U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

GATEWAY Demonstrations

LED System Performance in a Trial Installation—One Year Later

Host Site: Yuma Border Patrol, Yuma, Arizona

April 2015

Prepared for:

Solid-State Lighting Program
Building Technologies Office
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Prepared by:

Pacific Northwest National Laboratory

Yuma Border Patrol Area Lighting Retrofit
LED System Performance in a Trial Installation – One Year Later

Prepared in support of the DOE Solid-State Lighting Technology GATEWAY Program

Study Participants:
Pacific Northwest National Laboratory
U.S. Department of Energy

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Preface

The GATEWAY Program

This document is a report of observations and results obtained from a lighting evaluation project conducted under the U.S. Department of Energy (DOE) GATEWAY Program. The program supports field evaluations of high-performance solid-state lighting products in order to develop empirical data and experience with in-the-field applications of this advanced lighting technology. The DOE GATEWAY Program provides independent, third-party data for use in decision-making by lighting manufacturers, users, and other professionals. Though products used in the GATEWAY program may have been prescreened for performance, DOE does not endorse any commercial product or in any way provide assurance that other users will achieve similar results through use of these products.

Acknowledgements

Harry Hart, the Customs and Border Protection Yuma Sector Program Manager, has provided assistance throughout the installation and monitoring of the LED luminaires in the Yuma Sector Border Patrol Area. His support is greatly appreciated.

Executive Summary

The Yuma Sector Border Patrol Area is a high temperature and high solar radiation environment, providing an opportunity for the U.S. Department of Energy (DOE) to study thermal effects on outdoor light-emitting diode (LED) luminaires outside of the testing laboratory. Six LED luminaires were installed on three poles on the U.S.-Mexico border in February 2014 as part of a trial installation, which was detailed in a prior GATEWAY report.[1] The initial trial installation was intended as a short-term test of six luminaires installed on three poles before proceeding with the complete installation of over 400 luminaires. Unexpected delays in the full installation have prevented the detailed evaluations initially planned, but the six installed LED luminaires continue to be monitored, and over the past year illuminance measurements were recorded initially in February 2014 and again in September 2014 at about 2500 hours of operation and in March 2015 at about 5000 hours of operation.

Measured data at the project site after nominally 2500 hours and 5000 hours indicate that the illuminances are changing more rapidly than anticipated. The distribution of illuminance also changed, with values nearest to the pole increasing while the values decreased farther away from the pole, and the greatest decreases were at the points farthest from the pole. The average horizontal illuminance decreased by 18% near the primary fence and vertical illuminance decreased by 25% on the primary fence. These changes in the illuminances delivered by the lighting system occurred after 2500 hours of operation, and persisted after 5000 hours of operation. There was no measured shift in the color of the light.

The field measurements after 2500 and 5000 hours document the overall effects at the site, but they do not provide specific insights into the causes. Research that seeks to identify and quantify the causes is ongoing. The most likely causes for these observed changes are dirt accumulation combined with possible changes to the luminaire optical elements such as lenses. Other causes are possible, but seem less probable based on the measurements.

The Yuma site is an extreme environment. The luminaires in Yuma rarely get a break from the heat: high ambient temperatures and direct solar radiation heat up the luminaires throughout the day, and at sunset the LED luminaires turn on and generate internal heat just as the solar radiation stops and the ambient temperature begins to decrease.

PNNL researchers are exploring plans for thermal simulations of the luminaire as well as removal of one or more of the six luminaires from the site for detailed laboratory analysis. DOE also plans to collect additional data from the site to more fully assess possible effects from dirt accumulation and other site-specific effects. Future reports are planned to address these topics.

[1] For further information download the Yuma Border Patrol Area Lighting Retrofit: Trial Demonstration report prepared by the DOE Solid-State Lighting Program: http://energy.gov/sites/prod/files/2014/12/f19/gateway-yuma.pdf.

Acronyms and Abbreviations

CCT	correlated color temperature
CRI	color rendering index
DOE	U.S. Department of Energy
ESPC	Energy Savings Performance Contract
HID	high-intensity discharge
IES	Illuminating Engineering Society
IGA	investment grade audit
LDD	luminaire dirt depreciation
lx	lux
POE	Port of Entry
QMH	quartz metal halide
SPD	spectral power distribution
SSL	solid-state lighting
TMY2	Typical Meteorological Year 2

Contents

1. Introduction

Lumen and color maintenance, luminaire efficacy, and luminaire component lifetimes are all significant concerns when light-emitting diode (LED) luminaires are exposed to high ambient temperatures. These challenges are among the reasons why the Yuma Sector Border Patrol Area lighting retrofit on the U.S.-Mexico border was documented by the U.S. Department of Energy (DOE) Solid-State Lighting (SSL) GATEWAY program.

The retrofit is a DOE Federal Energy Management Program Energy Savings Performance Contract (ESPC) ENABLE project administered through the General Services Administration. This ESPC project required that a sample of luminaires be installed on three sequential poles as an investment grade audit (IGA) trial demonstration of the proposed design solution. The results were detailed in the Yuma Phase 1 Report.[2]

The Phase 1 report compared the installed LED luminaires to the incumbent high-intensity discharge (HID) lighting system installed in the Yuma Sector. This follow-up report does not include a comparison to the incumbent HID system, and instead documents the results of continued monitoring of the original installation of six LED luminaires (two luminaires on three sequential poles) for the trial demonstration. These luminaires have remained operational for over a year, providing an opportunity to record the performance in this challenging environment.

This report is part of a planned series that documents the installation of LED luminaires in the Yuma Sector Border Patrol Area. If a full installation of LED luminaires occurs, future reports will summarize the performance at the time of installation and the long-term performance of the LED luminaires in the high ambient temperature environment.

- **Yuma Phase 1.0 Report: Investment Grade Audit Trial Demonstration (Completed)**
  Describes the Yuma Sector Border Patrol Area and focuses on the IGA trial demonstration, including development of the lighting system design and photometric measurements recorded during the IGA trial demonstration.
- **Yuma Phase 1.1 Report: LED System Performance - One Year Later (Current Report)**
  Reviews the results of ongoing data collection, specifically field illuminance measurements of the six luminaires installed for the IGA.
- **Yuma Phase 2 Report: Initial Assessment of Full Installation (Pending)**
  Will summarize the installation and initial performance of the lighting system, focusing on a subset of the overall lighting system. Plans include sample photometric, thermal, and energy measurements, and the results of initial testing of a sample of luminaires prior to installation.
- **Yuma Phase 2 Updates (Pending)**
  Will review the results of ongoing data collection, including field illuminance measurements of a subset of the overall lighting system and laboratory testing of lumen depreciation and color shift for a sample of luminaires.

[2] For further information download the Yuma Border Patrol Area Lighting Retrofit: Trial Demonstration report prepared by the DOE SSL Program: http://energy.gov/sites/prod/files/2014/12/f19/gateway-yuma.pdf

- **Yuma Phase 3 Report: Long-term Assessment of Installation (Pending)**
  Final report that will encapsulate 30 months of data collection, providing an overview of the data collection and analysis of the effects of the environment on the LED system.

2. Background

The Yuma Sector Border Patrol Area, near the Yuma San Luis Port of Entry (POE), spans 9 miles south of Yuma, AZ, along the U.S.-Mexico border. The terrain and lighting system design for the 7.2 miles east of the POE are consistent, with 205 poles spaced 180 ft apart lining this section of the border. The three poles farthest east of the POE, poles 203 through 205, were selected for the trial demonstration, and six LED luminaires replaced the incumbent quartz metal halide (QMH) luminaires on these poles. To reduce the required luminous flux from the LED luminaires, the height of these poles was reduced from 64 ft to 40 ft, and the LED luminaires were designed to provide uniform illumination from the lower pole height. Poles 203 and 204 are shown in Figure 1, with the incumbent lighting system trailing into the distance toward the POE. Two LED luminaires were installed per pole with a custom tenon mount, pictured in Figure 2, replacing the three 1000 W QMH luminaires. The LED system was designed to replace only the two end QMH luminaires because the middle luminaire was not operational and the amount of light provided by the two QMH luminaires was considered acceptable. The long-term goal is to replace the QMH lighting system with an alternative that achieves a minimum energy savings of 50% while maintaining existing light levels.

Figure 1. Trial Demonstration Site on the U.S.-Mexico Border: Daytime. Photo taken from the east end of the 7.2 mile area between poles 205 (not pictured) and 204 (pictured, front), looking west. The QMH luminaires are mounted on the poles at a height of 64 ft and the LED luminaires are mounted at 40 ft—a difference that is visible in this image. The primary fence is on the left and the secondary fence is on the right.

This tactical border application was a challenge for LED luminaire technology because it required high luminous flux in a region with high ambient temperature and solar radiation. The 180 ft pole spacing and 125 ft spacing between the primary and secondary fences required each LED luminaire to cover approximately 11,250 ft^2 at a 40 ft mounting height. The 125 ft width is split by the pole line with a 45 ft distance to the primary fence and an 80 ft distance to the secondary fence, as illustrated in Figure 3. The 14 ft corrugated metal primary fence blocks visibility through the fence; however, the 12 ft metal mesh secondary fence allows border patrol agents to easily see through the fence.

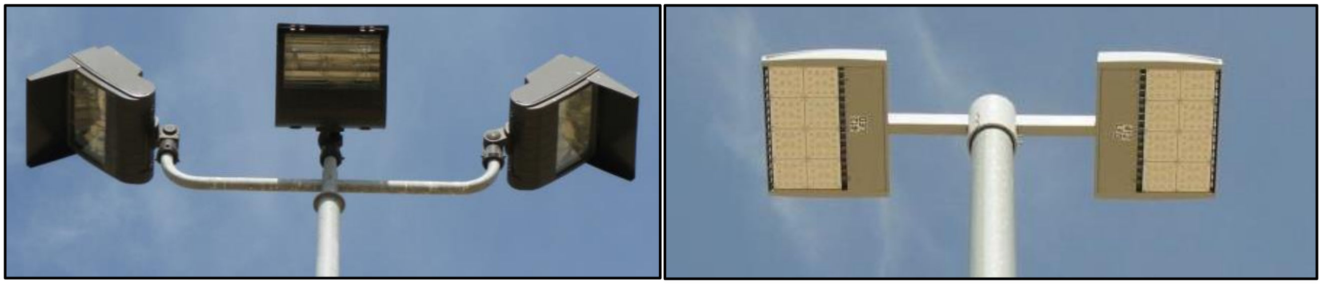

Figure 2. Incumbent QMH Luminaires (left) and LED Luminaires (right). A custom tenon was necessary to fit the diameter of the pole after the pole was cut to 40 ft, because the diameter of the tapered pole narrowed as the height increased. The QMH luminaires were originally installed with the lens tilted up from horizontal and shielded with visors to minimize stray light.

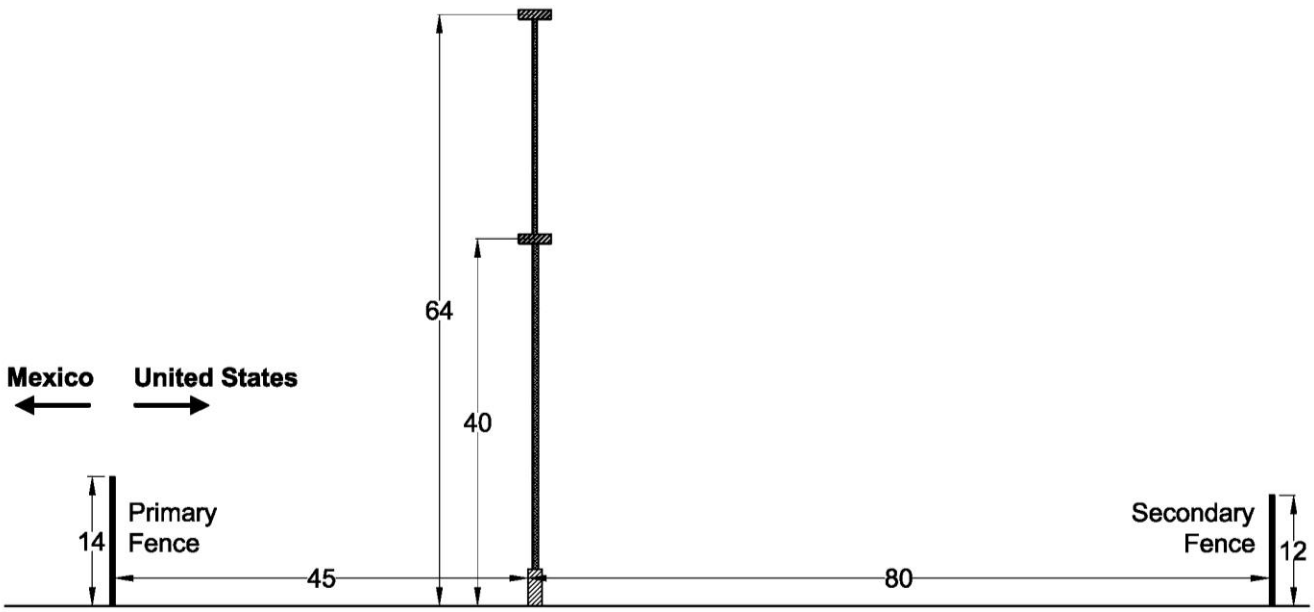

Figure 3. Schematic Elevation of the Yuma Sector Border Patrol Area East of the San Luis Port of Entry. The dimensions are not exact, but are representative of the 7.2 mile border area east of the POE. All dimensions are in feet. The elevation near the secondary fence was approximately 2 to 4 ft higher than the base of the concrete pole pedestal.

The LED luminaires have eight light squares,[3] each with Illuminating Engineering Society (IES) Type III luminous intensity distribution (as defined by IES RP-8-14). Six light squares illuminate the area between the pole and primary fence, a distance of 45 ft, and two of the light squares are rotated 180° to illuminate the 80 ft distance between the poles and secondary fence. The difference in the light levels between the primary and secondary side of the pole is visible in Figure 4. The primary fence and the 45 ft area between the pole and the primary fence required higher levels of illumination because these areas are the main focus of the border patrol agents at night. The border patrol agents often drive along the secondary fence, with a vehicle mounted spotlight providing additional light in the area near the secondary fence. The 7.2 miles east of the POE require continuous surveillance by border patrol agents, and the role of the lighting is to allow the border agents to perform their job tasks equally well day or night.

3 Light squares, bars, and packages are terms used by luminaire manufacturers to describe the scalable lumen output characteristic of their luminaires.

Figure 4. **Trial Demonstration Site on the U.S.-Mexico Border: Nighttime.** The 24 ft difference in height is visible in this image. The primary fence is on the left and on the right is the secondary fence—less noticeable in this image due to the relatively low light level on the fence.

3. Illuminance and Color Measurements

The initial illuminance measurements of the new LED system installed on poles 203 through 205 occurred on the evening of February 4, 2014. A second set of measurements—including both illuminance and color—occurred on September 17, 2014, at an estimated 2500 hours of operation. A third set of measurements occurred on March 3, 2015, at an estimated 4700 hours of operation, referenced as the nominal time of 5000 hours throughout this report. This third set of measurements intentionally occurred a few hundred hours before the 5000 hour mark to maintain ambient temperature consistency with the initial measurements. A primary goal of the third set of measurements was to compare the initial measurements to the nominal 5000 hour mark at the same environmental temperature to negate the effect of ambient temperature on luminaire lumen output, since the effect can only be estimated.

3.1 Color Measurements and Comparison

Color measurements were recorded to document changes in the spectral power distribution (SPD) of the luminaires over time, which could be caused by several factors including yellowing of the lens or LED color shift. It was not feasible to remove the fixtures for testing, so a Konica Minolta spectrophotometer[4] was used to take a single SPD measurement under each LED luminaire, 36 ft below the luminaire. This method can increase the possibility of other illumination sources affecting the measured values, but in this case there were no nearby sources of illumination contributing to the measurements.

The color metrics, listed in Table 1, were calculated by the CL-500A software from the SPD measurements. The results for each individual luminaire are very similar at both 2500 and 5000 hours, with the standard deviations of the measurements nearly identical. The average of the six measurements at 2500 and 5000 hours is also similar; the 33 K change in correlated color temperature (CCT) is well within the nominal tolerance listed in American National Standards Institute C78.377-2011[5]—which requires the CCT be 3985 ± 275 K for luminaires nominally rated at 4000 K.

4 The Konica Minolta CL-500A spectrophotometer was factory calibrated prior to purchase in November 2013.

5 American National Standards Institute - American National Lighting Group Specifications C78.377-2011. American National Standard for Electric Lamps—Specifications for the Chromaticity of Solid State Lighting (SSL) Products.

Table 1. Color Metric Summary for Measurements at 2500 and 5000 Hours of Operation. The SPD of each luminaire was measured at 2500 and 5000 hours with a Konica Minolta CL-500A spectrophotometer. The color metrics were calculated by the CL-500A software. The individual luminaires are denoted by pole number and cardinal direction relative to the pole (east or west). The HID average represents the average of eight measurements recorded east and west of poles 202 and 200 at both 2500 and 5000 hours. The operating hours of the HID lamps at the time of measurement was unknown. Pole 201 was not included because there was an unknown issue affecting the performance of those luminaires at 5000 hours. The LM-79 values are based on LM-79 tests submitted by Cooper to the Design Lights Consortium.

Measurement Location	Hours	Chromaticity Coordinates x	y	CCT	D_{uv}	CRI	R_9
HID Average	2500, 5000	0.368	0.386	4425	0.0082	66	-107
LED 205-East	2500	0.379	0.383	4075	0.0031	65	-30
	5000	0.379	0.380	4055	0.0018	65	-28
LED 205-West	2500	0.379	0.383	4074	0.0033	65	-30
	5000	0.381	0.381	4027	0.0020	65	-28
LED 204-East	2500	0.378	0.378	4088	0.0015	65	-29
	5000	0.377	0.375	4070	0.0000	65	-27
LED 204-West	2500	0.379	0.382	4061	0.0025	65	-30
	5000	0.380	0.379	4035	0.0011	65	-27
LED 203-East	2500	0.380	0.382	4059	0.0028	65	-30
	5000	0.381	0.381	4022	0.0018	65	-28
LED 203-West	2500	0.377	0.378	4115	0.0018	65	-30
	5000	0.378	0.376	4065	0.0006	65	-27
Std. Dev.	2500	0.001	0.002	19	0.0006	0	0
	5000	0.001	0.002	19	0.0007	0	1
Average	2500	0.379	0.381	4079	0.0025	65	-30
	5000	0.379	0.379	4046	0.0012	65	-28
LM-79 Values		0.390	0.400	3922	0.0077	66	-30

3.2 Illuminance Measurement Methodology

The same measurement procedure was used for the initial, 2500 hour, and 5000 hour illuminance measurements. The measurements were recorded at points in a rectangular grid that was initiated from the middle of the primary (south) face of the concrete pole pedestal at pole 204, with measurement points spaced uniformly at 15 ft intervals in both directions (north-south and east-west) as illustrated in Figure 5. The horizontal measurements were recorded approximately 9.5 in. above the ground and the illuminance meter was leveled for each measurement with a tripod head. This measurement setup is shown in Figure 6. Leveling was necessary because of the unevenness of the sandy terrain. Vertical illuminance measurements were recorded at heights of 4 and 8 ft at the fence, in line with the columns of horizontal illuminance measurements. The illuminance meter was not leveled for each vertical measurement; however, the illuminance meter plane was approximately parallel to the vertical fence plane. The 15 ft spacing of the measurement columns was marked with spray paint on the primary and secondary fences during the initial set of measurements, and these same markings were used for the 2500 and 5000 hour measurements.

A total of 117 horizontal and 52 vertical measurements were recorded between poles 203 and 205, centered on pole 204. The measurements extended 90 ft east (halfway toward pole 205) and 90 ft west (halfway toward pole 203) of pole 204. Only 81 initial horizontal measurements were recorded because the sun began to rise before the measurements could be completed.

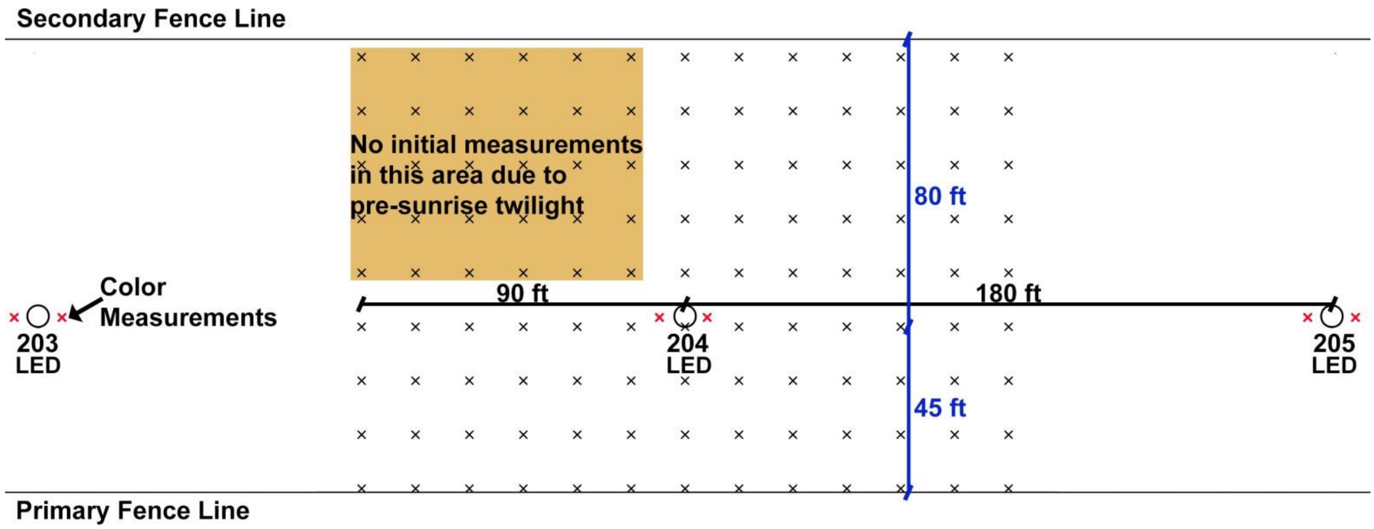

Figure 5. Layout of Grid Measurements. The measurements between poles 203 and 205 were recorded in a rectangular grid from the middle of the primary (south) face of the concrete pole pedestal at pole 204, with uniform 15 ft spacing in both directions. The horizontal measurements were recorded approximately 9.5 in. above the ground and the illuminance meter was leveled for each measurement with a tripod head. Vertical illuminance measurements were recorded at heights of 4 and 8 ft at the fence, along the same column as the horizontal illuminance measurements. A single color measurement was recorded under each LED luminaire, 36 ft below the luminaire.

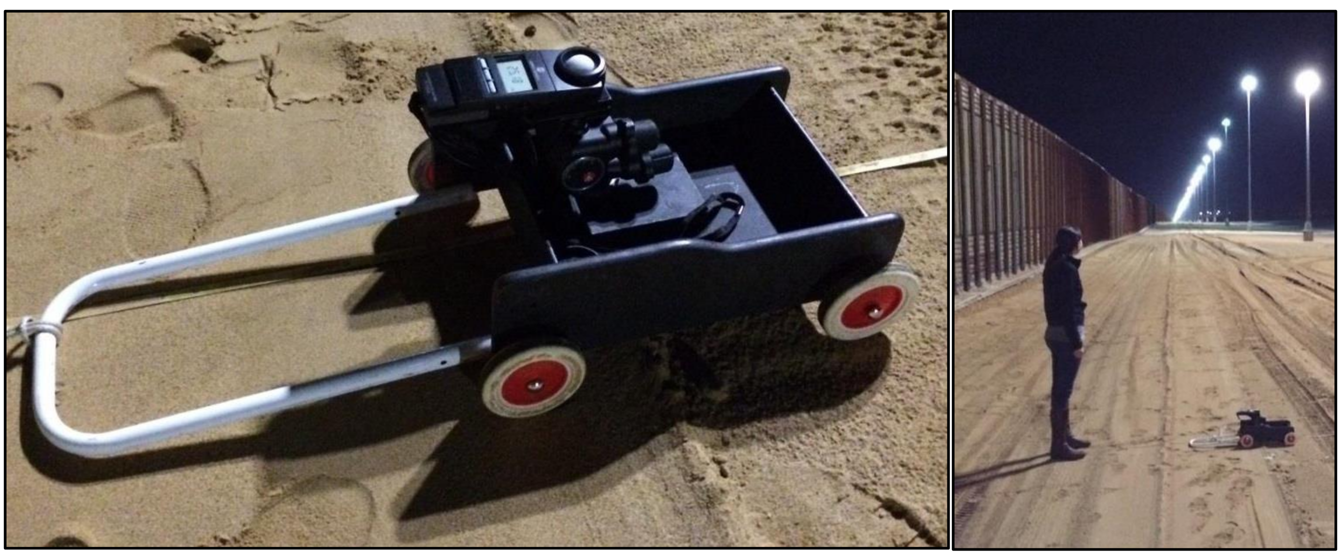

Figure 6. Illuminance Measurement Wagon. The illuminance meter was mounted on a tripod head, and the tripod head was attached to the base of the wagon. The knobs of the tripod head were used to adjust the front and lateral tilt of the illuminance meter to level the meter—with reference to the tripod head's leveling bubble.

The hours of operation were calculated based on the length of the day, specifically the hours of darkness—the actual time between sunset and sunrise. The daily hours of darkness for 2014 and 2015 in Yuma were obtained from the U.S. Naval Observatory.[6] The hours of darkness are assumed to be a close estimate of the operating hours of the LED luminaires because the luminaires are operated by photocontrols. The photocontrols were located approximately 4 ft off the ground and each pair of photocontrols (one for redundancy) controlled 23 to

6 U.S. Naval Observatory Astronomical Applications Department. Duration of Daylight/ Darkness Table for One Year: http://aa.usno.navy.mil/data/docs/Dur_OneYear.php.

27 poles. The exact time that the luminaires turned on and off was not documented; however, it was verified that the on/off cycle of the luminaires relies solely on the photocontrols, with no special settings.

Comparing illuminance measurements recorded in different ambient temperature conditions requires temperature correction because temperature directly affects LED luminaire lumen output—as temperature increases, lumen output decreases. Since lumen output varies with ambient temperature, many manufacturers provide guidance on adjusting the lumen output of their products for different ambient temperature conditions. Lumen multipliers were listed on the manufacturer specification sheet for the LED luminaires installed in the Yuma Sector Border Patrol Area.

On the product specification sheet, the luminaire manufacturer listed five different lumen multipliers corresponding to temperature points ranging from 10 to 50 °C (50 to 122 °F), as listed in Table 2. Linear interpolation was used to calculate the lumen multiplier if the average ambient temperature differed from these five points, shown in Table 3. The minor change in temperature over the measurement time did not have a considerable effect on the lumen multiplier, so the same lumen multiplier is applied to all measurements recorded at a given number of operating hours. The small difference in ambient temperature during the initial and 5000 hour measurements resulted in the same lumen multiplier for both sets of measurements. The illuminance measurements prior to the application of a lumen multiplier are listed in Appendix A. All values referenced in the main body of this report have been corrected for temperature.

Table 2. Temperature Correction Lumen Multipliers. The lumen multiplier values were listed on the LED luminaire manufacturer's specification sheet.

Temperature	Lumen Multiplier
10 °C (50 °F)	1.04
15 °C (59 °F)	1.03
25 °C (77 °F)	1.00
40 °C (104 °F)	0.96
50 °C (122 °F)	0.92

Table 3. Lumen Multiplier Used for Initial, 2500, and 5000 Hour Measurements. The lumen multipliers were calculated for the specific average temperature during the measurements by linearly interpolating between the temperatures provided by the manufacturer. Measured values were divided by the corresponding lumen multiplier to normalize all values to a 25 °C (77 °F) condition.

Hours of Operation	Average Measurement Temperature	Lumen Multiplier
Initial	13 °C (55 °F)	1.03
2500	32 °C (90 °F)	0.98
5000	15 °C (59 °F)	1.03

3.3 Illuminance Measurements: Initial

Results of the initial measurements are shown in Figure 7 for comparison to the 2500 and 5000 hour measurements. The initial measurements were previously reported[7]; however, the previously reported measurements were not temperature corrected. The LED luminaires had been installed for less than a week when the measurements were recorded, and had not been operated prior to installation. The number of horizontal measurements was limited due to pre-sunrise twilight, so the measurements northwest of the pole were estimated based on the measurements northeast of the pole. The five measurements directly between the pole and secondary fence were recorded between 6:40 and 6:50 a.m. Civil twilight (when the sun is 6° below the horizon) occurred at 7:04 a.m. and sunrise was at 7:30 a.m.

[7] Yuma Border Patrol Area Lighting Retrofit: Trial Demonstration: http://energy.gov/sites/prod/files/2014/12/f19/gateway-yuma.pdf.

	W90	W75	W60	W45	W30	W15	Pole	E15	E30	E45	E60	E75	E90	LED Initial (lx)	
8 ft	4.2	4.2	4.4	4.8	5.5	6.3	6.5	6.5	5.9	5.0	4.4	4.4	4.6	5.6 Avg	Secondary Fence (Vertical)
4 ft	4.5	4.6	4.9	5.5	6.5	7.2	7.4	7.4	6.9	6.0	5.5	5.4	5.7	7.4 Max	
	Secondary Fence													4.2 Min	
N75	3.7	3.8	3.9	4.0	4.1	4.3	4.4	4.3	4.1	4.0	3.9	3.8	3.7	8.1 Avg	3 Rows Closest to Secondary Fence (Horizontal)
N60	6.5	6.5	6.7	6.8	7.2	7.6	7.8	7.6	7.2	6.8	6.7	6.5	6.5	14.9 Max	
N45	13.1	13.1	12.6	12.9	13.6	14.7	14.9	14.7	13.6	12.9	12.6	13.1	13.1	3.7 Min	
N30	19.3	20.7	22.0	22.0	23.8	25.4	25.4	25.4	23.8	22.0	22.0	20.7	19.3	21.3 Avg	All (Horizontal)
N15	25.1	25.8	26.7	27.2	32.7	38.8	40.7	38.8	32.7	27.2	26.7	25.8	25.1	44.0 Max	
Pole	26.8	28.6	28.7	30.7	33.1	36.3	44.0	36.3	33.1	30.7	28.7	28.6	26.8	3.7 Min	
S15	27.1	27.7	28.6	29.7	33.5	37.7	40.2	38.0	35.3	32.2	31.6	29.8	27.4	27.6 Avg	3 Rows Closest to Primary Fence (Horizontal)
S30	26.2	26.8	27.0	27.0	27.9	29.2	29.2	29.7	29.7	28.1	29.8	28.9	26.4	40.2 Max	
S45	22.3	23.0	21.6	21.3	22.7	23.2	23.7	24.1	23.2	21.8	22.2	22.0	20.4	20.4 Min	
	Primary Fence													28.3 Avg	Primary Fence (Vertical)
4 ft	24.2	25.4	27.1	28.2	29.8	32.0	30.8	31.1	29.3	25.8	27.5	25.2	23.4	35.6 Max	
8 ft	20.7	22.8	26.9	31.4	32.6	35.3	35.6	35.3	33.4	30.9	27.9	22.6	20.8	20.7 Min	
	W90	W75	W60	W45	W30	W15	Pole	E15	E30	E45	E60	E75	E90		

Figure 7. LED Lighting System Horizontal and Vertical Illuminance Measurements: Initial. The horizontal measurements were recorded at 9.5 in. above ground and the vertical measurements were recorded at 4 ft and 8 ft above ground at the base of the fence. The horizontal measurements were recorded from the middle of the primary face of the pole pedestal at 15 ft intervals. The black solid line indicates measurements greater than or equal to 30 lx, and the white solid line indicates measurements greater than or equal to 20 lx. The area within the dashed black line was not measured and was estimated by mirroring the corresponding measurements on the other side of the pole. The square color represents the relative measured illuminance quantity: Green = low horizontal; Purple = high horizontal; Orange = low vertical; Yellow = high vertical. Values shown were normalized for a 25 °C (77 °F) condition.

3.4 Illuminance Measurements: 2500 Hours

In September 2014, after 2500 hours of operation, a complete set of horizontal and vertical measurements was recorded and the results are listed in Figure 8. All six luminaires were operational and had not been touched since installation. There were no reported comments on the LED lighting, which was viewed as favorable because the change had not caused any negative reactions.

	W90	W75	W60	W45	W30	W15	Pole	E15	E30	E45	E60	E75	E90	LED 2500 hr (lx)	
8 ft	4.4	4.5	4.7	5.2	5.9	6.6	6.9	6.8	6.2	5.3	4.7	4.6	4.7	5.8 Avg	Secondary Fence (Vertical)
4 ft	4.8	4.9	5.2	5.9	6.9	7.6	7.8	7.8	7.2	6.3	5.7	5.5	5.6	7.8 Max	
	Secondary Fence													4.4 Min	
N75	2.5	2.8	3.2	3.5	4.0	4.2	4.0	4.0	4.0	3.7	3.5	3.4	3.4	7.3 Avg	3 Rows Closest to Secondary Fence (Horizontal)
N60	4.5	4.8	5.4	6.2	6.8	8.0	7.4	7.5	6.9	6.6	6.2	5.7	5.5	15.5 Max	
N45	8.7	9.2	10.0	11.5	13.8	15.5	14.7	15.4	13.9	12.3	11.3	11.2	10.6	2.5 Min	
N30	15.3	16.6	18.4	20.0	24.4	27.2	27.3	28.0	25.6	21.9	19.7	17.3	15.7	19.5 Avg	All (Horizontal)
N15	19.2	21.2	23.0	27.8	35.9	43.5	45.8	44.8	36.5	28.1	24.1	20.9	19.7	55.6 Max	
Pole	20.5	23.1	26.5	31.1	36.1	42.3	55.6	42.3	36.5	30.5	25.1	21.8	20.4	2.5 Min	
S15	19.3	22.2	25.6	29.8	36.7	43.3	46.8	43.4	36.3	28.1	22.9	20.1	19.5	23.4 Avg	3 Rows Closest to Primary Fence (Horizontal)
S30	17.6	20.0	22.6	25.1	28.2	30.6	31.1	29.4	25.6	21.1	18.8	17.5	17.5	46.8 Max	
S45	15.5	16.5	16.2	17.1	19.2	19.8	20.2	19.3	17.1	14.8	13.4	12.9	13.2	12.9 Min	
	Primary Fence													21.3 Avg	Primary Fence (Vertical)
4 ft	16.4	18.7	20.0	21.2	23.9	27.3	26.5	25.7	22.5	19.7	17.8	15.9	15.3	29.9 Max	
8 ft	14.4	16.6	23.5	25.2	26.2	29.3	29.9	28.4	26.1	20.0	16.7	14.0	13.7	13.7 Min	
	W90	W75	W60	W45	W30	W15	Pole	E15	E30	E45	E60	E75	E90		

Figure 8. **LED Lighting System Horizontal and Vertical Illuminance Measurements: 2500 Hours.** The horizontal measurements were recorded at 9.5 in. above ground and the vertical measurements were recorded at 4 ft and 8 ft above ground at the base of the fence. The horizontal measurements were recorded from the middle of the primary face of the pole pedestal at 15 ft intervals in all cardinal directions. The black solid line indicates measurements greater than or equal to 30 lx, and the white solid line indicates measurements greater than or equal to 20 lx. The square color represents the relative measured illuminance quantity: Green = low horizontal; Purple = high horizontal; Orange = low vertical; Yellow = high vertical. Values shown were normalized for a 25 °C (77 °F) condition.

3.5 Illuminance Measurements: 5000 Hours

The same measurement methodology was repeated in March 2015 at 5000 hours of operation, resulting in the measurements listed in Figure 9. All six luminaires remained operational and had not been touched in the year since installation. Between the 2500 and 5000 hour measurements, a 4 to 6 in. layer of recycled asphalt gravel was added near the secondary fence, slightly increasing the height of the horizontal illuminance measurements for the three rows closest to the secondary fence. The increase in height may have increased the illuminance values; however, the average of three rows closest to the secondary fence remained similar between 2500 and

5000 hours, as did the secondary fence vertical measurements—which were measured relative to the bottom of the fence for both sets of measurements.

	W90	W75	W60	W45	W30	W15	Pole	E15	E30	E45	E60	E75	E90	LED 5000 hr (lx)	
8 ft	4.1	4.2	4.5	4.9	5.7	6.5	6.7	6.7	6.1	5.1	4.6	4.4	4.6	5.7 Avg	Secondary Fence (Vertical)
4 ft	4.6	4.7	5.1	5.8	6.9	7.6	8.6	7.6	7.2	6.2	5.6	5.4	5.5	8.6 Max	
	Secondary Fence													4.1 Min	
N75	3.1	3.2	3.2	3.5	3.9	4.3	4.3	4.1	4.0	3.7	3.6	3.4	3.2	7.2 Avg	3 Rows Closest to Secondary Fence (Horizontal)
N60	4.8	5.1	5.3	6.0	6.9	7.9	8.0	7.8	7.1	6.4	5.9	5.4	5.0	15.5 Max	
N45	8.7	8.7	9.5	11.2	13.3	15.2	15.5	15.3	13.7	11.7	10.6	9.7	9.1	3.1 Min	
N30	14.1	14.7	16.6	19.3	24.0	27.1	28.0	27.7	24.7	20.6	17.8	15.1	13.4	18.7 Avg	All (Horizontal)
N15	17.4	18.4	20.9	26.6	35.0	43.6	46.5	44.0	34.6	25.9	21.7	18.7	17.4	55.9 Max	
Pole	18.8	20.7	24.0	29.0	35.1	43.6	55.9	40.5	34.5	28.1	22.8	20.3	18.7	3.1 Min	
S15	17.9	19.8	23.0	27.4	34.4	42.0	45.3	40.2	32.8	25.6	22.1	19.6	18.5	22.5 Avg	3 Rows Closest to Primary Fence (Horizontal)
S30	17.0	18.4	20.3	22.5	25.6	28.3	28.3	27.5	24.4	21.1	19.5	18.1	17.4	45.3 Max	
S45	14.8	15.5	15.4	16.9	19.1	20.5	20.8	20.2	18.2	16.1	15.1	14.3	13.9	13.9 Min	
	Primary Fence													21.2 Avg	Primary Fence (Vertical)
4 ft	16.2	17.3	16.4	19.9	24.1	27.2	27.6	26.5	24.6	19.3	19.1	16.9	15.9	30.6 Max	
8 ft	13.5	15.5	18.0	22.6	26.7	30.2	30.6	29.6	25.8	21.3	18.3	15.2	13.9	13.5 Min	
	W90	W75	W60	W45	W30	W15	Pole	E15	E30	E45	E60	E75	E90		

Figure 9. LED Lighting System Horizontal and Vertical Illuminance Measurements: 5000 Hours. The horizontal measurements were recorded at 9.5 in. above ground and the vertical measurements were recorded at 4 and 8 ft above ground at the base of the fence. The horizontal measurements were recorded from the middle of the primary face of the pole pedestal at 15 ft intervals. The black solid line indicates measurements greater than or equal to 30 lx, and the white solid line indicates measurements greater than or equal to 20 lx. The square color represents the relative measured illuminance quantity: Green = low horizontal; Purple = high horizontal; Orange = low vertical; Yellow = high vertical. Values shown were normalized for a 25 °C (77 °F) condition.

4. Illuminance Measurement Comparisons

Examination of how illuminance changes over time includes not only considering averages and uniformity ratios, but also understanding how the distribution of light is or is not changing over time. The distribution of light produced by the LED luminaires changed considerably in the first 2500 hours of operation, and this change in distribution persisted through the next 2500 hours.

4.1 Illuminance Measurement Change: Initial and 5000 Hours

The key findings to date from this ongoing study are revealed by comparing the initial data set from February 2014 (at 0 hours) to the data set from March 2015 (at nominal 5000 hours). These data show the overall changes after the first year of operation, and because the ambient temperatures were nearly the same during the two measurement times, they can be compared without introducing uncertainty about the accuracy of the temperature correction factors. Comparing the 5000 hour measurements to the initial measurements reveals several important changes in the illuminances delivered by the lighting system after 5000 hours:

- The average horizontal illuminance decreased by 18% in the three measurement rows closest to the primary fence.
- The average vertical illuminance decreased by 25% on the primary fence.
- The average vertical illuminance on the secondary fence remained similar.
- The distribution of illuminance changed, with values nearest to the pole increasing while the values decreased farther away from the pole, and the greatest decreases were at the points farthest from the pole.

The reductions in average illuminance in the areas near the primary fence are a concern, since that is the primary task area for this application. However, average illuminance does not completely characterize the change in illuminance for this application. The averages indicate what is happening overall, but do not reveal the change in distribution over the 22,500 ft^2 area measured around pole 204. As stated in the fourth bullet above, this change in distribution increased illuminance near the pole and decreased illuminance farther away from the pole. Figure 10 shows this change in distribution for the measurements taken along the east-west line that includes pole 204, and Figure 11 shows a three-dimensional pseudo-color plot of the illuminance changes between 0 and 5000 hours.

The green areas shown in Figure 11 indicate areas where the measured illuminances after 5000 hours were greater than those measured at 0 hours, with the light green areas indicating zones where illuminance increased by 0% to 20% and dark green indicating the few points closest to the pole where the illuminance increased by more than 20%. The light red (pink) areas indicate zones where the illuminance decreased by 0% to 20% (shown as -20% in the legend) and the dark red areas farthest from the pole show those points where illuminance decreased by more than 20%. As discussed in Section 5, this pattern of changes in illuminance would not be expected from normal LED lumen depreciation—those changes would occur uniformly throughout the measurement area.

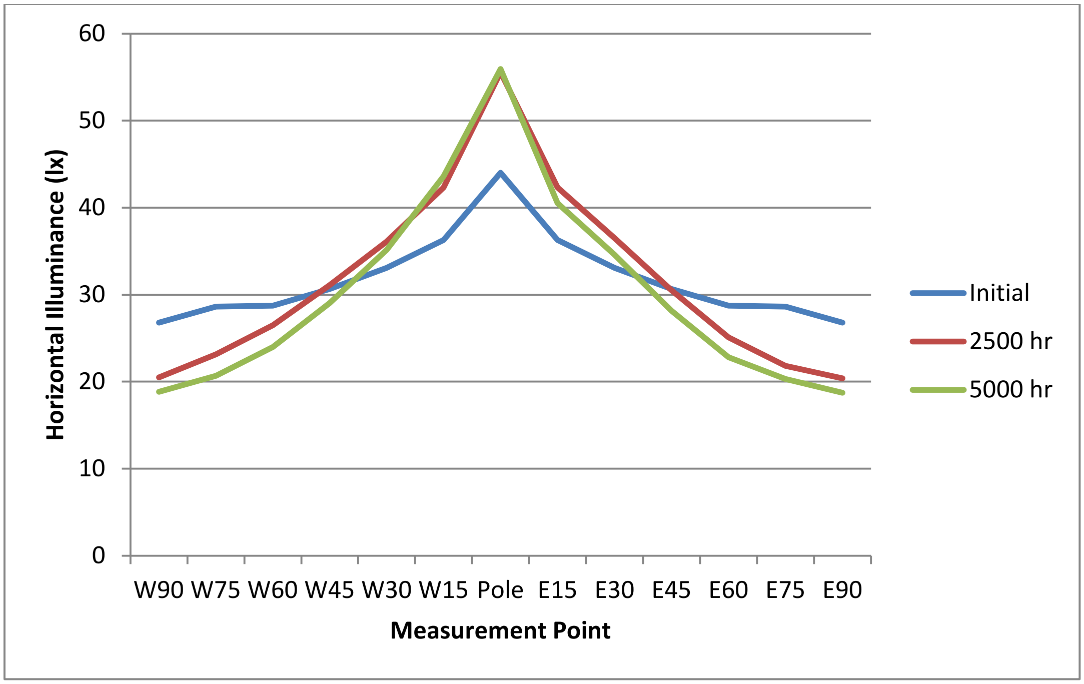

Figure 10. Measured Illuminances along East-West Line Centered at Pole 204 at Three Different Measurement Times. Illuminance values increased near the pole compared to the initial values, but decreased farther away from the pole. The numeric values in the labels along the horizontal axis indicate the distance from the pole in feet, and the letter indicates the direction from the pole. Illuminance values were normalized for a 25 °C (77 °F) condition.

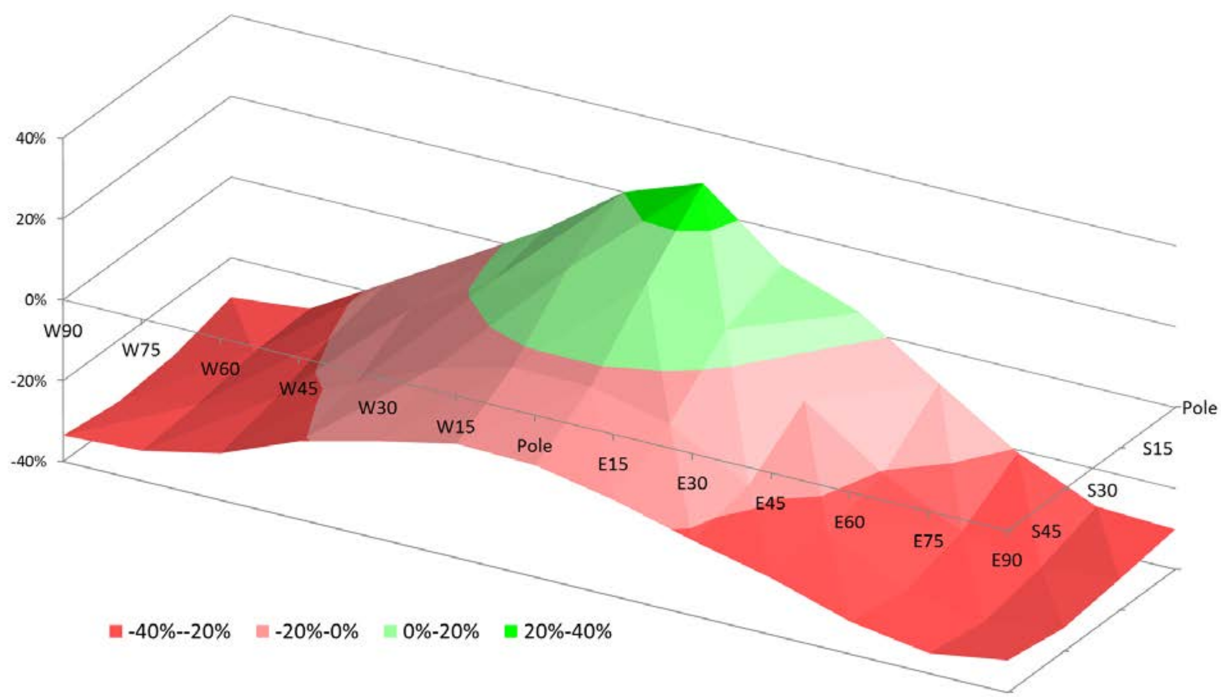

Figure 11. Relative Change in Illuminance between Initial and 5000 Hour Measurements. Green indicates areas where the illuminance increased and red indicates areas where the illuminance decreased. A uniform decrease in illuminance would appear as a flat plane below the 0% plane; the shape of this graph shows that the distribution of illuminance has changed. The numeric values in the labels along the horizontal axes indicate the distance from the pole in feet, and the letter indicates the direction from the pole. The primary fence at the U.S.-Mexico border stands just south of the measurement line shown as S45.

Table 4 summarizes the horizontal and vertical illuminances of five different areas within the primary and secondary fences for the initial, 2500, and 5000 hour measurements, and shows the overall changes summarized in the first three bullets above.

Table 4. LED Lighting System Horizontal and Vertical Illuminance Values. The table summarizes the measured illuminance values for six different areas within the primary and secondary fences. The horizontal measurements were recorded approximately 9.5 in. above the ground and the vertical measurements were recorded at 4 and 8 ft above the ground along the fences. Values shown were normalized for a 25 °C (77 °F) condition.

Area	Hours	Avg (lx)	Max (lx)	Min (lx)	Max/Min Ratio	Avg/Min Ratio
Secondary Fence (Vertical)	Initial	5.6	7.4	4.2	1.8	1.3
	2500	5.8	7.8	4.4	1.8	1.3
	5000	5.7	8.6	4.1	2.1	1.4
3 Rows Closest to Secondary Fence (Horizontal)	Initial	8.1	14.9	3.7	4.1	2.2
	2500	7.3	15.5	2.5	6.1	2.9
	5000	7.2	15.5	3.1	5.0	2.3
All (Horizontal)	Initial	21.3	44.0	3.7	12.0	5.8
	2500	19.5	55.6	2.5	21.8	7.6
	5000	18.7	55.9	3.1	18.0	6.0
3 Rows Closest to Primary Fence (Horizontal)	Initial	27.6	40.2	20.4	2.0	1.4
	2500	23.4	46.8	12.9	3.6	1.8
	5000	22.5	45.4	13.9	3.3	1.6
Primary Fence (Vertical)	Initial	28.3	35.6	20.7	1.7	1.4
	2500	21.3	29.9	13.7	2.2	1.6
	5000	21.2	30.6	13.5	2.3	1.6

4.2 Illuminance Measurement Change: Initial and 2500 Hours

The change in distribution between the initial and the 2500 hour illuminance measurements is illustrated in Figure 12. Values in black indicate an increase in the 2500 hour illuminance relative to the initial measured illuminance, while values in red indicate a relative decrease. The decrease is greater toward the primary fence, and the decrease in the horizontal illuminance along the primary fence is comparable to that of the primary fence vertical measurements. The greatest change is in the southeast corner, with a relative decrease in illuminance ranging from 0.34 to 0.41. In contrast, illuminance increased near the pole, with a relative increase between 0.12 and 0.17 immediately surrounding the pole.

There was some decrease in illuminance near the secondary fence, but the magnitude of relative change was less than near the primary fence. Nearly all vertical illuminance measurements on the secondary fence increased, but the relative change was less than 0.08. The illuminance values on or near the secondary fence were lower—as designed—so the relative change may be due to a minor difference in illuminance, or minor measurement error, or a combination of both. For example, the 0.11 relative change of the horizontal measurement point along the secondary fence directly behind the pole was the result of a decrease from the initial measurement of 4.4 to 4.0 lx. Although this is an 11% change, the absolute change of 0.4 lx could be explained by the illuminance meter measurement tolerances. A similar relative change of 0.15 for the horizontal measurement closest to the primary fence directly in front of the pole was the result of a decrease from the initial measurement of 23.7 to 20.2 lx, a much larger absolute change that is greater than any variation explained by meter tolerances.

		W90	W75	W60	W45	W30	W15	Pole	E15	E30	E45	E60	E75	E90
Vertical	8 ft	0.05	0.07	0.05	0.07	0.07	0.05	0.07	0.05	0.05	0.05	0.05	0.03	0.01
	4 ft	0.05	0.05	0.05	0.07	0.07	0.06	0.05	0.06	0.05	0.05	0.03	0.01	0.02
		Secondary Fence												
Horizontal	N75							0.11	0.07	0.02	0.07	0.10	0.11	0.08
	N60							0.05	0.01	0.03	0.02	0.07	0.12	0.15
	N45							0.01	0.05	0.02	0.04	0.10	0.14	0.19
	N30							0.07	0.10	0.08	0.00	0.10	0.16	0.19
	N15							0.12	0.15	0.12	0.04	0.10	0.19	0.21
	Pole	0.24	0.19	0.08	0.01	0.09	0.17	0.26	0.17	0.10	0.01	0.13	0.24	0.24
	S15	0.29	0.20	0.11	0.00	0.10	0.15	0.16	0.14	0.03	0.13	0.27	0.33	0.29
	S30	0.33	0.25	0.16	0.07	0.01	0.05	0.06	0.01	0.14	0.25	0.37	0.39	0.34
	S45	0.31	0.28	0.25	0.20	0.16	0.15	0.15	0.20	0.26	0.32	0.40	0.41	0.36
		Primary Fence												
Vertical	4 ft	0.32	0.27	0.26	0.25	0.20	0.15	0.14	0.17	0.23	0.24	0.35	0.37	0.34
	8 ft	0.30	0.27	0.13	0.20	0.20	0.17	0.16	0.19	0.22	0.35	0.40	0.38	0.34
		W90	W75	W60	W45	W30	W15	Pole	E15	E30	E45	E60	E75	E90

Figure 12. Illustration of Illuminance Measurement Relative Change: Initial to 2500 Hours. The relative change for each measurement point was calculated by dividing the difference between the initial and 2500 hour measurements by the initial measured illuminance. The red numbers indicates a negative relative change (initial greater than 2500) and the black numbers indicate a positive relative change (2500 greater than initial). The shade of gray indicates the magnitude and direction of the change: Light Gray = higher value than initial; Dark Gray = lower value than initial. The northwest corner is blank in this figure because those data were not measured during the initial measurements.

4.3 Illuminance Measurement Change: 2500 and 5000 Hours

The relatively minor changes in illuminance between 2500 hours and 5000 hours are shown in Figure 13. Some rectification occurred in the southeast corner, which had initially seen the greatest relative change between the initial and 2500 hour measurements. There was also a positive relative change along the center line between the pole and secondary fence. The decrease in illuminance between 2500 and 5000 hours was more uniform than it was between the initial and 2500 hour measurements, although the points farther from the pole generally continued to have a higher negative relative change compared with points closer to the pole. The measurement point farthest from the pole in the northwest corner had the highest relative change at 0.22. This is plausible due to the general illuminance increase in the northwest corner, and it is also important to note that although this is the highest relative change, it is a small absolute change of just 0.6 lx.

		W90	W75	W60	W45	W30	W15	Pole	E15	E30	E45	E60	E75	E90
Vertical	8 ft	0.07	0.07	0.05	0.05	0.03	0.02	0.03	0.02	0.02	0.03	0.03	0.05	0.03
Vertical	4 ft	0.03	0.03	0.01	0.01	0.00	0.01	0.10	0.02	0.01	0.02	0.01	0.01	0.01
Secondary Fence														
Horizontal	N75	0.22	0.16	0.01	0.01	0.02	0.02	0.07	0.02	0.00	0.00	0.04	0.01	0.05
Horizontal	N60	0.06	0.07	0.01	0.03	0.01	0.01	0.07	0.03	0.02	0.03	0.05	0.05	0.08
Horizontal	N45	0.01	0.05	0.05	0.03	0.03	0.02	0.06	0.00	0.01	0.05	0.07	0.14	0.14
Horizontal	N30	0.08	0.11	0.10	0.03	0.02	0.01	0.03	0.01	0.03	0.06	0.10	0.13	0.15
Horizontal	N15	0.09	0.13	0.09	0.05	0.02	0.00	0.02	0.02	0.05	0.08	0.10	0.10	0.12
Horizontal	Pole	0.08	0.11	0.10	0.07	0.03	0.03	0.01	0.04	0.05	0.08	0.09	0.07	0.08
Horizontal	S15	0.07	0.11	0.10	0.08	0.06	0.03	0.03	0.08	0.10	0.09	0.04	0.02	0.05
Horizontal	S30	0.04	0.08	0.10	0.10	0.09	0.07	0.09	0.07	0.05	0.00	0.04	0.03	0.01
Horizontal	S45	0.04	0.06	0.05	0.01	0.00	0.03	0.03	0.05	0.06	0.09	0.13	0.10	0.05
Primary Fence														
Vertical	4 ft	0.01	0.07	0.18	0.06	0.01	0.00	0.04	0.03	0.10	0.02	0.07	0.06	0.04
Vertical	8 ft	0.07	0.06	0.23	0.10	0.02	0.03	0.02	0.04	0.01	0.06	0.10	0.08	0.02
		W90	W75	W60	W45	W30	W15	Pole	E15	E30	E45	E60	E75	E90

Figure 13. Illustration of Illuminance Measurement Relative Change: 2500 to 5000 Hours. The relative change for each measurement point was calculated by dividing the difference between the 2500 and 5000 hour measurements by the 2500 hour measured illuminance. The red numbers indicates a negative relative change (2500 greater than 5000) and the black numbers indicate a positive relative change (5000 greater than 2500). The shade of gray indicates the magnitude and direction of the change: Light Gray = higher value than at 2500 hours; Dark Gray = lower value than at 2500 hours.

The overall changes in illuminances and distribution between the initial measurements and 5000 hour measurements are discussed above, and all the data points are shown in Figure 14. Even with some rectification in the southeast corner occurring between 2500 and 5000 hours, the general trend of luminous flux exiting the luminaire decreasing away from the pole and increasing close to the pole remained—very similar to the relative changes between the initial and 2500 hour measurements.

		W90	W75	W60	W45	W30	W15	Pole	E15	E30	E45	E60	E75	E90
Vertical	8 ft	0.02	0.00	0.00	0.02	0.04	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02
Vertical	4 ft	0.02	0.02	0.04	0.05	0.06	0.06	0.16	0.04	0.04	0.03	0.02	0.00	0.03
								Secondary Fence						
Horizontal	N75							0.04	0.04	0.02	0.07	0.07	0.10	0.13
Horizontal	N60							0.02	0.02	0.01	0.05	0.11	0.16	0.22
Horizontal	N45							0.04	0.04	0.00	0.09	0.16	0.26	0.30
Horizontal	N30							0.10	0.09	0.04	0.06	0.19	0.27	0.31
Horizontal	N15							0.14	0.14	0.06	0.05	0.19	0.28	0.31
Horizontal	Pole	0.30	0.28	0.17	0.05	0.06	0.20	0.27	0.12	0.04	0.08	0.21	0.29	0.30
Horizontal	S15	0.34	0.28	0.20	0.08	0.03	0.11	0.13	0.06	0.07	0.20	0.30	0.34	0.32
Horizontal	S30	0.35	0.31	0.25	0.17	0.08	0.03	0.03	0.08	0.18	0.25	0.35	0.37	0.34
Horizontal	S45	0.34	0.33	0.28	0.21	0.16	0.12	0.12	0.16	0.21	0.26	0.32	0.35	0.32
								Primary Fence						
Vertical	4 ft	0.33	0.32	0.40	0.29	0.19	0.15	0.10	0.15	0.16	0.25	0.31	0.33	0.32
Vertical	8 ft	0.35	0.32	0.33	0.28	0.18	0.14	0.14	0.16	0.23	0.31	0.34	0.33	0.33
		W90	W75	W60	W45	W30	W15	Pole	E15	E30	E45	E60	E75	E90

Figure 14. Illustration of Illuminance Measurement Relative Change: Initial to 5000 Hours. The relative change for each measurement point was calculated by dividing the difference between the initial and 5000 hour measurements by the initial measured illuminance. The red numbers indicates a negative relative change (initial greater than 5000) and the black numbers indicate a positive relative change (5000 greater than initial). The shade of gray indicates the magnitude and direction of the change: Light Gray = higher value than initial; Dark Gray = lower value than initial. The relative comparison between initial and 5000 hours does not require temperature correction due to similar ambient temperature. The northwest corner is blank in this figure because those data were not measured during the initial measurements.

5. Discussion

The magnitude of the overall reductions in illuminance and the apparent change in the distribution of light at the Yuma Sector Border Patrol Area trial demonstration site within the first 5000 hours of operation were unexpected, based on prior experiences with LED exterior lighting systems. The field measurements after 2500 and 5000 hours document the overall effects at the site, but they do not provide specific insights into the causes. Research that seeks to identify and quantify the causes is ongoing; for this report the possible causes are described in this section.

The Yuma site is an extreme environment, which is one of the reasons that the DOE chose to study this installation. The luminaires in Yuma rarely get a break from the heat: high ambient temperatures and direct solar radiation heat up the luminaires throughout the day, and at sunset the LED luminaires turn on and generate internal heat just as the solar radiation stops and the ambient temperature begins to decrease. For a typical year, as determined from Typical Meteorological Year 2 (TMY2) data sets,[8] the maximum temperature at sunset in this area is approximately 38 to 44 °C (101 to 112 °F) and the minimum is approximately 2 to 6 °C (36 to 43 °F).[9] The average nighttime temperature is 17 to 20 °C (63 to 68 °F). The high nighttime temperatures combined with some of the highest levels of solar radiation in the United States, as illustrated in Figure 15, result in a challenging environment for LED luminaires.

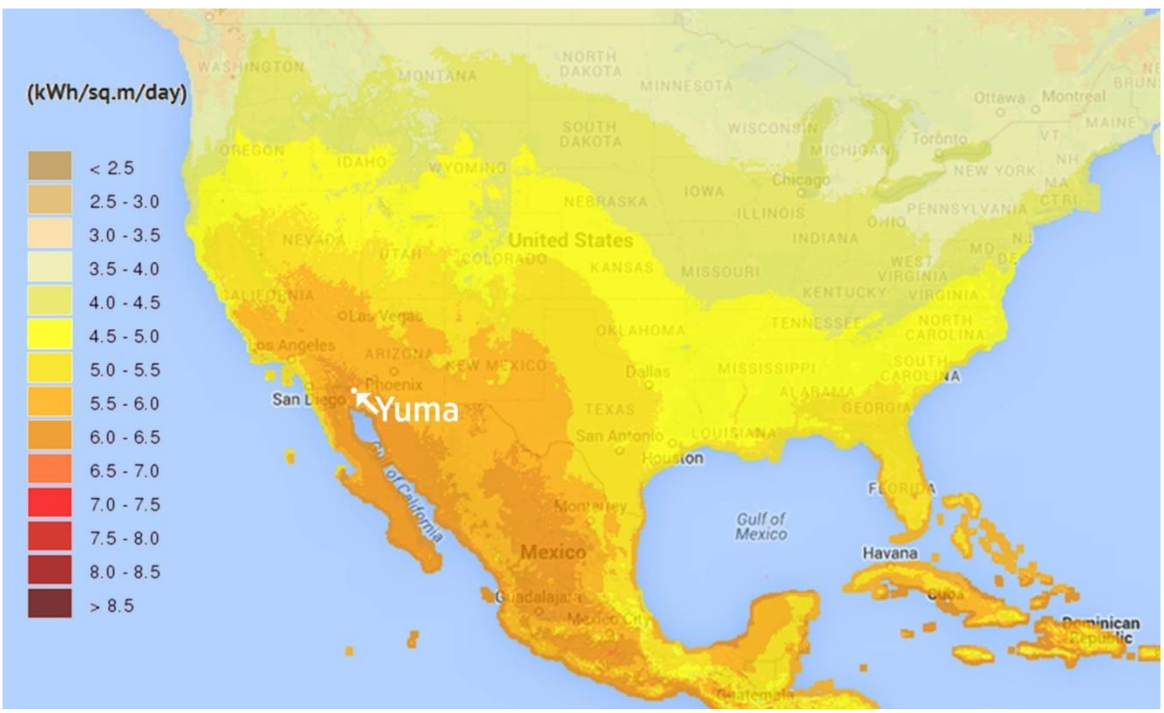

Figure 15. Average Annual Global Horizontal Irradiance (GHI) Grid (Source: National Renewable Energy Laboratory National Solar Radiation Data Base Data Viewer (mapsbeta.nrel.gov/nsrdb-data-viewer/). GHI includes both diffuse and direct irradiance for a horizontal collector.

8 U.S. Department of Energy. National Solar Radiation Data Base. Produced by the National Renewable Energy Laboratory. http://rredc.nrel.gov/solar/old_data/nsrdb/1961-1990/tmy2/.

9 A TMY2 data set was not available for Yuma, so the ranges reflect data from Phoenix and Tucson, AZ.

A few details illustrate the extreme thermal environment at the Yuma installation. Between the initial measurements in February 2014 and the 2500 hour measurements in September 2014, the daily high temperature exceeded 37.8 °C (100 °F) on 116 days. From May 25 to August 1, 2014, the daily high temperature exceeded 37.8 °C (100 °F) every day, with an average daily high temperature during those 68 days of 41.9 °C (107 °F) and an overall maximum temperature of 47.2 °C (117 °F). Of the 114 days from May 26 to September 16, 2014 (the 2500 hour measurement date), there were only 6 days where the maximum temperature was less than 37.8 °C (100 °F). These data show that the first 2500 hours of operation of the LED installation occurred during the extreme thermal season at Yuma. In contrast, there were only 12 days above 37.8 °C (100 °F) between the 2500 and 5000 hour measurements.

The weather conditions during the measurements are summarized in Table 5. During the 2500 hour measurements, the temperature varied between 30.6 and 32.8 °C (87 and 91 °F). During the 5000 hour measurements the temperature varied between 13.3 and 15.6 °C (56 and 60 °F), similar to the initial measurements, which varied between 12.8 and 13.3 °C (55 and 56 °F).

Table 5. Summary of Weather Conditions during Initial, 2500 Hour, and 5000 Hour Measurements. The table summarizes the measurement weather conditions, as recorded by Yuma Marine Corps Air Station[10] about 15 miles north of the installed luminaires. Temperature and humidity were also recorded at the site during the measurements using a non-calibrated meter, with similar results. There was no rain during any of the measurements.

Nominal Operating Hours	Temperature and Humidity	Moon Phase, Percent Moon Illuminated	Civil Twilight Set and Rise[a]	Time of Measure
Initial 2/5/2014	12.8 to 13.3 °C (55 to 56 °F); 55% to 64%	Waxing Crescent, 40% Illuminated[b]	Set 6:39 p.m. (2/4); Rise 7:04 a.m. (2/5)	4:30 a.m. to 6:50 a.m.
2500 9/16-17/2014	30.6 to 32.8 °C (87 to 91 °F); 38% to 48%	Waning Crescent, 34% Illuminated[c]	Set 7:07 p.m. (9/16); Rise 5:58 a.m. (9/17)	9:45 p.m. to 1:30 a.m.
5000 3/3/2015	13 to 16 °C (56 to 60 °F); 51% to 64%	Waxing Gibbous, 97% Illuminated	Set 7:01 p.m. (3/3); Rise 6:38 a.m. (3/4)	8:15 p.m. to 11:00 p.m.

[a] Civil twilight occurs when the sun is 6° below the horizon.
[b] Moon was not up during measurements.
[c] Moon rose at end of the horizontal measurements, before vertical measurements.

The extreme conditions in Yuma may have accelerated normal causes of light output reductions such as dirt depreciation and LED depreciation, and/or may have created unique causes such as changes in the LED lenses and drivers. Although the research to date has not studied the specific causes at Yuma, a number of potential causes are discussed in the following sections.

5.1 Dirt Depreciation

Depreciation in light output due to the accumulation of dirt on luminaire surfaces is a well-known effect, and is accounted for in lighting calculations through the light loss factor called luminaire dirt depreciation (LDD). The LDD factor is expressed as the percentage of light that will be maintained by a lighting system, given certain

[10] Wunderground Historical Weather: http://www.wunderground.com/history/.

assumptions about the amount of time the luminaire has been exposed to the environment, the operating environmental conditions, and the type of luminaire. Although the LDD estimation methods described in the IES Handbook[11] focus on interior lighting, the same principles are incorporated into the IES Recommended Practice for Roadway Lighting.[12]

Using the IES formula, the estimated LDD factor after 7 months (the 2500 hour data) is 95% for a clean environment and 82% for a dirty environment, and the LDD factor for 13 months (the 5000 hour data) is 93% for a clean environment and 72% for a dirty environment. Yuma's arid climate argues against using the IES dirty condition, which assumes a high degree of adhesion (as might be common in a humid environment, for example). Further, a prior GATEWAY study of streetlighting on the I35W bridge in Minneapolis, MN, found that an estimate based on the IES clean condition most closely matched the measured LDD data.[13] So while dirt depreciation may explain some of the overall reduction in illuminance, it does not seem to fully account for the measured data.

In addition to an overall reduction in light output, dirt accumulation on luminaires also tends to alter the light distribution by making it more diffuse. For optics such as those common to exterior luminaires that spread the light over large areas by delivering high intensity at high angles, this diffusion tends to increase the luminous intensity at low angles (close to nadir) and decrease the intensity at high angles. For example, Figure 16 shows the effect of dirt accumulation on the luminous intensity distribution from a luminaire tested in its dirty and clean conditions as part of a prior GATEWAY study. A change in distribution of this nature was also observed at the Yuma installation, where the illuminances increased at measurement points close to the pole and decreased farther away from the pole. Consequently, PNNL researchers believe that dirt accumulation on the LED luminaires at least partly explains the illuminance changes measured at the installation.

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[11] DiLaura et al. IES 10th Edition Lighting Handbook, pp. 10.28-10.30.
[12] Illuminating Engineering Society. ANSI/IES RP-8-14: Roadway Lighting, p. 35.
[13] For further information download the Long-term Testing Results for the 2008 Installation of LED Luminaires at the I-35 West Bridge in Minneapolis report developed by the DOE SSL Program: http://www1.eere.energy.gov/buildings/ssl/pdfs/gateway_i-35w_phaseII.pdf.

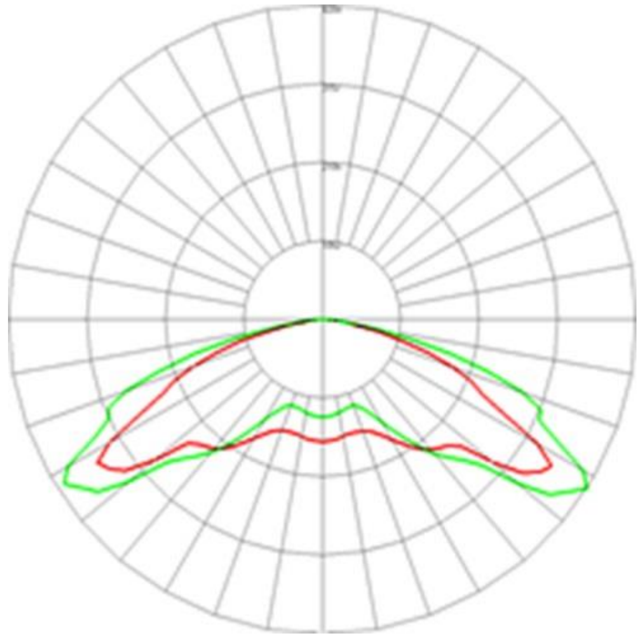

Figure 16. Distribution Effects of Dirt for an LED Streetlight Luminaire from the I-35W Bridge. The red plot shows the luminous intensity distribution from the “as is” or dirty luminaire prior to cleaning, and the green plot shows the distribution from the same luminaire after cleaning. For further information, download the Long-term Testing Results for the 2008 Installation of LED Luminaires at the I-35W Bridge in Minneapolis report developed by the DOE SSL Program: http://www1.eere.energy.gov/buildings/ssl/pdfs/gateway_i-35w_phaseII.pdf.

5.2 LED Depreciation

The LED luminaire manufacturer claims 90% lumen maintenance at greater than 60,000 hours for the luminaires used at the Yuma site. Based on LM-80 data reviewed by DOE, the light output from the LEDs used in the luminaires would be expected to provide slightly higher output after 5000 operating hours than their initial output, even at a case temperature of 105 °C (221 °F). Normal LED lumen depreciation was therefore not expected to be a major factor for this installation, even with the extreme environmental conditions. What is not known is whether the exposure to high ambient temperatures and direct solar radiation during the “off” cycles may cause some damage to the luminaire that results in LED lumen depreciation when operating. Further investigation of the luminaires used is needed to explore this possibility.

Because each LED package in the luminaires has the same secondary optic, LED lumen depreciation would not explain the change in the distribution of light found through the measured illuminance values. As a result, even if some accelerated LED depreciation may be occurring, it does not fully explain the results. However, any change in light distribution at the package level could contribute to the measured changes in illuminance. Data on this potential change is limited and monitoring change in luminous flux distribution is not currently included in LM-80 testing, which only tracks light output and color characteristics over time.

5.3 Changes in Lens Material

A previous study[14] prepared for DOE found that the absorptance of polycarbonate materials can increase over time; however, acrylates did not change. The luminaire manufacturer verified that, as shown in the patents for their optical system, the material used for the lenses in the LED luminaires at Yuma was acrylic. There is no

[14] Hammer Testing Findings for Solid-State Lighting Luminaires: apps1.eere.energy.gov/buildings/publications/pdfs/ssl/hammer-testing_Dec2013.pdf.

evidence that the material would change in absorptance due to the extreme thermal environment, and no color shift was measured between 2500 and 5000 hours of operation. The luminaire manufacturer stated that, in their testing, there was no deformation of the acrylic lens material during thermal testing at an ambient temperature of 50 °C (122 °F). However, if the extreme conditions at Yuma caused any change in positioning of the lenses or any deformation of the lens material, the light distribution from the luminaires would be altered. Since the measured data at Yuma showed both an overall decrease in illuminance and a change in the distribution of light, changes in the lenses used cannot be ruled out as a potential cause, and will be investigated further as the project progresses.

Another possible cause for the types of changes noted at Yuma is an increase in the diffusion of the lenses. As discussed previously, dirt accumulation can temporarily create this effect, but the original condition can be restored through cleaning. However, if the lenses were permanently etched, for example by windblown sand, the diffusion of light may increase in a manner consistent with the measured results. Hazing of the optic from exposure to heat or ultraviolet rays would similarly cause diffusion. Further investigation is planned to assess these possible causes.

5.4 Driver Changes

A potential reason for changes in LED luminaire light output is variations in the drivers, perhaps caused by the environmental conditions at the site. Product literature for the luminaires indicates a maximum recommended ambient temperature of 40 °C (104 °F), with an optional high ambient 50 °C (122 °F) configuration available; the high ambient option was used in the LED luminaires installed in Yuma. The temperature data for Yuma shows that the ambient temperatures measured during the times of the illuminance measurements were well under 40 °C (104 °F), and the daytime temperatures (when the luminaires were off) reached 47.2 °C (117 °F), approaching the limits of the high ambient recommended maximum temperature.

If the luminaires operated during these high daytime temperatures, they would be subject to thermal stresses that are at the limits of the recommended operating conditions. The operation of the photocontrols is checked monthly by covering the photocontrols for a brief time during the day and verifying that the connected luminaires turn on, so the LED luminaires do operate once each month for short periods of time during the day. If these conditions damaged a driver, reductions in light output for the LED board or boards controlled by that driver or even complete failure of the driver could result, which would be noticeable in the field. These effects were not observed during the measurements. Furthermore, changes in the LED drivers alone would not explain the distribution changes in the measured illuminances reported. While driver performance in extreme environmental conditions is a concern, it seems unlikely to be a major contributing cause for the effects documented at the Yuma project.

5.5 Measurement Error

There are several sources of potential measurement error, including the illuminance meters and measurement methodology. A calibrated Konica Minolta T-10A illuminance meter was used for both the 2500 hour and 5000 hour illuminance measurements, while a calibrated Konica Minolta T-1 illuminance meter was used for the initial measurements. Spot measurements were taken during the 5000 hour measurements with both the T-1 and T-10A producing similar results, and since both meters were in calibration during the testing, a systematic error is not likely. The meters were received from a NVLAP (National Voluntary Laboratory Accreditation Program) accredited calibration laboratory and have rated accuracy of 2% ± 1 digit, and the temperatures at the site during measurements were within the rated temperature range. Both meters have the same rated cosine correction characteristics. Overall, while the tolerances of the meters introduce a small degree of variation, the magnitude of the differences reported far exceeds those tolerances.

In terms of the measurement methods, a possible source of error is variation in the location of the measurement points. To minimize this error, the 15 ft grid spacing distances were marked with paint on the primary and secondary fences (and the underlying supporting concrete) during the initial measurements; those markings were still visible during the 5000 hour measurements and they were repainted then for future use. The other reference points used for establishing the measurement grid were the south faces of the concrete pedestals for each of the three poles supporting the LED luminaires. Because the measurement grid was thus anchored to permanent structures at the site, any differences in measured illuminances due to slight discrepancies in measurement point locations are likely to be minor, especially given the overall uniformity of the illuminance produce by the LED system.

Another possible source of error is the height of the measurement grid. Unlike typical street and parking lot lighting analyses, the Yuma measurements were taken on sand, so there is some chance that the vertical distance of the measurement points from the luminaires changed over the time between measurements. Because the primary fence is supported by a concrete base, any significant changes in the height of the sand would have been apparent to the researchers, and nothing unusual was noticed. Even if the height changed by 6 in. at a typical point, the illuminance would vary by less than 2%. Furthermore, any variations over time in the height of the measurement points would not produce the types of variations found in the distribution pattern of illuminance.

5.6 Orientation of Luminaires

Any changes in the orientation or aiming of the luminaires after installation would cause changes in the measured illuminances at the site. Although such changes are highly unlikely, DOE researchers noted that the "hot spots" of high illuminance produced by the HID luminaires noticeably moved during the data collection site visits, due to wind moving the tops of the 64 ft HID poles. Furthermore, the contractor who reduced the height of the three poles to 40 ft for the trial LED installation noted that the upper portions of the poles were bent from exposure to wind. Based on these observations, changes in the luminaire orientation caused by the environment are possible. However, the tapered poles have larger diameter at the 40 ft height, the wind forces are less at that height, and the custom tenon that holds the LED luminaires was designed for the anticipated environmental conditions. Furthermore, the pattern of the measured illuminances does not indicate a systematic change in any particular direction such as would be expected from a change in luminaire orientation or from any movement of the luminaires due to wind.

5.7 Electrical Changes

Light output from LED luminaires can be affected by variations in the electrical input to the luminaires. These variations would affect the light output from the luminaires uniformly, and would not produce the types of distribution changes observed at Yuma. The electrical distribution for the luminaires at Yuma operates on dedicated circuits so that other equipment does not affect them. Although electrical input has not been monitored during the site measurements, electrical variations are unlikely to be a cause of the observed change in distribution.

6. Conclusions

The Yuma Sector Border Patrol Area lighting LED trial demonstration was documented to better understand LED technology performance in a high ambient temperature and high solar radiation environment. The initial trial installation was intended as a short-term test of six luminaires installed on three poles before proceeding with the complete installation of over 400 luminaires. Unexpected delays in the full installation have prevented the detailed evaluations initially planned, but ongoing tracking of the performance of the installation provides useful insights. Measured data at the project site after nominally 2500 hours and 5000 hours indicate that the illuminances are changing more rapidly than anticipated. As described in this report, the most likely causes for these observed changes are dirt accumulation combined with possible changes to the luminaire optical elements such as lenses. Other causes are possible, but seem less probable based on the measurements.

A full understanding of the causes for the observed changes depends on understanding the effects of the ambient thermal conditions on the internal operation of the luminaire. The original plan for studying the complete installation included having several luminaires installed with internal thermocouples to enable ongoing monitoring. Since the full installation has been delayed and the study remains limited to the initial installation of six LED luminaires, DOE researchers are exploring plans for thermal simulations of the luminaire as well as removal of one or more of the six luminaires from the site for detailed laboratory analysis. DOE also plans to collect additional data from the site to more fully assess possible effects of dirt accumulation and other site-specific effects. Future reports are planned to address these topics.

Appendix A: Illuminance Measurements Without Temperature Correction

	W90	W75	W60	W45	W30	W15	Pole	E15	E30	E45	E60	E75	E90	LED Initial (lx)	
8 ft	4.3	4.3	4.6	5.0	5.7	6.5	6.7	6.7	6.1	5.2	4.6	4.6	4.8	5.7 Avg	Secondary Fence (Vertical)
4 ft	4.7	4.8	5.1	5.7	6.7	7.4	7.7	7.6	7.1	6.2	5.7	5.6	5.9	7.7 Max	
	Secondary Fence													4.3 Min	
N75	3.8	3.9	4.0	4.1	4.2	4.4	4.6	4.4	4.2	4.1	4.0	3.9	3.8	8.4 Avg	3 Rows Closest to Secondary Fence (Horizontal)
N60	6.7	6.7	6.9	7.0	7.4	7.9	8.1	7.9	7.4	7.0	6.9	6.7	6.7	15.4 Max	
N45	13.5	13.5	13.0	13.3	14.1	15.2	15.4	15.2	14.1	13.3	13.0	13.5	13.5	3.8 Min	
N30	20.0	21.4	22.7	22.7	24.6	26.3	26.3	26.3	24.6	22.7	22.7	21.4	20.0	22.0 Avg	All (Horizontal)
N15	25.9	26.7	27.6	28.1	33.8	40.1	42.1	40.1	33.8	28.1	27.6	26.7	25.9	45.5 Max	
Pole	27.7	29.6	29.7	31.7	34.2	37.5	45.5	37.5	34.2	31.7	29.7	29.6	27.7	3.8 Min	
S15	28.0	28.6	29.6	30.7	34.6	39.0	41.6	39.3	36.5	33.3	32.7	30.8	28.3	28.5 Avg	3 Rows Closest to Primary Fence (Horizontal)
S30	27.1	27.7	27.9	27.9	28.8	30.2	30.2	30.7	30.7	29.1	30.8	29.9	27.3	41.6 Max	
S45	23.1	23.8	22.3	22.0	23.5	24.0	24.5	24.9	24.0	22.5	23.0	22.7	21.1	21.1 Min	
	Primary Fence													29.3 Avg	Primary Fence (Vertical)
4 ft	25.0	26.3	28.0	29.2	30.8	33.1	31.8	32.2	30.3	26.7	28.4	26.1	24.2	36.8 Max	
8 ft	21.4	23.6	27.8	32.5	33.7	36.5	36.8	36.5	34.5	32.0	28.8	23.4	21.5	21.4 Min	
	W90	W75	W60	W45	W30	W15	Pole	E15	E30	E45	E60	E75	E90		

Initial Illuminance Measurements Recorded in February 2014—No Temperature Correction.

	W90	W75	W60	W45	W30	W15	Pole	E15	E30	E45	E60	E75	E90	LED 2500 hr (lx)	
8 ft	4.3	4.5	4.7	5.2	5.9	6.6	6.9	6.8	6.2	5.3	4.7	4.6	4.7	5.8 Avg	Secondary Fence (Vertical)
4 ft	4.8	4.9	5.2	5.9	6.9	7.6	7.8	7.8	7.2	6.3	5.7	5.5	5.6	7.8 Max	
	Secondary Fence													4.3 Min	
N75	2.5	2.7	3.1	3.4	3.9	4.1	3.9	3.9	3.9	3.6	3.4	3.3	3.3	7.2 Avg	3 Rows Closest to Secondary Fence (Horizontal)
N60	4.4	4.7	5.3	6.1	6.7	7.8	7.3	7.4	6.8	6.5	6.1	5.6	5.4	15.2 Max	
N45	8.5	9.0	9.8	11.3	13.5	15.2	14.4	15.1	13.6	12.1	11.1	11.0	10.4	2.5 Min	
N30	15.0	16.3	18.0	19.6	23.9	26.7	26.8	27.5	25.1	21.5	19.3	17.0	15.4	19.1 Avg	All (Horizontal)
N15	18.8	20.8	22.6	27.3	35.2	42.7	44.9	43.9	35.8	27.6	23.6	20.5	19.3	54.5 Max	
Pole	20.1	22.7	26.0	30.5	35.4	41.5	54.5	41.5	35.8	29.9	24.6	21.4	20.0	2.5 Min	
S15	18.9	21.8	25.1	29.2	36.0	42.5	45.9	42.6	35.6	27.6	22.5	19.7	19.1	23.0 Avg	3 Rows Closest to Primary Fence (Horizontal)
S30	17.3	19.6	22.2	24.6	27.7	30.0	30.5	28.8	25.1	20.7	18.4	17.2	17.2	45.9 Max	
S45	15.2	16.2	15.9	16.8	18.8	19.4	19.8	18.9	16.8	14.5	13.1	12.7	12.9	12.7 Min	
	Primary Fence													21.0 Avg	Primary Fence (Vertical)
4 ft	16.1	18.4	19.7	20.9	23.5	26.9	26.1	25.3	22.1	19.4	17.5	15.7	15.1	29.4 Max	
8 ft	14.2	16.3	23.1	24.8	25.8	28.8	29.4	28.0	25.7	19.7	16.4	13.8	13.5	13.5 Min	
	W90	W75	W60	W45	W30	W15	Pole	E15	E30	E45	E60	E75	E90		

2500 Hour Illuminance Measurements Recorded in September 2014—No Temperature Correction.

	W90	W75	W60	W45	W30	W15	Pole	E15	E30	E45	E60	E75	E90	LED 5000 hr (lx)	
8 ft	4.2	4.3	4.6	5.1	5.9	6.7	6.9	6.9	6.3	5.3	4.7	4.5	4.7	5.9 Avg	Secondary Fence (Vertical)
4 ft	4.8	4.9	5.3	6.0	7.1	7.8	8.9	7.9	7.4	6.4	5.8	5.6	5.7	8.9 Max	
	Secondary Fence													4.2 Min	
N75	3.2	3.3	3.3	3.6	4.0	4.4	4.4	4.2	4.1	3.8	3.7	3.5	3.3	7.4 Avg	3 Rows Closest to Secondary Fence (Horizontal)
N60	4.9	5.3	5.5	6.2	7.1	8.1	8.2	8.0	7.3	6.6	6.1	5.6	5.2	16.0 Max	
N45	9.0	9.0	9.8	11.5	13.7	15.7	16.0	15.8	14.1	12.1	10.9	10.0	9.4	3.2 Min	
N30	14.5	15.2	17.1	19.9	24.7	27.9	28.9	28.6	25.5	21.2	18.3	15.6	13.8	19.2 Avg	All (Horizontal)
N15	17.9	19.0	21.5	27.4	36.1	44.9	47.9	45.4	35.7	26.7	22.4	19.3	17.9	57.6 Max	
Pole	19.4	21.3	24.7	29.9	36.2	44.9	57.6	41.7	35.6	29.0	23.5	20.9	19.3	3.2 Min	
S15	18.5	20.4	23.7	28.2	35.5	43.3	46.7	41.4	33.8	26.4	22.8	20.2	19.1	23.2 Avg	3 Rows Closest to Primary Fence (Horizontal)
S30	17.5	19.0	20.9	23.2	26.4	29.2	29.2	28.3	25.1	21.8	20.1	18.7	17.9	46.7 Max	
S45	15.3	16.0	15.9	17.4	19.7	21.1	21.4	20.8	18.8	16.6	15.6	14.7	14.3	14.3 Min	
	Primary Fence													21.9 Avg	Primary Fence (Vertical)
4 ft	16.7	17.9	16.9	20.6	24.9	28.1	28.5	27.4	25.4	19.9	19.7	17.5	16.4	31.6 Max	
8 ft	13.9	16.0	18.6	23.3	27.6	31.2	31.6	30.6	26.6	22.0	18.9	15.7	14.4	13.9 Min	
	W90	W75	W60	W45	W30	W15	Pole	E15	E30	E45	E60	E75	E90		

5000 Hour Illuminance Measurements Recorded in March 2015—No Temperature Correction.

Horizontal and Vertical Illuminance Measurement Comparison —No Temperature Correction.

Area	Hours	Avg (lx)	Max (lx)	Min (lx)	Max/Min Ratio	Avg/Min Ratio
Secondary Fence (Vertical)	Initial	5.7	7.7	4.3	1.8	1.34
	2500	5.8	7.8	4.3	1.8	1.35
	5000	5.9	8.9	4.2	2.1	1.4
3 Rows Closest to Secondary Fence (Horizontal)	Initial	8.4	15.4	3.8	4.1	2.21
	2500	7.2	15.2	2.5	6.1	2.87
	5000	7.4	16.0	3.2	5.0	2.3
All (Horizontal)	Initial	22.0	45.5	3.8	12.0	5.79
	2500	19.1	54.5	2.5	21.8	7.64
	5000	19.2	57.6	3.2	18.0	6.0
3 Rows Closest to Primary Fence (Horizontal)	Initial	28.5	41.6	21.1	2.0	1.35
	2500	23.0	45.9	12.7	3.6	1.81
	5000	23.2	46.7	14.3	3.3	1.6
Primary Fence (Vertical)	Initial	29.3	36.8	21.4	1.7	1.37
	2500	21.0	29.4	13.5	2.2	1.56
	5000	21.9	31.6	13.9	2.3	1.6