Computer Design and Evaluation Tool for Illuminating Underground Coal-Mining Equipment

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Introduction

Industrial safety professionals recognize that adequate illumination is essential to a safe and productive work environment. The need for effective lighting in underground coal mines is even greater.[1] Designing appropriate lighting systems for these mines is no easy task because of the unique environment and work procedures encountered in underground coal-mining operations. Miners must depend totally on artificial lighting systems to see. Moreover, the working face is a low-reflectivity and low-contrast environment and is continually advancing or retreating.[2]

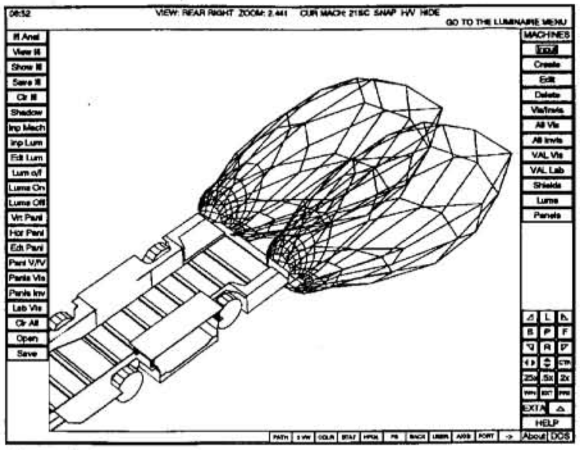

Figure 1

Laboratory mock-ups have been a major part of the process lighting equipment manufacturers must undergo to design an underground machine-mounted lighting system. The mock-ups often have taken considerable time. Furthermore, modifications to a lighting system (using different luminaires with an existing configuration or changing a luminaire's location, orientation, etc.) could require more time with additional mock-ups and laboratory measurements.

Understanding the need to improve this situation, the US Bureau of Mines has developed an alternate method for facilitating lighting system mock-ups. A PC-based, computer model, the Crewstation Analysis Program (CAP),* with the latest software technology enables users to design, alter, and evaluate underground machine-mounted illumination systems. Lux levels and distance are measured as the luminaire is moved incrementally through angular traverses about horizontal and vertical axes. The measurements and angles subsequently are entered into the model. From this input data, three-dimensional isolux or isofootcandle profiles are constructed for luminaires that can be placed at various locations and orientations on a mining machine. As an example, **Figure 1** shows a computer display of 21.5 lx or 2.00 fc profiles for luminaires mounted on a simulated mine-shuttle car. Using this information, the model allows the user to determine the lux level at different locations in space about the shuttle car.

How the model calculates illumination

During initial development of the CAP model, the isolux profile of the luminaire was determined using the inverse square law (ISL).[3] The method of gathering data comprised recording a single measurement of distance at 21.5 ±1.2 lx (2.00 ±0.11 fc) for angular traverses following 0.09 rad (5 degree) increments. This data was then used to find the illumination in space for any other distance at a given azimuth and elevation using the ISL.

Limitations, however, exist with this method.[4] The main one is that the ISL assumes a luminaire is a single point source of light, so long as the distance is greater than five times the largest dimension of the luminous area of the luminaire.[5] Also, by using a single measurement to calculate the illumination for a given luminaire in the CAP model a large error could result from an inaccurate measurement.

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**The illumination computer model, in the context of this paper, is a computer program comprising*

1. *scaled geometric models of mining machines and selected underground mine luminaires*
2. *photometric data on selected luminaires from laboratory measurements*
3. *regression-method equations to produce isolux or isofootcandle profiles (linear networks) using the photometric data*
4. *the means to position the luminaires on a mining machine model to match a specific system design*
5. *the means to evaluate the lighting system with respect to underground mine lighting standards*

The regression method used for the illumination model avoids these limitations. Seven measurements of distance and lux taken for each angular setting at 0.17 rad (10 degree) increments develop the best-fitting equation for each setting. This equation is then used to interpolate the lux level at any distance for that angular setting.

Increasing the increment of angular settings was done primarily to reduce the number of measurements to be made. Using the inverse square method, only one measurement was made at each setting compared with seven using the regression method. Considering the goals of the work and the sevenfold increase in the number of measurements per angular setting, USBM researchers decided to increase the interval between settings of azimuth and elevation from 0.09 rad (5 degrees) to 0.17 rad (10 degrees). This was done with the assurance that the isolux profiles would still accurately reflect the illuminance distribution of the selected luminaire without encumbering laboratory personnel to make a seemingly inordinate number of measurements.

Model conception

The ISL has well established that illumination at a point on a surface varies directly with the light intensity of a luminaire (or source) and inversely with the square of the distance between the luminaire and the point. The law is generally expressed as follows[6]:

$$E = (I/D^2)*\cos\theta \qquad (1)$$

where E=illumination (lx or fc) at the measured distance D

I=intensity of light source (candelas)

D=distance from the point source of light (m or ft)

θ=the angle between incident ray and normal to the surface

For the purposes of the CAP model, θ is zero; this in turn, makes cosθ equal to 1.0)

The distance is first transformed by raising it to a variable exponent and then taking the reciprocal. The transformed distances subsequently approximated linear data. Regression equations were generated using an iterative computer program that determined the optimal exponent for the distance factor. Good regression fits (typically very close to R=1.0) were developed using this approach. However, it became evident that using this procedure resulted in higher percentage errors at one end of the fitted regression line because of a weighting effect. To compensate for this, another transformation was done on the illuminance using a base-10 logarithm. This transformation reduced the scale and effectively negated the weighting effect observed without this method.

Thus, the first step in the current illumination computer model is to perform two transformations:

$$E' = \log(E) \qquad (2)$$

where E′= transformed illumination (lx or fc)

log(E) = base 10 log of the measured illumination

The second transformation to be performed changes the distance parameter using a variable exponent:

$$D' = \frac{1}{D^x} \qquad (3)$$

where D′ = transformed distance

D= distance (m or ft)

x = a variable exponent

The regression equation is then calculated:

$$\hat{E}' = \beta D' + C \qquad (4)$$

where $\hat{E}'$ = predicted illumination (transformed space)

β = regression slope

D′ = transformed distance

C = constant

Using an optimizing routine, the R-squared value (correlation coefficient) of the regression equation is evaluated to determine precisely how linear the data is, i.e., how close the fit is to the actual data. If the fit is not close enough, the exponent x is increased or decreased and the calculations are repeated. This continues until an equation is found that best fits the data, i.e., the equation giving the highest correlation coefficient.

Calculated lux values from this equation, according to a statistical analysis of preliminary data, has a mean very close to 0 percent and a standard deviation of between 3 and 10 percent from measured lux values. This indicates that more than 95 percent of all lux values calculated using this method are within 20 percent of the actual values and are evenly distributed. A higher probability of balancing the error factor exists with multiple luminaires.

With the regression method, error checking is enhanced in view of the sensitivity of the calculation. Given the seven measurements of lux and distance made for each angular setting, an apparent error, either in the measurement process or in transcribing the data, will readily show up in computing the regression. Statistical analysis of the appropriateness of the "fitted" curves over the entire range of the luminaire can be made. This provides an assessment of the quality of the measurements and analyses performed with a selected luminaire. Further, the regression method facilitates the monitoring of human error typically occurring in the process of data collection, data input entered into the model, as well as in the data analysis.

When comparing the regression method with the ISL, one notices that the two methods are not vastly different, in one sense. The regression method, which uses the basic ISL equation, does generate exponents for distance that fluctuate close to (above and below) the squared-value of distance for the ISL. Thus, one may say that the regression method "tweaks" or refines the ISL. Of course, the regression method is superior in tometry desired in underground coal mine lighting.

Table 1—Comparison of measured and computed lux levels at selected distances. The percent difference between the measured and computed levels is in parentheses.

Distance (m)	Measured (lx)	Inverse Sq. Law (lx)	Regression Eq. (lx)
0.30	853	1278 (-50)	887(-4.0)
0.91	132	142 (-7.6)	126 (4.5)
1.68	41.1	42.0 (-2.2)	40.0 (2.7)
2.35	21.5	21.5 (0.0)	21.5 (0.0)
4.12	7.10	6.99 (1.5)	7.21 (-1.5)
5.95	3.44	3.34 (2.9)	3.44 (0.0)
7.78	1.94	1.94 (0.0)	1.94 (0.0)

Table 1 displays an example of the results obtained with the regression method. Here measured and computed lux are compared according to distance. Note that readings include light reflected from some surfaces of very low reflectivity around the light source. The data in **Table 1** were obtained with the luminaire (at the top of **Table 2**) positioned at 0 rad or degrees azimuth and elevation. **Figure 2** is a graphical display comparing percent difference for the ISL and regression methods with distance.

Table 2 lists and describes a sampling of underground-mining luminaires, for which photometric measurements were made.

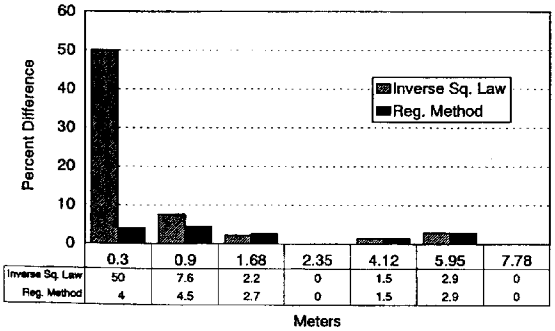

Figure 2

Collecting luminaire data

Although using the bureau's illumination software eliminates the need for mock-ups, photometric testing in the laboratory is necessary to produce 21.5 lx (2.00 fc) profiles for different models of mine luminaires. However, once this is done, the isolux profile of the luminaire can be used repeatedly in the CAP model for lighting system design. The darkroom laboratory at the Mine Safety and Health Administration Approval and Certification Center was used to collect photometric data. This laboratory was specifically designed and built for making photometric measurements and allows for collecting data with accuracy and reliability.

A Tektronix J16 photometer with a J6511 illuminance probe measured lux levels for luminaires.

Table 2—Selected underground mine luminaires that underwent photometric testing

Luminaire	Lamp	Rating
Explosion-proof, 0.18 by 0.15 by 0.11 m, heavy aluminum housing, 3 tempered-glass lenses, machine light	Incandescent	100 W @ 120 Vac
Explosion-proof, 0.13 by 0.10 by 0.11 m, ductile iron housing, tempered-glass lens, headlight	Incandescent, quartz halogen	50 W @ 12 V ac/dc
Explosion-proof, 0.97 by 0.08 m, polycarbonate lens/housing, machine light	Fluorescent	25 W @ 12 V ac
Explosion-proof, 0.13 by 0.12 by 0.10 m, aluminum housing, tempered-glass lens, headlight	Incandescent, quartz halogen	50 W @ 12 V ac/dc
Explosion-proof, 0.48 by 0.10 m, heavy aluminum housing, 2 polycarbonate threaded globe lenses, machine light	Fluorescent 2 threaded lamps	20 W (each lamp) @ 120 V ac
Explosion-proof, 0.20 by 0.13 by 0.11 m, steel housing, 3 tempered-glass lenses, machine light	Incandescent	100 W @ 120 V ac
Explosion-proof, intrinsically safe, 0.61 by 0.04 m, steel and brass housing, polycarbonate tube lens, machine light	Fluorescent	13 W @ 12 V dc

Besides undergoing factory calibration, the photometer was calibrated with a (secondary) standard light source, serial no. GS 45. The specification of the standard is 1207.9 lx (112.26 fc) at 0.50 m (1.64 ft), when lamp current maintains at 6.2693 A with a temperature of 295°K (72°F) and relative humidity of 55 percent.

The following procedures were used to collect the photometric data needed for the model.[1] The procedures are analogous to the photometric testing of floodlights using the Type B goniometer with fixed vertical axis.[7]

1. As shown in **Figure 3**, the lamp stand was placed at the end of the monorail supporting the photometer and permitting the photometer to be moved along a straight path away from the center of the lamp (**Figure 4**). The lamp stand is a heavy-duty camera tripod with attached custom-made brackets for holding each luminaire model. The tripod allows rotation of the luminaire 6.28 rad (360 degrees) in both azimuth and elevation.

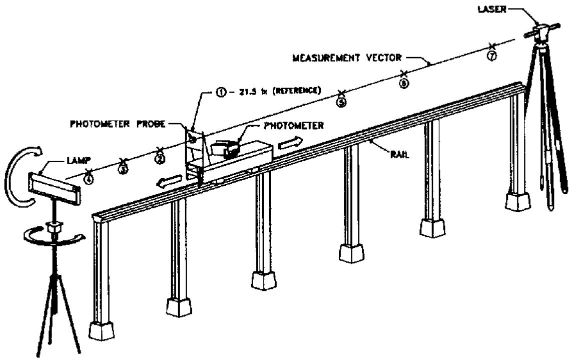

Figure 3

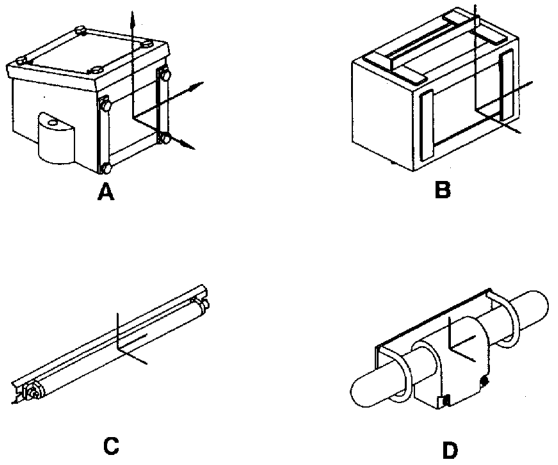

Figure 4

2. Using a laser, the center of the luminaire lens was aligned with the center of the photometer measuring probe. The luminaire was leveled side-to-side and fore-and-aft. This orientation was considered the zero azimuth and zero elevation setting for the selected luminaire (lab personnel assured that the luminaire lens and photometer probe were clean from dirt, smudges, etc.).

3. Power was switched on to both the photometer and the luminaire. The warm-up time generally comprised 60 mins.*

4. To maintain measurement accuracy, the voltage at the luminaire contacts was maintained at the luminaire manufacturer's specifications. Most lamps use either 12 V ac or V dc and 110 or 120 V ac. The main supply voltage was regulated at 120 ±1 V ac.

5. The photometer was zeroed as specified by the manufacturer. Also, precautions were taken so that extraneous light or reflections would not interfere with the measuring field of the photometer probe. All surfaces in front of the photometer probe were covered with flat black paint or flat black cloth to reduce reflectance. Laboratory personnel were careful about clothing worn and about remaining outside the measuring field of the probe.

6. The first measurement was made with the luminaire azimuth and elevation set at 0 rad or degrees. All measurements were made along the luminaire angular-setting aligned with the monorail.

7. The photometer probe was moved along the monorail until it read 21.5 ±1.2 lx (2.00 ±0.11 fc). The level and distance were then recorded. If the photometer did not read 21.5 ±1.2 lx (2.00 ±0.11 fc) anywhere along the full length of the rail due to limitations in its length, seven (roughly even-spaced) points were selected over the available rail length. The level and distance were then measured at these locations.

8. Next, the illuminance was measured at six other locations for the selected angular setting. Three roughly equal-spaced measurements were taken "inby" from the 21.5 lx position of the photometer probe to as close to the luminaire as possible. Then three roughly equal-spaced measurements were taken "outby" from the probe, as far from the luminaire as possible, or to a distance where the photometer reading falls to 1.1 ±0.05 lx (0.10 ±0.005 fc).

9. After lux measurements were made for all azimuths at 0.17 rad (10 degree) increments, the elevation was changed by an increment of 0.17 rad (10 degrees) and the process was repeated.

10. At regular intervals during the measurement

**Some lamps, such as compact fluorescents, may require up to 120 mins before they stabilize enough for measurements to be taken.*

process accuracy checks were made of the collected data. This usually occured after about 100 measurements were taken. Two measurements on either side of 0 rad or degrees azimuth (the line of the rail), were arbitrarily selected and checked for consistency with the first readings. The zero adjustment was checked at this time and readjusted as necessary.

Discussion

Studies involving application-distance photometry and near-field photometry for fluorescent luminaires, as well as IES lighting design practice, document the limitations of the ISL and offer alternatives to overcoming them.[4,6,9,10] Similarly, the regression method is presented as a means to overcome the shortcomings of the ISL and provides the accuracy and reliability needed for mine lighting design.

As mentioned above, the underground coal mine comprises a unique environment and work procedures. A typical working face of an underground coal mine is approximately 6.10 m (20 ft) wide. The mining machine in the mine entry (space between the walls of coal) is usually 3.05 m (10 ft) wide or more. This leaves 1.52 m (5 ft) on either side of the mining machine between the machine frame and the walls of coal (ribs). Moreover, machine-mounted luminaires are typically placed about the edge or recessed within the sides of the machine. Considering a double compact fluorescent luminaire with a maximum long dimensions of 0.61 m (2 ft) and applying the ISL with the five times rule would require a distance of 3.05 m (10 ft) for measurement of accurate illuminance. Obviously, this is impossible for the above working conditions. The mining regulations typically require 21.5 lx (2 fc) of illumination from within 0.30 m (1 ft) of the machine frame up to 1.52 m (5 ft) or more from the machine frame. Consequently, this shows the advantages of applying the regression method for near-field photometry.

Federal underground mine illumination standards

Regarding the end use of the CAP illumination model, it's important to understand the certification and requirements of mine lighting systems. As mentioned earlier, MSHA is responsible for enforcing underground mine-illumination standards as well as certifying lighting systems prior to being installed for operation underground. Evaluations of proposed illumination systems for an MSHA Statement of Test and Evaluation are manually taken about a mocked-up version of the selected underground mobile mining equipment with the lighting system appropriately mounted on it. Incident light measurements are taken in space with the photometer held vertically at selected points about the mocked-up mining machine. Levels measured must be at least 21.5 lx (2 fc) or greater at distances specified in the Federal coal mine regulations. If a lighting system passes this evaluation based on the minimum 21.5 lx (2 fc) requirement and complies with electrical standards, an STE is issued.

After a machine-mounted lighting system is operating underground, MSHA will enforce the mandatory luminance standard. The mine face, roof, and ribs in locations where mobile equipment operate must be illuminated with a minimum luminance of 0.21 cd/m^2. MSHA underground mine inspectors use a "go/no-go" meter to determine whether or not a mining section complies with this standard. The meter produces a red light signal if luminance falls below 0.21 cd/m^2 and a green light signal at and above this value.

Other issues of concern

Some comment is necessary regarding the cosine law. The CAP model can easily apply the cosine law in determining illuminance of a surface. However, the model attempts to duplicate the above STE process for certifying underground machine-mounted lighting systems. Because the process involves only measuring illumination at points in space, and not that of a surface, the model ignores the cosine law.

In a study dealing with broad-band photometry, Ouellette reported photometric errors of 1—11 percent in measurements of different triphosphor fluorescent sources using midpriced broad-band photometers.[11] The variation in errors was attributed mainly to mismatching in the relative spectral responsivity of the photometer with the spectral luminous efficiency of the human eye. He stated that photometric error "might not be significant in many routine illuminating engineering practices involving the estimation of average illuminance." Because the ultimate application of the computer model to underground mining involves similar illuminating-engineering practices, the errors inherent in photometric measurements from the spectral mismatching of the photometer with the luminaire are considered insignificant.

In making photometric measurements, some readings of illuminance were made at the 1.1 ±0.05 lx (0.10 ±0.005 fc) level. It is understood that the human eye at such illuminance levels does not necessarily respond photopically.[12] Although it is not intended as a means for correcting the spectral mismatches between the photometer and the luminaire, zeroing the photometer just before making a measurement at 1.1 ±0.05 lx (0.10 ±0.005 fc) is considered a prudent step to add to the procedures for collecting photometric data.

Rotating a luminaire in the horizontal and vertical planes can affect the output and stability of luminaires, particularly compact fluorescents, because the output and stability of luminaires is generally dependent on orientation.[12] As a critical part of this work, the photometry for the computer model cannot be done with the luminaire in one fixed orientation. Thus, the regression procedure used in the model does include uncertainties in photometric measurements resulting from moving the lamp in two different planes. The level of uncertainty can be estimated with information from the luminaire manufacturer.

Conclusions

The CAP illumination model is a computer software system that allows engineers to quickly analyze alternative lighting designs for underground coal mines by using illumination systems approved by MSHA. The model offers lighting vendors and mining companies greater flexibility in laying out illumination system designs and allows them to address more effectively the problem of glare in underground work areas. The regression illumination analysis method, central to the model, is an improvement over the ISL method in that it provides for near-field photometry. The regression analysis also accounts indirectly for reflected light* and allows for evaluating multiple light sources.[11] Moreover, the data shows the potential for using the method for other types of systems, but additional data would be necessary to confirm this.[12]

MSHA has approved the CAP model and uses it to certify machine-mounted illumination systems under their STE program. Similarly, lighting manufacturers are using the model, developed by the USBM and discussed in this paper, to apply for STEs from MSHA for newly designed or altered underground-mine lighting systems. The USBM plans include glare analysis as an added feature to the model in the near future.

Acknowledgments

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**** This occurs owing to surfaces in the immediate vicinity of the luminaire covered with flat black cloth or painted flat black. The reflectances of these surfaces are approximately 1—3 percent.***