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Optimal Roof Coverage and Identification of Potential Roof Problems in Underground Coal Mines Using LED Lighting

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OPTIMAL ROOF COVERAGE AND IDENTIFICATION OF POTENTIAL ROOF PROBLEMS IN UNDERGROUND COAL MINES USING LED LIGHTING

THESIS

A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Science in Mining Engineering in the
College of Engineering at the University of Kentucky

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ABSTRACT OF THESIS

OPTIMAL ROOF COVERAGE AND IDENTIFICATION OF POTENTIAL ROOF PROBLEMS IN UNDERGROUND COAL MINES USING LED LIGHTING

The popularity and implementation of light emitting diode (LED) lighting have increased drastically over recent years into both residential and industrial applications. However, due to MSHA permissibility requirements, LED lighting is not currently being fully utilized in underground coal mining. While previous research has focused on examining the benefits that LED lighting possesses over other common light sources, very few have been done to find the optimum configuration to illuminate underground excavations better for the safety of the miners. In this research, multiple experiments were conducted to evaluate the potential impacts LED lighting can have on underground mine safety. The optimal light setup that provided the most roof coverage was found to be between 5 and 7 feet of separation, which is similar to what is usually used on roof bolting machines. It was also determined that LED lighting performs well in terms of discontinuity identification compared to what is commonly used in underground coal mining. The results of this research will serve as a design parameter for lighting manufacturers to use. These tests were done to simulate possible lighting locations on a roof bolting machine, but the results can be employed for other underground equipment as well.

KEYWORDS: Underground Coal, LED Lighting, Mine Safety, Light Distribution, Light Comparison

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CHAPTER 1: INTRODUCTION

1.1: General

Since the beginning of underground coal mining, the threat of accidental roof falls has posed a grave danger to miners in all parts of the mine. Roof falls hazards are especially high for miners working near active mining areas and more specifically for those miners working near roof bolting machines. Miners working around roof bolting machines are more often exposed to unsupported roof conditions compared to other mine equipment requiring an operator. Fatalities due to roof falls in the United States has decreased drastically with the introduction of roof bolts in the 20th century, and thus fatalities associated with underground coal mining have also reduced. Figure 1.1 shows the number of roof fall fatalities compared with the total number of coal mining fatalities, surface and underground, in the United States for the past eleven years (MSHA [A], 2016).

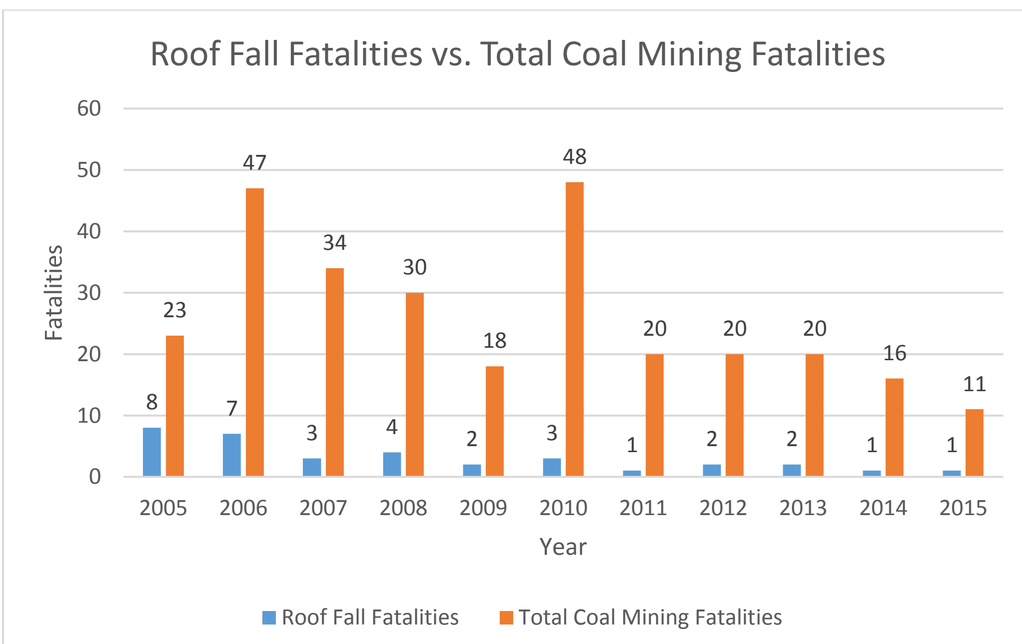


Figure 1.1: Roof Fall Fatalities Compared with Total Fatalities in US Coal Mines (MSHA [A], 2016)

Figure 1.1 shows that nearly 12% of all coal mining related fatalities since 2005 can be attributed to roof falls. While roof fall fatalities have decreased, the ultimate goal is to reduce the number of deaths to zero. If areas that pose potential roof fall hazards can be identified by the roof bolting machine operator, preventative measures such as spot bolting, strapping, or meshing can be done to increase roof stability. An operator's ability to recognize potential roof fall hazards is comprised of two components; experience and the capability to see the areas where potential roof falls could occur. Lighting is fundamental in the second component.

Light-emitting diode (LED) lighting has gained popularity over recent years in both industrial and consumer applications. The increased use of LED lighting is due primarily to the increased amount of light provided by LED lights while also possessing low energy consumption when compared to incandescent and fluorescent lighting. LED lights also possess lower maintenance costs due to their increased lifespan. However, LED lighting is not widely used throughout underground coals mines due to the lack of MSHA approval. To date, the only LED lights labeled permissible by MSHA are those that focus light into a beam, such as flashlights and cap lamps. The lack of approvals for the use of LED lights in mining equipment is because they have not been tested for intrinsically safe circuitry. Intrinsically safe means that any spark or heat generated by a circuit within a device is incapable of causing an ignition of a methane-air atmosphere or a coal dust layer (MSHA [B], 2016).

1.2: Scope of Work

The goal of this research is to examine the distribution of light in a typical underground coal mining panel according to different LED lighting sources and configurations. The results can be used by roof bolting machine designers and lighting manufacturers when submitting LED lamps to MSHA for permissibility testing. In general, lighting conditions in an underground coal mining environment are poor. Underground coal mine lighting is currently supplied by incandescent, fluorescent, or high-intensity discharge (HID) lighting. The addition of a brighter lighting source could help roof bolt machine operators to identify potential roof fall hazards during the bolting process and implement preventative measures immediately.

The first part of this research quantifies the effective light distribution of various lights utilizing differing configurations. This was completed within a simulation of a typical coal mine entry due to permissibility concerns. With this information, one can compare the distribution of LED lights with other lights commonly used in underground coal as well as determine which configurations optimize the light distribution. The second part of this research examines how differing geologic conditions appear under differing types of light. This was also completed with a simulation of geologic conditions. These results allow one to compare the visual differences of LED and other typical lighting sources to determine which will aid roof bolting machine operators the most when identifying potential roof fall hazards during the bolting phase of coal mining.

It must be noted that all sources of light tested during the present research were not approved by MSHA for use in underground coal mines at the time of the study, so an underground coal mine entry panel was recreated at the University of Kentucky Underground Lab. The results obtained from the research are to serve as a design recommendation to equipment manufacturers to implement an optimal light type and setup for their roof bolting machines or any other underground equipment. The issue of approval, health impacts, and permissibility are not examined in this research.

1.3: Organization of Work

Chapter 2 presents literature and background information concerning lighting history, history of lighting in underground coal mining, developments made in regards to the safety concerns of electric lighting, and recent research involving LED lighting. Chapter 3 will present data and results obtained during the mine panel simulation portion of this research. Chapter 4 presents data and results found during the discontinuity identification portion of this research. Finally, Chapter 5 will present the conclusions drawn from this research and provide suggestions for future work on this subject.

CHAPTER 2: LITERATURE REVIEW

2.1: Brief history of lighting

The history of lighting can be traced back to the days when mankind first developed fire. The first lamps invented used shells or hollowed rocks to contain a combustible material, such as dried leaves, grass, or wood, which was coated with animal fat to carry a flame (Illuminating Engineers Society (IES), 2011). As time progressed, the shells and rocks were supplanted by pottery and metals, the leaves and wood were superseded by cloth wicks, and the animal fat was exchanged for oil as candles and oil lamps became popular.

The first electric lamp was invented in 1801 by English chemist Sir Humphrey Davy and was first used for public lighting (IES, 2011). The carbon-arc lamp utilized two rods made of carbon as diodes to generate an electric spark as shown in Figure 2.1 (Whelan, 2010). The carbon-arc lamp was put into use throughout the 1800s and early 1900s to light large areas because they were inexpensive compared to oil lamps but had limitations that prevented residential use. These limitations include carbon monoxide emissions, radio frequency interference, buzzing sounds, and fire hazards due to excessive heat and sparks generated. However, the concepts of the carbon-arc lamp lead to the development of the fluorescent lamps currently in use today.

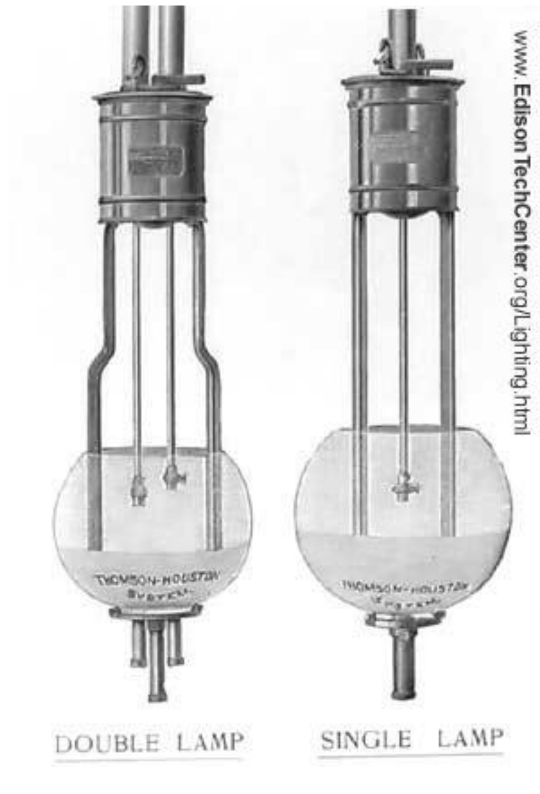


Figure 2.1: Carbon-arc Lamps Designed by Thomson-Houston Electric Company in 1880s (Whelan, 2010)

In 1878 and 1879, inventors Sir Joseph Wilson Swan of England and Thomas Edison of the United States patented their own versions of the incandescent light lamp (IES, 2011). However, only Edison was able to commercialize his invention and made it the success it is today, as shown in Figure 1.1Figure 2.2. The incandescent lamp utilizes an electric current to heat a filament, causing it to glow. After many failed iterations, Edison determined a carbon filament allowed the lamp to glow brighter and last longer.

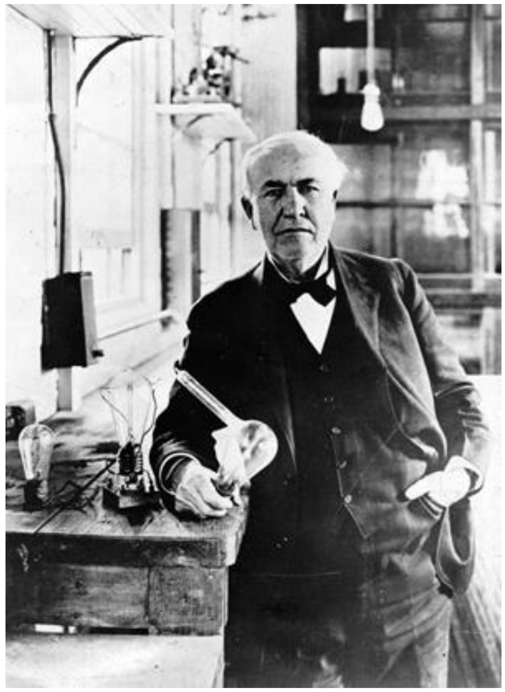


Figure 2.2: Thomas Edison with his Incandescent Lamp (IES, 2011)

Many other advancements in lighting technology occurred throughout history. The incandescent lamp was “modernized” when William Coolidge developed tungsten wire in 1909 (IES, 2011). The first neon lamps were developed by Georges Claude in 1911. The fluorescent lamp was patented in 1926 by Edmund Germer of Germany, with the compound fluorescent lamp being introduced in 1981. The first practical LED was developed by Nick Holonyak Jr. of the United States in 1962, which was enhanced in 1999 when new technology improved efficacy (lumens per watt) and color of LEDs. Luminous efficacy is defined as the efficiency of converting electrical energy to light. These developments presented LED lighting as a potential replacement to traditional lighting sources.

2.2: Popular sources of lighting today

There are several sources of lighting available today, ranging from solar powered outdoor lamps to high intensity discharge. However, the three most common sources in use today are incandescent, fluorescent, and LED. Incandescent lamps, as was discussed in section 2.1, use an electric current to cause a metallic filament to glow. Incandescent lights have several advantages when compared to other lamps types, such as being inexpensive, turning on instantly, are available in a wide range of sizes and shapes, and providing visually pleasing light (Department of Energy (DoE) [A], 2013). These advantages have helped the incandescent lamp become the most commonly used lamp in residential buildings. However, incandescent lamps have low efficacy (10 to 17 lumens per watt) and have a shorter average operating life (750 to 2,500 hours) when compared to LED and compact fluorescent lamps (CFLs). These drawbacks make the incandescent lamp the least efficient and have the highest operating cost of the three most popular lamp types.

The fluorescent lamp is another popular lamp in use today and works similarly to carbon-arc lamps. An electric arc passes between two cathodes within the lamp to excite gases, such as mercury (American Lighting Association (ALA), 2014). The energy produced from the gases generates a radiant energy which is converted to visible light through a phosphor coating in the lamp. There are two types of fluorescent lamps, CFL and tube. Both types are available in numerous shapes and sizes, with CFLs designed to be used as replacements for incandescent lamps. Fluorescent lamps are on average more energy efficient and last longer than incandescent lamps, using 25%-35% less energy and last between 7,000 and 24,000 hours (DoE, 2013). CFLs specifically have been shown to use 75% less energy than incandescent lamps, but are more expensive to purchase. CFLs are best used in areas where lighting is needed for long periods of time. The main disadvantage with fluorescent lamps is that they must be disposed of properly due to the mercury contained within the lamp.

The third most popular, and fastest growing, lamp today is the LED lamp. Light is produced within an LED lamp when voltage is applied to negatively charged semiconductors (ALA, 2014). This voltage causes electrons within the lamp to combine and create a unit of light called a photon. LED lamps are among the most efficient lamps in the lighting industry today and have “the potential to fundamentally change the future of lighting in the United States” (DoE, 2013). LED lamps use at least 75% less energy and last 25 times longer than an incandescent lamp. LED lamps are small, emit very little heat, require no need for reflectors, and are available in many shapes and colors, as depicted in Figure 2.3.

Figure 2.3: Colored LED Lights (New York University, 2014)

2.3: Brief history of underground mine lighting

Sammarco has stated that “adequate illumination is crucial in underground coal and metal/nonmetal mine safety…” (2010). This is due to the fact that miners predominantly rely upon visual cues to identify hazards associated with ground fall, slips/trips/falls, moving machinery, and other threats. In the earliest days of mining, open flames were used to illuminate underground mines. Candles and oil lamps were put into use by the Greeks and Romans, but neither light source was able to be utilized safely in mines where large quantities of methane and other gasses were present. The first safety lamp that would not cause explosions was developed in the early 19th century, shown in Figure 2.4. These safety lamps were the most common lighting source for underground mines through the first half of the 20th century.

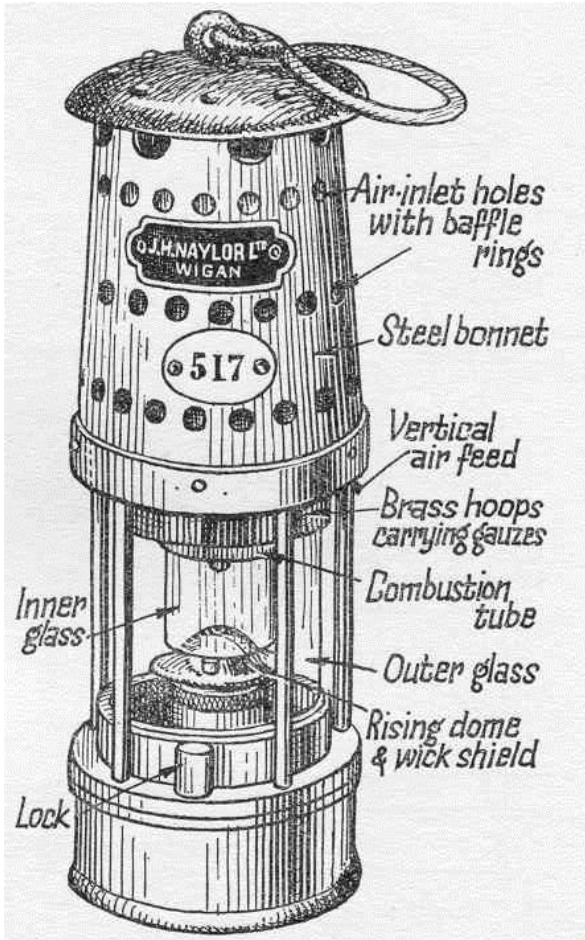


Figure 2.4: Mine Safety Lamp (mining-memorabilia.co.uk, 2014)

The electric lamp was not implemented into underground mining operations for several decades even after their increase in commercial and industrial popularity (Sammarco and Carr, 2010). The high installation costs of installing the wiring required to light all workings of a mine were not practical and no reliable power sources were available at the time for portable lights. There were also concerns whether or not electric lamps were safe to place in underground mines. However, there was a large demand for safer lighting systems at the face due to the large number of explosion related fatalities caused by mine gas ignition. The United States Bureau of Mines (USBM) began working with Thomas Edison in 1914 to develop personal electric lamps to be used by miners. Edison discovered a way to power a lamp using a small, rechargeable battery that was light enough to be carried on a miner's belt. The Edison electric cap lamp, seen in Figure

2.5, was approved by the USBM in 1915. This allowed electric lamps to gain acceptance in the mining industry and eventually replace older technologies.

Figure 2.5: 1915 Edison Electric Cap Lamp (Sammarco and Carr, 2010)

2.4: Safety concerns of electric lamps

As was discussed in the previous section, electric lamps were not implemented into underground mines quickly due to explosion concerns in gassy mines (Sammarco and Carr, 2010). The USBM conducted many tests investigating the likeliness an incandescent lamp bulb with either carbon or tungsten filaments could ignite mine gases when the filament was exposed. To do this, bulbs from eight different manufacturers were testing with varying degrees of filament exposure. These filament exposures were smashed bulb, bulb with its tip cut off, bulb with a hole in its neck, and a pre-exposed filament suddenly exposed to voltage in a natural gas and air mixture. Results showed that ignition could occur with natural gas concentrations as low as 5%. Because of these results, safety features had to be built into cap lamps approved by the USBM to prevent incandescent lamps from operating if the bulb was broken.

As the electric lamp gained popularity in underground mining operations, the USBM needed to set standards to prevent mine gas ignition by electric lamps. Characteristics of lamps that were examined include potential to ignite gas, tendency to unexpected extinction, potential to spill electrolyte, amount of light produced, light distribution, bulb life, bulb characteristics, battery life, cord life, durability, reliability, and ease of repair (Clark and Ilsley, 1917). Tests were developed by H.H. Clark and L.C. Ilsley to test each parameter in order to approve different types of electric lamps for use in underground mines. By August of 1916, around 70,000 USBM-approved electric lamps were in use with approximately 2,000 lamps installed per week.

2.5: Advancements in underground mine lighting

The cap lamp has become one of the most trusted and reliable pieces of equipment used by nearly every underground miner (Sammarco and Carr, 2010). Advancements in technology helped reduce weight and volume of batteries required to power lamps, as well as increased battery life of three to four years. New reflectors were designed when the more efficient tungsten-halogen lamp replaced the incandescent lamp. Fluorescent cap lamps were developed and tested by the USBM during the 1970s. The new cap lamp was evaluated based on light output, battery capacity, charging time, system weight, and compatibility with existing systems. The fluorescent cap lamp, shown in Figure 2.6, was approved by USBM, and showed superior light output and significantly improved bulb life when compared to incandescent lamps. The fluorescent cap lamp saw little use in industry, due to its increased size, weight, and costs. However, machine mounted fluorescent lamps saw increased usage.

Figure 2.6: Fluorescent Cap Lamp (Sammarco and Carr, 2010)

The USBM also conducted research during the 1970s and 1980s to evaluate machine mounted lighting once the advantage for lighting on continuous miners and roof bolters was established (Sammarco and Carr, 2010). These studies installed lights on conventional machinery, continuous machinery, longwall machinery, and area lighting for a wide range of operations (Ketler, 1979). New lighting technologies of the time, such as fluorescent and mercury-vapor lamps, were tested by the USBM in a laboratory setting using mockups like the one shown in Figure 2.7 as well (Sammarco and Carr, 2010). The main issues addressed were light distribution, reliability and durability of lighting systems, and safety concerns. The USBM also worked with equipment manufacturers to integrate lighting systems into equipment during factory production rather than requiring after-market installation.

Figure 2.7: Wooden Mockup Used by USBM to Evaluate Machine Mounted Lighting (Sammarco and Carr, 2010)

During this time, the USBM also established minimum lighting requirements within underground coal mines that are still used today. The Underground Coal Mining Handbook (Lewis, 1986) was developed to provide a reference on underground coal mine lighting. The overall goal of the handbook is to provide an understanding of the various factors that need to be considered to design and implement a mine illumination system that provides good vision and comfort. The report provides a minimum lighting standard that must be achieved when lighting an underground coal mine. The luminous intensity within a miner's normal field of vision should not be less than 0.06 foot-lamberts, or 0.02 candela per square foot. This standard is still utilized in Title 30 Code of Federal Regulations (CFR) under CFR 75.1719-3. The CFR also provides the necessary working area that must be lighted around a roof bolting machine (Cornell University, 2016). CFR 75.1719-1 requires that in areas with a mining height of five feet or less that the face, ribs, floor, and exposed surfaces of mining equipment within five feet from the machine must be visible. It also states for mines with greater than five feet of height that the face, ribs, floor, and exposed surfaces of mining equipment within the same distance of the mining height must be visible, with the exception of only five feet from the rear of the machine in this situation. No requirements are listed for the roof, however the 0.06 foot-lamberts would still apply since the roof is within the miner's field of vision.

2.6: LED Research

The National Institute for Occupational Safety and Health (NIOSH) and the Institute of Electrical and Electronics Engineers (IEEE) both continue mine illumination research today as LED lamps have become increasingly popular. Previous research has shown that lighting with an increased amount of short wavelength spectral content can improve visual conditions in low-light scenarios, such as nighttime driving and underground mining. The goal of NIOSH LED lighting research was to compare LED lamps to other lamps commonly used in mining. In 2009, NIOSH researchers investigated the effectiveness of different machine mounted lighting technologies on visual performance (Reyes, Gallagher, and Sammarco, 2009). Thirty-six people were taken to NIOSH's human performance research lab in Pittsburgh, Pennsylvania. The subjects were split evenly into age groups; young (eighteen to twenty-five years old), middle-aged (ages forty to fifty), and older (ages fifty-one and up). The interior of the facility was painted flat black to simulate lighting conditions in an underground environment. Subjects were placed in an observation station, shown in Figure 2.8, to ensure each person was in a fixed position and prevent confounding data based on a person's point of view. This also prevented the test subject from walking around the darkened facility during the test. Electronic actuators were installed to raise and lower the seat ensuring all subjects conducted the test at the same height, equivalent to the height of the fiftieth percentile standing male (five feet and five inches). Subjects were also required to wear all normal personal protection equipment.

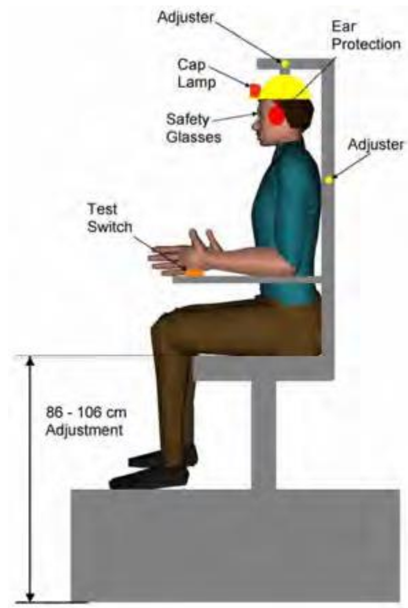


Figure 2.8: Observation Station Schematic Used by Reyes, Gallagher, and Sammarco (2009)

Area lights were installed on a continuous miner and were used to create four different lighting configurations (Reyes, Gallagher, and Sammarco, 2009). These configurations consisted of incandescent and LED lamps, incandescent lamps only, fluorescent lamps only, and fluorescent and LED lamps. The subjects were given a minimum of fifteen minutes to allow their eyes to adjust to the darkened environment, then performed a peripheral motion detection study, a trip and fall study, and a discomfort glare study. During the peripheral motion test, subjects were required to press and hold a mouse button while observing a flip-dot matrix. When one of the three circle targets set at twenty, forty, and fifty degrees off axis with the matrix started rotating, the test subject was to release the mouse button and the reaction time was recorded over five trials. The experimental setup can be seen in Figure 2.9. The sequence of target activation and activation time delay were varied to prevent previous tests influencing current tests. The dependent variables for this experiment were the time required to detect target movement and number of missed targets. A target was considered missed if detection time exceeded 4.2 seconds. On average, the fluorescent and LED configuration provided the most light to each target and led to the lowest reaction times in terms of both age groups and target angles, seen in Table 2.1. The final conclusions of the test is that the

LED and fluorescent lighting combination provided the best peripheral detection due to the increased amount of short wavelength light provided, which was similar to results found in previous experiments (Sammarco et al., 2008).

Table 2.1: Measured Lux Values at Targets of Peripheral Detection Test (Reyes, Gallagher, and Sammarco, 2009)

Target Position (degrees)	Incandescent and LED	Incandescent	Fluorescent	Fluorescent and LED
20	2.89 lux	2.62 lux	2.76 lux	3.00 lux
-40	1.96 lux	1.50 lux	2.11 lux	2.58 lux
-50	2.30 lux	1.26 lux	2.57 lux	3.69 lux

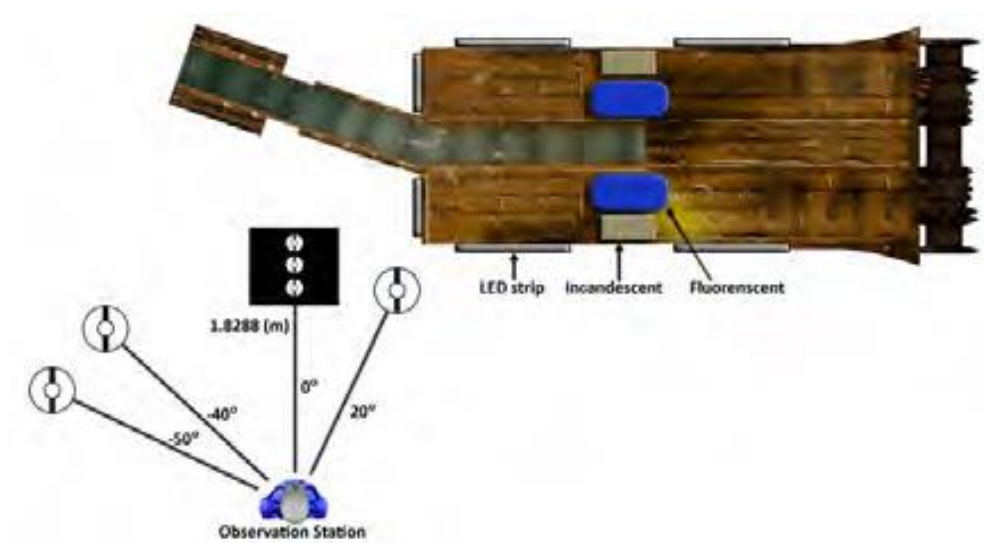


Figure 2.9: Experimental Layout for Peripheral Motion Detection Study (Reyes, Gallagher, and Sammarco, 2009)

The trip and fall study was conducted by setting up multiple objects behind a black curtain so test subjects could not see their placement. Objects were placed in areas near (six feet) and far (9 feet) away from the subject, as shown in Figure 2.10. When the curtain was removed, the subject was required to point out the trip hazard with a laser pointer and count the number of hazards. Test subjects were allotted ten seconds to detect the trip hazards. The time needed to count the hazards as well as any “missed” hazards were recorded. The independent variables for this experiment were age group and lighting conditions. The results showed that younger subjects could detect the obstructions on average three seconds faster than middle aged and older subjects and that both configurations using LED lighting required one second less time to find trip hazards. It was also determined that the interaction between age group and lighting was not significant, which indicates that that the LED lighting configurations could provide similar improvements to all age groups.

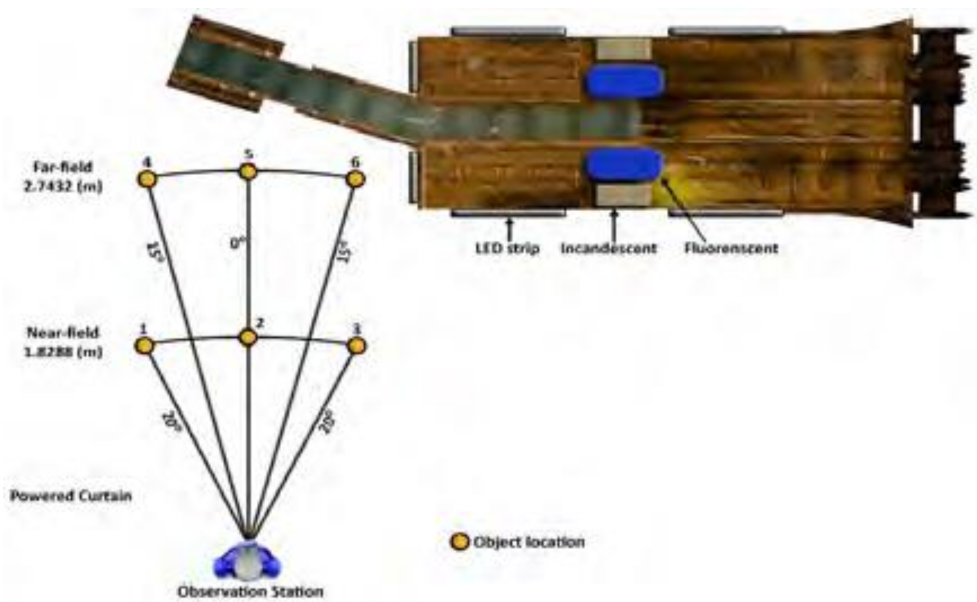


Figure 2.10: Experimental Layout for Trip and Fall Detection Study (Reyes, Gallagher, and Sammarco, 2009)

The glare discomfort test required subjects to stand in two different locations near the rear of the continuous miner, shown in Figure 2.11, and describe discomfort using a nine point De Boers scale, with one being “unbearable” and nine considered “just noticeable”. The two positions the test subjects were placed was determined based on the most likely positions a continuous miner operator would stand during normal operation, one being four feet from the rear corner and the other approximately nine feet diagonally from the rear corner. The responses of each subject were recorded and analyzed utilizing age group, lighting, and position as factors. Results show an interaction between lighting and position, shown by the graph in Figure 2.12. The incandescent and LED configuration provided the least glare discomfort, followed by similar ratings between incandescent only and the LED-fluorescent combination, then fluorescent being the most discomforting.

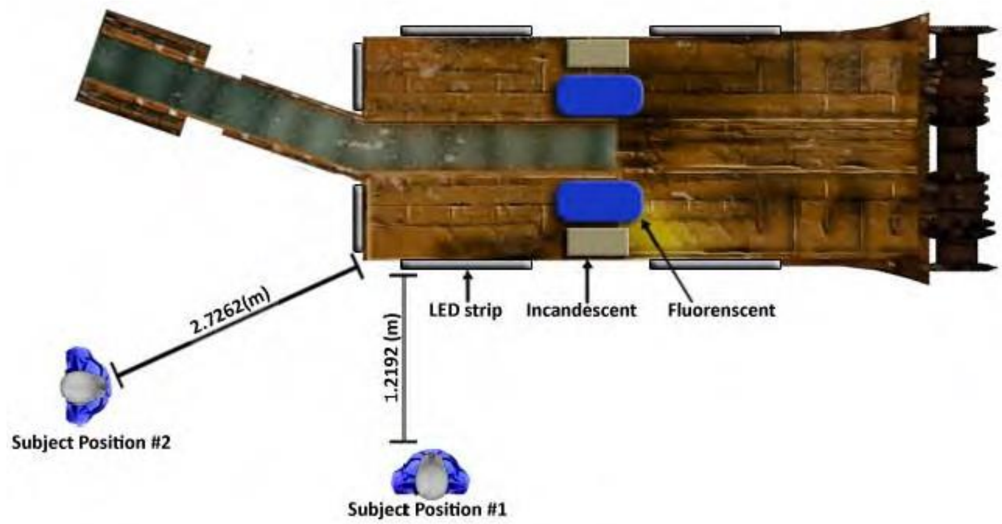


Figure 2.11: Experimental Layout for Glare Discomfort Study (Reyes, Gallagher, and Sammarco, 2009)

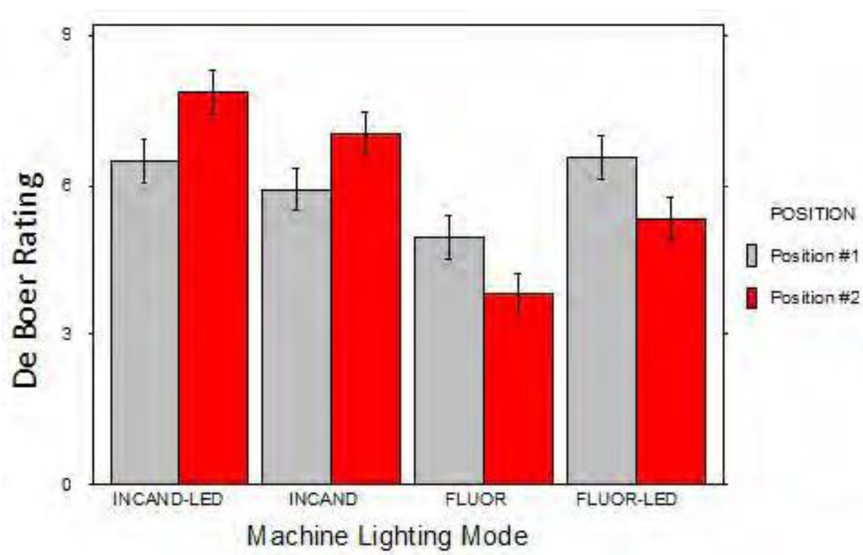


Figure 2.12: Glare Ratings by Lighting Mode and Position (Reyes, Gallagher, and Sammarco, 2009)

Overall results from these experiments show that age has a significant impact on visual performance (Reyes, Gallagher, and Sammarco, 2009). However, lighting conditions also play a significant factor. LED combinations with other light sources provided the best results compared to the other sources tested. The LED and fluorescent lighting mode provided the best results during the peripheral vision detection study due to the increased amount of short wavelength light provided and increased illuminance. The LED and incandescent mode provided the quickest reaction times for the trip fall study, but the differences were not statistically significant when compared to the LED and fluorescent mode. Thus it was determined that the increased illumination likely provided the superior detection time, as well as an increase in short wavelength light. The final conclusion of the paper states that “the use of LED lights, as an auxiliary source of area lighting, would improve the visual performance of miners working around the perimeter of a machine” (Reyes, Gallagher, and Sammarco, 2009).

Research was completed comparing the visual performances between incandescent and solid-state LED cap lamps (Sammarco and Lutz, 2007). The experiment took place at the same research site and utilized the same observation station discussed previously. Test subjects were asked to complete a trip and fall study which included four different object location patterns placed between the near-field (six feet) and far-field (twelve feet) of the subject, as seen in Figure 2.13. Near-field distance was determined based on the distance of two strides for the average male and far-field distance was based upon the distance where the floor receives most light from the cap lamp due to its mounting on the miner’s helmet. The objects were set up behind a black curtain to prevent the subjects from seeing their placement. When the subject was ready, the black curtain was removed and the data acquisition software began recording time. An object was identified when the subject counted each out loud while pointed to it with a laser pointer. Subjects were given fifteen seconds to identify as many objects as possible, and any object failed to be detected was considered a “missed object”. Three different cap lamps were evaluated. The first cap lamp was a MSHA-approved incandescent lamp to serve as the reference throughout the experiment. The second was a MSHA-approved cap lamp utilizing one phosphor-white LED as the light source. The final cap lamp was jointly developed by NIOSH and the Lighting Research Center of Rensselaer Polytechnic

Institute. This lamp uses two phosphor-white LEDs as the light source. Detection time when using the incandescent cap lamp was 55.3% greater than the prototype LED cap lamp and 43.5% greater than the LED cap lamp. Subjects also never failed to identify all tripping hazards when using either LED cap lamp, but when using the incandescent cap lamp three total objects were not identified. These results allow the researchers to infer that the shorter wavelengths found in cool-white LEDs could provide significant visual performance improvements compared to incandescent lights when utilized as cap lamps.

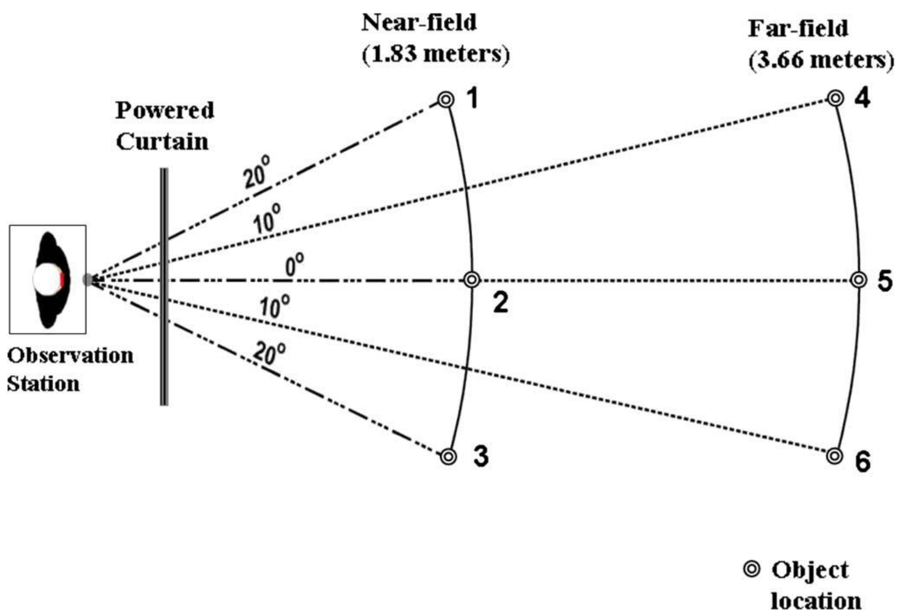


Figure 2.13: Experimental Layout for Cap Lamp Trip and Fall Study (Sammarco and Lutz, 2007)

Evaluation of the differing effects on peripheral vision performance when using incandescent and LED cap lamps have also been examined (Sammarco et al, 2008). Thirty subjects were split into three testing groups based upon age. Experimentation was conducted at the NIOSH Mine Illumination Laboratory, which is a simulated, underground coal mine environment that is sixteen feet wide and seven feet tall. The laboratory is coated with material that has the color and reflectivity of 10% that is similar to a coal mine. Each subject sat in the observation station depicted in Figure 2.8 to perform the peripheral vision test. The experimental setup and procedure was the similar to the peripheral vision test previously discussed, with each subject conducting five tests. The first two tests were practice to familiarize the subject with the testing procedure and equipment. The three remaining tests each used a different cap lamp. Each cap lamp was the same as the lamps utilized in the experiment discussed previously. Figure 2.14 depicts the setup for this experiment.

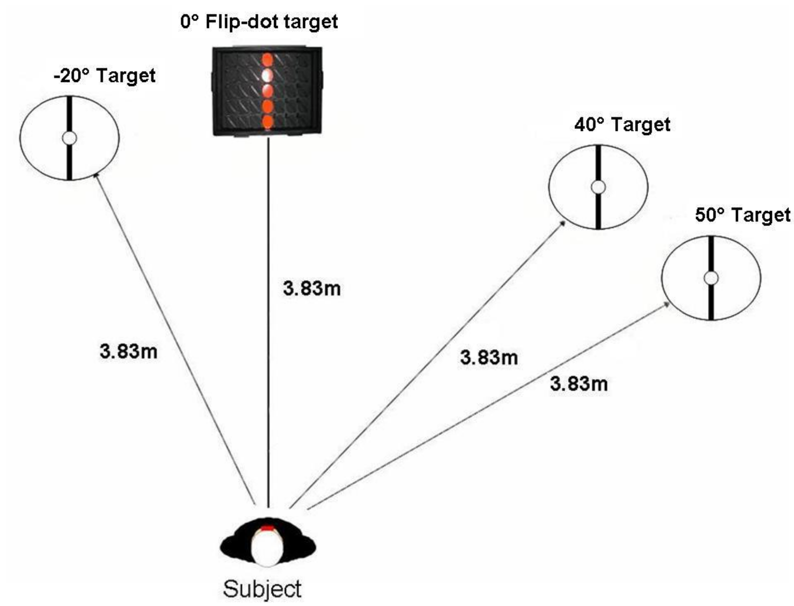


Figure 2.14: Experimental Layout for Peripheral Motion Test (Sammarco et al, 2008)

After testing, an analysis of variance was used to determine the different effect of each variable tested; age group, light type, and angle of target (Sammarco et al, 2008). Evaluation of detection time results concluded that all three variables had a significant effect. Subjects in the younger group (age eighteen to twenty-five years old) had significantly faster reaction times than subjects in the middle age group (forty to fifty years old). Differences between the middle and older (greater than fifty years old) age groups were not significantly different. The prototype LED provided a significant improvement in detection time compared to the commercial LED. Detection times using the prototype LED cap lamp were 11% and 15% faster when compared to the incandescent and commercial LED respectively. Differences between the incandescent and commercial LED were not statistically significant. The angle of the targets also had a sizable impact on detection times. The further the target was from the center line, the greater time the subject took to identify the movement. The forty degree target had a 16% increase in detection time compared to the twenty degree target, while the detection time for the fifty degree target had a 76% increase. All three conditions were deemed significantly different from each other. Data analysis on the number of missed targets indicated significant interaction between age group and target location. The frequency of missed targets was greatest for the fifty degree target, then usually followed by the forty and twenty degree targets with the exception of the young age group, which had more twenty degree missed targets. The middle age group had the most missed targets, followed by the older age group with slightly fewer missed targets, then the young age group with a large reduction in missed targets. Due to the shorter wave length within the prototype LED cap lamp, it was determined that these type of LED cap lamps with short wavelengths could provide improved peripheral vision detection. The variance analysis showed little interaction between light source and age group, which indicates that the LED cap lamp could provide similar benefits to all age groups in aiding peripheral vision.

Technological comparisons between incandescent and LED cap lamps have also been evaluated through experimentation (Sammarco et al, 2009). The relative lumen maintenance curve and spectral power distribution of three different cap lamps were evaluated by NIOSH. These cap lamps include a LED lamp with an internal heat sink powered by a six volt nickel-hydride battery, an incandescent lamp powered by a four volt lead-acid battery, and a second incandescent lamp powered by a six volt nickel-hydride battery. All lamps were new at the beginning of testing and were subjected to two discharge cycles lasting ten hours. Data gathered automatically by a computer between the two cycles were compared to one another. Light output was measured by a photometrically calibrated photosensor. Results show that the incandescent cap lamps experience a sharp reductions in light output within the first few minutes of testing, shown in Figure 2.15. This is due in large part to incandescent lamps lack of regulation circuitry to prevent loss of output due to voltage drop within the battery. By the end of the ten hour cycle, the incandescent cap lamp with the nickel-hydride battery saw a 65% decrease in light output compared to the initial value, while the lead-acid battery powered incandescent lamp experienced a 56% output reduction. However, the LED cap lamp, which utilizes regulatory circuity, only experienced a 4% drop in light output over the ten hour period. This drop was attributed to the LED heating up rather than the voltage drain within the battery. When thermal equilibrium is reached, the light output of the LED cap lamp was relatively stable.

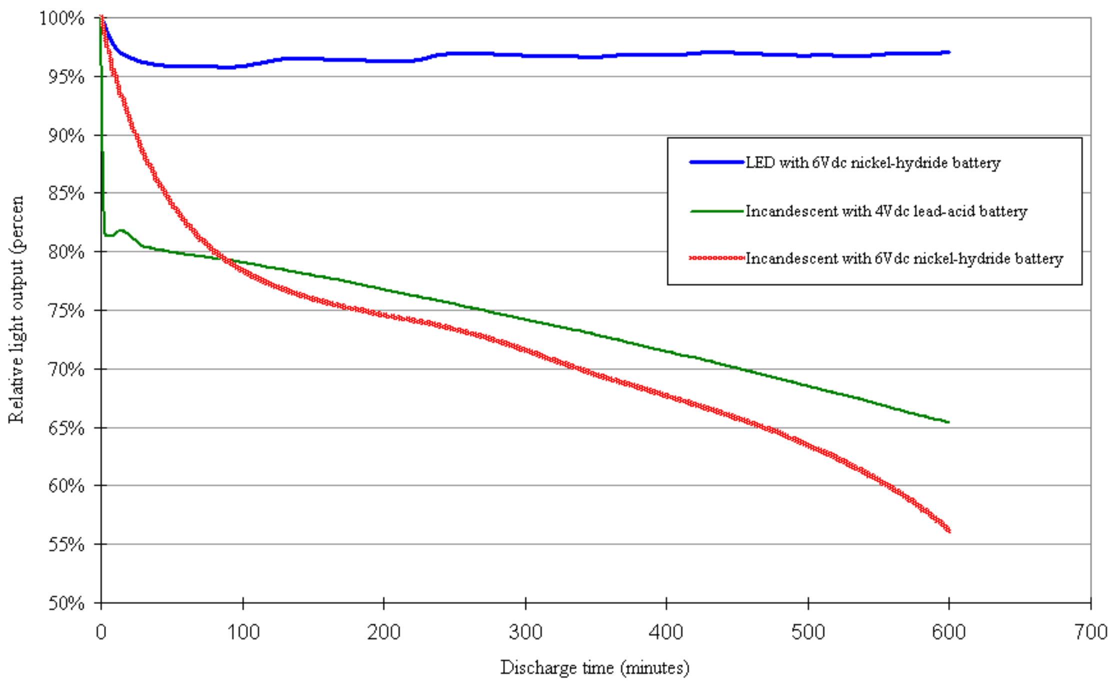


Figure 2.15: Light Output over Ten Hour Discharge Period (Sammarco et al, 2009)

The study goes on to explain that a second effect caused by the lack of regulatory circuitry in the incandescent lamps is the change of spectral composition in the light (Sammarco et al, 2009). When the power sources of the incandescent systems are at lower operating voltages, the spectral distribution shifts toward long visible wavelengths that could be detrimental to peripheral vision in underground lighting conditions. As previously discussed in research conducted by Sammarco, shorter wavelength light is more beneficial to miners in an underground mining environment.

The electrical and photometric characteristics were also examined during testing during the ten hour period for the LED and lead-acid powered incandescent system (Sammarco et al, 2009). All measurements taken during this step of experimentation were taken at room temperature (twenty-five degrees Celsius) with negligible airflow. A three-channel power analyzer measured the electrical characteristics, shown in Table 2.2. Photometric characteristics of LED and incandescent lights are also shown in Table 2.3. The LED lamp utilized less current and less power than the incandescent lamp. The LED lamp also had a smaller drop of luminous flux and efficacy than the incandescent lamp. Even though the LED technologies tested were dated at the time of experimentation, final results indicate several potential benefits LED lighting systems have over incandescent systems. LED lights provide higher system efficacy, which results in improved lighting conditions over short time periods or consistent conditions over longer periods. Systems could become more compact because smaller batteries could be used to power lights. The controlled circuitry present in LED lights also allows lighting from the system to be more constant during shift duration while providing the short wavelength light most beneficial to workers in an underground environment. These benefits could potentially benefit the safety and production of miners.

Table 2.2: Electric Characteristics of LED and Incandescent Cap Lamps (Sammarco et al, 2009)

Source	Time	Voltage (V)	Current (A)	Power (W)
LED	0 min	6.82	0.365	2.49
	10 min	6.66	0.375	2.50
	300 min	5.99	0.424	2.54
	600 min	5.74	0.444	2.55
Incandescent	0 min	3.39	1.088	3.69
	10 min	4.28	1.055	4.52
	300 min	4.13	1.04	4.30
	600 min	4.03	1.025	4.13

Table 2.3: Photometric Characteristics of LED and Incandescent Cap Lamps (Sammarco et al, 2009)

Source	**Time**	**Luminous Flux (lm)**	**Efficacy (lm/W)**	**CIE 1931 chromaticity (x,y)**		**Correlated color temperature (K)**	**General color rendering index (Ra)**
LED	0 min	36.0	14.5	0.3252	0.3283	5851	73
	10 min	35.7	14.3	0.3251	0.3281	5857	74
	300 min	35.2	13.9	0.3245	0.3274	5890	74
	600 min	35.0	13.7	0.3243	0.3269	5905	74
Incandescent	0 min	38.7	10.5	0.4411	0.4067	2951	100
	10 min	30.8	6.8	0.4463	0.4082	2880	100
	300 min	27.7	6.4	0.4489	0.4089	2847	100
	600 min	24.9	6.0	0.4513	0.4094	2815	100

Performance characteristics between LED and compact fluorescent lights (CFLs) have also been examined (Di Mauro, 2014). Eight lamps, four CFL and four LED, from different manufacturers were utilized during experimentation. All lamps had rated power values of approximately eight watts. All experimental tests were conducted at the rated voltage of 230 volts and frequency of fifty hertz. The line current of each lamp was determined first and then graphed through waveforms. The waveforms show that the CFL lamps were strongly distorted, each possessing a total harmonic distortion of current over 100%. However, the LED lamps showed much less distortion, with total harmonic distortion of current values between 31% and 81%. Total harmonic distortion is defined as “the overall deviation from its fundamental component of a distorted waveform” (Di Mauro, 2014). Essentially the total harmonic distortion evaluates how well an electronic device is using power. Lower values indicate that the device will operate properly and last longer. The power factors of each lamp reveal interesting results. The power factor is a ratio of how much power is used by a circuit, real power, over how much is applied to the circuit, apparent power. Factors closer to one indicate less power loss in a circuit. All CFL lamps resulted in power factors of approximately 0.6, but the LED lamps obtained power factors between 0.52 and 0.82. Two of the LED lamps obtained the 0.82 power factor, but the harmonic distortion difference between both lamps was almost double (31% to 60%). Also the LED lamp with the worst power factor had a harmonic distortion of 62%, which was among the lowest tested in all lamps. This was attributed to the high fundamental power factor within the lamp.

Tests were continued to examine the active power and power factor of each lamp at variable voltage, using the assumption that the network utilizes voltage lower than the rated voltage of each lamp (Di Mauro, 2014). The active power in all CFL lamps behaved similarly. A linear relationship is present when the voltage applied the lamps is increased, which indicates the lamp load of a CFL behaves dependent of voltage. The LED lamps had different trends when graphing applied voltage against active power. One LED lamp had constant active power at the varying applied voltages, while others possessed a logarithmic trend. These results show that the active power within LED lamps are not dependent on applied voltage. Similar results were obtained when examining power factor at various voltages, power factor increases at lower voltages. However, results from the previous experiment were confirmed. All LED lamps obtained higher power factors than the CFLs. The paper concludes in listing other advantages LED lamps have over CFLs. LED lamps do not contain toxic substances such as mercury, which allows LED lamps to pose little environmental concerns. LED lamps also have higher average lifetimes than CFL lamps.

A similar study was completed by Indian researchers in regards to CFL and LED comparisons (Kumar, 2011). Following standards set by IEEE-1459-2010, the reactive, active, and distortion powers of ten Philips twenty watt CFLs and one Philips ninety watt

LED was examined. A Fluke power quality analyzer was utilized to measure the harmonic content of the lamps. Results show that the distortion in the CFL was much higher than the distortion in the LED, from Table 2.4. It was also shown that the LED lamp had higher power factors than the CFLs tested. The study continues to discuss that CFLs predominant harmonic order is third, which means that the current has no sequence in nature. This is known to cause overloading in neutral conductors, which was stated as a potential issue in India because most secondary power distribution networks are utilizing neutral conductors.

Table 2.4: Distortion Power Analysis (Kumar, 2011)

Lamp Parameter	Lamp Type	
	CFL	LED
Nominal RMS voltage applied to lamp load (V)	230	230
Total RMS current through lamp load (A)	1.359	0.4
Voltage THD at terminals (%)	2.3	1.8
Current THD in load (%)	96.9	8.5
Fundamental RMS voltage (V)	229.8	229.8
Harmonic RMS voltage (V)	4.2	4.1
Fundamental RMS current (A)	0.976	0.39
Harmonic RMS current (A)	0.946	0.09
Total apparent power (VA)	310	83.09
Fundamental apparent power (VA)	225.2	82.1
Non-fundamental apparent power (VA)	213.1	12.7
Total active power (W)	198	81.8
Fundamental active power (W)	197	81.6
Harmonic active power (W)	1	0.2
Total reactive power (var)	237	14.5
Fundamental reactive power (var)	109	13.7
Non-fundamental reactive power (var)	213.1	4.7
Total power factor	0.64	0.94
Fundamental power factor	0.875	0.98
Distortion power factor	0.732	0.96
Prominent harmonic order	3^{rd}	5^{th}
Peak factor	3.19	1.68

An annual life cycle cost was estimated during this research as well (Kumar, 2011), evaluating factors such as efficacy, working life-span, lamps cost, power costs, and energy consumption. The LED lamp resulted in higher efficacy, higher life-span, lower energy consumption, and lower annual electricity cost. However, the CFL lamp was deemed the most cost effective, at 357.70 rupees per year (approximately 5.24 US dollars using conversion rate as of February 29, 2016) where the LED was 430.80 rupees per year (6.32 US dollars). Since the study was conducted in India, not many quality LED lamps are present and LED technology is very limited. The cost to produce LED lamps in India is also higher, which is preventing the widespread use of LEDs in the country. The research team was forced to purchase a single, expensive LED in order to ensure high product quality. Other LED lamps are available at a lower price, but the researchers were concerned these lamps would be of lower power quality. A less expensive LED would have resulted in a much lower annual life cycle cost, possibly making LED the most cost effective. However, both CFL and LED were found to be vastly more effective than incandescent lamps, which resulted in a cost of 1,406 rupees per year (20.61 US dollars).

Photometric data analysis and comparisons have been used to compare the distribution of light between different light sources for public lighting systems (Rodrigues et al, 2011). Three different lamps, high pressure sodium (HPS), low power LED, and high power LED, were set up over a gridded out roadway near the School of Engineering of the Federal University of Juiz de Fora in Brazil. The roadway, classified as a “main urban walkway” by the Brazilian standard for public lighting, utilizes a public lighting system consisting of HPS lamps with conventional electromagnetic ballasts. The Brazilian standard requires this type of roadway to have a minimum average illuminance of five lux (lumen per square meter) on the work plane and a uniformity factor of 20%. Only three light poles were tested using the LED lamp configurations in a way where influences from other lighting sources in the area were negligible. Photometric data was collected within the grid, charted, and then analyzed using classical photometry. Using the obtained data, the maximum, minimum, and median illuminances values can be found to calculate the uniformity factor. Results from experimentation, shown in Table 2.5 and Figure 2.16, show that all three technologies met the standard requirements, but show some differences. The HPS lamps produce an average illuminance value about two times higher than both LED lamps, but this result was expected because the HPS lamp uses 250 watts of power while the high power LED lamps only uses 120 watts and the low power

LED uses 97.53 watts. The uniformity coefficients (U_0) for both LED lamps were marginally improved when compared to the HPS lamp.

Table 2.5: Photometric Results for High-power LED Lamp (Rodrigues et al, 2011)

Luminaire	E_{med}	E_{min}	E_{max}	U_0
HPS	22.0 lux	7.5 lux	34.6 lux	0.34
Low Power LED	9.1 lux	3.9 lux	21.7 lux	0.42
High Power LED	8.8 lux	3.2 lux	13.9 lux	0.36

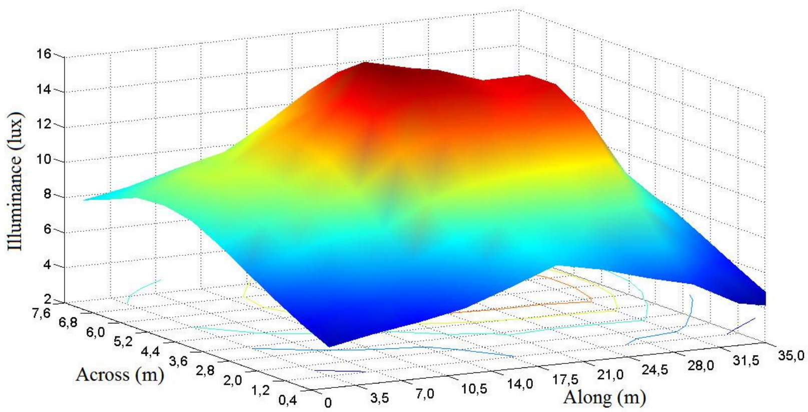


Figure 2.16: Photometric Chart for High-power LED Lamp (Rodrigues et al, 2011)

The potential LED lighting could have on reducing the number of accidents in the mining industry has also been examined (Yenchek and Sammarco, 2010). Investigators examined accident records from the MSHA to find accidents relating to maintenance and operation of mine luminaries. Between the years of 2002 and 2006, 140 such accidents were found, resulting in 3668 lost work days, 925 days of restricted work, and zero fatalities. When examining the accidents based on mining type, as depicted in Figure 2.17, sixty-four (64) of the 140 accidents occurred at mining operations extracting bituminous coal, with stone mining having the second most accidents at thirty-five (35). The leading injuries from these 140 accidents were sprains and strains (forty reports), laceration and puncture wounds (thirty-nine reports), fractures and chips (eighteen reports), and bruises (thirteen reports). Fingers were the most commonly injured body part (twenty-six reports), followed by the back (eighteen reports) and eyes (ten reports). Of the 140 accidents, 53% occurred during the maintaining or repairing of machine-mounted, portable, and fixed lighting sources. The increased life of a LED lamp can help reduce the frequency of these types of injuries by providing an exposure reduction. The authors also state that LED lamps can reduce the severity of eye injuries caused by exploding bulbs that occurred during the broken glass injuries found in eight of the 140 cases because LED lamps are less likely to explode. Since LED lights use less power than other form of lighting, batteries would be integrated into the cap lamp headpiece to power LED lamps. This would remove the need for a power cable for cap lamps, thus result in the elimination of cap light cable related accidents, found in twenty-four (24) of the 140 accident reports.

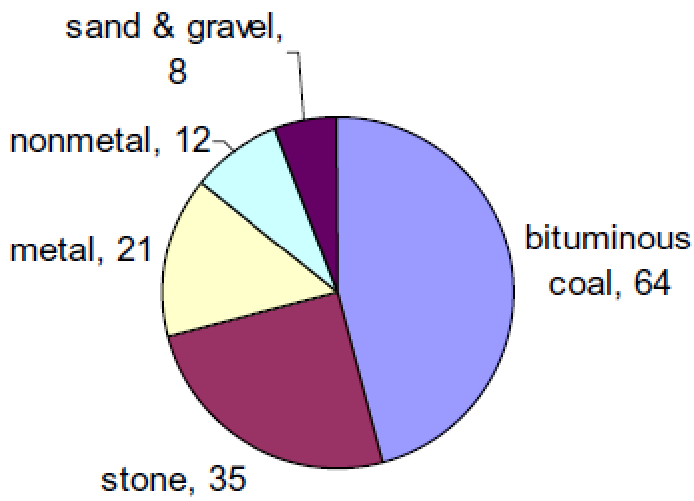


Figure 2.17: Lighting Accidents by Mining Classification (Yenchek and Sammarco, 2010)

CHAPTER 3: MINE PANEL SIMULATION

3.1: Introduction

To determine the discontinuity capabilities of LED lights, the effective light distribution of LED area lamps needs to be discovered. Poor lighting conditions can increase the risk of accidents in an underground mining environment, but can also contribute to less than adequate visual inspection of the roof and ribs of a panel.

3.2: Mine Panel Simulation Experimental Procedure

A simulated coal mine entry was constructed in the University of Kentucky Explosives Research Team's (UKERT) underground laboratory in Georgetown, Kentucky, to test the light distribution provided by different LED light sources and configurations. A simulated underground coal mine entry had to be constructed in an underground limestone mine because none of the lamps tested are approved by the MSHA for underground coal mines at the moment of this research. The entry, shown in Figure 3.1 and Figure 3.2, is 20 feet wide, five (5) feet tall, and 30 feet long and was constructed out of wood. The lights were placed on a table at a center point located 10 feet from the entry opening. The table is 3 feet tall, and the lights were installed in a position 2 feet from the roof, which simulates the position the lights would be located on the underside of an automated temporary roof support (ATRS) of a roof bolting machine. Black plastic was used to recreate the roof of the mine entry. The reflectance of the black plastic was not evaluated to determine if there was an influence on lux readings, but if an influence was present it would be common throughout the entire entry so the results would not be effected.

Figure 3.1: Recreated Entry (exterior)

Figure 3.2: Recreated Entry (interior)

Fifty-two (52) points were established within the simulated entry to measure the light distribution. Thirty-six (36) of these points were located on the roof at a four (4) foot spacing in both directions. The remaining sixteen (16) points were located two (2) feet below the roof and were also spaced at a four (4) foot spacing. The majority of the points were established on the roof because initial testing results demonstrated a lack of sufficient lighting in that place. The remaining points provide an indication on how well the rest of the entry is lit. Figure 3.3 shows the schematic used for the tests. The light distribution within the simulated coal mine entry was determined using an Extech HD450 light meter, and all values were recorded in lux (lumens per square meter or the amount of light falling on a surface). All lights were powered by a twelve-volt battery, which is available to power the illumination system on roof bolting machines.

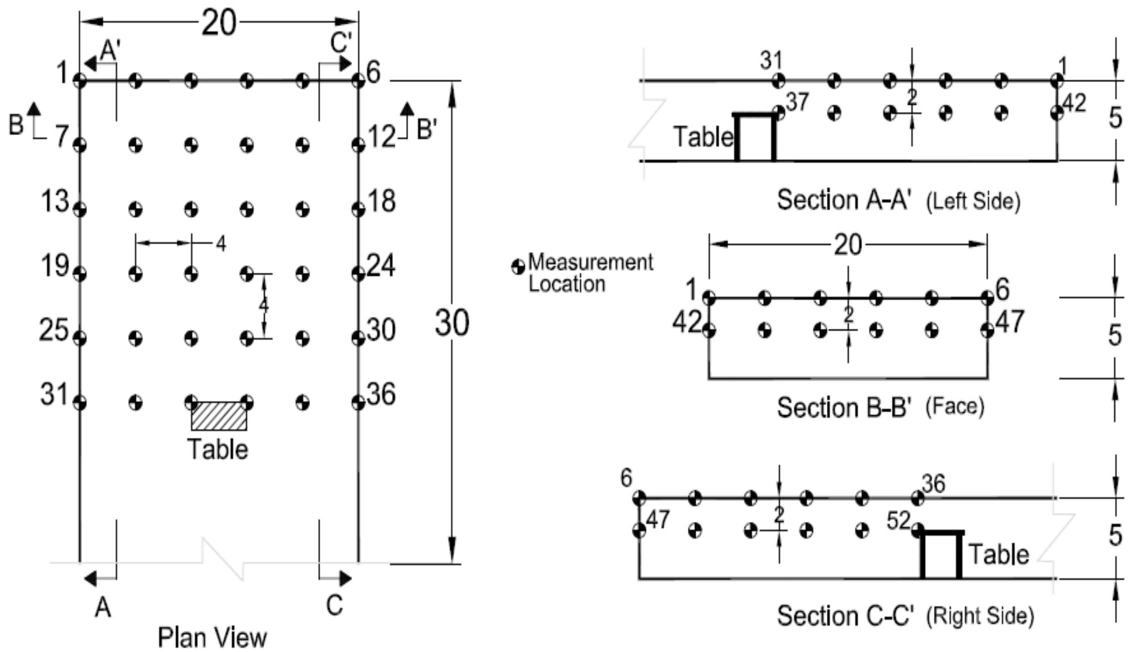


Figure 3.3: Experimental Schematic

Ten different types of LED, halogen, and high-intensity discharge (HID) lights were obtained from multiple manufacturers (to be referred as Manufacturer A and Manufacturer B) to test within the simulated panel. These lights are included in Table 3.1.

Table 3.1: Lights Tested during Mine Panel Simulation

	Manufacturer	# LED lights	Angle	Note
1	Vision X	4	60	
2	Vision X	4	90	
3	Vision X	6	60	
4	Vision X	6	90	
5	Vision X	15		Light Bar
6	Vision X	NA		Halogen euro flood beam pattern
7	Vision X	NA		Halogen horizontal flood pattern
8	Vision X	NA		HID euro flood beam pattern
9	Vision X	NA		HID horizontal flood pattern
10	Hella	NA		280N LED surface mining light with close range light pattern

The light angle in Table 3.1 refers to the degree value the light cone exits the lamp (Figure 3.4). The euro flood beam pattern is a hybrid of a horizontal flood beam and vertical flood beam patterns, but its useful lighting coverage is not as effective as the horizontal flood or vertical flood beam patterns. The euro beam does not have a horizontal range as effective as the horizontal flood pattern nor the vertical range of a vertical flood pattern (Figure 3.5). The halogen and HID lights were used to establish a comparison of LED lights to other lighting systems available. After obtaining the lights, the next step was to determine the effective light distributions of various lamp configurations in a simulated underground coal mining environment.

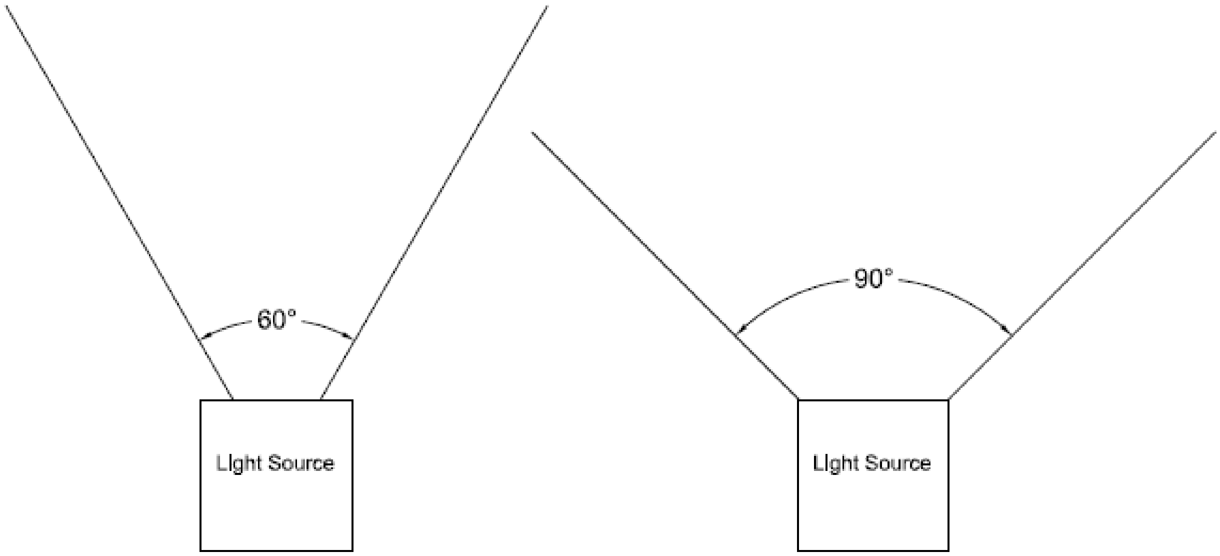


Figure 3.4: Depiction of Light Angle

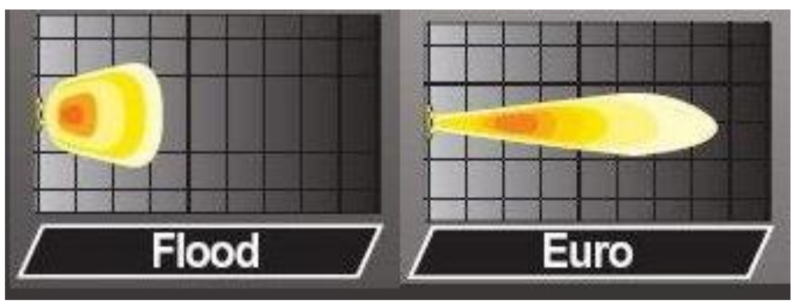


Figure 3.5: Difference between Flood and Euro Beam Patterns, Plan View (Delonix Auto, 2015)

Pairs of each light obtained were tested at seven, five, three, and one foot apart (centered in simulated mine) to determine the impact of light spacing on the distribution of the light in the entry. The LED light bar was the lone exception to this setup. Only two configurations for the light bar were tested, a single bar located at the center of the table and two light bars separated seven feet from the extreme ends (Figure 3.6 shows the setup configurations). Also, an example light setup is shown in Figure 3.7 and Figure 3.8. Figure 3.7 illustrates what would be seen when standing behind and to the left of the roof bolting machine, while Figure 3.8 shows what would be seen by the machine operator.

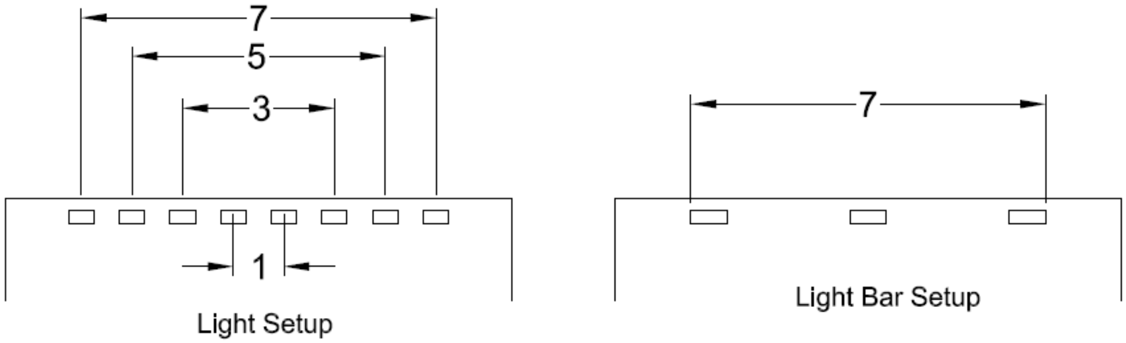


Figure 3.6: Light Setup (feet)

Figure 3.7: Example light setup (behind and left of roof bolt machine)

Figure 3.8: Example light setup (roof bolt machine operator perspective)

3.3: Mine Panel Simulation Results

Photographic results and light distribution contours are shown in Figure 3.9 through Figure 3.46. The origin on each contour correlates to point 1 in the schematic shown in Figure 3.3. The data for light was recorded in lux, which is defined as a lumen per square meter or the amount of visible light over an area.

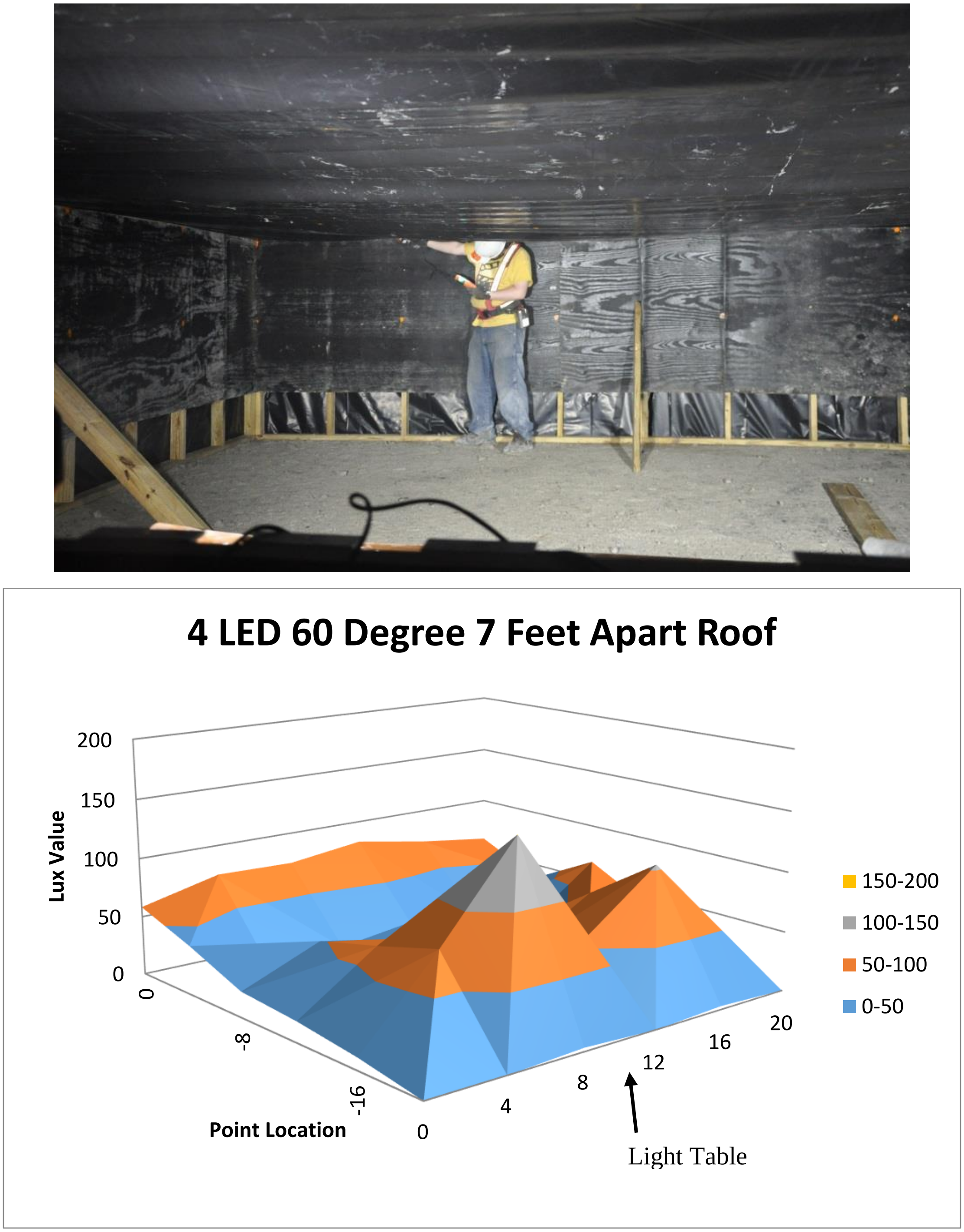


Figure 3.9: 4 LED 60 Degree 7 Feet Apart Photographic Result and Roof Light Contour

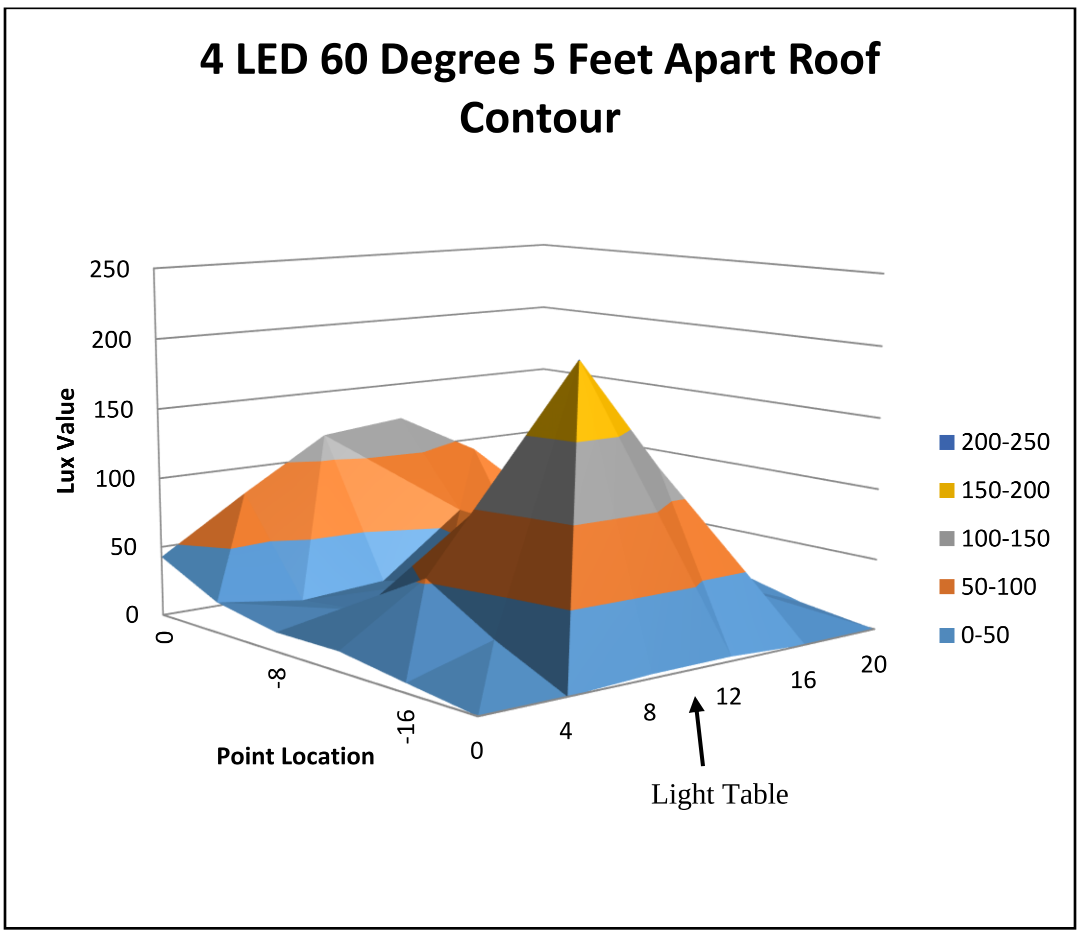


Figure 3.10: 4 LED 60 Degree 5 Feet Apart Photographic Result and Roof Light Contour

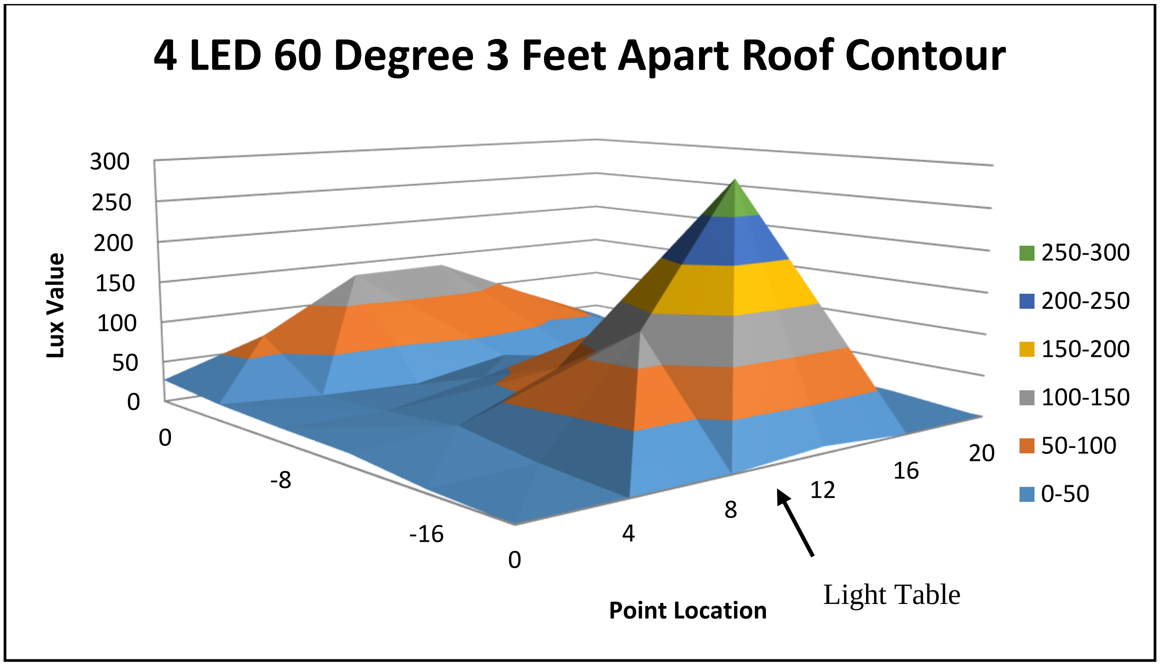


Figure 3.11: 4 LED 60 Degree 3 Feet Apart Roof Light Contour

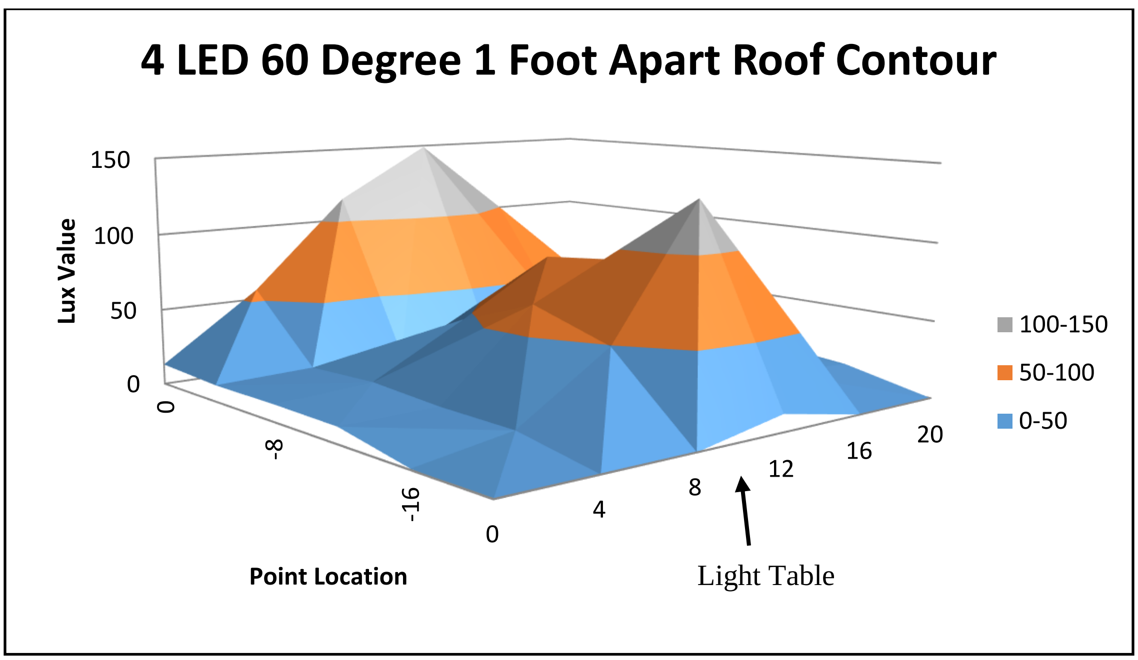


Figure 3.12: 4 LED 60 Degree 1 Foot Apart Roof Light Contour

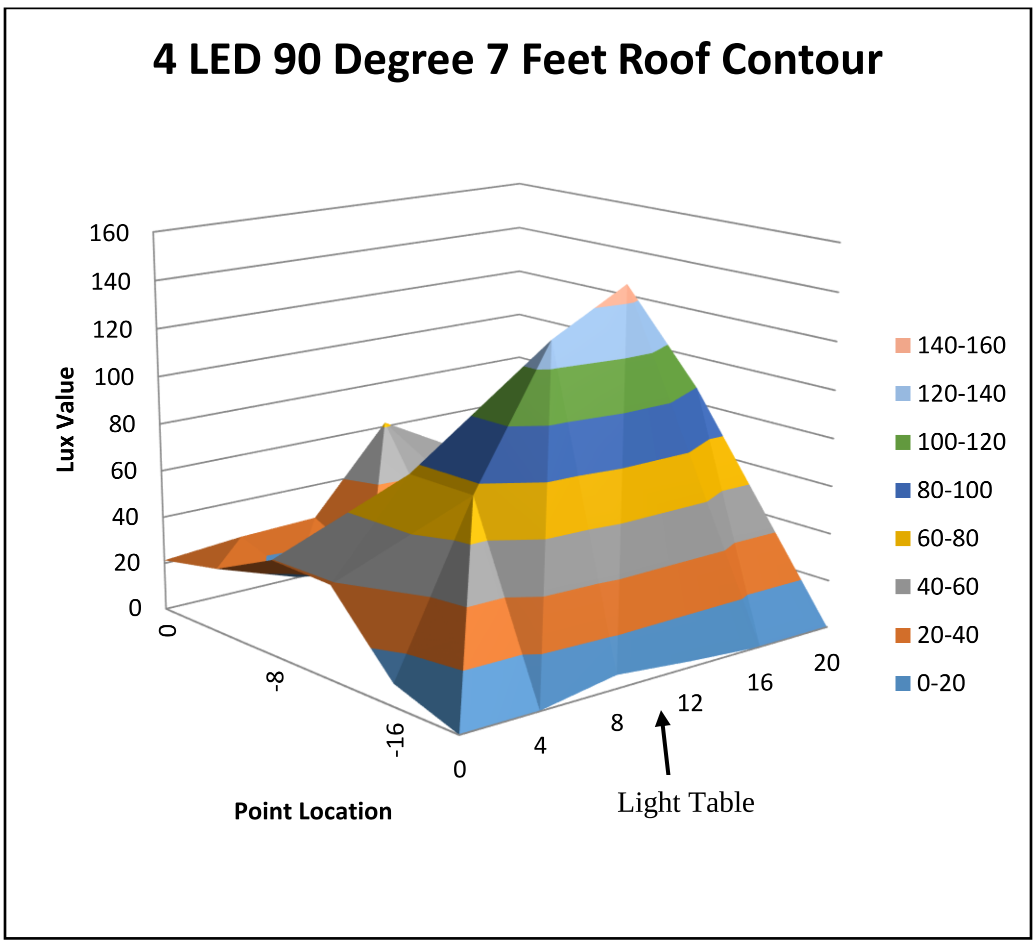


Figure 3.13: 4 LED 90 Degree 7 Feet Apart Photographic Result and Roof Light Contour

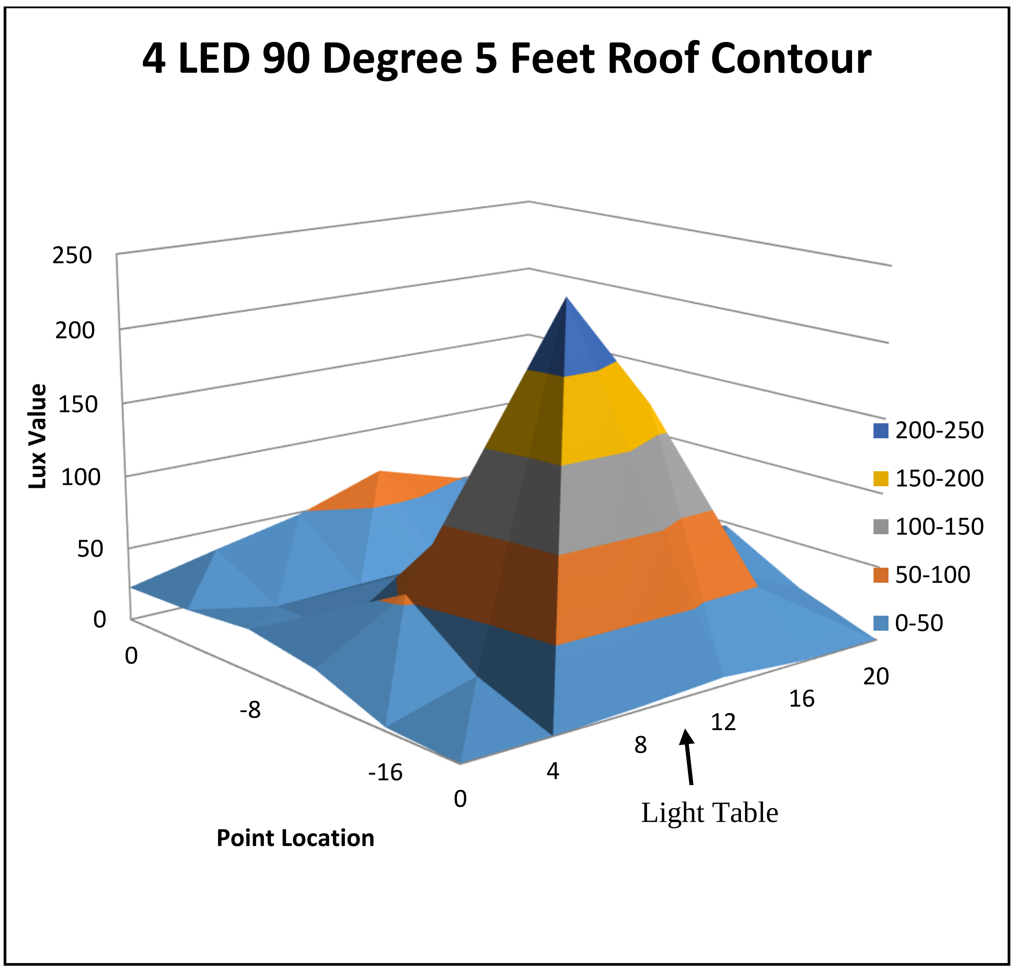


Figure 3.14: 4 LED 90 Degree 5 Feet Apart Photographic Result and Roof Light Contour

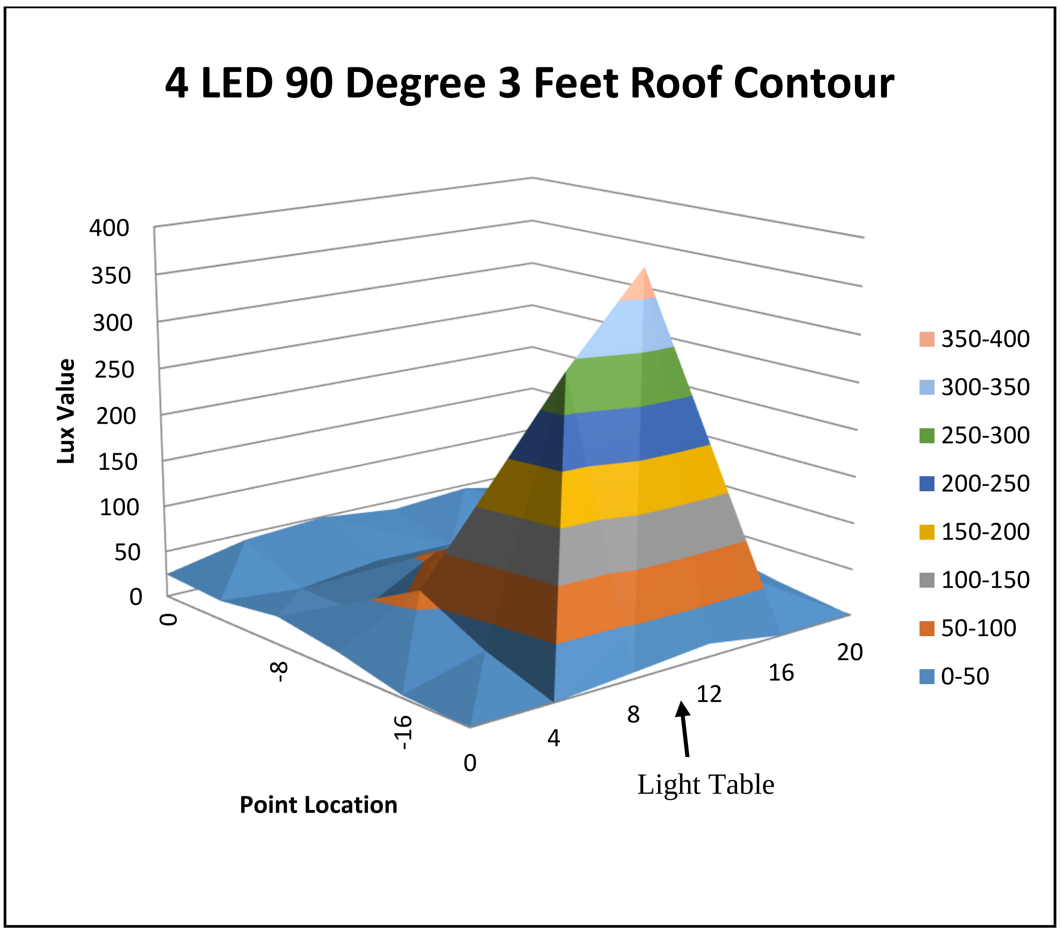


Figure 3.15: 4 LED 90 Degree 3 Feet Apart Photographic Result and Roof Light Contour

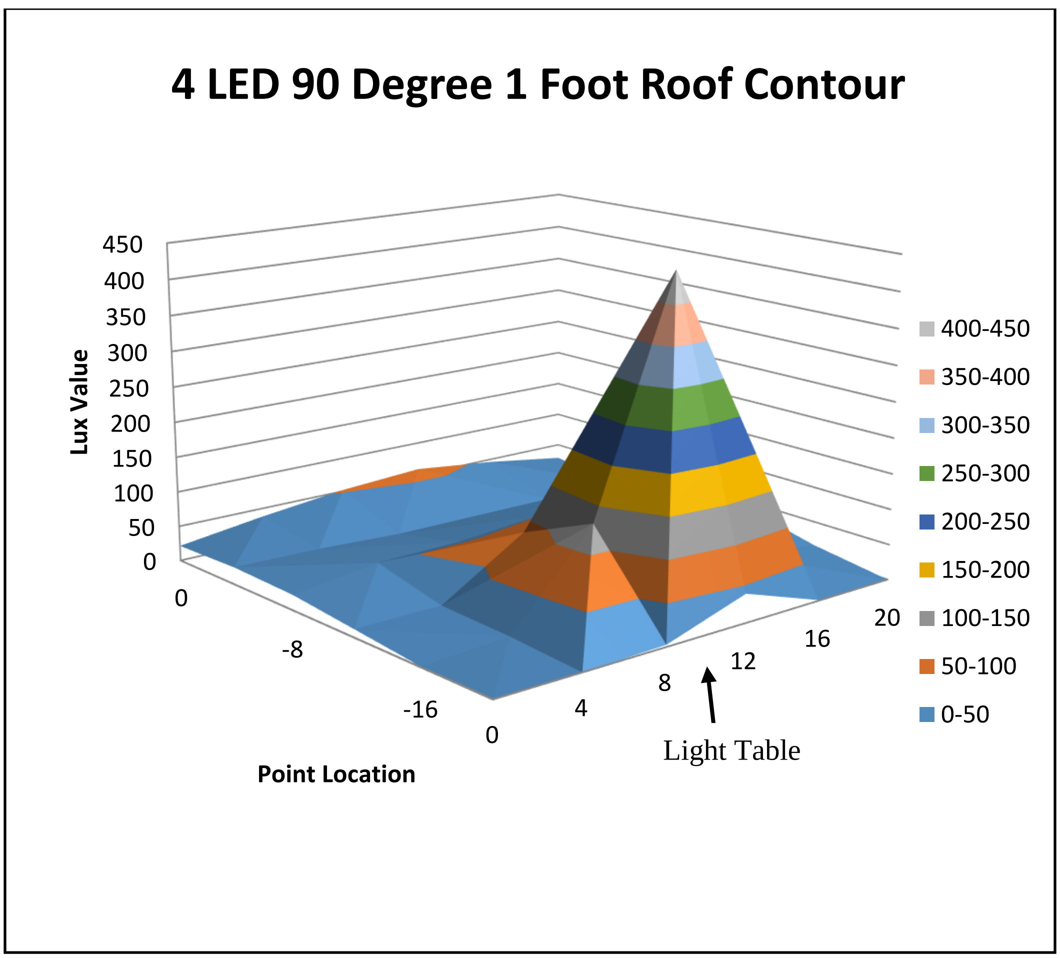


Figure 3.16: 4 LED 90 Degree 1 Foot Apart Photographic Result and Roof Light Contour

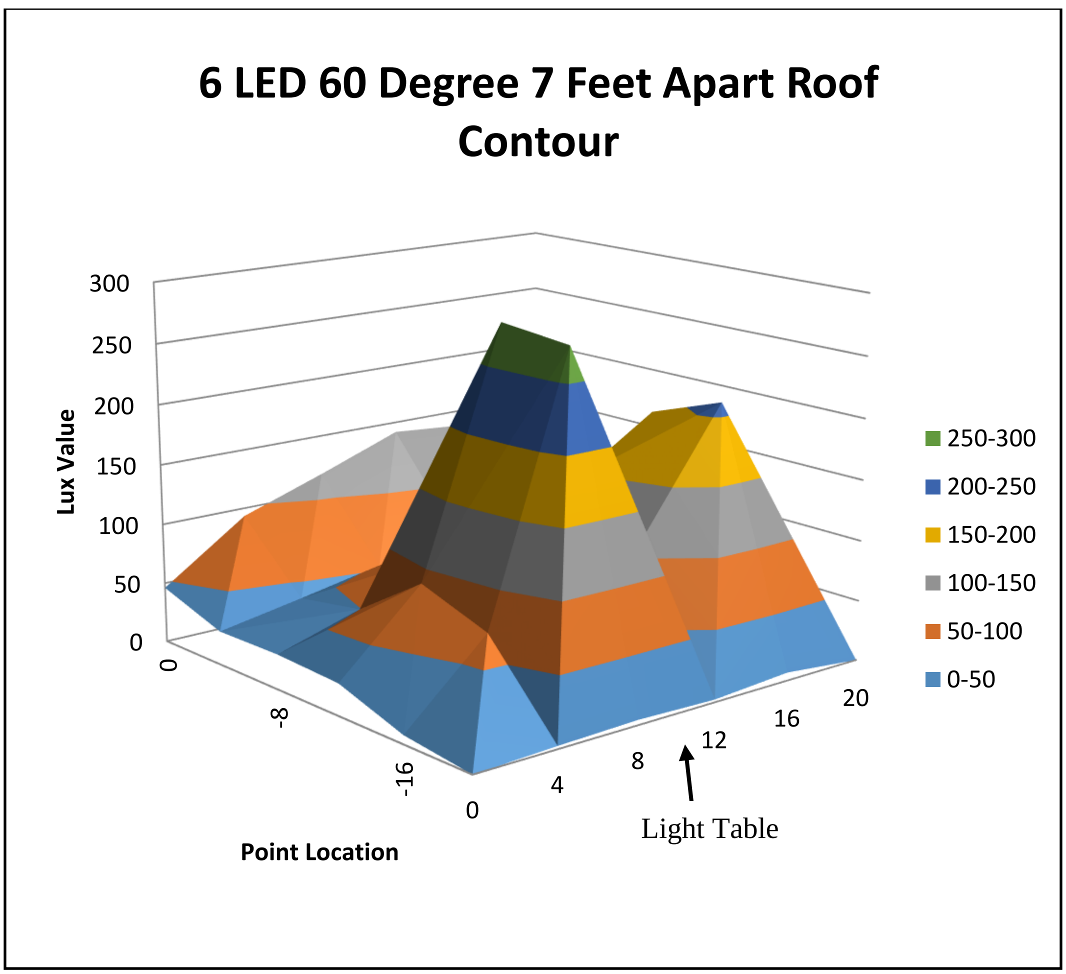


Figure 3.17: 6 LED 60 Degree 7 Feet Apart Photographic Result and Roof Light Contour

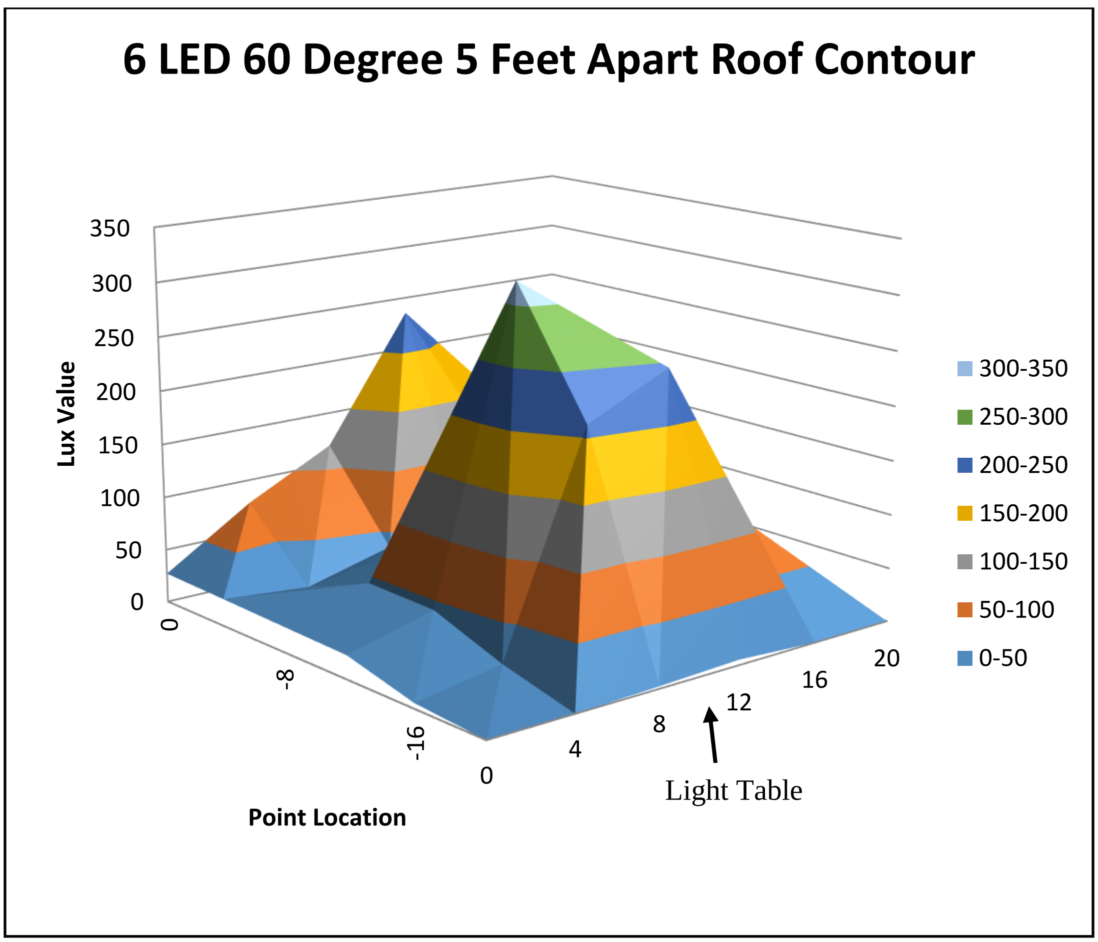


Figure 3.18: 6 LED 60 Degree 5 Feet Apart Photographic Result and Roof Light Contour

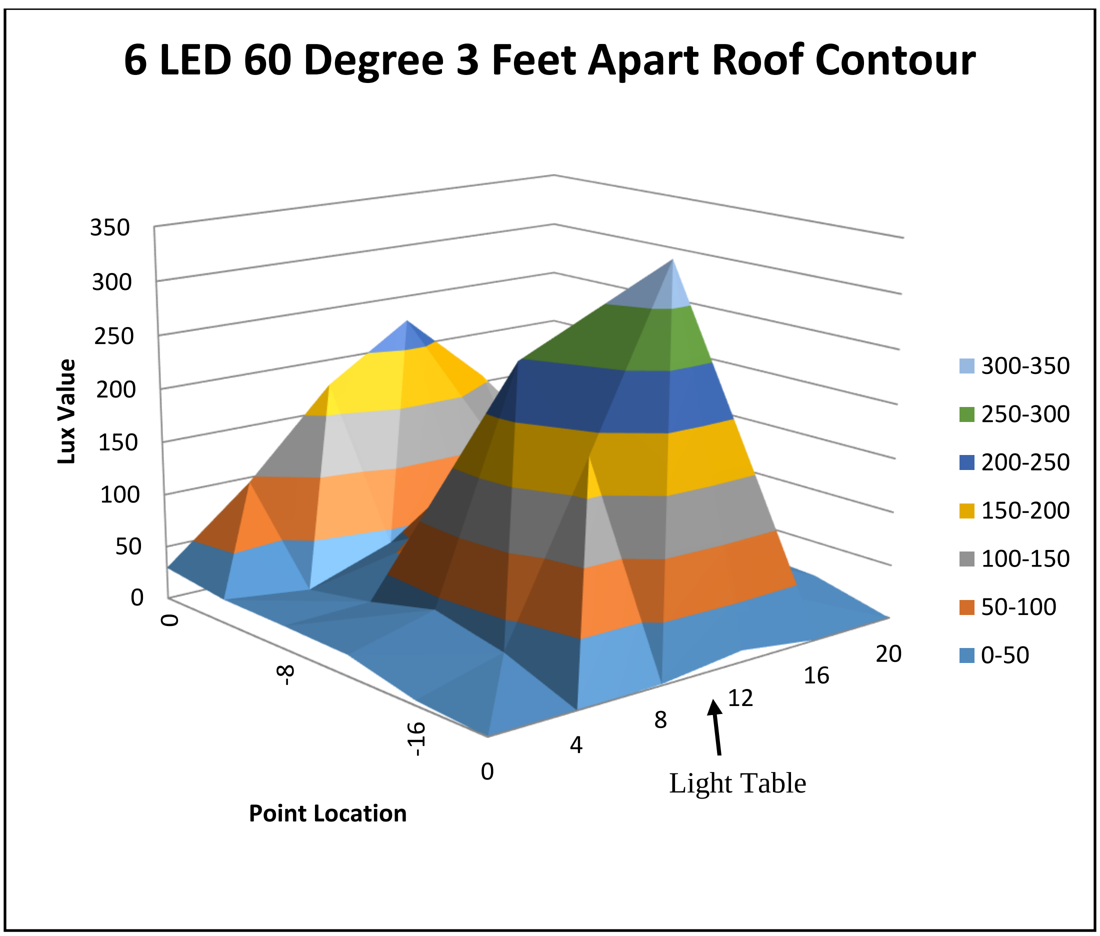


Figure 3.19: 6 LED 60 Degree 3 Feet Apart Photographic Result and Roof Light Contour

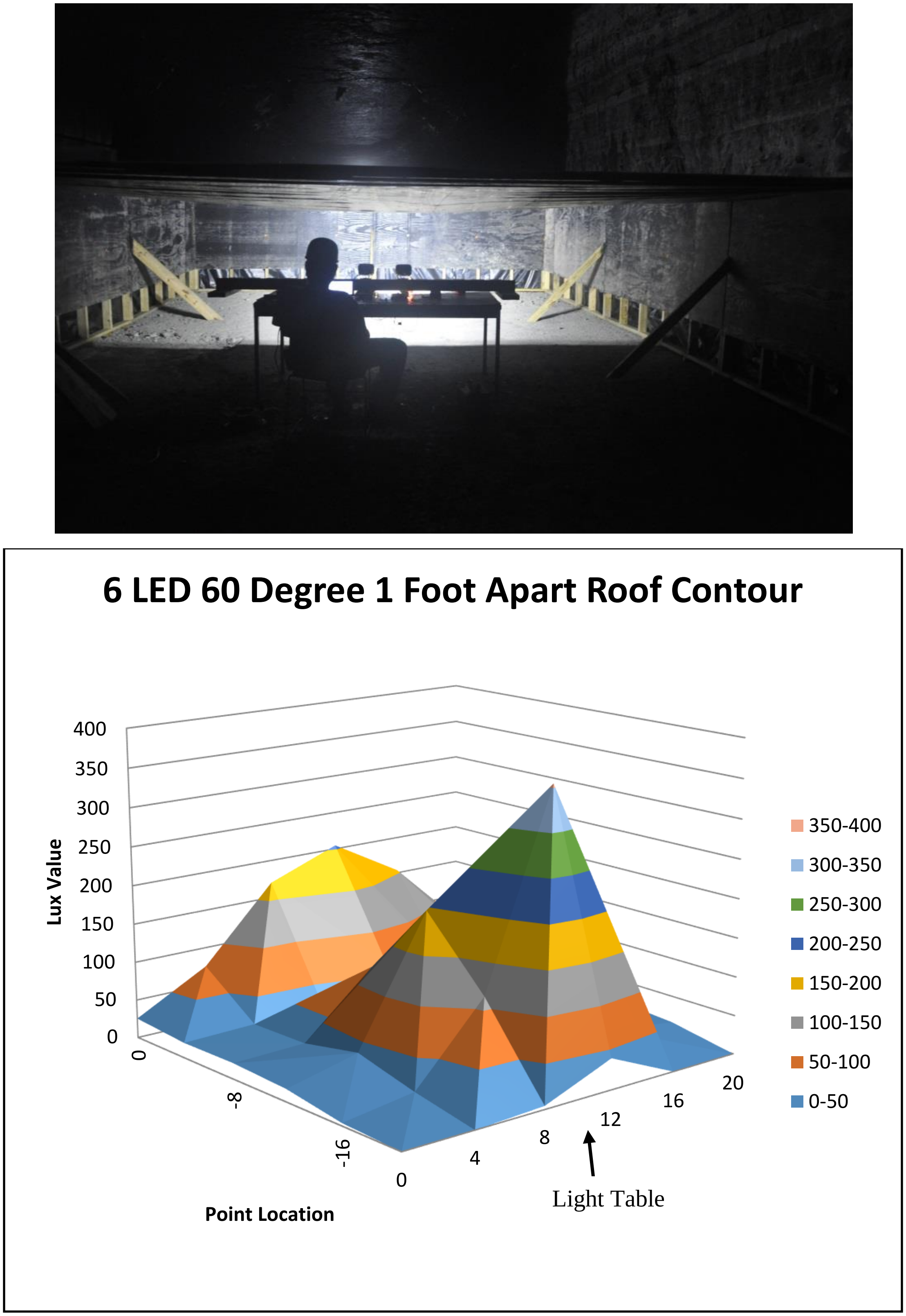


Figure 3.20: 6 LED 60 Degree 1 Foot Apart Photographic Result and Roof Light Contour

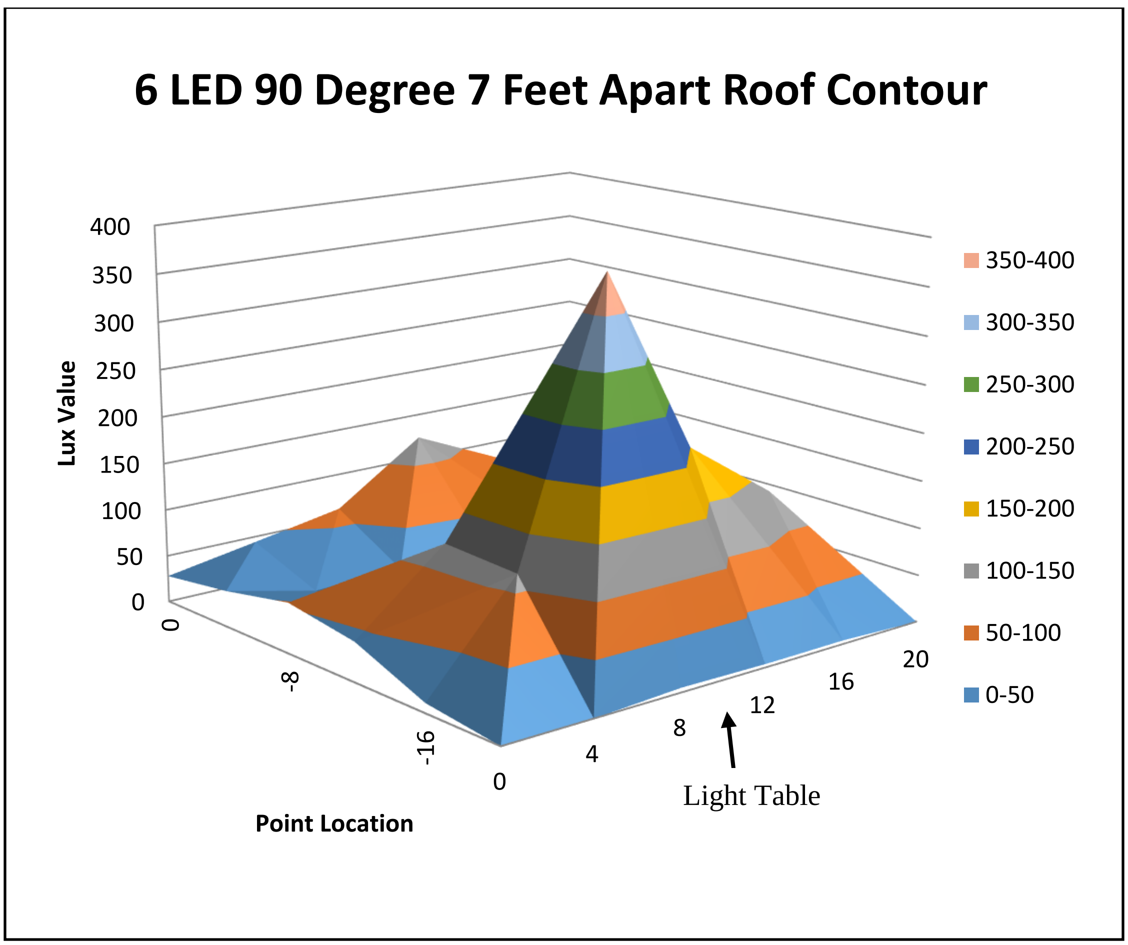


Figure 3.21: 6 LED 90 Degree 7 Feet Apart Photographic Result and Roof Light Contour

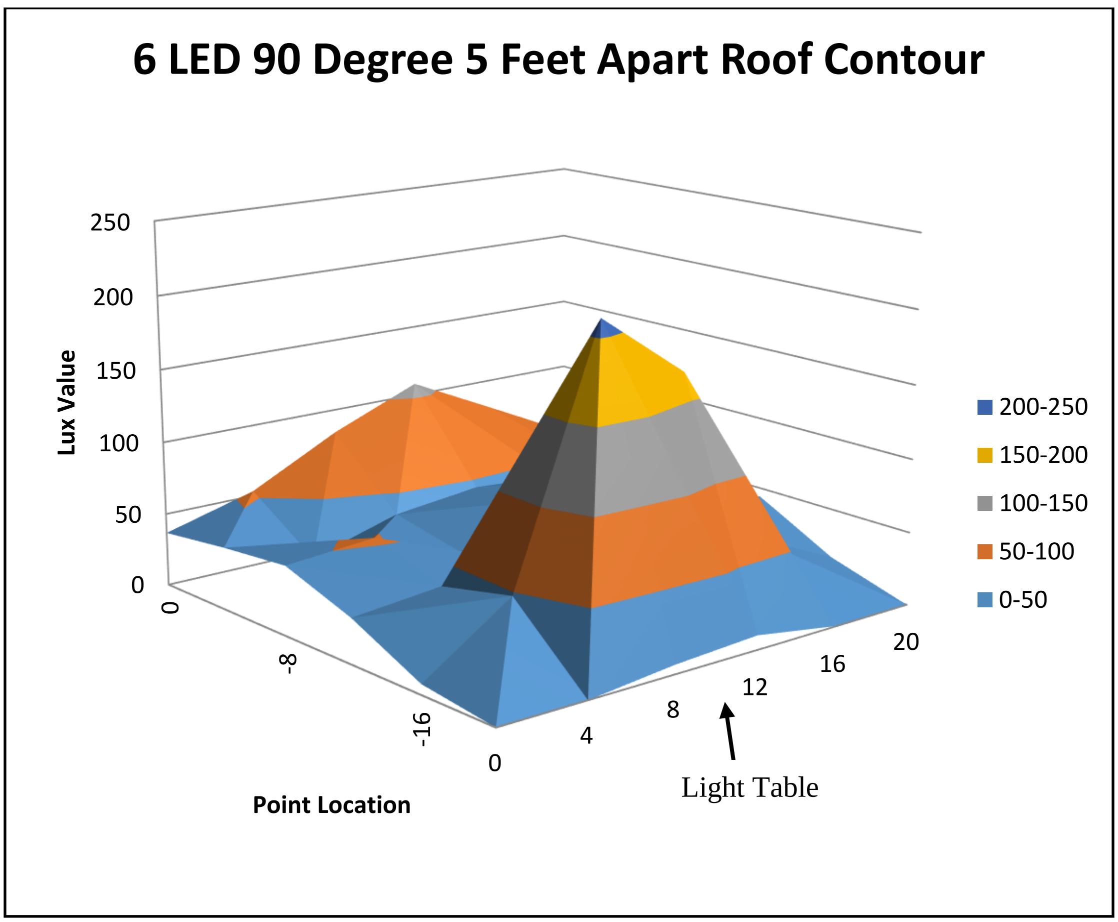


Figure 3.22: 6 LED 90 Degree 5 Feet Apart Photographic Result and Roof Light Contour

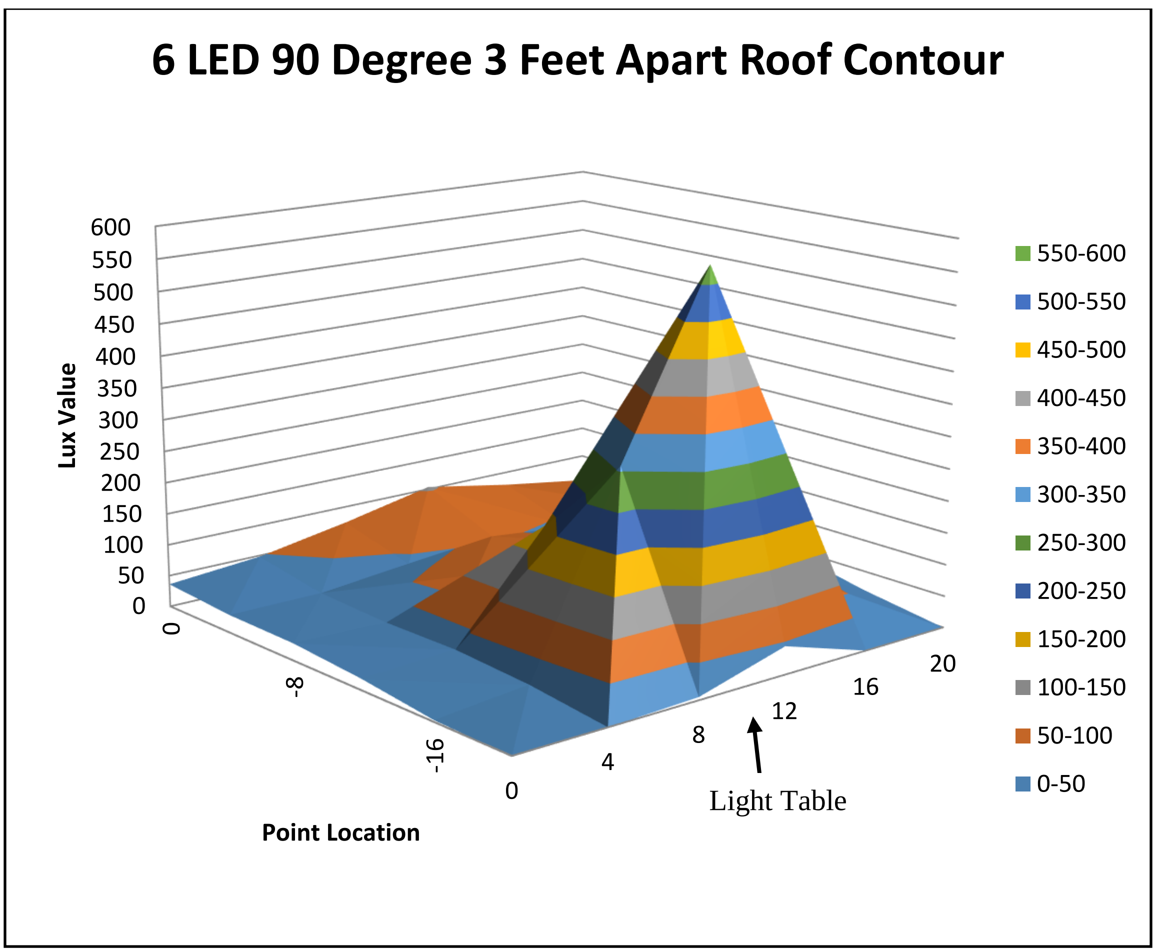


Figure 3.23: 6 LED 90 Degree 3 Feet Apart Photographic Result and Roof Light Contour

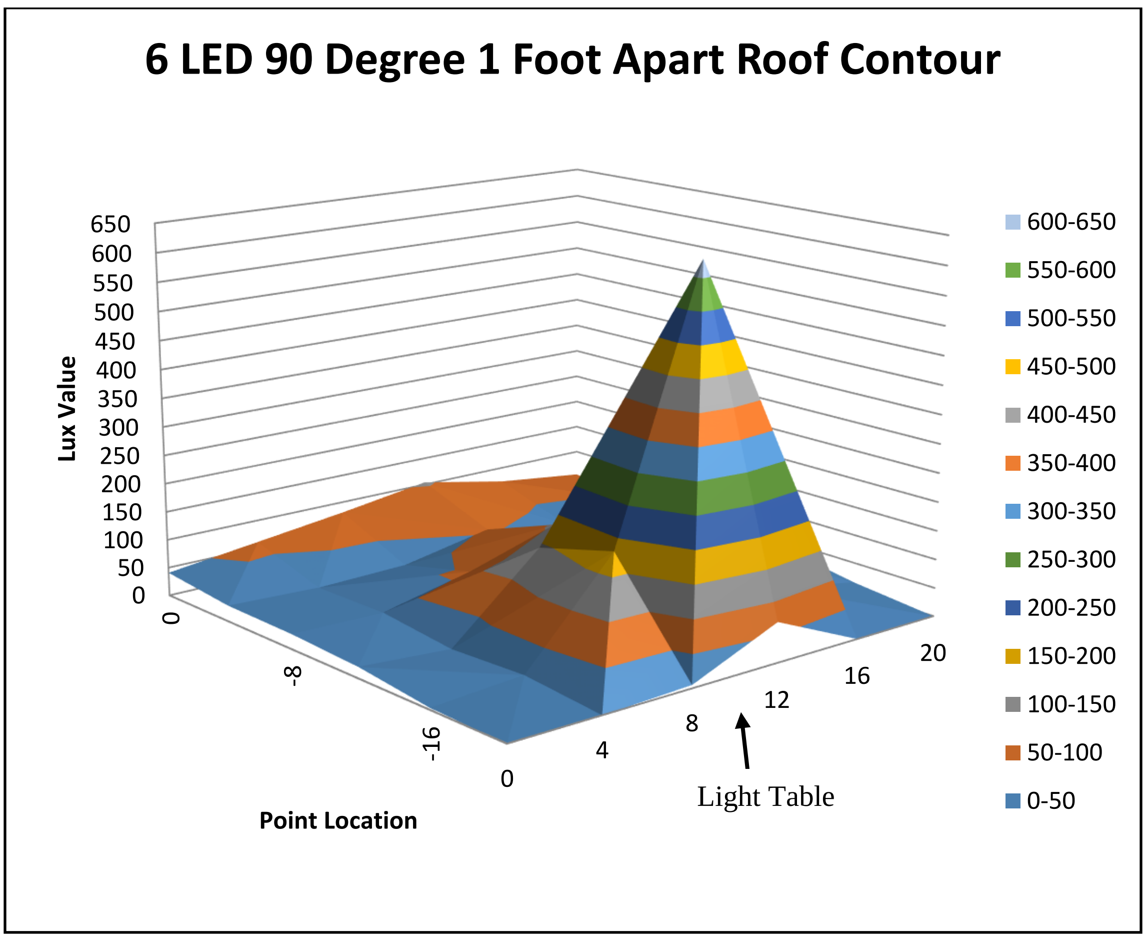


Figure 3.24: 6 LED 90 Degree 1 Feet Apart Photographic Result and Roof Light Contour

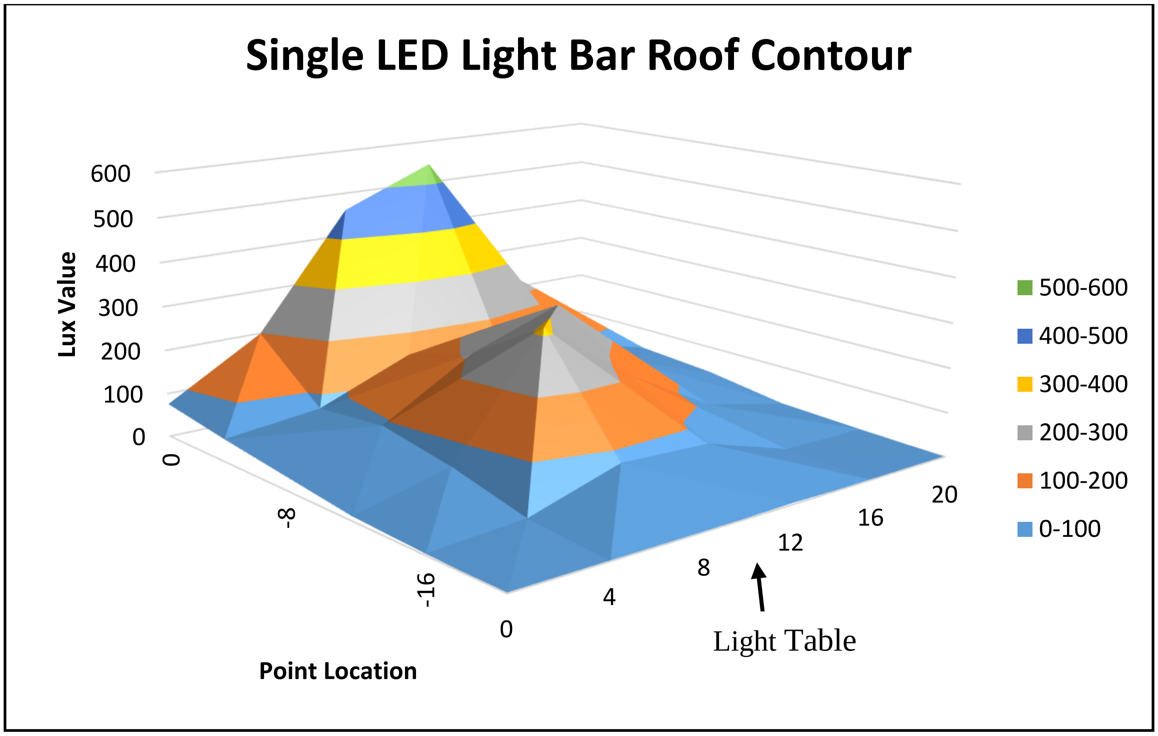


Figure 3.25: Single 15 LED Light Bar on Center of Table

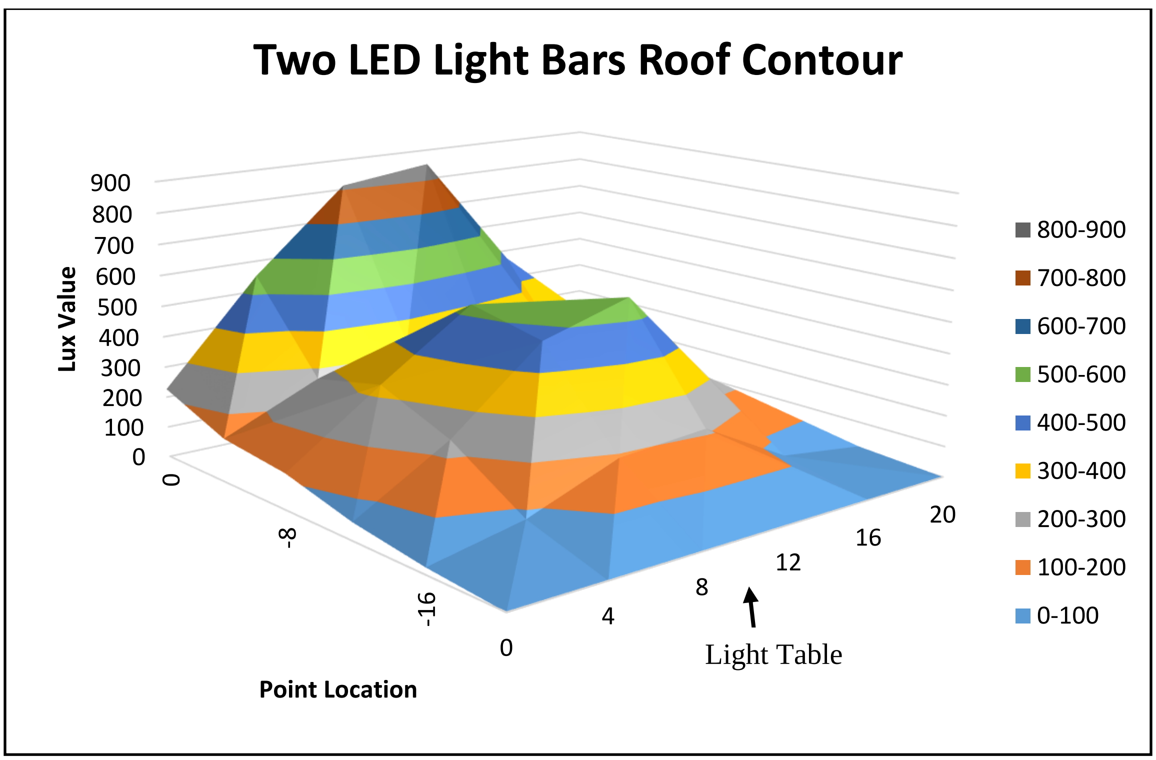


Figure 3.26: Two 15 LED Light Bars Separated 7 Feet from Ends

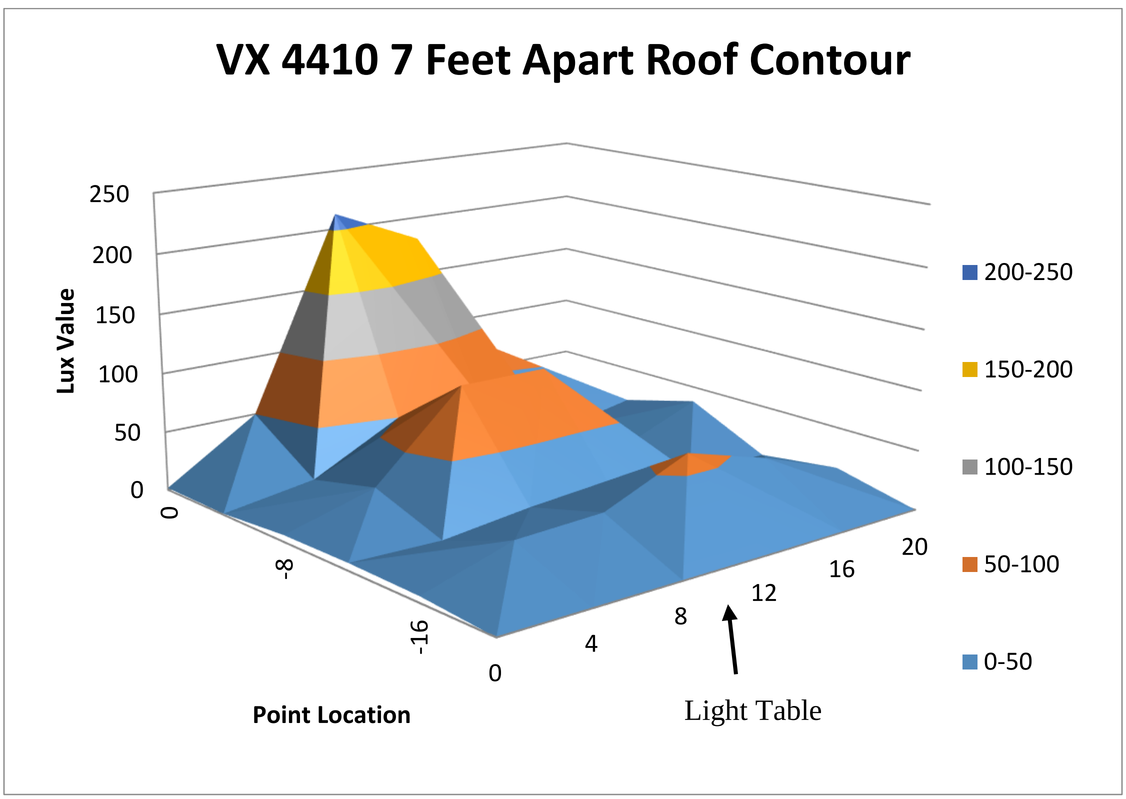


Figure 3.27: Euro Beam Halogen 7 Feet Apart Photographic Result and Roof Contour

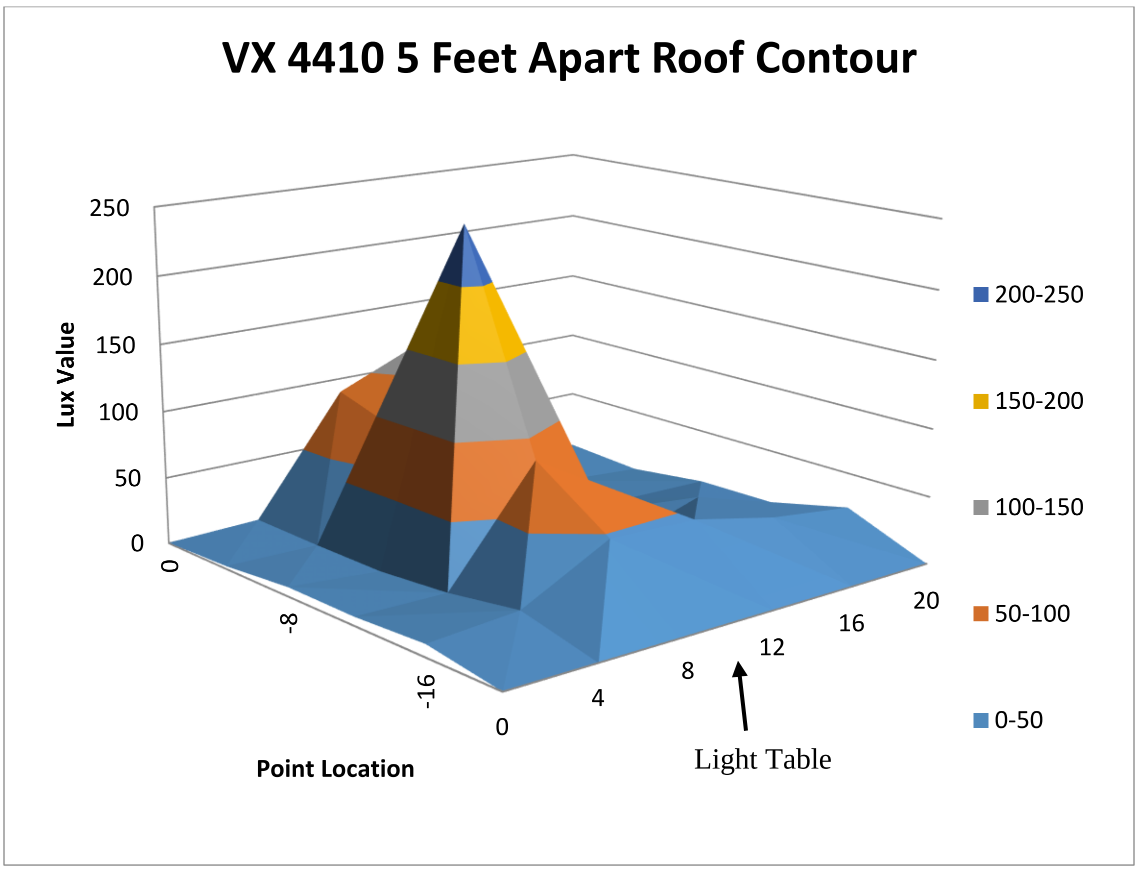
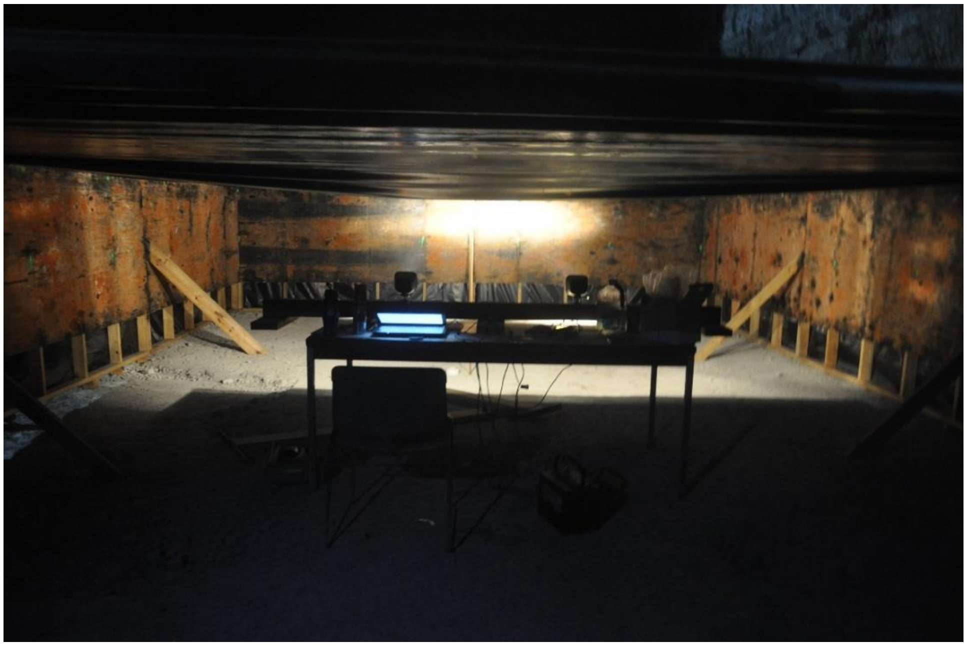


Figure 3.28: Euro Beam Halogen 5 Feet Apart Photographic Result and Roof Contour



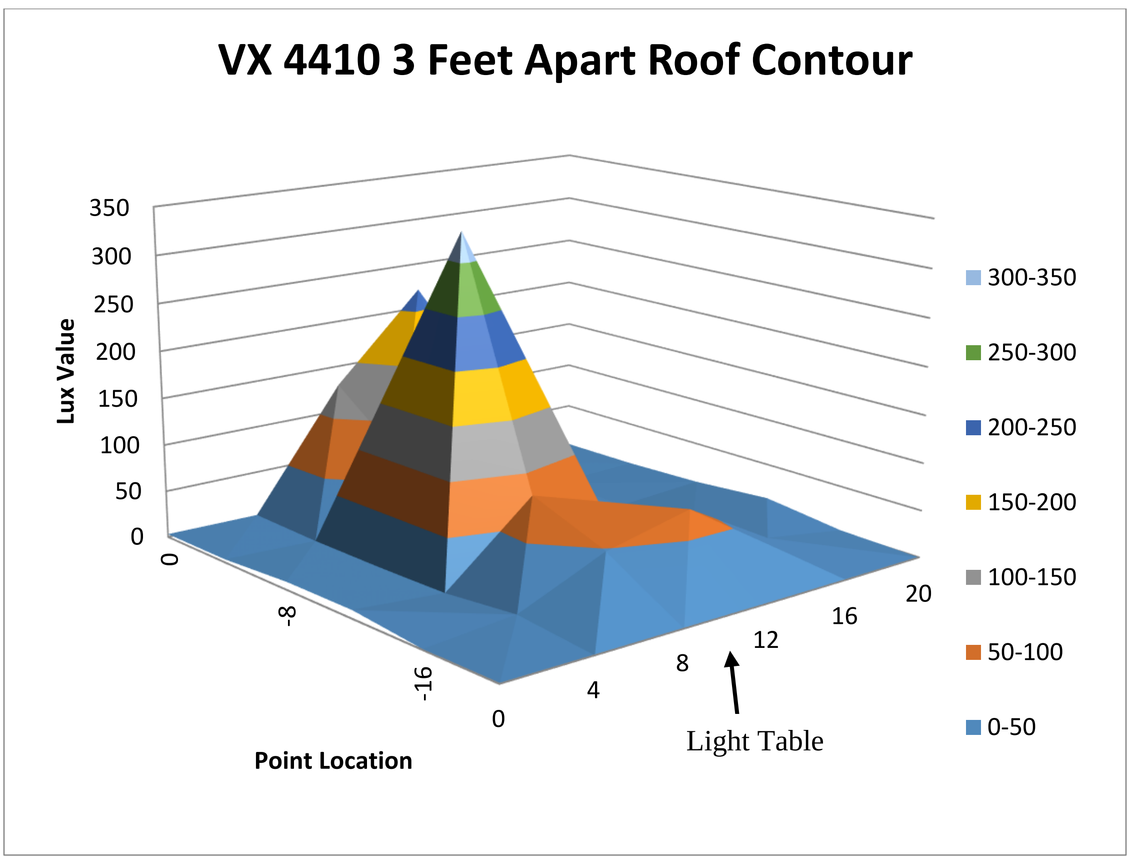
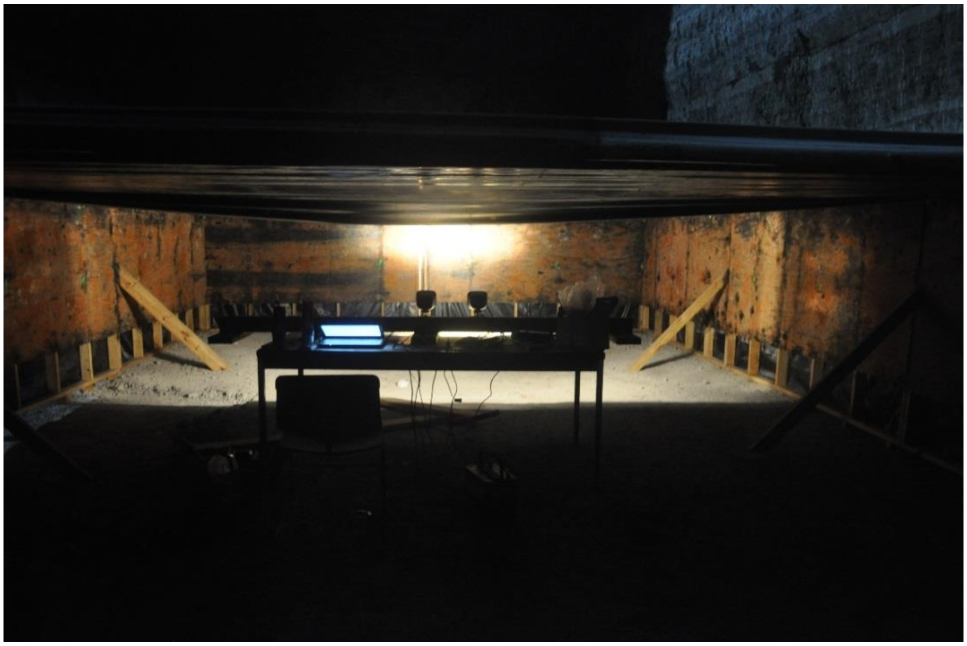


Figure 3.29: Euro Beam Halogen 3 Feet Apart Photographic Result and Roof Contour



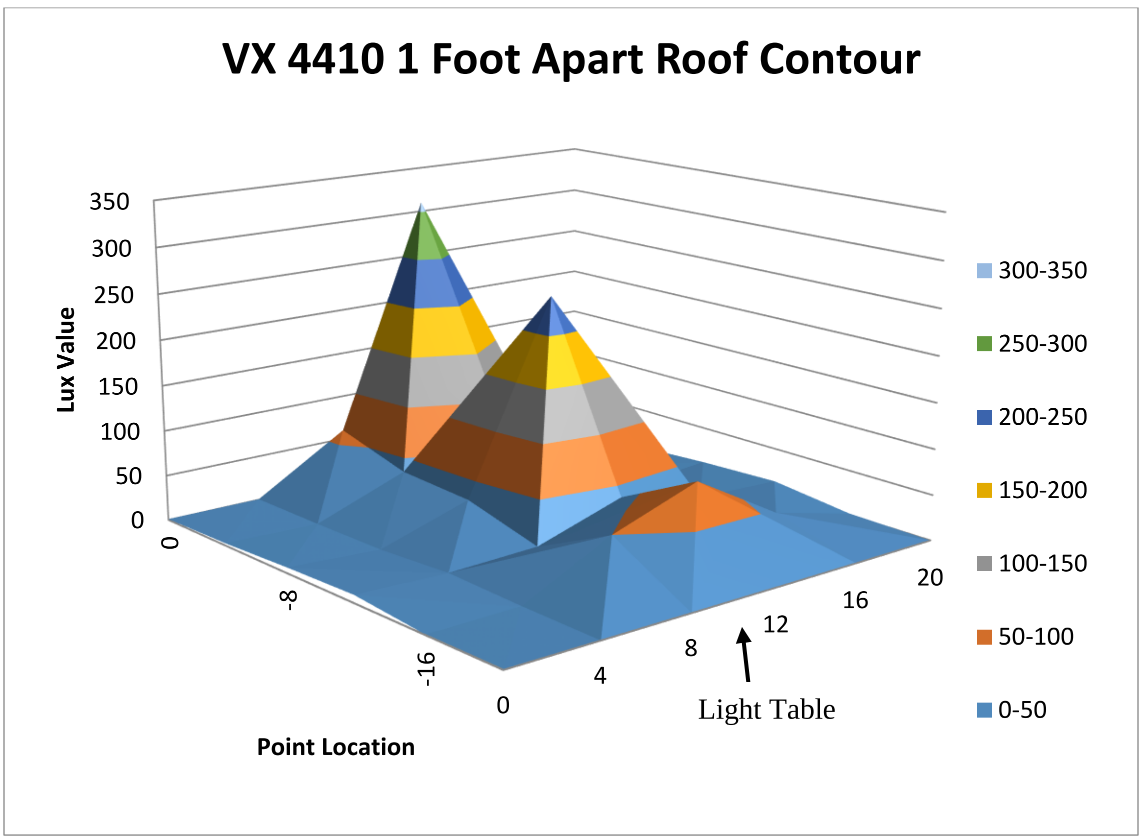


Figure 3.30: Euro Beam Halogen 1 Foot Apart Photographic Result and Roof Contour

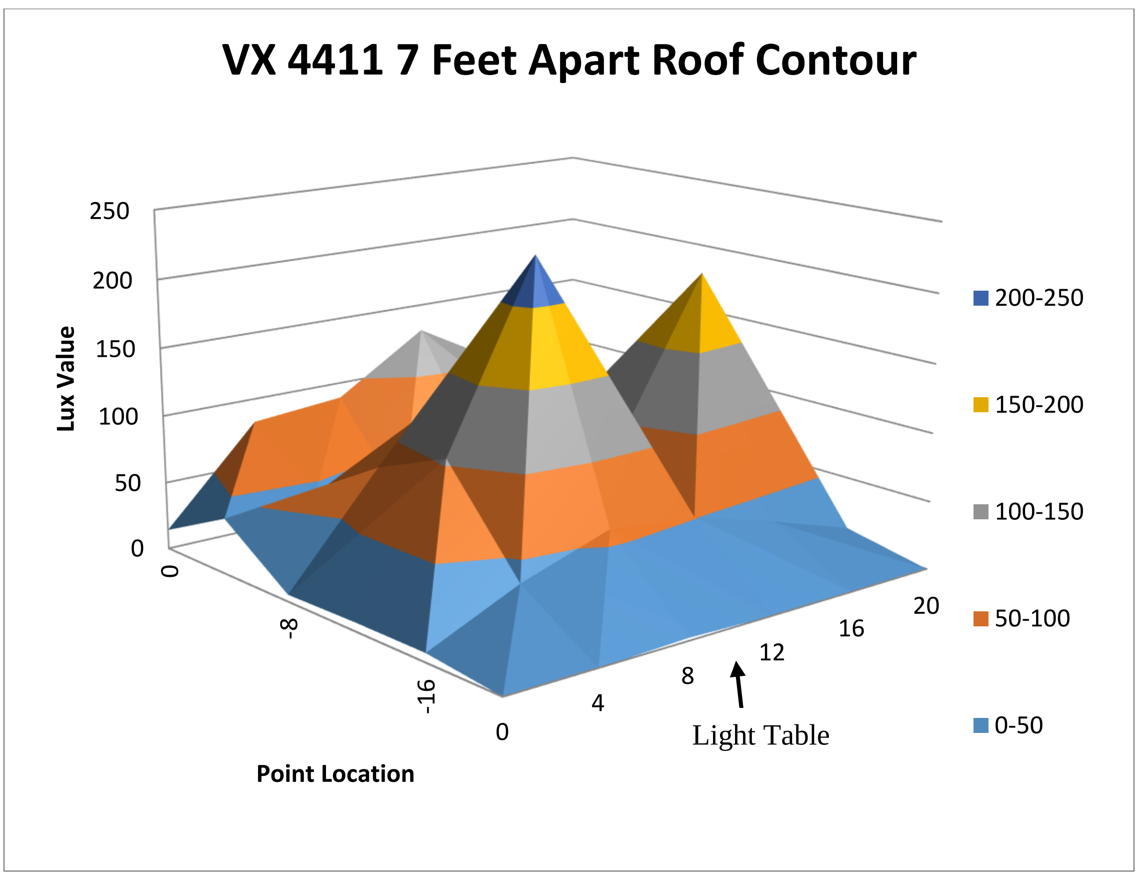


Figure 3.31: Horizontal Flood Beam Halogen 7 Feet Apart Photographic Result and Roof Contour

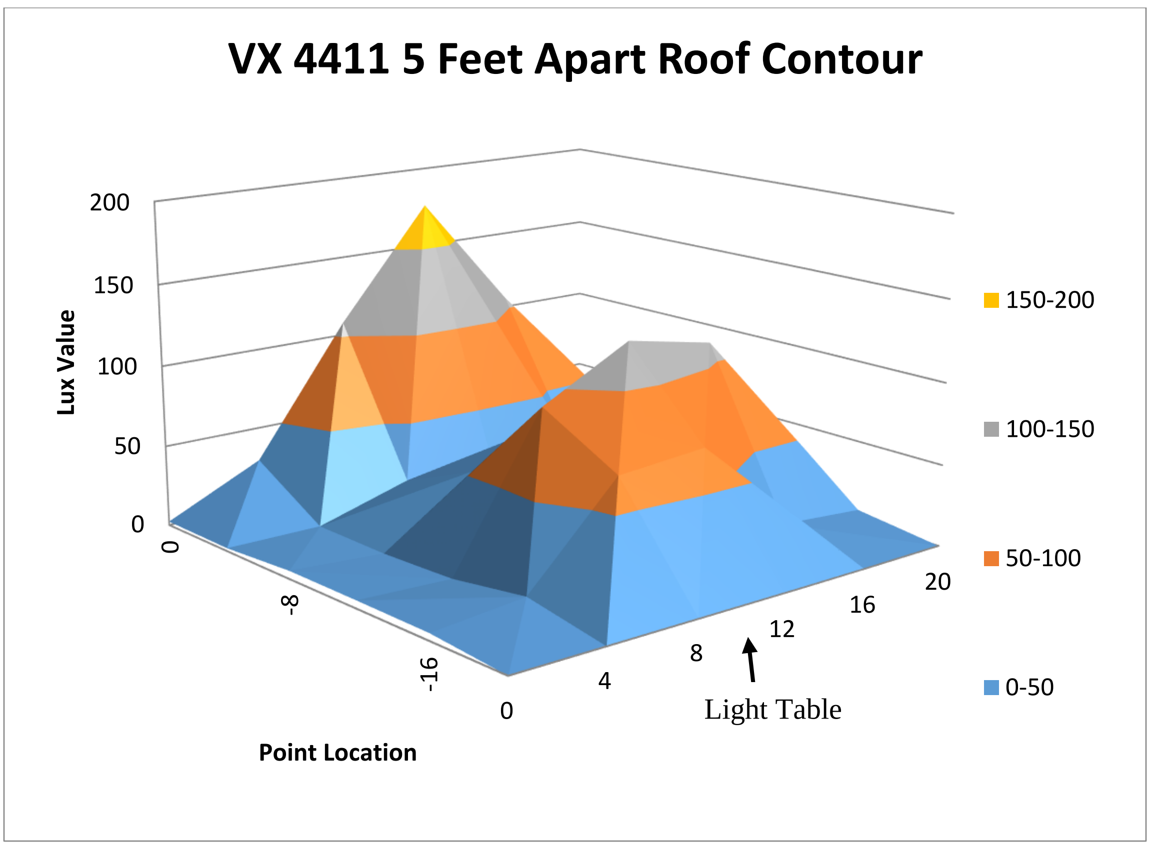


Figure 3.32: Horizontal Flood Beam Halogen 5 Feet Apart Photographic Result and Roof Contour

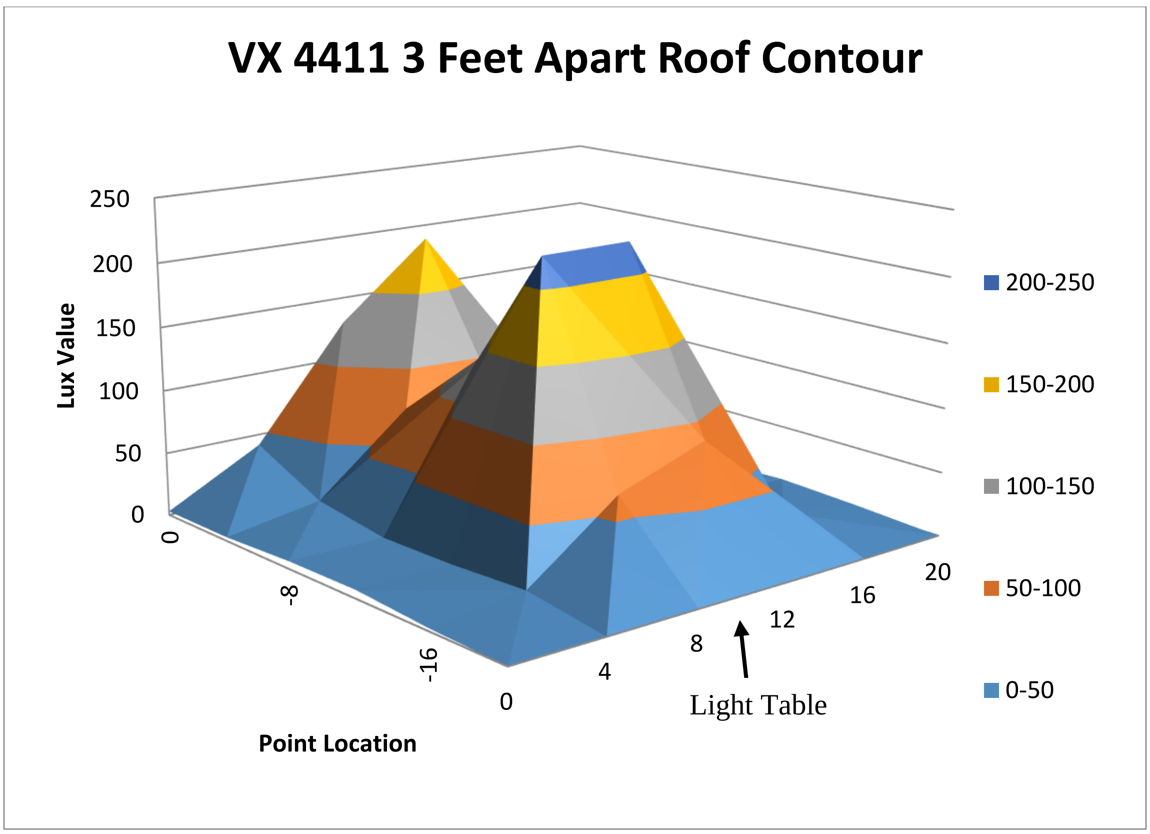
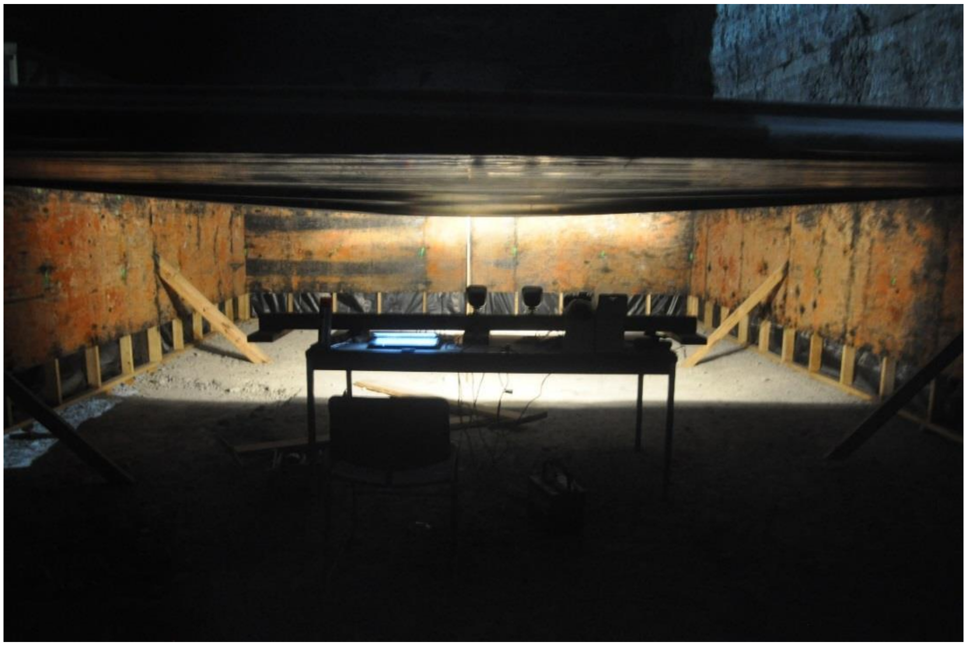


Figure 3.33: Horizontal Flood Beam Halogen 3 Feet Apart Photographic Result and Roof Contour



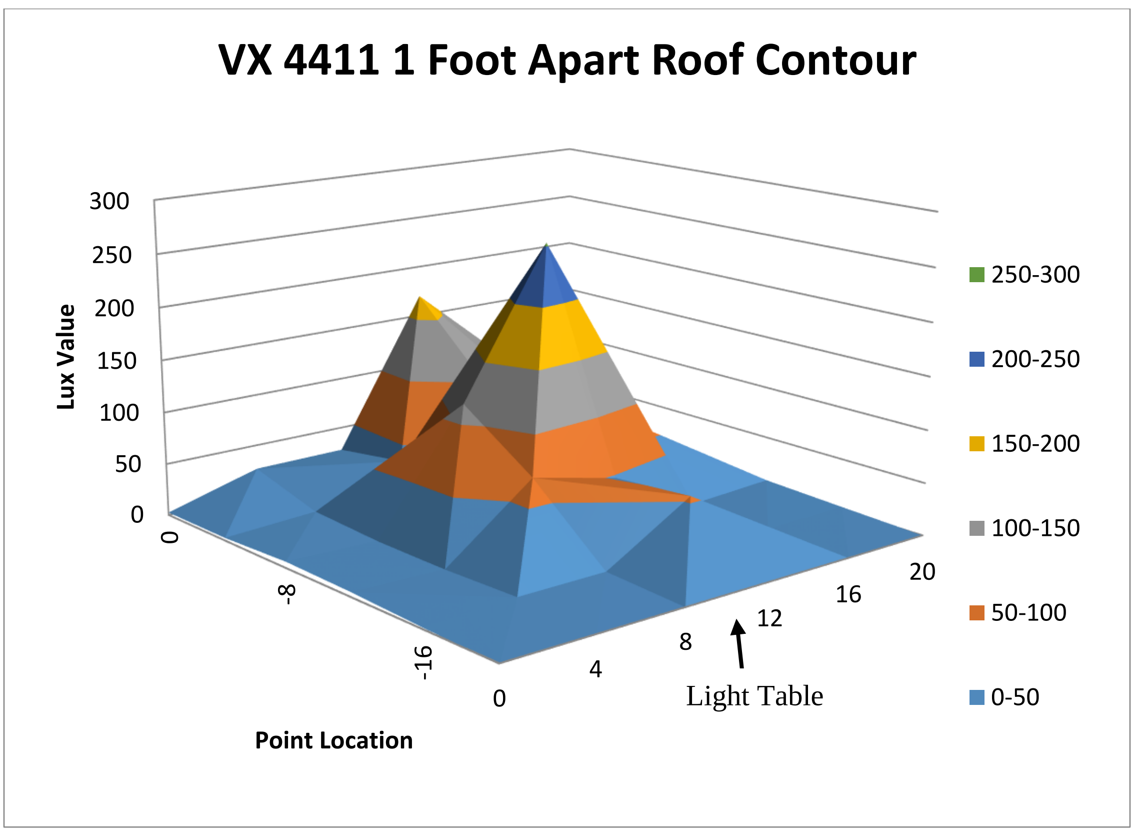


Figure 3.34: Horizontal Flood Beam Halogen 1 Foot Apart Photographic Result and Roof Contour

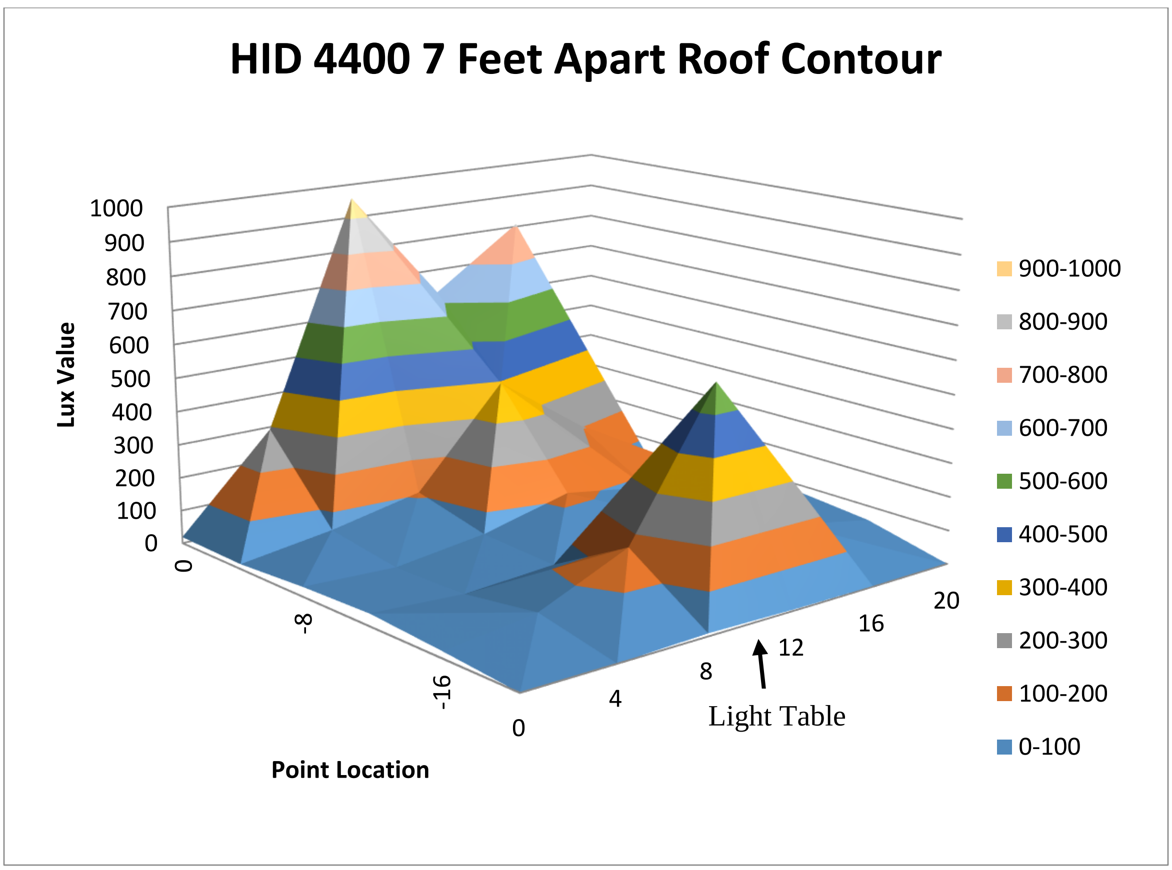


Figure 3.35: Euro Beam HID 7 Feet Apart Photographic Result and Roof Contour

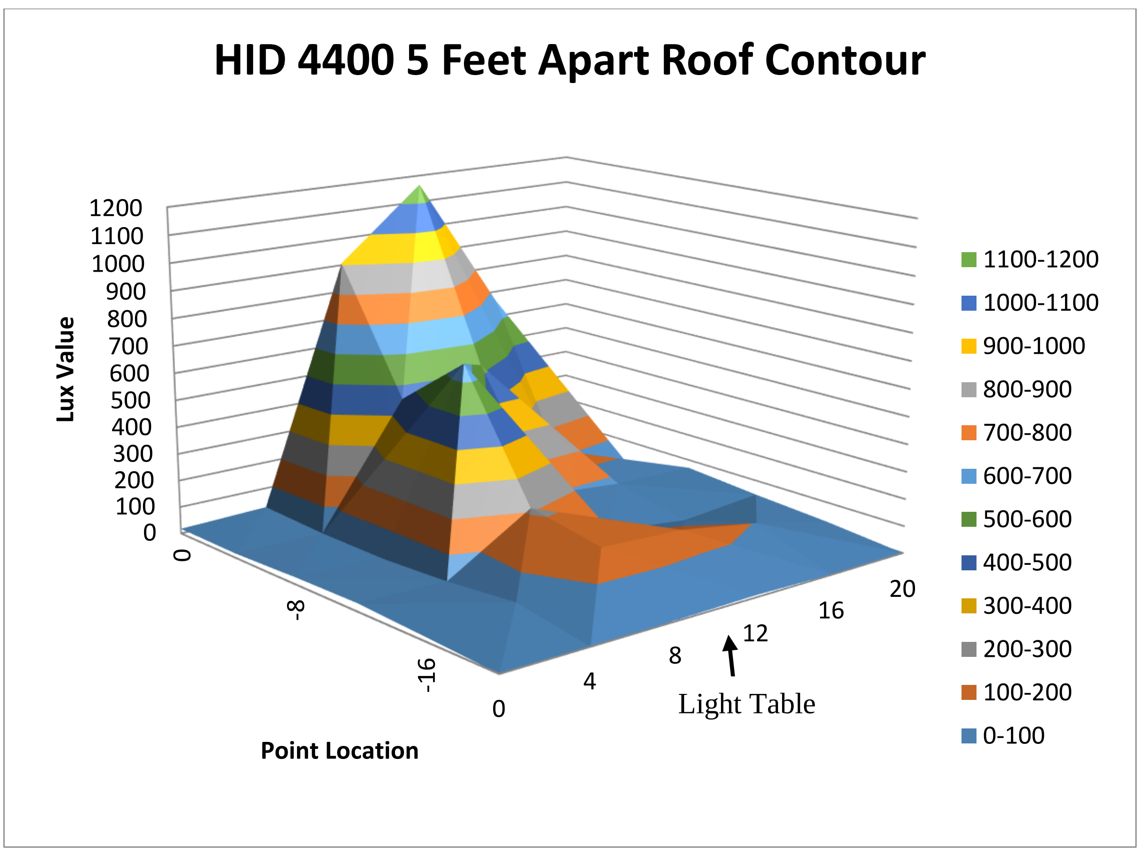


Figure 3.36: Euro Beam HID 5 Feet Apart Photographic Result and Roof Contour

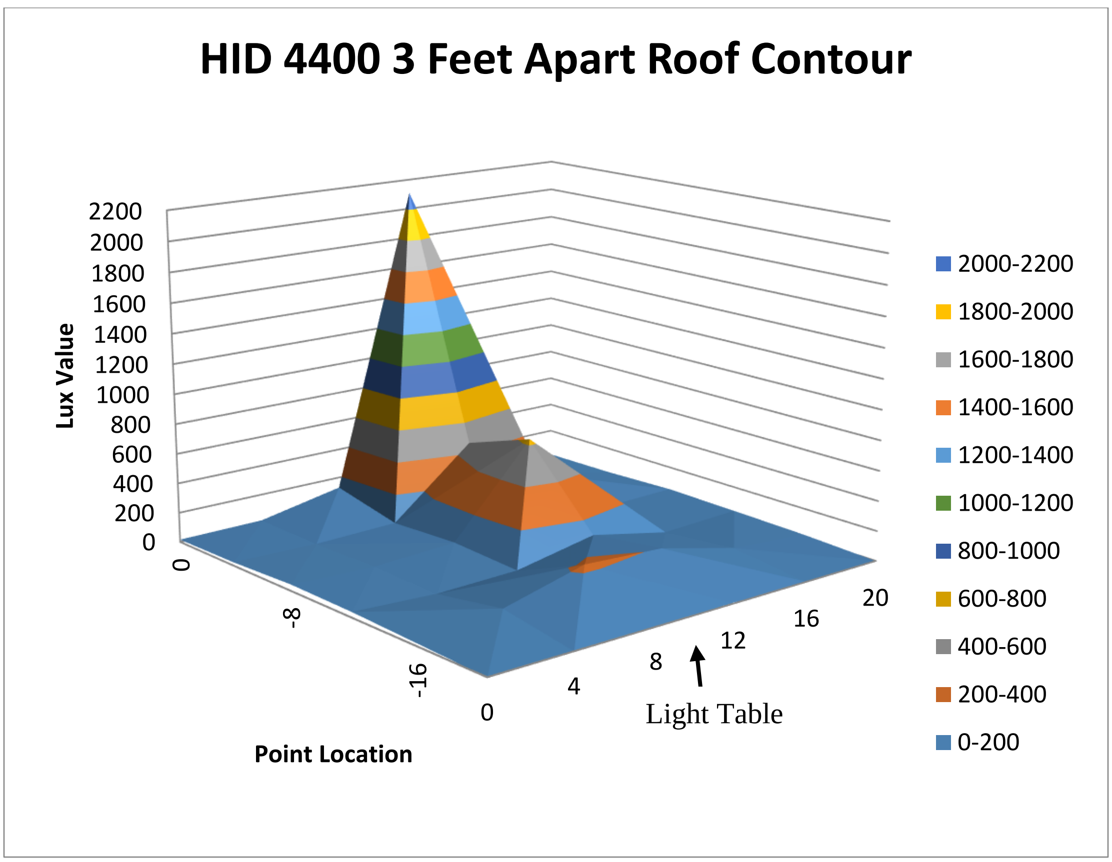
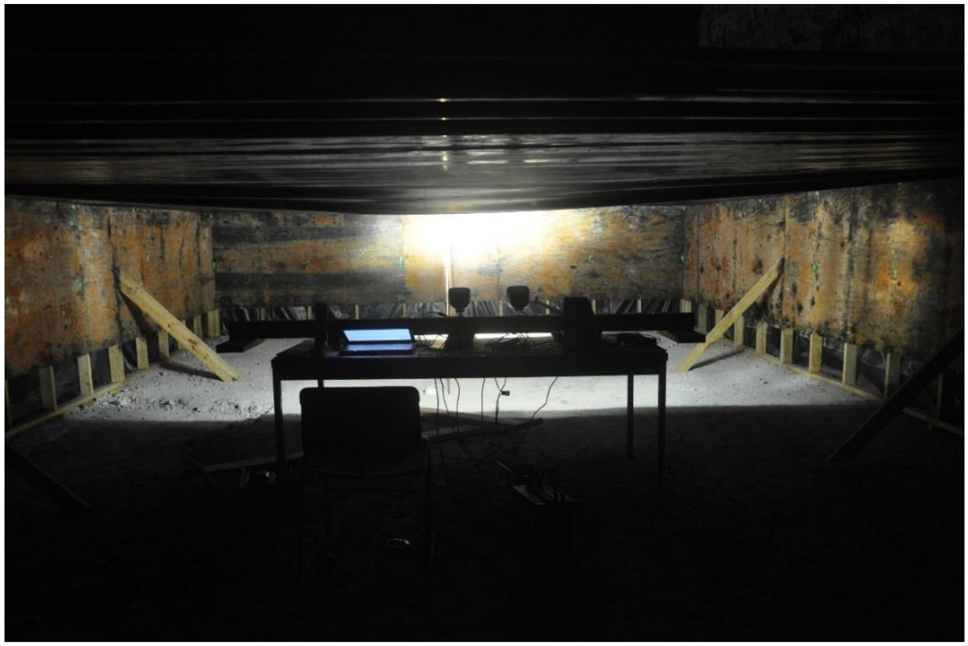


Figure 3.37: Euro Beam HID 3 Feet Apart Photographic Result and Roof Contour



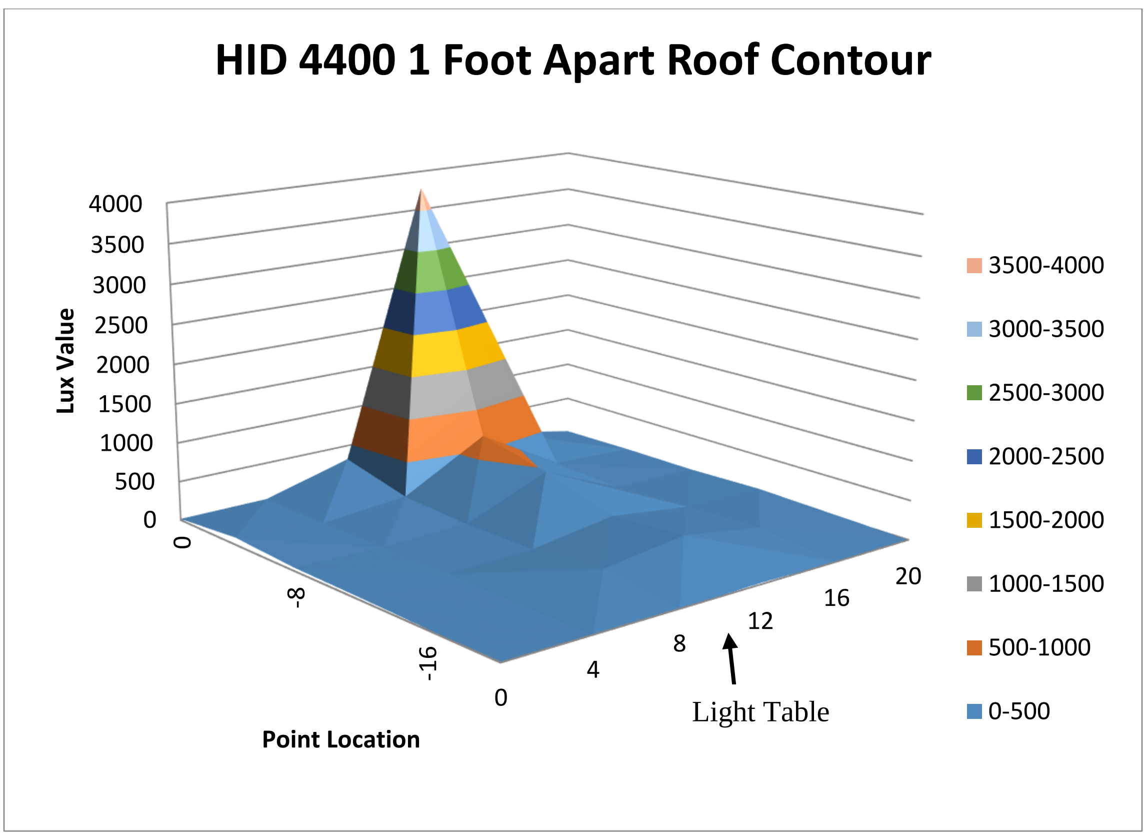


Figure 3.38: Euro Beam HID 1 Foot Apart Photographic Result and Roof Contour

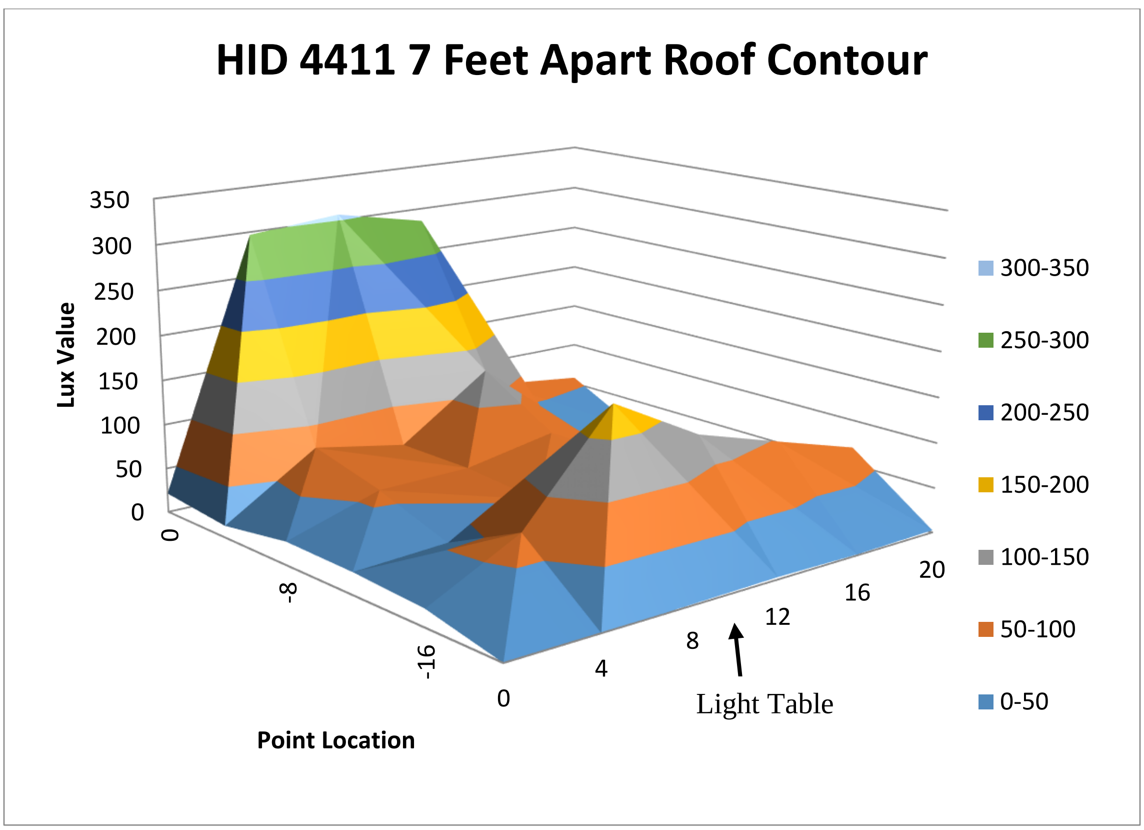


Figure 3.39: Horizontal Flood Beam HID 7 Feet Apart Photographic Result and Roof Contour

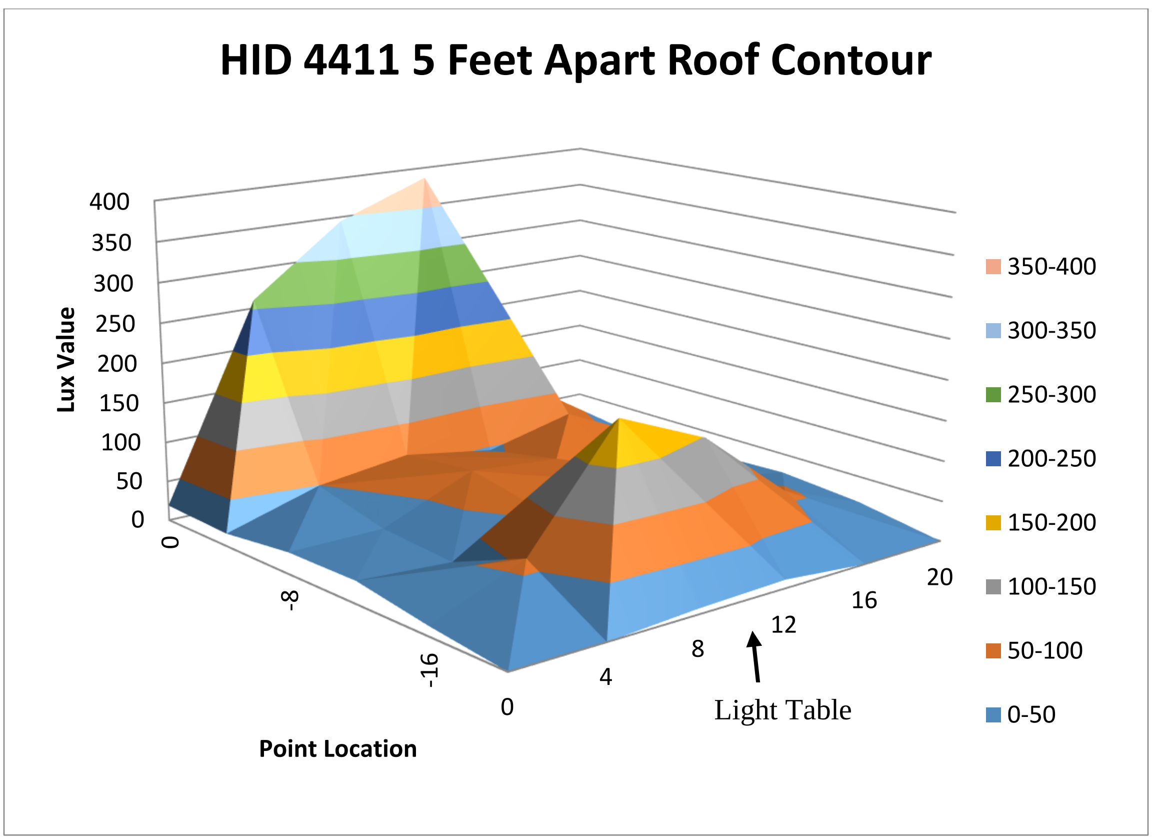
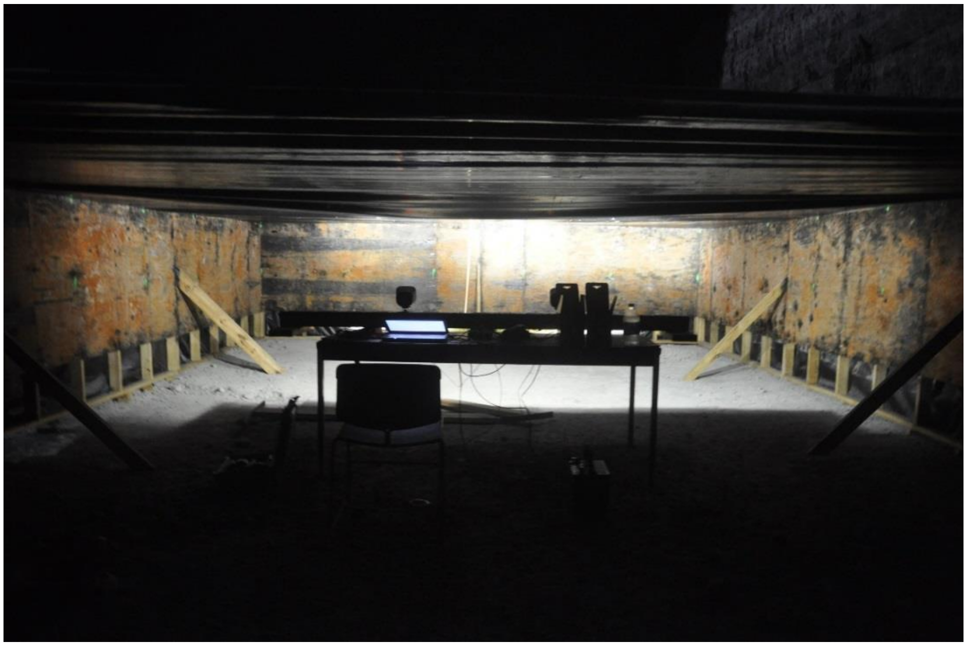


Figure 3.40: Horizontal Flood Beam HID 5 Feet Apart Photographic Result and Roof Contour



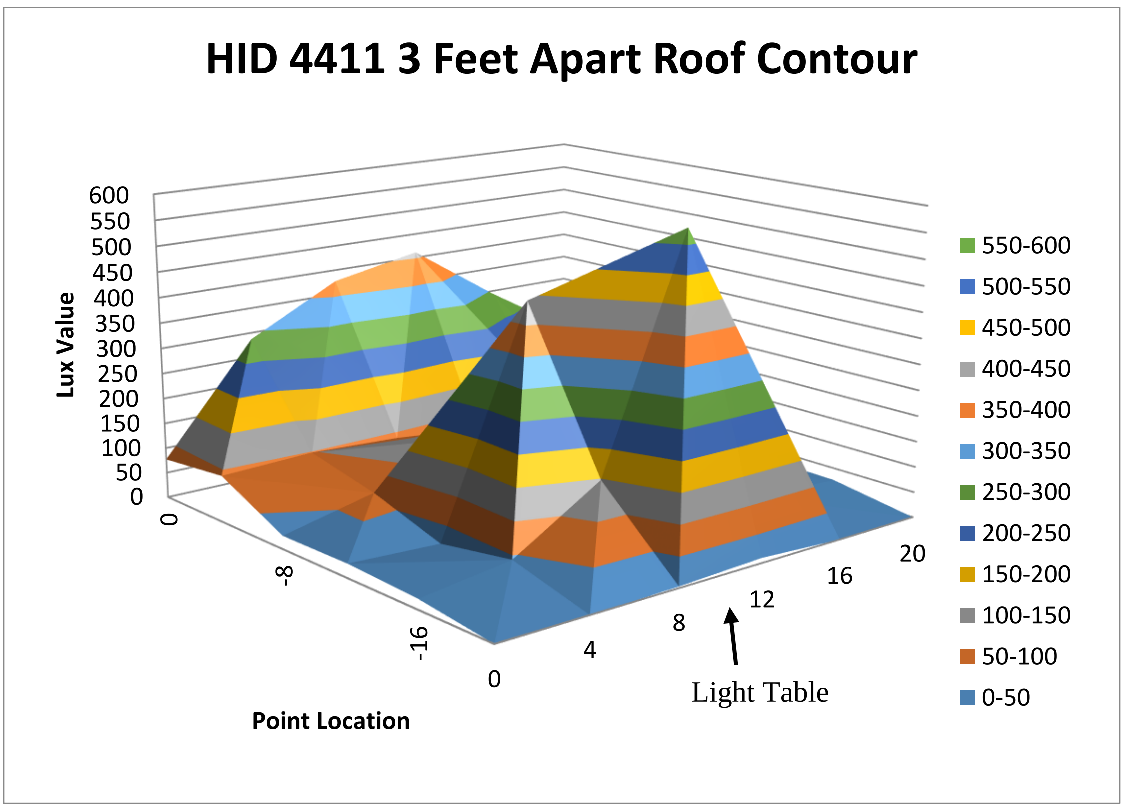


Figure 3.41: Horizontal Flood Beam HID 3 Feet Apart Photographic Result and Roof Contour

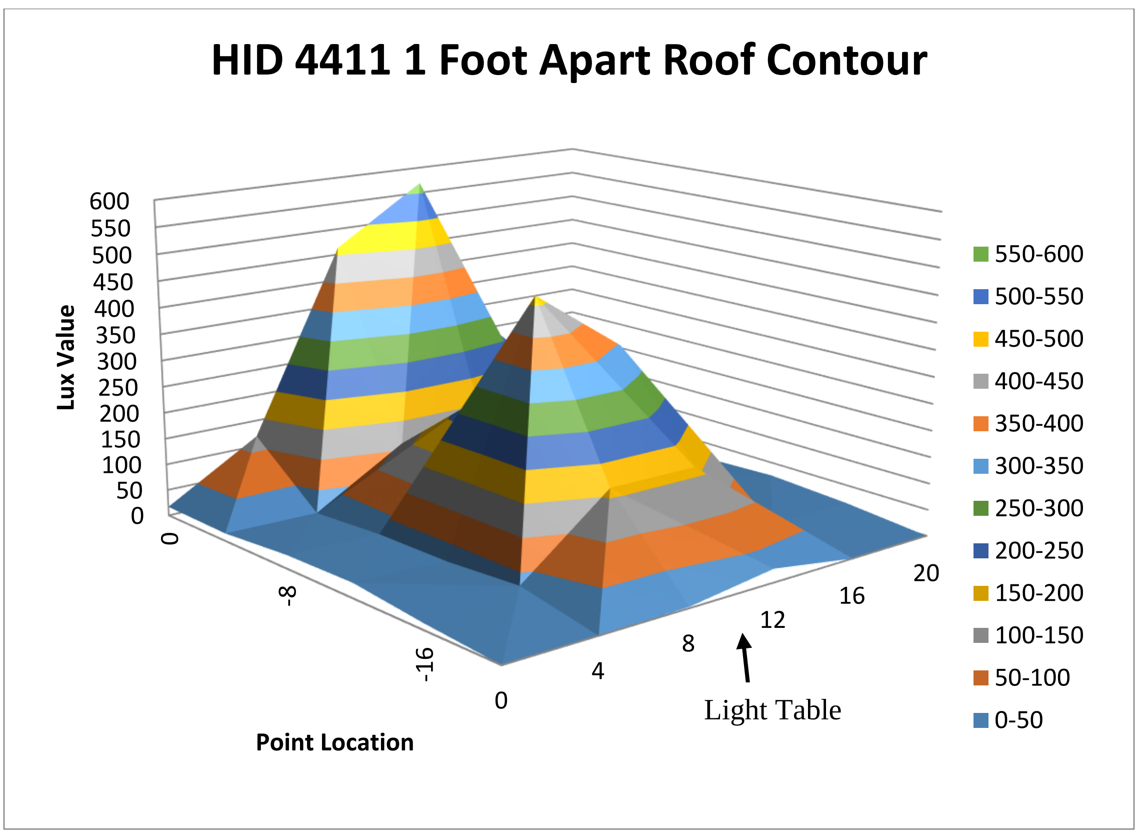
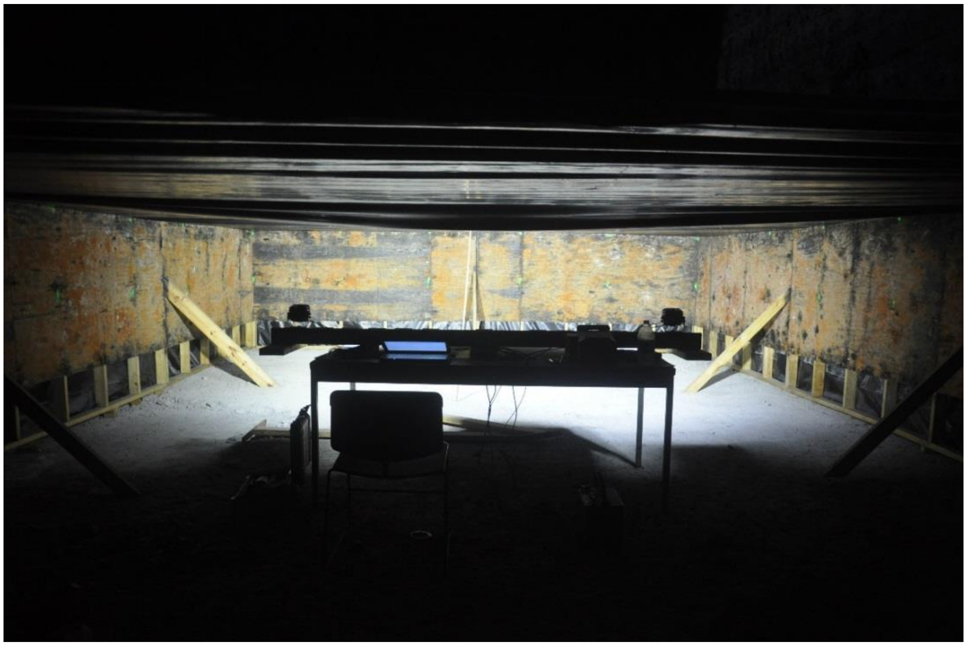


Figure 3.42: Horizontal Flood Beam HID 1 Foot Apart Photographic Result and Roof Contour



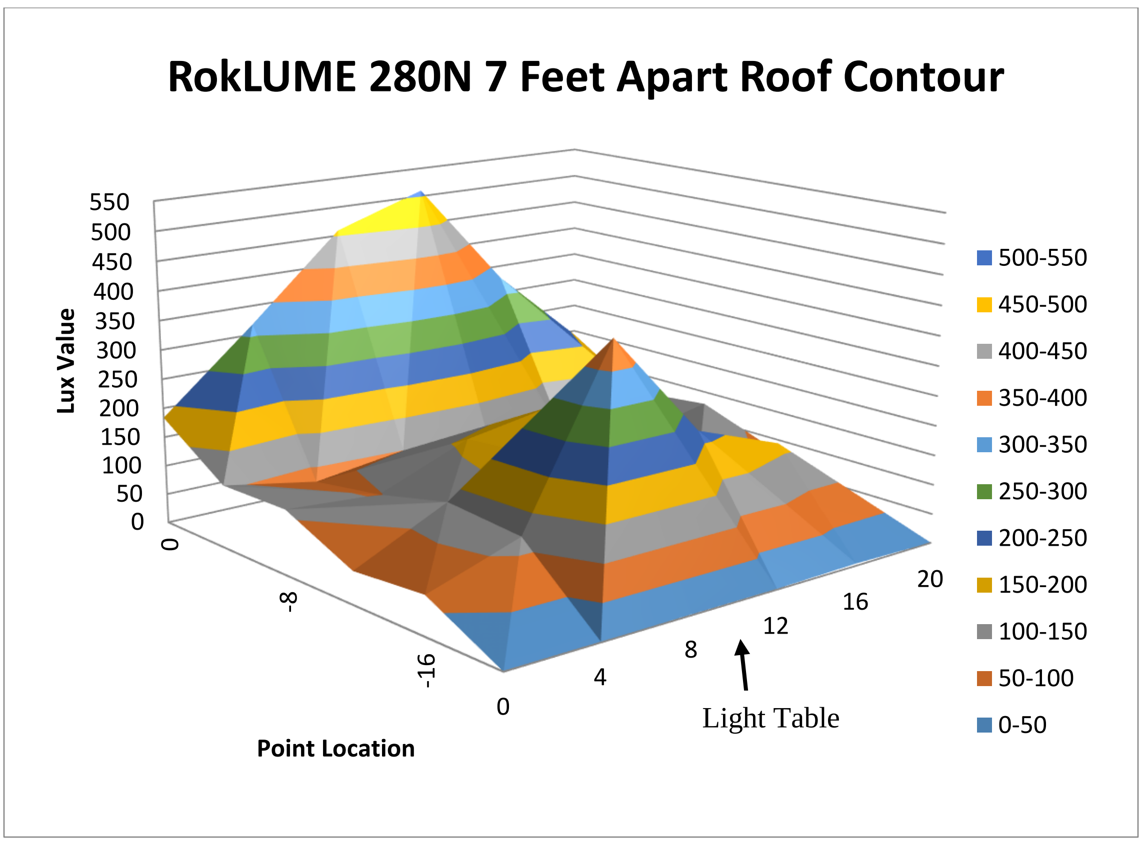
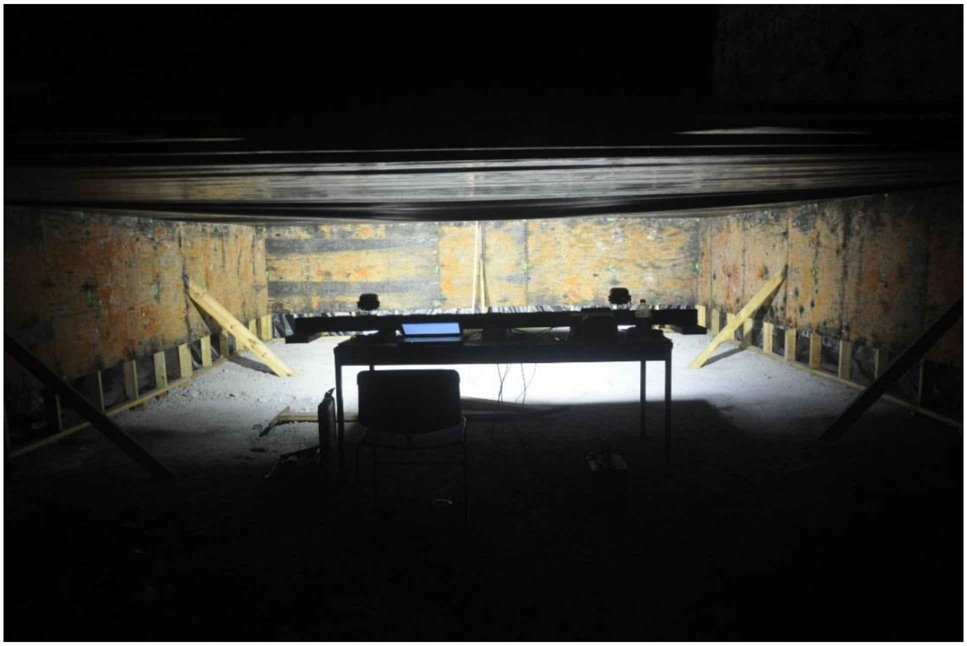


Figure 3.43: Hella LED 7 Feet Apart Photographic Result and Roof Contour



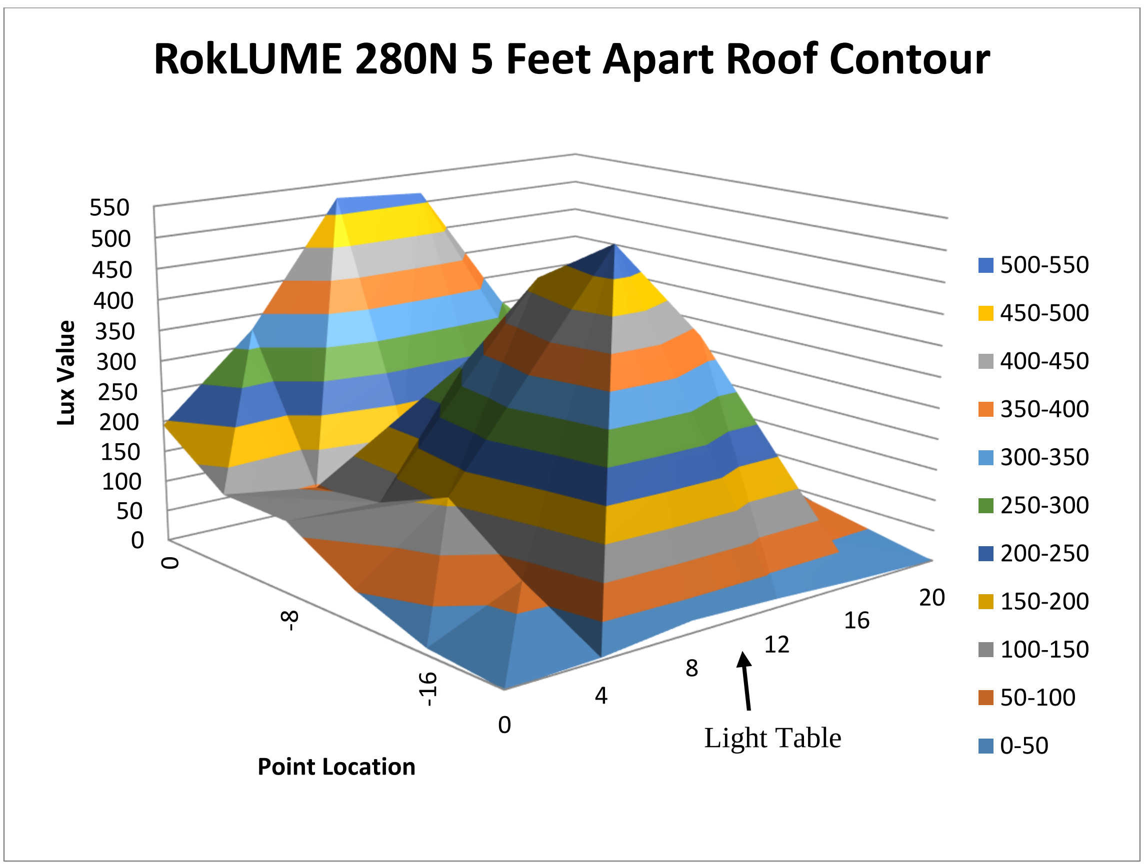
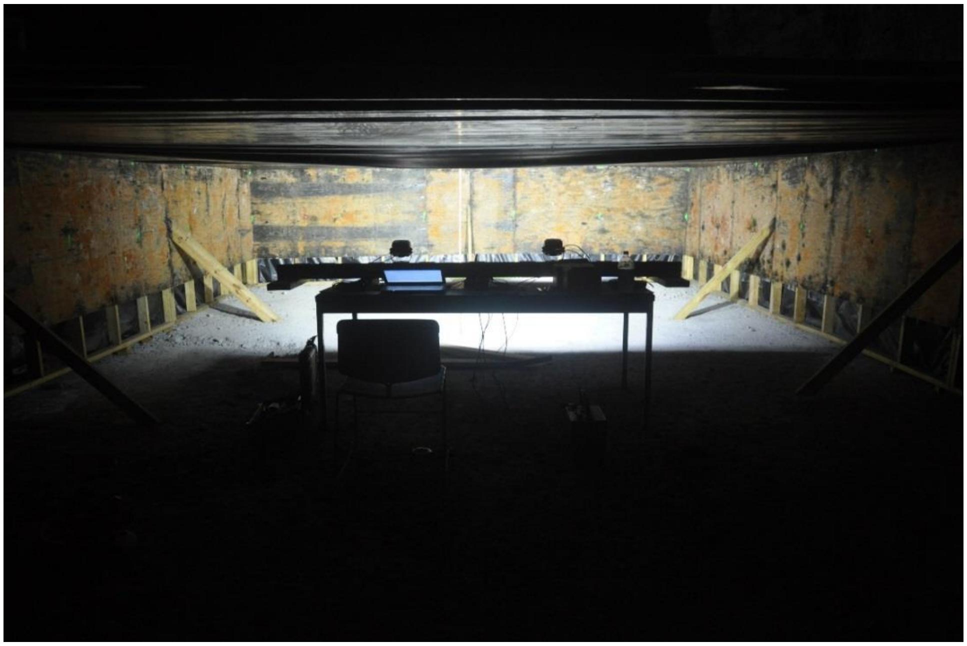


Figure 3.44: Hella LED 5 Feet Apart Photographic Result and Roof Contour



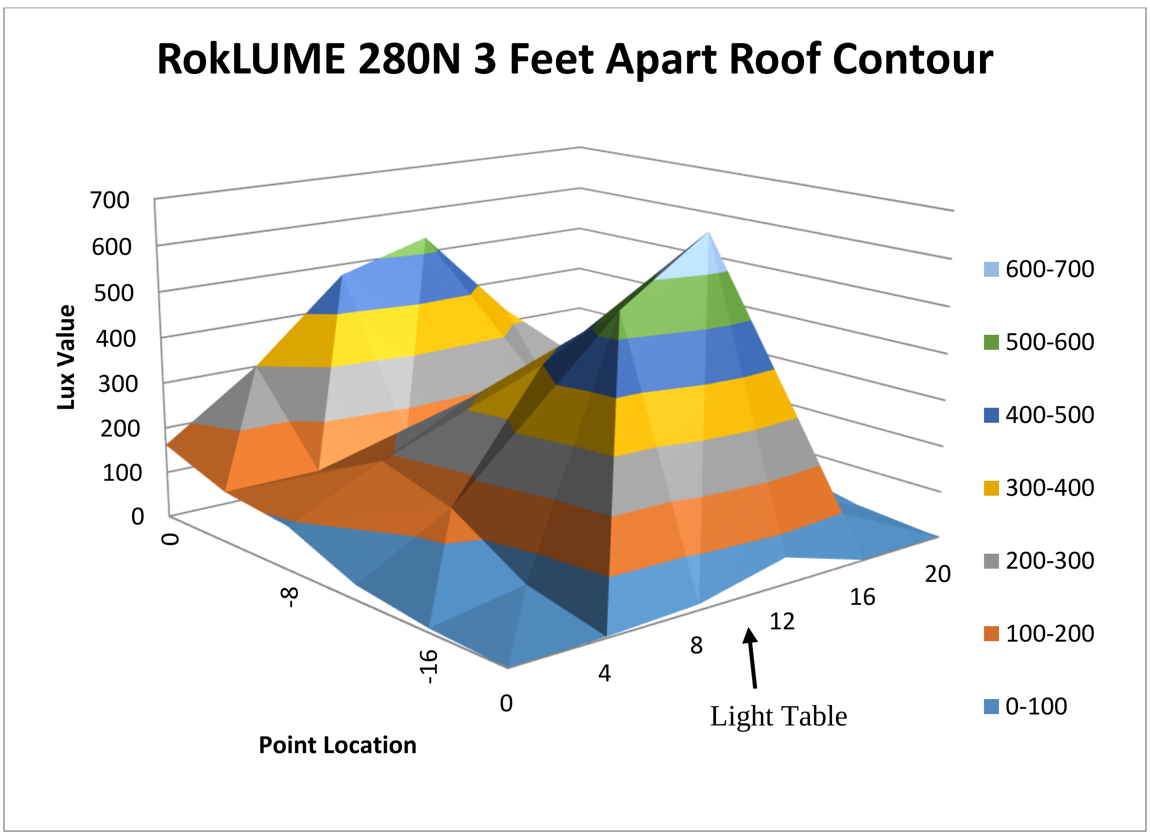
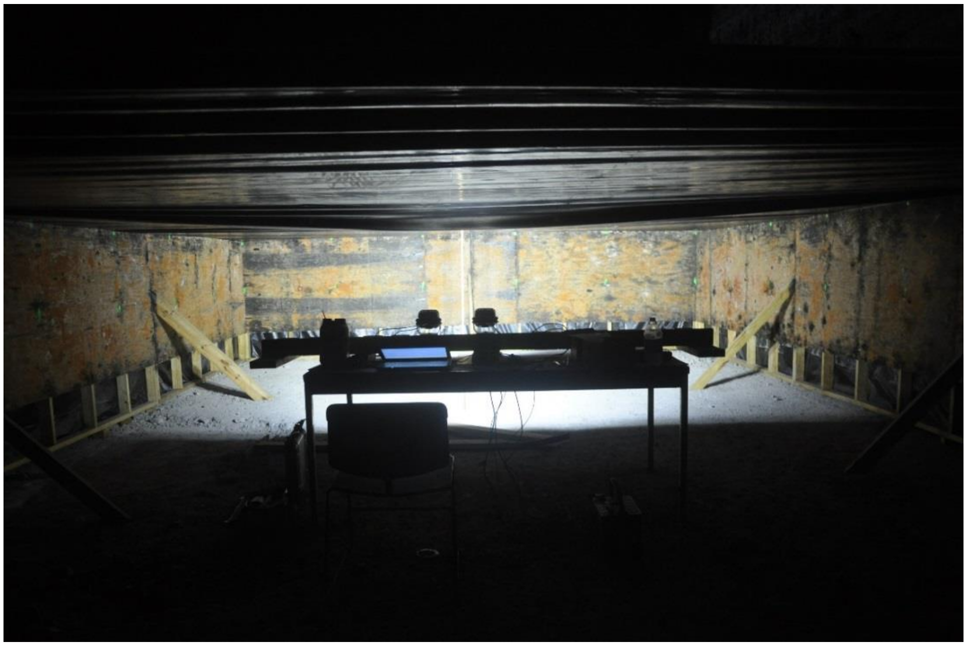


Figure 3.45: Hella LED 3 Feet Apart Photographic Result and Roof Contour



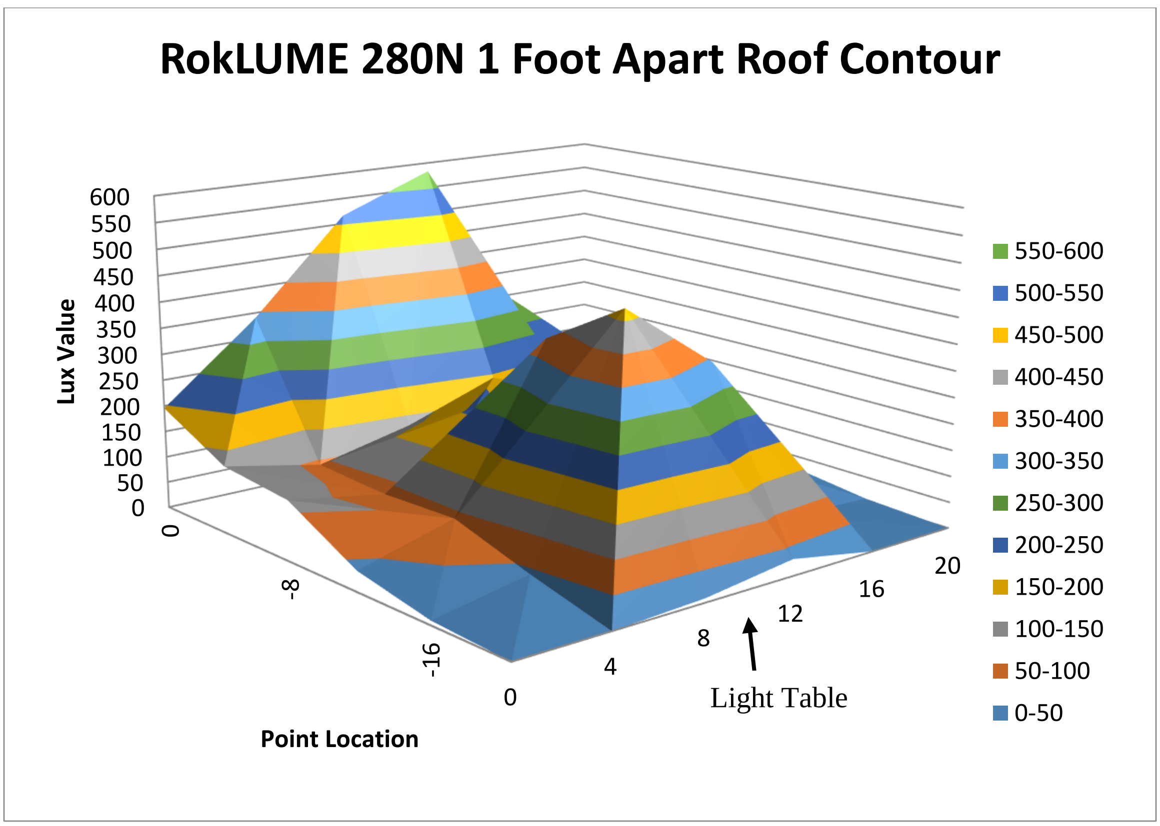


Figure 3.46: Hella LED 1 Foot Apart Photographic Result and Roof Contour

Table 3.2 and Table 3.3 show data obtained from all thirty-eight configurations tested. Table 3.2 ranks all configurations based on average lux values, where Table 3.3 ranks the configurations based on average lux values normalized to power consumption. This was done because the lamps that utilize more lights were seen to generate more light, but these would also use more power to operate. This unit was developed to serve as a comparison between light setups. It was later determined that this value does not provide an indication of light performance within the entry. When two lights were powered by a single power source, each average lux value was divided by two times the rated wattage. Wattage values used were the wattage equivalents shown on the packages each light was received in or from the manufacturer website. No power analysis studies were conducted on each light. The four LED lights were rated at 20 watts, six LED lights at 30 watts, LED lightbars at 75 watts, Hella LED at 56 watts, halogen lights at 100 watts, and HID lights at 35 watts. However, when comparing the normalized data to the contours, it was seen that there was very little correlation between the lux to wattage ratio and light coverage. So it was determined that a second analysis was required to provide a better coverage comparison.

Table 3.2: Average Lux Rankings

Rank	Light type	Avg Lux	Rank	Light type	Avg Lux	Rank	Light type	Avg Lux
1	2 LED lightbars	217.65	14	Hz flood (HID 4411) HID 1ft	77.12	27	4 LED 60 deg 3ft	39.34
2	Hella LED 3ft	173.40	15	6 LED 60 deg 7ft	73.68	28	4 LED 90 deg 1ft	37.91
3	Hella LED 5ft	172.53	16	6 LED 60 deg 5ft	68.55	29	4 LED 90 deg 7ft	35.78
4	Euro (HID 4400) HID 1ft	155.76	17	6 LED 60 deg 3ft	67.57	30	4 LED 90 deg 5ft	35.53
5	Hella LED 1ft	154.64	18	6 LED 60 deg 1ft	62.19	31	4 LED 60 deg 1ft	34.82
6	Hella LED 7ft	151.37	19	6 LED 90 deg 3ft	60.82	32	HZ flood (VX 4411) halogen 3ft	33.34
7	Euro (HID 4400) HID 3ft	126.86	20	6 LED 90 deg 7ft	59.91	33	Euro (VX 4410) halogen 7ft	28.45
8	Euro (HID 4400) HID 5ft	126.10	21	6 LED 90 deg 1ft	58.88	34	HZ flood (VX 4411) halogen 1ft	26.14
9	Euro (HID 4400) HID 7ft	118.50	22	6 LED 90 deg 5ft	47.03	35	Euro (VX 4410) halogen 3ft	25.72
10	Hz flood (HID 4411) HID 3ft	103.48	23	HZ flood (VX 4411) halogen 7ft	42.35	36	HZ flood (VX 4411) halogen 5ft	25.57
11	Single LED light bar	102.39	24	4 LED 60 deg 7ft	42.28	37	Euro (VX 4410) halogen 5ft	24.91
12	Hz flood (HID 4411) HID 5ft	87.77	25	4 LED 60 deg 5ft	40.68	38	Euro (VX 4410) halogen 1ft	24.24
13	Hz flood (HID 4411) HID 7ft	82.02	26	4 LED 90 deg 3ft	40.61			

Table 3.3: Normalized average lux rankings

Rank	Light type	Avg Lux/ Watt	Rank	Light type	Avg Lux/ Watt	Rank	Light type	Avg Lux/ Watt
1	Euro (HID 4400) HID 1ft	2.23	14	6 LED 60 deg 5ft	1.14	27	4 LED 90 deg 5ft	0.89
2	Euro (HID 4400) HID 3ft	1.81	15	6 LED 60 deg 3ft	1.13	28	4 LED 60 deg 1ft	0.87
3	Euro (HID 4400) HID 5ft	1.80	16	Hz flood (HID 4411) HID 1ft	1.10	29	6 LED 90 deg 5ft	0.78
4	Euro (HID 4400) HID 7ft	1.69	17	4 LED 60 deg 7ft	1.06	30	Single LED light bar	0.68
5	Hella LED 3ft	1.55	18	6 LED 60 deg 1ft	1.04	31	HZ flood (VX 4411) halogen 7ft	0.21
6	Hella LED 5ft	1.54	19	4 LED 60 deg 5ft	1.02	32	HZ flood (VX 4411) halogen 3ft	0.17
7	Hz flood (HID 4411) HID 3ft	1.48	20	4 LED 90 deg 3ft	1.02	33	Euro (VX 4410) halogen 7ft	0.14
8	2 LED lightbars	1.45	21	6 LED 90 deg 3ft	1.01	34	HZ flood (VX 4411) halogen 1ft	0.13
9	Hella LED 1ft	1.38	22	6 LED 90 deg 7ft	1.00	35	Euro (VX 4410) halogen 3ft	0.13
10	Hella LED 7ft	1.35	23	4 LED 60 deg 3ft	0.98	36	HZ flood (VX 4411) halogen 5ft	0.13
11	Hz flood (HID 4411) HID 5ft	1.25	24	6 LED 90 deg 1ft	0.98	37	Euro (VX 4410) halogen 5ft	0.12
12	6 LED 60 deg 7ft	1.23	25	4 LED 90 deg 1ft	0.95	38	Euro (VX 4410) halogen 1ft	0.12
13	Hz flood (HID 4411) HID 7ft	1.17	26	4 LED 90 deg 7ft	0.89			

After completing the initial comparison, it was determined that a comparison of the amount of poor lighting in each setup would be beneficial. To complete this, two dimensional contours using the data obtained with the three dimensional contours previously shown were developed using Carlson design software. Using these contour plots, it is possible to calculate the percentage of area that received certain levels of light. Poor lighing usually occurs in areas with less than 50 lux (The Engineering ToolBox, 2016). The value of 50 lux is usually typical for areas with dark surroundings where the need for large amounts of visual detail are not necessary, such as parking lots or rarely used areas in the home (Table 3.4). From the plan view contours shown in Figure 3.47 through Figure 3.52., the areas that received less than 50 lux of lighing can easily be seen and calculated. Figure 3.53 lists the percent of area less than 50 lux found within each plan view contour.

Table 3.4: Recommended Light Levels for Different Work Spaces (Autodesk, 2015)

Activity	Illumination (lux, lumen/m^2)
Interiors rarely used for visual tasks (parking lots, nighttime sidewalk)	50
Interiors with minimal demand for visual acuity (corridors, loading bay)	100-150
Interiors with low demand for visual acuity (dining rooms, restrooms)	200
Interiors with some demand for visual acuity (libraries, lecture theaters)	300
Interiors with moderate demand for visual acuity (computer work, reading, kitchen)	500
Interiors with demand for good visual acuity (drawing offices, general electronics work)	750
Interiors with demand for superior visual acuity (detailed electronics assembly, drafting)	1000
Interiors with demand for maximum visual acuity (hand tailoring, precision assembly)	1500-2000+

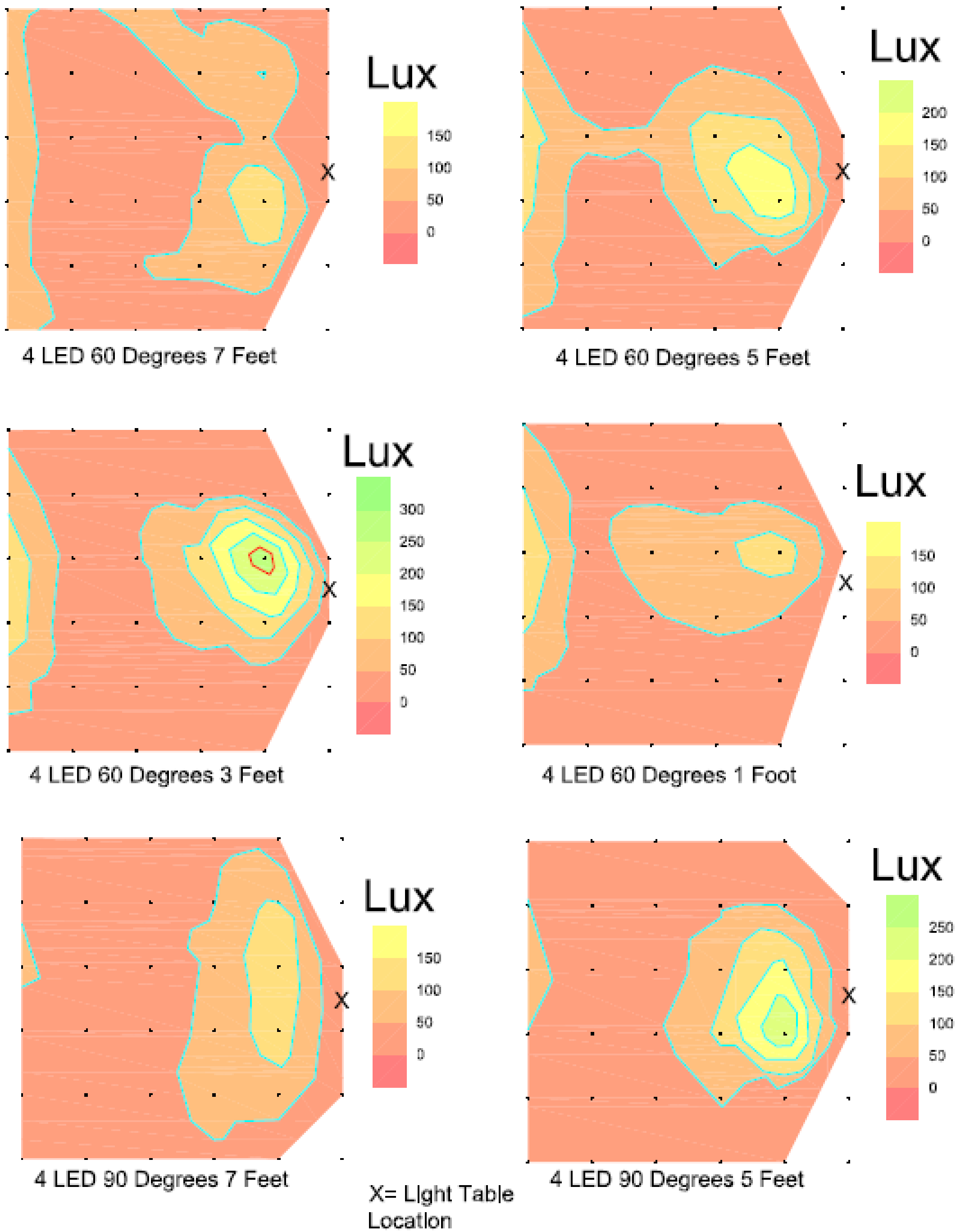


Figure 3.47: Two Dimensional Lux Contours (1)

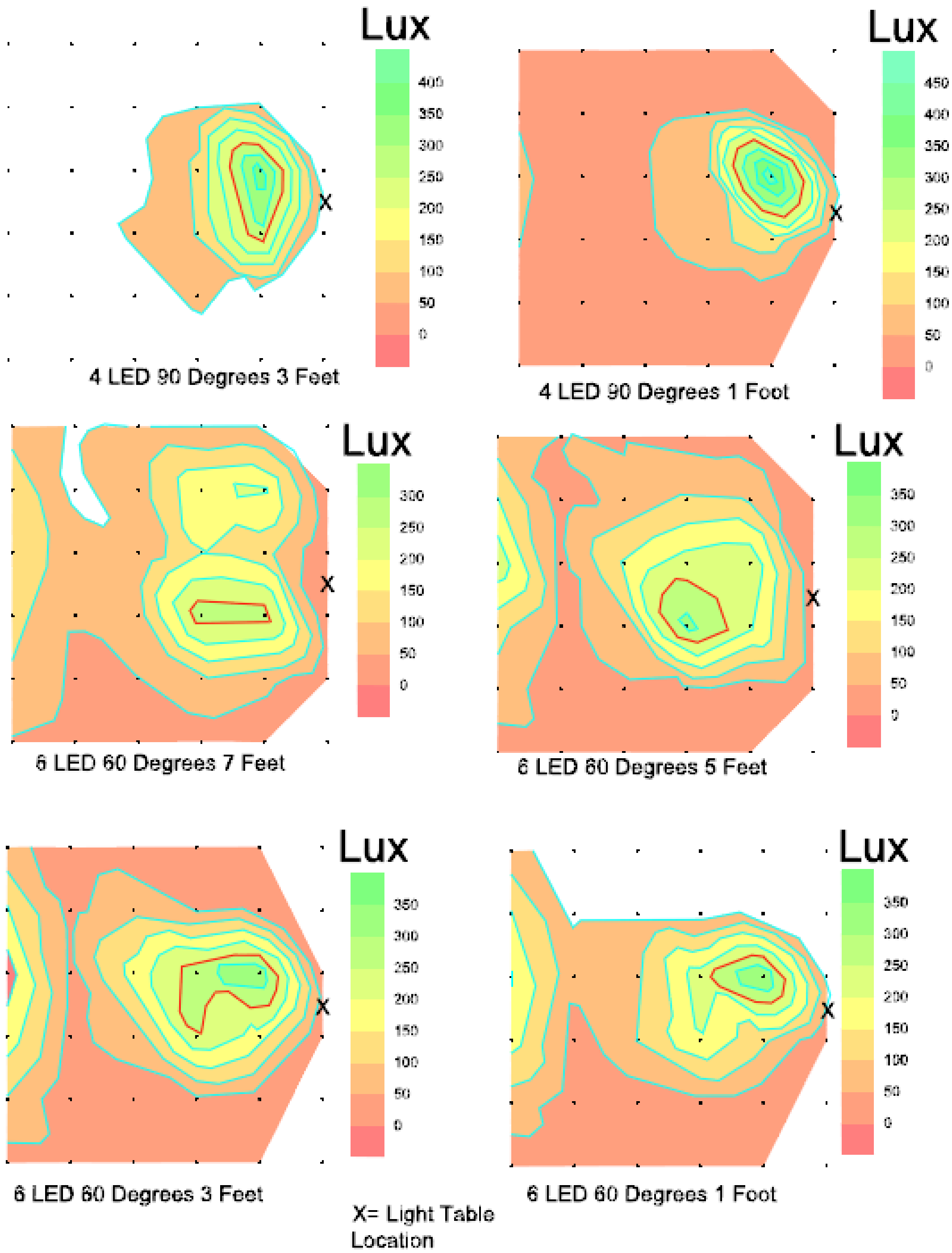


Figure 3.48: Two Dimensional Lux Contours (2)

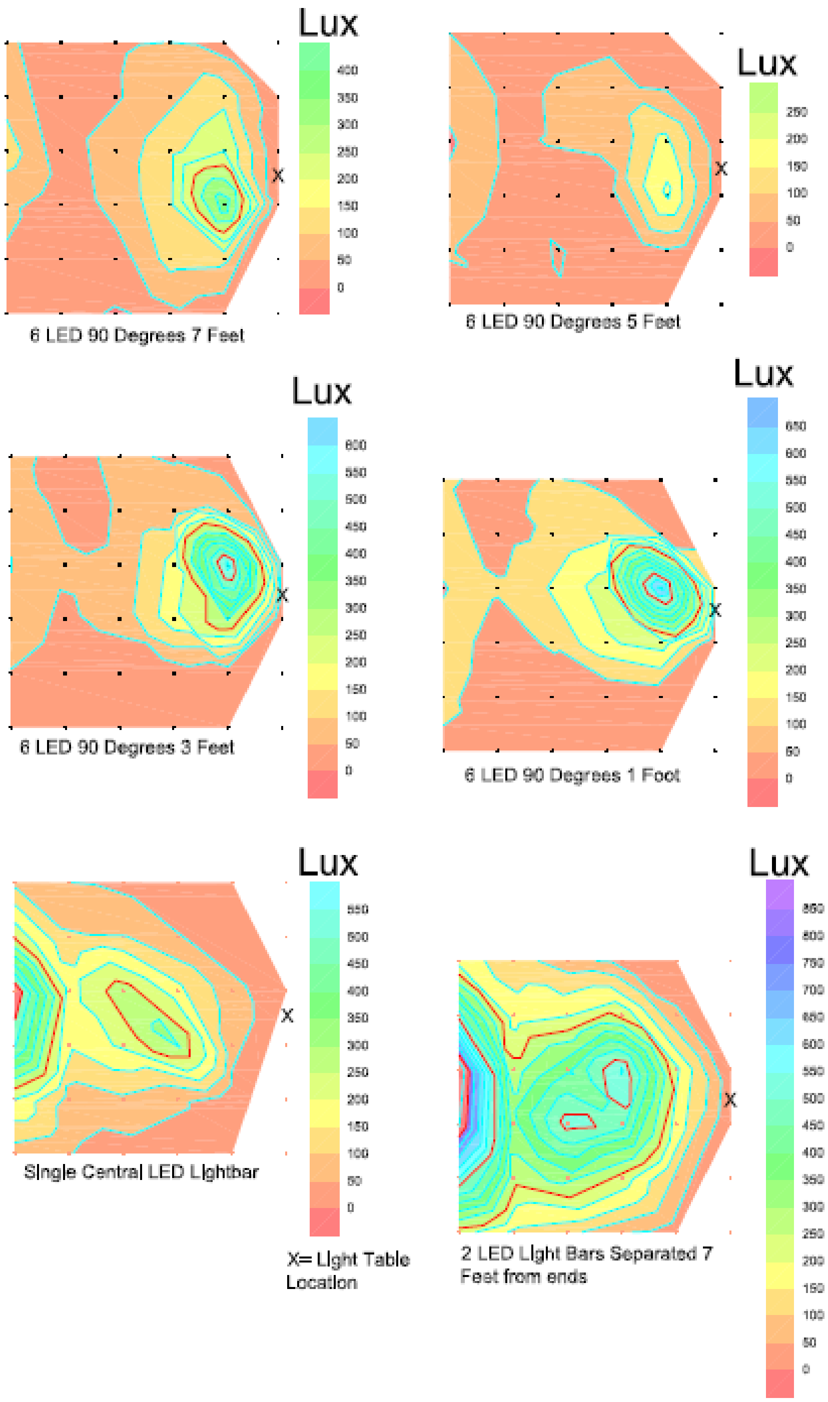


Figure 3.49: Two Dimensional Lux Contours (3)

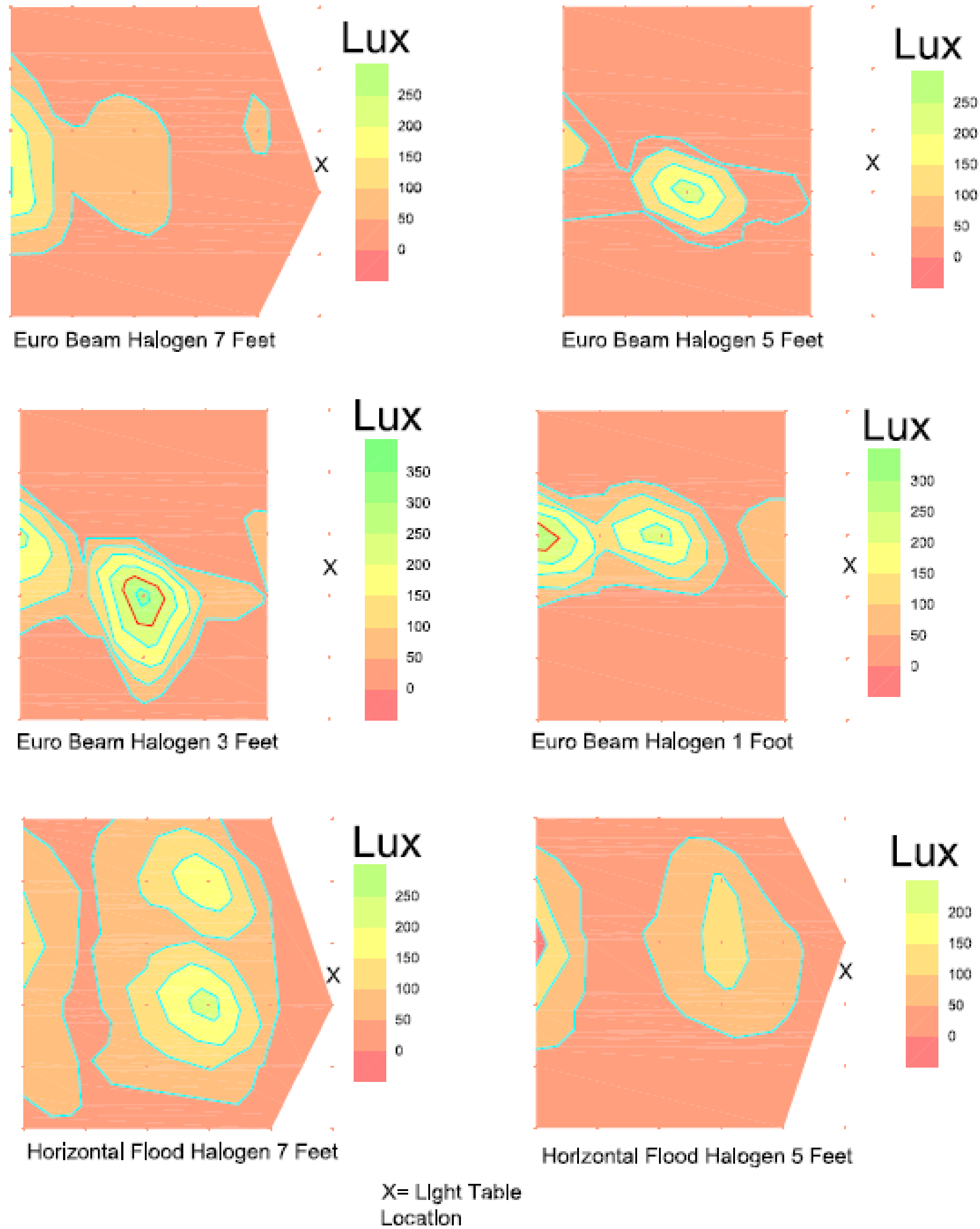


Figure 3.50: Two Dimensional Lux Contours (4)

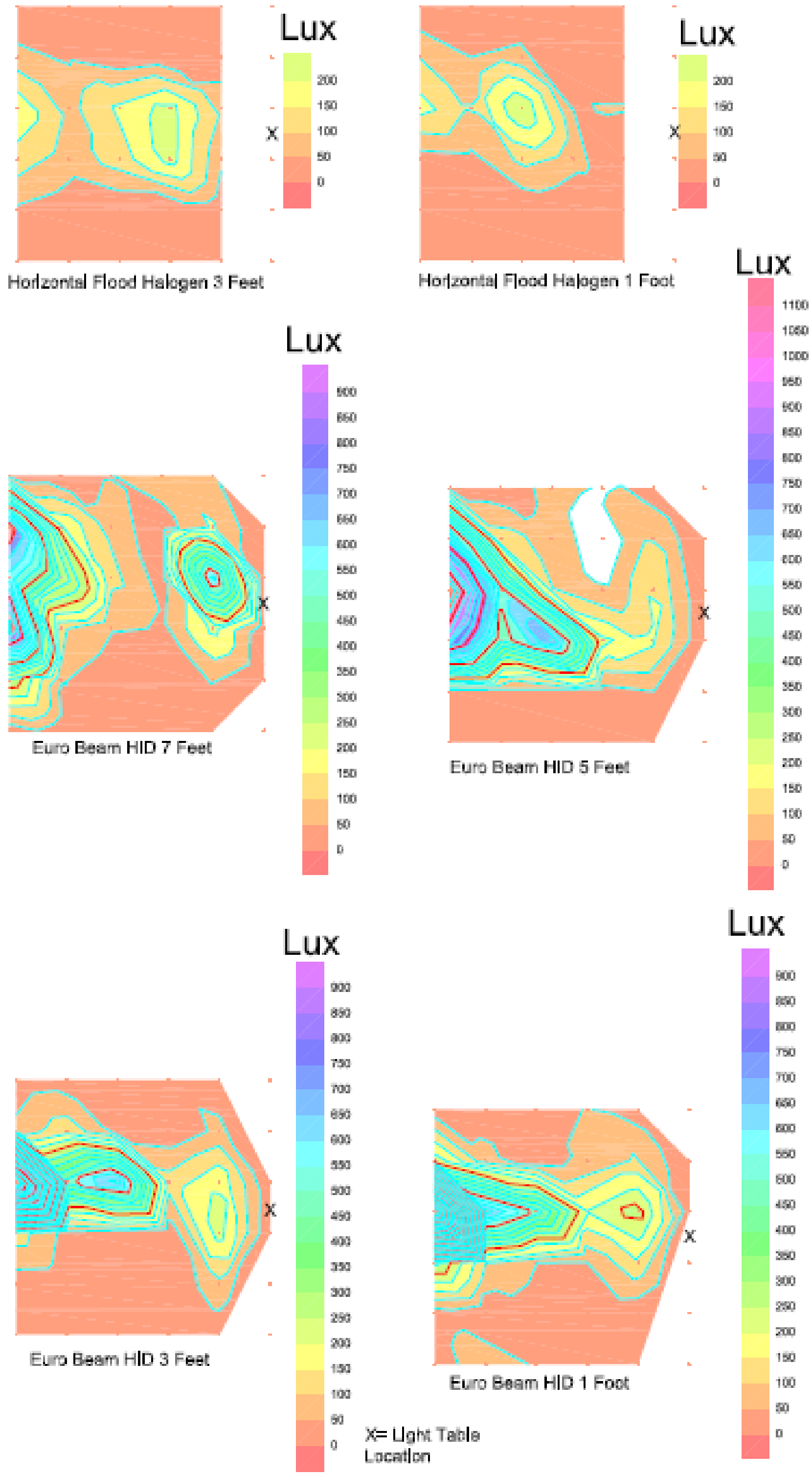


Figure 3.51: Two Dimensional Lux Contours (5)

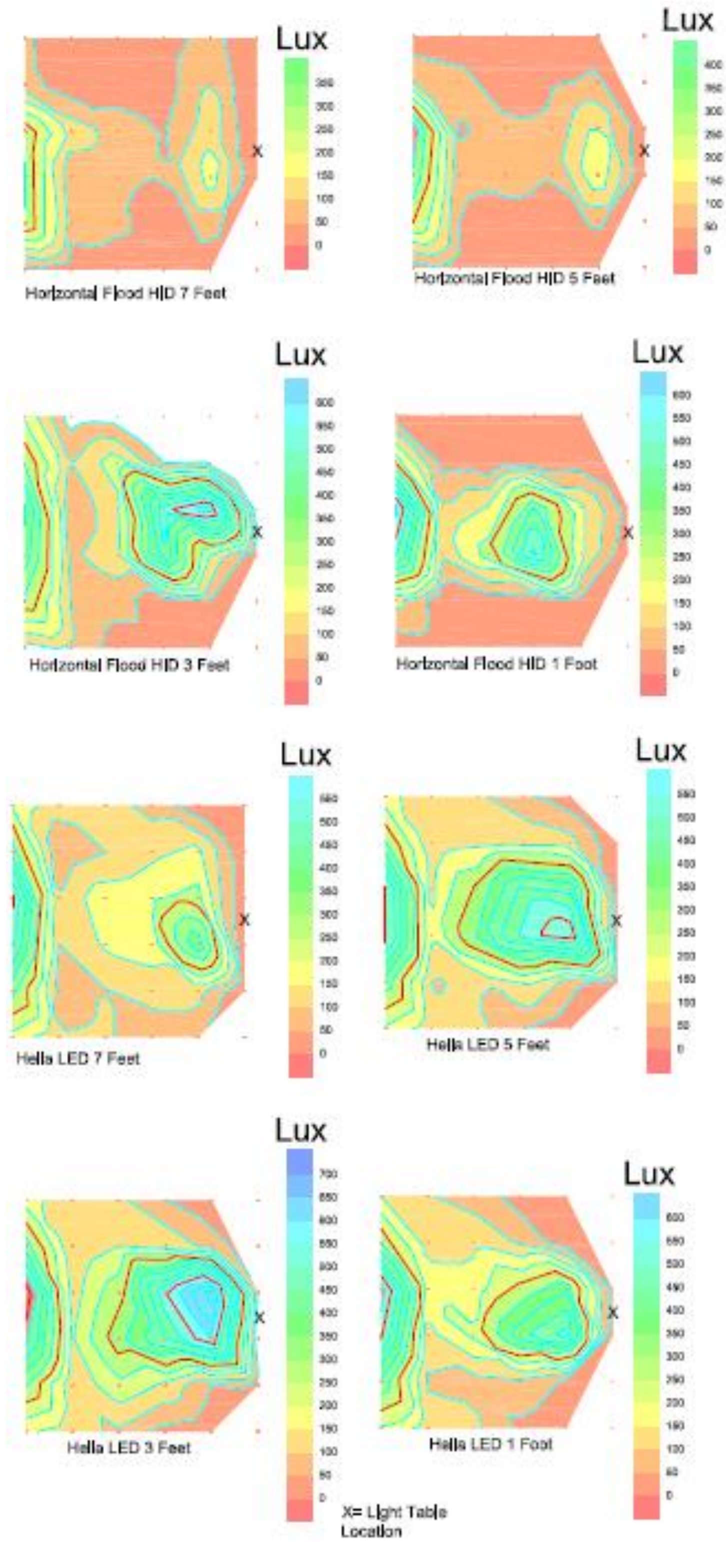


Figure 3.52: Two Dimensional Lux Contours (6)

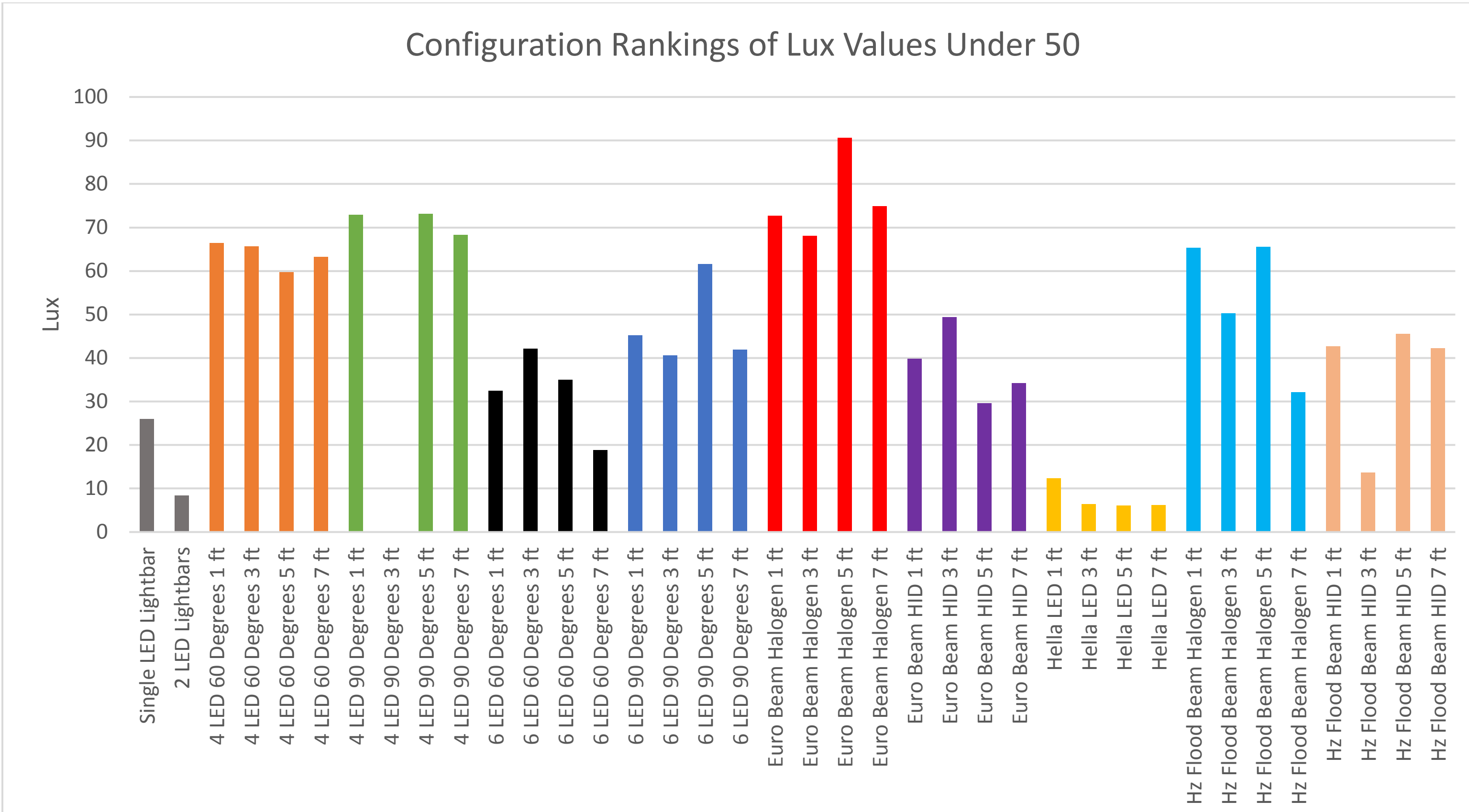


Figure 3.53: Configuration Percentages under 50 Lux

3.4: Mine Panel Simulation Results Discussion

From the contour plots, it can be seen that the distance between lights possess an expected impact on the light distribution. As the lights were placed closer together, more light was recorded along the central areas of the roof and less was recorded along the edges and walls. This pattern was most evident in the halogen and HID lights, whereas the Hella LED light performed very well at the seven and five foot intervals and average on the three and one foot spacing. The VisionX LED lamps showed negligible variation between setup configurations of the same light, but the light distribution to the rib and roof above the roof bolting machine was impacted. When these lights are further apart, there are two peaks present above the machine in nearly every configuration with good distribution to the ribs. As these lights are placed closer to each other, the two peaks merge into a single large peak and the distribution to the ribs is reduced.

The average lux values show that the highest averages for most lights were recorded at the five and three foot intervals, while the average at the seven and one foot intervals tend to be lower. However, the contour plots show that the seven foot intervals provided a more uniform coverage than the other intervals. The one foot interval was the lower because this interval lead to numerous zero and low readings in the simulation.

The number of LEDs used follows an expected pattern. When comparing the contours based on the number of lights, the graphs are nearly the same shape with no significant differences other than being shifted up in the z-direction. This shows that as the number of lights is increased, the lux values at each point increase but have very little impact on the distribution of light.

The impact of different light angles can be observed when comparing the results obtained within each contour chart. For example, the four LED experiments show that as the light angle increased, the amount of light that reached the roof above the face was less. However, the light that reached the roof above the roof bolter was higher with the ninety degree LED lights than with the sixty degree lights. The six LED configurations follow a similar pattern, except for the five feet separation trial where the sixty degree light provided a higher lux value above the roof bolter. The difference of lux values to the roof above the face are more significant than the differences of light reaching the roof above the roof bolter between light angles.

The light bars performed differently than the other lights tested. The highest concentrations of lux values were located at the face and the center of the roof in the simulated entry, resulting in a better distribution of light. Increasing the number of light bars increases the lux readings on the roof but has little impact on the distribution.

The type of light used follows an expected pattern. When comparing the contours of all three types of lighting, the graphs are significantly different. Halogen had very low peaks and many recordings of zero compared to both HID and LED. The HID lights had very high peaks when compared to LED, but the coverage was not as good. The average lux values also show these trends. LED and HID both recorded high averages for most configurations, while halogen had very low average lux values. The normalized data provides interesting results. In terms of average lux values per watts of power consumed, the euro pattern HID lights were the highest followed by multiple LED configurations. This can be attributed to the very large readings recorded while using the euro HID lights and relatively low power consumption. However, the contours of these lights show that the coverage provided is inferior compared to most LED lights and the horizontal flood LED. This data does illustrated that both LED and HID lighting is more efficient than halogen lighting, which had the lowest normalized average lux values. The normalized data provided little insight into the roof coverage of each light, so these results are not very helpful.

The impact of different light angles can also be observed when comparing the results obtained within each contour chart for the halogen and HID lights. The coverage provided by the horizontal flood beam lamps is superior to that of the euro beam lamps. Since the horizontal flood beam has an increased horizontal range than the euro pattern, an increased amount of light was recorded at the edges of the simulation. The horizontal flood lights also allowed more light to reach the roof above the roof bolter than the euro beam lights. The difference of lux values to the roof above the face follows the opposite pattern. The euro beam provided more light in this aspect due to its superior vertical range.

The results obtained from the two dimensional contour analysis corroborates some of the patterns previously discussed. When examining Figure 3.53, seven of the top ten light configurations used LED lights. The low, under 50 lux, percentage values show that these LED lights provided adequate lighting over the entire roof. This means that a large amount of useful light will be provided to miners, especially those who operate roof bolting machines. LED lights performed well with this analysis, obtaining similar results to the HID lights and better results than the halogen lights. The spacing patterns previously discussed are generally followed as well. As the lights are placed closer together, the percentage of poor lighting increased. The best light coverage was usually found while using the five or seven foot spacing options. The patterns for light angle are not followed in the two dimensional contour analysis. Values found with the varying angle LEDs and when comparing the horizontal flood beam and euro beam HIDs and halogens showed no real pattern. This may be due to measurement errors or issues discovered when using the Carlson software package. Some values were not graphed correctly due to boundary conditions, see the 4 LED, 90 degree light at a three foot spacing for an example.

There is a potential issue present when comparing results obtained within the panel simulation. Between the time when the first LED lights were tested and when the halogen and HID lights were tested, the black paint inside the panel had sweated off due to the moisture conditions within UKERT's lab. This most likely causes a reduction in the amount of reflectivity within the simulation, thus resulting in lower lux readings for the halogen, HID, and Hella LED lights. No more paint was available to correct this issue, but the light distribution field should see little change due to this.

CHAPTER 4: DISCONTINUITY IDENTIFICATION

4.1: Introduction

Once the effective light distribution of each light was discovered, the ability of LED lighting to aide in the location of potential geologic issues needed to be examined. This was again done through simulations since LED area lighting is not approved by MSHA. Geologic issues are generally located through the presence of shading, shadows, or reflectivity if caused by coal, such as slickensides. It is expected that the improved roof coverage and better lighting conditions will be beneficial to roof bolt machine operators while visually inspecting the roof. If potential issues are found, preventative measures can be taken to prevent roof failure.

4.2: Discontinuity Identification Experimental Procedure

Experimentation for the discontinuity lighting portion of the research took place in the basement of the Mining and Minerals Resources Building at the University of Kentucky. Multiple samples of coal and shale were obtained from the Red Hawk Number 1 mine in Printer, Kentucky. Limestone samples were also obtained from the UKERT laboratory in Georgetown, Kentucky. The rock samples were set up on the center of a wooden eight foot by eight foot board to simulate differing roof conditions and geologic discontinuities found in underground coal mines. These include coal roof, slickensides, cracked and fractured roof rock, and micro-fractures.

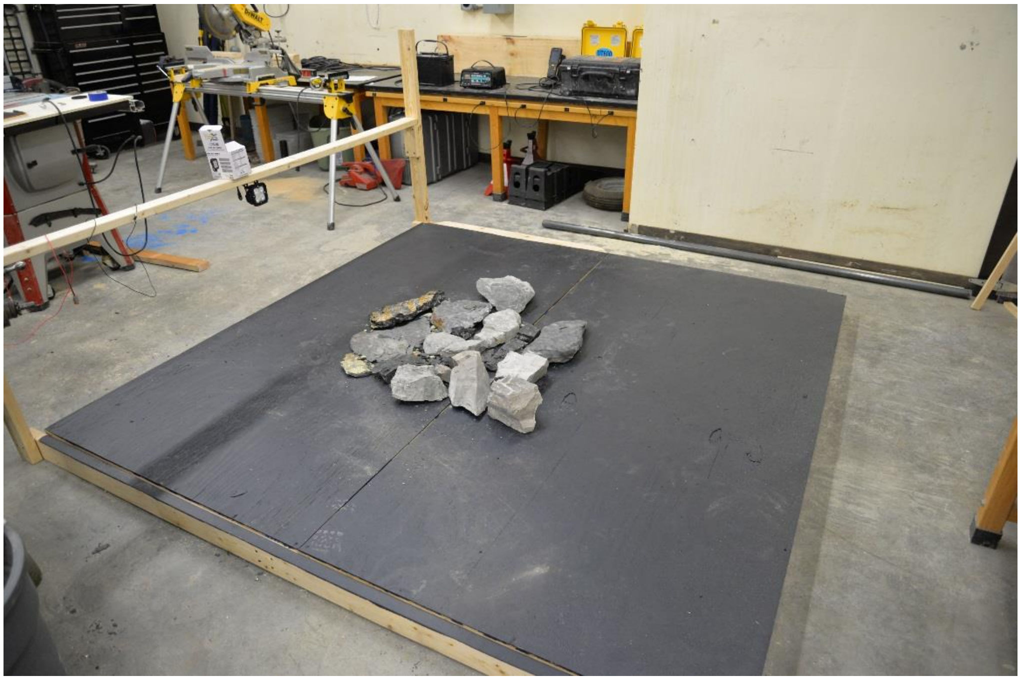


Figure 4.1: Discontinuity Identification Experimental Setup

Nine total lights were testing during this portion of experimentation. These lights are listed in Table 4.1.

Table 4.1: Lights Tested during Discontinuity Identification

	Manufacturer	# LED lights	Angle	Note
1	Vision X	4	60	
2	Vision X	4	90	
3	Vision X	6	60	
4	Vision X	6	90	
5	Vision X	NA		Halogen euro flood beam pattern
6	Vision X	NA		Halogen horizontal flood pattern
7	Vision X	NA		HID euro flood beam pattern
8	Vision X	NA		HID horizontal flood pattern
9	Hella	NA		280N LED surface mining light with close range light pattern

Each light was tested with three different rock configurations. After the first setup, the rocks were rotated ninety degrees clockwise in order to represent differing discontinuity orientations and new shading locations. The rocks were then rotated ninety degrees clockwise again from the second setup for the third and final setup. The light was mounted above the midpoint along the board's side, with the light base 23.5 inches above the board as shown in Figure 4.1. This height was selected because it was determined that the light would be approximately two feet from the roof of an underground coal mine when mounted onto the ATRS of a roof bolting machine. A twelve volt battery was used to power each light. After each light was tested with the first rock setup, the rocks were rotated ninety degrees clockwise and tested again. This process was repeated for one additional configuration with a second ninety degree rotation, as is shown in Figure 4.2 through Figure 4.4. During each setup approximately sixteen photos were taken with each light. Visual inspections were made and notes were recorded as well as light readings using an Extech HD450 light meter.

Figure 4.2: Rock Setup One

Figure 4.3: Rock Setup Two

Figure 4.4: Rock Setup Three

4.3: Discontinuity Identification Results

The results from the discontinuity identification portion of the research will be discussed in this section. Photometric and photographic data for each setup utilizing each light will be presented and compared. This section will conclude with a presentation of the light that performed best at each setup. The averages were calculated in order to present a comparison of how well each light provided light to the rock setup.

4.3.1: Rock Setup One

The photometric data for rock setup one utilizing the different LED lights is presented in Table 4.2. Photographs of each LED light are shown in Figure 4.5.

Table 4.2: Photometric Data Using LED Lights for Rock Setup One

Discontinuity/ Reading Location	4 LED 60 degrees (lux)	4 LED 90 degrees (lux)	6 LED 60 degrees (lux)	6 LED 90 degrees (lux)	Hella RokLume 280 N (lux)
Coal Roof	245.6	361.8	305.7	497.0	596.0
Slickenside	289.4	289.5	255.9	332.8	541.0
Cracked Limestone	267.2	376.4	267.6	312.9	608.0
Shale Microfracture	293.5	294.8	388.8	333.3	917.0
Loose Shale Roof	177.7	211.1	170.5	294.1	411.0
Cracked Dark Shale	148.0	227.7	166.5	307.4	429.0
Limestone Face	448.0	368.9	550.0	538.0	1163.0
Recessed Shale	131.7	123.4	188.9	181.5	421.0
Average	250.1	281.7	286.7	349.6	635.8

i) 4 LED 40 degrees   ii) 4 LED 60 degrees

iii) 6 LED 40 degrees   iv) 6 LED 60 degrees

v) Hella RokLume 280N

Figure 4.5: LED Photos of Rock Setup One

When analyzing the LED lights utilized during the first rock setup, the Hella RokLume 280N LED light generated the highest amount of lux values. At 635.8 average lux, the RokLume 280N generated nearly twice the amount of average light as the VisionX lamp using six LEDs with a ninety degree light angle, 349.6 lux. The average lux values also show the trend that as more LEDs are added, higher average lux values are seen over the setup. This explains why the Hella RokLume LED obtained the highest average lux value. This lamp utilizes eight LEDs, while the VisionX lamps use either four or six LEDs. However, this trend was expected. The data also shows that more light is seen when a wider light angle is used. The wider angle allows more light to reach the outer edges of the setup, thus creating the higher average.

Visual results of all LED lights were similar. Every simulated discontinuity was easily identified. It was discovered that the two primary indicators of potential issues were shadows and reflectivity. Shadows provide indication of cracking, microfractures, and breaks in the rock. Reflectivity provides indication of issues caused by coal remaining on the roof or within slickensides. As the LED lights got brighter, these indicating factors were usually easier to identify. However, there were occasions where the light was so bright that the shadow indications were more difficult to locate. Figure 4.6 presents an example of this issue. While the Hella RokLume LED light was the brightest of all LED lights, it presented an issue with identifying the microfracture within a shale rock sample. The LED lights with lower lux values performed marginally better in terms of visual performance for this discontinuity. Figure 4.7 and Figure 4.8 show how coal is seen using LED lights.

i) 6 LED 60 degrees

ii) 6 LED 90 degrees

iii) Hella RokLume 280N

Figure 4.6: Shale Microfracture Using Hella RokLume 280N Light

Figure 4.7: Coal Roof Rock Using 4 LED 60 Degree Light

Figure 4.8: Coal Roof Rock Using Hella RokLume 280N Light

Photometric data utilizing the halogen lights for rock setup one are presented in Table 4.3. Photographs for both halogens are shown in Figure 4.9. The euro beam pattern is a combination of the horizontal flood and vertical flood beam patterns. However, the euro pattern does not have the horizontal range a horizontal flood lamp has nor the vertical range of a vertical flood lamp.

Table 4.3: Photometric Data Using Halogen Lights for Rock Setup One

Discontinuity/ Reading Location	Euro beam pattern (lux)	Horizontal flood beam pattern (lux)
Coal Roof	166.5	234.0
Slickenside	53.1	66.3
Cracked Limestone	25.5	39.7
Shale Microfracture	37.3	71.6
Loose Shale Roof	49.3	47.9
Cracked Dark Shale	62.2	53.7
Limestone Face	49.9	66.8
Recessed Shale	20.7	18.9
Average	58.1	74.9

i) Euro beam pattern

ii) Horizontal flood beam pattern

Figure 4.9: Halogen Photos of Rock Setup One

The photometric data shows that the horizontal flood lamp produced more light over the simulated discontinuities than the euro flood beam. The average lux value when using the horizontal flood lamp was 74.9, while the euro pattern produced 58.1 lux on average. The most likely cause of this difference is due to the differing horizontal range of the lamps. While the larger readings on the edges of the rock setup were expected, larger readings further away from the light were not. This may indicate that an increased horizontal range of the light field is more desirable than a longer reach in terms of roof lighting.

Visual results between both halogen lights were nearly identical. The simulated discontinuities were identified, but not easily. Due to the reduced brightness, the shine of coal and shadows were not as pronounced as other light forms. The horizontal flood performed slightly better than the euro pattern due to its increased horizontal range providing more light. Photographs from this setup can be seen in Figure 4.10 through Figure 4.13.

Figure 4.10: Shale Microfracture Using Halogen Euro Beam Pattern

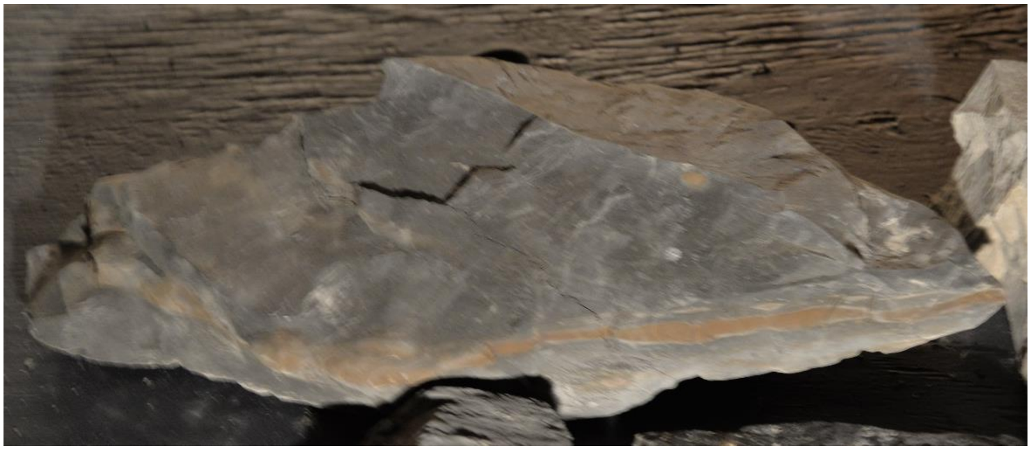


Figure 4.11: Shale Microfracture Using Halogen Horizontal Flood Beam Pattern

Figure 4.12: Coal Roof Rock Using Halogen Euro Beam Pattern

Figure 4.13: Coal Roof Rock Using Halogen Horizontal Flood Beam Pattern

Photometric data utilizing the HID lights for setup one are presented in Table 4.4. Photographs for both halogens are shown in Figure 4.14.

Table 4.4: Photometric Data Using HID Lights for Rock Setup One

Discontinuity/ Reading Location	Euro beam pattern (lux)	Horizontal flood beam pattern (lux)
Coal Roof	339.2	466.0
Slickenside	108.1	128.8
Cracked Limestone	73.3	121.6
Shale Microfracture	104.0	128.2
Loose Shale Roof	94.7	137.4
Cracked Dark Shale	68.1	110.1
Limestone Face	128.6	165.7
Recessed Shale	67.5	75.9
Average	122.9	166.7

i) Euro beam pattern

ii) Horizontal flood beam pattern

Figure 4.14: HID Photos of Rock Setup One

Similar to the halogen results, photometric data of both HID lights show that the horizontal flood lamp produced a higher average lux value than the euro beam pattern. These results add more to the theory that improved horizontal flood lighting may by more useful in underground mining. Visual results were similar between both types of lights, comparable to all other lights tested. However, due to the increased brightness of the HID lights, shadows and shine were easy to see. The horizontal flood HID performed marginally better than the euro beam, again similar to the halogen lamps. Photographs from this setup can be seen in Figure 4.15 through Figure 4.18.

Figure 4.15: Shale Microfracture Using HID Euro Beam Pattern

Figure 4.16: Shale Microfracture Using HID Horizontal Flood Beam Pattern

Figure 4.17: Coal Roof Using HID Euro Beam Pattern

Figure 4.18: Coal Roof Using HID Horizontal Flood Beam Pattern

Table 4.5 shows the averages of all lights tested during the first rock board setup. Of all the lights tested, every LED lamp obtained a higher average lux value than all other halogen and HID lamps. The halogen lamps had the lowest average lux values.

Table 4.5: Rock Setup One Average Lux Values

4 LED 60 degree (lux)	4 LED 90 degree (lux)	6 LED 60 degree (lux)	6 LED 90 degree (lux)	Hella Rok Lume LED (lux)	Euro beam halogen (lux)	Horizontal flood beam halogen (lux)	Euro beam HID (lux)	Horizontal flood beam HID (lux)
250.1	281.7	286.7	349.6	635.8	58.1	74.9	122.9	166.7

The increased brightness helped the LED lamps perform better in locating potential geologic issues within the setup. Increased brightness made it easier to locate cracking and fracturing due to more pronounced shadows. The lights also made it easier to locate potential issues caused by coal due to the increased reflectivity. The light color did not seem to have a large impact on these results, however it can have some subjective results. The HID lights were the most visually displeasing due to its blue coloring and how the light “flickers”. The yellow color of the halogen lights were visually pleasing, but they also had the lowest average lux values. The white LEDs were not visually uncomfortable, but less pleasing than the halogen lights. The HID lights also required a brief charging period before they reached full brightness, whereas both the halogen and LED lights did not require this time to charge.

4.3.2: Rock Setup Two

The photometric data for rock setup two utilizing the different LED lights is presented in Table 4.6. Photographs of each LED light are shown in Figure 4.19. During the process of creating this setup, the microfractured shale sample broke, but was kept and used to simulate stacked fracturing. Multiple readings were also recorded if a sample received a large amount of shading as well as light.

Table 4.6: Photometric Data Using LED Lights for Rock Setup Two

Discontinuity/ Reading Location		4 LED 60 degrees (lux)	4 LED 90 degrees (lux)	6 LED 60 degrees (lux)	6 LED 90 degrees (lux)	Hella RokLume 280 N (lux)
Coal Roof		116.5	150.4	147.7	146.0	358.3
Slickenside		207.9	228.7	352.5	308.6	592.0
Cracked Limestone		161.0	126.9	274.4	222.1	442.0
Fractured Shale		168.6	122.7	396.6	227.6	468.0
Loose Shale Roof		69.4	58.9	140.8	173.2	333.8
Cracked Dark Shale	Lighted	266.2	361.5	587.0	627.0	443.0
	Shaded	77.3	98.5	68.7	95.7	103.5
Limestone Face		378.8	603.0	759.0	804.0	1141.0
Recessed Shale		163.7	189.1	322.2	253.5	552.0
Average		178.8	215.5	338.8	317.5	492.6

i) 4 LED 60 degrees

ii) 4 LED 90 degrees

iii) 6 LED 60 degrees

iv) 6 LED 90 degrees

v) Hella RokLume 280N

Figure 4.19: LED Photos of Rock Setup Two

Photometric results in Rock Setup Two show similar trends compared to Rock Setup One. The Hella RokLume 280N LED light again generated the highest amount of lux values. At 492.6 average lux, the RokLume 280N generated over 150 more average lux values than the second highest light using six LEDs and a sixty degree light angle, 338.8 lux. The average lux values also help confirm the trend that as more LEDs are added, higher average lux values are seen over the setup. The Hella RokLume LED again obtained the highest average lux value. However, the trend that more light is seen when a wider light angle is used was not seen when using the six LED lights. The average lux value was slightly higher for the sixty degree light when compared to the ninety degree light. This is most likely caused by either the large amount of readings that were taken in central areas of the setup or errors that may have taken place during measurement. Readings located at the edges (coal roof and loose shale roof) gave higher values using the ninety degree light than the sixty degree light.

Visual results of all LED lights were similar. Every simulated discontinuity was easily identified, as was the same during the first setup. As the LED lights got brighter, the indicating factors of shine and shadow were easier to identify. During this setup there was an issue with identifying the fractured shale from the light position. The only indication of a potential issue with this shale sample that could be seen from the light location was a small, jagged edge protruding from the top of the sample. The LED lights all performed adequately when identifying this edge, but the brighter lights performed marginally better. Photographs from this setup can be seen in Figure 4.20 and Figure 4.21.

i) 4 LED 60 degrees

ii) 6 LED 90 degrees

iii) Hella RokLume 280N

Figure 4.20: Fractured Shale Using LED Lights


i) 4 LED 60 degrees ii) 6 LED 90 degrees

iii) Hella RokLume 280N

Figure 4.21: Coal Roof Using LED Lights

Photometric data utilizing the halogen lights for rock setup two are presented in Table 4.7. Photographs for both halogens are shown in Figure 4.22.

Table 4.7: Photometric Data Using Halogen Lights for Rock Setup Two

Discontinuity/ Reading Location		Euro beam pattern (lux)	Horizontal flood beam pattern (lux)
Coal Roof		29.6	31.5
Slickenside		30.5	37.1
Cracked Limestone		22.1	27.0
Fractured Shale		18.3	31.3
Loose Shale Roof		18.2	20.3
Cracked Dark Shale	Lighted	197.3	120.0
	Shaded	18.2	20.3
Limestone Face		97.0	108.5
Recessed Shale		25.8	43.2
Average		50.8	48.8

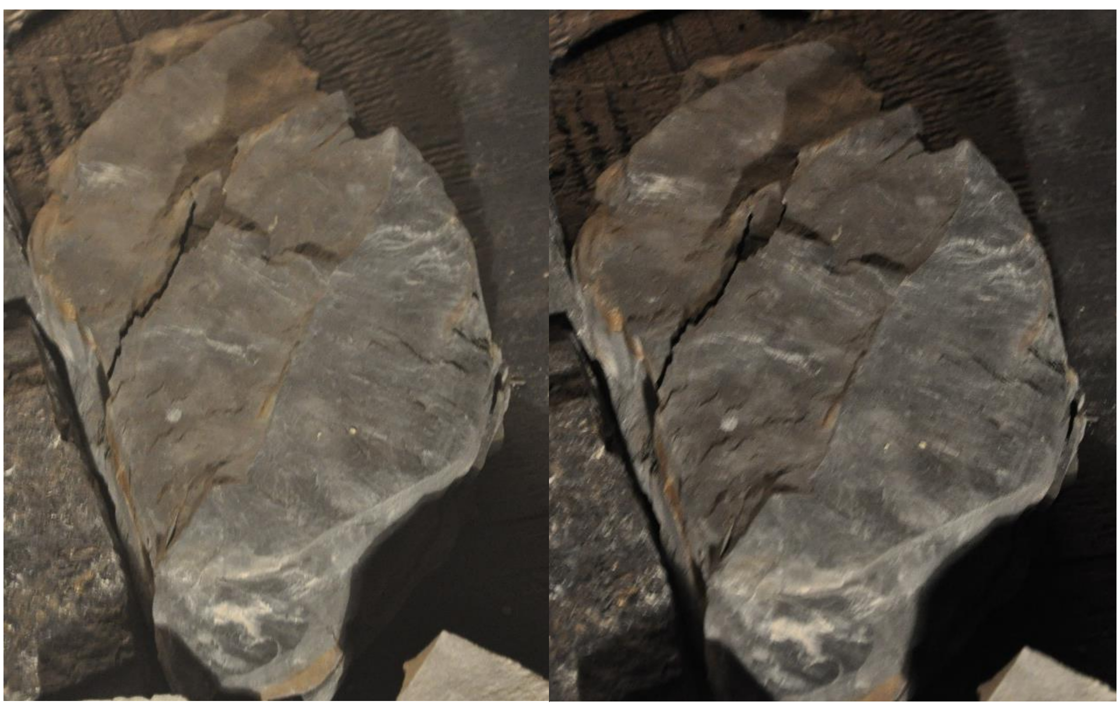
i) Euro beam pattern

ii) Horizontal flood beam pattern

Figure 4.22: Halogen Photos of Rock Setup Two

Photometric data between euro beam and horizontal flood halogen patterns produced nearly identical average lux values. However, upon closer examination of individual data points, the horizontal flood beam gave higher lux values at all but one location. This is most likely due to the point being located in a front, central position of the setup, thus receiving more light from the lamp with a lower illumination spread. Individual results reinforce to the theory that an increased horizontal range of the light field may be more desirable than a longer reach in terms of roof lighting.

Visual results between both halogen lights were nearly identical. The simulated discontinuities were identified, but not easily. Due to the reduced brightness, the shine of coal and shadows were not as pronounced as other light forms. The jagged edges of the fractured shale sample were surprisingly easy to locate with both halogen lights. Since less shadow was present for the edge to blend against, the lower amount of light made the edge easier to identify. Photographs from this setup can be seen in Figure 4.23 and Figure 4.24.



i) Euro beam pattern ii) Horizontal flood beam pattern

Figure 4.23: Fractured Shale Using Halogen Lights

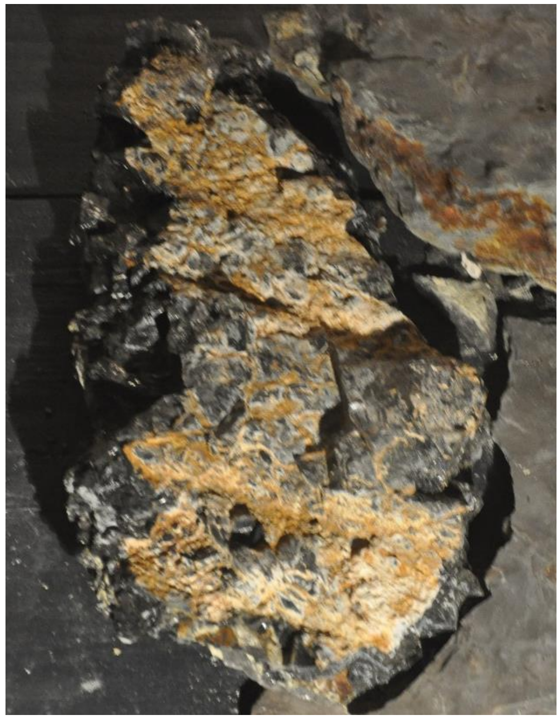


Figure 4.24: Coal Roof Using Halogen Euro Beam Pattern

Photometric data utilizing the HID lights for setup two are presented in Table 4.8. Photographs for both halogens are shown in Figure 4.25.

Table 4.8: Photometric Data Using HID Lights for Rock Setup Two

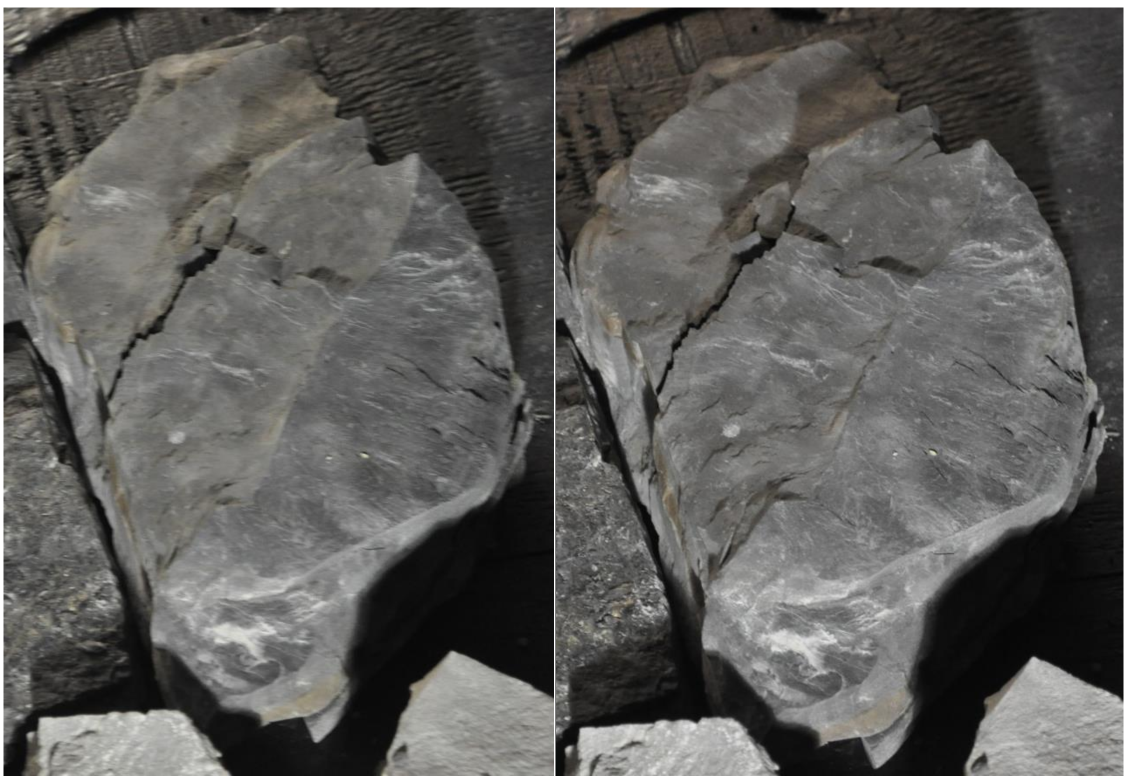
Discontinuity/ Reading Location		Euro beam pattern (lux)	Horizontal flood beam pattern (lux)
Coal Roof		81.4	83.1
Slickenside		83.8	138.1
Cracked Limestone		62.7	83.8
Fractured Shale		59.1	114.5
Loose Shale Roof		49.7	47.7
Cracked Dark Shale	Lighted	245.7	330.7
	Shaded	26.7	37.1
Limestone Face		190.6	260.7
Recessed Shale		76.0	108.5
Average		97.3	133.8

i) Euro beam pattern

ii) Horizontal flood beam pattern

Figure 4.25: HID Photos of Rock Setup Two

The average lux values using HID lighting for setup continue to reinforce the theory that the horizontal range of the light field may be more important in terms of underground lighting than the vertical range. While using the horizontal flood beam, the average lux value was nearly forty lux higher than with the euro beam pattern. Visual results were similar between both types of lights, comparable to all other lights tested. However, due to the increased brightness of the HID lights, shadows and reflectivity were easy to see. Both HID lights did an adequate job illuminating the jagged edge identification of issues within the fractured shale sample. The horizontal flood HID performed marginally better than the euro beam, again similar to the halogen lamps as well as the lights in setup one. Photographs from this setup can be seen in Figure 4.26 and Figure 4.27.



i) Euro pattern ii) Horizontal flood pattern

Figure 4.26: Fractured Shale Using HID Lights

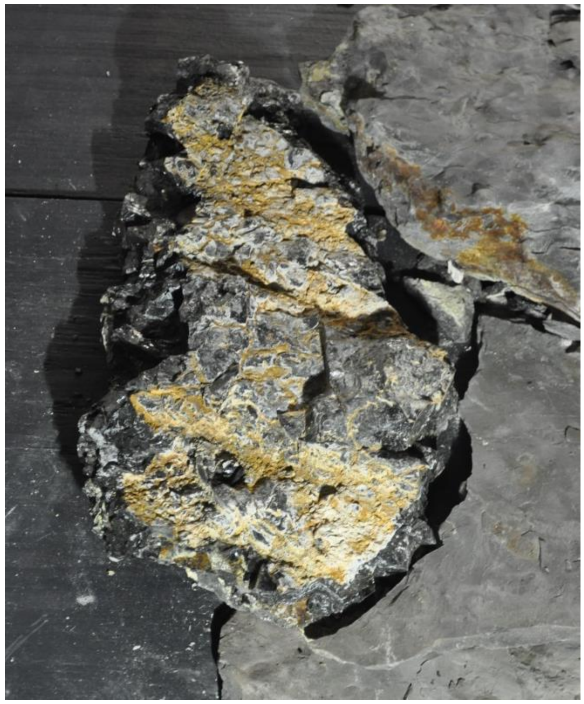


Figure 4.27: Coal Roof Using HID Euro Beam Pattern

Table 4.9 shows the average lux values of all lights tested using the second rock board setup. For the second trial, LED lamps again obtained the highest average lux value when compared to halogen and HID lamps. The halogen lamps also recorded the lowest average values for the second trial.

Table 4.9: Rock Setup Two Average Lux Values

4 LED 60 degrees (lux)	4 LED 90 degrees (lux)	6 LED 60 degrees (lux)	6 LED 90 degrees (lux)	Hella RokLume LED (lux)	Euro beam halogen (lux)	Horizontal flood beam halogen (lux)	Euro beam HID (lux)	Horizontal flood beam HID (lux)
178.8	215.5	338.8	317.5	492.6	50.8	48.8	97.3	133.8

Overall results from the second rock setup are nearly identical to the first setup. The increased brightness again helped the LED lamps perform better in locating potential geologic issues within the setup. Increased brightness made it easier to locate cracking and fracturing due to more pronounced shadows. The lights also made it easier to locate potential issues caused by coal due to the increased reflectivity. Light color had a minimal impact on these results, however can have some subjective results similar to what was found during the first setup. HID lights were again found to be the most visually displeasing due to its blue coloring and how the light "flickers". The halogen lights were again more visually pleasing due to their yellow color, but also had the lowest average lux values. The white light color of the LEDs was not visually uncomfortable, however was still slightly less pleasing visually than the halogen lights. The issue with the HID requiring a brief charge period before reaching full brightness was still present. There also may be a potential issue in the amount of heat generated by the lights. After each test, the casings of the LED lights were surprisingly warm when compared to the other lights. This issue may be minor, but it is also worth noting.

4.3.3: Rock Setup Three

The photometric data for rock setup three utilizing the different LED lights is presented in Table 4.10. Photographs of each LED light are shown in Figure 4.28. Multiple readings were also recorded if a sample received a large amount of shading as well as light or to see how much light difference there was between the top of the shale sample and the face of the shale sample.

Table 4.10: Photometric Data Using LED Lights for Rock Setup Three

Discontinuity/ Reading Location		4 LED 60 degrees (lux)	4 LED 90 degrees (lux)	6 LED 60 degrees (lux)	6 LED 90 degrees (lux)	Hella RokLume 280N (lux)
Coal Roof		449.0	294.2	684.0	509.0	1023.0
Slickenside	Lighted	263.4	274.0	503.0	385.8	670.0
	Shaded	13.9	19.3	25.4	37.1	97.9
Cracked Limestone		145.9	235.0	253.5	368.3	525.0
Fractured Shale	Face	295.3	285.2	364.3	552.0	779.0
	Top	237.1	646.0	516.0	841.0	699.0
Loose Shale Roof		134.4	130.0	185.6	198.5	483.0
Cracked Dark Shale	Lighted	209.8	189.0	304.7	203.0	430.0
	Shaded	13.9	19.3	25.4	37.1	97.9
Limestone Face		263.4	503.0	430.0	813.0	718.0
Recessed Shale		190.8	292.6	348.5	469.0	530.0
Average		201.5	262.5	330.9	401.3	550.3

i) 4 LED 60 degrees

ii) 4 LED 90 degrees

iii) 6 LED 60 degrees

iv) 6 LED 90 degrees

v) Hella RokLume 280N

Figure 4.28: LED Photos of Rock Setup Three

Photometric results in Rock Setup Three give more credence to the theories developed from setups one and two. The Hella RokLume 280N LED light again generated the highest amount of lux values. At 550.3 average lux, the RokLume 280N generated over 150 more average lux values than the second highest light using six LEDs and a ninety degree light angle, 401.3 lux. The average lux values also help confirm the trend that as more LEDs are added, higher average lux values are seen over the setup. The Hella RokLume LED again obtained the highest average lux value. The trend that more light is seen when a wider light angle is used was again seen with all LED lights during this setup. The average lux value for the ninety degree LED lights were higher than the sixty degree lights. Since the rock samples were more spread out horizontally with respect to the light, the wider angle allowed for the samples along the edges of the setup to receive more light.

Visual results of all LED lights were similar. Every simulated discontinuity was easily identified, as was the same during the previous setups. As the LED lights got brighter, the indicating factors of reflectivity and shadow were easier to identify. The fractures within the shale sample were easily identified during this setup due to the large amount of shadows that could be seen in the sample. All LED lights performed the same in regards to identifying this geologic issue. Photographs from this setup can be seen in Figure 4.29 and Figure 4.30.

i) 4 LED 90 degrees

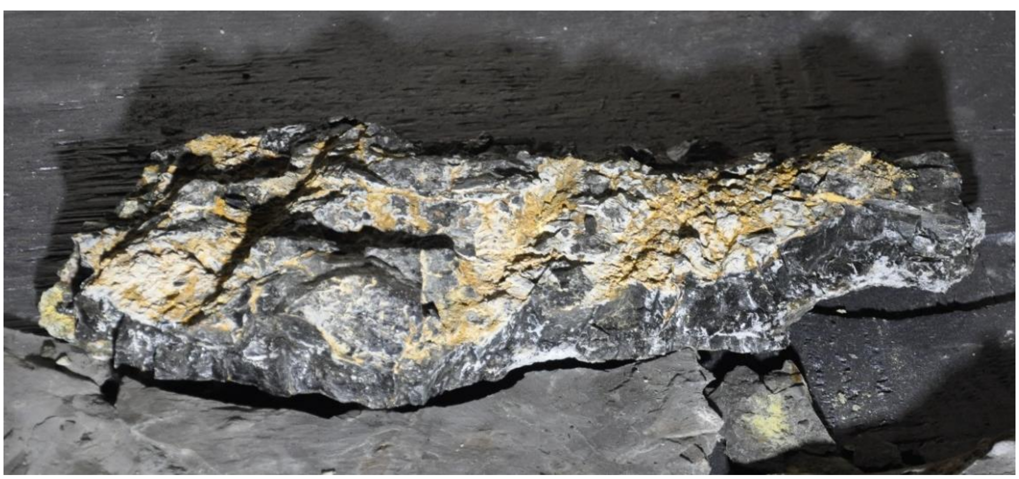
i) 6 LED 90 degrees

ii) Hella RokLume 280N

Figure 4.29: Fractured Shale Using LED Lights

i) 4 LED 60 degrees

ii) 6 LED 90 degrees



iii) Hella RokLume 280N

Figure 4.30: Coal Roof Using LED Lights

Photometric data utilizing the halogen lights for rock setup three are presented in Table 4.11. Photographs for both halogens are shown in Figure 4.31.

Table 4.11: Photometric Data Using Halogen Lights for Rock Setup Three

Discontinuity/ Reading Location		Euro beam pattern (lux)	Horizontal flood beam pattern (lux)
Coal Roof		23.6	53.3
Slickenside	Lighted	22.9	40.1
	Shaded	0.8	1.1
Cracked Limestone		27.4	39.0
Fractured Shale	Face	171.9	205.5
	Top	60.8	81.8
Loose Shale Roof		9.7	23.6
Cracked Dark Shale	Lighted	12.9	21.6
	Shaded	0.8	1.1
Limestone Face		100.2	133.7
Recessed Shale		42.7	58.1
Average		43.1	59.9

i) Euro beam pattern

ii) Horizontal flood beam pattern

Figure 4.31: Halogen Photos of Rock Setup Three

Average lux values obtained from the photometric data of euro and horizontal flood halogen patterns varied slightly. As was found during the first setup, the horizontal flood beam resulted in a higher average lux value over the setup. This result continues to validate the theory that an increased horizontal range of the light field may be more desirable than a longer reach in terms of roof lighting.

Visual results between both halogen lights again were nearly identical. Simulated discontinuities were identified, but not easily. Due to the reduced brightness, the reflectivity of coal and shadows were not as pronounced as other light forms. The fractures within the shale sample were easily seen due to the shadows caused by the rock. Both halogen lights performed adequately when identifying this discontinuity. Photographs from this setup can be seen in Figure 4.32 through Figure 4.34.

Figure 4.32: Fractured Shale Using Halogen Euro Beam Pattern

Figure 4.33: Fractured Shale Using Halogen Horizontal Flood Beam Pattern

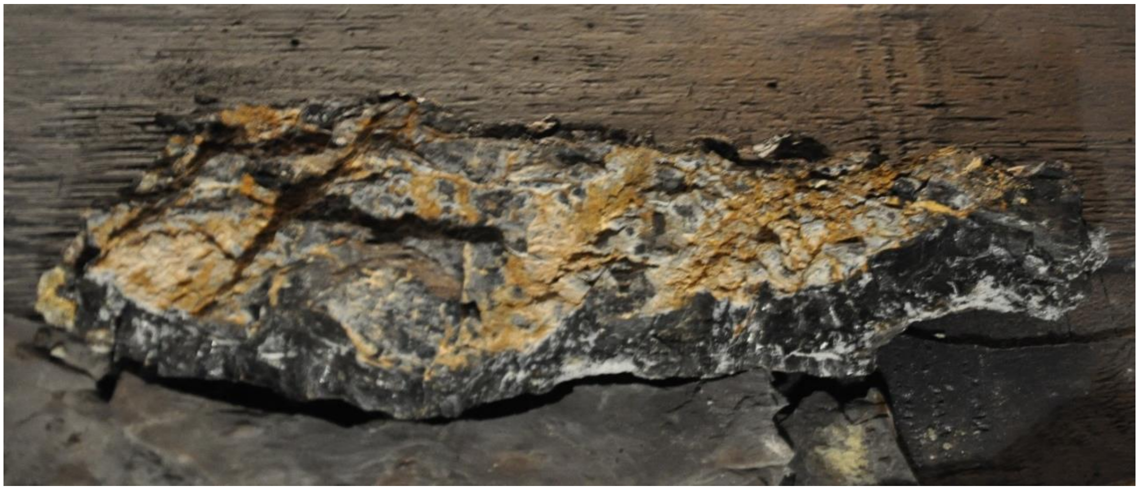


Figure 4.34: Coal Roof Using Halogen Horizontal Flood Beam Pattern

Photometric data utilizing the HID lights for rock setup three are presented in Table 4.12. Photographs for both halogens are shown in Figure 4.35.

Table 4.12: Photometric Data Using HID Lights for Rock Setup Three

Discontinuity/ Reading Location		Euro beam pattern (lux)	Horizontal flood beam pattern (lux)
Coal Roof		101.6	152.9
Slickenside	Lighted	84.6	121.3
	Shaded	8.6	17.9
Cracked Limestone		68.1	106.7
Fractured Shale	Face	359.7	473.0
	Top	114.5	271.9
Loose Shale Roof		53.8	82.4
Cracked Dark Shale	Lighted	69.0	95.0
	Shaded	8.6	17.9
Limestone Face		295.9	344.7
Recessed Shale		123.3	154.6
Average		117.1	167.1

i) Euro beam pattern

ii) Horizontal flood beam pattern

Figure 4.35: Photos of Rock Setup Three Using HID Lights

Average lux values using HID lighting during the final setup continue to validate the theory that the horizontal range of the light field may be more important in terms of underground lighting than the vertical range. While using the horizontal flood beam, the average lux value was fifty lux higher than with the euro beam pattern, 167.1 lux verses 117.1 lux. Visual results were similar between both types of lights, comparable to all other lights tested. However, due to the increased brightness of the HID lights, shadows and reflectivity were easy to see compared to the halogen lights. Both HID lights did an adequate job illuminating the shadows present within the fractured shale sample. The horizontal flood HID performed marginally better than the euro beam, again similar to the all other halogen and HID lights tested. Photographs from this setup can be seen in Figure 4.36 through Figure 4.39.

Figure 4.36: Fractured Shale Using HID Euro Beam Pattern

Figure 4.37: Fractured Shale Using HID Horizontal Flood Beam Pattern

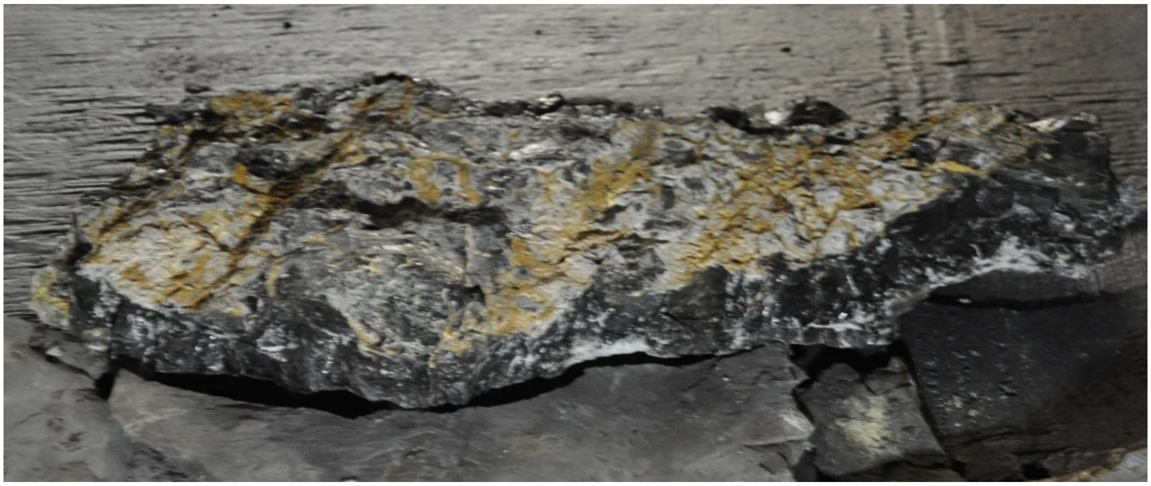


Figure 4.38: Coal Roof Using HID Euro Beam Pattern

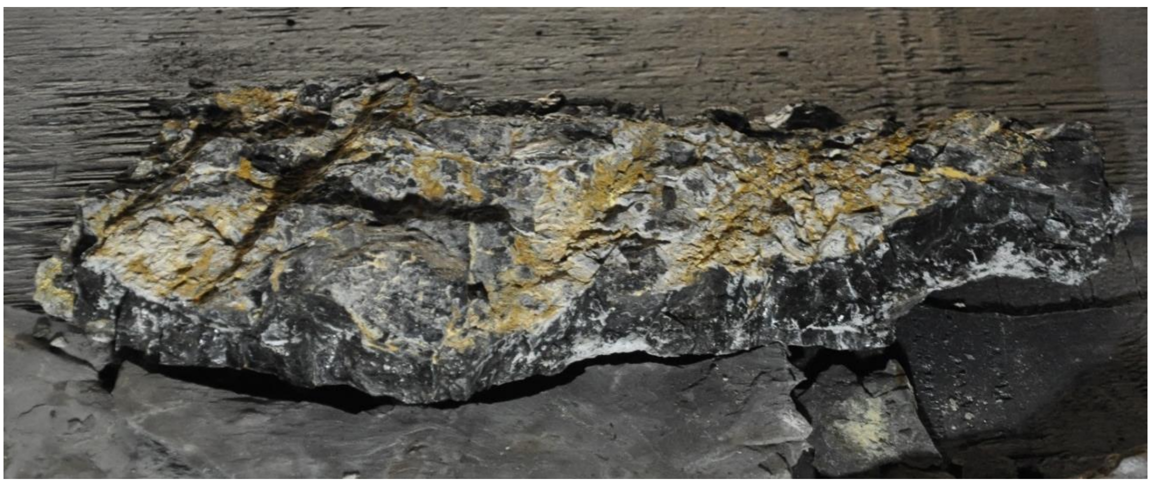


Figure 4.39: Coal Roof Using HID Horizontal Flood Beam Pattern

Table 4.13 shows the average lux values of all lights tested during the final rock board setup. As was found in both trial one and two, LED lights obtained the highest average lux values during setup three testing. Halogen lights again resulted in the lowest average lux values.

Table 4.13: Rock Setup Three Average Lux Values

4 LED 60 degrees (lux)	4 LED 90 degrees (lux)	6 LED 60 degrees (lux)	6 LED 90 degrees (lux)	Hella RokLume LED (lux)	Euro beam halogen (lux)	Horizontal flood beam halogen (lux)	Euro beam HID (lux)	Horizontal flood beam HID (lux)
201.5	262.5	330.9	401.3	550.3	43.1	59.9	117.1	167.1

Results from the third rock setup mimic the results found from the first two setups. The increased brightness of the LED lamps allowed for better performance in locating potential geologic issues within the setup. The increase in the amount of light made it easier to locate cracking and fracturing due to more pronounced shadows. The brightness also made it easier to locate potential coal issues due to the increased reflectivity. Light color had again appeared to have a minimal impact on these results, but the same subjective results are present that were found during the two previous setups. HID lights were still the most visually displeasing due to its blue coloring and how the light "flickers" while in use. The halogen lights were more visually pleasing because of their yellow color, but were still the least bright of all lights tested. The white light color of the LEDs was not visually uncomfortable, however was still slightly less pleasing visually than the halogen lights. The issues of HID charge time and casing heat were also still present in the third setup.

4.4: Discontinuity Identification Discussion

Results from all three rock setups provided nearly the same conclusions. Of all the lights tested, LED performed very well in terms of discontinuity identification compared to halogen and HID lights. During experimentation, it was discovered that the best indicators of potential geologic issues in rock are shadows. Potential discontinuities caused by coal were found due to the increased reflectivity coal possesses compared to rock typically found in Appalachian coal mines. These identifying factors are what allowed LED lighting to perform very well. Shadows and reflectivity were easier to locate due to the superior brightness LED lighting has over both halogen and HID lighting. The LED lights were also one of the easier lights to operate. LED lights, as well as halogen lights, attained full brightness as soon as the light was activated. However, the HID lights required nearly one minute before reaching full brightness. The LED lights were also among the best lights visually. The soft white color made the LED lights comfortable of the eyes. The halogen lights were also comfortable due to their yellow color, but their low brightness also aided the visual comfort. The HID lights were the harshest due to their blue color and how the lights flicker while in use. The LED lights were the brightest tested, easiest to operate, and among the most visually comfortable to use.

Some results found during this portion of experimentation may be in error. The most likely source is the location of the light meter may not have been in the exact same spot while taking readings. This could cause a discrepancy in the recorded lux values and skew the average. However, every attempt was made to reduce the impact of this error. The visual comfort results are subjective to anyone conducting the test, since people may have differing opinions on what is deemed comfortable. Yet, since these visual results discussed correlate with the findings from a NIOSH study conducted by John Sammarco in 2009, these results could have merit and may require more experimentation. It is currently unknown if the heat created by LED operation on the light casing could have a detrimental impact in underground coal mining, thus would need to be examined in depth as well.

CHAPTER 5: CONCLUSIONS

Results from both sets of experimentation indicate that LED lighting can potentially have a positive impact in underground coal mining. Mine panel simulations show that LED lighting is superior to halogen in terms of average lux values and normalized average lux values, while LED lighting obtained similar results to HID lighting. LED lights also recorded better light coverage on the simulated roof than the halogen and HID lights. This increase in lighting can help reduce accident risk in the mining environment. The discontinuity identification results also showed that LED lights performed well at identifying potential geologic issues. This could lead to an improvement in early detection of hazards during the roof bolting process, and thus further reduce accident risk.

The light that performed best throughout all experimentations was the Hella RokLume 280N LED. This light provided the best roof coverage no matter which interval was used. This light also provided adequate lighting when examining roof rock for potential ground control issues due to the large amount of light it generates. In terms of roof coverage, the five foot and seven foot configurations provided the largest amounts of useful light for nearly every light source. These setups provided the least amount of roof coverage under 50 lux. Lights that provided the higher averages during the discontinuity identification experiments performed best during this portion of the research. Higher averages resulted in more light, which was very helpful when identifying shading and reflectivity of rock masses. These visual properties were found to be the largest visual indicators of potential discontinuity issues. These results indicate that LED lighting can have positive impacts in the underground coal mining industry, and they would be best used at an interval between five and seven feet on the ATRS of a roof bolting machine.

It cannot be said with certainty that the lights used meet the standards set in CFR 75.1719. The standard set is based on units of luminance, or the light intensity the eye receives from the illumination. Values recorded during experimentation were in units of illuminance, or the amount of light that is received by the surface. There is no accurate relationship between these units, so it is currently unknown if these lights provide the minimum lighting standard, but it is believed that the minimum standards would be meet by the LED lights. Additional experimentation within the simulated panel utilizing units of luminance would provide the necessary evidence to prove that LED lighting provides what is needed in an underground coal mine.

As was previously discussed, panel simulations indicate that the best average lux value and coverage usually occurs when using the five or seven foot intervals. Roof bolting machines used by industry tend to have lights located four to six feet apart on the ATRS, so similar results could be seen if these LED lights were used on a roof bolting machine. Fletcher model DDR roof bolters have two options available to provide power to the illumination system, either 120 volts or twelve volts. A twelve volt battery was utilized to power every light tested during both experiments, so each light could be used on a model DDR roof bolter using the twelve volt option.

The largest issue with the LED lights tested is that they are not approved by MSHA for underground coal mining use. Results obtained from these simulations show that LED lighting can have a beneficial impact in underground coal mining and can easily be implemented into current roof bolting machine technology. This should allow industry to focus on permissibility requirements for LED area lighting on machines.

Assuming LED lights are approved, the next issue is implementation. As was seen with incandescent lighting, some coal mines may be hesitant to implement LED lighting due to the costs it will take to convert their current illumination to be compatible with LEDs. LED lights are currently more expensive to purchase than other forms of lighting, which would result in a higher startup cost. There may also be issues with converting a mine's current illumination system to be more compatible with LED lighting technology. Altering the current illumination system would require sizable funding, not to mention the man hours lost converting the illumination system. However, there would be several benefits financially to using LED lighting. The most significant benefit being LED's lower power consumption. Table 5.1 (DoE [B], 2013) presents a brief comparison of LED, incandescent, energy efficient incandescent, and compound fluorescent light sources in terms of lifespan and annual energy cost for a single light source. One LED light can save nearly four dollars in a year. Several hundred LED lights may be in use in an underground mine, so this four dollar savings in a year for one light could increase to hundreds possibly thousands of dollars saved annually by a mining operation. Table 5.1 also shows that LED lights have lifespans around 25 times longer than traditional incandescent lamps. This would results in less maintenance time replacing mine luminaries as well as lower the number of times lamps need to be purchased. A financial study of the costs of LED lighting were not part of this research, but an in depth investigation could provide the evidence mine operators need to move forward with implementing LED lighting once it is approved for use.

Table 5.1: Comparison between Traditional Incandescent, Halogen Incandescent, CFL, and LED (DoE [B], 2013)

	60W Traditional Incandescent	43 W Energy-Saving Incandescent	15 W CFL		12 W LED	
			60 W Traditional	43 W Halogen	60 W Traditional	43 W Halogen
Energy Costs Saved (%)	-	-25%	-75%	-65%	-75-80%	-72%
Annual Energy Costs	$4.80	$3.50	$1.20		$1.00	
Bulb Life (hours)	1000	1000-3000	10,000		25,000	

Future work for this subject could include an alternative method for discontinuity identification testing. The method presented in this research is highly subjective and was completed by a single person. This allowed for that person to gain knowledge about the rock setups and could have an impact on how easily the discontinuities were identified. A less subjective testing method would be helpful in evaluating the identification capabilities of LED lighting.

Another subject that could be evaluated with LED lighting is the identification of bedding planes. New lighting sources and lighting colors could potentially have an impact on how different colors of rock appear, making it easier or more difficult to identify bedding planes for rock. Weak bedding planes could result in more roof falls. These new lighting sources could help identify these areas and preventative roof control practices can be used to prevent roof falls. This also can aid in determine the Rock Quality Designation for a rock mass, which gives an indication of the strength of the rock mass used in many mine design software programs.

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