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Yuma Border Patrol Area Lighting Retrofit

Final LED System Performance Assessment of Trial and Full Installation

April 2018

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Final LED System Performance Assessment of Trial and Full Installation

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

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Pacific Northwest National Laboratory
U.S. Department of Energy
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Preface

The U.S. Department of Energy's Solid-State Lighting program documents the performance of SSL products and systems based on standardized laboratory test results, additional specialized testing, mock-up studies, and real-world field evaluations. This information is provided publicly for several purposes: 1) to track SSL technology performance improvement over time; 2) to identify technology challenges that impact performance and application of SSL; 3) to spur continued advancements in SSL technology, product design, and application; and 4) to maximize energy efficiency and decrease U.S. energy use, while improving lighting quality. 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. SSL technology continues to evolve quickly, so evaluation results should always be understood in the context of the timeframe in which products were acquired, tested, installed, and operated. Especially given the rapid development cycle for SSL products, specifiers and purchasers should always seek current information from manufacturers when evaluating such products. The two programs primarily involved in product evaluations are CALiPER and GATEWAY.

CALiPER

When CALiPER was launched, its role was largely to test products and compare actual performance to manufacturer claims and to benchmark technologies. Early CALiPER testing also contributed fundamentally to the development of standardized photometric test methods specifically for SSL and the associated accreditation of testing laboratories. As the SSL market has matured, CALiPER has transitioned its evaluations to new products and functions, such as OLED-based luminaires and color-tunable products, as well as long-term product performance. CALiPER continues to support the development of new test procedures and application guidance, with DOE investigations providing data that is essential for understanding the most current issues facing the SSL industry. Data are gathered primarily through laboratory testing and mock-up installations.

GATEWAY

GATEWAY conducts field evaluations of high-performance SSL products to collect empirical data and document experience with field installations. GATEWAY provides independent, third-party data for use in decision-making by lighting manufacturers, users, and other professionals. Real-world installations often reveal product limitations and application issues that are not apparent from laboratory testing. GATEWAY typically documents pre- and post-installation light levels, color characteristics, energy intensity, and other performance attributes, and addresses application and maintenance of SSL products. In some cases, GATEWAY returns to projects after months or years of operation to take additional site measurements or remove luminaires and send to accredited laboratories for testing. While not possible for every project, such follow-up measurements have yielded useful data on dirt depreciation, color shift, luminous intensity distribution changes, and lumen depreciation over time.

For more information on the DOE SSL program, please visit energy.gov/eere/ssl/solid-state-lighting.

Acknowledgements

The ongoing and significant support from Eaton is gratefully acknowledged, and this project could not have been completed without their commitment to collaboration with the GATEWAY program. The continued support of Harry Hart, the Customs and Border Protection Yuma Sector Program Manager, along with Customs and Border Protection agents and staff, is greatly appreciated.

Executive Summary

Evaluation of the LED lighting installed in the Yuma Sector Border Patrol Area continues to provide a better understanding of LED technology performance in a high ambient temperature and high solar radiation environment, beginning with the initial trial installation of six LED luminaires in February 2014. This report follows-up on a report published in April 2016 showing illuminances changing more rapidly than anticipated after 7000 hours of operation. These changes were assumed to be mostly, if not completely, caused by dirt accumulation based on the results of field and laboratory measurements confirming the effect of dirt not only on lumen output, but also on the distribution of light exiting the luminaire. One last opportunity to measure this first-generation LED system came in September 2016 at 11000 hours of operation. The measured illuminance was found to have decreased over 50% for these field-cleaned luminaires after 11000 hours of operation. Possible reasons for this unexpected result are explained in this report, but the root causes of these effects remain unknown.

Also recorded during this September 2016 visit were measurements of a second-generation LED system installed less than a week prior to the measurements. These measurements were repeated on August 30, 2017 at 4000 hours of operation, allowing for a comparison to the initial measurements as well as a comparison to the performance of the first-generation LED system. After 4000 hours of operation, the second-generation was performing similarly to the first-generation system after 5000 hours of operation. The luminaires were not maintained or cleaned during these time periods. One difference was that at initial installation the second-generation luminaires exhibited color over angle variability that produced noticeable color differences on the illuminated sand beneath the system; this persisted at 4000 hours. While the color differences were very noticeable on the sand at the project site, they may be less noticeable in a more typical street lighting or parking lot application.

As SSL technology continues to evolve, the nature and the extent of the data that product developers, manufacturers, and specifiers need in order to evaluate the performance of products and systems is changing. The development of relevant testing and reporting procedures and metrics of acceptability necessarily lags behind the identification of the need for certain types of data. Determination of spectral power distribution (SPD) and related color metrics at different angles is not currently included in standardized outdoor luminaire photometric testing. The results from this evaluation also highlight the gap that exists between laboratory-based performance testing of LED products and systems and their in-field performance. While standard test methods such as IES LM-80 and defined calculation techniques such as TM-21 and TM-28 provide a critical part of the information needed for SSL, the results from this project show that system and field application conditions can make it difficult to predict installed performance over time as there are numerous variables not accounted for in the LM-80 test standard.

The initial energy, lighting quality, and maintenance benefits relative to the incumbent high-intensity discharge system were well documented and produced very satisfactory results for Customs and Border Protection; however, the evaluation raises questions regarding the long-term performance of LED systems in high-temperature environments. Ongoing improvement of current test methods and standards for LED devices, as well as new approaches to product and system development, are needed to better characterize the performance of LED lighting systems.

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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 concerns are among the reasons why the Yuma Sector Border Patrol Area lighting retrofit on the U.S.-Mexico border was evaluated 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 previous Yuma Phase 1 reports.[2]

The Phase 1.0 report compared the six LED luminaires that were installed for the IGA in February 2014 to the incumbent high-intensity discharge lighting system installed in the Yuma Sector. The Phase 1.1 report discussed the performance of the trial system after 2500 and 5000 hours of operation, including the greater than anticipated change in illuminance levels and illuminance distribution. These findings led to the further investigation documented in Phase 1.2, with additional measurements and consideration of possible explanations for the changes. This Phase 2.0 report details the final measurements of the trial system prior to its removal as part of the full installation in the fall of 2016. Each report for this project is described below.

- **Yuma Phase 1.0 Report: Investment Grade Audit Trial Demonstration (Published December 2014)** 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 in February 2014.
- **Yuma Phase 1.1 Report: LED System Performance - One Year Later (Published April 2015)** Reviews the results of ongoing data collection, specifically field illuminance measurements of the six luminaires installed for the IGA, comparing the measured data after 2500 and 5000 hours to data measured after the initial installation.
- **Yuma Phase 1.2 Report: LED System Performance - Two Years Later (Published April 2016)** Reviews the results of ongoing field illuminance measurements after 7000 hours of operation, along with laboratory tests of two of the six luminaires, and field temperature measurements recorded inside two new luminaires installed at the site.
- **Yuma Phase 2.0 Report: Final Assessment of Trial and Full Installation (Current Report)** Final illuminance measurements of the trial installation after 11000 hours of operation are compared to previous measurements. Performance of four second-generation luminaires from the full installation is also compared at initial_2 and 4000_2 hours of operation.[3]

2 For further information, download the entire series of reports prepared by the DOE SSL program: energy.gov/eere/ssl/downloads/trial-demonstration-area-lighting-retrofit.
3 The subscript “2” denotes operating hours of the second-generation luminaires.

2 Background Review

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 lining this section of the border east of the POE are consistent, with 205 poles spaced 180 ft apart. The three poles farthest east of the POE, poles 203 through 205, were selected for the trial demonstration, and LED luminaires replaced the incumbent quartz metal halide (QMH) luminaires on these poles.

2.1 Trial System Design

The LED luminaires were designed to provide uniform illumination from a 40 ft pole height. Pole 203 is shown in Figure 1, with the incumbent lighting system trailing into the distance toward the POE. Two LED luminaires replaced three 1000 W QMH luminaires on each pole, pictured in Figure 2. The LED system was designed to replace only the two outer QMH luminaires because the middle luminaire was not operational and the amount of light provided by the two QMH luminaires was considered acceptable. The goal of the ESPC was 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.

Photo looking west from the east end of the 7.2 mile area between poles 204 (not pictured) and 203 (pictured, front). 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 (south) is on the left and the secondary (north) fence is on the right.

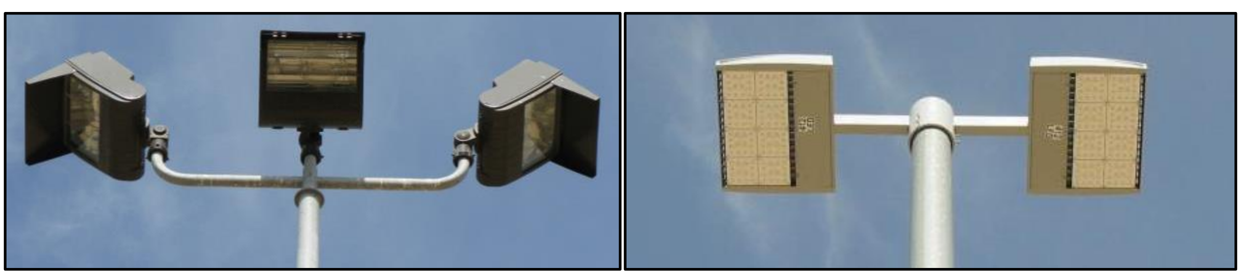

Figure 2. Incumbent QMH Luminaires (left) and LED Luminaires (right).

A custom tenon was necessary to fit the diameter of the pole after the pole height was reduced to 40 ft, because the diameter of the tapered pole widened from top to bottom. The QMH luminaires were originally installed with the lens tilted up from horizontal and shielded with visors to minimize stray light. In contrast, the LED luminaires were installed with luminous aperture horizontal (i.e., not tilted upward).

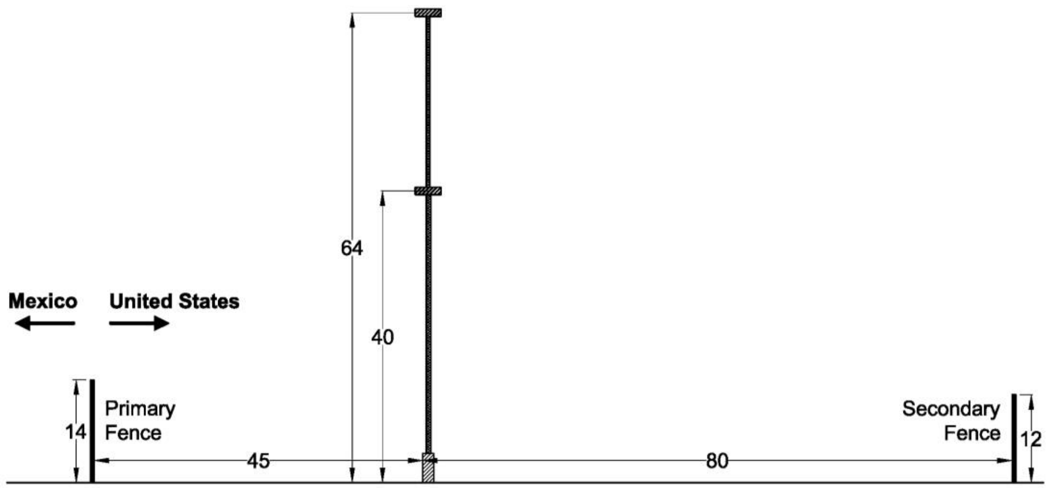

Figure 3. Schematic Elevation of the Yuma Sector Border Patrol Area East of the San Luis Port of Entry.

The dimensions 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 about 2 to 4 ft higher than the base of the concrete pole pedestal.

The 125 ft width of the border area 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 trial LED luminaires had eight light squares,[4] each with Illuminating Engineering Society (IES) Type III luminous intensity distribution (as defined in Annex E of ANSI/IES RP-8-14). Six light squares illuminated the area between the pole and primary fence, a distance of 45 ft, and two of the light squares were rotated 180° to illuminate the 80 ft distance between the poles and secondary fence. 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 7.2 miles east of the POE require continuous surveillance by border patrol agents, and the role of the lighting is to enable the agents to perform their job equally well day or night.

2.2 Illuminance Measurement Methodology

The same measurement procedure was used for all illuminance measurements taken at the site. The measurements were recorded at points in a rectangular grid that originated from the middle of the primary (south) face of the concrete pole pedestal, with measurement points spaced uniformly at 15 ft intervals in the cardinal directions (north-south and east-west) as illustrated in Figure 4. The horizontal measurements were recorded approximately 9.5 in. above the ground and the illuminance meter was mounted to a tripod head that was leveled for each measurement. This measurement setup is shown in Figure 5. Leveling was necessary because of the unevenness of the sandy terrain. Vertical illuminance measurements were recorded at heights of 4 and 8 ft at each of the two fences, 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 later measurements.

For pole 204 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 pre-sunrise twilight was reached before the measurements were completed. After the full installation of the second-generation luminaires, the measurements were recorded between pole 200 and 201.

4 *Light squares* and *bars* are terms used by some luminaire manufacturers to describe the scalable lumen output characteristic of their luminaires.

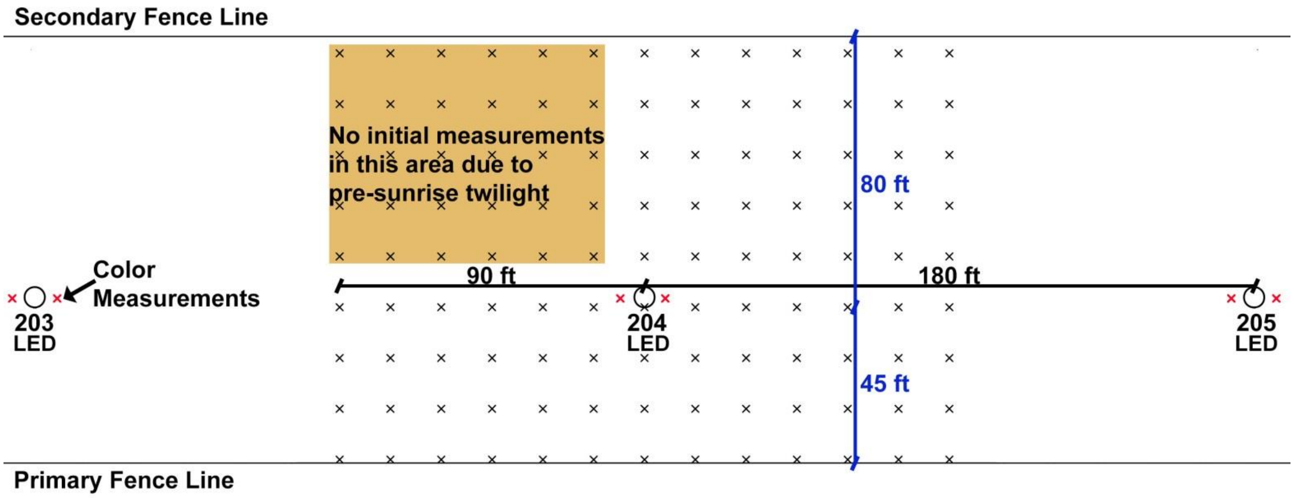

Figure 4. Layout of Grid Measurements.

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 each fence, in line with each column of horizontal illuminance measurements. A single color measurement was recorded under each LED luminaire at pole 204, 4 ft above the ground (36 ft below the luminaire). The same methodology was applied when measuring illuminance at other poles on the site.

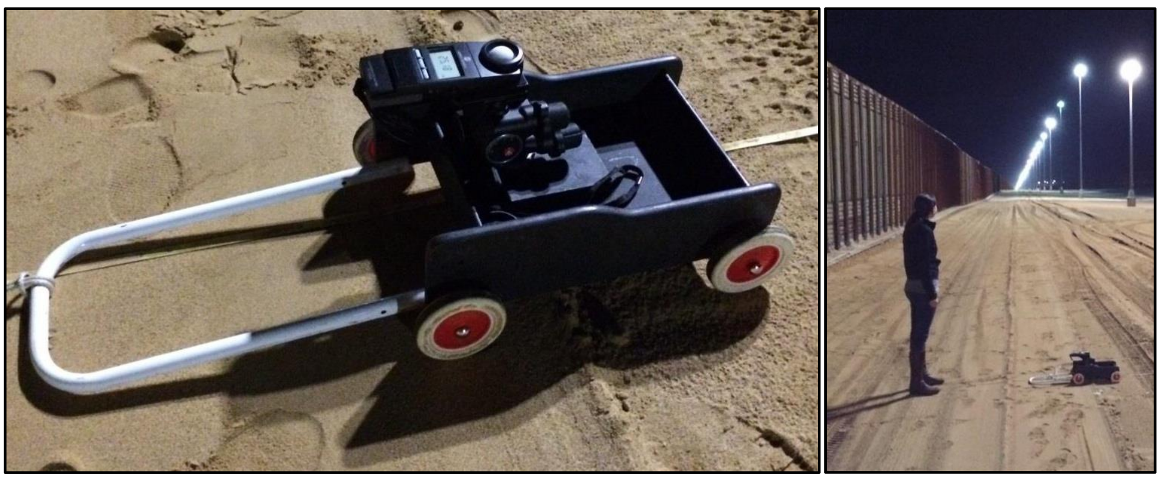

Figure 5. Illuminance Measurement Wagon.

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.

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. On the product specification sheets for the first- and second-generation luminaires, the luminaire manufacturer listed five different lumen multipliers corresponding to ambient temperature points ranging from 10°-50°C (50°-122°F) for the first generation and 0°-50°C (32°-122°F), as listed in Table 1. Linear interpolation was used to calculate the lumen multiplier if the average ambient temperature differed from these five points, shown in Table 2. The minor change in temperature over the few hours of measurement time had no considerable effect on the lumen multiplier, so the same lumen multiplier is applied to all measurements recorded at a given number of operating hours. All values referenced in the main body of this report have been corrected for temperature.

Table 1. Temperature Correction Lumen Multipliers.

The lumen multiplier values were listed on the LED luminaire manufacturer's specification sheet for the first- and second-generation luminaires.

Ambient Temperature	Lumen Multiplier	
	First Generation	Second Generation
0°C (32°F)	---	1.02
10°C (50°F)	1.04	1.01
15°C (59°F)	1.03	---
25°C (77°F)	1.00	1.00
40°C (104°F)	0.96	0.99
50°C (122°F)	0.92	0.97

Table 2. Lumen Multiplier Used for Initial, 2500, 5000, 7000, 11000, Initial$_2$, and 4000$_2$ Hour Measurements.

The lumen multipliers were calculated for the specific average ambient 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
7000	33°C (92°F)	0.98
11000, Initial$_2$	26°C (78°F)	1.00
4000$_2$	37°C (99°F)	0.99

2.3 Laboratory Testing

After 7000 hours of operation, the research team decided to conduct full testing of the two first-generation luminaires on pole 204. The luminaire removed from the east side of pole 204 is designated luminaire A herein, and the luminaire removed from the west side is designated luminaire B. The removed luminaires were driven to Phoenix, AZ (to minimize disruption of the dirt) for the first laboratory test conducted by LightLab in Phoenix, AZ to closely estimate the field conditions prior to the luminaires being packed and shipped to the Eaton laboratory in Georgia. The results of the testing done at both laboratories are shown in Table 3, with a description of the orientation of the luminaire in Figure 6.

Table 3. Laboratory Test Results.

The notation indicates whether the luminaire was dirty or clean, luminaire A or B, and the testing laboratory. The peak intensity values are examined in two orthogonal planes because of the bi-symmetrical design of the luminaires, with less light directed toward each fence (vertical plane defined by 0° and 180° horizontal angles) than toward neighboring poles (vertical plane defined by 90° and 270° horizontal angles). The vertical angle at which peak intensity occurred for each cleaned luminaire was used for comparison with the respective dirty condition.

Test	Total Output (lumens)	Peak Intensity at 90° Horizontal Angle (candela)[b]	Peak Intensity at 0° Horizontal Angle (candela)[c]	Intensity at Nadir (candela)
Dirty B LightLab	23,812	11,024	4070	3765
Dirty B Eaton	24,956	11,643	4226	3883
Clean B Eaton	27,472	15,471	5565	3218
Dirty A Eaton[a]	27,782	12,970	5208	3990
Clean A Eaton[a]	29,881	17,558	6138	3436

[a] Both of the drivers in luminaire A were replaced at Eaton's laboratory prior to testing.
[b] Peak intensity at 90° horizontal angle (parallel to fences) for both luminaires was at a vertical angle of 62.5°.
[c] Peak intensity at 0° horizontal angle (toward primary fence) at a vertical angle of 57.5° for luminaire B and 55.0° for luminaire A.

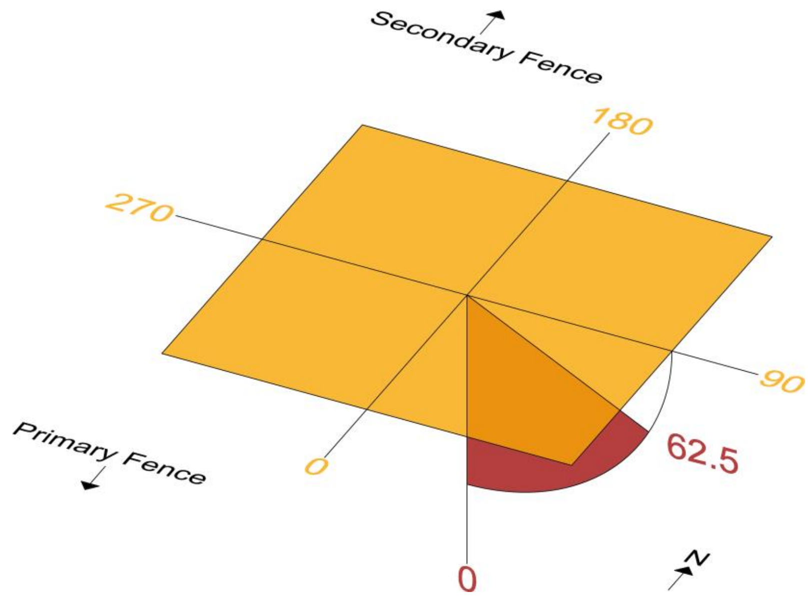

Figure 6. Luminaire Orientation Schematic.

The horizontal angles (gold) are used to describe the photometric performance of the luminaire, and the 62.5° vertical angle (red) is illustrated in the 90° horizontal plane. View is from above.

The LM-79 test of luminaire B completed at LightLab also recorded colorimetric data. As described in the Phase 1.1 report, color measurements were recorded in the field at 2500 and 5000 hours of operation to document changes in the spectral power distribution (SPD) of the luminaires over time, and were compared to a sphere test of a new luminaire of the same model completed by the manufacturer. As summarized in Table 4, the laboratory and field color measurements show little change; the color properties of the luminaire seem to have remained consistent over 7000 hours of operation.

Table 4. Summary of Colorimetric Measurements at 2500, 5000, and 7000 Hours of Operation.

The SPD directly beneath each luminaire on pole 204 was measured at 2500 and 5000 hours with a Konica Minolta CL-500A illuminance spectrophotometer. The individual luminaires are denoted by pole number and cardinal direction relative to the pole (east or west). The 7000 hour data for luminaire B were measured at LightLab, in the "as-is" condition. The manufacturer-rated values are based on LM-79 test reports from 2012 that were submitted by Eaton to the DesignLights Consortium.

Measurement Location	Hours	Chromaticity Coordinates x	Chromaticity Coordinates y	CCT[1]	D_{uv}[2]	CRI[3]	R_9[4]
LED 204-B (East)	2500	0.378	0.378	4088	0.0015	65	-29
	5000	0.377	0.375	4070	0.0000	65	-27
	7000 (Lab)	0.382	0.385	4030	0.0034	65	-30
LED 204-A (West)	2500	0.379	0.382	4061	0.0025	65	-30
	5000	0.380	0.379	4035	0.0011	65	-27
Manufacturer Data	New (Lab)	0.390	0.400	3922	0.0077	66	-30

[1] Correlated color temperature
[2] Distance to the blackbody locus
[3] Color rendering index
[4] Red color sample fidelity

3 Photometric and Colorimetric Field Measurements

The initial illuminance measurements of the first-generation LED system installed on poles 203 through 205 occurred on the evening of February 4, 2014. The measurements centered on pole 204. A second set of measurements occurred on September 17, 2014, at an estimated 2500[5] 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. The fourth and final set of measurements at pole 204 occurred at an estimated 7000 hours of operation on September 23, 2015. The following day, the two luminaires on pole 204 were replaced with new second-generation luminaires that had been instrumented with thermocouples. The original first-generation luminaires were removed from pole 204 for additional testing and analysis. The full installation of the second-generation luminaires (all 205 poles) beginning in August 2016 resulted in the removal of the initial luminaires on poles 203 and 205 in addition to the thermocoupled luminaires on pole 204. Before these luminaires were removed, a final set of measurements was taken to document the performance of these early LED products. On the evenings of September 20 and 21, 2016, measurements were recorded at poles 203 and 205 at 11,200 hours of operation, referenced as 11000 hours throughout the report. At the same time, the initial_2 illuminance measurements of the second-generation LED system, with a subscript “2” to denote the operating hours of the second-generation luminaires, were recorded between poles 200 and 201. Nearly a year later, on August 30, 2017, this second-generation LED system was measured again after 4100 hours of operation, referenced as 4000_2 hours throughout this report. Figure 7 illustrates the luminaire installation phases, and Figure 8 shows the time of year of the measurements between February 2014 and August 2017.

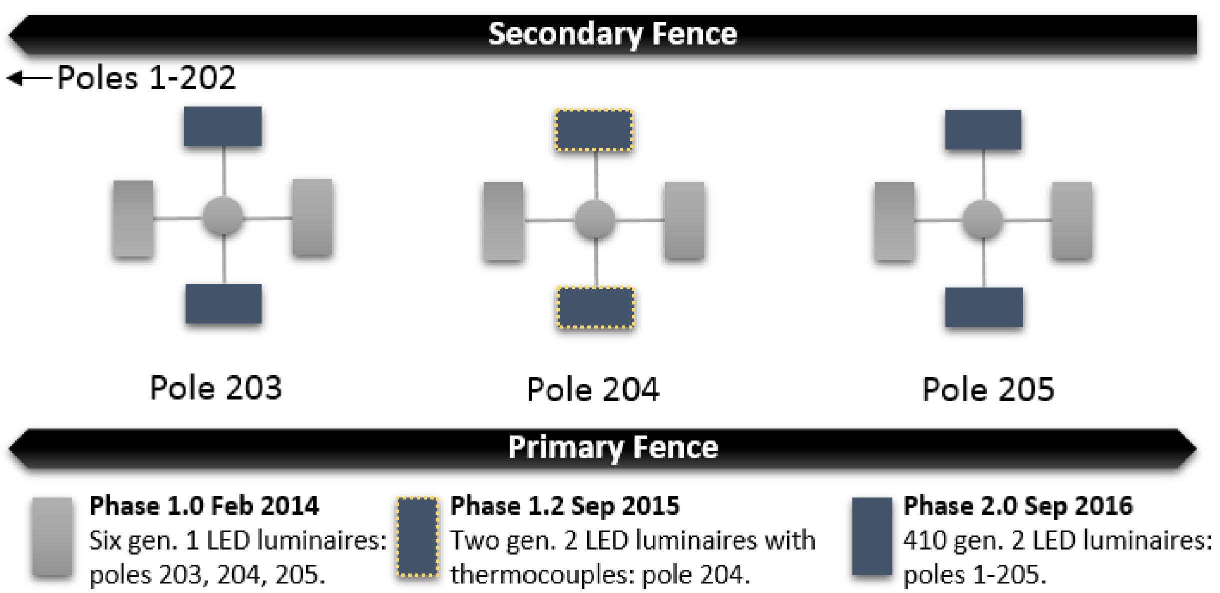

Figure 7. LED Luminaire Installation Schematic.

The trial installation of six first-generation luminaires occurred in February 2014, with two of the first-generation luminaires replaced in September 2015 with two second-generation luminaires on pole 204 that had additional thermocouples for monitoring. In September 2016, the remaining four first-generation luminaires and the two second-generation luminaires with thermocouples were replaced by six second-generation luminaires as part of the full installation of over 400 luminaires along the 7.2 miles east of the San Luis POE.

5 The hours of operation were calculated based on the length of the day, i.e., the time between sunset and sunrise, which is approximately when the photocontrols turned the luminaires on and off as determined from the thermocouple data.

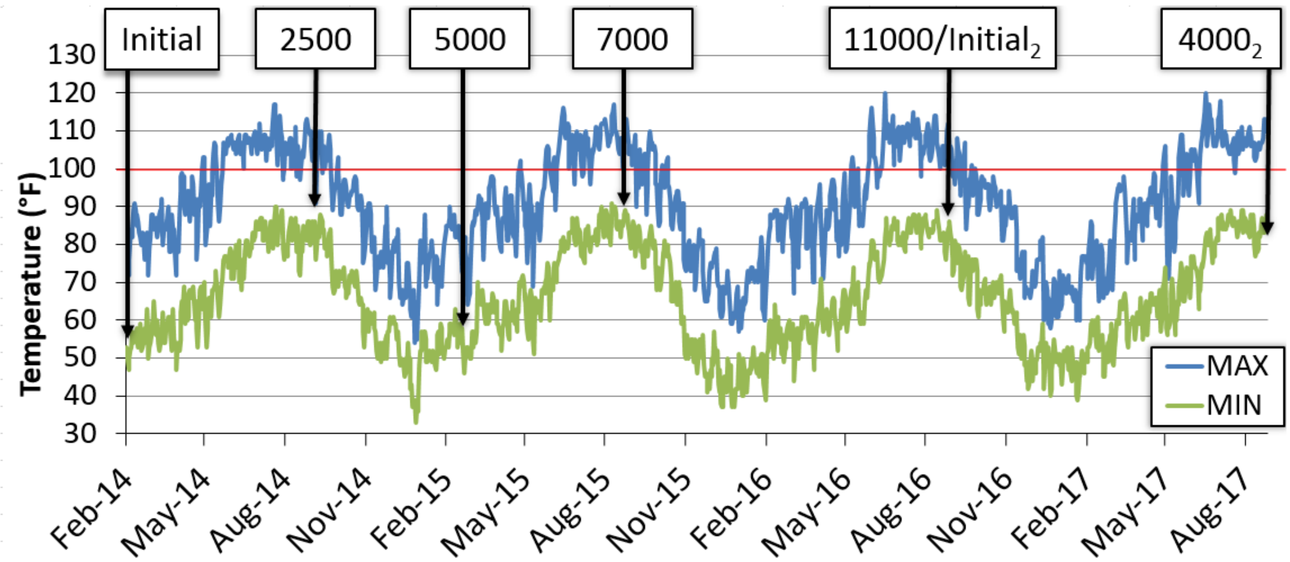

Figure 8. Measurement Timeline.

This timeline illustrates the time of year when each measurement occurred between February 2014 and August 2017. Also shown are the maximum (blue) and minimum (green) daily temperatures. The subscript "2" indicates the measurements of the second-generation luminaires that were part of the full installation.

3.1 Illuminance – First-Generation Luminaires

Results of the initial, 2500-, 5000-, and 7000-hour measurements were previously reported[6] and are included in Appendix A, and detailed weather data for each measurement set are included in Appendix B. The same measurement methodology was repeated in September 2016 at 11000 hours of operation, resulting in the measurements listed in Figure 9, except that measurements shown were recorded at pole 203 and pole 205. Measurements were recorded at these poles because of the prior removal of the first-generation luminaires at pole 204. All luminaires remained operational and had not been adjusted, cleaned, or otherwise serviced after they were installed. The initial hope was to document the dirt depreciation on poles 203 and 205, but the luminaires were field-cleaned 1 day ahead of schedule, during the afternoon of September 20, so no measurements could be recorded for the fixtures in a dirty state at 11000 hours. The 11000-hour measurements were taken with a calibrated illuminance meter[7] at pole 205 less than 6 hours after the luminaires were cleaned, and the following evening a smaller set of measurements was taken at pole 203.

Examining illuminance changes over time extends beyond averages and uniformity ratios, including understanding how the distribution of light may be changing over time. As described in the Phase 1.1 and Phase 1.2 reports, the distribution of light produced by the LED luminaires changed considerably in the first 2500 hours of operation, and the trend continued to the 7000-hour measurements. Another considerable change, this time in average illuminance, was documented at 11000 hours of operation at poles 203 and 205 when comparing these illuminance measurements to the initial measurements at pole 204.

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6 See *Yuma Border Patrol Area Lighting Retrofit: Trial Demonstration* prepared by the DOE SSL program: energy.gov/eere/ssl/downloads/trial-demonstration-area-lighting-retrofit.
7 T-10A Konica Minolta illuminance meter (30011584/20011162) calibrated July 8, 2016, was still within tolerance when calibrated again November 27, 2017.

	W90	W75	W60	W45	W30	W15	Pole	E15	E30	E45	E60	E75	E90	LED 11000 hr (lx) - 205 only	
8 ft	2.1	2.1	2.2	2.3	2.5	2.7	2.6	2.7	2.5	2.3	2.2	2.1	2.1	2.4 Avg	Secondary Fence (Vertical)
4 ft	2.1	2.2	2.4	2.6	2.8	3.0	2.9	3.0	2.8	2.6	2.4	2.2	2.1	3.0 Max	
	Secondary Fence													2.1 Min	
N75	1.1	1.3	1.4	1.5	1.6	1.7	1.6	1.7 1.0	1.6 1.0	1.5 1.0	1.4 0.9	1.3	1.1	3.4 Avg	3 Rows Closest to Secondary Fence (Horizontal)
N60	2.1	2.5	2.8	2.8	3.1	3.2	3.1	3.2 1.9	3.1 1.9	2.8 1.8	2.8 1.6	2.5	2.1	6.6 Max	
N45	5.6	5.6	5.7	5.6	6.2	6.6	6.3	6.6 3.8	6.2 3.8	5.6 3.4	5.7 3.0	5.6	5.6	1.1 Min	
N30	10.3	9.1	10.0	9.9	11.2	11.8	11.4	11.8 6.7	11.2 6.8	9.9 6.3	10.0 5.6	9.1	10.3	9.7 Avg	All (Horizontal)
N15	14.8	12.6	12.3	12.7	14.8	17.3	17.7	17.3 11.0	14.8 10.7	12.7 9.1	12.3 7.8	12.6	14.8	22.3 Max	
Pole	17.9	14.6	14.4	15.0	15.5 10.5	16.7 10.2	22.3 10.5	16.7 13.7	15.5 10.6	15.0 9.9	14.4 9.0	14.6	17.9	1.1 Min	
S15	13.6	12.1	12.4	13.5	15.4	16.8	17.9	16.8 11.0	15.4 10.5	13.5 10.0	12.4 9.2	12.1	13.6	12.0 Avg	3 Rows Closest to Primary Fence (Horizontal)
S30	13.4	11.6	10.9	11.3	12.4	13.2	13.3	13.2 8.4	12.4 8.5	11.3 8.3	10.9 8.0	11.6	13.4	17.9 Max	
S45	11.4	9.6	8.3	8.4	9.4	10.3	10.3	10.3 6.7	9.4 6.6	8.4 6.4	8.3 6.1	9.6	11.4	8.3 Min	
	Primary Fence													12.2 Avg	Primary Fence (Vertical)
4 ft	13.4	11.2	10.8	11.2	13.7	13.6	14.5	13.6	13.7	11.2	10.8	11.2	13.4	15.7 Max	
8 ft	11.0	9.8	9.6	11.7	13.1	15.1	15.7	15.1	13.1	11.7	9.6	9.8	11.0	9.6 Min	
	W90	W75	W60	W45	W30	W15	Pole	E15	E30	E45	E60	E75	E90		

Figure 9. LED Lighting System Horizontal and Vertical Illuminance Measurements: 11000 Hours, Poles 203 (gray) and 205 (black).

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 each 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 gray text indicates measured illuminance at pole 203 at the same respective points. The measurements west of pole 205 were mirrored for the east side for this figure and associated analysis; since there were no poles east of pole 205, the values east of the pole were lower than the values west of the pole. 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.

Comparing the 11000-hour measurements at pole 205, after the luminaires had been cleaned, to the initial measurements on pole 204 reveals several important changes in the illuminances delivered by the lighting system:

- The average horizontal illuminance decreased by 56% in the three measurement rows closest to the primary fence.

- The average vertical illuminance decreased by 57% on the primary fence.
- The average vertical illuminance decreased by 56% on the secondary fence.
- The decrease between 11000 hour and initial measurements had a uniform distribution, unlike previous comparisons; this uniformity can likely be attributed to the cleaning of the luminaires before the measurements.

The low illuminance values in the area surrounding pole 205 were not expected, so the following evening, on September 21, 2016, additional horizontal measurements were taken at 39 points in the area surrounding pole 203 using the same measurement methodology. The illuminance at any given point around pole 203 was always lower than what was measured at the same respective point for pole 205. Figure 10 illustrates how illuminance changed along the pole line from the initial measurements at pole 204 to the 11000 hour measurements at poles 203 and 205, and Figure 11 shows the lower illuminance areas surrounding poles 203 and 205. The remainder of this report will only focus on the measurements from pole 205 since this set of data is more complete, but the data at pole 203 corroborates a considerable decrease in illuminance. Table 5 summarizes the recorded horizontal and vertical illuminance measurements from the initial measurements recorded in February 2014 to the 11000 hour measurements in September 2016.

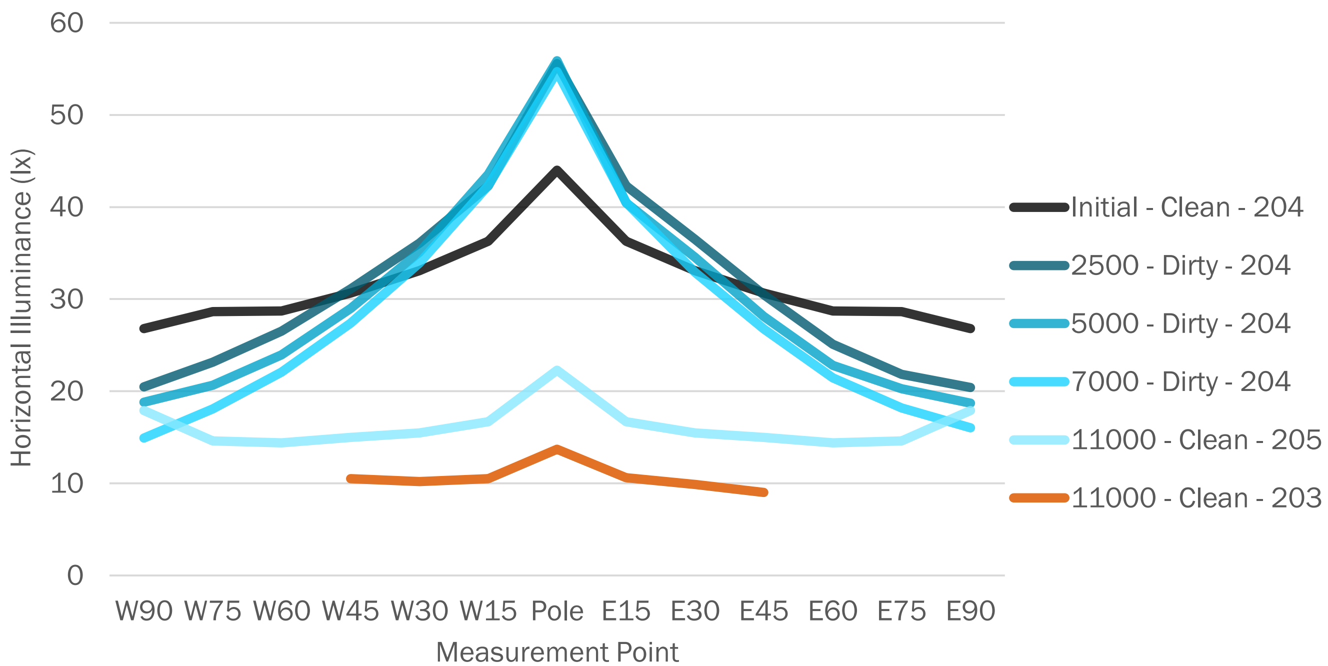

Figure 10. Measured Illuminances along East-West Line Centered at Pole 204 at Four Different Measurement Times, and for Poles 205 and 203 at 11000 Hours.

The trial installation luminaires were initially clean, and then cleaned again at 11000 hours. 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.

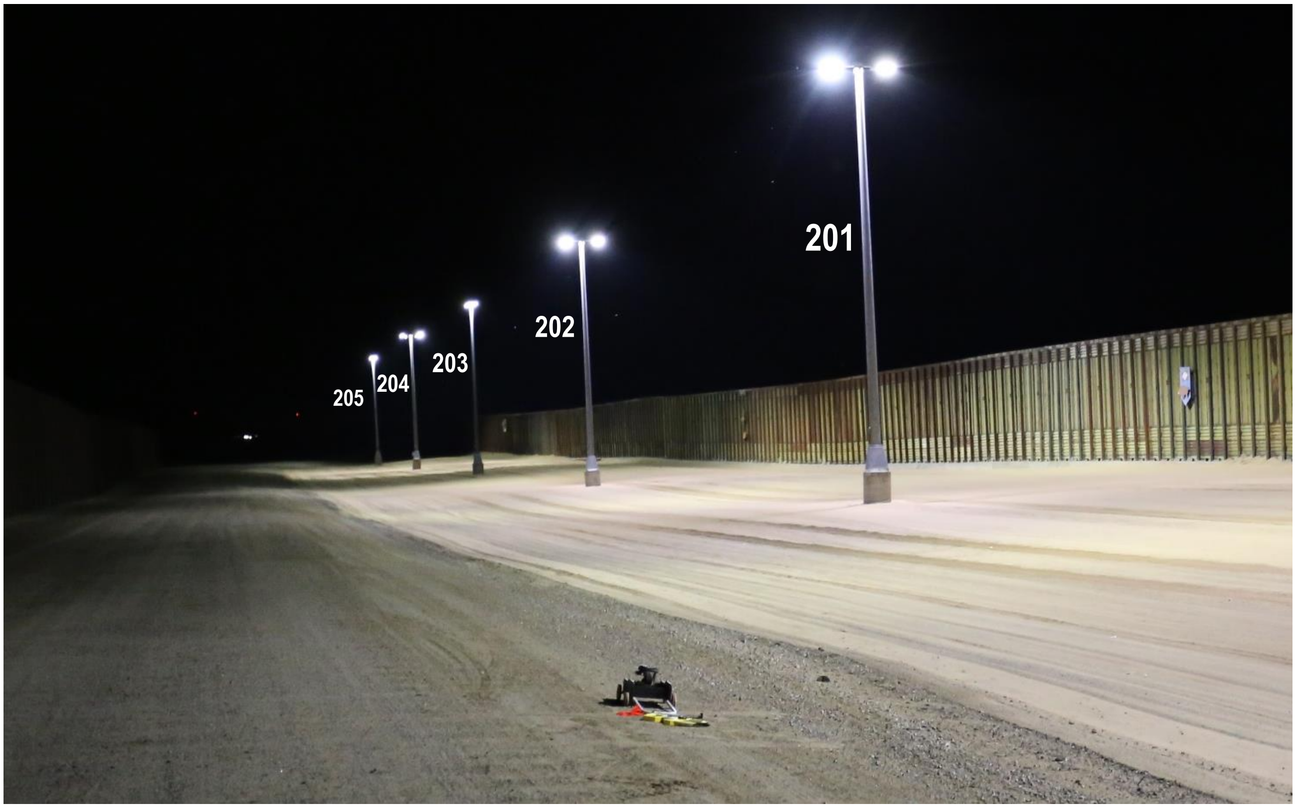

Figure 11. Yuma Sector Border Area: First- and Second-Generation LED Luminaires.

This photo was taken looking east from the area near pole 201 in September 2016. The second-generation luminaires installed in September 2016 as part of the full installation are on poles 201 and 202. The thermocoupled second-generation luminaires installed in September 2015 are on pole 204. The first-generation luminaires installed in February 2014 are on poles 203 and 205. Visible in this photo is a cooler color of sand near poles 201 and 202, and a warmer color of sand farther from the poles. This photo also shows the darkness surrounding pole 203 due to the depreciated output of its luminaires; the area around Pole 205 is relatively dark for the same reason, but also because it is the last pole in this 7.2 mile stretch of border east of the POE.

Table 5. LED Lighting System Horizontal and Vertical Illuminance Values Summary.

The table summarizes the measured illuminance values (lux; lx) for five 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 each fence. 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
	7000	5.1	7.2	3.7	2.0	1.4
	11000	2.4	3.0	2.1	1.4	1.2
Three 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
	7000	6.8	15.1	2.2	6.7	3.0
	11000	3.4	6.6	1.1	6.0	3.1
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
	7000	17.5	54.7	2.2	24.3	7.8
	11000	9.7	22.3	1.1	20.3	8.8
Three 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
	7000	20.8	45.3	10.5	4.3	2.0
	11000	12.0	17.9	8.3	2.2	1.5
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
	7000	18.7	28.2	9.5	3.0	2.0
	11000	12.3	15.8	9.6	1.6	1.3

3.2 Illuminance – Second-Generation Luminaires

The full installation of the more than 400 second-generation LED luminaires along the 7.2 miles east of the San Luis POE was completed in the fall of 2016, leading to considerable energy and maintenance savings. Energy reduction per pole in this area was approximately 69% compared to the QMH lighting system. As of August 2017, there had been only three second-generation LED luminaires that needed to be replaced over the entire 9 miles east and west of the San Luis POE. Prior to the retrofit, 8-10 of the QMH luminaires needed maintenance every month using a special truck to reach the 65 ft mounting height.

Illuminance measurements were recorded in the area between poles 200 and 201 on the evening of September 21, 2016—within approximately a week of the second-generation luminaires being installed as part of the full installation—as shown in Figure 12. This initial_2 set of measurements was then repeated after 4000_2 hours of operation on August 30, 2017, with the results shown in Figure 13. Table 6 summarizes the recorded horizontal and vertical illuminance measurements from the initial_2 measurements recorded in September 2016 to the 4000_2 hour measurements in September 2017. The detailed weather data for each measurement set is included in Appendix B. The luminaires had not been adjusted, cleaned, or otherwise maintained between the initial_2 measurements in September 2016 and the 4000_2-hour measurements in August 2017.

	Pole	E15	E30	E45	E60	E75	Mid	W75	W60	W45	W30	W15	Pole	LED Initial$_2$ (lx)	
8 ft														Avg	Secondary Fence (Vertical)
4 ft														Max	
	Secondary Fence													Min	
N75	3.2	3.3	3.1	2.7	2.1	1.6	1.5	1.6	2.1	2.5	3.2	3.7	3.3	11.4 Avg	3 Rows Closest to Secondary Fence (Horizontal)
N60	12.3	12.9	9.4	8.2	6.5	6.0	6.1	6.3	7.4	9.6	12.5	14.9	14.2	28.7 Max	
N45	28.7	28.6	24.9	20.0	18.1	17.9	17.4	17.5	17.3	18.9	22.2	26.7	27.3	1.5 Min	
N30	34.0	33.1	29.2	26.2	25.3	24.4	22.7	20.7	20.7	22.9	27.8	31.8	32.4	24.2 Avg	All (Horizontal)
N15	34.3	38.0	37.4	34.0	30.5	32.5	33.8	30.8	29.7	35.0	36.8	39.5	33.7	65.7 Max	
Pole	48.0	65.1	43.9	33.2	32.5	34.5	34.2	31.5	30.1	30.3	39.6	65.7	48.7	1.5 Min	
S15	38.6	39.6	29.4	24.3	22.3	20.5	20.2	21.2	22.2	23.8	29.1	39.5	39.4	27.0 Avg	3 Rows Closest to Primary Fence (Horizontal)
S30	32.8	33.5	27.2	22.9	21.1	20.6	21.9	23.8	24.3	25.8	31.2	37.0	35.5	39.6 Max	
S45	25.3	25.9	25.2	24.0	23.7	23.3	23.7	23.6	24.1	24.6	26.0	26.8	27.3	20.2 Min	
	Primary Fence													29.6 Avg	Primary Fence (Vertical)
4 ft	35.0	34.4	32.9	30.5	30.6	29.3	28.0	27.6	27.5	28.1	29.0	32.5	34.3	37.0 Max	
8 ft	37.0	34.9	31.7	30.0	27.9	28.8	24.7	23.2	23.1	22.8	25.1	28.6	31.1	22.8 Min	
	Pole	E15	E30	E45	E60	E75	Mid	W75	W60	W45	W30	W15	Pole		

Figure 12. Second-Generation LED Lighting System Horizontal and Vertical Illuminance Measurements: Initial$_2$.

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 only the primary fence. The horizontal measurements were recorded from the middle of the primary face of the pole pedestal at 15 ft intervals between poles 200 and 201. The black solid line bounds measurements greater than or equal to 30 lx, and the white dotted line bounds measurements greater than or equal to 20 lx. 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.

	Pole	E15	E30	E45	E60	E75	Mid	W75	W60	W45	W30	W15	Pole	LED 4000_2 hr (lx)	
8 ft														Avg	Secondary Fence (Vertical)
4 ft														Max	
	Secondary Fence													Min	
N75	2.6	2.9	2.7	2.4	1.9	1.6	1.4	1.5	1.7	1.9	2.5	2.5	2.6	9.0 Avg	3 Rows Closest to Secondary Fence (Horizontal)
N60	8.9	9.7	8.2	6.4	5.1	4.9	4.8	5.1	5.8	6.6	9.4	10.3	9.6	23.6 Max	
N45	22.9	23.6	20.4	16.7	14.8	13.8	13.4	13.7	14.2	15.4	18.6	20.5	20.5	1.4 Min	
N30	29.4	29.1	25.8	23.9	22.4	19.4	17.2	16.4	17.3	20.2	23.9	27.2	27.5	20.3 Avg	All (Horizontal)
N15	33.5	38.2	35.3	29.9	24.1	23.1	22.8	21.9	23.4	29.6	34.2	38.0	32.8	61.5 Max	
Pole	40.9	58.6	39.3	29.0	25.7	23.4	22.8	22.6	24.2	27.8	38.3	61.5	42.4	1.4 Min	
S15	37.4	38.1	28.7	22.6	19.0	16.1	15.5	16.5	18.8	22.3	28.7	39.1	36.7	22.5 Avg	3 Rows Closest to Primary Fence (Horizontal)
S30	30.2	30.8	24.1	19.4	17.2	15.5	15.8	17.2	19.4	21.9	26.9	33.2	32.7	39.1 Max	
S45	21.0	20.9	19.3	17.3	16.0	15.1	15.1	15.4	16.2	15.8	18.8	20.4	22.1	15.1 Min	
	Primary Fence													21.7 Avg	Primary Fence (Vertical)
4 ft	28.0	27.6	25.5	21.7	20.0	18.9	18.1	18.8	20.0	21.1	22.8	25.7	26.4	29.4 Max	
8 ft	29.4	27.5	24.5	21.2	18.8	17.2	15.2	15.4	15.9	16.8	19.8	23.4	24.7	15.2 Min	
	Pole	E15	E30	E45	E60	E75	Mid	W75	W60	W45	W30	W15	Pole		

Figure 13. Second-Generation LED Lighting System Horizontal and Vertical Illuminance Measurements: 4000_2 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 only the primary fence. The horizontal measurements were recorded from the middle of the primary face of the pole pedestal at 15 ft intervals between poles 200 and 201. The black solid line bounds measurements greater than or equal to 30 lx, and the white dotted line bounds measurements greater than or equal to 20 lx. 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.

Table 6. Second-Generation LED Lighting System Horizontal and Vertical Illuminance Values Summary.

The table summarizes the measured illuminance values for five different areas within the primary and secondary fences between poles 200 and 201. 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 primary fence. 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
Three Rows Closest to Secondary Fence (Horizontal)	$Initial_2$	11.4	28.7	1.5	19.1	7.6
	4000_2	9.0	23.6	1.4	16.7	6.4
All (Horizontal)	$Initial_2$	24.2	65.7	1.5	43.7	16.1
	4000_2	20.3	61.5	1.4	43.6	14.4
Three Rows Closest to Primary Fence (Horizontal)	$Initial_2$	27.0	39.6	20.2	2.0	1.3
	4000_2	22.5	39.1	15.1	2.6	1.5
Primary Fence (Vertical)	$Initial_2$	29.6	37.0	22.8	1.6	1.3
	4000_2	21.7	29.4	15.2	1.9	1.4

Comparing the 4000_2 hour measurements to the initial measurements between poles 200 and 201 reveals several important changes in the illuminances delivered by the lighting system:

- The average horizontal illuminance decreased by 17% in the three measurement rows closest to the primary fence.
- The average horizontal illuminance decreased by 16% for all horizontal measurements.
- The average vertical illuminance decreased by 27% on the primary fence.
- The decrease between 4000_2 and $initial_2$ measurements generally increased with distance from the pole.

3.3 Color – Second-Generation Luminaires

The SPD was recorded with the Konica Minolta CL-500A Illuminance Spectrophotometer[8] at each measurement point along with the $initial_2$ and 4000_2 illuminance measurements. The SPD measurements were recorded on a horizontal plane at about 6 ft above ground after the illuminance measurement was recorded.[9] SPD measurements were not recorded at the same points as the illuminance measurements for the first-generation luminaires as no visual difference in color was noted; however, the second-generation luminaires produced visually noticeable differences in color on the sand that seemed to change based on distance of the illuminated point (as opposed to viewer) from the pole as can be seen in the photograph in Figure 14. The calculated CCT values from these SPD measurements are displayed in Figure 15, with corresponding chromaticity diagrams shown in Figure 16. The average shift in CCT between the $initial_2$ and 4000_2 color measurements was 152 K. Comparing the initial and 4000_2 measurements reveals a shift in chromaticity across all data points with an average $\Delta u'v'=0.0081$ and a maximum $\Delta u'v'=0.0117$. The measured CCT was also plotted in comparison to the angle from nadir to the measurement point, showing that the higher CCTs were closer to the pole and the lower CCTs were farther from the pole. This relationship between angle from nadir and CCT remains after 4000_2 hours of operation, with an overall shift to lower CCTs.

8 CL-500A Konica Minolta Illuminance Spectrophotometer (10002008) calibrated July 8, 2016 and July 10, 2017.
9 The meter was held above the head of researcher (same researcher for all measurements) to avoid influence of clothing on the SPD measurements. SPD measurements were not recorded near the ground due to limitations of meter and environment.

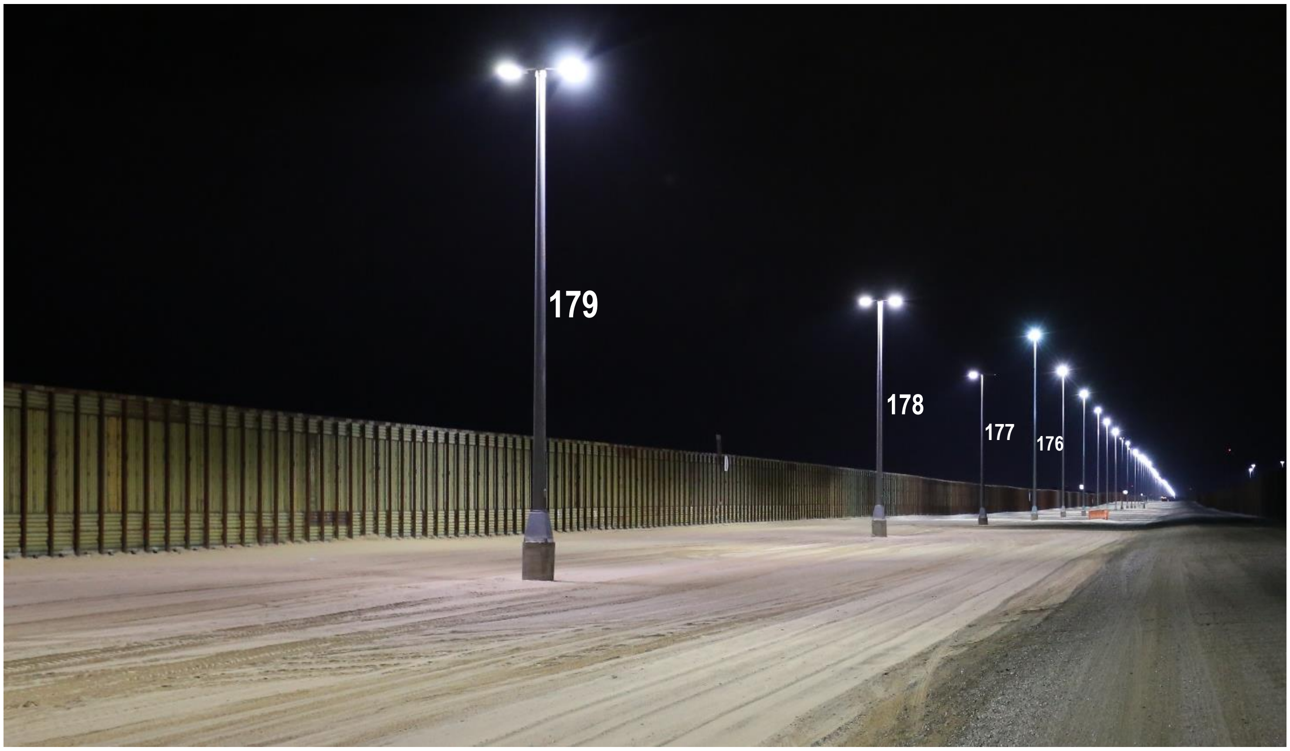

Figure 14. Yuma Sector Border Area: Second-Generation LED Luminaires and Incumbent QMH Luminaires.

Photo was taken looking west from the area near pole 179 in September 2016 during full installation of second-generation LED luminaires. The LED luminaires are on poles 179-177, with the incumbent QMH luminaires on poles 176 and beyond. Visible in this photo is a cooler color of sand near pole 179 and then a warmer color of sand farther from the pole. Pole 177 has only one luminaire operating, with a dark area between pole 177 and the secondary fence. Installation of luminaires only happened during the day.

Initial$_2$ Measurements

	Pole	E15	E30	E45	E60	E75	Mid	W75	W60	W45	W30	W15	Pole
	Secondary Fence												
N45	3961	3947	3917	3886	3864	3877	3888	3847	3833	3871	3912	3945	3956
N30	4054	4049	4049	3979	3900	3870	3868	3870	3945	4042	4056	4050	4051
N15	4097	4153	4186	4141	3982	3837	3795	3825	3967	4195	4222	4207	4114
Pole	4277	4173	4073	3971	3902	3834	3799	3815	3893	3940	4051	4179	4286
S15	4200	4142	4107	4073	4009	3902	3865	3886	3973	4028	4098	4119	4154
S30	4121	4095	4061	3991	3926	3874	3836	3824	3858	3930	4013	4050	4073
S45	3860	3838	3837	3800	3791	3769	3769	3772	3802	3819	3814	3808	3820
	Primary Fence												
<-- 199	Pole	E15	E30	E45	E60	E75	Mid	W75	W60	W45	W30	W15	Pole

4000$_2$ Measurements

	Pole	E15	E30	E45	E60	E75	Mid	W75	W60	W45	W30	W15	Pole
	Secondary Fence												
N45	3808	3802	3790	3782	3788	3792	3793	3753	3732	3734	3755	3766	
N30	3883	3888	3884	3845	3776	3769	3762	3754	3787	3859	3862	3853	3847
N15	3911	3965	3995	3957	3826	3733	3697	3712	3809	3962	3976	3961	3889
Pole	4041	3974	3911	3840	3769	3722	3691	3698	3765	3810	3889	3969	
S15	3992	3950	3927	3891	3828	3772	3745	3750		3857	3910	3932	3972
S30	3916	3883	3866	3819	3779	3744		3707	3721	3766	3831	3824	3902
S45	3724	3708	3714	3687	3687	3654	3667	3656	3684	3698	3698		3750
	Primary Fence												
<-- 199	Pole	E15	E30	E45	E60	E75	Mid	W75	W60	W45	W30	W15	Pole

Figure 15. Second-Generation LED Lighting System CCT Measurements: Initial$_2$ and 4000$_2$.

Poles 200 and 201 are located on the midline of the left and right measurement edges. The square colors represent the range of the initial$_2$ measurements, generally representing CCT values: orange < 3900 K, 3900 K ≤ gray ≤ 4000 K, blue > 4000 K. In comparison to the initial$_2$, the cool color temperatures shifted more than the warm color temperatures, with all of the CCTs decreasing in color temperature by an average of 152 K. Some 4000$_2$ measurements were not recorded, indicated by a blank box.

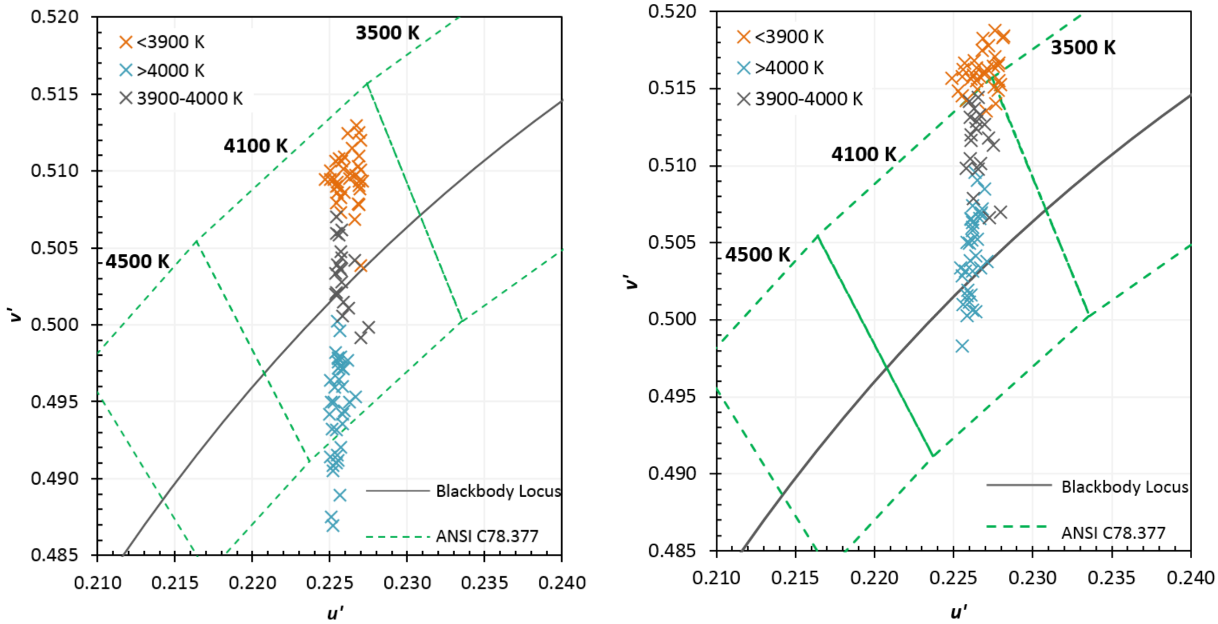

Figure 16. Second-Generation LED Lighting System Chromaticity: Initial$_2$ (left) and 4000$_2$ (right).

The chromaticity coordinates are plotted on the CIE 1976 Chromaticity Diagrams (u', v'). The diagrams are scaled to isolate the 4100 K range of the ANSI C78.377-2017 bin, outlined in green. Colored data points represent the initial$_2$ CCT values as shown in Figure 15: orange < 3900 K, 3900 K ≤ gray ≤ 4000 K, blue > 4000 K.

4 Temperature Measurements of Second-Generation Luminaires

Prior to field-installation, two second-generation LED luminaires were each instrumented with nine ANSI Type J thermocouples and installed on pole 204 on September 24, 2015. This report covers the 361 day period that full day measurements were collected on the thermocoupled second-generation luminaires, from September 25, 2015, through September 19, 2016. Illuminance measurements were not recorded for these luminaires. The following analysis focuses on the hottest ambient air temperature day (June 19, 2015, which had the highest maximum temperature), and includes comparisons to the coldest ambient temperature day (December 16, 2015, which had the lowest minimum temperature) and a typical ambient temperature day[10] (October 22, 2015). For additional details on the thermocouple installation, see previous report.[11]

4.1 Field Measurements - Temperature

Each luminaire had eight internal thermocouples: one placed at the temperature measurement point (TMPLED) of each of six LED packages (locations shown in Figure 17), one attached to the interior top surface of the luminaire housing, and one attached to the temperature measurement point (TMPPS) of one of the two LED drivers per luminaire.[12] An additional thermocouple measured the ambient air temperature outside each luminaire, for a total of nine thermocouples per luminaire (18 per pole).

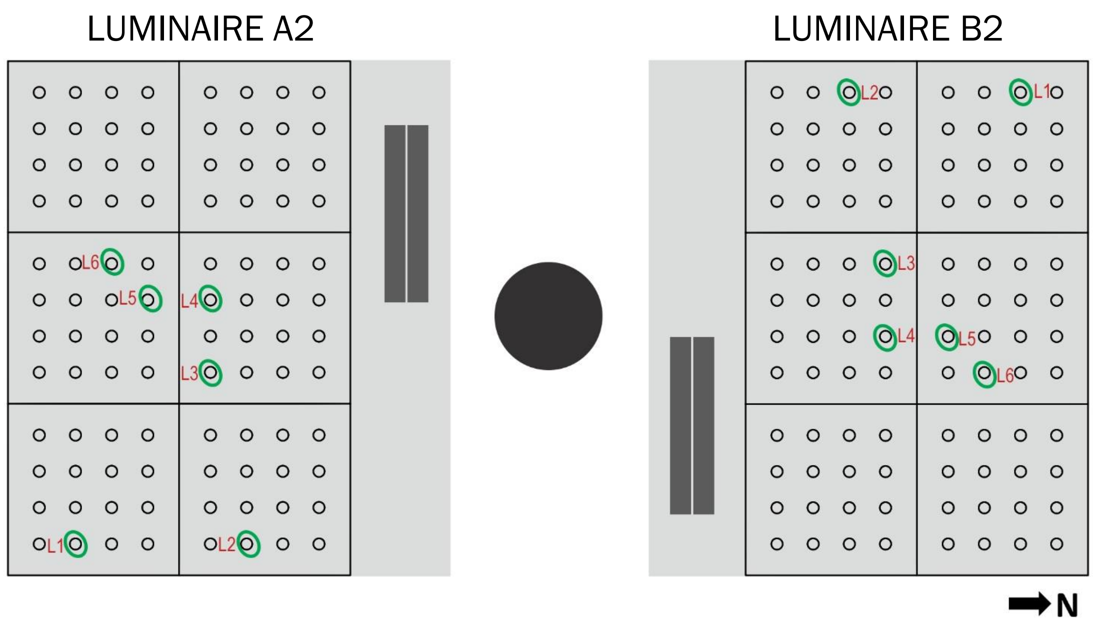

Figure 17. LED Thermocouple Placement Schematic.

The green ovals indicate the six LED packages in each luminaire that had thermocouples installed on the TMP_{LED}. The view of the luminaires is from below. The dark gray rectangles indicate the general location of the two drivers per luminaire, and the solid black circle represents pole 204. When the next-generation luminaires were added to the pole, they were oriented 90° relative to the luminaires they replaced for optimal performance. The next-generation luminaires have six squares and an optical design that differs from the original LED luminaires.

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10 The typical ambient temperature day was selected as a day that was close to the averages of the daily max, min and average temperatures during this 361-day period.

11 See *LED System Performance in a Trial Installation—Two Years Later* prepared by the DOE SSL program: energy.gov/eere/ssl/downloads/trial-demonstration-area-lighting-retrofit.

12 The DesignLights Consortium uses the terms TMPLED and TMPPS to refer to the temperature measurement points for the LED package and the LED driver, respectively (www.designlights.org). Similarly, ENERGY STAR uses the terms TMPLED and TMPC (www.energystar.gov/luminaires).

The luminaires were from the same product family and were the same wattage, but with two different optical distributions. Luminaire B2 had a nominal IES Type II distribution, and A2 had a similar distribution except with spill control to minimize light behind the luminaire. The 24-gauge thermocouple wires were about 60 ft long, extending from the luminaires through the tenon and pole, into the data logger enclosure at the base of the pole. The data loggers stored the data at 1-minute intervals and were periodically downloaded on-site.

4.2 Measurement Comparisons

The temperatures measured on the hottest, coldest, and typical days are summarized in Table 7 for the two luminaires. The LED packages in luminaire B2 were on average warmer than in luminaire A2 during operating hours, while the A2 driver was always warmer than the B2 driver when luminaires were operating. The LED package maximum temperatures were almost always higher than the driver temperatures, and the LED package minimum temperatures were typically lower than the driver temperatures. These differences are illustrated in Figure 18. The LED package and driver temperatures were more similar to each other than to the ambient and housing temperatures for both luminaires. The LED packages always experienced the greatest range in temperatures, no matter the ambient temperature.

Table 7. Temperature Measurement Summary: September 25, 2015, to September 19, 2016.

The table lists temperature statistics for the hottest day, a typical day, and the coldest day. The typical day was defined as a day that was close to the averages of the daily max, min, and average temperatures during this 361-day period. Temperature data for each category is separated into when the luminaires were not operating (red) and were operating (green). Only the temperatures during the times shown in the left column are included, to capture temperatures after the luminaires had cooled down after operating all night and to capture temperatures only after the luminaires had been on for about 30 minutes.

Day Type Date	Metric	Ambient (°C)				All LEDs (°C)				Driver (°C)				Top of Housing Interior (°C)			
		A2		B2		A2		B2		A2		B2		A2		B2	
Hottest Day 6/19/16 Off: 7:30 am – 8:00 pm On: 8:30 pm – 5:30 am	Max	48.2	42.8	50.3	43.7	54.6	69.2	54.1	74.4	52.8	66.2	52.8	59.6	53.2	46.1	53.6	45.7
	Min	32.3	28.8	32.0	28.8	32.8	49.6	33.5	53.5	33.3	56.2	32.5	48.7	33.2	34.4	32.8	34.1
	Avg	44.4	33.8	44.7	33.9	48.1	58.9	47.6	64.8	47.1	61.0	47.1	54.3	47.6	40.1	47.7	39.9
Typical Day 10/22/15 Off: 8:30 am – 6:00 pm On: 6:30 pm – 6:30 am	Max	31.3	28.3	34.0	28.2	42.1	59.9	39.7	64.9	39.1	56.3	39.0	50.3	40.1	35.9	39.8	34.7
	Min	21.1	16.0	23.0	16.6	23.4	38.6	22.5	43.7	24.0	41.1	22.8	39.6	23.3	23.8	22.7	23.6
	Avg	28.4	21.5	30.4	21.5	35.4	48.9	33.4	54.9	34.2	51.3	34.0	44.6	34.9	30.0	34.6	28.6
Coldest Day 2/16/15 Off: 9:30 am – 5:45 pm On: 6:15 pm – 7:30 am	Max	15.6	14.2	16.8	13.0	20.1	43.8	17.8	52.0	17.8	40.8	18.3	34.5	18.5	19.8	18.8	18.9
	Min	8.0	1.6	10.0	0.3	10.7	22.8	8.4	26.7	9.8	28.5	8.8	22.4	10.1	9.1	9.4	8.1
	Avg	13.2	6.8	14.7	7.5	16.6	33.1	14.9	37.8	15.5	36.4	15.6	29.1	16.0	14.0	16.2	13.5

Figure 19 disaggregates the LED package data, showing the variation in temperature between the LED packages. The measured LED packages at the outer edge of the luminaire are L1 and L2, and the remaining measured LED packages are located in the center of the luminaire. L1 reached temperatures similar to the inner LED packages (L3, L4, L5, L6), while L2 tended to operate at slightly lower temperatures. The L6 temperature measurements are not included for luminaire B2 in this report as data from this thermocouple were very different from the other thermocouples, perhaps due to a faulty thermocouple or improper placement of the thermocouple.

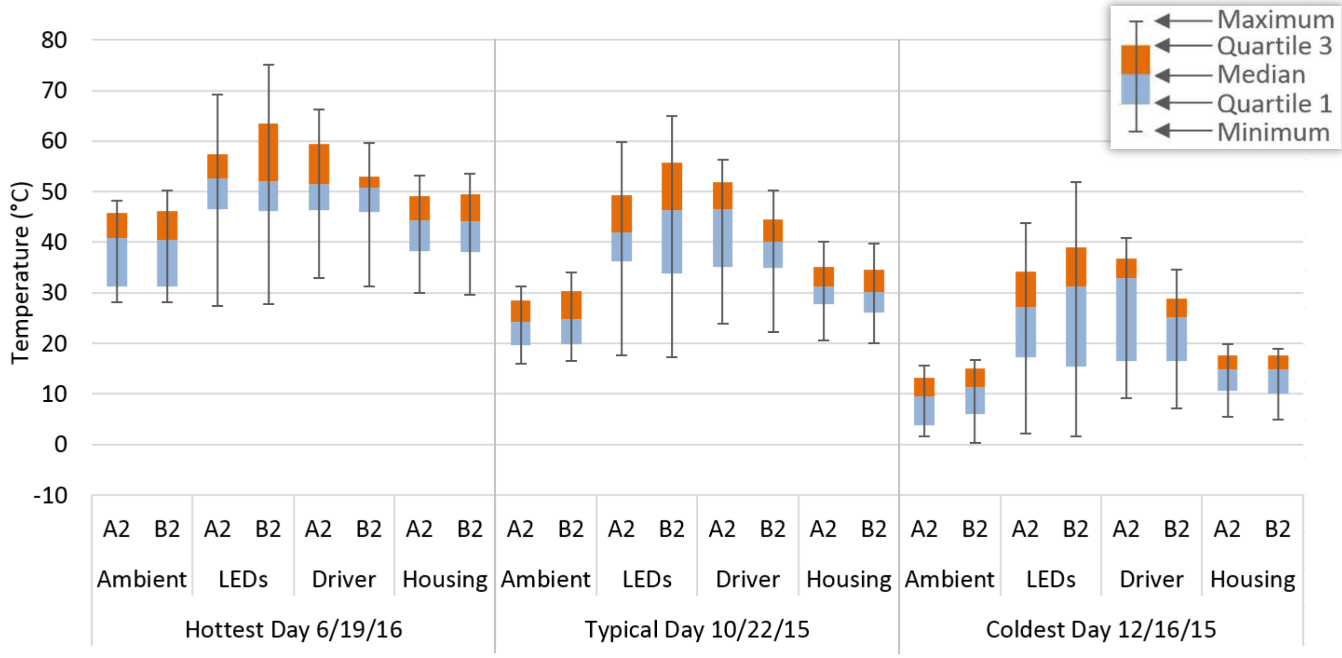

Figure 18. Temperature Measurement Box and Whisker Plot: September 25, 2015, to September 19, 2016.

The box-plot shows the temperatures on the hottest day, a typical day, and the coldest day. The ends of the whiskers represent the maximum and minimum of all of the 1-minute interval data. The typical day was defined as the day that was close to the averages of the daily max, min, and average temperatures during this 361-day time period.

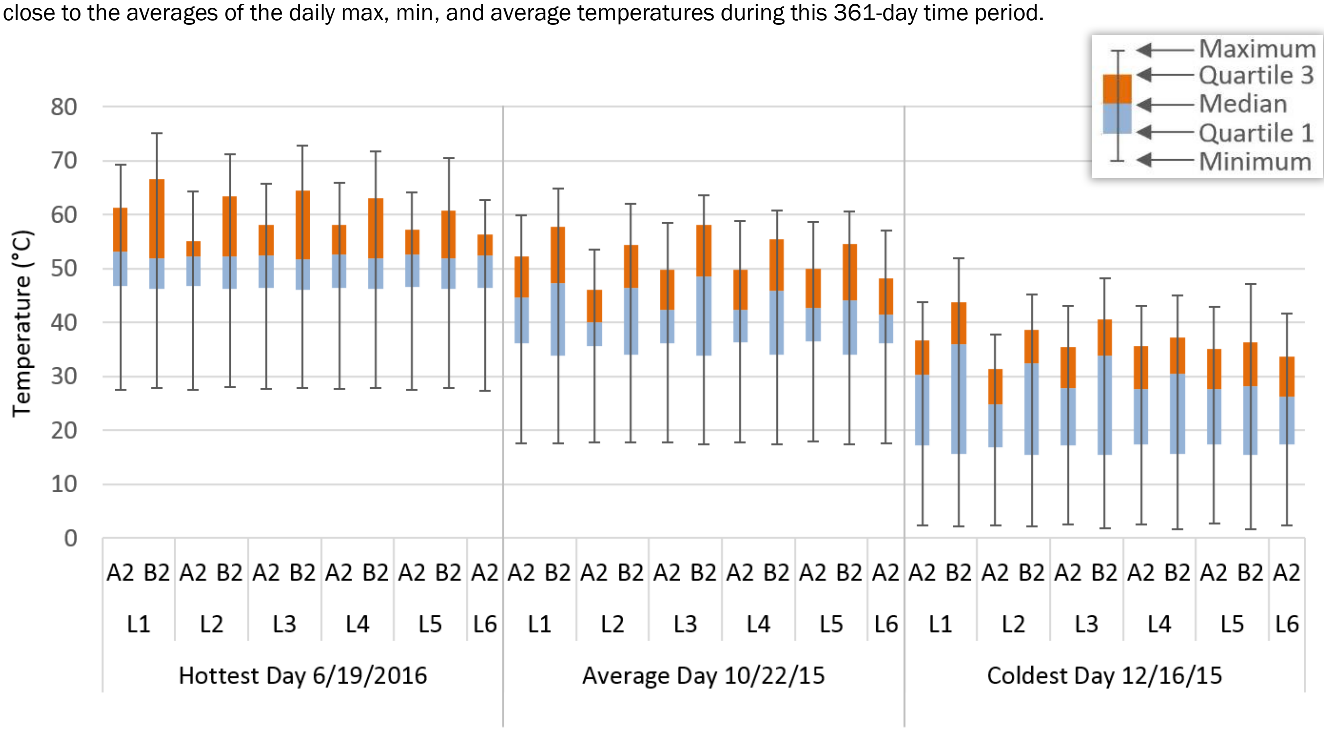

Figure 19. LED Temperature Measurement Box and Whisker Plot: September 25, 2015, to September 19, 2016.

The box-plot shows the range of temperatures on the hottest day, a typical day, and the coldest day. The ends of the whiskers represent the maximum and minimum of the 1-minute interval data. B2 L6 was not included in the analysis. The typical day was defined as the day that was close to the averages of the daily max, min and average temperatures during this 361-day time period.

The change in temperatures over the span of the hottest day (June 19, 2016) and into the morning of the next day is plotted in Figure 20. The LED packages operated at temperatures similar to the driver temperature in luminaire A2, and operated above the driver temperature in B2. The LED packages tended to respond similarly to changes throughout the day, and were influenced by minor changes in ambient temperature during operation. The ambient and housing temperatures were higher during the day, when the luminaires were not operating, than at night, when the luminaires were operating. The driver and LED packages were hottest at night when the luminaires were operating. The effect of solar radiation is also evident in the plot; as the sun rose, the difference in temperature widened between the luminaire components and the ambient temperature, and as the sun set, the temperatures narrowed again until the luminaires began operating.

The temperatures from June 18 to 24, 2016, are plotted in Figure 21. This is the hottest week, with an average daily maximum temperature of 44°C (111°F). The temperature pattern remained similar throughout the week. The temperatures of the A2 LEDs during the day on June 18 were similar to the temperatures earlier that morning when the luminaire was operating. The temperatures of the LEDs when the luminaires were not operating often came close to the same temperatures as when the luminaires were on during the week. The temperatures of the LEDs in B2 reached above 70°C (158°F).

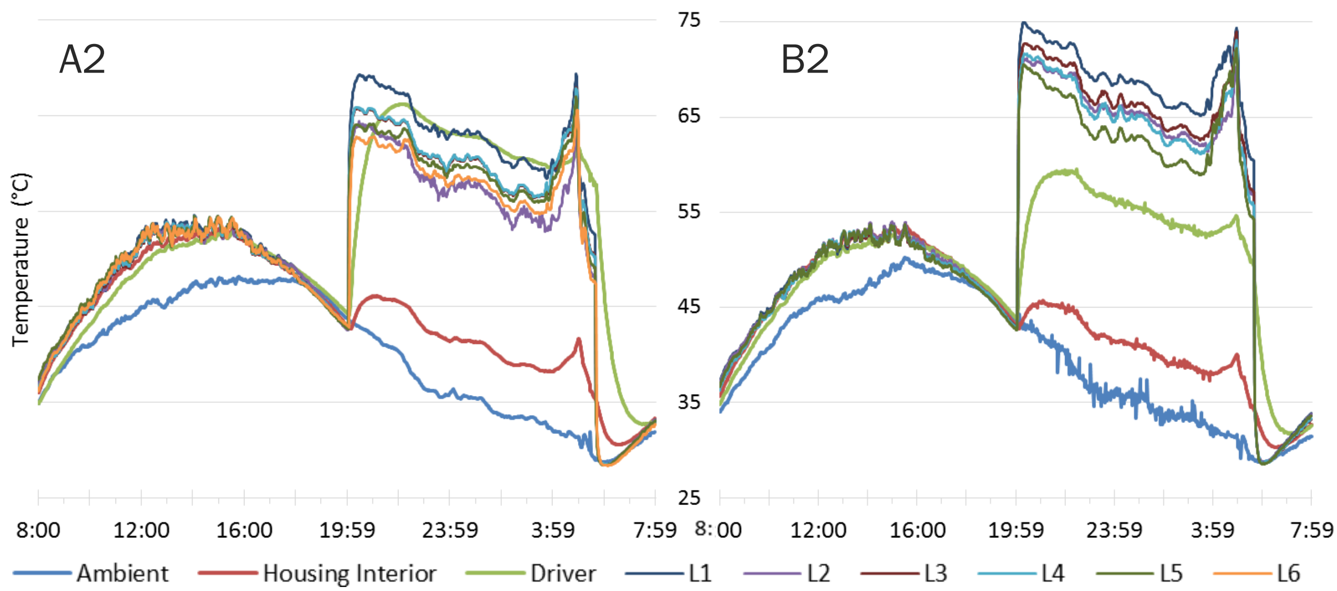

Figure 20. Thermocouple Measurements: June 19, 8:00 a.m., to June 20, 7:59 a.m., 2016.

The 1-minute-interval thermocouple measurements for the hottest ambient temperature day recorded for luminaires A2 and B2.

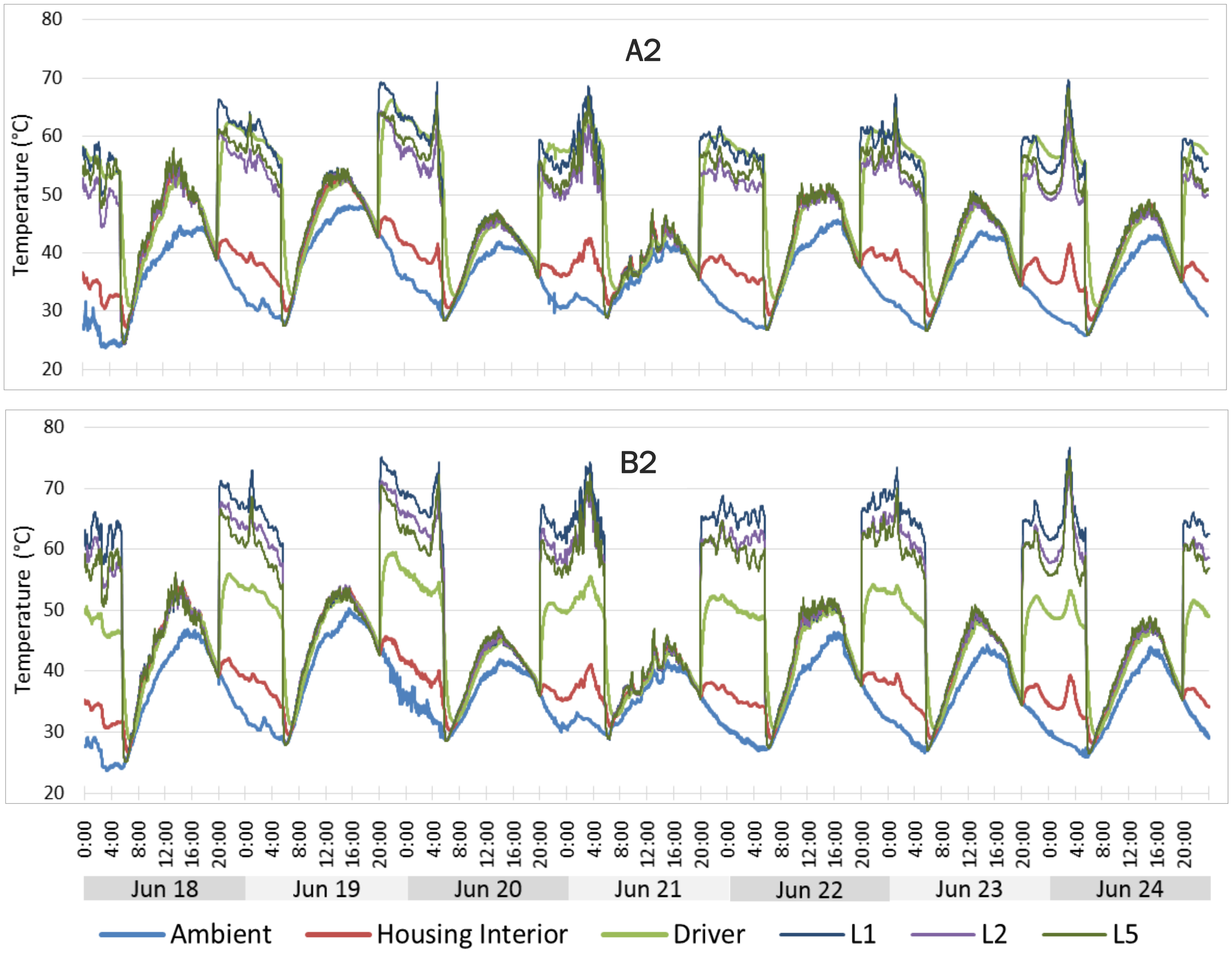

Figure 21. Thermocouple Measurements: June 18 to June 24, 2016.

The 1-minute-interval thermocouple measurements for the hottest ambient temperature week recorded for luminaires A2 and B2. Only L1, L2, and L5 are shown to aide visibility of the temperature. L1 is typically the hottest, although it is located on the outside of the luminaire along with L2, which is typically the coolest. L5 varies between the temperatures of L1 and L2.

5 Discussion

5.1 Depreciation of Measured Illuminance

As discussed in Section 3.1 and illustrated in Figure 10, the measured illuminances decreased on average during the initial 7000 hours of operation for the first-generation luminaires installed as part of the initial three pole, six luminaire trial installation. A change in the distribution of illuminance was also recorded, with illuminances near the pole increasing while those farthest from the pole decreased considerably. In the previous Yuma report,[13] it was concluded that these changes in illuminance were mostly, if not completely, caused by dirt depreciation, based on the nature of the measured illuminances and on LM-79 testing of two luminaires that were removed from the site and tested in both dirty and clean conditions.

The remaining four first-generation luminaires had been field-cleaned immediately before the 11000-hour illuminance measurements; therefore, the significant decrease in illuminance that was recorded was not likely caused by dirt depreciation. Figure 22 shows the relative decreases between the initial measurements and the 11000-hour measurements.[14] Of the 91 points measured, 82 had a relative decrease of at least 50%; only one point had a relative decrease of less than 40% after 11000 hours of operation. Possible causes for these dramatic and unexpected changes in illuminance are explored further in Section 5.2.

After 4000_2 hours of operation, the measured depreciation in illuminance of the second-generation luminaires installed in the full installation was similar to that of the first generation of luminaires after 5000 hours, as shown in Table 8. There are several differences between the first- and second-generation luminaires, including the material of the secondary (outer) optics, and the orientation of the luminaires was also changed for the full installation, as illustrated previously in Figure 7. Because of these changes, a meaningful analysis of the illuminance distribution changes is not possible, but the similarity in the overall illuminance depreciation seems to indicate that the second-generation luminaire installation experienced variations over the first 4000 hours from dirt depreciation and other field factors comparable to the variations of the pilot installation of first-generation luminaires.

13 See *LED System Performance in a Trial Installation—Two Years Later* prepared by the DOE SSL program: energy.gov/eere/ssl/downloads/trial-demonstration-area-lighting-retrofit.

14 Measurements from 0 to 7000 hours of operation were completed near pole 204; those luminaires were removed and replaced after the measurements were recorded. Measurements at 11000 hours were therefore completed near pole 205.

		W90	W75	W60	W45	W30	W15	Pole	E15	E30	E45	E60	E75	E90
Vertical	8 ft							0.60	0.59	0.58	0.54	0.51	0.53	0.55
	4 ft							0.61	0.59	0.59	0.57	0.57	0.60	0.63
		Secondary Fence												
Horizontal	N75							0.64	0.60	0.61	0.62	0.64	0.66	0.70
	N60							0.60	0.58	0.57	0.59	0.58	0.61	0.68
	N45							0.58	0.55	0.55	0.56	0.55	0.57	0.57
	N30							0.55	0.54	0.53	0.55	0.54	0.56	0.47
	N15							0.57	0.55	0.55	0.53	0.54	0.51	0.41
	Pole							0.49	0.54	0.53	0.51	0.50	0.49	0.33
	S15							0.56	0.56	0.56	0.58	0.61	0.59	0.50
	S30							0.54	0.56	0.58	0.60	0.63	0.60	0.49
	S45							0.57	0.57	0.60	0.61	0.63	0.56	0.44
		Primary Fence												
Vertical	4 ft							0.53	0.56	0.53	0.57	0.61	0.56	0.43
	8 ft							0.56	0.57	0.61	0.62	0.66	0.57	0.47
		W90	W75	W60	W45	W30	W15	Pole	E15	E30	E45	E60	E75	E90

Figure 22. Difference in Measured Illuminance over Time for the First-Generation Luminaires: Initial (Pole 204) to 11000 Hours (Pole 205).

The relative change for each measurement point was calculated by dividing the difference between the initial and 11000-hour measurements by the initial measured illuminance. Red font indicates a negative relative change (initial greater than 11000). The shades of gray indicate the magnitude and direction of the change: light gray = less relative change; dark gray = more relative change. The left half is blank because only half of the measurements at pole 205 were compared due to there being no poles east of pole 205 (only half the measurements had contributions from adjacent luminaires). The measurements used were the measurements west of pole 205, but for comparison purposes were mirrored to the east side as there was only a complete set of initial measurements for the east side of pole 204.

Table 8. Comparison of Illuminance Measurements of First- and Second-Generation Lighting Systems.

The measured illuminance near the secondary fence is less than near the primary fence, as designed, so a small change in measured illuminance results in a larger percent change compared to the primary fence. These measurements were taken without cleaning these luminaires.

	First Generation Initial to 5000 Hours	Second Generation $Initial_2$ to 4000_2 Hours
Average Horizontal Illuminance		
Three rows closest to secondary fence	-11%	-21%
Three rows closest to primary fence	-18%	-16%
All horizontal measurements	-12%	-16%
Average Vertical Illuminance		
Primary fence	-25%	-27%

5.2 Testing and Analysis of First-Generation Luminaires after 11000 Hours of Operation

As shown in Figure 10, measured illuminance in the area surrounding the first-generation luminaires installed in February 2014 decreased considerably at 11000 hours of operation in a clean state compared to the values measured at 7000 hours in a dirty state. The four remaining first-generation luminaires were removed from the site after the 11000-hour measurements and replaced with the second-generation luminaires as part of the full installation. The removed luminaires were sent to Eaton's testing laboratory for further evaluation. Eaton evaluated possible losses of light output, including driver performance and degradation in luminaire optical materials due to causes such as etching from windblown sand and discoloration or deformation due to extreme thermal conditions. The results of those evaluations did not yield any clear evidence of damage that might help explain the field-measured data.

Each of the four luminaires were tested in the Eaton photometric laboratory, certified by NVLAP for LM-79 testing procedures. Although an original test report for each luminaire did not exist, the results of this testing of the luminaires removed from the field were compared to a reference test report that served to represent the initial performance of the first generation luminaires. According to data reported by Eaton to PNNL, three of the four luminaires had light output that was less than the initial test, by 6, 7 and 14% respectively. The fourth luminaire had light output that was 1% greater than that measured in the initial test. These results from laboratory testing do not match the field-measured decrease in illuminance of more than 50%. The results also showed that the four tested luminaires had luminous intensity distributions that were similar to that of the reference luminaire.

After the luminaires and light squares were evaluated in the Eaton laboratories, the light squares were sent to the LED package supplier for further assessment. Those assessments identified an optical issue that may have caused unexpected field performance. The LED packages had a primary lens as part of the integrated package from the LED component supplier, and the luminaire manufacturer added a secondary lens on top of the LED packages. In some cases, it appeared that the secondary lens may have been installed in such a way that it contacted the primary lens, causing some deformation over time that could have affected the light output and distribution. These effects may have been a result of the original factory assembly or may have been caused by manufacturer modifications in the field during the trial installation. The luminaire manufacturer reported that this optical interference or deformation appeared to primarily affect the light squares located in the corners of the luminaire, or about 25% of the total LED packages. This optical issue may help explain the reductions in light output shown in the laboratory testing, and may have contributed to the reduced illuminances measured in the field, but it is unlikely to fully explain the illuminance reductions.

The results of the field data collection and the laboratory evaluations make it impossible to exactly define and quantify the causes of the measured results. While some of the possible causes may be unique to the specific luminaire and conditions of the pilot installation, including the rotation of two squares per luminaire in the field, the effects reported may have been partially caused or accelerated by the extreme temperatures at Yuma, described in Section 4. Whatever the causes, the results from this project illustrate that laboratory-derived performance data such as those generated from IES LM-80 testing may not always be a good predictor of actual field performance. The relevant LM-80 data reviewed by DOE for this project indicated less than 2% depreciation in light output over 10,000 operating hours at the operating LED current, even at a case temperature of 105°C (221°F).

5.3 Color Over Angle Variations in the Second-Generation Luminaires

As presented in Section 3.3 and illustrated in Figure 15 and Figure 16, the second-generation luminaires exhibited noticeable color variation at different angles from nadir, with higher CCT values measured closest to the pole and lower CCT values measured farther away from the pole. These variations were documented during the initial measurements taken shortly after the luminaires were installed, and the variations over angle remained consistent at the time of the 4000_2-hour measurements. Figure 15 shows that the variations were greatest along the east-west axis (along the pole line), with a variation of nearly 500 K over the 90-foot distance from the pole to the mid-point between poles. Figure 16 illustrates that the color variations represented a shift in both CCT (distance along the Planckian locus) and in D_{uv} (distance above or below the Planckian locus). At the time of the initial measurements, the lower CCT points were above the Planckian locus and the higher CCTs were below the Planckian locus. The maximum Δu'v' was 0.0117.

Color over angle variation of this nature was not observed for the first-generation luminaires installed in February 2014. The variation was most likely caused by optical elements, which were changed from the first-generation to the second-generation luminaires. Color over angle variations are not documented during routine luminaire photometric testing using IES LM-79 procedures (and producing IES formatted electronic files with luminous intensity data), but some testing laboratories have the capability to conduct color over angle testing.

While the color differences were very noticeable on the sand at the project site, they may be less noticeable in a more typical street lighting or parking lot application. Regardless, the observed effect for this project highlights a potential performance concern for SSL luminaires that was not typically considered with traditional lighting systems. ENERGY STAR® V2.0 does include color angular uniformity requirements in Section 2.5 for indoor luminaires.

5.4 Color Shift Over Time in the Second-Generation Luminaires

As documented in a previous GATEWAY report that focused on interior lighting applications,[15] variations in both light output and SPD over time can be a concern for LED lighting installations. Detailed SPD measurements were not collected for the evaluations of the first-generation luminaires, although limited field measurements showed almost no change in SPD or related color metrics between 2500 and 5000 hours (as shown previously in Table 4). Detailed SPD data were recorded for the second-generation luminaires during the initial_2 and 4000_2 hour measurements. As summarized in Section 3.3, the average CCT shift was a decrease of 152 K during this time, and an increase in D_{uv}.

15 See *Long-Term Evaluation of SSL Field Performance in Select Interior Projects* prepared by the DOE SSL program: https://energy.gov/eere/ssl/downloads/long-term-evaluation-ssl-field-performance-select-interior-projects.

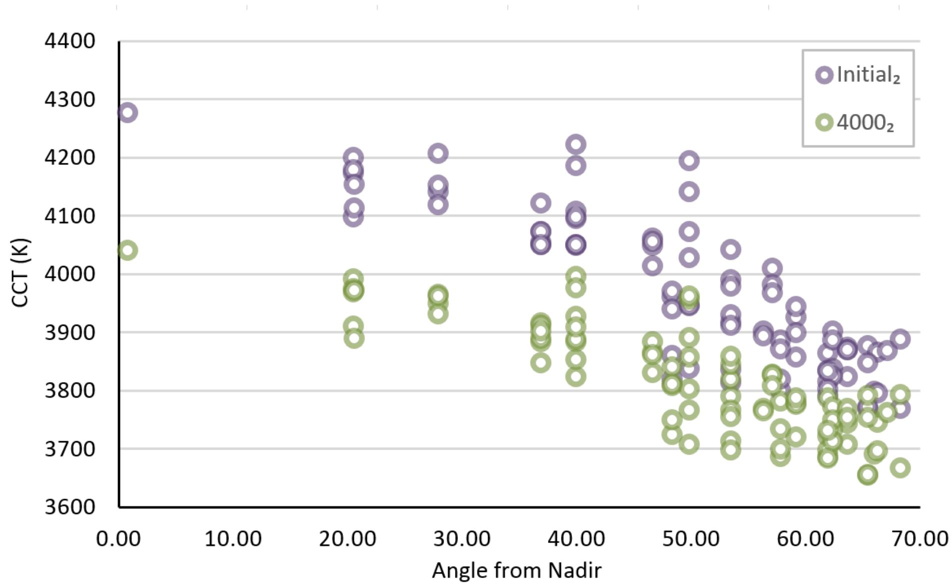

Figure 23. CCT at Initial₂ and 4000₂ Hours of Operation versus Angle from Nadir to Measurement Point.

The CCT measured at each point is plotted versus the angle from nadir to measurement point. CCT decreased over time at all angles.

Figure 23 illustrates both the CCT change over time and the CCT change over angle, and shows the systematic decrease in CCT over the first 4000 hours of operation for each of the measurement points. The measured color variations over time exceeded those that would be expected based on LM-80 data for the LEDs, and exceeded those reported for most of the installations evaluated in the earlier GATEWAY report on interior projects. While determining the root cause of these variations is beyond the scope of this project, other published data[16] may offer possible explanations. These reports identify high ambient and operating temperatures as factors which may contribute to color shift in LED packages, and provide color shift data from accelerated testing methods that are similar to the color shift measured in Yuma. These accelerated testing methods were conducted at elevated temperature and humidity levels, which do not replicate the conditions at Yuma, but they do indicate the possible effects of environmental conditions on the degradation processes associated with color shift. The actual junction temperatures experienced by the LEDs are determined by a combination of the ambient conditions and the thermal design of the luminaire; determining those separate effects was not possible for this project.

5.5 Temperature

As shown previously in Figure 20, the measured LED temperatures often exceeded 65°C in the B2 luminaire when it was operating during the night of June 19, 2016, and were generally about 5°C lower in luminaire A2. Notably, the LED temperatures in both luminaires often exceeded 50°C when the luminaires were not operating during the day on that date. Figure 24 shows that the LED temperatures in both luminaires during the daylight hours on June 19, 2016 (when the luminaires were off) actually exceeded the LED temperatures during the nighttime hours on December 22, 2015 (when the luminaires were on).

16 See reports referenced in *LED Luminaire Reliability: Impact of Color Shift* prepared by the DOE SSL program: https://energy.gov/eere/ssl/technical-reports-briefs.

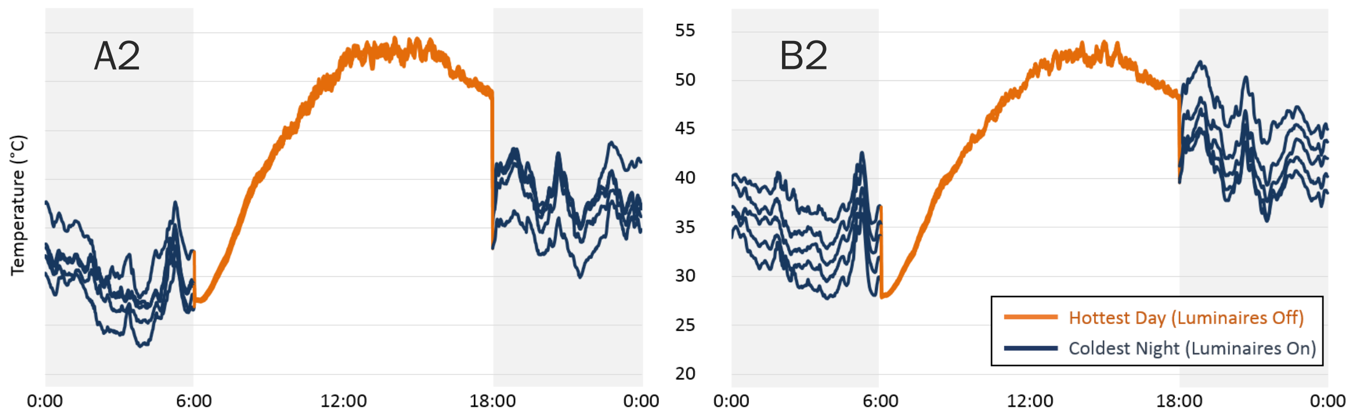

Figure 24. Comparison of June 19, 2016, with Luminaires Off (orange) and December 22, 2015, with Luminaires On (blue).

This figure shows the temperature of the LEDs in two luminaires (A2 and B2) over a 24-hour period, broken into two parts: the orange representing when the luminaires *were not* operational during the day on June 19, 2016 (the warmest date recorded), and the blue representing when the luminaires *were* operating during the night on December 22, 2015 (the coldest date recorded). The measured LED temperatures when the luminaires were off on the warmest day exceeded those when the luminaires were on during the coldest night.

This observation indicates an interesting scenario for the luminaires during the hottest days in Yuma. For example, the LEDs in the B2 luminaire had temperatures of about 30°C at 8:00 AM on June 19, 2016, when the luminaire was off. By noon, the LED temperatures were above 50°C, and remained there for a number of hours before cooling to below 45°C by early evening. At about 8:00 PM, the luminaire turned on, and the temperatures quickly rose to over 70°C as shown in Figure 20. When the luminaire turned off in the pre-dawn twilight on June 20, the LED temperatures rapidly dropped to about 30°C, then almost immediately began to rise with the rising ambient temperatures and increasing solar radiation onto the luminaire housing. Figure 21 in Section 4 illustrates that this cycle repeats daily during the summer in Yuma.

These elevated temperatures and rapid changes in temperature did not cause immediate parametric failure of the luminaires, either of the initial two luminaires or of the full installation that was completed in 2016. Whether or not the high ambient temepratute conditions contributed to the illuminance and SPD changes reported here can not be determined from this project, but the results indicate that further explorations of LED performance under high ambient conditions is warranted.

6 Conclusion and Lessons Learned

The DOE GATEWAY program has evaluated and reported on the Yuma Sector Border Patrol Area lighting retrofit since the initial trial installation of six LED luminaires in February 2014. Lumen and color maintenance, luminaire efficacy, and luminaire component lifetimes are all significant concerns when LED luminaires are exposed to high ambient temperatures such as those encountered in Yuma. Phase 1 of the project compared the initial performance of the trial installation to the incumbent high-intensity discharge lighting system, and documented changes in illuminance and illuminance distribution during the LED luminaires' first 7000 hours of operation. Phase 1 included the removal and laboratory testing of two first-generation LED luminaires, and these were replaced with two second-generation luminaires, each outfitted with nine thermocouples that collected detailed thermal data over the course of a year.

This Phase 2 report documented the performance of the remaining four first-generation trial installation luminaires after 11000 operating hours. The report also included an evaluation of the full installation of second-generation LED luminaires over the initial 4000_2 hours of operation, and a more detailed examination of temperature data that was collected over nearly an entire year. The following list summarizes the key lessons learned based on the extensive data gathered over nearly 4 years in this high-temperature environment, and highlights some ongoing industry needs.

1. The LED lighting systems installed at Yuma, like many other examples documented through GATEWAY and other programs, provided substantial benefits in energy reduction, lighting uniformity, and maintenance savings compared to the incumbent high-intensity discharge system.

2. Reductions in light output due to dirt depreciation for the LED luminaires at Yuma were similar to those predicted using IES luminaire dirt depreciation estimation methods, and similar to those reported for several other LED systems evaluated by the GATEWAY program.[17]

3. During the initial operating period (7000 hours for the first-generation luminaires and 4000 hours for the second-generation luminaires), reductions in average illuminance and changes in illuminance distribution were consistent with variations that could be expected due to dirt depreciation.

4. Illuminance levels produced by the first-generation luminaires decreased dramatically between 7000 and 11000 operating hours. Possible reasons for this unexpected result were explained in this report, but the root causes of these effects are not known at this time. It may be that the causes were related to the unique conditions of the trial installation of first-generation luminaires, but it also may be that the high-temperature environment contributed to these effects.

5. The measured SPDs and related color characteristics for the second-generation luminaires changed over 4000 hours, to a greater extent than expected. The high-temperature environment in Yuma may have caused or at least contributed to these effects, although luminaire design characteristics can also contribute to accelerated shifts in SPD.

6. The second-generation luminaires exhibited color over angle variability that produced noticeable color differences on the illuminated sand beneath the system. Determination of SPD and related color metrics at different angles is not currently included in standardized outdoor luminaire photometric testing. This type of variability may not be as noticeable in other outdoor applications; however, the result demonstrates that as SSL technology continues to evolve, the nature and the extent of the data that product developers, manufacturers, and specifiers need in order to evaluate the performance of products and systems is also changing. The development of relevant testing and reporting procedures and metrics of acceptability necessarily lags behind the identification of the need for certain types of data.

17 See Luminaire dirt depreciation (LDD): Field data from several exterior lighting projects: https://www.energy.gov/eere/ssl/solid-state-lighting.

7. The results from this evaluation highlight the gap that still exists between laboratory-based performance testing of LED products and systems and their in-field performance. While standard test methods such as LM-80 and defined calculation techniques such as TM-21 and TM-28 provide a critical part of the information needed for SSL, the results from this project show that system and field application conditions can make it difficult to predict installed performance over time. These predictions are likely more difficult in extreme conditions, such as those encountered at Yuma.

With more than 40 reports over the last 10 years, the DOE GATEWAY program has evaluated both the advantages and the challenges of many different SSL applications. The multi-year evaluation of the LED installation in Yuma also serves this purpose – while the initial energy, lighting quality, and maintenance benefits relative to the incumbent high-intensity discharge system were well documented and produced very satisfactory results for Customs and Border Protection, the evaluation raises questions regarding the long-term performance of LED systems in high-temperature environments. Ongoing improvement of current test methods and standards for LED luminaires, as well as new approaches to product and system development, are needed to improve performance of LED lighting systems.

Appendix A: Illuminance Measurements

	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		

LED Lighting System Horizontal and Vertical Illuminance Measurements of First Generation Luminaires on Pole 204: 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 each 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 bounds measurements greater than or equal to 30 lx, and the white dashed line bounds 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. 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.

	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		

LED Lighting System Horizontal and Vertical Illuminance Measurements of First Generation Luminaires on Pole 204: 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 each 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 bounds measurements greater than or equal to 30 lx, and the white dashed line bounds measurements greater than or equal to 20 lx. 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.

	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		

LED Lighting System Horizontal and Vertical Illuminance Measurements of First Generation Luminaires on Pole 204: 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 each 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 bounds measurements greater than or equal to 30 lx, and the white dashed line bounds measurements greater than or equal to 20 lx. 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.

	W90	W75	W60	W45	W30	W15	Pole	E15	E30	E45	E60	E75	E90	LED 7000 hr (lx)	
8 ft	3.7	3.8	4.2	4.8	5.7	6.4	6.4	6.2	5.5	4.8	4.1	3.7	3.7	5.1 Avg	Secondary Fence (Vertical)
4 ft	4.5	4.6	4.9	5.6	6.7	6.9	7.2	7.0	6.3	5.2	4.5	4.1	3.8	7.2 Max	
	Secondary Fence													3.7 Min	
N75	2.2	2.6	3.0	3.4	3.8	4.0	4.1	4.1	3.8	3.6	2.9	3.1	2.9	6.8 Avg	3 Rows Closest to Secondary Fence (Horizontal)
N60	3.9	4.4	5.1	5.7	6.7	7.7	7.6	7.6	7.1	6.0	5.4	5.1	4.7	15.1 Max	
N45	7.5	8.0	9.5	10.2	12.8	14.9	15.1	15.1	13.7	11.2	10.3	9.5	8.6	2.2 Min	
N30	11.7	13.5	15.6	18.0	22.3	25.9	26.8	26.9	24.9	19.4	16.9	14.7	12.7	17.5 Avg	All (Horizontal)
N15	14.5	16.9	19.4	24.0	32.4	41.7	45.2	42.8	33.7	24.5	19.9	17.5	15.3	54.7 Max	
Pole	14.9	18.1	22.1	27.4	33.9	42.3	54.7	40.5	32.9	26.8	21.5	18.2	16.0	2.2 Min	
S15	13.9	17.2	21.0	26.3	33.6	41.2	45.3	40.6	33.2	25.6	20.7	17.2	15.2	20.8 Avg	3 Rows Closest to Primary Fence (Horizontal)
S30	12.8	15.5	18.6	20.5	24.3	28.8	29.7	28.1	24.1	18.0	17.3	15.1	13.9	45.3 Max	
S45	10.8	12.7	13.6	15.5	18.1	19.5	19.8	19.0	16.7	13.9	12.5	11.2	10.5	10.5 Min	
	Primary Fence													18.7 Avg	Primary Fence (Vertical)
4 ft	11.8	13.9	18.6	21.8	22.9	25.5	26.0	24.8	20.7	16.2	14.3	12.6	10.9	28.2 Max	
8 ft	10.6	13.3	19.0	22.4	25.9	27.6	28.2	26.4	22.1	16.1	13.4	10.5	9.5	9.5 Min	
	W90	W75	W60	W45	W30	W15	Pole	E15	E30	E45	E60	E75	E90		

LED Lighting System Horizontal and Vertical Illuminance Measurements of First Generation Luminaires on Pole 204: 7000 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 each 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 bounds measurements greater than or equal to 30 lx, and the white dotted line bounds measurements greater than or equal to 20 lx. 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.

Appendix B: Weather Data

Summary of Weather Conditions during Initial, 2500-Hour, 5000-Hour, 7000-Hour, 11000-Hour, Initial$_2$, and 4000$_2$-Hour Measurements.

The table summarizes the measurement weather conditions, as recorded at the Yuma Marine Corps Air Station[18] 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	13°C (55°-56°F); 55%-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 9/16/2014 - 9/17/2014	31°-33°C (87°-91°F); 38%-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°-16°C (56°-60°F); 51%-64%	Waxing Gibbous, 97% Illuminated[d]	Set 7:01 p.m. (3/3); Rise 6:38 a.m. (3/4)	8:15 p.m. to 11:00 p.m.
7000 9/23/2015	31°-34°C (88°-93°F); 33%-44%	Waxing Gibbous, 75% Illuminated[d]	Set 6:58 p.m. (9/23); Rise 6:03 a.m. (9/24)	8:15 p.m. to 11:05 p.m.
11000 9/20/2016 - 9/21/2016	23°-25°C (73°-77°F); 67%-69%	Waning Gibbous, 79% Illuminated[d]	Set 7:01 p.m. (9/20); Rise 6:01 a.m. (9/21)	9:15 p.m. to 12:20 a.m.
11000 and Initial$_2$ 9/21/2016	26°-28°C (79°-82°F); 67%-82%	Waning Gibbous, 68% Illuminated[b]	Set 7:00 p.m. (9/21); Rise 6:02 a.m. (9/22)	7:55 p.m. to 10:45 p.m.
4000$_2$ 8/30/2017	37°-38°C (98°-100°F); 19%-21%	Waxing Gibbous, 64% Illuminated[d]	Set 7:30 p.m. (8/30); Rise 5:47 a.m. (8/31)	9:20 p.m. to 12:05 a.m.

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

18 Weather Underground Historical Weather: wunderground.com/history/.

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