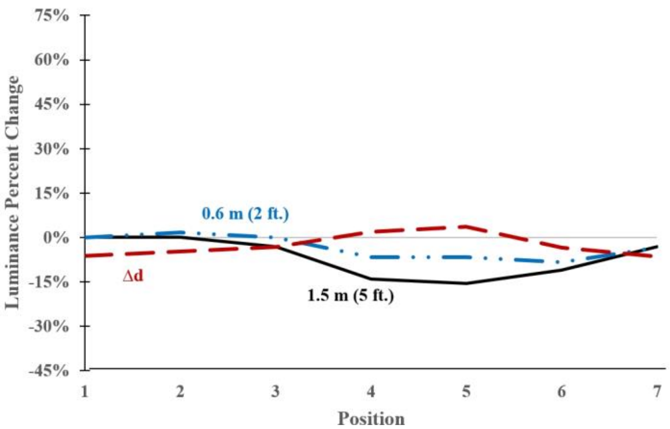

Fig. 2. The luminance percentage change in the laboratory, with respect to position 1 for each distance of 1.5 m (5 ft) and 0.6 m (2 ft) to the reference target, for the various photometer positions. The Δd represents differences between 1.5 m (5 ft) and 0.6 m (2 ft).

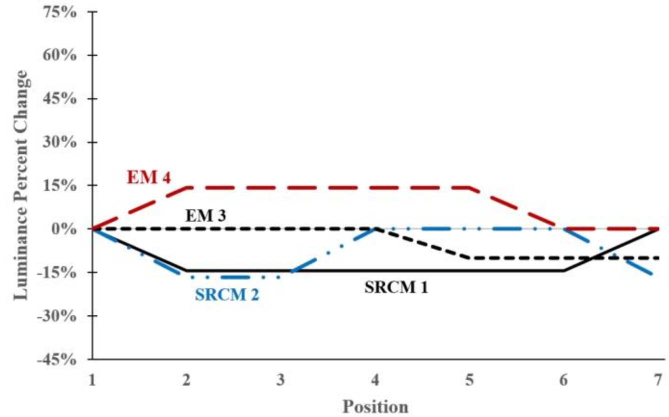

Fig. 3. The luminance percentage change, with respect to position 1, for the various photometer positons at each rib location. The measurement distance was 1.5 m (5 ft).

B. Mine Results

The PMEX photometer zero offset was 0.01 fL (0.03 cd/m^2) and was measured by turning all lights off. The following mine data results are based on the measured value of luminance and do not account for the zero offset because it would be impractical to measure zero offset in the field given all lights would need to be turned off, then turned on and given time for the lights to stabilize.

1) Initial Luminance

Table IV lists the initial values of luminance at each rib location for position 1, at a measurement distance of 1.5 m (5 ft), and a rib illuminance of 16.1 lux (1.5 fc). The data indicate the initial luminance and rib reflectance variability among the four rib locations. The rib reflectance is calculated using (1).

Table IV. Initial measurements of luminance at position 1, and calculated reflectance at the distance of 1.5 m (5 ft) given a rib illuminance of 16.1 lux (1.5 fc).

Rib	Luminance (fL)	Calculated Reflectance
SRCM 1	0.07	0.047
SRCM 2	0.06	0.040
EM 3	0.10	0.067
EM 4	0.07	0.047

2) Data Set 1: Distance of 1.5 m (5 ft) with various photometer positions and no rib surface alterations

Data set 1 was used to generate Fig. 3. The rib surfaces were dry and unaltered by the researchers. All luminance percentage change data are with respect to position 1; thus, this figure depicts the luminance percentage change due to variations of photometer position (Table III) for each rib location. The luminance percentage change ranged from 14.3% for EM 4 to −16.7% for SRCM 2. The median change for all positions and rib locations was 0.0%.

3) Data Set 2: Distance of 1.5 m (5 ft) with various photometer positions and with rib surface alterations

Data set 2 was used to generate Fig. 4. The rib surfaces were dry and were altered by using a pick to randomly chip away some of the rib surface. The alterations resulted in freshly exposed coal and changed the surface unevenness. All luminance percentage change data are with respect to data set 1 at a distance of 1.5 m (5 ft); thus, Fig. 4 depicts the effect on luminance given a slightly different rib surface with all other factors unchanged. The luminance percentage change ranged from −16.7% for SRCM 2 to 20% for SRCM 1. The median change for all positions and rib locations was 0.0%.

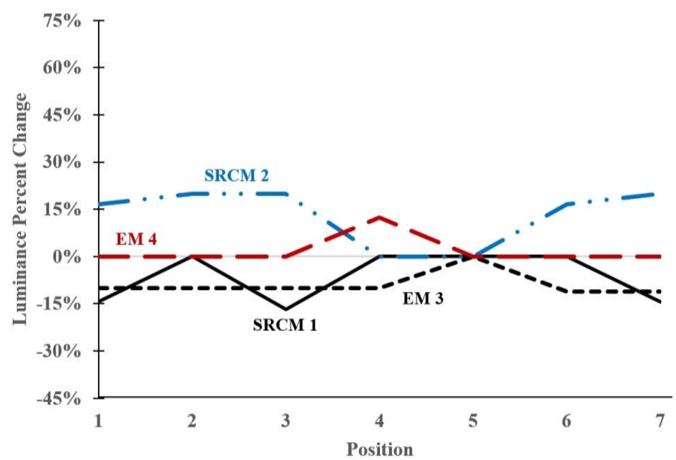

Fig. 4. The luminance percentage change, with respect to data set 1, for the various photometer positons at each rib location with rib surface alterations. The measurement distance was 1.5 m (5 ft).

4) Data Set 3: Distance of 0.6 m (2 ft) with various photometer positions and no rib surface alterations.

Data set 3 was used to generate Fig. 5. The rib surfaces were dry and unaltered by the researchers. All luminance percentage change data are with respect to position 1; thus, Fig. 5 depicts the luminance percentage change due to variations of photometer position at a distance of 0.6 m (2 ft). The luminance percentage change ranged from −25.0% to 25% for SRCM 1. The median change for all positions and rib locations was 0.0%.

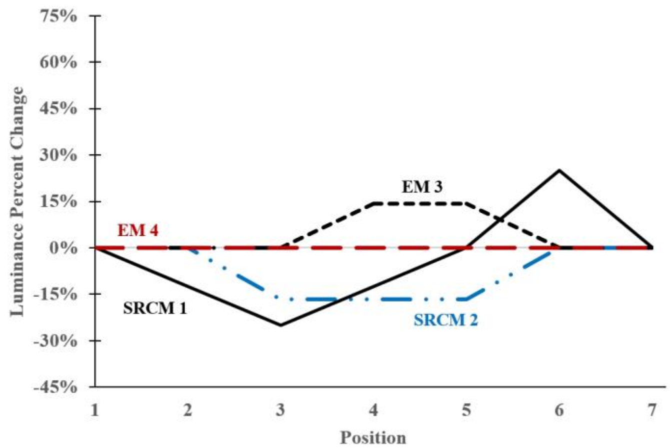

Fig. 5. The luminance percentage change, with respect to position 1, for the various photometer positon at each rib location. The measurement distance was 0.6 m (2 ft).

5) Data Set 4: Distance of 0.6 m (2 ft) with various photometer positions and with rib surface alterations.

Data set 4 was used to generate Fig. 6. The rib surfaces were dry and were altered by using a pick to randomly chip the rib surface. The alterations resulted in some freshly exposed coal and changed the surface unevenness. All luminance percentage change data are with respect to data set 3 at a distance of 0.6 m (2 ft); thus, Fig. 6 depicts the effect on luminance given a slightly different rib surface with all other factors unchanged. The luminance percentage change ranged from −25.0% SRCM 1 to 14.3% for EM 3. The median change for all positions and rib locations was −16.7%. Note that SRCM 2 data were inadvertently omitted during the field measurements.

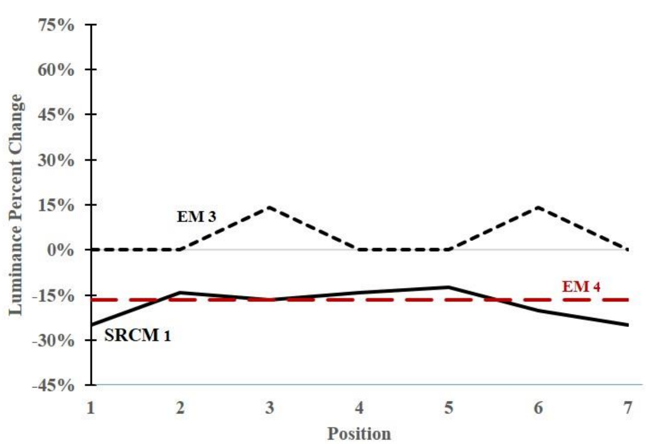

Fig. 6. The luminance percentage change, with respect to position 1, for the various photometer positons at each rib location with rib surface alterations. The measurement distance was 0.6 m (2 ft).

6) Data Set 5: Distance of 0.6 m (2 ft) with various photometer positions and with wet rib surfaces.

Data set 5 was used to generate Fig. 7, which depicts a comparison between data set 4 (dry rib at 0.6 m (2 ft)) and the fifth data set (wet rib at 0.6 m (2 ft)); thus, the figure depicts the effect on luminance given a wet rib surface for various photometer positions. The luminance percentage change ranged from −42.9% for EM 3 to 0.0% for EM 4 and SRCM 1. The median change for all positions and rib locations was −20.0%.

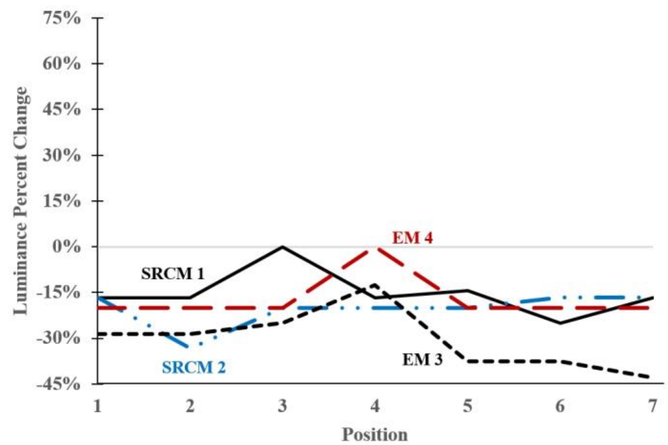

Fig. 7. The luminance percentage change, with respect to data set 5 that had dry rib surfaces for the various photometer positons. Each rib location had wet rib surfaces. The measurement distance was 0.6 m (2 ft).

7) Distance affect on luminance measurement

Fig. 8 depicts the luminance percentage change when comparing data set 2 measured at a distance of 1.5 m (5 ft) and data set 3 measured at a distance of 0.6 m (2 ft); thus, Fig. 8 depicts the effect on luminance given a change of measurement distance at the various photometer positions for each of the rib locations. The luminance percentage change at photometer position 1 (0° horizontal and 0° vertical angle) ranged from −22.2% for EM 4 to 33.3% for SRCM 1. However, the luminance percentage change ranged from −33.3% for EM 4 to 66.7% for SRCM 1 when considering all photometer positions and all rib locations. The median change for all positions and rib locations was −14.3%.

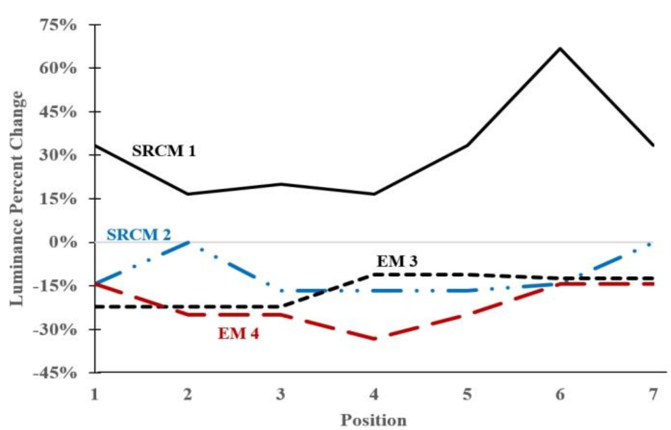

Fig. 8. Luminance percentage change due to decreasing the measurement distance from 1.5 m (5 ft) to 0.6 m (2 ft).

V. Discussion

A. Laboratory Measurements

The data depicted by Fig. 2 indicated that the reference target had diffuse specular reflectance properties. The reflectance was largely diffuse for positions 1 through 3 at the 1.5 m (5 ft) and 0.6 m (2 ft) distances. However, a component of spectral reflectance became evident at positions 4 through 6 given the decrease in luminance. A comparison of measurements between 1.5 m (5 ft) and 0.6 m (2 ft) indicated a median luminance percentage of only −3.3%, which was expected given that luminance is independent of distance if the measurement surface area illumination and reflectance are the same. It is noted that the data of Fig. 2 depicts the measurement distance differences for various photometer positions.

B. Mine Measurements

The zero offset was 0.01 fL (0.03 cd/m^2) for the PMEX photometer, therefore the field measurements would need to account for this offset. The zero offset is unknown among multiple PMEX photometers, so it is possible that the zero offsets would differ. The mine results present relative luminance percentage changes for various conditions. These data do not include the accuracy of the photometer, which would also vary among photometers depending on the time since their last calibration.

Some mine measurements were made under conditions where two factors were varying, likely resulting in interactions between those two factors. For instance, data set 2 had the two factors of rib surface condition and photometer position change. In experimental studies, the factors are more tightly controlled to ideally vary one factor at a time. However, in practice multiple factors are likely changing at the same time, as occurred during some of the mine measurements.

In general, a visual inspection of Fig. 3 through 8 does not reveal any discernible patterns in the luminance percentage change with respect to the photometer angles and photometer measurement distances. There appears to be combinations of luminance percentage changes that are constant and those that vary for portions of the photometer angles. Fig. 3 is an example where SRCM 1 luminance percentage change is constant from positions 2 to 6 but changes between positions 1–2 and 6–7. This indicates that the rib surfaces have diffuse specular reflectivity, which most coal surfaces without rock dust in a dry coal mine exhibit [8]. Consequently, the measured luminance will: 1) vary with the photometer angle when specular reflectance is encountered, and 2) be relatively constant when diffuse reflectance is encountered.

1) Initial Luminance

The initial luminance measurements at position 1 indicate a range of 0.210 cd/m^2 (0.06 fL) at SRCM 2 to 0.343 cd/m^2 (0.10 fL) at EM 4, which is a 67% increase even though each measurement was made at the same distance and with the same rib illumination of 16.1 lux (1.5 fc). The distance between these rib locations is only about 305 m (1,000 ft). The distance between EM 3 and EM 4 is only 9.1 m (30 ft), yet the respective luminance values at position 1 differed by 30.0%. One factor that varied among these initial luminance measurements was the rib surface condition (surface unevenness and composition of coal and shale) that affected the rib reflectance, which was calculated to range from 4.02% to 6.74%.

The data indicate that luminance measurements can be highly dependent upon the measurement location at a particular mine given that the surface reflectance can vary greatly. This poses a major issue for field measurements of luminance given the substantial reflectance variations and the major impact that reflectance has on luminance. For every 1% increase in reflectance, there will be a 25% increase in luminance, assuming that the illuminance is constant as calculated by (1).

2) Photometer Position

The data depicted in Fig. 3 and Fig. 5 indicate that photometer positon affects measured luminance. This is likely the result of differences in measurement area location, measurement area size and shape, and differences in the corresponding diffuse specular reflectance. For instance, at a distance of 1.5 m (5 ft) from the rib surface, a horizontal photometer offset of 10° changes the measurement area location by about 26.7 cm (10.5 in.); a 10° horizontal and 5° vertical photometer position increases the measurement area by 6.18%, or 221.5 cm^2 (34.3 in^2).

The largest range of luminance percentage changes (Fig. 5) occurred at a distance of 0.06 m (2 ft), −25% for position 3 to +25% for position 6 at rib location SRCM 1. This is likely due to factors that affect luminance being more dominant within the smaller measurement area. These factors seem to have a lesser impact when the measurement area is much larger. At 1.5 m (5 ft) position 1 (0° horizontal, 0° vertical), the measurement area is 0.36 m^2 (555.9 in^2) in contrast to 0.06 m^2 (88.9in^2.) at a distance of 0.6 m (2 ft). Thus, the factors that affect luminance would be “averaged” over a much larger area.

In the controlled conditions of this study, a tripod was used and the horizontal and vertical angles were measured to precisely control the orientation of the photometer to the rib. It would be expected that a much greater degree of variance of horizontal vertical angles would be encountered in the field given a tripod and laser-sight would probably not be used, and that there would be variations among each person making hand-held measurements given the subjective nature of the alignment of the photometer to the rib. Thus, it is likely that field measurements would significantly exceed the −25% to +25% luminance changes due to the photometer positions with respect to the rib.

3) Rib Surface

Fig. 4 and Fig. 6 depict the luminance percentage change due to rib surface changes at the measurement distances of 1.5 m (5 ft) and 0.6 m (2 ft) and given the various photometer positions. These data differ from the data described in the prior initial luminance section in that the rib surfaces at a given rib location were altered. Again, the data indicate that the rib surface is an important factor for luminance measurements as evidenced by the luminance percentage change range (Fig. 6) for SRCM 1 of −25% for positon 1 to 16.7% for positon 1 at SRCM 2 (Fig. 4). It is noted that these data reflect the changes from multiple factors: rib alterations, distance, and photometer position. The photometer position and distance factors can be eliminated when inspecting the data at position 1 (0° horizontal and 0° vertical) where at a distance of 1.5 m (5 ft) the data indicated a luminance percentage change that ranged from −14.29% to 16.67%, and 0% to −25.0% for the 0.6 m (2 ft) distance. Therefore, the data at position 1 provide additional support that rib surface is an important factor for luminance measurements.

4) Distance

Fig. 8 depicts the luminance percentage change due to decreasing the measurement distance from 1.5 m (5 ft) to 0.6 m (2 ft), given the various photometer positions. The data indicate a luminance percentage change that ranged from −33% to 67%. This is likely due to the variations of diffuse specular reflectance of the measurement areas caused by the surface irregularities. The measurement areas differ by more than a factor of 6, where at 1.5 m (5 ft) for position 1 the measurement area is 0.36 m^2 (558.0 in^2), while at 0.6 m (2 ft) the area is reduced to .06 m^2 (93.0 in^2). The smaller measurement area will yield greater susceptibility to surface variations. It would be expected that a greater range of luminance percentage change would be encountered in field measurements because of diffuse specular reflectance variations due to surface irregularities and differences in coal and potential layers of other materials, such as shale. It appears that making luminance measurements at 0.6 m (2 ft) instead of making a measurement at 1.5 m (5 ft) is likely to have a significant impact given the −33% to 67% luminance change caused by reducing the distance to 0.6 m (2 ft) in this limited study. The photometer position factor can be eliminated when inspecting Fig. 8 at position 1 (0° horizontal and 0° vertical). The data indicated a luminance percentage change of 33.3% for SRCM 1 when reducing the measurement distance from 1.5 m (5 ft) to 0.6 m (2 ft). Thus, these data provide additional support that the distance is an important factor for luminance measurements.

The laboratory percentage luminance change from 1.5 m (5 ft) to 0.6 m (2 ft) for photometer positions 1 through 7 ranged from 1.82% to −6.45% with an average of 2.66% (0.039 σ). This is in stark comparison to the corresponding mine measurement data that ranged from −33.3% to 66.7% with an average of −4.4% (0.232 σ). This is likely because the laboratory reference target reflectance is much more consistent compared to the various rib locations.

5) Wet versus Dry, and Photometer Positions

Fig. 7 depicts the luminance percentage changes between a dry and wet rib at 0.6 m (2 ft) at various photometer positions. Adding water to the rib surface increases the specular component of a diffuse specular rib, thus the luminance values will typically decrease. In general, the data indicated that a wet rib decreased the luminance where the maximum change was −42.9% for position 7 at EM 3. The photometer position factor can be eliminated when inspecting Fig. 7. At position 1 the luminance changes ranged from −28.6% for EM 3 to −16.7% for SRCM 1. Thus, the wetness of the rib is an important factor.

C. Limitations

The wet and dry measurements were made for a small set of four rib locations. It is unknown how much variation would exist if many more rib locations were measured in the SRCM and EM. Furthermore, it is unknown the range of measurement variations that would be encountered given the conditions at various coal mines and variations due to people making the measurements.

The measurement resolution of the PMEX photometer is only 0.01 fL, so the measurement values of 0.21 cd/m^2 (0.06 fL) could likely range from 0.060 fL to 0.069 fL, or about 8.3% to −6.7%. Therefore, the measurement resolution is coarse, and this likely affected some of the data collected in this study. Note that during measurements the photometer’s digital display values would sometimes bounce back and forth in the value of the least significant digit. For those cases, the larger value was selected as the datum.

This study focused on relative changes in luminance for various conditions that would potentially be experienced in a mine environment; the study did not evaluate the accuracy of the PMEX photometer for various types of mine lighting that include white fluorescent, “amber” lighting created by using an amber globe with a fluorescent lamp, incandescent, and LED light sources. This is important because the photometer’s spectral response with respect to the spectral variations among these light sources is an error source. Specifically, the photometer uses a silicon photodetector sensor with a photometric filter that together are designed to match the spectral responsivity of the human eye. It is calibrated against an incandescent reference lamp named Illuminant A that has a color temperature of 2856K. Measurement light sources similar to the incandescent reference lamp will yield relatively accurate measurements. For instance, a ±3% error would typically be encountered measuring a filament lamp at a color temperature of 2856K. However, if the spectral content of the light source varies significantly from Illuminant A, then errors can become quite significant. It would be expected that the greatest luminance errors would occur when measuring the luminance when an amber light source is used, given this varies significantly from the light source used to calibrate the photometer. One solution would be to use a spectroradiometer that separates the light source into its constituent wavelengths and samples measurements about every nanometer of wavelength, yielding greater accuracy for numerous types of light sources. However, the disadvantages of using a spectroradiometer include cost and increased expertise needed for proper usage. Quantifying the photometer’s errors with respect to its spectral response to various types of light sources would be an important future study. Another important area to investigate is how the reflectance of coal changes given these various types of light sources. The reflectance of coal is affected by the illumination source visible wavelength content [1, 8, 14]. For instance, the reflectance of bituminous coal with 87.6% carbon content varies from about 9.5% to about 10.25% from the visible wavelengths of 280 nm to about 375 nm, while the reflectance of anthracite coal with 94% carbon content will vary from about 9% to about 12.5% for the same visible wavelength range [14]. Thus, the luminance of coal will vary because of the coal reflectance changes due to visible wavelength variations among light sources, even if the coal surface illumination is constant.

VI. Concluding Remarks

This study was conducted to better understand the importance of some of the factors that affect luminance measurements in a coal mining environment. This is a first step in providing pertinent information needed before conducting a large-scale study of numerous mines in order to collect statistically inferable data.

It appears that the factors of coal surface reflectivity, measurement distance, degree of perpendicularity of the photometer to the measuring surface, changes in rib surfaces, and the surface conditions of wet versus dry are all significant factors that must be addressed. Specifically, there was up to a 67% variation in calculated rib reflectance at a measurement distance of 1.5 m (5 ft), even though the measurement locations were relatively close together. For rib location SRCM 1, there was a 33.3% change in luminance when the measurement distance was reduced to 0.6 m (2 ft) without variations in the photometer position (position 1), and from −33% to 67% when including photometer position variations; up to ±25% change in luminance when varying the photometer positions at the measurement distance of 0.6 m (2 ft), and −16.7% to 14.3% at the 1.5 m (5 ft) measurement distance; a luminance percentage change that ranged from −14.29% to 16.67% at a distance of 1.5 m (5 ft) when the rib face was altered and without variations in the photometer position. Wet versus dry surfaces for EM 3 had a −42.9% luminance change at a measurement distance of 0.6 m (2 ft).

The data presented in this study reflect the relative changes in luminance given the numerous factors affecting luminance measurement. Based on the limited data collected, it appears that it is impractical to use a hand-held photometer to make luminance measurements of a coal surface. The fact that SRCM 2 data were inadvertently omitted does not change this conclusion. The missing data would strengthen this conclusion if these data indicated luminance percentage changes that exceeded those reported in this paper. The study did not address the accuracy of the photometer, especially when measuring various mine lighting sources such as white fluorescent, "amber" fluorescent, incandescent, and LED. Inaccuracies will occur because the photometer is calibrated to a specific tungsten-filament light source that differs in light color from other mine lighting sources; however, the magnitude of these inaccuracies is not known. This accuracy issue would be very desirable to address for future research.

VII. Disclaimer

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

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