Comparison of cap lamp and laser illumination for detecting visual escape cues in smoke

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Abstract
The Illuminating Engineering Society of North America reports that an underground mine is the most difficult environment to illuminate (Rea, 2000). Researchers at the U.S. National Institute for Occupational Safety and Health (NIOSH) Office of Mine Safety and Health Research (OMSHR) are conducting ongoing studies designed to explore different lighting technologies for improving mine safety. Underground miners use different visual cues to escape from a smoke-filled environment. Primary and secondary escapeways are marked with reflective ceiling tags of various colors. Miners also look for mine rail tracks. The main objective of this paper is to compare different lighting types and ceiling tag colors to differentiate what works best in a smoke-filled environment. Various cap lamps (LED and incandescent) and lasers (red, blue, green) were compared to see which options resulted in the longest detection distances for red, green and blue reflective markers and a section of mine rail track. All targets advanced toward the human subject inside of a smoke-filled room to simulate the subject walking in a mine environment. Detection distances were recorded and analyzed to find the best cap lamp, laser color and target color in a smoke environment. Results show that cap lamp, laser color and target color do make a difference in detection distances and are perceived differently based on subject age. Cap lamps were superior to lasers in all circumstances of ceiling tag detection, with the exception of the green laser. The incandescent cap lamp worked best in the simulated smoke compared to the LED cap lamps. The green laser was the best color for detecting the tags and track compared to the red and blue lasers. The green tags were the easiest color to detect on the ceiling. On average, the track was easier for the subjects to detect than the ceiling tags.

Key words: Visual detection, Mine safety, Illumination, Health and safety, Mine escape

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Introduction

The purpose of this research was to determine which color ceiling tags are easier to see in a smoke environment using different cap lamps (LED and incandescent) and different color lasers to simulate miners escaping from a smoke-filled mine in an emergency situation. Also, the same cap lamps and lasers were used to detect a moving rail track section in smoke to simulate a miner walking in a mine. 30 CFR parts 75.380 and 75.381 require that there be at least two separate and distinct travelable passageways as escapeways that are clearly marked to show route and direction of travel to the surface (30 CFR, 2010). The color, size and spacing of the escapeway markers are not specified, so they vary significantly among mines.

Prior U.S. National Institute for Occupational Safety and Health (NIOSH) research on miner self-escape includes an evaluation of devices that could provide information to evacuating miners in areas with limited visibility. These devices were a safety cane, green laser pointer and the Miniguide Ultrasonic Mobility Aid (Harteis et al., 2011). Miners had the most favorable opinion of the safety cane but did not want to carry it routinely. Other research involved interviewing miners who had escaped a smoke-filled mine in the past. The miners reported that they had a difficult time seeing the ceiling tags because they had to bend over to walk or crawl in the thick smoke. Also, they followed mine track, stopping lines, rows of props, footprints and water lines (Vaught et al., 2000).

Previous mine illumination research has shown that improving light quality decreases mining accidents by enhancing visual performance in the detection and recognition of hazards (Daly, 2001; Merritt et al., 1983). To enhance the safety of underground miners, NIOSH researchers have focused on developing a new light-emitting diode (LED) cap lamp that improves the ability of miners to detect hazards by using multiple LEDs and specialized optics that better illuminate slip, trip and fall

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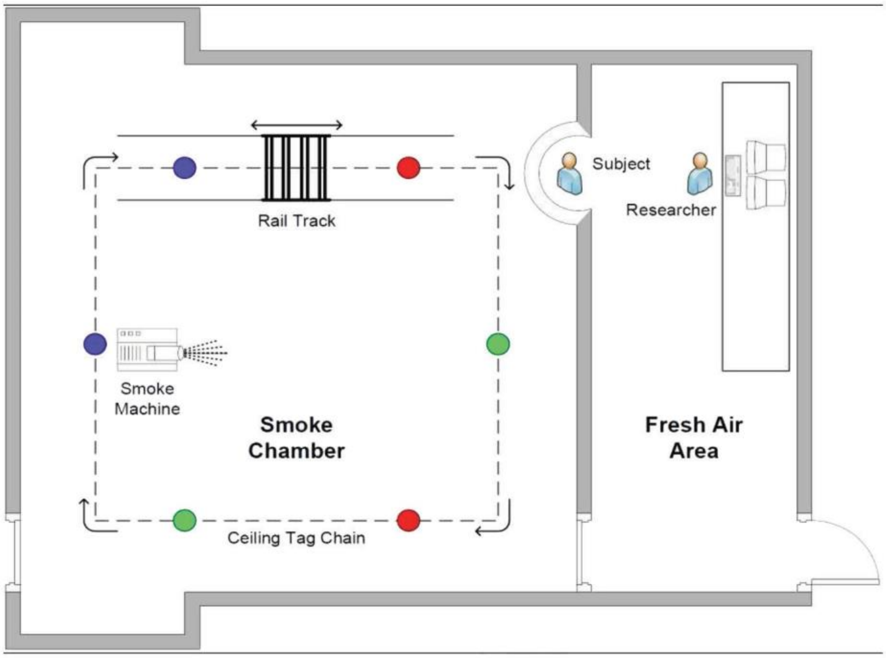

Figure 1 — Floor plan of the Mine Illumination Laboratory smoke chamber.

(STF) hazards and moving machinery hazards. Compared to other commercially available LED cap lamps, the NIOSH LED cap lamp improved floor hazard detection up to 82%, and improved peripheral motion detection—crucial for detecting moving machinery hazards—up to 79% (Reyes et al., 2011). However, mine illumination research has not scientifically determined the visibility of escape cues in smoke conditions. The visibility of ceiling tags and tracks is very important for miner rescue and self-escape in smoke.

The primary objectives of this study were to determine if ceiling tag color, type of cap lamp, color of laser light and subject age are factors for visual detection in an underground simulated smoke environment. Human subject testing was conducted using green, red and blue ceiling tags and a section of track as the visual cues. The light sources were incandescent and LED cap lamps as well as red, green and blue lasers. The test subjects were divided into three age groups to find out what differences in detection distances existed related to age.

Subjects. Federal employees at the Bruceton, PA, location of NIOSH were recruited to be subjects. Subjects signed an informed consent form and were instructed about their right to withdraw freely from the research at any time without penalty. The protocol was approved by the NIOSH Human Subjects Review Board. None of the subjects were directly involved with this research, and most of the subjects were not familiar with alternative miner cap lamps or had used them infrequently. Subjects with radial keratotomy, monocular vision, glaucoma or macular degeneration were excluded. The subject ages used in the testing were chosen to represent the young (18-25) and older (40-50+) age groups to represent the average age of U.S. miners. Only subjects who passed vision tests for distance visual acuity of 20/40 or better, contrast sensitivity of 1.72 to1.92 values of log contrast sensitivity, the absence of color vision deficiency and peripheral vision of at least 80° for each eye were accepted for the study.

There were 31 subjects in the study: 23 male and 8 female. There were 10 subjects each in the age groups of youngest (18 to 25 years) and middle (40 to 50 years) and 11 subjects in the oldest (50+ years). The average ages were 20.1 years, 44.6 years and 50.5 years, respectively. The age group from 26 to 39 years was not used because there are generally minimal changes in vision for those ages (Blanco et al., 2005). The average subject age was about 40 years, which is representative of the average U.S. mine worker's age of 41.8 years (BLS, 2009).

Experimental layout and apparatus

Smoke chamber. The NIOSH Mine Illumination Laboratory (MIL) in Pittsburgh contains a smoke chamber (Fig. 1) and the associated test apparatuses to conduct mine illumination research in a simulated smoke-filled environment. The overall dimensions of the chamber are 8.4 m (27.5 ft) long by 3.3 m (10.8 ft) wide. The smoke chamber was sealed from the outside air to contain the simulated smoke. It was also constructed to isolate the human subjects, and researchers conducting the testing, from the smoke during the testing; thus, the human subjects were in a fresh air environment with no direct contact between their eyes and the smoke, which could have caused eye irritation. A transparent window located at one end of the chamber (right side of Fig. 1) enabled the subject to see into the smoke-filled chamber. Theatrical smoke was used to simulate smoke from a mine fire.

The smoke chamber simulated an underground coal mine. The roof was constructed using plywood coated with a rough-textured material of dark color and a uniform spectral reflectivity of about 5% for the visible spectrum, which is typical for coal. The walls were made of "coalcrete," which is a combination of coal, cement and fly ash. Thus, the walls matched the texture, color and reflectivity of coal.

To create a simulated smoke-filled environment, theatrical smoke machines were used. Theatrical smoke machines use a water-based, food-grade glycol (propylene glycol, 30% and triethylene glycol, 30%) solution to generate a synthetic "smoke" atmosphere. The fluid is heated to the point of vaporization and then exhausted into the atmosphere, where it condenses to form droplets. Due to the nature of the glycols present in theatrical smoke, there may be some irritation to the mucus membranes as a result of the drying properties of the glycols. The most common effects for a similar concentration (175 to 851 mg/m^3) over a similar exposure time are dryness of the throat and eyes; these symptoms disappear once the exposure ends (Wieslender et al., 2001). Propylene glycol has a very low degree of skin and eye irritation demonstrated through several animal studies. It has also been shown to have a low incidence of irritancy in human subjects when exposed to high concentrations (>50%) of the chemical (CIREP, 1994). It is important to note that the subjects and researchers conducting the testing were physically isolated from the theatrical smoke used in the smoke chamber; thus, it did not cause discomfort nor pose a health or safety risk to the subjects or researchers conducting the testing.

To maintain a consistent smoke environment, a smoke density feedback sensor was used in conjunction with the smoke generator. The smoke feedback sensor consists of a photocell and laser located 1 m apart inside of a hollow tube with openings in the sides for the smoke to pass through. Trials prior to

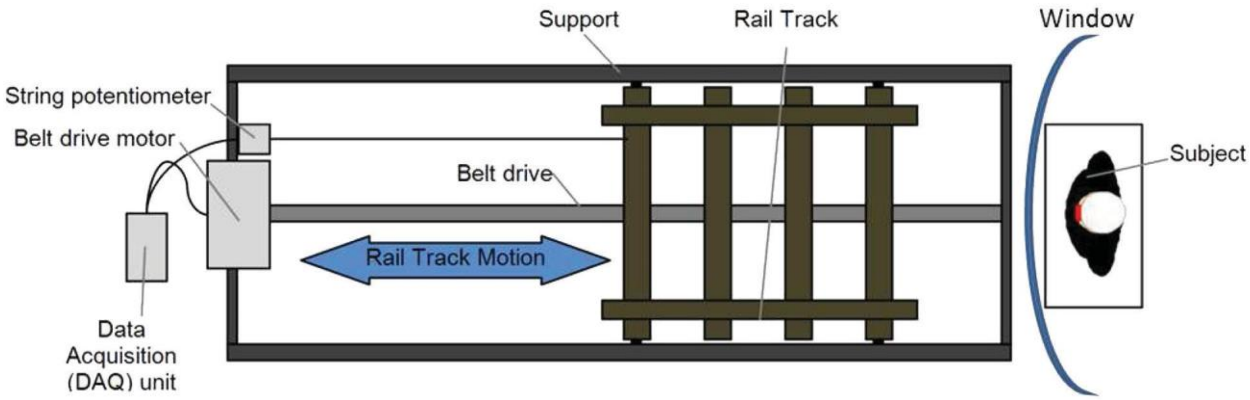

Figure 2 — The moving track section that was placed on the test chamber floor.

Table 1 — Cap lamp electrical and photometric data.

Cap lamp	Electrical characteristics			Photometric characteristics	
	Supply voltage, vdc	Supply current, amps	watts	wavelength, nm	Correlated color temp., K
1	4.00	1.00	4.00	780	2,847
2	4.00	0.76	3.04	452	8,039
3	2.80	0.24	0.67	448	6,356

testing determined the optimum density that allowed the test subjects to detect the tags in most cases, while also allowing the data to show differences between the different age groups and varying tags. Two fans inside of the chamber circulated the smoke and kept the smoke density consistent. The smoke optical density (OD), which is a measure of light transmission through smoke, was maintained at 0.028/m calculated using Eq. (1):

$$OD = (1/d) \text{ Log10 } (I_0/I) \quad (1)$$

where d = length of light path in meters,
I_0 = initial transmission of light path in clear air, and
I = transmission of light path in smoke (Rasbash, 1975).

Test apparatus. Test apparatus located inside of the smoke chamber includes colored ceiling tags on a continuous chain loop mounted to the ceiling and a moving section of track on the floor. The tags and track travel toward the human subjects in the smoke to mimic the person walking (0.91 m/sec (3 ft/sec)) through a mine. In a real mine disaster, miners will follow roof tags, tracks and life lines to escape the hazardous environment (Vaught et al., 2000).

Ceiling tags. Colored tags were hung on a continuous loop chain that was suspended from the ceiling as depicted by Fig. 1. Twelve colors were available. According to the manufacturer, green and red tags are the most popular for use in mines, so these colors were selected. The blue color was selected arbitrarily. Each tag was 3.8 cm (1.5 in.) in diameter and 10.2 cm (4.0 in.) long. The colored tags slowly advanced at human walking speed through the smoke to the subjects until the subjects indicated that they detected the ceiling tag. An electromechanical apparatus mounted to the roof of the simulated mine advanced the continuous loop of tags. The colored tags were spaced at unequal distances to help reduce predictability. The test subject indicated when the tag was detected by releasing a mouse button. The distance to detection was measured electronically by counting the chain links and was recorded by a data acquisition unit connected to a personal computer (PC) for data analysis.

Track. Miners have followed mining track during escape of a mine emergency (Vaught et al., 2000). A 1.2-m- (4-ft-) wide by 1.5-m- (5-ft-) long section of mining track was mounted on a drive mechanism as shown in Fig. 2. This section of track traveled toward the test subject at approximately human walking speed. The test subject indicated when the track was detected by releasing a mouse button. The distance to detection was measured electronically using a string potentiometer that attached to the moving track and was recorded by a data acquisition unit connected to a personal computer (PC) for data analysis.

Light sources. *Cap lamps.* Three U.S. Mine Safety and Health Administration (MSHA) approved cap lamps were used for testing. Each cap lamp was new, powered at levels for a fully charged battery, and each had a cord that connected to a power source located behind the subject. The cap lamps' electrical and photometric data are listed in Table 1. Cap lamp 1 used an incandescent bulb as the light source. Cap lamp 2 used a single phosphor-white LED as the primary light source. Cap lamp 3 was developed by NIOSH to improve the ability of miners to see mining hazards. It uses multiple, phosphor-white LEDs as the primary light source along with secondary optics to better illuminate the mine floor and ribs. Cap lamp 3 has three settings (low, medium and high light intensities) that enable variations of light intensity and distribution. The medium light intensity setting was used because the high intensity caused excessive illumination of the smoke particles, thus making it difficult to see the ceiling tags or track. This produces an undesirable visual environment, similar to that experienced when using high beams on an automobile while driving in fog. The low cap lamp setting was primarily intended to provide a minimal amount of light during low battery conditions as a means to

Table 2 — The target illuminances given the various light sources. Cap lamps 1, 2 and 3 are, respectively, the incandescent, LED, and NIOSH LED cap lamps. Illuminance values are in lux.

Target	Cap lamps			Laser			Average (all light sources)
	1	2	3	Red	Green	Blue	
Ceiling tag	4.73	6.62	12.32	1.23	2.72	0.10	4.62
Track	1.63	8.03	4.15	1.26	3.01	0.12	3.03

extend the battery life.

Each cap lamp was mounted on a linear rail mechanism located within the smoke chamber to avoid glare from the viewing window. The cap lamps were mounted as they would be when attached to a miner's protective helmet. The linear rail mechanism was connected to a series of arms and levers such that each cap lamp could be physically placed in position from outside the smoke chamber in front of the human subject.

Lasers. Green, red and blue eye-safe Class IIIa laser diode light sources were used to illuminate the targets. All lasers were low power (< 5 mW output) and had the following peak wavelengths: green = 532 nanometers (nm), red = 650 nm and blue = 405 nm. These are the same type of handheld lasers used by people giving presentations. There are some risks to using these lasers that should be noted. According to the Health Physics Society, Class IIIa lasers can be hazardous if directly viewed for a very short time period. Possible hazards include startle effects, flash-blindness, and glare and after-images if a person is struck directly in the eye by the laser beam. To address this hazard, the lasers were mounted in fixtures inside of the smoke chamber pointed away from the human subjects. The fixtures were mounted at two locations: near the cap lamps to illuminate the ceiling tags and on the floor to illuminate the track. Thus, there was no risk of the subjects looking into the laser.

Originally, the subjects were to hold and manipulate the laser, using it to search for the ceiling tags and the floor track. Pilot tests revealed that visual detection of the ceiling tags and floor track was highly dependent on the search pattern used by the subject. Thus, the search time could be very long and would have confounded data quantifying the moving target detection distance used to measure visual performance. Thus, all the lasers were mounted in fixed positions and locations to eliminate the search pattern factor.

Target illuminance. The target visibility will depend on factors that include target size, shape and target illuminance, which is used to quantify the density of luminous flux striking a surface (Whitehead and Bokosh, 1992). In general, the greater the illuminance, the more visible an object will be. Table 2 lists the target illuminances given the various light sources. The ceiling tag and track illuminances were measured at 1.83 m (6 ft) using a Konica Minolta T-10 Series illuminance meter. Measurements were taken when the chamber was smoke filled.

Procedures. The tests were conducted in the MIL with one subject at a time. Subjects were given 15 minutes for their eyes to adjust to the darkened environment of the MIL. After the dark adjustment, subjects were instructed to stand near the clear window of the smoke chamber (Fig. 1) with their chin on a chin rest so as to enable a consistent field of view among the subjects. The chin rest height was fixed at 1.5 m (5 ft) to accommodate the 50th percentile male standing height. Shorter subjects stood on a platform so that they could comfortably use the chin rest. Taller subjects stooped slightly to use the chin rest.

Instructions were given during the dark adaption time period. The subjects also conducted warm-up tests involving the cap lamp, laser pointer, and both targets to become more familiar with the testing. The subjects used a handheld, pushbutton device to start and stop the tests. The subjects depressed the pushbutton to start the test and released it when they detected a target approaching them in the smoke.

The subjects first used the cap lamps to illuminate the ceiling tags and track. The presentation order was randomized for the type of cap lamp and the type of target—ceiling tag or track. Each ceiling tag color and the track were presented three times (three repetitions). Once all combinations of cap lamps and targets were presented, the subject was given a brief rest. Next, the lasers were used to illuminate the ceiling tags and track. The presentation order was randomized for the laser color and the type of target.

Data analysis. Analysis of variance (ANOVA) was used to evaluate the effects of age groups (youngest, middle and oldest), lighting (cap lamps and lasers) and replications on the various visual targets in the smoke chamber. The four visual targets included a section of track on the floor and three colors of ceiling tags presented at the ceiling level (green, red and blue). For each of the four targets, the effect of lasers and cap lamps were examined separately. The distance at which targets were detected was the dependent variable, with larger values of distance indicating improved visual performance in target detection.

Table 3 — Results for the various combinations of light sources and targets.

	Ceiling tag	Track
	Avg. detection distance [std deviation], m (in.)	Avg. detection distance [std deviation], m (in.)
Incandescent	1.97 (77.39) [0.38 (15.02)]	2.63 (103.55) [0.76 (30.02)]
LED	1.82 (71.85) [0.38 (14.83)]	2.54 (99.91) [0.27 (10.54)]
NIOSH LED	1.88 (73.96) [0.34 (13.55)]	2.45 (96.45) [0.40 (15.84)]
Green laser	2.44 (96.07) [0.64 (25.29)]	2.75 (108.46) [0.29 (11.52)]
Red laser	1.72 (67.73) [0.55 (21.78)]	2.36 (92.85) [0.30 (11.64)]
Blue laser	1.43 (56.44) [0.76 (30.11)]	2.28 (89.66) [0.34 (13.51)]
Overall	1.88 (73.91) [0.51 (20.10)]	2.50 (98.48) [0.39 (15.51)]

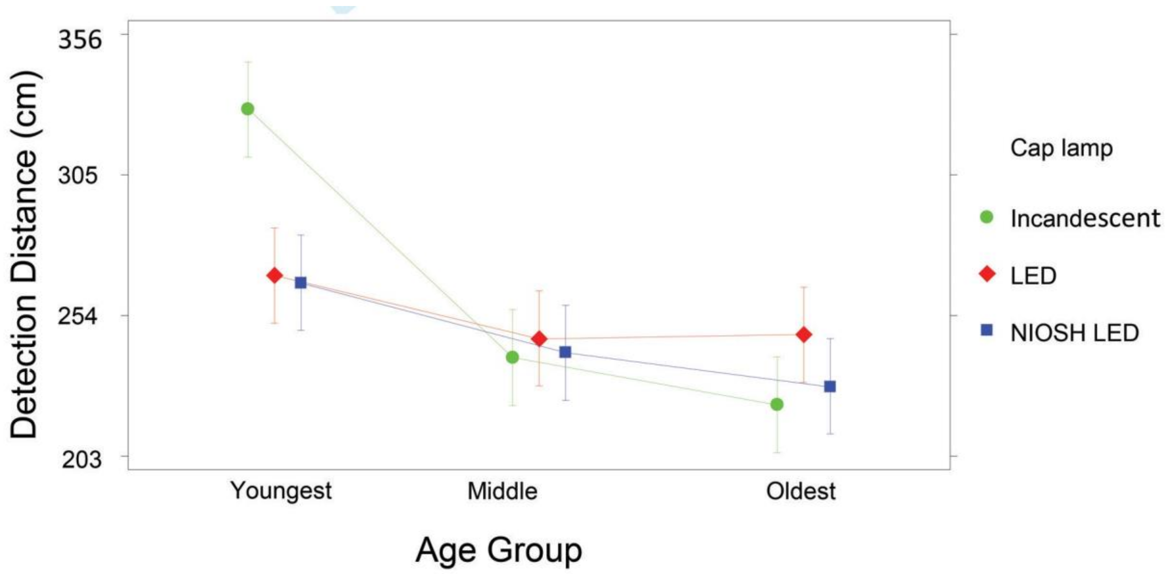

Figure 3 — Age group vs. the track detection distance when using cap lamps.

The alpha level was set at 0.05 for all analyses.[1] When statistically significant differences existed, post hoc analysis was performed in order to determine where the significant differences lie among the variable means. Therefore, Tukey's honestly significant difference (HSD) test was used. This test applies simultaneously to the set of all pairwise comparisons and identifies where the difference between two means is greater than the standard error would be expected to allow.

Results

Table 3 lists the results for the various combinations of light sources and targets. The detection distances indicate the visual performance, where the greater the distance, the better the performance. The following sections on the detection of the track and ceiling tags provide detailed statistical analyses. In some cases, the main effects were significant, but in some cases, two-way interactions also existed. Some three-way interactions also existed, thus making those results irresoluble, so these results were not included.

Detection of track. Given the use of cap lamps and lasers, the average track detection distance was 2.50 m (80.05 in.). The ANOVA for detection of the track using cap lamps demonstrated a significant interaction between age group and type of cap lamp ($F_{4,54} = 8.44$, $p < 0.001$)[2]. Figure 3 illustrates the nature of this interaction. As can be seen in this figure, the interaction is characterized by improved performance (a longer distance is better) in the youngest age group with the incandescent cap lamp. Post hoc analysis indicated that this condition was the only one significantly different from any of the other eight cap lamp/age group combinations ($p < 0.05$). Receptions (reps) were also a significant factor in performance ($F_{2,162} = 4.71$, $p < 0.05$). The first rep was found to be associated with slightly poorer performance (2.48 m (97.44 in.) detection on average) compared to the second (2.61 m (102.57 in.)) and third reps (2.54 m (99.90 in.)).

When using the lasers to detect the track, significant main effects were found for age group ($F_{2,27} = 5.17$, $p < 0.05$), laser ($F_{2,54} = 64.32$, $p < 0.001$), and reps ($F_{2,162} = 6.68$, $p < 0.01$). Post hoc tests indicated that performance was significantly better ($p < 0.05$) for the youngest age group (avg. detection distance = 2.61 m (102.6 in.)) versus the oldest group (avg. detection distance = 2.31 m (90.88 in.)). Comparison of laser color indicated better performance with the green laser (2.75 m (108.46 in.) average detection) compared to either the red or blue lasers (2.36 m (92.85 in.) and 2.28 m (89.66 in.) average detection distances, respectively). The first rep was found to be associated with slightly poorer performance (2.41 m (94.80 in.) detection on average) compared to the second (2.48 m (97.63 in.)) and third reps (2.50 m (98.54 in.)).

Detection of ceiling tags. Given the use of cap lamps and lasers, the average ceiling tag (all colors) detection distance was 1.88 m (73.91 in.). The detection results for each color of ceiling tag when using the cap lamps and lasers follow.

Green tags. The type of cap lamp used had a significant effect on the detection distance for the green tags ($F_{2,54} = 8.74$, $p < 0.001$). Specifically, the LED cap lamp demonstrated slightly poorer performance with an average detection distance of 1.87 m (73.6 in.) compared to the NIOSH LED (1.95 m (76.7 in.)) and the incandescent (2.00 m (78.8 in.)) cap lamp. There was an interaction detected between age groups and reps ($F_{4,162}$

[1] The alpha level, the significance level of a hypothesis test, is the upper boundary for Type I errors. If the *p*-value of the test is less than the alpha level, then the null hypothesis that there is not a statistically significant difference is rejected. A typical alpha is $\alpha = 0.05$.

[2] $F(4,54) = 8.44$, $p < 0.001$ indicates the significance of the interaction effect, where $F(4,54) = 8.44$ is the *F*-statistic result that is basically a ratio variance explained by the effect in question (in this case it is the interaction between age and track detection distance) and the error variance. In this result, the 4 = degrees of freedom (*df*) for the numerator (or the effect) and the 54 is the *df* denominator (the error variance). This resulting statistic is then compared to the *F* distribution and using the *df*, a level of significance is obtained. This significance level (when a priori set to 0.05) suggests that the test result is not likely to occur by chance. In other words, if $p < 0.05$, then the null hypothesis that there is not a statistically significant difference is rejected.

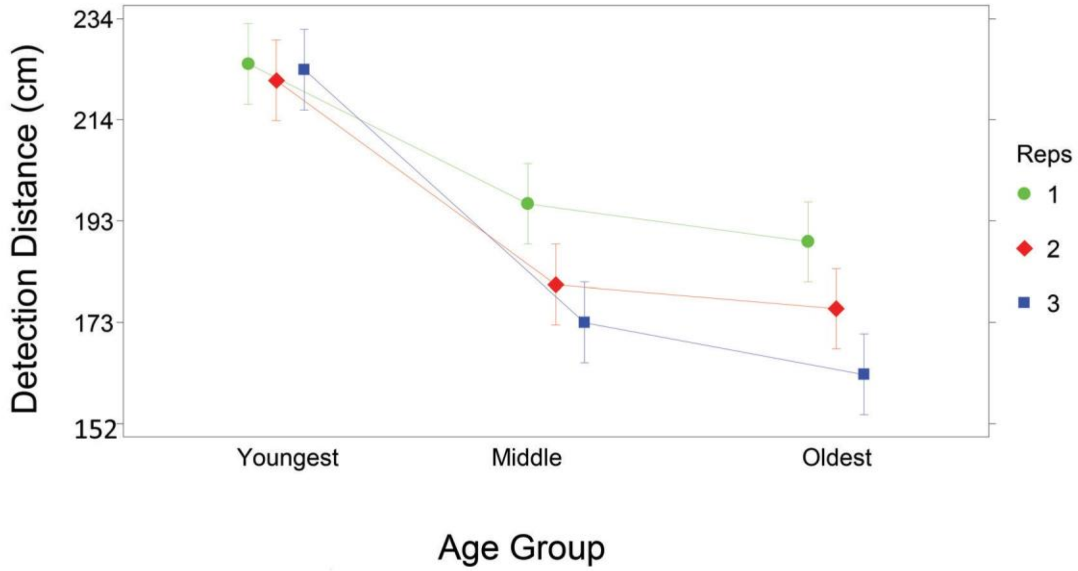

Figure 4 — Age group and replications vs. distance for trials using green tags and cap lamps.

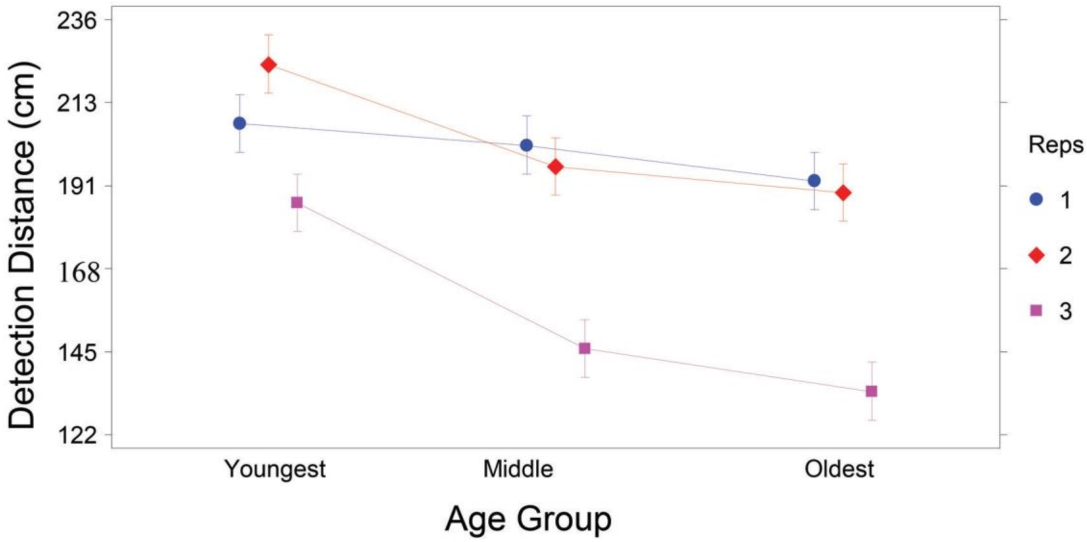

Figure 5 — Age group and replications vs. distance for trials using red tags.

= 3.23, $p < 0.05$), as illustrated in Fig. 4. As can be seen from this figure, the youngest age group exhibited almost no variability in performance between reps; however, there appeared to be increasing variability in performance between reps for the middle-age group and the oldest age group, with some deterioration in performance apparent on successive reps.

The analysis of detection of green tags using lasers resulted in a significant three-way interaction between age group, laser and reps ($F_{8,159} = 2.47$, $p < 0.05$). The pattern of this triple interaction made interpretation of these results irresoluble.

Red tags. The type of cap lamp employed again had a significant effect on the detection distance for the red tags ($F_{2,54} = 2.47$, $p < 0.05$). In this case, performance using the incandescent cap lamp (average detection distance = 1.97 m (77.6 in.)) was superior to either of the LED cap lamps (NIOSH LED = 1.82 m (71.7 in.) and LED = 1.79 m (70.5 in.)). Once again, a significant age group by reps interaction was observed ($F_{4,162} = 6.98$, $p < 0.001$). This interaction is illustrated in Fig. 5, which shows a modest decline in performance by age for reps 1 and 2; however, rep 3 resulted in decreased performance for all age groups (but more dramatic declines are seen with the two oldest age groups).

Detection of the red tags using lasers resulted in two significant interactive effects. The first of these was an age group by laser interaction ($F_{4,54} = 2.66$, $p < 0.05$). This interaction can be seen in Fig. 6. While performance always appears to be best for the green laser, followed by the red and then the blue lasers, it appears that for the youngest group, performance using the red laser was almost equivalent to that of the green laser when identifying red tags. Oldest age groups seemed to have a clearer decrement from green to red to blue lasers. It is noteworthy that the distance at which the red tags could be identified with the green laser was almost double that of the blue laser.

Blue tags. Detection of the blue tags using cap lamps resulted in significant interactions for both cap lamps by reps ($F_{4,162} = 52.85$, $p < 0.001$) and age by reps ($F_{4,162} = 52.85$, $p < 0.001$); thus, the performance for each cap lamp when detecting the

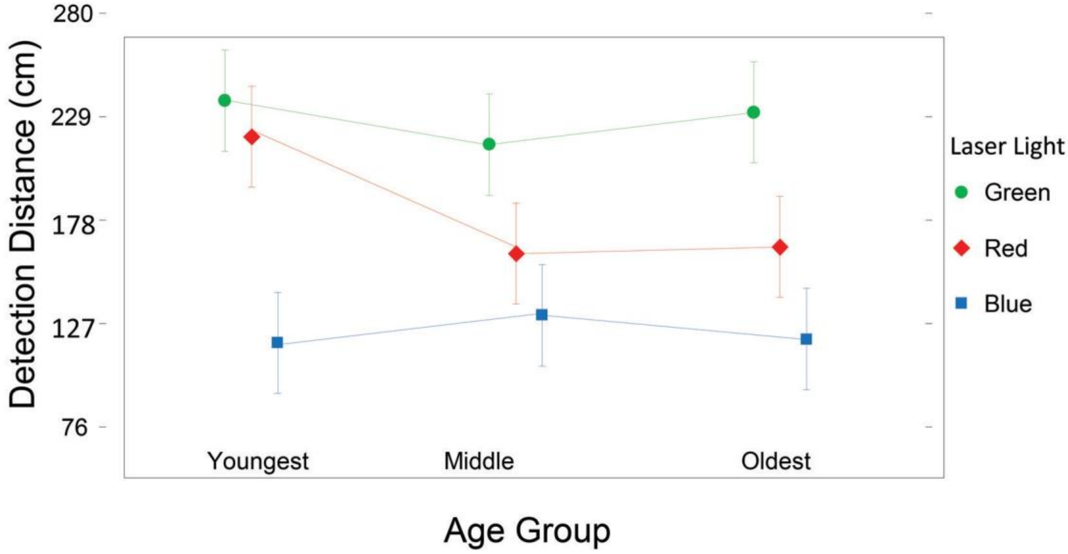

Figure 6 — Age group vs. detection distance for different laser colors using the red target.

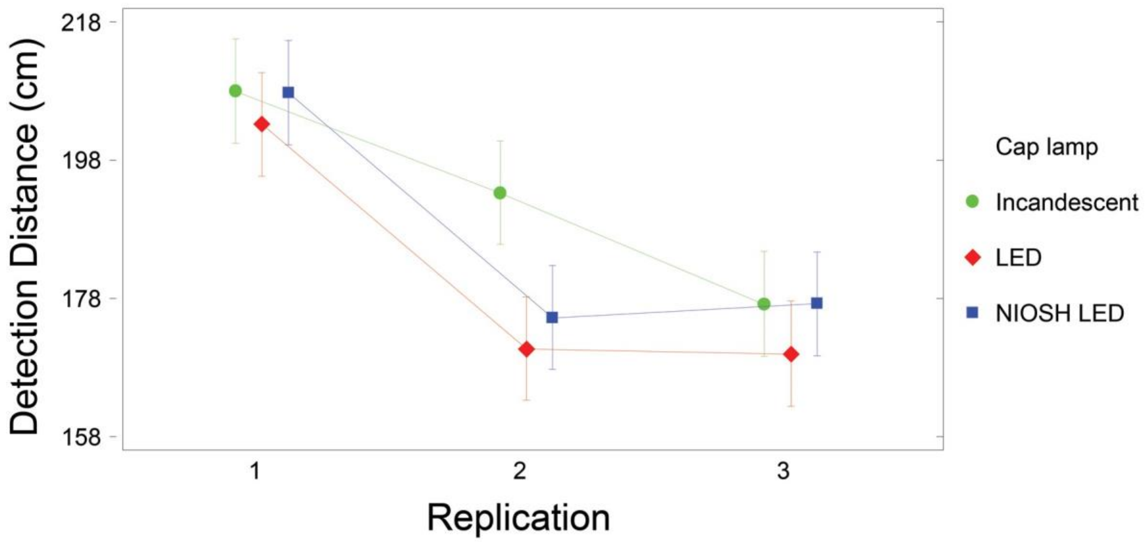

Figure 7 — Replications vs. detection distance of blue tags with different cap lamps.

blue ceiling tag is difficult to interpret given the multiple interactions. Figure 7 illustrates the effectiveness of cap lamps by replicate interaction, while Fig. 8 shows the effectiveness of cap lamps by age. The lights vs. replicate interaction shown in Fig. 9 illustrates a clear decline in performance between the first replication and subsequent replication; however, the incandescent cap lamp does not show as precipitous a drop from the first to the second rep compared to LED cap lamps. The NIOSH LED maintains a slight but constant advantage compared to the commercial LED from rep to rep.

Figure 8 shows the interaction between age groups and reps. All age groups show a decline in performance with succeeding reps, with the exception of the youngest age group, which shows an increase in performance in the third rep compared to the second.

Detection of the blue tags with lasers resulted in an age group by light interaction ($F_{4,54} = 3.04$, $p < 0.05$), shown in Fig. 9. Tukey pairwise comparisons of the means of this interaction demonstrate that the green laser always resulted in significantly better performance than either the red or the blue lasers ($p < 0.05$). The only significant difference between the red and blue lasers was the difference between them for the oldest age group. Differences between red and blue lasers were not significantly different for the two youngest age groups ($p > 0.05$).

Discussion

Results of the current study indicate rather complex relationships among the lights used in smoke conditions, the type of target being detected and the age group performing the tasks. However, while several interactions were present for many of the comparisons tested, a number of important findings can be gleaned from this study.

One generalized message from the current study was that, on average, the track was easier for the subjects to detect than the ceiling tags, where the average detection distances were 2.50 m (98.48 in.) and 1.88 m (73.9 in.), respectively. This was likely due to the significantly larger size of the track compared to the ceiling tags. Furthermore, it appeared that the incandescent cap lamp conferred a benefit to the youngest subjects when detecting the track (Fig. 3); however, this benefit was not observed for the two older age groups. The incandescent cap lamp color-corrected temperature is indicative of a warm-white

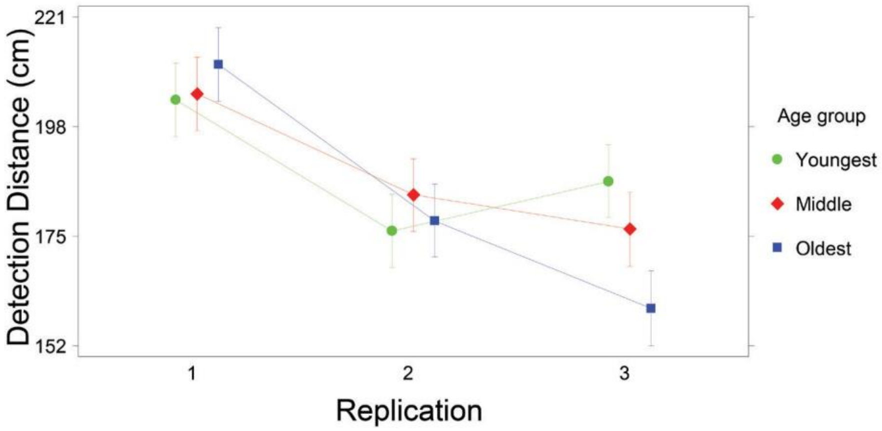

Figure 8 — Replications vs. detection distance of blue tags for different age groups.

there was a tendency for the middle and oldest group performance to deteriorate faster than the youngest group with the second and third reps when detecting ceiling tags. This pattern was reversed, however, with track detection.

Repetitions were also shown to be a significant factor in the detection of the ceiling tags when using the cap lamps. In general, there was a trend of decreasing performance as the repetitions increased. This could be indicative of glare produced by the cap lamps. In addition to illuminating the ceiling tags, the cap lamps illuminate the smoke such that light will be reflected back to the eyes of the subject. This reflected light can cause glare that can impair one's ability to see the targets in the smoke. Glare is proportional to the illuminance measured at the eyes. The average illuminance at the eyes was 2.0 lux when using the cap lamps compared to an average of 0.04 lux from the lasers. Repetitions were also shown to be a significant factor in the detection of the track when using either the cap lamps or the lasers. In general, there was a trend of improving performance as the repetition increased. This could be indicative of a learning effect, where performance improves as subjects become more familiar with the testing. Glare-induced eye fatigue was not as much of a factor because the subjects were looking down to see the track, thus avoiding the glare caused by the cap lamps.

We now note several limitations with the study concerning the light sources, smoke, targets and subjects. First, the positioning of the light sources was fixed so as to enable consistency among all subjects for the detection of the targets; hence, the results pertain to a given positioning of the light sources.Actual miners might remove their cap lamps from their hard hats and use them as a hand-held flashlight, thus causing the positioning and resulting performance to vary. Next, the theatrical smoke used for the testing was a white-colored smoke, which would differ from some mine fires if a rubber item such as a conveyor belt was burning. A black smoke would be more likely in that situation. Further, variations in the smoke due to density, particulate size, reflectivity and color would differ from actual mine fires. Thus, detection distances in the field could vary from a laboratory-controlled atmosphere. Also, the ceiling tags and track section used in the testing were clean, which may or may not be a real world case in an active mine environment. Rock dust and coal often cover the reflective tags and the track. The study was also limited by the ceiling tag colors chosen for the human subject testing. Three representative colors were chosen but there are nine other colors available. Other aids such as a lifeline are used to orient miners to the escapeways. However, the lifeline was not used in our testing, given that it is primarily a tactical aide where miners feel the shape of the cones that indicate the direction of the escapeway. Lastly, subjects with color vision deficiencies (color blindness) were not included in the study. The most frequent forms of human color blindness are collectively called "red-green color blindness;" therefore, we do not know how well subjects with color blindness would have detected the red, blue and green ceiling tags.

light, which will result in better color rendition that could have been apparent to only the youngest subjects.

When lasers were used to detect the track, the green laser led to a 17% to 21% improved performance compared to the red and blue lasers, respectively. This is likely due to the spectral sensitivity of the eye, which has greater sensitivity to green compared to red or blue. In addition, there was a significant age difference in detection performance of the track with the lasers. Specifically, the youngest age group had the best performance when lasers were used. The superior performance for the youngest group was also evident (Fig. 3) when cap lamps were used. Thus, age is a significant factor when detecting the rail, and this result is consistent with other mine illumination research (Sammarco et al., 2009a; 2009b).

The results tended to be more straightforward (with fewer interactions) when the track was the target, suggesting that other influences were more likely to affect the results when the ceiling tags were being detected. But again, important findings can be gleaned from the ceiling tag testing. Better performance of the green laser was observed when identifying ceiling tags, followed by the red and then the blue laser. Colors of the tags were more difficult to distinguish with the lasers compared to the cap lamps. The lasers seemed to create a halo of light in the theatrical smoke and the ceiling tags tended to show up as silhouettes, with the exception of the green ceiling tag and green laser combination.

Cap lamps were superior to lasers in all circumstances of ceiling tag detection, except when using the green laser. However, differences in performance among the cap lamps were not as clear-cut as the differences among lasers. The incandescent cap lamp showed indications of performing better in these smoke conditions, with the NIOSH LED being slightly better than the LED cap lamp by small margins in most cases. It is not exactly clear why this is the case, but it is possible that the brighter white LED cap lamps reflected more off of the white theatrical smoke used in these tests and the incandescent cap lamp enabled better color rendering. It should be noted that in a real mine fire situation, the smoke would be darker (gray or black) in nature, and it is not known whether the benefit of the incandescent light in white smoke would transfer to situations in which smoke is much darker in nature.

Though not always consistent, and sometimes obscured by interactions, there were declines evident in performance with age—typically a large difference between youngest and middle and less of a difference between middle and oldest. There were some tendencies for different lights to affect age groups in different ways as shown in Figs. 3-6 and 9. Furthermore,

Conclusions

Results show that cap lamp type, laser color and target color do make a difference in detection distances, as well as subject age. Cap lamps were superior to lasers in all circumstances of

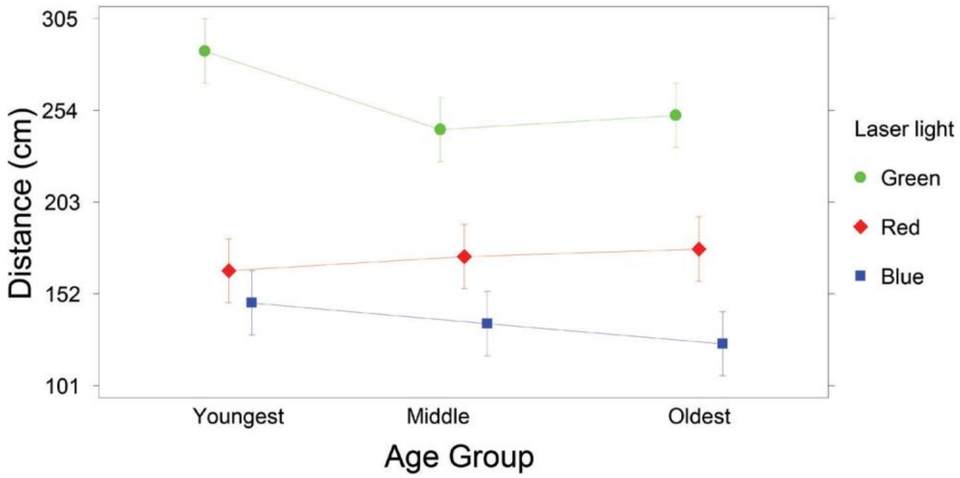

Figure 9 — Age group vs. detection distance of blue tags using different laser colors.

ceiling tag detection, with the exception of the green laser. The incandescent cap lamp worked best in the simulated smoke compared to the LED cap lamps. The green laser was the best color for detecting the tags and track compared to the red and blue lasers. The green tags were the easiest color to detect on the ceiling. On average, the track was easier for the subjects to detect than the ceiling tags.

This study provides some insight on the complex nature of seeing in a smoke environment and detecting colored ceiling tags and track for escaping when illuminated by cap lamps and various laser colors. The type of cap lamp, laser color, visual target type, ceiling tag color and subject age all play a part in detecting visual escape aides in smoke. Much was learned from this study, which can provide a foundation for additional research to determine how to enhance cap lamps to improve visual performance in smoke, to determine if better visual performance could be afforded by different ceiling tag colors and to determine the effects of dark-colored smoke. The potential impacts could lead to new cap lamp designs and a standardization of ceiling tag colors that are the most visible in smoke. Collectively or separately, these impacts could improve miner safety and the knowledge gained could potentially cross over to benefit others, such as firefighters.

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Disclaimers

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.

References

Blanco, M., Hankey, J., Dingus, T., 2005, *Phase II-Study 2: Visual Performance During Nighttime Driving in Rain. Enhanced Night Visibility Series*, vol. IV. U.S.Department of Transportation.

BLS, 2009, *Current Population Survey*, Table 16: Employed persons by detailed industry, sex, and age, annual average 2009, United States Bureau of Labor Statistics.

Code of Federal Regulations, 2010, Washington DC: U.S. Government Printing Office, Office of the Federal Register.

CIREP (Cosmetic Ingredient Review Expert Panel), 1994, "Final report on the safety assessment of propylene glycol and polypropylene glycol," *Journal of the American College of Toxicology*, No. 13, pp. 437-491.

Daly, C.,2001, *Close Aspect Lighting in Underground Coal Mines*, Australian Coal Association Research Program, (ACARP) #C7032.

Harteis, S.P., Alexander, D.W., Chasko, L.L., and Slaughter, C.J., 2011, "Evaluation of devices to enhance miner self-escape in smoke-filled entries," Society for Mining, Metallurgy, and Exploration (SME) Annual Meeting, Feb 27-March 02, 2011, Denver CO, Preprint 11-001.

Merritt, J., Perry, T., Crooks, W., and Uhlaner, J., 1983, Recommendations for minimal luminance requirements for metal and nonmetal mines, Contract J0318033. U.S. Bureau of Mines, Pittsburgh, PA.

Rasbash, D.J., 1975, "Sensitivity criteria for detectors used to protect life," *Fire International*, Vol. 5, No. 40, pp. 30-49.

Rea M.S., ed., 2000, *Lighting Handbook: Reference & Application*, 8th ed., New York, NY: Illuminating Engineering Society of North America.

Reyes, M., Sammarco, J., Srednicki, J., and Gallagher, S., 2011, "Comparative evaluation of light emitting diode cap lamps with an emphasis on visual performance in mesopic lighting conditions," *Proceedings of the IEEE Industry Applications Society 44th Annual Meeting*, Orlando, FL, October 2011.

Sammarco, J., Reyes, M., Bartels, J., and Gallagher, S., 2009a, "Evaluation of peripheral visual performance when using incandescent and LED miner cap lamps," *Proceedings of the IEEE Transactions of Industry Applications*, Vol. 45, No. 6, pp. 1923-1929.

Sammarco, J., Reyes, M., and Gallagher, S., 2009b, "Do light-emitting diode cap lamps enable improvements in miner safety?" *Mining Engineering*, Vol. 61, No. 6., pp. 43-49.

Vaught, C., Brnich, M.J., Mallett, L.G., Cole, H.P., Wiehagen. W.J., Conti. R.S., Kowalski. K.M., and Litton. C.D., 2000, *Behavioral and Organizational Dimensions of Underground Mine Fires*, U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Informational Circular, IC 9450, 124 pp.

Wieslander, G., Norback, D., and Lindgren, T., 2001, "Experimental exposure to propylene glycol mist in aviation emergency training: acute ocular and respiratory effects," *Journal of Occupational and Environmental Medicine*, Vol. 58, pp. 649-655.

Whitehead, K. and Bockosh, G., 1992, *Society for Mining, Metallurgy, and Exploration (SME) Mining Handbook*, 2nd Edition, Vol. 1, Chap. 11.9.

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FOREWORD

As the 2013 president of the Society for Mining, Metallurgy and Exploration, Inc., I am pleased to present the 2013 issue of the *Transactions of the Society for Mining, Metallurgy and Exploration*, Vol. 334. The timely publication of professional papers that promote the advancement of scientific and technical knowledge is critical for enabling technology transfer. SME plays a key role in this process through its publications. Communication within the mining community is the key to a successful profession and society. This technology exchange continues a tradition that dates back to the 1871 meeting of 22 mining engineers in Wilkes-Barre, PA, that resulted in the founding of AIME; those individuals envisioned that these transaction volumes "would form a most valuable and greatly needed addition to our professional literature." This volume fulfills that pledge.

The 2013 *Transactions* contains 73 papers covering most every aspect of the mining life cycle and encompassing the diverse sectors of our industry including coal, industrial minerals, metals, health and safety and computational methods. It includes all 18 papers published in 2013 in the Technical Papers Section of *Mining Engineering* magazine (Vol. 65) and all 33 papers published in 2013 in *Minerals & Metallurgical Processing* (Vol. 30). Additionally, this volume contains 22 papers that are being published for the first time in this issue. The papers presented in this volume were written by some of the most distinguished professionals in the industry worldwide.

Some of the many research highlights from 2013 include discussions of perennial issues, such as how to adequately prepare the next generation of mining engineering students for the workforce (Frimpong et al., pp. 44-52) and how to predict and prevent coal mine bursts and bumps (Pariseau, pp. 60-68), the highly anticipated February Rare Earths issue of *Minerals & Metallurgical Processing*, and papers analyzing electrical injuries in the U.S. Mining industry (Homce and Cawley, p. 367-375) the latest in assessing the safety and efficiency of operations.

All 73 technical papers were peer-reviewed. The process of review and publication requires much hard work by authors, reviewers and our publications staff. As the 2013 president of SME and on behalf of all our members, I would like to extend our gratitude to all whose volunteer efforts contributed to the publication of this volume.

Jessica E. Kogel
2013 SME
President

Volume 334
Transactions of the Society for Mining, Metallurgy and Exploration, Inc.

Volume 334 contains three sections of technical papers:

- **Section 1:** Includes all papers published in the Technical Papers Section of *Mining Engineering* in 2013, Vol. 65, including the January through April, June, July and August, and October through December issues (no technical papers were published in the May or September issues). *Mining Engineering* papers are identified as “*Mining Engineering*, Vol. 65” in the index.
- **Section 2:** Includes all papers published in the February, May, August and November 2013 issues of *Minerals & Metallurgical Processing*, Vol. 30, Nos. 1, 2, 3 and 4. *Minerals & Metallurgical Processing* papers are identified as “*Minerals & Metallurgical Processing*, Vol. 30” in the index.
- **Section 3:** This section includes papers published only in this volume. *Transactions* papers are identified as “*Transactions*, Vol. 334” in the index.

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This section contains papers published only in this volume. All papers passed peer review and were accepted for publication between October 16, 2012 and October 15, 2013.

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