

GATEWAY

Demonstrations



LED System Performance in a Trial Installation—Two Years Later

Host Site: Yuma Border Patrol, Yuma, Arizona

April 2016

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Solid-State Lighting Program
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Prepared by:

Pacific Northwest National
Laboratory

Yuma Border Patrol Area Lighting Retrofit LED System Performance in a Trial Installation – Two Years Later

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

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

Andrea M Wilkerson
Gregory P Sullivan¹
Robert G Davis

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Pacific Northwest National Laboratory
Richland, Washington 99352

¹ Principal, Efficiency Solutions, Inc., Richland WA

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Preface

The GATEWAY Program

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

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The continued support of Harry Hart, the Customs and Border Protection Yuma Sector Program Manager, is greatly appreciated. The technical knowledge and hard work of Dennis Decker and James Espino of Fluoresco Services is gratefully recognized. The ongoing and significant support of Bob Smith and Reed Bradford of Eaton is thankfully acknowledged; the success of the project was greatly facilitated by their commitment to collaboration with the GATEWAY program, and the commitment of their management.

Executive Summary

The Yuma Sector Border Patrol Area is a high temperature and high solar radiation environment, providing an opportunity for the U.S. Department of Energy (DOE) to study thermal effects on outdoor light-emitting diode (LED) luminaires. This is the third report documenting LED luminaire performance in the Yuma Sector. The first report documented the trial installation of six LED luminaires installed in February 2014, comparing them to the incumbent high-intensity discharge lighting system. The second report discussed the performance of the trial system after 2500 and 5000 hours of operation, including unanticipated illuminance changes. These findings led to further investigation of the trial installation to provide possible explanations for those changes; this third report summarizes results of those investigations to date including measurements at 7000 hours of operation.

The distribution of light produced by the LED luminaires changed considerably in the first 2500 hours of operation, and persisted after 5000 and 7000 hours of operation. Comparing the 7000 hour measurements to the initial measurements reveals several important changes in the illuminances delivered by the lighting system:

- The average horizontal illuminance decreased by 25% in the three measurement rows closest to the primary fence (at the border).
- The average vertical illuminance decreased by 34% on the primary fence.
- The distribution of illuminance changed, with values nearest to the pole increasing by more than 10% while the values decreased farther away from the pole, and the greatest percent decreases were at the points farthest from the pole.

The cause of these changes was unknown, but dirt depreciation was expected to explain most if not all of the change in illuminance. In order to understand the effects of dirt, two luminaires were carefully removed for testing in a photometric laboratory, first dirty and then again after cleaning. The testing revealed that luminous intensity values at angles where peak intensity occurs *decreased* due to dirt by 15% to 26%, while the intensity directly beneath the luminaire *increased* due to dirt by 16% to 21%. These results are consistent with the field measurements of illuminance recorded in the Yuma Sector.

The laboratory measurements confirmed the effect of dirt not only on lumen output, but also on the distribution of light exiting the luminaire. The change in distribution raises an important question for manufacturers, specifiers, and researchers: How should lighting system designs account for distribution changes due to dirt accumulation? Careful optical design may lead to superior illuminance uniformity during pre-installation photometric analyses; however, the results from this investigation demonstrate that the uniformity will change as the luminaires accumulate dirt. In practice, this finding indicates that the effects of an optimized optical design can be compromised by dirt accumulation, and sustained performance may require regular maintenance.

Documentation of the Yuma Sector Border Patrol Area lighting LED trial demonstration continues to provide a better understanding of LED technology performance in a high ambient temperature and high solar radiation environment. Two next-generation luminaires replaced the original LED luminaires removed for laboratory testing. These next-generation luminaires were modified with thermocouples installed so that the temperature of various luminaire components could be recorded at one-minute intervals. These measurements began in September 2015 and are expected to continue into the summer of 2016, providing a more complete picture of the effects of high ambient temperatures and high levels of solar radiation. A future report is planned to address the performance of the luminaires after continued exposure to this extreme environment.

Acronyms and Abbreviations

CCT	correlated color temperature
CRI	color rendering index
DOE	U.S. Department of Energy
ESPC	Energy Savings Performance Contract
IES	Illuminating Engineering Society
IGA	investment grade audit
LDD	luminaire dirt depreciation
LLD	LED package lumen depreciation
LLF	light loss factor
NVLAP	National Voluntary Laboratory Accreditation Program
POE	Port of Entry
QMH	quartz metal halide
SPD	spectral power distribution
SSL	solid-state lighting
TMP _{LED}	LED package temperature measurement point
TMP _{PS}	LED driver temperature measurement point

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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 documented by the U.S. Department of Energy (DOE) Solid-State Lighting (SSL) GATEWAY program.

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

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 further investigation of the trial installation to document and provide possible explanations for those changes; this report summarizes the results of those investigations to date.

Each report for this project is described below. The Phase 1 reports focus on the trial installation of the six LED luminaires in the Yuma Sector. The full installation of LED luminaires along this section of the border is expected; if that installation occurs, future reports (Phase 2) will summarize the performance at the time of installation and the long-term performance of the LED luminaires in the high ambient temperature environment.

- **Yuma Phase 1.0 Report: Investment Grade Audit Trial Demonstration (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 at the initial installation.
- **Yuma Phase 1.2 Report: LED System Performance - Two Years Later (Current Report)**
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 Report: Initial Assessment of Full Installation (Pending)**
Will summarize the installation and initial performance of the lighting system, focusing on a subset of the overall lighting system. Plans include field and laboratory measurements.

¹ For further information, download the Yuma Border Patrol Area Lighting Retrofit: Trial Demonstration report and Yuma Border Patrol Area Lighting Retrofit: LED System Performance in a Trial Installation-One Year Later report prepared by the DOE SSL program: <http://energy.gov/eere/ssl/downloads/trial-demonstration-area-lighting-retrofit>.

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

2.1 Trial System Design

To reduce the required luminous flux from the LED luminaires, the height of these poles was reduced from 64 ft to 40 ft, and the LED luminaires were designed to provide uniform illumination from the lower pole height. Pole 203 is shown in Figure 1, with the incumbent lighting system trailing into the distance toward the POE. Two LED luminaires were installed per pole with a custom tenon mount, pictured in Figure 2, replacing the three 1000 W QMH luminaires. The LED system was designed to replace only the two end QMH luminaires because the middle luminaire was not operational and the amount of light provided by the two QMH luminaires was considered acceptable. The long-term goal is to replace the QMH lighting system with an alternative that achieves a minimum energy savings of 50% while maintaining existing light levels.



Figure 1. Trial Demonstration Site on the U.S.-Mexico Border. Photo taken 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 is on the left and the secondary fence is on the right.

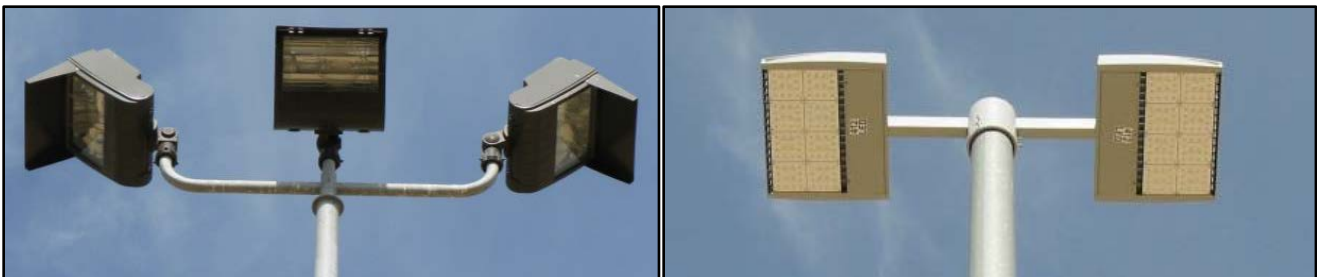


Figure 2. Incumbent QMH Luminaires (left) and LED Luminaires (right). A custom tenon was necessary to fit the diameter of the pole after the pole height was reduced to 40 ft, because the diameter of the tapered pole narrowed as the height increased. The QMH luminaires were originally installed with the lens tilted up from horizontal and shielded with visors to minimize stray light. In contrast, the LED luminaires were installed with luminous aperture horizontal (i.e., not tilted upward).

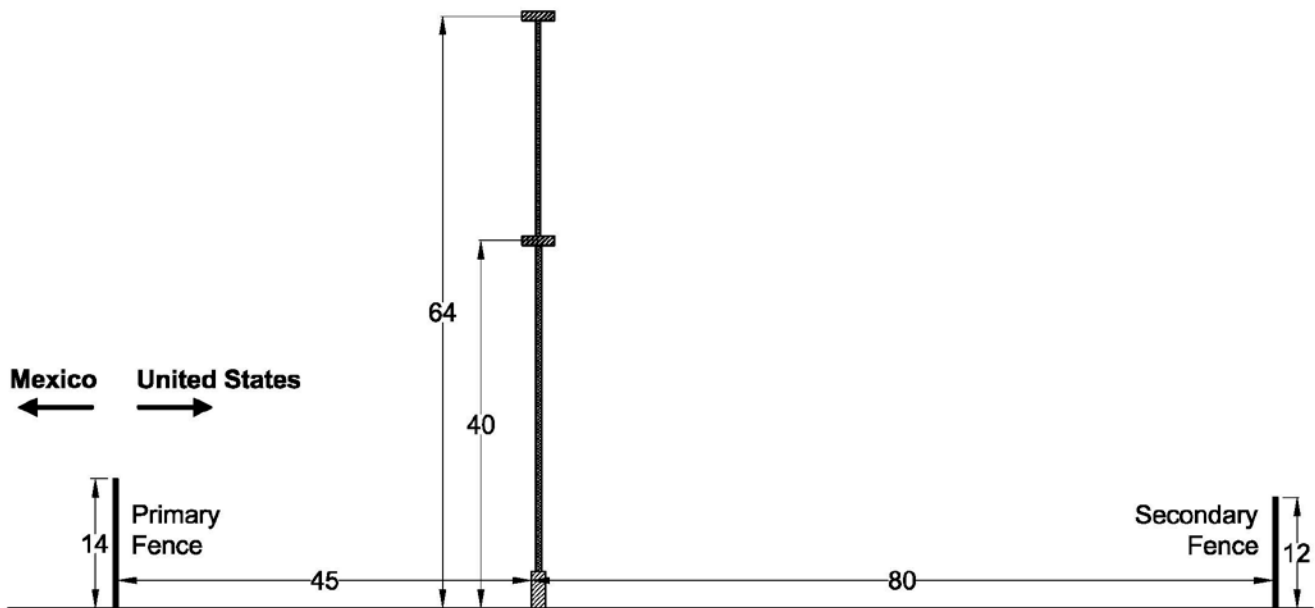


Figure 3. Schematic Elevation of the Yuma Sector Border Patrol Area East of the San Luis Port of Entry. The dimensions are not exact, but are representative of the 7.2 mile border area east of the POE. All dimensions are in feet. The elevation near the secondary fence was approximately 2 to 4 ft higher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

The 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 have eight light squares,¹ each with Illuminating Engineering Society (IES) Type III luminous intensity distribution (as defined in Annex E of IES RP-8-14). Six light squares illuminate the area between the pole and primary fence, a distance of 45 ft, and two of the light squares are rotated 180° to illuminate the 80 ft distance between the poles and secondary fence. The 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 was initiated from the middle of the primary (south) face of the concrete pole pedestal at pole 204, with measurement points spaced uniformly at 15 ft intervals in both directions (north-south and east-west) as illustrated in Figure 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.

¹ *Light squares* and *bars* are terms used by some luminaire manufacturers to describe the scalable lumen output characteristic of their luminaires.

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.

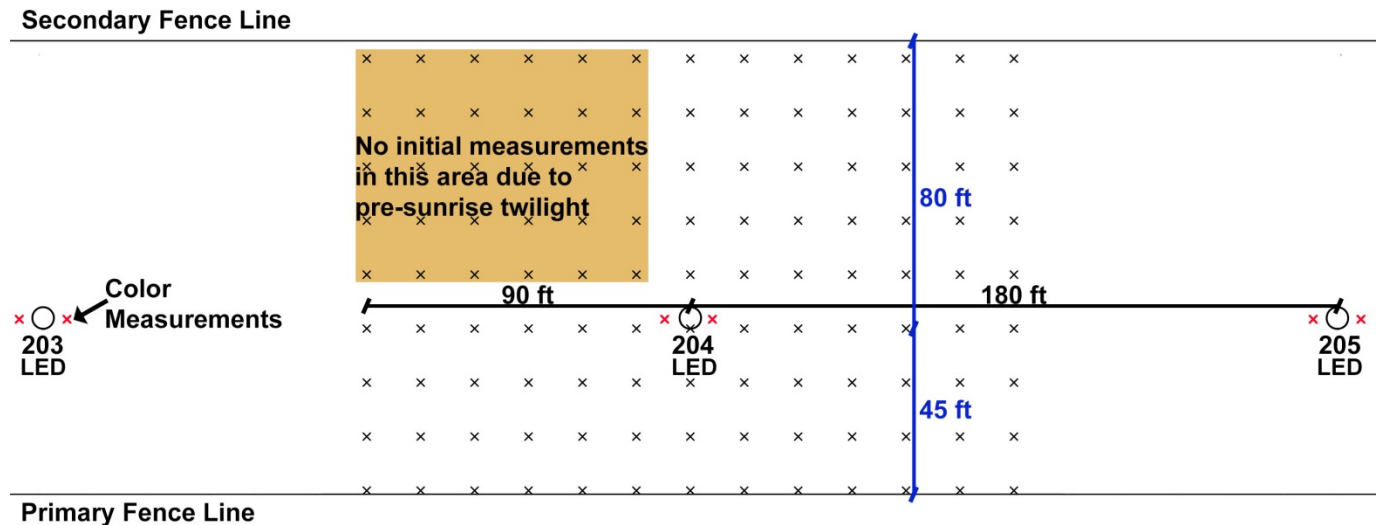


Figure 4. Layout of Grid Measurements. The measurements between poles 203 and 205 were recorded in a rectangular grid from the middle of the primary (south) face of the concrete pole pedestal at pole 204, with uniform 15 ft spacing in both directions. The horizontal measurements were recorded approximately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



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 sheet, the luminaire manufacturer listed five different lumen multipliers corresponding to temperature points ranging from 10 to 50 °C (50 to 122 °F), as

listed in Table 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.

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

Table 2. Lumen Multiplier Used for Initial, 2500, 5000, and 7000 Hour Measurements. The lumen multipliers were calculated for the specific average temperature during the measurements by linearly interpolating between the temperatures provided by the manufacturer. Measured values were divided by the corresponding lumen multiplier to normalize all values to a 25 °C (77 °F) condition.

Hours of Operation	Average Measurement Temperature	Lumen Multiplier
Initial	13 °C (55 °F)	1.03
2500	32 °C (90 °F)	0.98
5000	15 °C (59 °F)	1.03
7000	33 °C (92 °F)	0.98

3. Photometric Measurements and Comparisons

The initial illuminance measurements of the new 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 2500¹ 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 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 luminaires that had been instrumented with thermocouples. 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 taken to a local laboratory for photometric testing before being shipped to another laboratory for additional testing and analysis.

3.1 Laboratory Measurements and Comparisons

The laboratory testing of the luminaires was first conducted at LightLab International in Phoenix, AZ, followed by additional testing at Eaton's Cooper Lighting Photometric Laboratory² in Peachtree City, GA. The laboratory testing in Phoenix was completed to replicate in-field conditions as closely as possible by removing and transporting the luminaires from the site near Yuma to Phoenix. The goal was to test both luminaires in Phoenix in their "dirty" condition, but due to the failure of one of the two LED drivers in luminaire A at the laboratory, only luminaire B was tested. The luminaires were then carefully packaged (still in their dirty condition) and shipped to Eaton in Georgia, where the drivers in luminaire A were replaced and both luminaires were tested, first dirty and then again after cleaning. A total of five IES LM-79 goniophotometer tests were therefore completed, three for luminaire B and two for luminaire A, summarized in Table 3. Figure 6 illustrates the orientation of each luminaire relative to the primary and secondary fences.

Whenever a luminaire is removed from an installation for testing, the process of removal, packing, and shipping is likely to affect the accumulated dirt on the luminaire surfaces. For this project, the research team decided to conduct full testing of the luminaires at the Eaton laboratory to more easily enable proper cleaning and inspection of the optical elements after initial "as-is" tests were conducted. The laboratory testing conducted by LightLab in Phoenix was done to provide closely estimate the field conditions, before the luminaires were packed and shipped to the Eaton laboratory in Georgia. However, even for testing at a local facility, some of the dirt accumulation on the luminaires may have been affected as the luminaires were removed and transported by personal vehicle to Phoenix. The electrician did his best to minimize contact with the luminaire lenses and other optical surfaces when removing and packing the luminaires, but completely avoiding contact was not possible due to the size and weight of the luminaires. The electrician photographed the original LED luminaires before removing them, to document the "as-is" condition.

¹ The hours of operation were calculated based on the length of the day, the time between sunset and sunrise, which is approximately when the photocontrols turned the luminaires on and off.

² Both laboratories at the time of testing were accredited by the National Voluntary Laboratory Accreditation Program (NVLAP) for testing energy efficient lighting products including SSL luminous intensity measurements, as listed by NVLAP's website: www.nist.gov/nvlap/.

Table 3. Laboratory Test Results. The notation indicates if 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-symmetric 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.

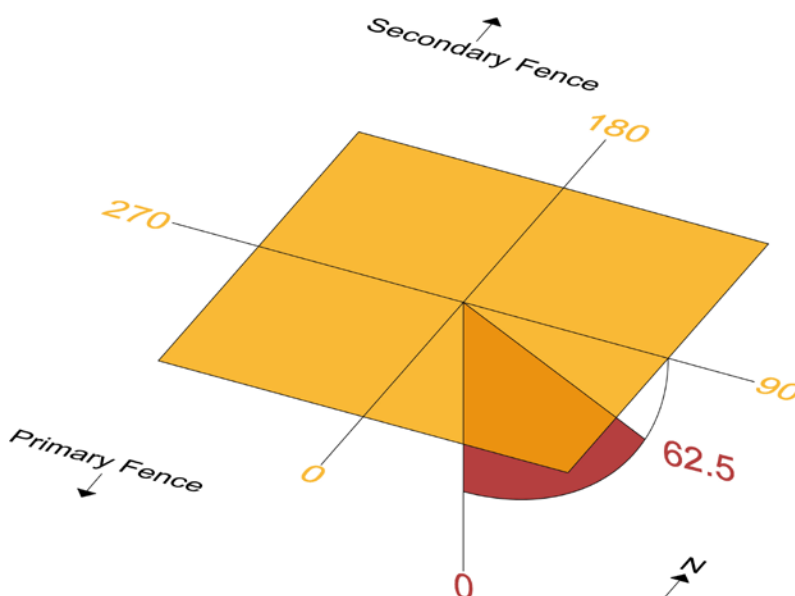


Figure 6. Luminaire Orientation Schematic. The horizontal angles (gold) are used to describe the photometric performance of the luminaire, and the 62.5° vertical angle (red) is illustrated in the 90° horizontal plane. View is from above.

The shipping of the luminaires from LightLab to Eaton was also done carefully, but further changes in the dirt accumulation may have occurred in shipping. As shown in Table 3, the results from the “as-is” or “dirty” test of luminaire B at the Eaton laboratory showed 3% to 5% higher output than the test of the same luminaire conducted at LightLab. This finding may indicate that some dirt was removed from the luminaire during packing and shipping, but it is also within the range of variation typically found in round-robin laboratory testing conducted by industry groups.^{1,2} Implications are further explored in Section 5.1, along with detailed comparisons of the “dirty” versus “clean” tests of the two luminaires.

¹ Summary Report on Testing Variability and Repeatability prepared by the DOE SSL program: www.cornusa.org/uploads/CORM_2009_Paget-CALiPER_Variability.pdf.

² Solid State Lighting Annex: 2013 Interlaboratory Comparison prepared by the International Energy Agency 4E Solid State Lighting Annex Task 2 and Task 3: ssl.iea-4e.org/files/otherfiles/0000/0067/IC2013_Final_Report_final_10.09.2014a.pdf.

The LM-79 test of luminaire B completed at LightLab also recorded colorimetric data. As described in the Phase 1.0 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 the initial 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 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 2012 LM-79 test reports submitted by Eaton to the DesignLights Consortium.

Measurement Location	Hours	Chromaticity Coordinates		CCT	D _{uv}	CRI	R ₉
		x	y				
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

3.2 Field Measurements - Illuminance

Results of the initial, 2500 and 5000 hour measurements were previously reported¹ and are included in Appendix A, and detailed weather data for each measurement set is included in Appendix B. The same measurement methodology was repeated in September 2015 at 7000 hours of operation, resulting in the temperature-corrected measurements listed in Figure 7. All six luminaires remained operational and had not been adjusted, cleaned, or otherwise maintained since installed in February 2014.

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 report, the distribution of light produced by the LED luminaires changed considerably in the first 2500 hours of operation, and the trend continued at the 5000 hour measurements. These changes persisted through 7000 hours of operation.

Comparing the 7000 hour measurements to the initial measurements reveals several important changes in the illuminances delivered by the lighting system:

- The average horizontal illuminance decreased by 25% in the three measurement rows closest to the primary fence.
- The average vertical illuminance decreased by 34% on the primary fence.
- The average vertical illuminance on the secondary fence decreased slightly.
- The distribution of illuminance changed, with values nearest to the pole increasing by more than 10% while the values decreased farther away from the pole, and the greatest decreases were at the points farthest from the pole.

¹ Yuma Border Patrol Area Lighting Retrofit: Trial Demonstration: energy.gov/eere/ssl/downloads/trial-demonstration-area-lighting-retrofit.

The change in distribution between the initial measurements and 2500 hour measurements, along with the continued decrease of light farther away from pole 204, is illustrated in Figure 8. The summary of the horizontal and vertical measurements is listed in Table 5.

	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		

Figure 7. LED Lighting System Horizontal and Vertical Illuminance Measurements: 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 lux (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.

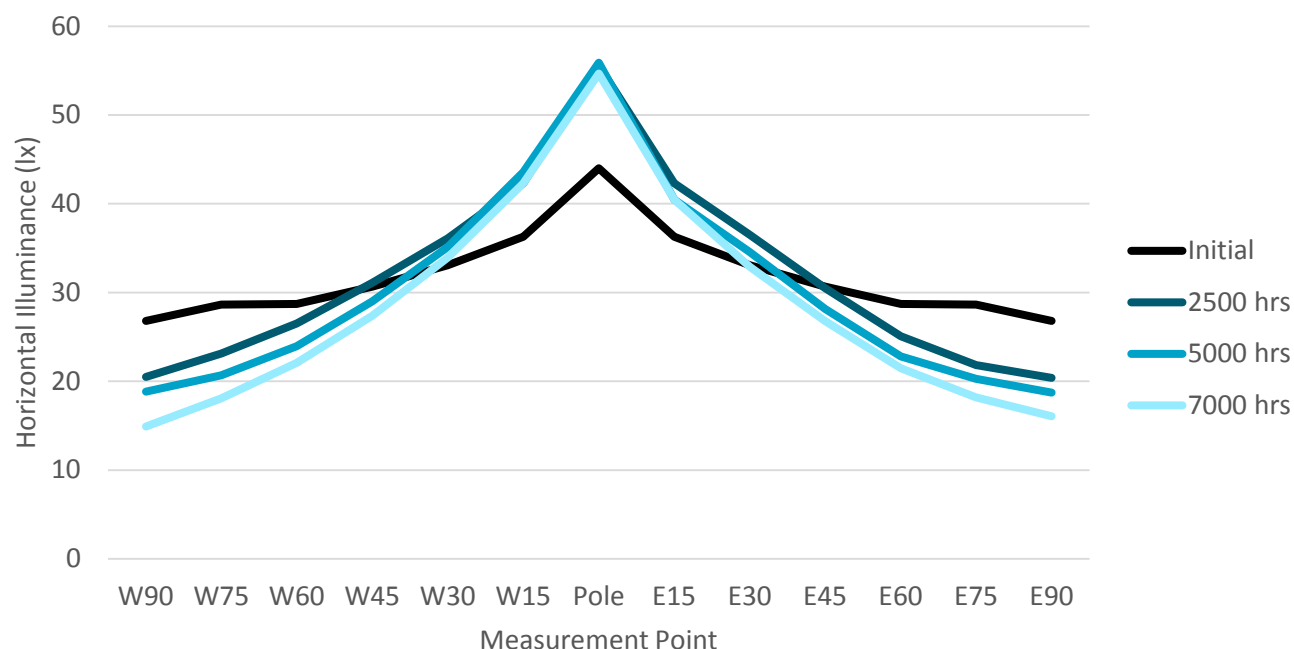


Figure 8. Measured Illuminances along East-West Line Centered at Pole 204 at Four Different Measurement Times. Illuminance values increased near the pole compared to the initial values, but decreased farther away from the pole. The numeric values in the labels along the horizontal axis indicate the distance from the pole in feet, and the letter indicates the direction from the pole. Illuminance values were normalized for a 25 °C (77 °F) condition.

Table 5. LED Lighting System Horizontal and Vertical Illuminance Values. The table summarizes the measured illuminance values 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
3 Rows Closest to Secondary Fence (Horizontal)	Initial	8.1	14.9	3.7	4.1	2.2
	2500	7.3	15.5	2.5	6.1	2.9
	5000	7.2	15.5	3.1	5.0	2.3
	7000	6.8	15.1	2.2	6.7	3.0
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
3 Rows Closest to Primary Fence (Horizontal)	Initial	27.6	40.2	20.4	2.0	1.4
	2500	23.4	46.8	12.9	3.6	1.8
	5000	22.5	45.4	13.9	3.3	1.6
	7000	20.8	45.3	10.5	4.3	2.0
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

4. Temperature Measurements and Comparisons

Prior to field-installation, two later-generation LED luminaires were each instrumented with nine Type J thermocouples. The luminaires were installed in the field on September 24, 2015, with the temperature measurements beginning later that day. This report covers a period spanning 148 days, from September 25, 2015 through February 19, 2016. The analysis focuses on the hottest ambient temperature day (September 25, 2015), and includes comparisons to the coldest ambient temperature day (December 16, 2015) and typical ambient temperature day¹ (November 22, 2015).

4.1 Field Measurements - Temperature

Each luminaire has eight internal thermocouples: one placed at the temperature measurement point (TMP_{LED}) of each of six LED packages (locations shown in Figure 9), one attached to the interior top surface of the luminaire housing, and one attached to the temperature measurement point (TMP_{PS}) of one of the two LED drivers per luminaire.² An additional thermocouple measures the ambient air temperature outside each luminaire, shown in Figure 10.

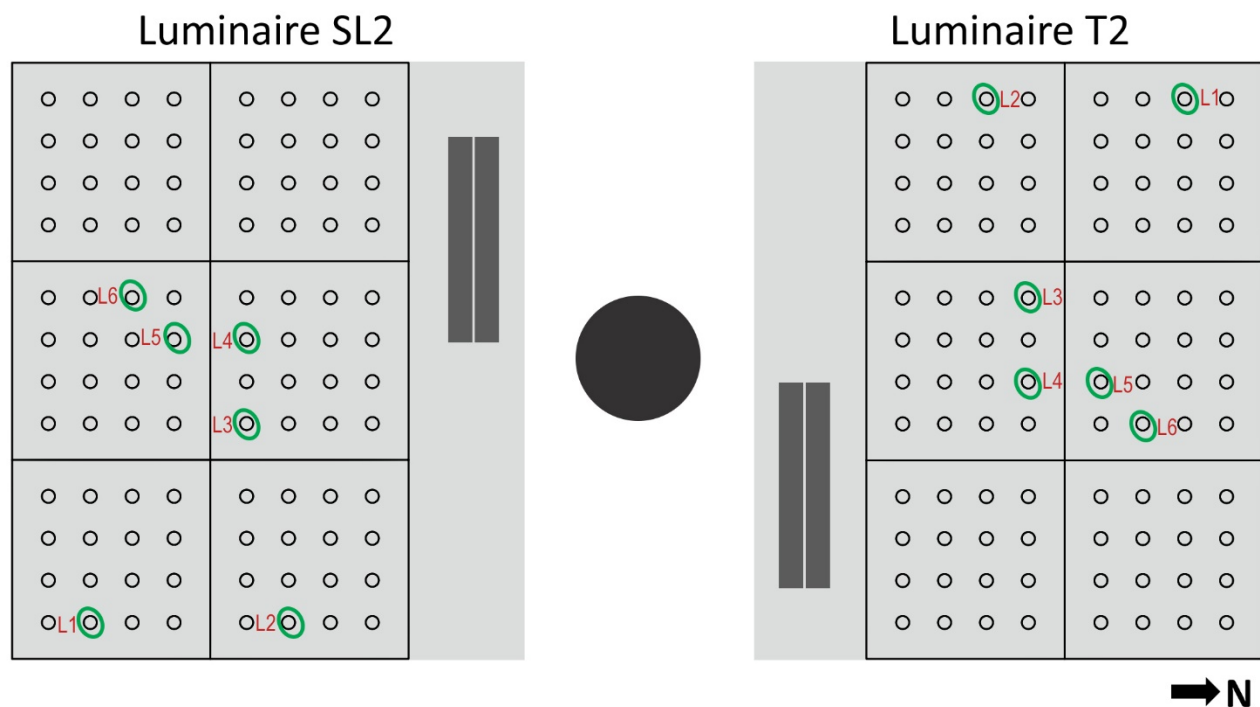


Figure 9. LED Thermocouple Placement Schematic. The green ovals indicate the six LED packages in each luminaire that had thermocouples installed on the TMP_{LED}. The view of the luminaires is from below. The dark gray rectangles indicate the general location of the two drivers per luminaire, and the solid black circle represents pole 204. When the next-generation luminaires were added to the pole, they were oriented 90 degrees relative to the luminaires they replaced (luminaires A and B) for optimal performance. The next-generation luminaires have six squares and an optical design that differs from the original LED luminaires.

¹ The typical ambient temperature day is defined as the day that is closest to the averages of the daily max, min and average temperatures during this 148 day period.

² The DLC uses the terms TMP_{LED} and TMP_{PS} 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 TMP_{LED} and TMP_C (www.energystar.gov/luminaires).



Figure 10. Luminaires Instrumented with Thermocouples. Eight thermocouples were placed on the internal components of each luminaire and one thermocouple measures the ambient temperature at each luminaire, shielded by the cylinder hanging from the luminaire and attached to a small block of metal that was suspended down the center of the cylinder. The two luminaires are within the same product family, but with different optical designs as indicated by T2 and SL2.

The thermocouple wires are about 60 ft long, extending from the luminaires through the tenon and pole, into the data logger enclosure at the base of the pole. This vented, weatherproof enclosure houses five Hobo Onset UX120 four-channel thermocouple loggers, shown in Figure 11. The five loggers can record measurements for up to four thermocouples each, for a total of 20 possible measurements. Eighteen thermocouples were used for the luminaires, with an additional thermocouple measuring the internal ambient temperature of the enclosure (for verification that the temperature did not exceed the rated temperature of the data loggers) and another thermocouple measuring the ambient temperature outside of the enclosure, using a solar radiation shield to block the thermocouple from direct sun (for comparison to the ambient measurements taken at the luminaire). The data loggers store the data at one-minute intervals and are periodically downloaded on-site.

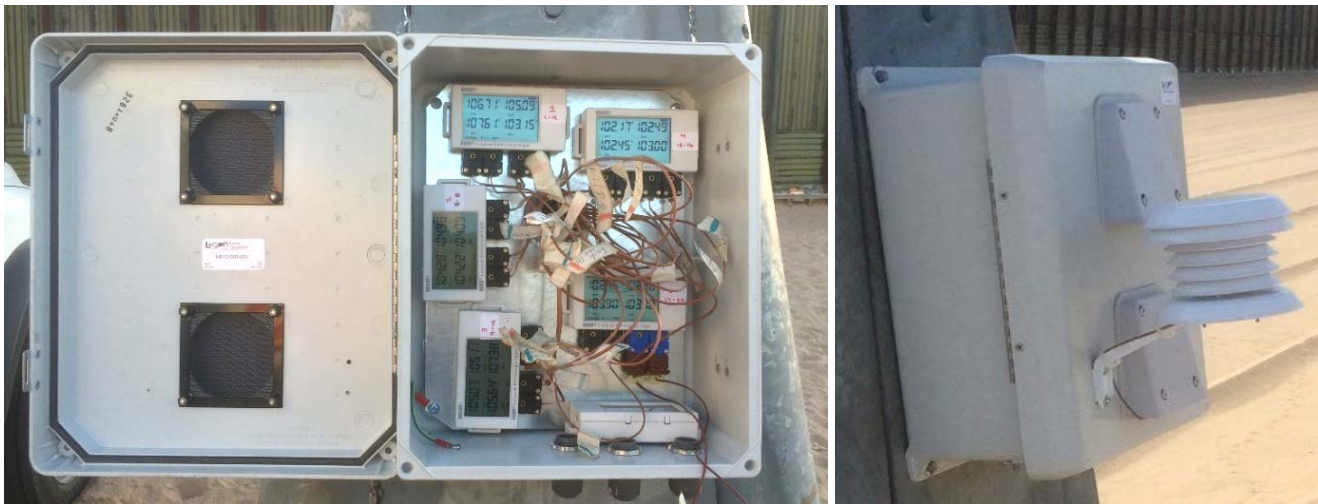


Figure 11. Data Logger Enclosure. The interior of the data logger enclosure (left photo) houses the five active data loggers, plus an extra substitute logger. Attached to the exterior (right photo) is the solar radiation shield.

4.2 Measurement Comparisons

The temperatures measured on the hottest, coldest, and typical days are summarized in Table 6 for the two luminaires. The two luminaires are from the same product family and are the same wattage, but with two different optical distributions. Luminaire T2 has a nominal IES Type II distribution, and SL2 has a similar distribution with spill control so less light exits behind the luminaire. The LED packages in T2 were almost always warmer than SL2, while the SL2 driver was always warmer than T2. The LED package maximum temperatures were always higher than the driver temperatures, with the minimum LED package temperatures lower than the driver temperatures, and the averages close to each other. These differences are illustrated in Figure 12. The LED package and driver temperatures were more similar to each other than to the ambient and

housing temperatures for both luminaires. On the hottest day, there was a large range in the higher temperatures, particularly for the LED packages.

Table 6. Temperature Measurement Summary: September 25, 2015 to February 19, 2016. The table lists temperature statistics for the hottest day, a typical day, and the coldest day. The typical day was defined as the day that was closest to the averages of the daily max, min, and average temperatures during this 148 day period.

Day Type Date	Metric	Ambient (°C)		LEDs (°C)		Driver (°C)		Top of Interior Housing (°C)	
		SL2	T2	SL2	T2	SL2	T2	SL2	T2
Hottest Day 9/25/15	Max	43.6	45.8	67.9	75.0	64.6	59.8	50.4	49.8
	Min	27.5	27.8	28.5	29.5	36.3	34.4	32.9	32.3
	Ave	35.3	36.1	52.0	54.5	52.7	50.1	42.2	41.5
Typical Day 11/22/15	Max	26.5	27.5	47.9	55.2	47.4	41.3	29.3	29.4
	Min	12.0	11.9	12.1	11.9	18.8	17.1	15.4	14.9
	Ave	18.9	19.5	33.0	35.3	35.6	31.8	23.2	23.0
Coldest Day 12/16/15	Max	15.6	20.4	43.8	52.0	40.8	34.5	19.8	18.9
	Min	1.6	-3.5	2.3	1.7	9.2	7.1	5.4	5.0
	Ave	8.9	9.5	25.3	27.4	27.2	22.8	14.1	13.9

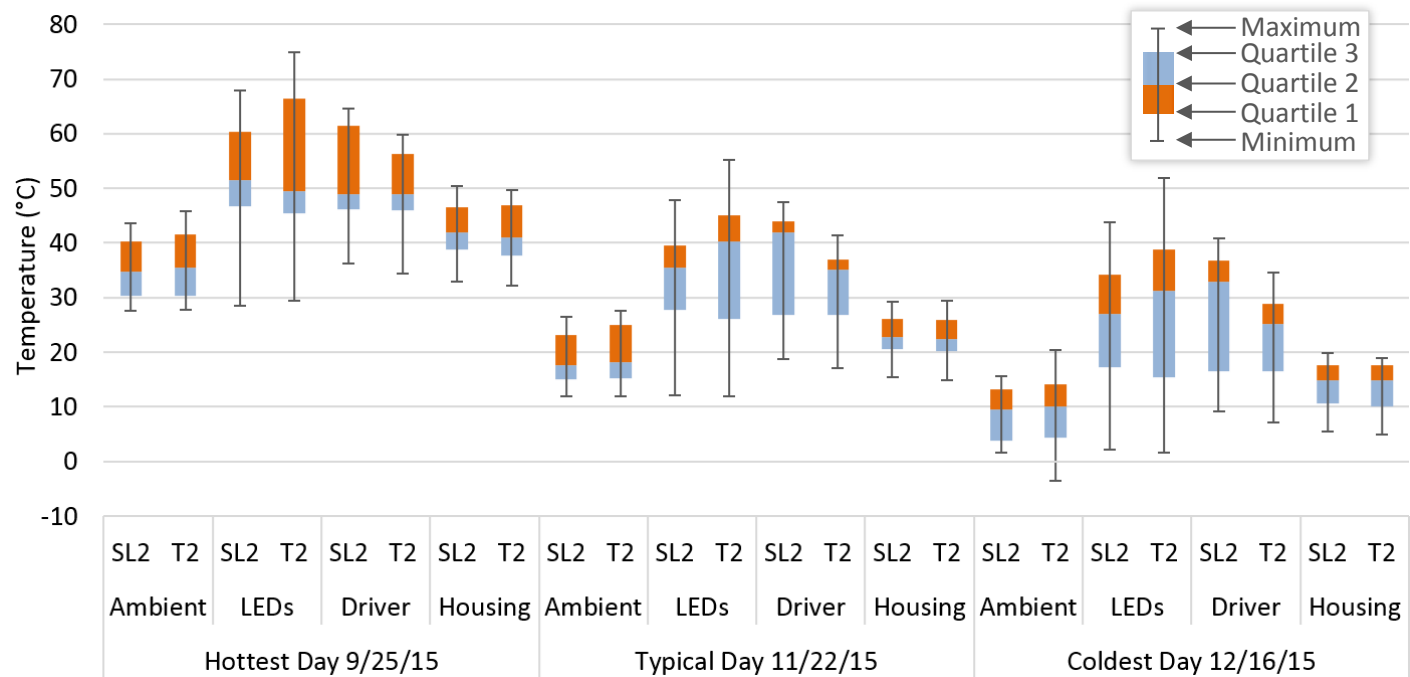


Figure 12. Temperature Measurement Box and Whisker Plot: September 25, 2015 to February 19, 2016. The box-plot shows the temperatures on the hottest day, a typical day, and the coldest day. The ends of the whiskers represent the maximum and minimum of all of the one-minute interval data. The typical day was defined as the day that was closest to the averages of the daily max, min, and average temperatures during this 148 day period.

Figure 13 disaggregates the LED package data, showing the variation in temperature between the LED packages. The LED packages at the outer edge of the luminaire are L1 and L2, and the remaining LED packages measured are located in the center of the luminaire. L1 reached temperatures similar to the internal LED packages (L3, L4, L5, L6), while L2 operated at slightly lower temperatures in both luminaires. The L6 temperature measurements

are not included for luminaire T2 in this report. Data from this thermocouple were very different from the data from others, perhaps due to a faulty thermocouple or improper placement of the thermocouple.

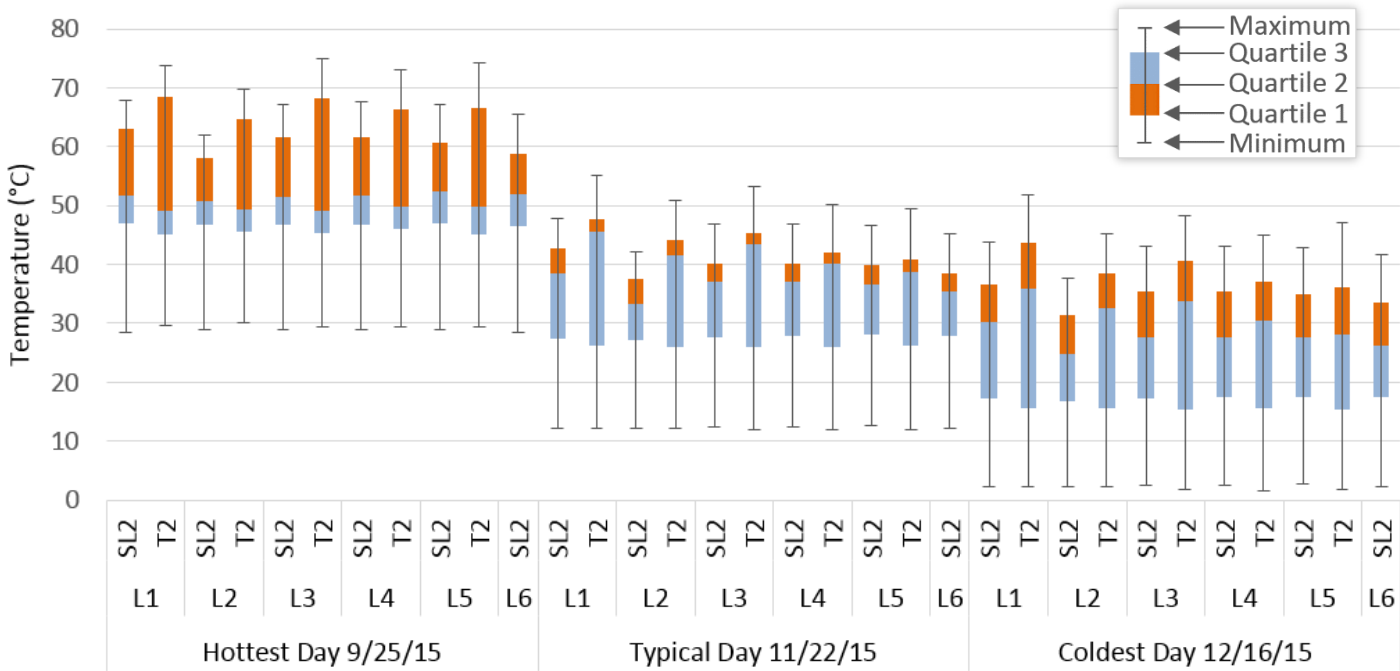


Figure 13. LED Temperature Measurement Box and Whisker Plot: September 25, 2015 to February 19, 2016. The box-plot shows the range of temperatures on the hottest day, a typical day, and the coldest day. The ends of the whiskers represent the maximum and minimum of the one-minute interval data. T2 L6 was not included in the analysis. The typical day was defined as the day that was closest to the averages of the daily max, min and average temperatures during this 148 day time period.

The change in temperatures over the span of the hottest day (September 25) and into the morning of the next day is plotted in Figure 14. The LED packages operated at temperatures similar to the driver for luminaire SL2, and operated above the driver temperature in T2. 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 there was increasing separation between the luminaire components and the ambient temperature, and as the sun set the temperatures returned to similar values until the luminaires began operating.

The temperatures over the span of the hottest week, September 25 to October 1, 2015, are plotted in Figure 15. The pattern remained similar throughout the week. Luminaire component temperatures increased on September 29 during the day, yet ambient temperatures remained similar. This is likely due to an increase in solar radiation, as suggested by the housing interior temperature.

To further research the effects of prolonged exposure to high temperatures and thermal cycling, the thermocouple data will be recorded into the summer of 2016. The data will be collected until the test luminaires are removed as part of the Phase 2 installation of the final LED luminaires along the 7.2 miles of the border; a report summarizing all of the collected data will be issued thereafter.

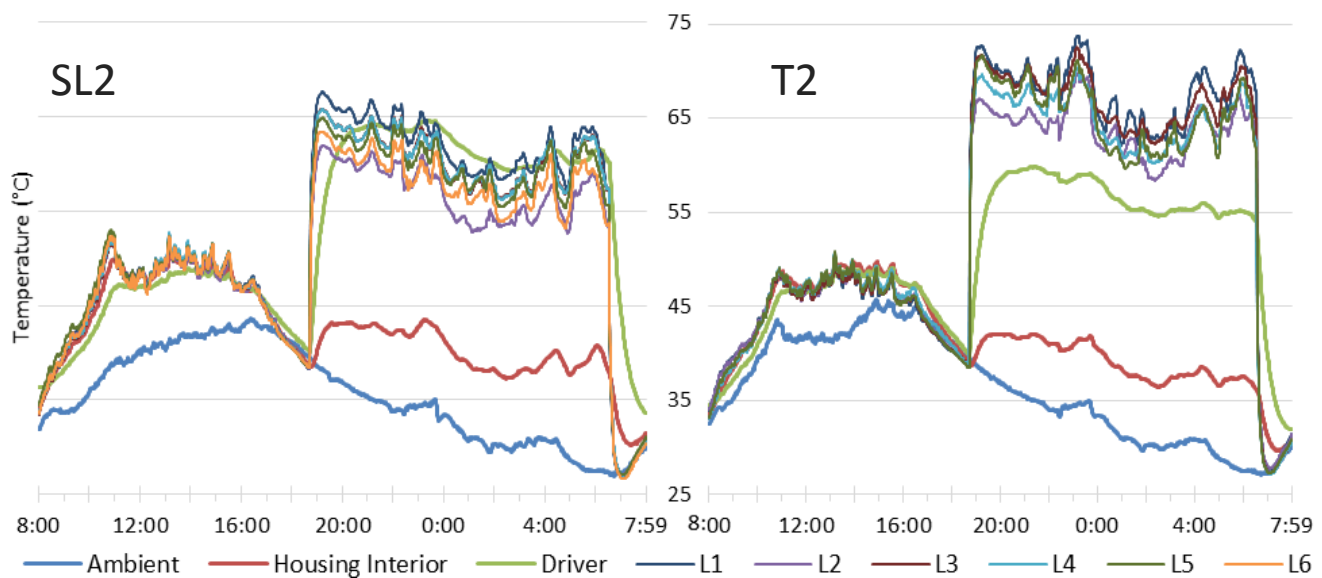


Figure 14. Thermocouple Measurements: September 25 8:00 a.m. to September 26 7:59 a.m., 2015. The one-minute interval thermocouple measurements for the hottest ambient temperature day recorded for luminaires SL2 and T2.

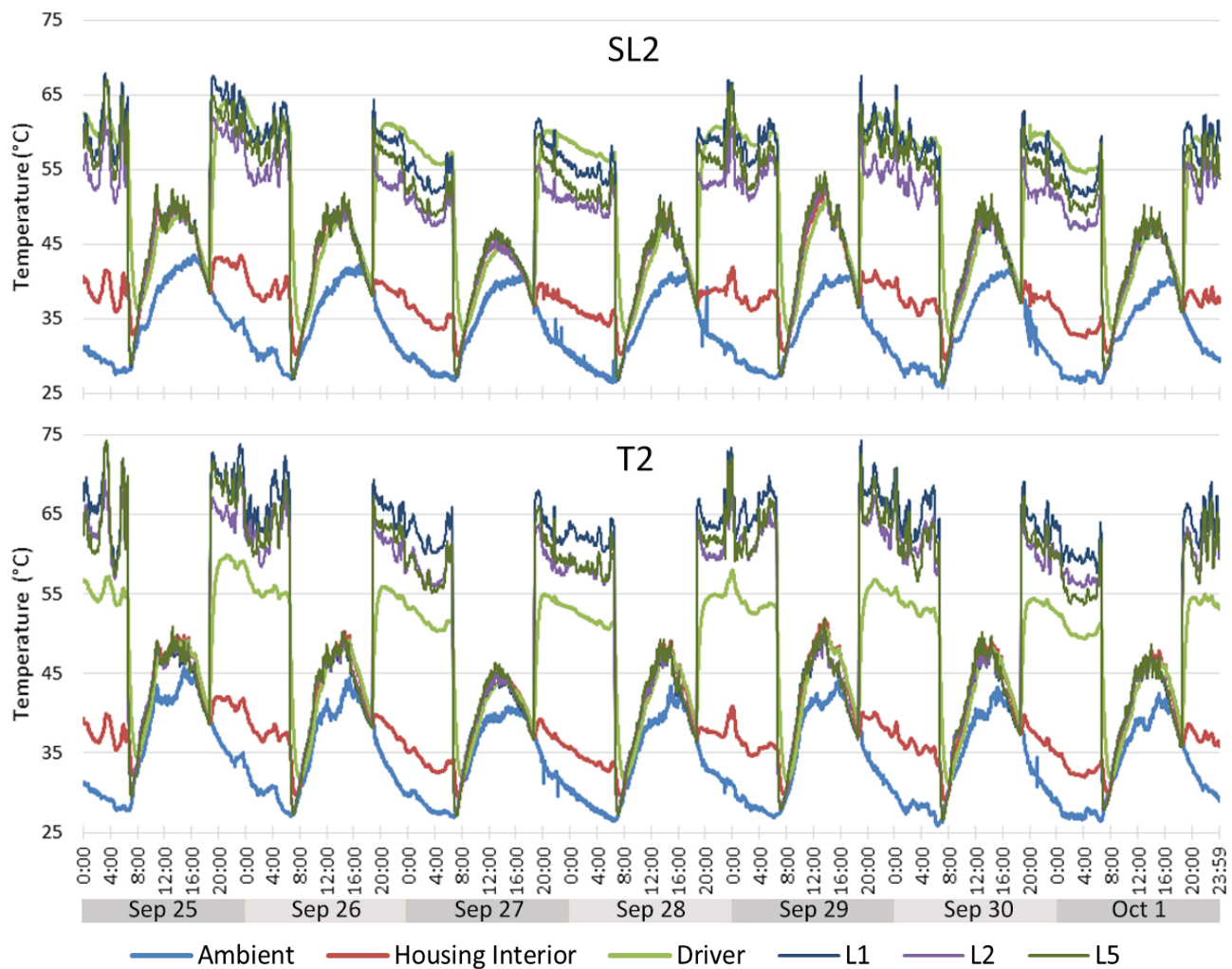


Figure 15. Thermocouple Measurements: September 25 to October 1, 2015. The one-minute interval thermocouple measurements for the hottest ambient temperature week recorded for luminaires SL2 and T2. Only L1, L2 and L5 are shown to aide visibility of the temperature. L1 is typically the hottest, L2 is typically the coolest and L5 varies between the temperatures of L1 and L2.

5. Discussion

5.1 Dirt Depreciation

Depreciation in light output due to the accumulation of dirt on luminaire surfaces is a well-known effect, and is accounted for in lighting calculations through the luminaire dirt depreciation (LDD) light loss factor. The LDD factor is expressed as the percentage of light that will be maintained by a lighting system, given certain assumptions about the amount of time the luminaire has been exposed to the environment, the operating environmental conditions, and the type of luminaire. Although the LDD estimation methods described in the IES Handbook¹ focus on interior lighting, the same principles are incorporated into the IES Recommended Practice for Roadway Lighting.²

While the LDD factor estimates the overall reduction in light output from luminaires due to dirt accumulation, it does not estimate changes in light distribution that may be caused by dirt. For optics such as those common to exterior luminaires that spread light over large areas by delivering high intensity at high angles, this diffusion tends to increase the luminous intensity at low angles (close to nadir) and decrease the intensity at high angles. This phenomenon was reported in an earlier GATEWAY study of roadway lighting on the I-35 West Bridge in Minneapolis, where accumulated dirt on luminaires removed from the installation was shown to increase the luminous intensity values at low angles near nadir (0°) while decreasing the intensities at higher angles above 40° from nadir.³

The measured illuminances at the Yuma site, as shown in Figure 8, are consistent with this understanding of the effects of dirt on intensity distribution. The illuminances directly beneath and near the luminaire have increased relative to the initial measurements, while they have decreased farther away from the luminaire, at angles where the luminaire is designed to provide peak intensity. Figure 16 provides a more in-depth look at the illuminance changes. The black values in this figure show relative increases in illuminance over time, while the red values show relative decreases. Illuminances near the pole have increased, while those farther away have decreased.

¹ DiLaura et al. IES 10th Edition Lighting Handbook, pp. 10.28-10.30.

² Illuminating Engineering Society. ANSI/IES RP-8-14: Roadway Lighting, p. 35.

³ For further information, download the Long-term Testing Results for the 2008 Installation of LED Luminaires at the I-35 West Bridge in Minneapolis report: eere.energy.gov/buildings/ssl/pdfs/gateway_i-35w_phasel1.pdf.

		W90	W75	W60	W45	W30	W15	Pole	E15	E30	E45	E60	E75	E90
Vertical	8 ft	0.12	0.10	0.06	0.01	0.03	0.02	0.01	0.04	0.07	0.05	0.09	0.18	0.21
	4 ft	0.02	0.02	0.01	0.01	0.03	0.04	0.03	0.05	0.08	0.14	0.19	0.25	0.34
Secondary Fence														
Horizontal	N75							0.08	0.04	0.07	0.10	0.26	0.19	0.22
	N60							0.03	0.01	0.01	0.11	0.19	0.21	0.27
	N45							0.02	0.03	0.00	0.13	0.18	0.27	0.34
	N30							0.05	0.06	0.05	0.12	0.23	0.29	0.34
	N15							0.11	0.10	0.03	0.10	0.25	0.32	0.39
	Pole	0.44	0.37	0.23	0.11	0.03	0.17	0.24	0.12	0.01	0.13	0.25	0.36	0.40
	S15	0.49	0.38	0.27	0.12	0.00	0.09	0.13	0.07	0.06	0.21	0.34	0.42	0.44
	S30	0.51	0.42	0.31	0.24	0.13	0.01	0.02	0.05	0.19	0.36	0.42	0.48	0.47
	S45	0.52	0.45	0.37	0.27	0.20	0.16	0.16	0.21	0.28	0.36	0.44	0.49	0.48
Primary Fence														
Vertical	4 ft	0.51	0.45	0.31	0.23	0.23	0.20	0.15	0.20	0.29	0.37	0.48	0.50	0.54
	8 ft	0.49	0.42	0.29	0.29	0.21	0.22	0.21	0.25	0.34	0.48	0.52	0.54	0.54
		W90	W75	W60	W45	W30	W15	Pole	E15	E30	E45	E60	E75	E90

Figure 16. Difference in Measured Illuminance over Time: Initial to 7000 Hours. The relative change for each measurement point was calculated by dividing the difference between the initial and 7000 hour measurements by the initial measured illuminance. The red numbers indicates a negative relative change (initial greater than 7000) and the black numbers indicate a positive relative change (7000 greater than initial). The shade of gray indicates the magnitude and direction of the change: light gray = higher value than initial; dark gray = lower value than initial. The northwest corner is blank in this figure because those data were not measured during the initial measurements.

Polar plots of the luminous intensity distributions from the luminaires also illustrate the effects of accumulated dirt on the luminaires, as shown in Figure 17. For the 90° horizontal angle (extending between luminaire and pole) and the 0° horizontal angle (extending from luminaire toward the primary fence), the diagrams clearly illustrate the large decrease in intensity at higher vertical angles due to dirt, and the increase in intensity at lower vertical angles near nadir (0°).¹

¹ The orthogonal planes at 0° and 90° horizontal angles were chosen for this discussion to illustrate the effects of dirt and to facilitate comparison to the measured illuminances.

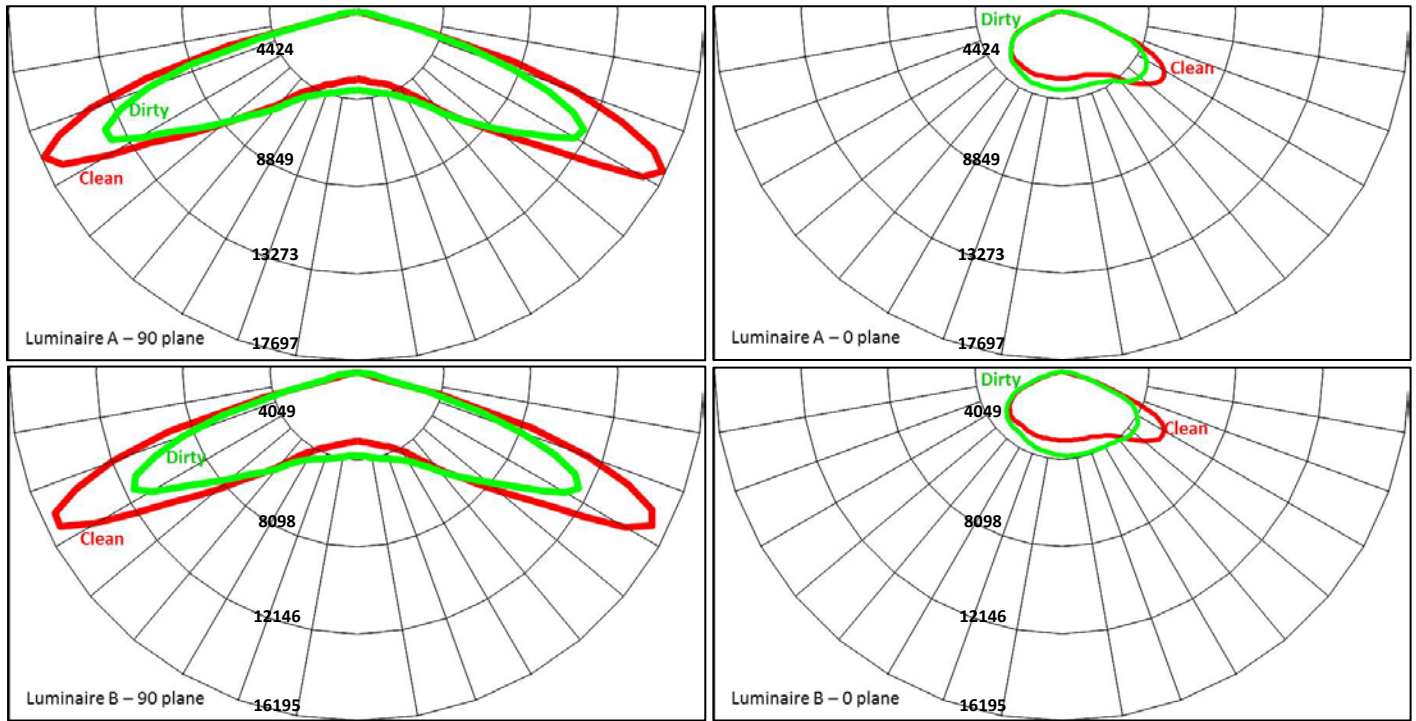


Figure 17. Polar Plots of Luminous Intensity Values for Clean and Dirty Conditions. The polar plots show the measured intensity of light in two vertical planes. The peak intensity values are examined in two orthogonal planes because of the bi-symmetric design of the luminaires, with less light directed toward each fence (vertical plane defined by 0° and 180° horizontal angles, with 0° towards the primary fence and shown on the right side of the diagram) than toward neighboring poles (vertical plane defined by 90° and 270° horizontal angles, with 90° shown on the right side of the diagram).

Luminaire dirt depreciation, therefore, could explain the type of change in illuminance distribution that has occurred at the Yuma project site over time, but the question remains whether the magnitudes of the changes are also consistent with dirt accumulation. The photometric testing of the two luminaires removed from the site provides insight into this question. The overall results from the five separate tests are summarized in Table 3; a direct comparison of the dirty versus clean condition tests is provided in Table 7. This table shows that the overall effect of dirt on the luminaires was a reduction in light output of 7.0% for luminaire A and 9.2% for luminaire B. Using the IES LDD formula, the estimated LDD factor after 20 months (the time from the initial installation to the removal of the two luminaires for testing, corresponding to the 7000 hour illuminance data) is 91.4% for a clean environment and 80.7% for a dirty environment.¹ The prior study of the I-35 West Bridge found that an estimate based on the IES clean condition most closely matched the measured LDD data. That is also true for the Yuma data—the measured depreciation in total light output due to dirt on the luminaire was 93.0% for luminaire A and 90.8% for luminaire B, very consistent with the 91.5% predicted by the IES LDD formula.

Although the IES LDD formula provides a good estimate of the overall reduction in light output due to dirt for this project, it does not enable estimates of the effects of dirt on the intensity distribution from a luminaire. As discussed above, dirt accumulation alters the intensity distribution from a luminaire by diffusing the light, and the data in Table 7 confirm that this occurred in Yuma. While the luminous intensity values at angles where peak intensity occurs *decreased* due to dirt by 15% to 26%, the intensity directly beneath the luminaire *increased* due to dirt by 16% to 21%, results that are consistent with the expected distribution change caused by dirt.

¹ Note that although LDD is referred to as a depreciation factor, it expresses the percentage of light that is maintained after accounting for the depreciation due to dirt.

Table 7. Comparison of Dirty and Clean Laboratory Test Results. The notation indicates if 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-symmetric 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 of the cleaned luminaires 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 Eaton	24,956	11,643	4,226	3,883
Clean B Eaton	27,472	15,471	5,565	3,218
Percent Change Due to Dirt	-9.2%	-24.7%	-24.1%	+20.7%
Dirty A Eaton ^a	27,782	12,970	5,208	3,990
Clean A Eaton ^a	29,881	17,558	6,138	3,436
Percent Change Due to Dirt	-7.0%	-26.1%	-15.2%	+16.1%

^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.

The overall effect of dirt on the two luminaires tested was therefore consistent with the predictions of the IES LDD formula and the diffusing effect dirt is expected to have on the intensity distribution; however, the question remains whether the magnitudes of the changes in distribution are consistent with the measured changes in illuminance distribution. This is more difficult to compare directly, since many factors can affect field illuminance measurements, and since matching the illuminance measurements to specific intensity values from a single luminaire does not fully describe the effects of the entire lighting system on a single measurement point. However, the following observations indicate that most, if not all, of the measured effect at the site may have been caused by dirt accumulation.

- Illuminance directly beneath the luminaires increased by 24% at 7000 hours (Figure 16), while the luminous intensity at nadir increased by 16% and 21% respectively from the two luminaires (Table 7).
- Illuminances at points that were 75 and 90 ft away from the pole and along the axis of the line of poles (Figure 16 points W90, W75, E75, and E90) decreased by 36% to 44% at 7000 hours. These measurement points align with vertical angles of 62° and 66° at the 90° horizontal angle, which is where the peak intensity for that vertical plane occurs. The peak luminous intensity decreased by 25% and 26% respectively from the two luminaires (Table 7).
- Illuminances at points that were straight out from the pole at the primary fence (Figure 16 point S45 and the two vertical points on the fence along the same line) decreased by 15% to 21% at 7000 hours. These measurement points align with vertical angles between 48° and 55° at the 0° horizontal angle, which is where the peak intensity for that vertical plane occurs. The peak luminous intensity decreased by 15% and 24% respectively from the two luminaires (Table 7).

The discussion above is based on Table 7, which compares the results of one test of each luminaire in the condition in which it arrived at the testing laboratory with the results of a test after the luminaire was cleaned. There are several explanations for the fact that the measured field illuminances show equivalent or greater effects than those estimated by the luminaire photometric tests:

- The differences may be the result of normal variations in field measurement conditions compared to laboratory testing and of the limitations stated above when comparing relative changes in intensity from laboratory-tested luminaires to relative changes in field-measured illuminances.
- The differences may be the result of some dirt being inadvertently removed from the luminaires in the process of packaging, shipping, and preparing for testing. As discussed previously and as shown in Table 3, the luminaire tested in Phoenix produced 3% to 5% less light than it did when tested after packaging and shipping to the test lab in Georgia. While this difference may reflect normal differences between testing labs, it also may indicate that the dirt was affected during packing and shipping. The results summarized in this section are consistent with the possibility that the luminaire had more dirt accumulation before it was removed from the pole and shipped to the test labs.
- The differences may be the result of factors other than dirt affecting the performance of the luminaires. The Phase 1.0 report discussed possible effects due to the extreme thermal environment in Yuma, and raised the possibility that factors such as depreciation of the LEDs, changes in the luminaire optical elements, and performance of the LED drivers may be affected by the thermal conditions. The next section discusses these possibilities.

As a final observation about the dirt accumulation on the luminaires in Yuma, it is noted that dirt does not accumulate uniformly across the entire luminaire nor even across any individual LED package's optical assembly. Figure 18 shows a close-up view of part of luminaire A from a photograph taken by the electrical contractor before removing the luminaire from the pole for testing, and additional photographs are included in Appendix C. This photo reveals that the apparent combination of wind, moisture, and dirt produce an overall effect that is not uniform across the optical elements of the luminaire, making a priori predictions of the realistic field effects very difficult.



Figure 18. Dirt Accumulation on Luminaire A. This photograph was taken by the electrician prior to removing the luminaire.

5.2 Additional Depreciation Considerations

Luminaire dirt depreciation is just one of the many light loss factors that reduce lumen output over time. As examined in the Phase 1.1 report, LED package lumen depreciation, lens material changes, driver changes, measurement error, orientation of luminaires, and electrical changes all are possible contributors. LDD explains most if not all of the lumen depreciation documented; however, other contributors are still possible.

LED package lumen depreciation remains an unlikely contributor given what is currently known about LED package technology and the IES LM-80 data for the LED packages used in these luminaires, reviewed by DOE. The maximum LED package temperature measured in the field at the TMP_{LED} ranged from 43.8 °C on December 16, 2015 to 75.0 °C on September 25, 2015. According to the LM-80 data, these two temperatures should result in the same light output from the LED packages at 7000 hours of operation. Degradation in light output from the LEDs would produce an overall uniform reduction in illuminances but would not be expected to change illuminance distribution; this type of uniform illuminance change was not observed with the field measurements.

Changes in the lens material in the luminaires could change intensity distribution; such changes are possible given the high temperatures in this application. According to Eaton, deformation of the acrylic used in these luminaires requires temperatures above 105 °C. The temperature of the acrylic in the T2 and SL2 luminaires was never measured; however, the highest temperature measured at an LED package was 80.9 °C. Based on this, it seems unlikely that the lenses deformed due to excessive heat.

The luminaire intensity distribution could be altered if the lenses were etched or diffused by sandblasting, which is a concern for this project given the high winds that can occur in the desert environment; however, no effects of sandblasting were observed by the manufacturer when the lenses were examined under a microscope. Furthermore, any intensity distribution changes due to sandblasting or due to deformation would not be recovered through cleaning; the fact that the shape of the intensity distribution of the two luminaires was mostly restored after cleaning indicates that the effects were most likely caused by accumulated dirt and not permanent changes such as those from sandblasting or deformation.

The operating temperature of the drivers and possible fluctuations in the electrical supply will be evaluated as part of the ongoing investigation.

6. Conclusion

Documentation of the Yuma Sector Border Patrol Area lighting LED trial demonstration continues to provide a better understanding of LED technology performance in a high ambient temperature and high solar radiation environment. Measurement data at the project site showed illuminances changing more rapidly than anticipated. As previously predicted, these observed changes are mostly if not completely caused by dirt accumulation. The laboratory measurements confirmed the effect of dirt not only on lumen output, but also on the distribution of light exiting the luminaire. The change in distribution raises an important question for manufacturers, specifiers, and researchers: How should lighting system designs account for distribution changes due to dirt accumulation? Careful optical design may lead to superior illuminance uniformity during pre-installation photometric analyses; however, the results from this investigation demonstrate that the uniformity will change as the luminaires accumulate dirt. In practice, this finding indicates that the effects of an optimized optical design may be negated by dirt accumulation, and sustained performance may require regular maintenance.

Continued recording of the temperature of the luminaire components will provide a more complete picture of the effects of high ambient temperatures and high levels of solar radiation. A future report is planned to address the performance of the luminaires after continued exposure to this extreme environment.

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: 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: 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: 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.

Appendix B: Weather Data

Summary of Weather Conditions during Initial, 2500 Hour, 5000 Hour, and 7000 Hour Measurements. The table summarizes the measurement weather conditions, as recorded by Yuma Marine Corps Air Station¹ about 15 miles north of the installed luminaires. Temperature and humidity were also recorded at the site during the measurements using a non-calibrated meter, with similar results. There was no rain during any of the measurements.

Nominal Operating Hours	Temperature and Humidity	Moon Phase, Percent Moon Illuminated	Civil Twilight Set and Rise ^a	Time of Measure
Initial 2/5/2014	12.8 to 13.3 °C (55 to 56 °F); 55% to 64%	Waxing Crescent, 40% Illuminated ^b	Set 6:39 p.m. (2/4); Rise 7:04 a.m. (2/5)	4:30 a.m. to 6:50 a.m.
2500 9/16-17/2014	30.6 to 32.8 °C (87 to 91 °F); 38% to 48%	Waning Crescent, 34% Illuminated ^c	Set 7:07 p.m. (9/16); Rise 5:58 a.m. (9/17)	9:45 p.m. to 1:30 a.m.
5000 3/3/2015	13 to 16 °C (56 to 60 °F); 51% to 64%	Waxing Gibbous, 97% Illuminated	Set 7:01 p.m. (3/3); Rise 6:38 a.m. (3/4)	8:15 p.m. to 11:00 p.m.
7000 9/23/2015	34 to 31 °C (93 to 88 °F); 33% to 44%	Waxing Gibbous, 75% Illuminated	Set 6:58 p.m. (9/23); Rise 6:03 a.m. (9/24)	8:15 p.m. to 11:05 p.m.

^a Civil twilight occurs when the sun is 6° below the horizon.

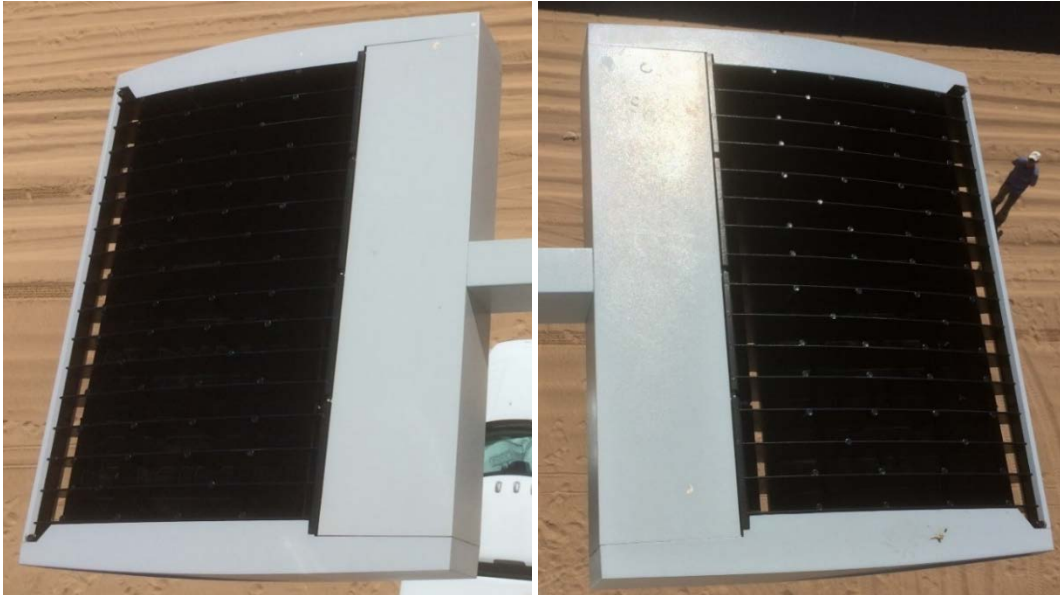
^b Moon was not up during measurements.

^c Moon rose at end of the horizontal measurements, before vertical measurements.

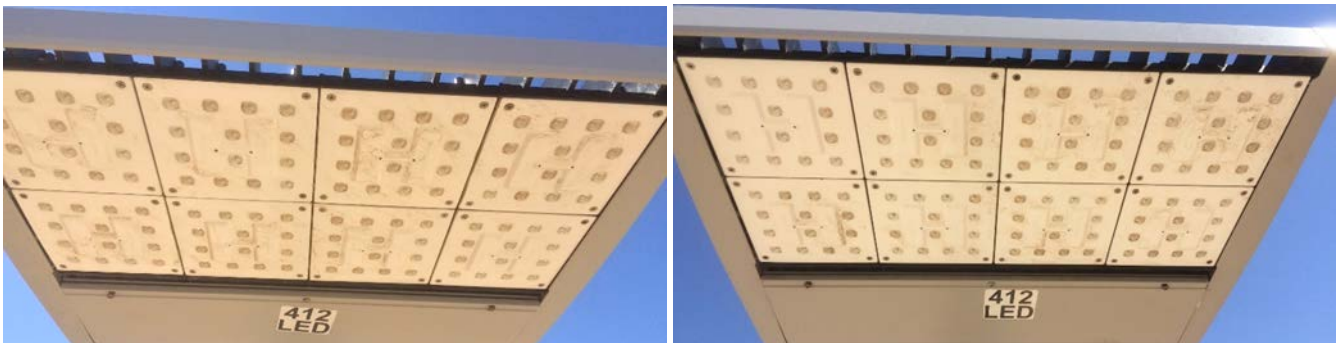
¹ Wunderground Historical Weather: wunderground.com/history/.

Appendix C: Photographs

Luminaire A (left) and Luminaire B (right) Top View



Luminaire A (left) and Luminaire B (right) Bottom View



Close-up of Luminaire B

