Phase 2: Mogul Base LED Replacement Lamps

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A Report of BPA Energy Efficiency's Emerging Technologies Initiative

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Abstract

Mogul base LED replacement lamps are being marketed as equivalent replacements for incumbent HID lamps. In Phase 2, LRC conducted photometric and electrical testing on 17 additional mogul base LED lamps to inform the DesignLights Consortium (DLC) on these products' performance in consideration of them being added to the Qualified Products List (QPL). LRC found that 6 of the 17 lamps met the minimum tested DLC QPL criteria for retrofit kits when the lamps were placed in decorative outdoor luminaires, area lighting luminaires, roadway luminaires and high bay luminaires. The lamps tested in wall pack luminaires did not meet the applicable retrofit kit criteria. At ambient temperatures of 65°C, the relative light output of several tested high bay and wall pack lamp-luminaire combinations decreased by 20% compared to relative light output at 25°C.

An Emerging Technologies for Energy Efficiency Report

The following report was funded by the Bonneville Power Administration (BPA) as an assessment of the state of technology development and the potential for emerging technologies to increase the efficiency of electricity use. BPA is undertaking a multi-year effort to identify, assess and develop emerging technologies with significant potential for contributing to efficient use of electric power resources in the Northwest.

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The Lighting Research Center (LRC) at Rensselaer Polytechnic Institute is the world's leading center for lighting research and education. Established in 1988 by the New York State Energy Research and Development Authority (NYSERDA), the LRC has been pioneering research in energy and the environment, light and health, transportation lighting and safety, and solid-state lighting for more than 25 years. Internationally recognized as the preeminent source for objective information on all aspects of lighting technology and application, LRC researchers conduct independent, third-party testing of lighting products in the LRC's state of the art photometric laboratories, the only university lighting laboratories accredited by the National Voluntary Laboratory Accreditation Program (NVLAP Lab Code: 200480-0). LRC researchers are continuously working to develop new and better ways to measure the value of light and lighting systems, such as the effect of light on human health. The LRC believes that by accurately matching the lighting technology and application to the needs of the end user, it is possible to design lighting that benefits both society and the environment.

Acknowledgments

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Project Background

In December 2013, Washington State University Energy Program (WSU) / Bonneville Power Administration (BPA) requested that the LRC create a work plan for market characterization and performance testing of mogul base LED replacement lamps to support cost-effective LED retrofits for multiple types of lighting applications, particularly high bay and decorative post top, also including wall pack, yard light and cobra head.

The LRC proposed that the project be broken into three phases. The first phase (published on BPA's website[1]) consisted of market characterization and pilot photometric testing of representative mogul base LED lamps alone and in luminaires, in order to develop a testing plan to ensure application equivalency. The second phase, which is the subject of this report, consists of additional performance testing of mogul base LED replacement lamps in representative luminaire types and analyses. The third proposed phase would consist of field demonstrations to determine real-world performance and acceptability.

Seven tasks were completed in Phase 2. This report describes results for each task in Phase 2.

- **Task 1**: Project management.
- **Task 2**: HID persistence testing of several HID lamps using line voltage.
- **Task 3**: Expanded pilot testing of select mogul base LED replacement lamps and representative luminaires to be evaluated against DLC requirements for retrofit kits.
- **Task 4**: Application efficacy calculations to serve as an example of performance equivalency evaluations.
- **Task 5**: Brightness calculations to serve as an additional example of performance equivalency evaluations
- **Task 6**: High temperature testing for selected high bay and wall pack luminaire combinations.
- **Task 7**: Write report.

[1] http://www.bpa.gov/EE/Technology/EE-emerging-technologies/Projects-Reports-Archives/Documents/Mogul_LED_Lamps_LRC_BPA_Phase1_finalNov24.pdf

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Task 2: HID Persistence Testing

Some utilities are concerned that HID lamp sockets that have the ballast bypassed for LED replacement lamp retrofits could be eventually relamped with a conventional HID lamp. In other words, will the energy savings persist when the LED replacement lamp is replaced at end of life? To address this persistence concern, LRC tested several HID lamps, using line voltage provided directly to the socket to determine if the HID lamps would light when connected directly to AC line voltage.

Although all of the tested lamps were expected to start with an input voltage of 528V and higher (and 305V for all of the lamps with rated wattages of less than 175W), the 50W, 100W and 150W lamps did not start at these input voltages. It is possible that the 50W, 100W and 150W lamps may require a pulse-start ballast to operate, but are mislabeled as probe-start lamps.

- None of the tested MH lamps would start with an input voltage of 132V, even when a high-voltage spark was applied. This seems to indicate that there isn't a safety concern if HID lamps are located in a bypassed fixture with 120V nominal line voltage.
- Several of the lamps started at an input voltage of 305V and all started when a spark from the high voltage generator was used. This result seems to indicate there is a safety concern for these types of bypassed systems when input voltages of 277V or higher are used.
- More lamps might start at even higher ambient temperatures (> 25 ^{0}C), but this requires further research.

Task 3: Expanded Photometric Testing

Although most of the lamp-luminaire combinations tested did not meet the current DLC QPL performance criteria for the tested applications, the results indicate that there are products in the marketplace that could meet the DLC retrofit kit performance requirements in place. Life testing was not a part of this research program and no conclusions are being drawn as to the lifetime performance of these products.

- 46% (5 of 11) of the mogul base LED lamps tested in Phase 2 for use in area, decorative outdoor and roadways luminaires exceeded all of the tested minimum applicable DLC criteria for retrofit kits for these applications.
- One of the three the mogul base LED lamps tested in Phase 2 in a high bay luminaire exceeded all of the tested minimum applicable DLC criteria for retrofit kits for this application.
- None of the two mogul base LED lamps tested in Phase 2 for wall pack luminaires met the minimum applicable DLC criteria for retrofit kits for this application.
- The luminous efficacy criterion is the hardest criterion for the tested mogul base LED lamps to meet. 56% of the tested mogul base LED lamps could meet the minimum applicable DLC efficacy criteria for retrofit kits for approved applications.

- The measured luminaire efficacy for the yard light combination was the highest efficacy measured. 35% of the lamp-luminaire combinations demonstrated luminaire efficacies of 80 LPW or higher.

Task 4: Application Efficacy Calculations

Several of the tested decorative outdoor, yard light and high bay combinations were evaluated in terms of their application efficacy which considers the energy efficiency of light delivered to the required task plane. The decorative outdoor luminaires were evaluated in an example roadway application, the yard light combinations were evaluated in a parking lot application, and the high bay combinations were evaluated in an example warehouse application. The Luminaire System Application Efficacy (LSAE) results for each luminaire application show the LSAE results as a function of mounting height and luminaire spacing that meets the required photometric criteria.

- Comparing the luminaire combinations, AC5 has the highest LSAE value, but does not have the longest pole spacing. AC3 has the second highest LSAE value and the longest pole spacing. The tested combinations have much shorter pole spacing's than typical spacing's of incumbent luminaires, suggesting that a one-for-one replacement with the tested luminaires would result in light levels lower than the recommended IES RP-8-00 lighting criteria.
- Of all four tested yard light combinations, YL5 has the highest LSAE value, 32.9 LPW, at a mounting height of 10 feet. If these yard lights were to be spaced out regularly to meet the IES RP-20-98 lighting criteria, YL1 offers the largest coverage areas over a range of mounting heights, even though its LSAE values are lower than YL5.
- Four of the tested high bay luminaire combinations could meet the IES lighting criteria for industrial spaces. The four luminaire combinations that were able to meet the required IES lighting criteria have low LSAE values in the base case warehouse layout. In order to meet the uniformity requirements, the luminaires must be spaced fairly close together (10 - 15 feet apart).
- Overall, when several LED replacement lamps were tested in DLC test luminaires, LSAE analysis indicated that luminaire spacing would need to be relatively close together, in order to meet the lighting requirements of typical applications. Existing luminaire spacing based on incumbent technology appears likely to be too far apart, at least for this generation of LED lamps tested to allow one-for-one retrofits that meet the lighting requirements. In one-for-one retrofits with the tested LED replacement lamps, additional new luminaires would be required in order to provide adequate lighting. This calls into question any cost advantage of LED replacement lamps compared to new LED integrated luminaires which may be able to use incumbent spacing and meet the lighting requirements.

Task 5: Brightness Calculations

The tested LED mogul luminaire combinations yield an average 50% increase in brightness perception for low light level installations relative to HPS installations designed to the same light level. Using a published brightness function would allow specifiers to equate lighting simulated installations based on equal brightness and yield additional energy savings relative to legacy technology.

Task 6: High Temperature Testing

Several high bay and wall pack luminaire combinations were tested in a thermal chamber and light output was measured at 25°C and 65°C. The relative light output in the high bay luminaires decreased by 22%, on average, when the ambient temperature was increased to 65°C with a reduction range of 13% to 33% depending on the lamp luminaire combination. The luminaire combinations with the lowest relative light output at the elevated temperatures had an external driver mounted in the ballast enclosure. These lamps also included a fan attached to the lamp assembly. For the wall pack luminaires, the relative light output decreased by 17%, on average, when the ambient temperature was increased to 65°C.

After operating the luminaire at an elevated temperature of 65°C and resetting the chamber to 25°C, the relative light output was similar (within 1 percent) to that measured during the initial 25°C period.

Recommended Modifications to DLC Technical Requirements

The photometric testing and subsequent evaluations conducted in Phases 1 and 2 indicate that there is a need for additional specification and performance information about mogul base LED lamps in order for these lamps to be included in the DLC QPL retrofit kit category. Several points are made suggesting modifications to the DLC testing requirements based on the testing results.

Task 2: HID Persistence Testing

Background

Some utilities are concerned that HID lamp sockets that have the ballast bypassed for LED replacement lamp retrofits could be eventually relamped with a conventional HID lamp. To address this persistence concern, LRC tested several HID lamps, using line voltage provided directly to the socket to determine if the HID lamps would light when connected directly to AC line voltage.

The following ANSI documents were used to determine applicable lamps' minimum starting characteristics:
ANSI C78.43-2004 - *American National Standard for Electric Lamps—Single-Ended Metal Halide Lamps*
ANSI C78.42-2009 – *American National Standard for Electric Lamps—High-Pressure Sodium Lamps*

Based on the starting characteristics given in these standards (see Table 1), it was determined that only metal halide (MH) lamps would need to be tested because all high pressure sodium (HPS) lamps require an additional high-voltage pulse (over 1000 V) to start the lamps.
The minimum open circuit voltages (OCV) shown in Table 1, are given for ambient temperatures colder than room temperature. Several of the lamps show a temperature trend that seems to indicate that lower OCVs could allow the lamps to start at room temperature. Given the OCVs shown in Table 1, almost all of the probe-start lamps of less than 175W would be expected to start with an input voltage of 277V or higher, and it is possible that the 175W, 250W and 400W lamps may start at 277V or higher given the fact that lower voltages are required to start the lamps at higher temperatures.

Table 1: ANSI Lamp Starting Voltage Requirements

ANSI C78.43-2004							
Single-ended lamps	Base	Minimum Open circuit voltage (OCV)					
		Volts RMS		Volts peak		Time (minutes)	
		10°C	-30°C	10°C	-30°C	10°C	-30°C
39-watt, M130	G8.5, G12, E26	209	209	296	296	0.5	2
50-watt, M110	E26	235	235	332	332	10s	2
70-watt, M98	E26	235	235	332	332	10s	2
100-watt, M90	E26	235	235	332	332	10s	2
150-watt, M102	E26	235	235	332	332	10s	2
175-watt, M57	E26 / E39	350	382	495	540	2	2
175-watt, pulse start, M152	E26 / E39	254	254	359	359	2	2
250-watt, M58	E39	350	382	495	540	2	2
250-watt, pulse start,M153	E39	254	254	359	359	2	2
320-watt,pulse start, M154	E39	254	254	359	359	2	2
400-watt, M59	E39	350	482	495	540	2	2
400-watt, pulse start,M155	E39	254	254	359	359	2	2
1000-watt, M47	E39	440	530	622	750	2	2
1500-watt, M48	E39	440	530	622	750	2	2
1650-watt, M112	E39	440	530	622	750	2	2

ANSI C78.42-2009				
Single-ended lamps	Base	Minimum rms OCV	Pulse height (V)	Pulse width (V)
35-Watt 52-Volt S76 HPS lamp	E26	110	2500-4000	1 us at 2250
50-Watt 52-Volt S68 HPS lamp	E26 / E39	110	2500-4000	1 us at 2250
70-Watt 52-Volt S62 HPS lamp	E26 / E39	110	2500-4000	1 us at 2250
100-Watt 55-Volt S54 HPS lamp	E26 / E39	110	2500-4000	1 us at 2250
150-Watt 55-Volt S55 HPS lamp	E26 / E39	110	2500-4000	1 us at 2250
150-Watt 100-Volt S56 HPS lamp	E39	198	2500-4000	1 us at 2250
200-Watt 100-Volt S66 HPS lamp	E39	198	2500-4000	1 us at 2250
250-Watt 100-Volt S50 HPS lamp	E39	198	2500-4000	1 us at 2250
310-Watt 100-Volt S67 HPS lamp	E39	198	2500-4000	1 us at 2250
400-Watt 100-Volt S51 HPS lamp	E39	198	2500-4000	1 us at 2250
430-Watt 116-Volt S145 HPS lamp	E39	198	2500-4000	1 us at 2250
600-Watt 110-Volt S106 HPS lamp	E39	198	4000-5000	2 us at 3600
750-Watt 120-Volt S111 HPS lamp	E39	198	4000-5000	2 us at 3600
1000-Watt 250-Volt S52 HPS lamp	E39	456	3000-5000	4 us at 2700

Method

Seven MH lamps were procured and tested by the LRC, as shown in Table 2. Four of these lamps were already owned by the LRC and had been used previously. Three of the lamps were purchased from a local distributor. Although the 50W and 150W MH lamps are categorized as probe-start lamps by their ANSI code, their respective manufacturers describe them as pulse-start lamps. According to the local distributor, these lamps are meant to be used on a probe-start ballast but can be used on a pulse-start ballast as well.

Several of these lamps are only available with a medium base, but these lamps were included in the testing in case a mogul adaptor was used in situ.

Table 2: Tested MH Lamps

Single-ended lamps ANSI Code	Manufacturer	Model Number	New?	Base	Ballast Type
50-watt, M110	Eiko	MH50/U/MED	Yes	E26	Probe*
70-watt, M98	Sylvania	MCP70/U/MED/830	No	E26	Probe
100-watt, M90	Philips	MHC100/U/M/3K ELITE	Yes	E26	Probe
150-watt, M102	GE	MVR/U/MED	Yes	E26	Probe*
175-watt, M57	Sylvania	M175/U	No	E39	Probe
250-watt, M58	Philips	MH250/U	No	E39	Probe
400-watt, M59	Venture	MH400W/U/ED28	No	E39	Probe
* Manufacturer categorizes this lamp as pulse-start lamp although ANSI lamp code indicates it operates on a probe-start ballast.					

The circuit for testing HID lamp standoff voltage consisted of an AC power supply (Pacific Power Supply Model 345 AMX), a 960 ohm current-limiting resistor and the lamp under test all connected in series. These components are shown in the schematic below (Figure 1). Use of the current-limiting resistor prevented excessive current flowing in the circuit in the event that an arc was struck in the HID lamp, preventing a non-passive failure. With no current flowing, the full voltage of the AC power supply is impressed across the lamp terminals. The resistor value chosen limited the maximum possible arc current to 0.55 A_{rms} for the maximum line voltage of 528 V_{rms} (I = Vac/R).

An actual circuit in situ might not have a comparable resistive load and have a slower response time. In that case, a lighted lamp could draw too much current. The safety implications of this scenario will be explored in Phase 3 testing.

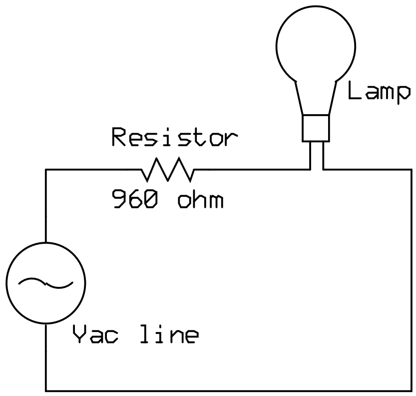


Figure 1: HID lamp testing circuit

A Plexiglas and metal enclosure was positioned around the lamp and sockets for safety.
The lamps were each tested 3 times and the input voltage was applied for 2 minutes or until the lamp demonstrated a sustained arc for a brief period of time (1 to 3 seconds). Each of the lamps was tested in ascending order of power (from low to high) at a given input voltage before the lamp was retested again so that each test on a particular lamp was separated in time for an independent test. Once the lamps were tested 3 times at a lower voltage, they were tested at a higher voltage three times, then at the highest voltage three times. Using Table 3 as a reference, the lamps were tested in order of increasing power going down the rows, then across the trial and voltage columns, from left to right.

The input voltages used for the test were 132V (120V + 10%), 305V (277V + 10%), and 528V (480V + 10%). These input voltages are the nominal line voltages plus a 10% tolerance. The 10% tolerance was selected for testing because it is more conservative than the national steady state voltage regulation standards of +/- 5%.[2]

For lamps that did not strike an arc (i.e. start) for any of the test voltages a second test was conducted. For this test a high-voltage, high-frequency generator[3] (tesla coil) was used to initiate breakdown of the gas in the lamp's arc tube. The high voltage generator was then removed from the vicinity of the lamp and the lamp was observed to determine whether the ac line test voltage was sufficient to maintain electrical conduction in the lamp (i.e. sustain the arc). This generator was used to simulate a high-voltage transient that might occur on the line.

Results

The results for each test are shown in Table 3. At 132V, none of the tested MH lamps would start, even when a spark from the high-voltage generator was applied.

Four of the tested MH lamps (70W, 175W, 250W, and 400W) would start every time with an input voltage of 305V or higher. The 100W MH lamp did not start in any of the tests, except at

[2] http://www.pge.com/includes/docs/pdfs/mybusiness/customerservice/energystatus/powerquality/voltage_tolerance.pdf
[3] http://www.electrotechnicproducts.com/bd-10a-high-frequency-generator/

the end of the testing cycles when 528V was applied for the third time. Two additional tests for this lamp alone showed that the lamp started at 528V. When a spark was applied in addition to the 305V or 528V input voltage, all of the tested MH lamps started and sustained an arc.

At 305V, the 400W MH lamp flashed once but did not sustain an arc. 70W, 175W, and 250W lamps started and sustained an arc at this input voltage and higher.

Table 3: Lamp starting results. N – lamp did not start during 2 minute sustained input voltage. Y – lamp did start during 2 minute sustained input voltage.

ANSI Code	Model Number	Ballast Type	Temp (^{0}C)	132V (120V + 10%)			305V (277V + 10%)			528V (480V + 10%)			132V w/ spark	305V w/ spark	528V w/ spark
				Trial			Trial			Trial			Trial		
				1	2	3	1	2	3	1	2	3	1	1	1
50-watt, M110	MH50/U/MED	Probe	25.8	N	N	N	N	N	N	N	N	N	N	Y	Y
70-watt, M98	MCP70/U/MED/830	Probe	25.8	N	N	N	Y	Y	Y	Y	Y	Y	N	N/A	N/A
100-watt, M90	MHC100/U/M/3K ELITE	Probe	26	N	N	N	N	N	N	N	N	Y	N	Y	N/A
150-watt, M102	MVR/U/MED	Probe	25.9	N	N	N	N	N	N	N	N	N	N	Y	Y
175-watt, M57	M175/U	Probe	25.7	N	N	N	Y	Y	Y	Y	Y	Y	N	N/A	N/A
250-watt, M58	MH250/U	Probe	25.8	N	N	N	Y	Y	Y	Y	Y	Y	N	N/A	N/A
400-watt, M59	MH400W/U/ED28	Probe	26	N	N	N	Y	Y	Y	Y	Y	Y	N	N/A	N/A
N/A - lamp started with input voltage, did not require high voltage "spark" to start.															

Task 3: Expanded Mogul Base LED Replacement Lamp Testing

Background

To increase the number of lamp/luminaire combinations sampled in Phase 1 testing, the LRC tested 17 more bypassed mogul base lamp-luminaire combinations in Phase 2. The 17 luminaires tested were evaluated against DesignLights Consortium (DLC) requirements for retrofit kits.

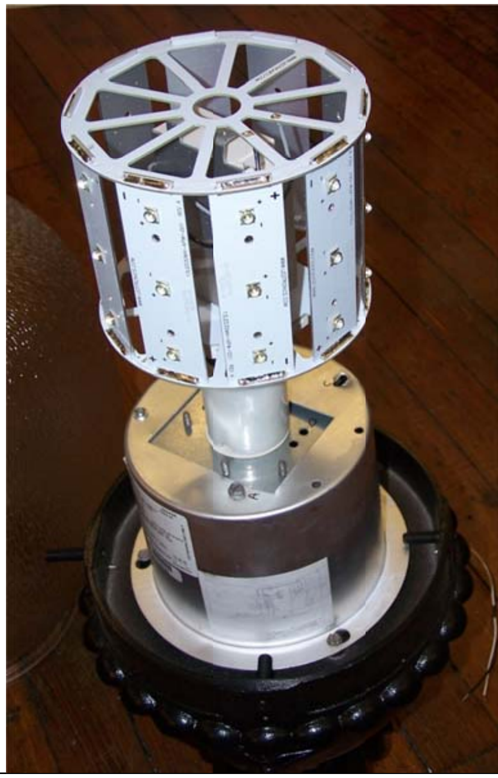
Products Tested

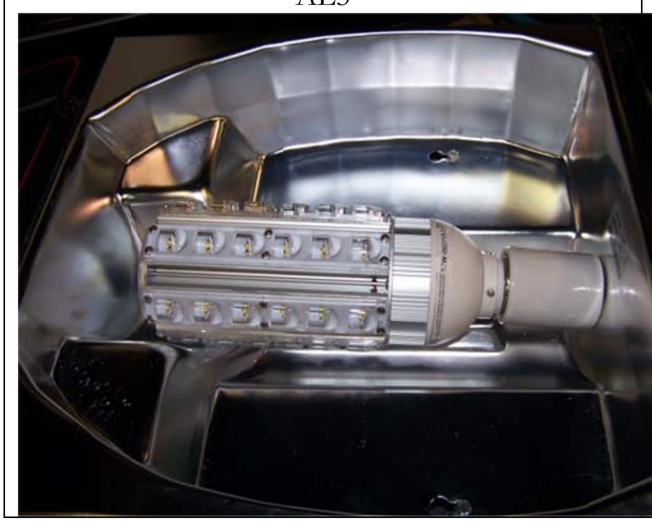
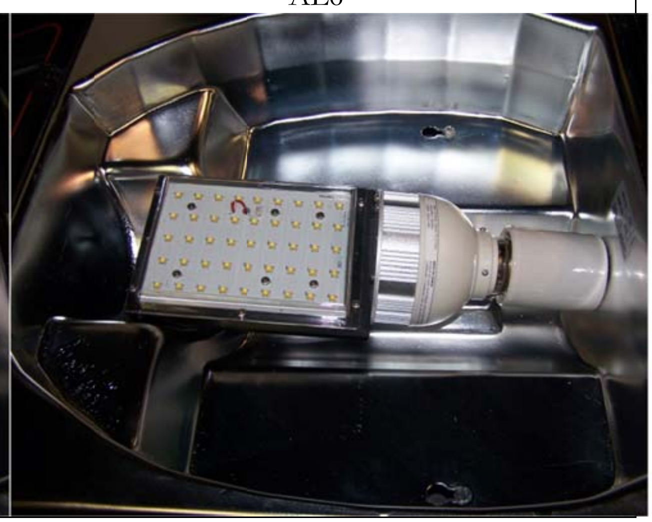
Table 4 shows the LRC identification numbers allocated to each of the received and tested mogul base LED replacement lamps and lamp-luminaire combinations. All of the lamps tested in this task bypassed the magnetic ballasts, so that 120V was wired directly into the lamp socket or external LED driver. As in Phase 1, a combination code was assigned to each mogul base LED lamp and luminaire combination to be used for reporting purposes. Table 5shows photographs of each lamp-luminaire combination tested in this phase.

Table 4: LRC identification numbers and codes for lamps and luminaires measured in Phase 2. First six digits in Product ID represent the luminaire ID, second six digits represent the lamp ID. Combination codes: AC – acorn decorative outdoor light, AL – area light, CL – cobrahead luminaire (roadway luminaire), HB – high bay luminaire, WP – wallpack luminaire, YL – yard light.

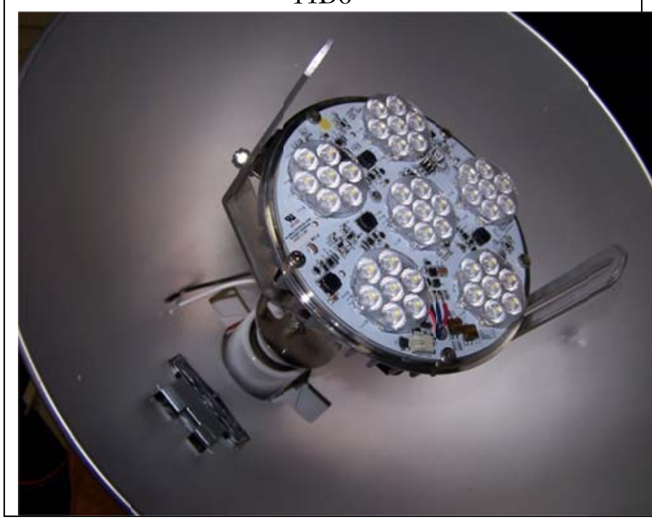
Manufacturer	Lamp Model	LRC Lamp ID	LRC Luminaire ID	LRC Product ID (Lamp_ Luminaire)	Combination Code
LEDTRONICS	LED30MH-30X2W-XPW-001	109457	Acorn 109480	109480_109457	AC1
Light Efficient Design	LED-8024M42	109468	Acorn 109481	109480_109468	AC2
EIKO	C0820-PT-45W-40K-W MOGUL	109526	Acorn 109482	109480_109526	AC3
Neptun Light	LED-48080-UNV 4100K MOGUL	109533	Acorn 109483	109480_109533	AC4
LEDTRONICS	LED30MH-600-TPW-001	109529	Acorn 109484	109480_109529	AC5
S3J Electronics	WRBE40-360-052-5-277-E	109530	Area Light 109465	109465_109530	AL5
S3J Electronics	WRBE40-059-5-277-T3	109531	Area Light 109465	109465_109531	AL6
ECO-SMART	G90-C30NP	109536	Cobrahead 109467	109467_109536	C4
Premium	G80-S45 4000-4500K	109532	Cobrahead 109467	109467_109532	C5
Bbier	BB-HJD-053	109527	Cobrahead 109467	109467_109527	C6
Bbier	BB-HJD-053	109528	Cobrahead 109467	109467_109528	C7
Light Efficient Design	LED-8030M42	109523	High Bay 109464	109464_109523	HB4
Light Efficient Design	LED-8026M42	109524	High Bay 109464	109464_109524	HB5
Global Tech	GTSOL5498-YW-SOLY-120/277-HO-L75	109534	High Bay 109464	109464_109534	HB6
Light Efficient Design	LED-8002M42	109525	Wall Pack 109470	109470_109525	WP5
LED Global Supply	GS-CE40-60HB-W	109537	Wall Pack 109470	109470_109537	WP6
Synergy Lighting	SYN-LED-40W-GLB	109535	Yard Light 109469	109469_109535	YL5

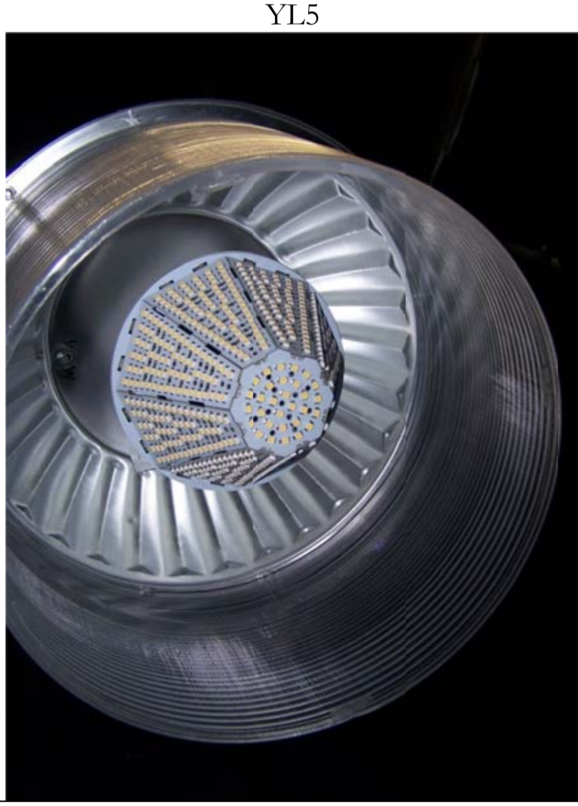
Table 5: Lamp-luminaire combinations tested in Phase 2

AC1	AC2
	
AC3	AC4
	

AC5	
	
AL5	AL6
	

C4	C5
	
C6	C7
	

HB4	HB5
	
HB6	
	

WP5	WP6
	
YL5	
	

Test methods

During the Phase 2 testing, the mogul base LED lamps were tested in a preapproved DLC luminaire (see Phase 1 report for more details). DLC requires 7 electrical and photometric metrics for retrofit kits. LRC used the test methods given in LM-79 to conduct its electrical and photometric testing. Six of the 7 metrics can be reported as a result of electrical and photometric testing using an integrating sphere: power factor (PF), total harmonic distortion (THD), light output (lumens), luminaire efficacy (lm/W), correlated color temperature (CCT) and color rendering index (CRI).

The two lamps received from S3J Electronics (lamps 109530 and 109531) were tested in the area luminaire. These lamps were too long to fit in the luminaire reflector (see photographs on left side of Figure 2), so the socket extender was removed from the luminaire in order for the lamps to fit inside (as shown in photographs on right side of Figure 2). Photometric testing was completed with this socket configuration.

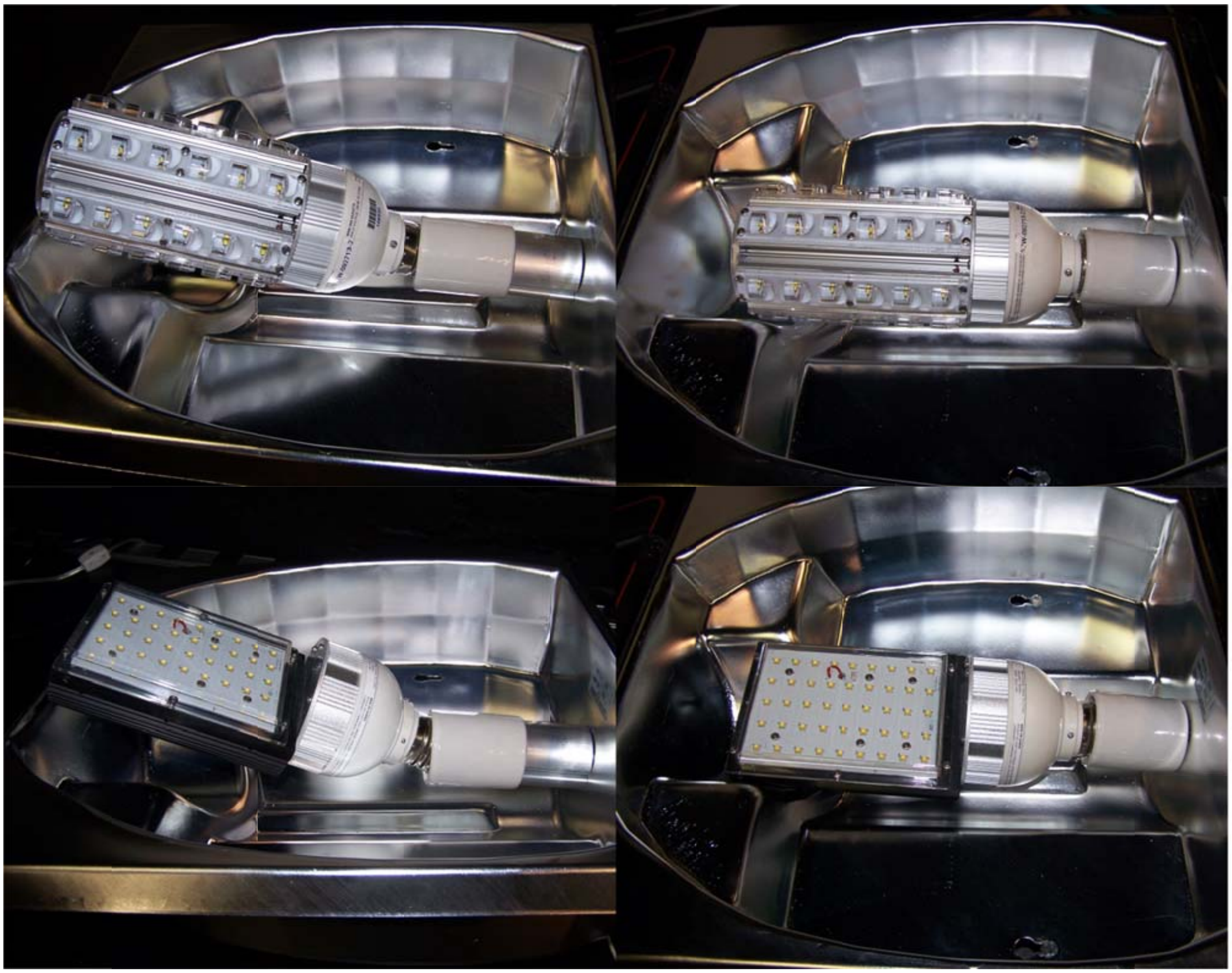


Figure 2: Socket extender in area luminaire had to be removed to allow mogul base LED lamps 109530 and 109531 to fit inside.

LRC used a 2-meter integrating sphere to test the lamp-luminaire combinations. Custom software was developed by the LRC to operate the products in the integrating sphere, monitor the lamps during testing and ensure that the testing tolerances allowed in LM-79 are monitored. The ballast was bypassed according to the LED lamp manufacturer instructions while the mogul base LED lamps were operated in the applicable luminaire. The total expanded (k=2) uncertainty in the 2-meter integrating sphere for the products tested in Phases 1 and 2 in light output is ± 2.3%. The total expanded (k=2) uncertainty of CCT in the 2-meter integrating sphere for the products tested ranges from -26 K to 9 K for low CCTs and from -45 K to 36 K for high CCTs (up to 6500 K). The total expanded (k=2) uncertainty in CRI is 0.6.

To determine the zonal lumens, LRC pilot tested the luminous intensity distribution (spatial distribution) of the tested high bay and yard light luminaires with the mogul base LED lamps, using a moving-mirror goniophotometer.[4] An IES file was created from the goniometric results and the zonal lumens were determined by evaluating the IES file in photometric evaluation software (Photometric Toolbox 32, Lighting Analysts, Inc.).

The decorative acorn luminaires were sent to a UL lighting testing lab in Allentown, PA for goniophotometric testing. UL provided the LRC with IES files that were used for photometric and application efficacy analysis.

DLC Electrical and Photometric Technical Requirements for Retrofit Kits

Table 6 and Table 7show the minimum criteria and tolerances for DLC QPL retrofit kits. LRC used these values and tolerances to determine if the 17 tested products met the applicable criteria for retrofit kits.

Table 6: DLC criteria and tolerances for outdoor and high bay retrofit kits.

Metric	Minimum Required Value	Tolerance
Power Factor (PF)	≥ 0.9	-3%
THD	≤ 20%	5%
Light Output	Depends on category (300 – 10,000 lumens)	-10%
Luminaire Efficacy	Depends on category (60 – 85 lm/W)	-3%
CCT	≤5700K	Defined by ANSI C78.377-2011 For the Nominal 5700 K CCT category, the target CCT and tolerance is 5667 K +/- 355 K
CRI	Depends on category (65-80)	-2 CRI
Zonal Lumens	Depends on category	See Table 7

[4] The moving mirror goniophotometer system is not currently within the scope of the LRC's NVLAP accreditation.

Table 7: DLC zonal lumens criteria and tolerances for outdoor and high bay retrofit kits.

Application	Zone/Spacing Criteria	Nominal Requirement	Tolerance	Requirement with Tolerance
25) Retrofit Kits for Outdoor Pole/Arm-Mounted Area and Roadway Luminaires	0-90°	100%	-1%	≥99%
	80-90°	≤10%	3%	≤13%
26) Retrofit Kits for Outdoor Pole/Arm-Mounted Decorative Luminaires	0-90°	≥65%	-3%	≥62%
28) Retrofit Kits for Outdoor Wall-Mounted Area Luminaires	0-90°	100%	-3%	≥97%
	80-90°	≤10%	3%	≤13%
34) Retrofit Kits for High-Bay Luminaires for Commercial and Industrial Buildings	20-50°	≥30%	-10%	≥20%

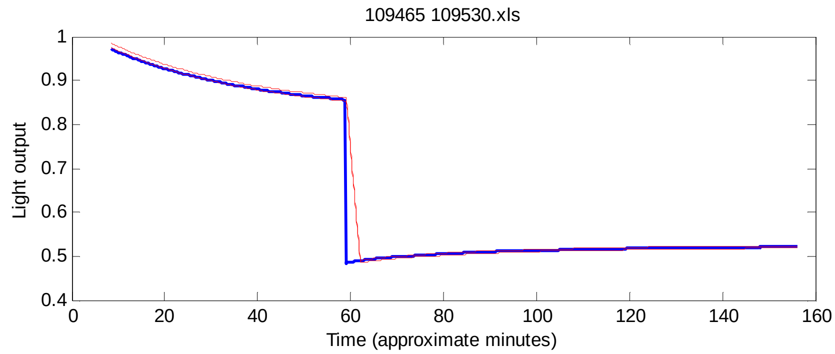
Luminaire Results

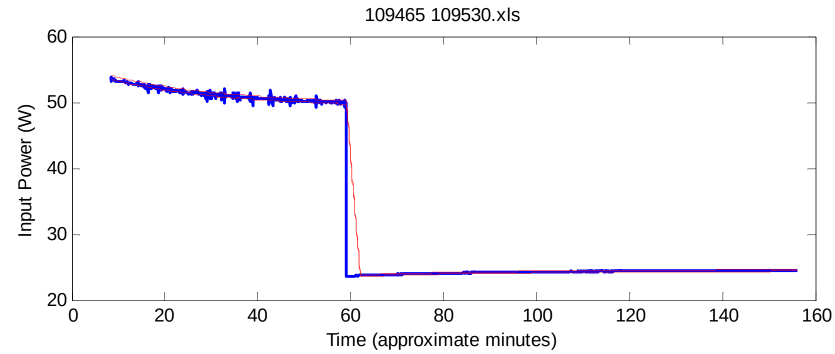
Table 8 and Figures 3-7 show the integrating sphere results for the 17 tested luminaire-lamp combinations. All 17 of the luminaire-lamp combinations were able to be measured and provided stable, accurate results in the sphere.

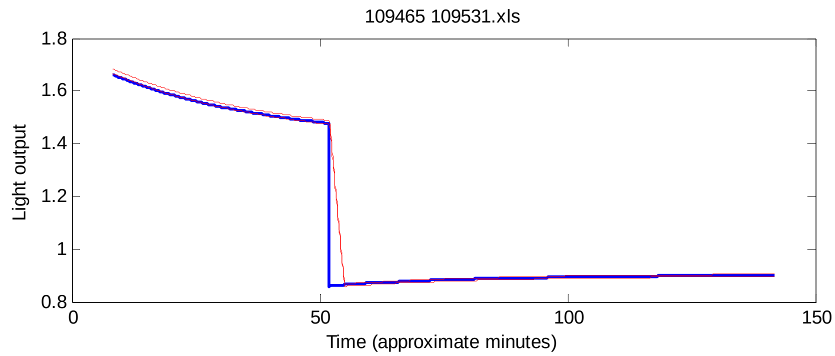
Figure 3 shows the stabilization curves for four tested luminaires. These luminaires showed a marked reduction in power and light output while the lamps were operated in the luminaire during the stabilization period of sphere testing. The lamps that demonstrated this behavior came from two manufacturers. Luminaire AL5 (109465_109530) contains a lamp with a rated power of 52W. This lamp demonstrated a power demand of about 50W for a while then suddenly decreased to 23.5W, with a corresponding reduction in light output. Luminaire AL6 (109465_109531) also contains a lamp from the same manufacturer with a rated power of 56W. This lamp demonstrated a power demand of 59W for a while then suddenly decreased to 29W, with a corresponding reduction in light output. Luminaires C6 (109467_109527) and C7 (109467_109527) each contain a lamp from the second manufacturer with a rated power of 50W. During stabilization, the lamps were observed to gradually reduce power demand from 51W down to 34W (for C6) and from 51W down to 36W (for C7). The reported data shown in Table 5 is for the stabilized, lower power and light output data.

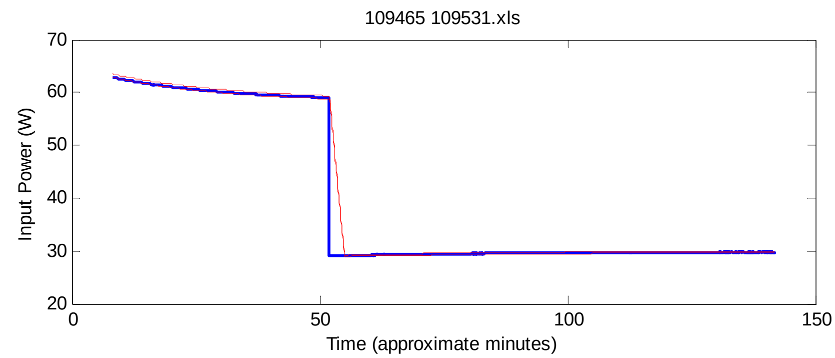
Table 8: Measured electrical and photometric results for mogul base LED lamps operated in preapproved luminaires. First six digits in Product ID represent the luminaire ID; second six digits represent the lamp ID.

Code	Product ID	Temp. sphere (°C)	Voltage (V)	Power (W)	Power Factor (%)	THD (%)	Light Output (lm)	CCT (K)	CRI	Luminaire Efficacy (lm/W)
AC1	109480_109457	24.5	120.08	36.8	0.98	16.19	2810	6213	73	76.4
AC2	109480_109468	25.64	120.06	43.7	0.94	10.44	4267	3835	82	97.7
AC3	109480_109526	25.5	120.03	44.2	0.99	12.03	3991	4041	67	90.3
AC4	109480_109533	25.08	119.85	80.3	0.98	8.55	7036	4228	74	87.6
AC5	109480_109529	24.37	120.14	27.6	0.98	13.09	2643	4775	76	95.9
C4	109467_109536	24.9	120.07	29.5	0.97	13.08	2338	4028	75	79.3
C5	109467_109532	25.33	120.01	41.7	0.99	14.72	2176	4094	83	52.2
C6	109467_109527	25.17	120.04	33.9	0.98	16.85	2458	5947	83	72.6
C7	109467_109528	24.79	120.02	36.4	0.98	13.95	2460	5960	83	67.5
AL5	109465_109530	24.89	120.09	24.5	0.96	16.50	1572	4904	72	64.2
AL6	109465_109531	25.16	120.06	29.8	0.98	13.02	2855	4021	77	95.9
YL5	109469_109535	24.38	120.04	37.3	0.98	13.63	4466	4142	81	119.9
WP5	109470_109525	24.89	120.04	41.6	0.95	11.73	2160	4474	87	51.9
WP6	109470_109537	25.29	120.12	59.82	0.363	56.8	2661	4221	74	44.5
HB4	109464_109523	24.6	119.82	150.7	0.93	33.98	10623	3958	82	70.5
HB5	109464_109524	24.43	119.85	102.6	0.86	33.25	7828	3958	82	76.3
HB6	109464_109534	25.02	119.79	129.4	1.00	4.10	10127	4025	73	78.3


109465 109530.xls
Light output
Time (approximate minutes)


109465 109530.xls
Input Power (W)
Time (approximate minutes)


109465 109531.xls
Light output
Time (approximate minutes)


109465 109531.xls
Input Power (W)
Time (approximate minutes)

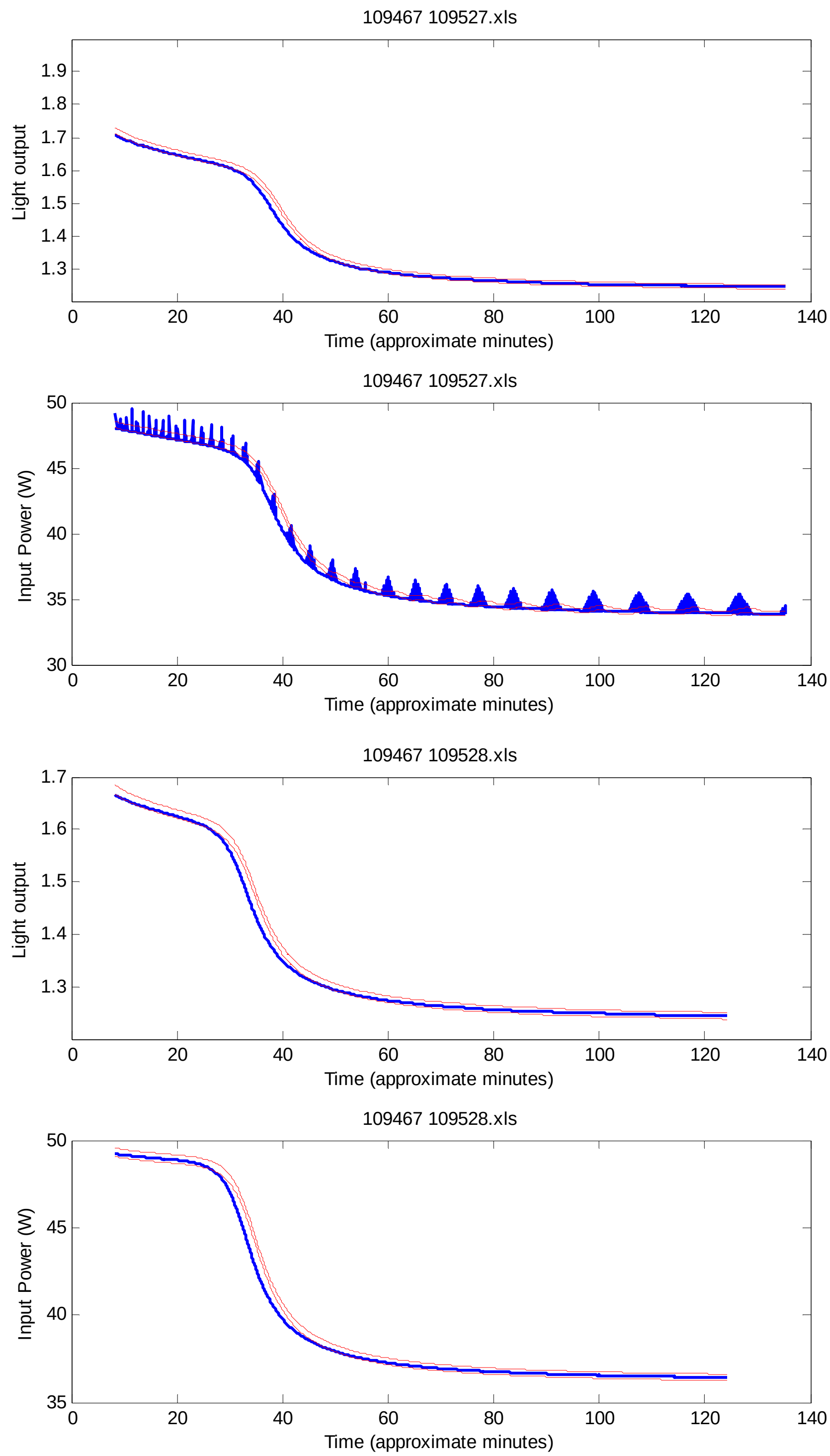


Figure 3: Stabilization curves for 4 mogul base LED lamps that showed drastic reductions in light output and power demand while stabilizing in integrating sphere. The blue line indicates the measured value. The red lines indicate the tolerances allowed under LM-79 testing protocols.

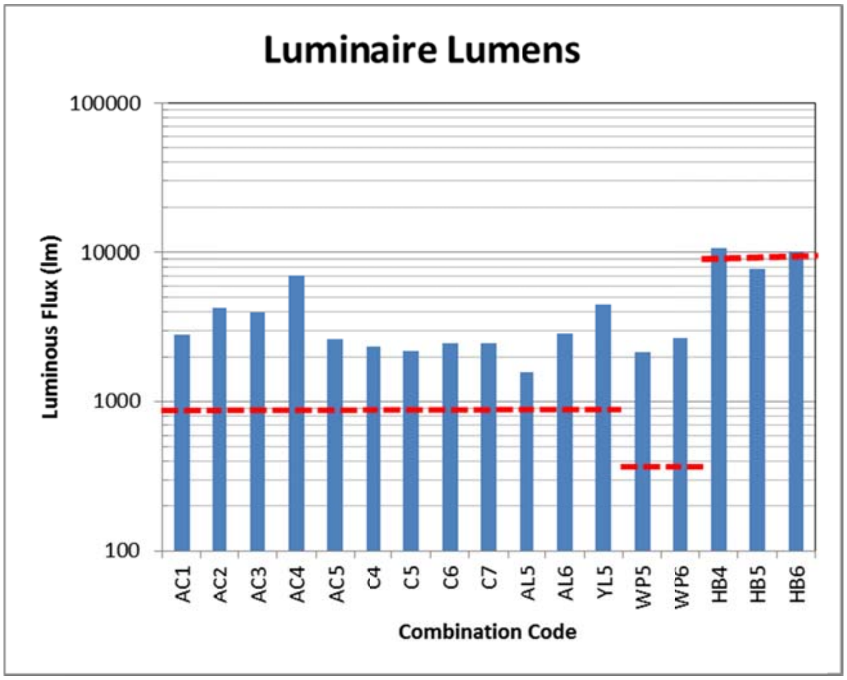


Figure 4: Measured light output for 17 luminaire-lamp combinations. The dashed red line indicates the minimum light output for retrofit kits for that application, including the tolerance. For the yard light (YL5), the minimum light output is for retrofit kits for outdoor pole-mounted area lights.

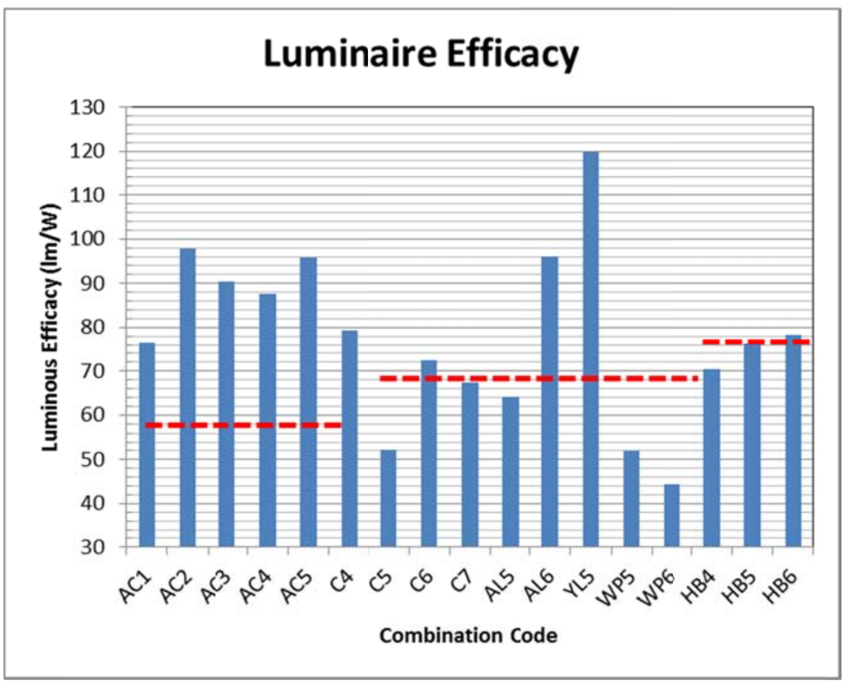


Figure 5: Measured luminaire efficacy for 17 luminaire-lamp combinations. The dashed red line indicates the minimum efficacy for retrofit kits for that application, including the tolerance. For the yard light (YL5), the minimum efficacy is for retrofit kits for outdoor pole-mounted area lights.

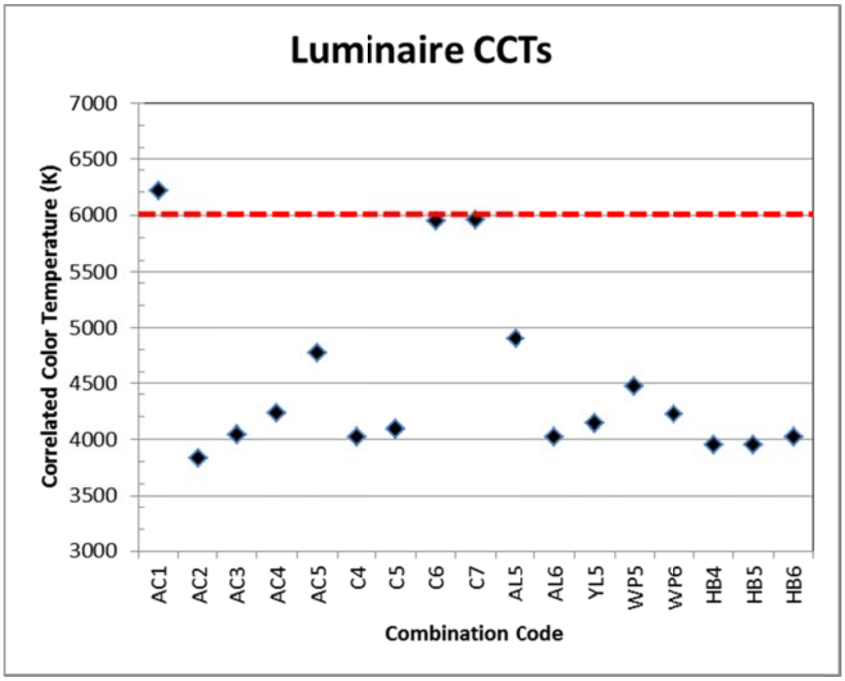


Figure 6: Measured CCT for 17 luminaire-lamp combinations. The dashed red line indicates the maximum CCT retrofit criteria for that application, including the tolerance. For the yard light (YL5), the maximum CCT is that for retrofit kits for outdoor pole-mounted area lights.

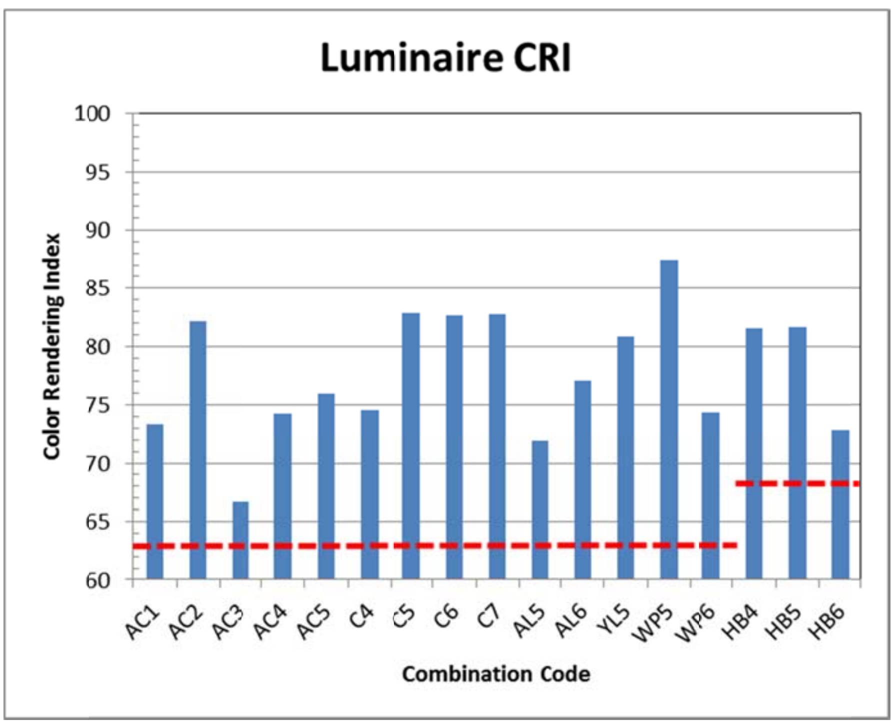


Figure 7: Measured CRI for 17 luminaire-lamp combinations. The dashed red line indicates the minimum CRI for retrofit kits for that application, including the tolerance. For the yard light (YL5), the minimum CRI is for retrofit kits for outdoor pole-mounted area lights.

Results relative to DLC Criteria

Table 9 indicates the Phase 2 measured luminaire performances relative to the applicable DLC performance requirements for retrofit kits for each luminaire type.

Sixteen of the measured mogul base LED lamp-luminaire combinations are comparable to applicable QPL retrofit categories (high bay, decorative acorn, area, roadway and wall pack luminaires); the other mogul base LED lamp-luminaire combination is a yard light, which is not an approved QPL category. Only 6 of the 16 (38%) lamp-luminaire combinations passed all of the applicable tested DLC performance criteria, primarily because 7 of the remaining 11 products did not meet the minimum luminaire efficacy requirement (including both of the wall pack luminaire combinations).

- 14 of the 16 luminaire-lamp combinations exceeded the minimum applicable DLC PF criteria (WP6 and HB5 did not pass).
- 13 of the 16 luminaire-lamp combinations exceeded the minimum applicable DLC THD criteria (WP6, HB4 and HB5 did not pass).
- 15 of the 16 luminaire-lamp combinations exceeded the minimum applicable DLC light output criteria (except for HB5).
- 15 of the 16 luminaire-lamp combinations exceeded the minimum applicable DLC CCT criteria (except for AC1).
- All 16 of the measured lamp-luminaire combinations exceeded the minimum applicable DLC CRI criteria.
- Only 9 of the 16 luminaire-lamp combinations exceeded the minimum applicable DLC efficacy criteria.

Table 9: LED mogul base lamp performance relative to applicable DLC retrofit kit performance criteria. Lamp-luminaire combinations that pass the DLC QPL requirements for retrofit kits are shaded in green. The yard light metrics are not shaded in green, as described in the text, because there is no yard light category in the DLC QPL. The pass ratings indicated with an asterisk in the Zonal Lumens column are based on pilot testing data using a moving-mirror goniophotometer at the LRC.

Code	Product ID	Pass DLC PF Criteria?	Pass DLC THD Criteria?	Pass DLC Light Output Criteria?	Pass DLC Efficacy Criteria?	Pass DLC CCT Criteria?	Pass DLC CRI Criteria	Pass DLC Zonal Lumens Criteria?
AC1	109480_109457	PASS	PASS	PASS	PASS	FAIL	PASS	FAIL
AC2	109480_109468	PASS	PASS	PASS	PASS	PASS	PASS	FAIL
AC3	109480_109526	PASS	PASS	PASS	PASS	PASS	PASS	PASS
AC4	109480_109533	PASS	PASS	PASS	PASS	PASS	PASS	FAIL
AC5	109480_109529	PASS	PASS	PASS	PASS	PASS	PASS	PASS
C4	109467_109536	PASS	PASS	PASS	PASS	PASS	PASS	not tested
C5	109467_109532	PASS	PASS	PASS	FAIL	PASS	PASS	not tested
C6	109467_109527	PASS	PASS	PASS	PASS	PASS	PASS	not tested
C7	109467_109528	PASS	PASS	PASS	FAIL	PASS	PASS	not tested
AL5	109465_109530	PASS	PASS	PASS	FAIL	PASS	PASS	not tested
AL6	109465_109531	PASS	PASS	PASS	PASS	PASS	PASS	not tested
YL5	109469_109535	PASS	PASS	PASS	PASS	PASS	PASS	PASS*
WP5	109470_109525	PASS	PASS	PASS	FAIL	PASS	PASS	not tested
WP6	109470_109537	FAIL	FAIL	PASS	FAIL	PASS	PASS	not tested
HB4	109464_109523	PASS	FAIL	PASS	FAIL	PASS	PASS	PASS*
HB5	109464_109524	FAIL	FAIL	FAIL	FAIL	PASS	PASS	PASS*
HB6	109464_109534	PASS	PASS	PASS	PASS	PASS	PASS	PASS*

The yard light is not a covered category given in the DLC QPL. However, the measured results can be compared to DLC criteria for similar applications. The single mogul base LED lamp tested in the yard light would have passed all of the retrofit kit criteria for outdoor arm-mounted area and roadway luminaires. Since the yard light has a prismatic refractor, it is more similar to a decorative luminaire in that it produces both uplight and downlight. Applying the zonal lumens criteria for decorative outdoor luminaires to this category may be more applicable, since these luminaires do not focus all the light downward by design.

Task 4 – Application Efficacy Calculations

Background

To address the concern that mogul base LED lamp luminaire performance is equivalent to HID luminaire performance at a limited range of mounting heights, the LRC conducted Luminaire System Application Efficacy (LSAE) calculations to analyze the application efficacy at various mounting heights for the high bay, yard light and decorative acorn luminaire types. The LRC computed LSAE values by using the measured intensity distributions from Phases 1 and 2.

Traditionally, luminaire system efficacy is used to evaluate the energy efficiency potential of a luminaire. However, this metric is not sufficient to determine how well a given luminaire will deliver light to an application, because light distribution, mounting height and luminaire-to-task geometry are not considered. These factors are important for a given lighting application to be deemed acceptable and efficient.[5] Application efficacy, on the other hand, considers the energy efficiency of light delivered to the required task plane, and is defined as the average luminous flux per unit of power (lm/W).

The LSAE metric is a form of application efficacy that addresses the issue of performance in a given application. It only considers the light on the task plane that meets the photometric requirements of the given task.

Method

As an example of LSAE calculations, the LRC used IES files to conduct photometric simulations for three applications: parking lots, roadways and warehouses. The yard light and high bay luminaire combinations were tested on a moving mirror goniophotometer at the LRC.[6] The intensity distributions for the tested decorative acorn luminaires were obtained from goniophotometric testing at UL.

The results shown in all three applications below are only indicative of the application efficacy values for the tested luminaires in the specific simulated application; if the tested lamp were to be tested in a different luminaire or another sample of the lamp were to be tested, the results would likely differ. Similarly, if the applications were to change (e.g. if different reflectance values were used or for different luminaire-to-task geometry), the results would also likely differ.

Parking Lot Application

For the yards lights, the web-based ASSIST Recommends Parking Lot Luminaire Calculator[7] was used to compute LSAE for parking lot applications per the ASSIST recommends… publication "Recommendations for Evaluating Parking Lot Luminaires"[8]. The web-based calculator was used to determine how well each tested luminaire combination met the IES RP-20-98 illuminance criteria using a task plane defined by the luminaire's lateral and vertical intensity distributions. Mounting heights from 5 feet to 45 feet were investigated for each

[5] http://www.lrc.rpi.edu/programs/solidstate/assist/pdf/AR-ParkingLotEvaluation-Revised-Jan2010.pdf
[6] This is pilot data from the LRC moving-mirror goniophotometer.
[7] http://www.lrc.rpi.edu/parkinglot/#intro
[8] http://www.lrc.rpi.edu/programs/solidstate/assist/pdf/AR-ParkingLotEvaluation-Revised-Jan2010.pdf

luminaire combination. The LSAE reported is the application efficacy when the IES RP-20 illuminance criteria are met. At each mounting height, the estimated maximum spacing between luminaires also is reported, since the application efficacy is for a given luminaire layout.

Three yard light combinations tested in Phase 1 and one yard light combination tested in Phase 2 were included in this analysis. Another yard light from Phase 1 (YL4) could not be evaluated because the luminaires would not stabilize during the goniophotometric testing.

Roadway Application

For the decorative acorn luminaires, the LSAE was computed per the methods described in the ASSIST recommends… publication "Recommendations for Evaluating Street and Roadway Luminaires"[9]. The method simulates a collector street with four lanes and the luminaires arranged in a staggered layout on each side of the street. Mounting heights from 15 feet to 45 feet were used in this application, and the maximum pole spacing that allows the layout to meet the RP-8-00 luminance or illuminance criteria was determined using AGI32 illumination engineering software[10]. Maximum pole spacing was rounded down to nearest 5 foot increment. Post-processing of the illuminance values was completed in spreadsheet software to compute the LSAE values.

Five decorative acorn luminaires tested in Phase 2 were evaluated as an example of LSAE calculations for a roadway simulation.

High Bay Application

For the high bay luminaires, one typical aisle of a warehouse was simulated in AGi32. The warehouse created was similar to the typical warehouse geometry shown in the CEE Warehouse Lighting Design Template[11], but not exactly the same based on the research teams' experience with warehouse lighting demonstrations and case studies. Notable differences and similarities between the CEE template and the LSAE simulation are as follows:

- Room dimensions in CEE Template: 72' length x 150' width by 28' height. The LSAE room dimensions: 64' length x 100' width x 40' height. In the LSAE simulation, 3.25' deep open trusses on 10-foot centers are mounted to the ceiling perpendicular to the racks. The truss surface reflectances are 50%.
- The aisle width was changed from 11.2' in the CEE template to 9'-6" in the LSAE simulation based on DELTA warehouse evaluations.
- CEE used 10'-0" wide shelves that were 3.4' high. Shelves were 8' wide and 4' high for LSAE simulations.
- 60%/50%/20% surface reflectance values were used for ceiling/walls and floor in the LSAE calculations. CEE used 80%/30%/20% surface reflectance values respectively.

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[9] http://www.lrc.rpi.edu/programs/solidstate/assist/pdf/AR-RoadwayEvaluation.pdf

[10] http://www.agi32.com/

[11] http://www.efficiencyvermont.com/Docs/for_my_business/lighting_programs/CEE_CommLight_Warehouse1.0_09242012.pdf

- CEE used a fixed luminaire mounting height of 24 feet, LSAE used varying mounting heights.
- Open shelves were used for both CEE and LSAE calculations.
- For the racks: CEE used 50% reflectance for shelves, 30% for vertical structure, and 80% for horizontal structure. In contrast, 50% reflectance was used for all rack surfaces in LSAE.
- Large labels on the packages were assumed and used to determine light levels.
- A light loss factor (LLF) of 0.7 was used for the LED luminaire combinations; this is the same LLF used in the CEE calculations.

Calculation points using 1-foot centers were located on the floor and racks to measure horizontal and vertical illuminance respectively. Luminaire mounting heights from 25 feet to 40 feet were examined, and at each mounting height, luminaire spacing values ranging from 10 feet to 40 feet were simulated, in 5 foot increments. For each luminaire layout, illuminance values were calculated and exported to spreadsheet software for post processing. The LSAE values reported are based on the IES illuminance criteria shown in **Error! Reference source not found.** being met.

Table 10: Maintained illuminance levels per IES Handbook 10th Edition, p.30.6, Table 30.2: Industrial Illuminance Recommendations- Warehousing and Storage.

		Average Illuminance (lux)	Avg: Min Ratio
Horizontal Illuminance at floor	Bulky, Large Labels	100	5:1
Vertical Illuminance on face of racks	Bulky, Large Labels	50	5:1

Figure 8 shows a rendering of the LSAE warehouse template with the calculation points on the aisle floor and face of the rack.

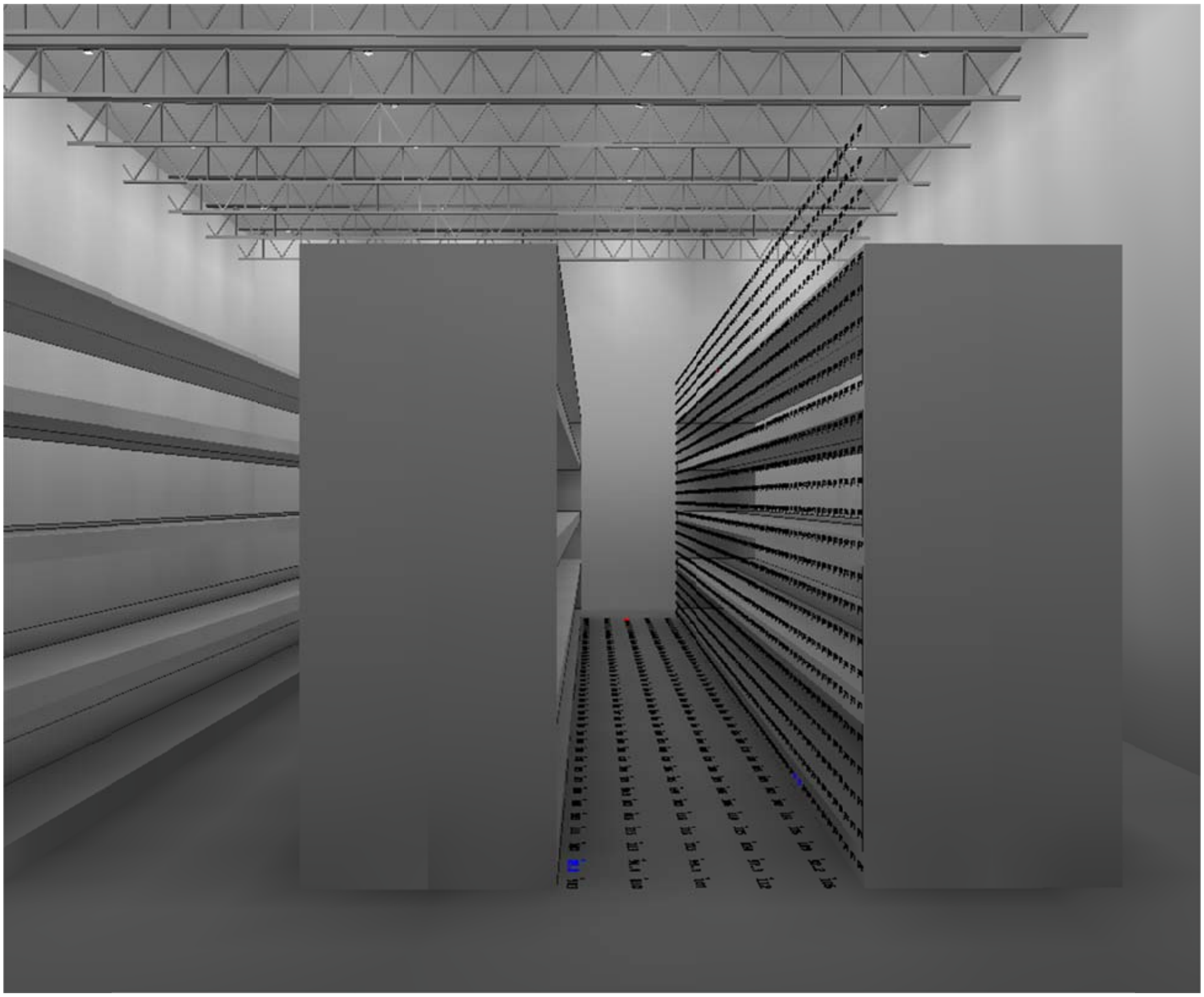

Figure 8: AGi32 rendering of warehouse scenario used to conduct LSAE analyses.

Four high bay lamp-luminaire combinations were analyzed for LSAE, including one combination from Phase 1 (HB1) and three combinations from Phase 2 (HB4, HB5 and HB6).

Results

Parking Lot Lighting LSAE Results

Figure 9 shows the LSAE results for the four tested yard light combinations. As seen in the LSAE graphs, there is an optimal mounting height for each luminaire combination based on its light output and intensity distribution—typically around 10 to 15 feet high..

Of all four tested yard light combinations, YL5 has the highest LSAE value, 32.9 LPW at a mounting height of 10 feet. If these yard lights were to be spaced out regularly to meet the IES RP-20-98 lighting criteria, YL1 offers the largest coverage areas over a range of mounting heights, even though its LSAE values are lower than YL5.

In order to determine how this luminaire ranks in a “one-for-one” retrofit for an existing installation, the lighting specifier would review these results and compare the pole spacing to their existing luminaire layout and to other lighting options. Lighting products that cannot meet the required lighting criteria at the existing mounting height and pole spacing would necessitate additional luminaires, and possibly poles, which would negate any cost advantage of an LED replacement lamp versus an integrated LED luminaire chosen for the existing luminaire positions.

As an example of this comparison, one manufacturer’s 150W HPS area light[12] (system power: 190W) can meet the IES RP-20-98 lighting criteria with estimated spacing of 140’ x 110’ at a mounting height of 30 feet[13]. At this spacing and mounting height (MH), its LSAE is 7.3 lm/W. If a parking lot illuminated with this luminaire layout was retrofitted with YL5 luminaire combinations on a one-for-one basis (without adding additional luminaires or poles), the minimum light level would be 70% lower than the RP-20-98 minimum horizontal illuminance requirement. Even if brightness B2 is accounted for (as in Task 5 below), the minimum light level would still be 55% too low.

In order for luminaire combination YL5 to meet RP-20 at an MH of 30’, additional luminaires and poles would need to be added because the coverage area of this luminaire is only 2500 SF per pole (50’ x 50’ spacing) , which is 84% smaller than the coverage area of the HPS luminaire, at 15,400 SF per pole (140’ x 110’ spacing). Also, the LSAE value of YL5 would be lower (3.1 lm/W) than the incumbent HPS value of 7.3 lm/W.

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[12] Gardco Gullwing 150W HPS_G18-4XL-150H

[13] Using published photometry from the manufacturer.

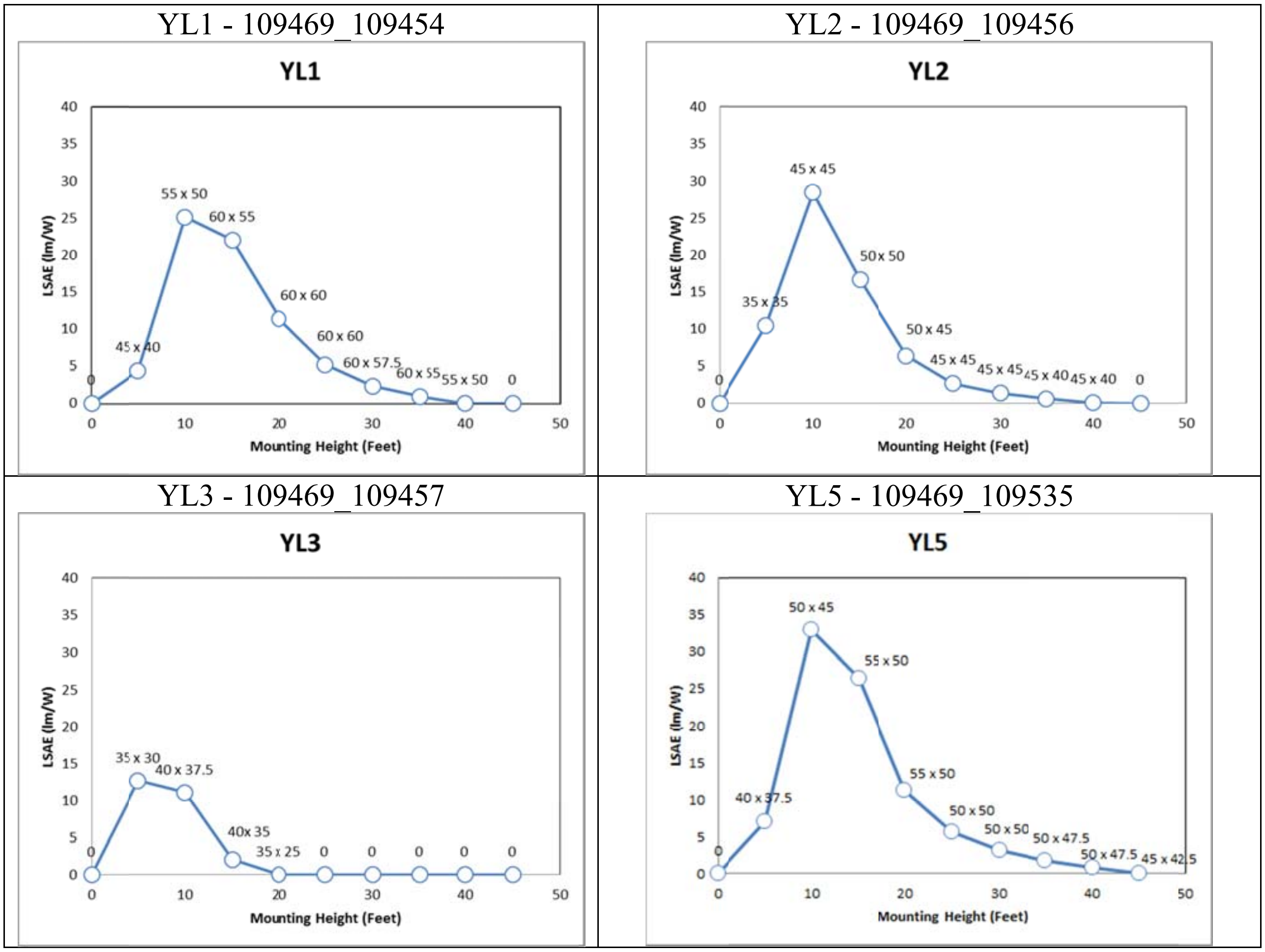


Figure 9: LSAE graphs for mogul base LED area lights and yard lights showing LSAE as a function of varying mounting heights. The data labels show the estimated longitudinal and transversal spacing between luminaires to meet the recommended lighting criteria.

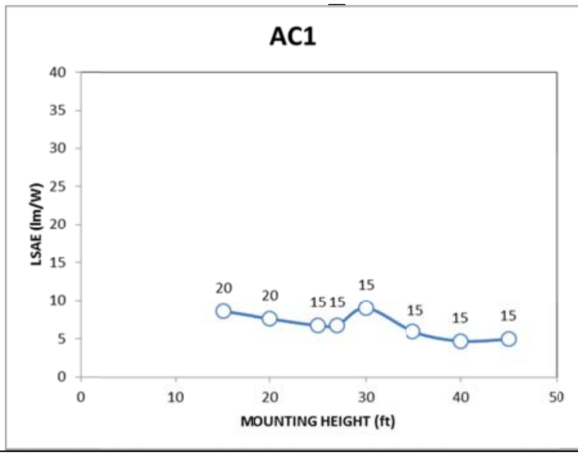
Decorative Roadway Lighting LSAE Results

Figure 10 show the LSAE results for five tested decorative (acorn) outdoor light combinations. Similar to the parking lot applications results, each luminaire combination has an optimal mounting height that results in the longest pole spacing and highest LSAE values.

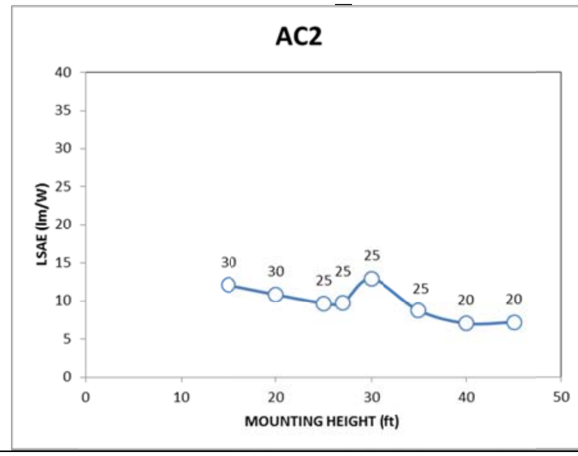
Comparing the luminaire combinations, AC5 has the highest LSAE value but does not have the longest pole spacing. AC3 had the second highest LSAE value and the longest pole spacing. A review of street lighting standards from ten utility and municipality publications found that the average pole spacing for decorative luminaires was 126 feet, with a range of 50 to 200 feet. The tested combinations have much shorter pole spacing's than those typically used, suggesting that a one-for-one replacement with the tested luminaires would result in light levels lower than the recommended IES RP-8-00 lighting criteria.

As with the parking lot application, to compare performance in a retrofit application, the lighting specifier would compare LSAE values and pole spacing's for replacement lighting technologies to the incumbent's current performance at the design mounting height. In new construction applications, where mounting height is a possible design variable, LSAE graphs can show lighting specifiers what the optimum mounting height is for each lighting technology, in order to guide energy efficient and cost effective lighting designs that meet the required lighting criteria.

AC1 - 109480_109457



AC2 - 109480_109468



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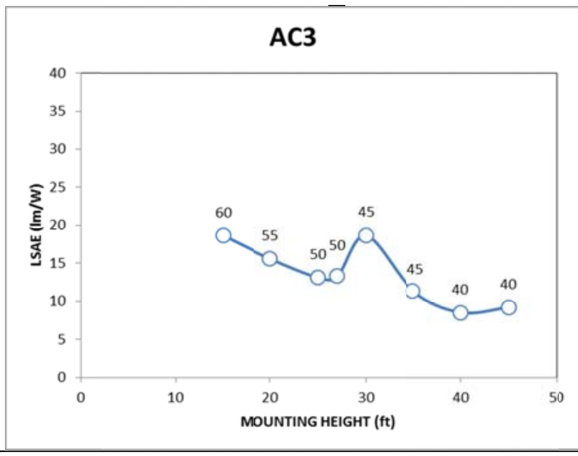
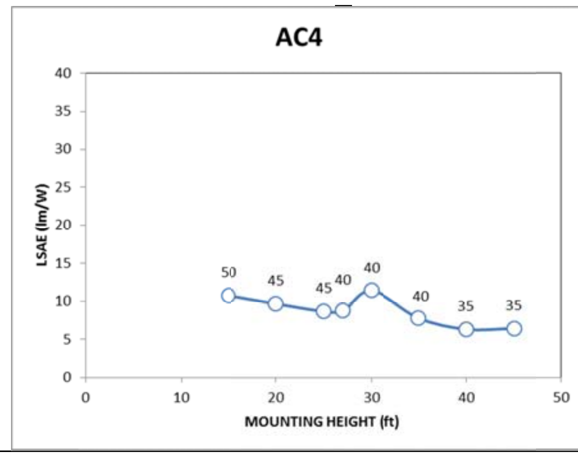


AC4 - 109480_109533



AC5 - 109480_109529

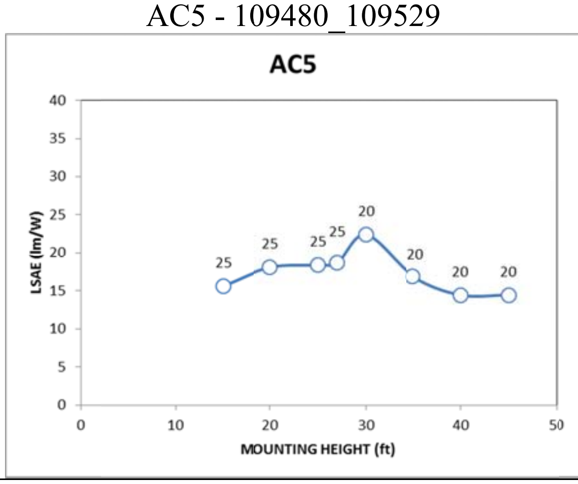


Figure 10: LSAE graphs for mogul base LED acorn (decorative) luminaires showing LSAE as a function of varying mounting heights. The data labels show the estimated same side pole spacing between luminaires to meet the recommended RP-8 roadway lighting criteria.

High Bay Lighting LSAE Results

All four of the tested high bay luminaire combinations could meet the IES lighting criteria for industrial spaces (as shown in Table 11. The luminaire combinations that were able to meet the required IES lighting criteria had low LSAE values in the given layout. In order to meet the uniformity requirements, the luminaires had to be spaced fairly close together (10 - 15 feet apart). At lower mounting heights, this often yielded average light level values that exceeded the average criterion, and these illumination values were not included as a result.

For example, if an existing space with luminaires mounted at 25 feet that were spaced 15 feet or less apart was retrofitted with the HB1 combination, the layout would meet uniformity requirements and exceed light level requirements. However, if an existing space had wider luminaire spacing, then additional luminaires (at additional cost) would be needed in order to meet uniformity requirements.

Table 11: Calculated LSAE values for four high bay combinations.

Combination ID	Product ID	Maximum LSAE Value (lm/W)	MH at Max. LSAE (Feet)	Luminaire spacing at this MH (Feet)	Application notes
HB1	109464_109459	14.8	25	15	Exceeds required light levels, meets uniformity criteria (hor. and vert.)
HB4	109464_109523	17.3	30	15	Meets required light levels, meets uniformity criteria with this geometry (hor. and vert.)
HB5	109464_109524	14.8	25	10	Meets required light levels, meets uniformity criteria with this geometry (hor. and vert.)
HB6	109464_109534	16.1	35	15	Meets required light levels, meets uniformity criteria with this geometry (hor. and vert.)

Task 5 Brightness Calculations

Background

Specifiers frequently use photometric light output as a method of determining equivalency among different lighting products. In the case of LED mogul lamps, some manufacturers claim equivalency to legacy HID lamps even when the light output is much lower than the base-case HID lamp. While there is some uncertainty as to what the equivalent claims are based on because they are not stated (e.g. perceived scene brightness or lower mounting heights), there are many studies showing that exterior environments illuminated by "white" light sources look brighter and feel safer than when the same environment is illuminated to the same level by HPS luminaires[14]. Perceived brightness is due to visual input from all three cone photoreceptors – S, M and L. Environments illuminated by "cool white" light sources, such as LED or metal halide luminaires, will appear brighter, for the same light level, because their higher short-wavelength content stimulates the S cones more than when a "warm white" light source is used. In contrast, the photopic luminous efficiency function is based on input only from M and L cones, and does not include visual channel input from S cones. Photometrically-accurate lighting software programs used for lighting layouts, as well as commercial illuminance and luminance meters, use the photopic luminous efficiency function to weight spectral power distributions (SPDs) and as a result do not accurately characterize perceived brightness.

To address the question that brightness perception can be used to determine equivalency between mogul base LED replacement lamps and HID lamps, in addition to light output comparisons, the LRC will compute the predicted apparent brightness values using SPDs for 32 lamp-luminaire combinations for each of the 6 applications from Phases 1 and 2.

Method

Apparent brightness perception is calculated using a published model that has input from the S cone photoreceptor as well as the photopic luminous efficiency function[15]. The B2 Brightness function is used for low light level predictions and the S cone function is modulated by a light-level dependent gain value of 2.

$$B2(\lambda) = V(\lambda) + 2S(\lambda)$$

Figure 11 shows the B2 brightness function and the photopic luminous efficiency function, with the value of the function at 555 nm equal to 1.

[14] Rea et al. 2014. Spectral considerations for outdoor lighting: Designing for perceived scene brightness. Lighting Res. Technol. 2014 (OnlineFirst).

[15] Rea, Mark S. 2013. Value Metrics For Better Lighting. DOI:10.1117/3.1000979

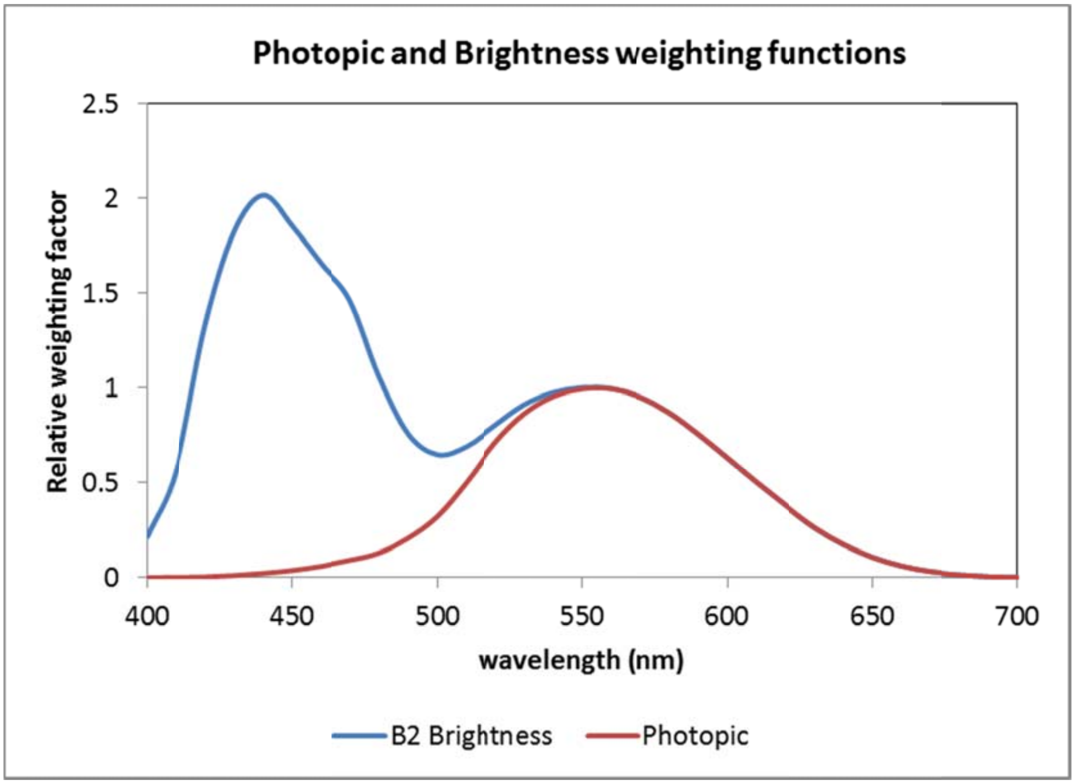


Figure 11: The B2 Brightness function compared to the photopic luminous efficiency function used to characterize photometric values.

The 32 SPDs measured in Phases 1 and 2 were normalized to provide the same weighted photopic illuminance value (i.e. each SPD was normalized to have a photopic sum = 1). This step was also conducted for a 400W HPS lamp to serve as the base case. The B2 function was then multiplied on a wavelength-by-wavelength basis against each of the normalized SPDs and the weighted values were summed to obtain a B2 brightness value for each SPD. Finally, the LED mogul B2 values were divided by the HPS B2 value to obtain a relative brightness ratio for each tested LED mogul luminaire combination relative to the brightness of an HPS luminaire at low light levels [< 25 lx (2.5 fc)].

Results

Table 12 and Figures 12 and 13 show the relative brightness ratios for each tested luminaire combination. The HPS brightness ratio is defined as 1, as this luminaire serves as the base case. The results show that low light level environments illuminated by the LED mogul lamp luminaire combinations could appear about 40-80% brighter than if illuminated by HPS lamps. On average, low light level spaces would appear 50% brighter using these combinations than HPS luminaires providing the same light level.

Table 12: Predicted perceived brightness values and brightness ratios using the B2 function for tested LED mogul luminaire combinations from Phases 1 and 2.

	LRC ID (last 2 digits of luminaire and lamp code)	B2 Brightness	Brightness relative to HPS
Phase 1	400W HPS	1.19	1.00
	64-59	1.91	1.61
	64-71	1.70	1.43
	65-61	1.78	1.50
	65-66	1.84	1.55
	65-68	1.60	1.35
	65-72	2.11	1.78
	67-60	1.79	1.51
	67-73	2.09	1.76
	69-54	1.67	1.41
	69-56	1.72	1.45
	69-57	2.17	1.83
	69-58	1.54	1.30
	70-51	1.70	1.43
	70-52	1.72	1.44
	70-55	1.95	1.64
	70-62	1.76	1.48
Phase 2	64-23	1.63	1.37
	64-24	1.62	1.37
	64-34	1.69	1.43
	65-30	1.90	1.60
	65-31	1.68	1.41
	67-27	2.02	1.70
	67-28	2.02	1.70
	67-32	1.71	1.44
	67-36	1.68	1.41
	69-35	1.67	1.41
	70-25	1.82	1.54
	80-26	1.74	1.46
	80-29	1.80	1.52
	80-33	1.74	1.47
	80-57	2.17	1.83
	80-68	1.60	1.35

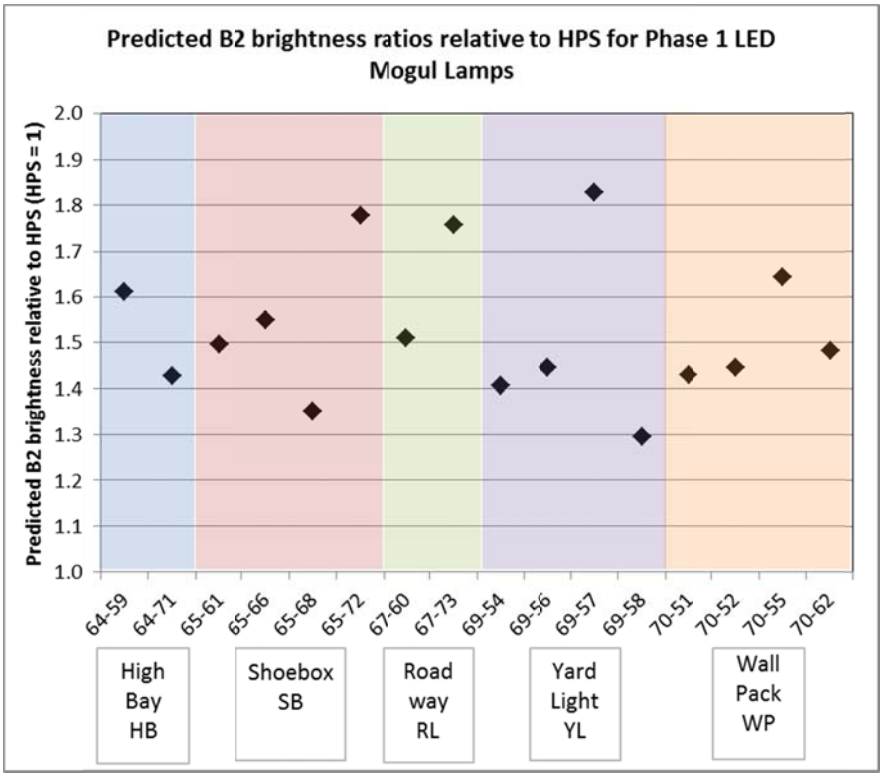


Figure 12: Predicted brightness ratios, relative to HPS for Phase 1 LED mogul lamp luminaire combinations.

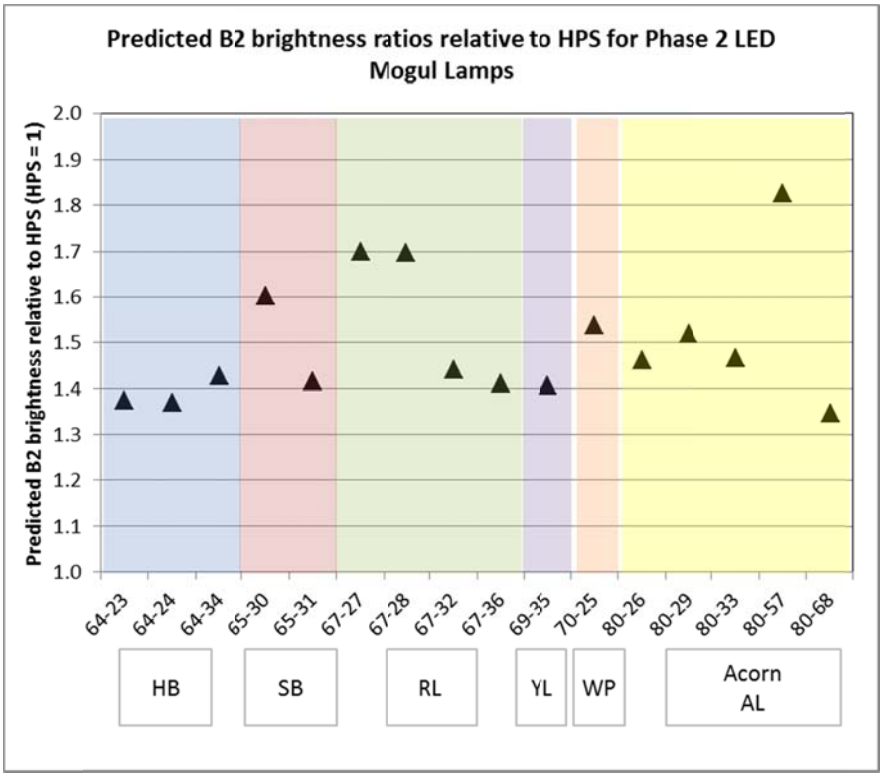


Figure 13: Predicted brightness ratios, relative to HPS for Phase 2 LED mogul lamp luminaire combinations.

These brightness ratios could be included in the QPL as an additional method of determining equivalency. For example, the 53W AL1 area light luminaire combination tested in Phase 1 (109465_109461) has a predicted brightness ratio of 1.5 relative to a 190 W HPS area light if both were providing the same light level. Figure 14 shows a sample parking lot illuminated by five 190 W HPS luminaires meeting the RP-20-14 pre-curfew lighting criteria. The total power demand from 5 luminaires is 950 W.

Figure 15 shows the results for the same parking lot illuminated using thirteen AL1 luminaires to meet RP-20-14 criteria. The total power demand from 13 luminaires is 694 W.

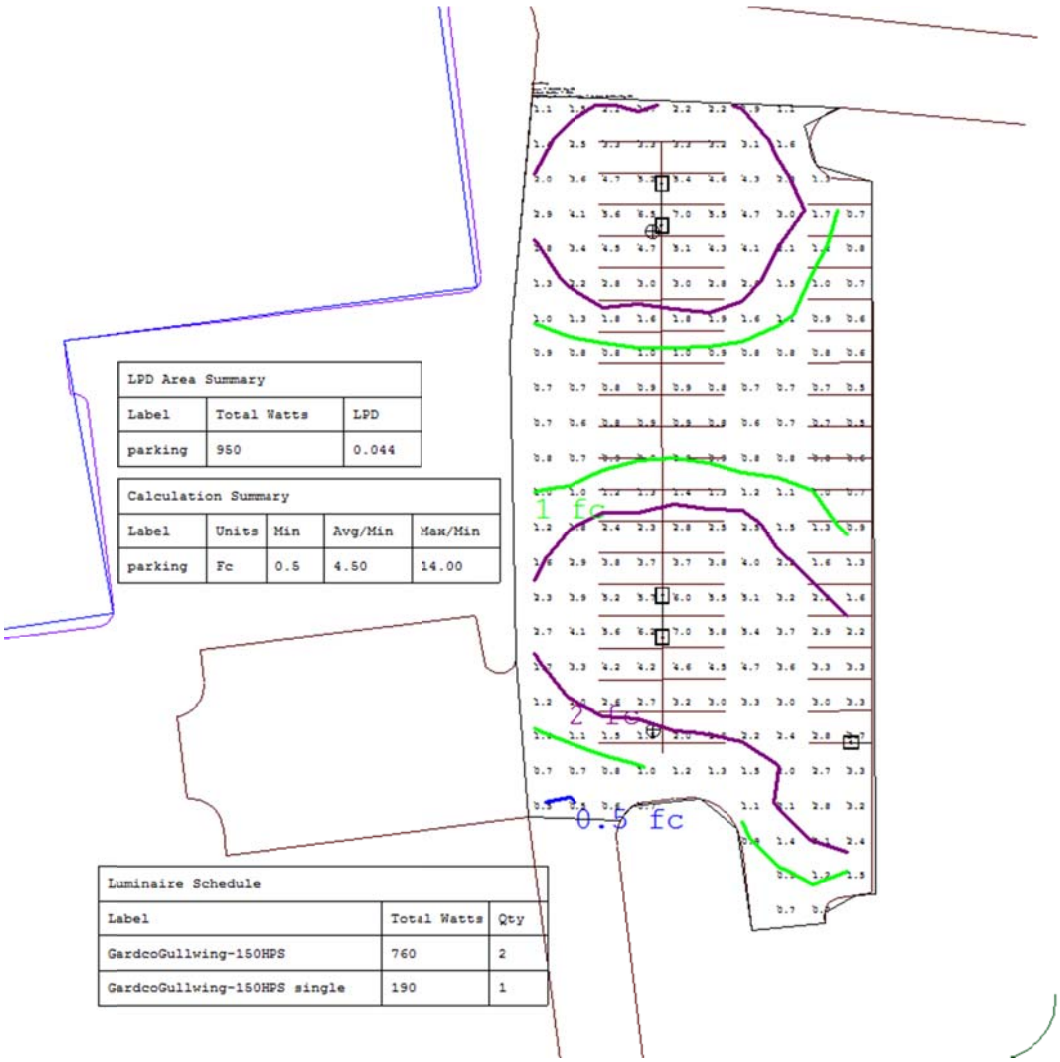


Figure 14: Sample parking lot illuminated to RP-20-14 criteria with five 190W HPS luminaires using a 25 ft. mounting height. Total power demand equals 950 W.

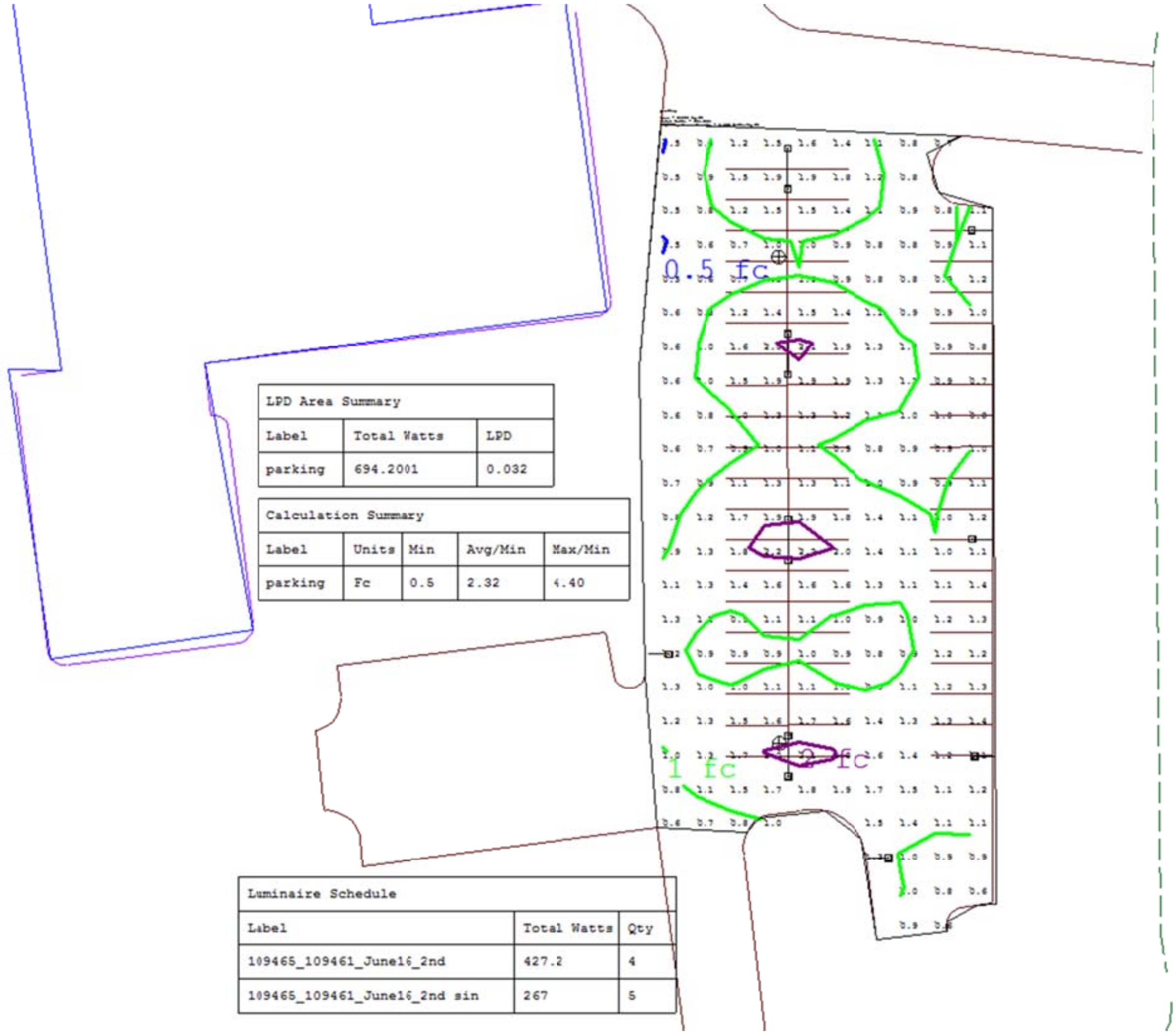


Figure 15: Sample parking lot illuminated to RP-20-14 criteria with thirteen 53W LED mogul replacement lamp luminaires using a 25 ft. mounting height. Total power demand equals 694 W.

The photopic light level under the LED mogul luminaire combination could be reduced by 33% of the light level relative to that under the HPS luminaire, and both lighting environments would be perceived to be equally bright and equally safe. Assuming a linear relationship between light output and dimming, each LED mogul luminaire could be reduced to 36 W (a reduction of 51% in power demand for the entire site relative to the HPS installation) and both installations would be perceived to be equally bright and safe.

Figure 16 shows the results of a one-for-one retrofit with five AL1 luminaires replacing the five HPS luminaires. In this scenario, the 0.5 footcandle minimum illuminance criterion is reduced to 0.33 to account for the increased brightness factor of this luminaire. The blue-shaded illuminance values shown in Figure 16 are lower than the adjusted 0.33 footcandle minimum criterion. Replacing the incumbent HID luminaires with AL1 luminaires, with the same pole layout, results in much lower light levels. This retrofitted layout does not meet the adjusted minimum light level and the RP-20-14 uniformity criterion.

Figure 16: Sample parking lot illuminated with five 53W AL1 luminaires using a 25 ft. mounting height. Total power demand equals 267 W.

Task 6: High Temperature Testing

Background

To address the concern that mogul base LED replacement lamp performance will degrade under high temperature ambient conditions, such as those that occur in unconditioned spaces, the LRC pilot tested 6 lamp-luminaire combinations for relative light output, including 4 high-bay combinations, and 2 wall pack combinations.

Method

The LRC used a Cincinnati Sub-Zero (CSZ) Z-Plus Temperature and Humidity Test Chamber (Model ZP(H)-8)[16] to conduct the thermal testing for both luminaire types. Figure 17 shows the test chamber monitoring a high bay luminaire within.

Figure 17: CSZ Test Chamber and computer monitoring setup. Luminaire energized inside the test chamber is the tested high bay luminaire.

Three thermocouples were used to monitor relevant temperatures inside the test chamber: one attached to the LED replacement lamp inside the luminaire (Figure 18), a second attached above the lamp inside the luminaire (Figure 19) and a third outside the luminaire measuring the ambient temperature in the chamber (Figure 20).

[16] http://www.cszindustrial.com/Products/Temperature-Chambers/Z-Plus-Test-Chambers.aspx

Figure 18: Thermocouple attached to the lamp

Figure 19: Thermocouple monitoring temperature inside the luminaire

Figure 20: Thermocouple monitoring temperature inside test chamber

A photodiode was located on a rack below the luminaire to continuously monitor light output, as shown in Figure 21. The current value measured from the photodiode (in nA) was multiplied by a constant value of 8.0E+05 to display a light output value, shown with arbitrary units.

Figure 21: Photodiode located on rack below luminaire monitoring luminaire light output

The thermocouple temperatures and light output were monitored using a custom LabVIEW software program (screen capture shown in Figure 22) and measurements were recorded to a text file every thirty seconds.

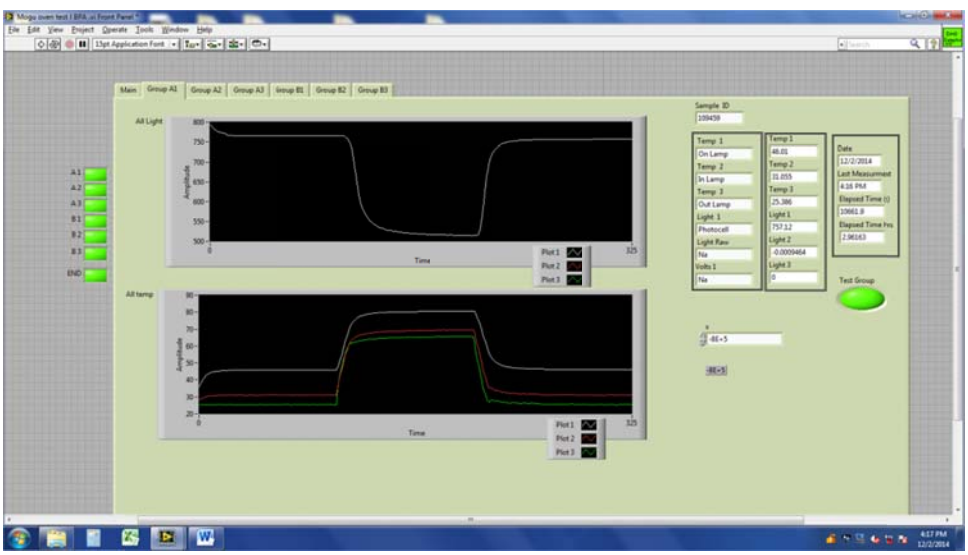


Figure 22: Screen capture from LabVIEW showing light output (top graph) and three temperatures being monitored as test chamber set point is changed from 25°C to 65°C and then back down to 25°C.

The luminaires were energized using 120V rms ac and operated continuously as the thermal chamber temperature was changed. The thermal chamber setpoint was set so that the ambient chamber temperature with the luminaire running was either 25°C (±1°C) or 65°C (±1°C). The ambient chamber temperature was initially set to 25°C (±1°C), then increased to 65°C (±1°C) and decreased again to 25°C (±1°C) to complete the experiment. Both light output and temperature were monitored for stability before the chamber setpoint was changed. Luminaire output was considered stable when light output changed by 2% or less over 30 minutes.

Table 13 shows the LRC lamp ID numbers and luminaire codes identifying each tested product. Two of the luminaires had external drivers which were mounted in the ballast enclosure above the luminaire reflector. These two products also had a fan attached to the lamp assembly. Figure 23 shows the external drivers and the ballast enclosure.

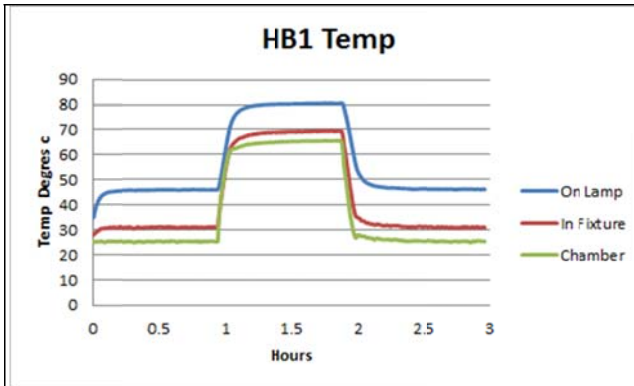
Table 13: Luminaires tested in thermal test chamber

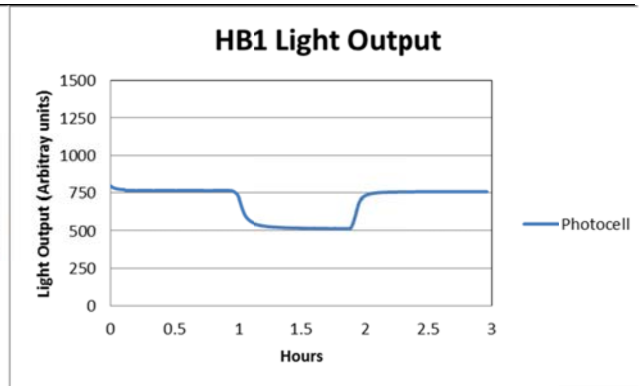
LRC Lamp ID	LRC Luminaire Code	Notes
109459	HB1	External driver mounted in ballast enclosure; includes fan
109523	HB4	
109524	HB5	
109534	HB6	External driver mounted in ballast enclosure; includes fan
109525	WP5	
109537	WP6	

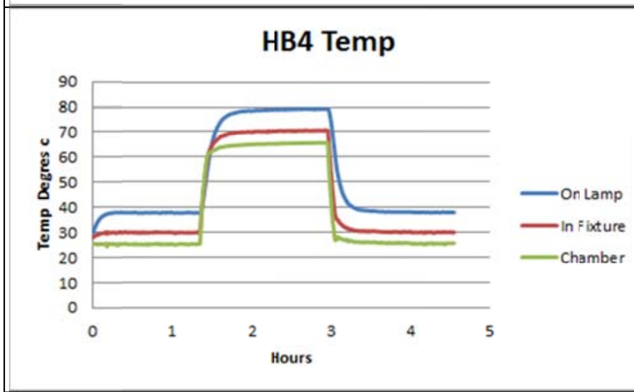
Figure 23: External LED drivers for mogul base replacement lamps mounted in luminaire ballast enclosure (HB1 on left, HB6 on right)

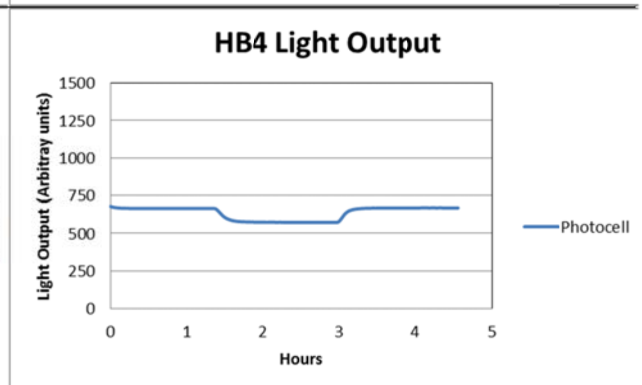
Results

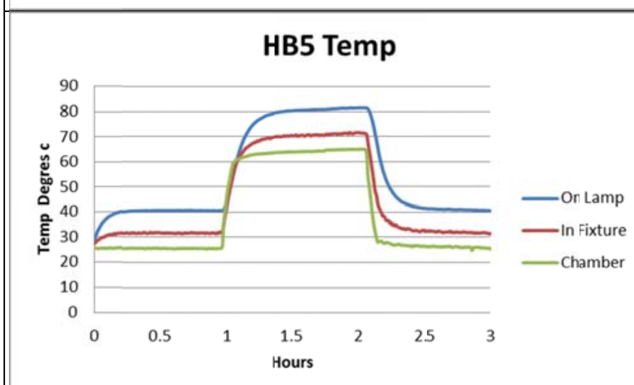
Figure 24 shows the monitored temperature and light output values for each luminaire as it was monitored in the test chamber. The X axis shows the time duration, the Y axis shows measured temperatures for the graphs on the left and light output for the graphs on the right. In the temperature graphs, the green line shows the ambient chamber temperature, the red line shows the thermocouple in the luminaire, and the blue line shows the thermocouple on the lamp. The green line on these graphs indicates that the ambient temperature is at 25°C for about an hour, then rises to 65°C for approximately another hour, then decreases to 25°C for the final hour of the test. The graphs on the right show the light output during the same testing protocol (higher at 25°C than at 65°C). As noted by the Y axis values on the graph, the wall packs had significantly lower light output than the high bay luminaires. WP5 has a longer test duration because it took longer for the light output to stabilize at each temperature interval.

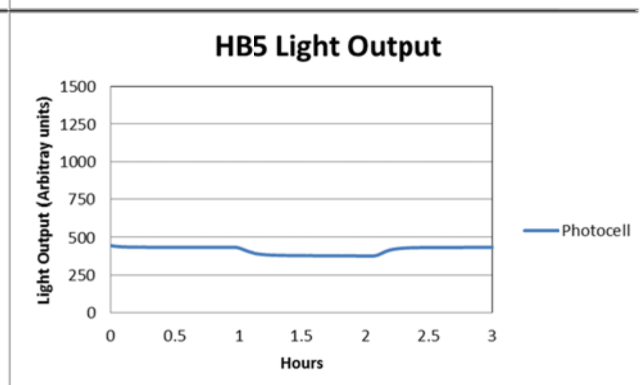

HB1 Temp
Temp Degres c
90
80
70
60
50
40
30
20
10
0
0
0.5
1
1.5
2
2.5
3
Hours
On Lamp
In Fixture
Chamber

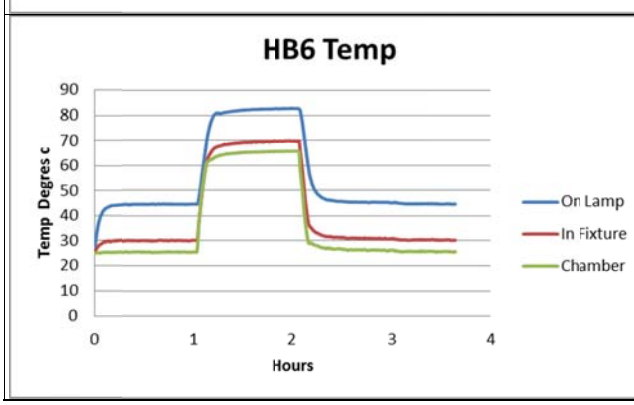

HB1 Light Output
Light Output (Arbitray units)
1500
1250
1000
750
500
250
0
0
0.5
1
1.5
2
2.5
3
Hours
Photocell

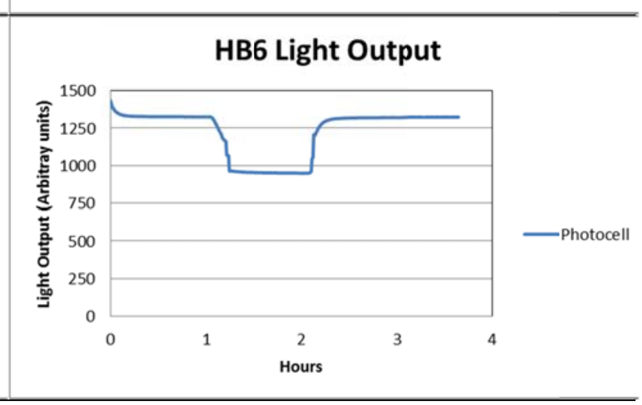

HB4 Temp
Temp Degres c
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
5
Hours
On Lamp
In Fixture
Chamber


HB4 Light Output
Light Output (Arbitray units)
1500
1250
1000
750
500
250
0
0
1
2
3
4
5
Hours
Photocell


HB5 Temp
Temp Degres c
90
80
70
60
50
40
30
20
10
0
0
0.5
1
1.5
2
2.5
3
Hours
On Lamp
In Fixture
Chamber


HB5 Light Output
Light Output (Arbitray units)
1500
1250
1000
750
500
250
0
0
0.5
1
1.5
2
2.5
3
Hours
Photocell


HB6 Temp
Temp Degres c
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
Hours
On Lamp
In Fixture
Chamber


HB6 Light Output
Light Output (Arbitray units)
1500
1250
1000
750
500
250
0
0
1
2
3
4
Hours
Photocell

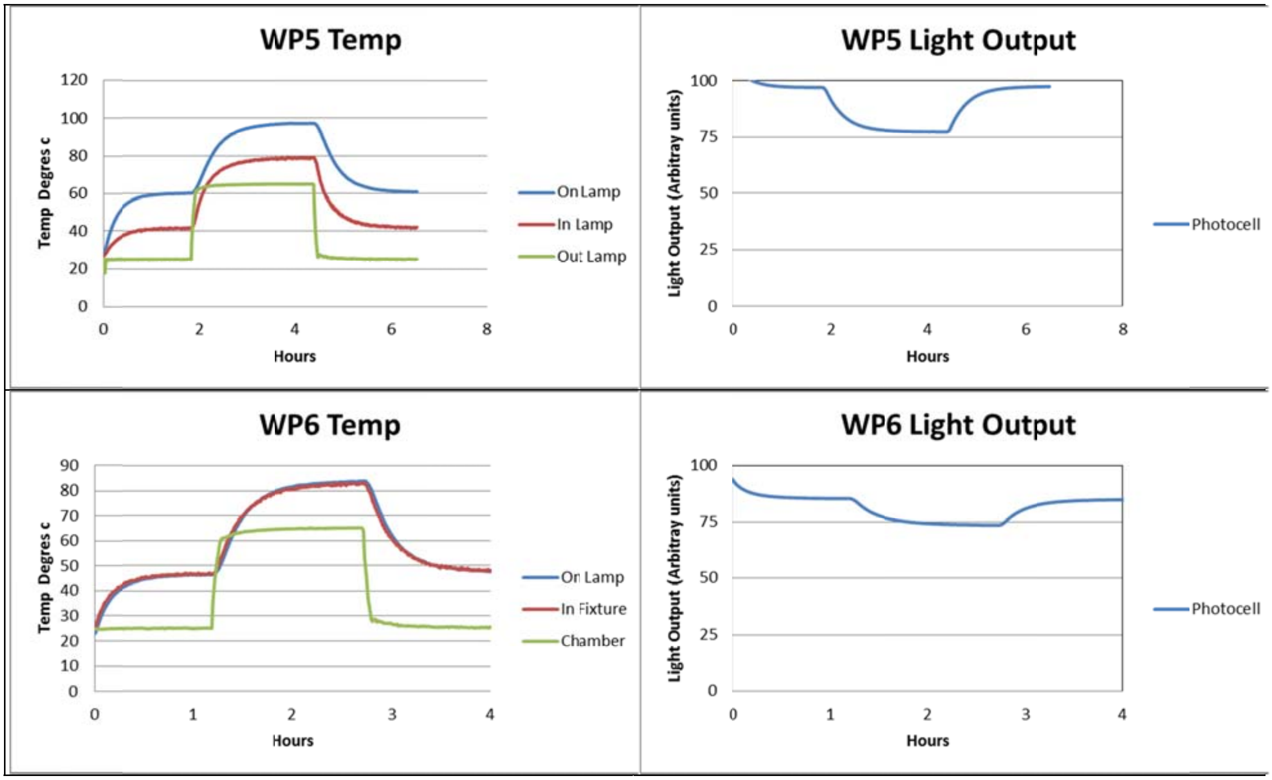


Figure 24: Temperature and light output curves for each measured luminaire in test chamber.

Figure 25 shows the stable relative light output values at 65°C in percent relative to the measured light output at 25 C. The relative light output in the high bay luminaires decreased by 22%, on average, when the ambient temperature was increased to 65°C with a reduction range of 13% to 33% depending on the lamp luminaire combination. The luminaires with the lowest relative light output at the elevated temperatures were the two with the external driver mounted in the ballast enclosure. These lamps also included a fan attached to the lamp assembly. In the wall pack luminaires, the relative light output decreased by 17%, on average, when the ambient temperature was increased to 65°C.

As shown in Table 14, when the test chamber was reset to 25°C after operating the luminaire at the elevated temperature for about one hour, the relative light output was similar (within 1 percent) to that initially measured during the initial 25°C period.

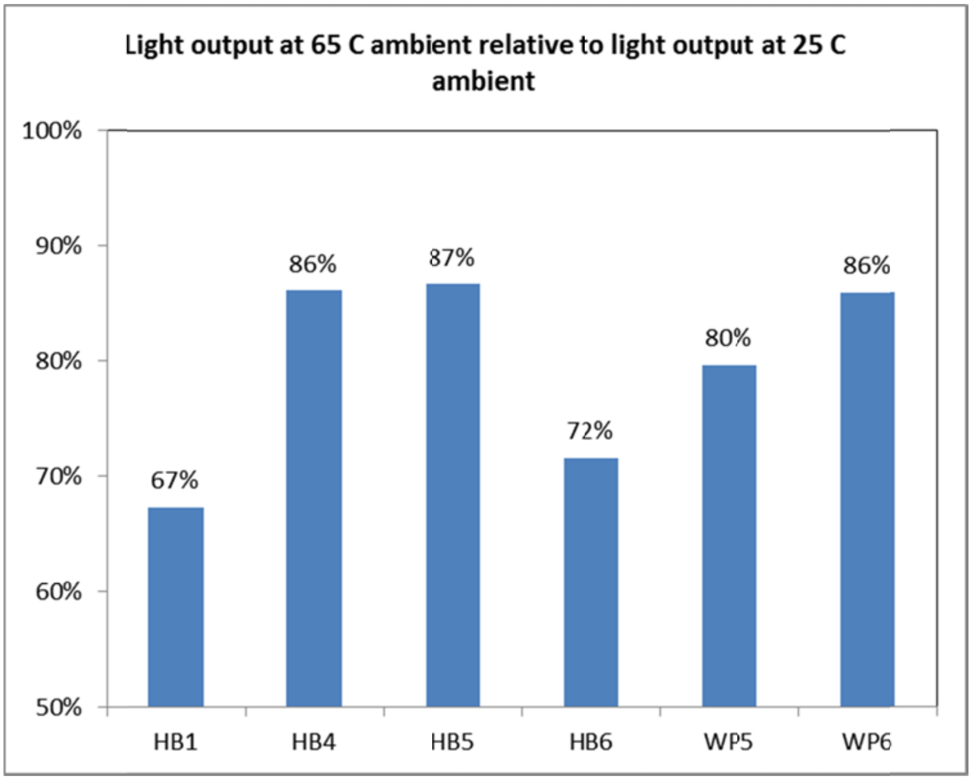


Figure 25: Light output for each tested luminaire at 65°C relative to light output at 25°C.

LRC Lamp ID	LRC ID	Stabilized light output at 65 C divided by light output at 25 C	Stabilized light output at 25 C at end of test divided by initial stabilized light output at 25 C	Notes
109459	HB1	0.67	0.99	External driver mounted in ballast enclosure and fan on lamp assembly
109523	HB4	0.86	1.01	
109524	HB5	0.87	1.00	
109534	HB6	0.72	1.00	External driver mounted in ballast enclosure and fan on lamp assembly
109525	WP5	0.80	1.00	
109537	WP6	0.86	1.00	

Table 14: Light output values for each tested luminaire at 65°C relative to light output at 25°C and light output after returning to 25°C relative to initially stabilized 25°C operation.

Recommended Modifications to DLC Technical Requirements

The photometric testing and subsequent evaluations conducted in Phases 1 and 2 indicate that there is a need for additional specification and performance information about mogul base LED lamps in order for these lamps to be included in the DLC QPL retrofit kit category. The following points are suggested modifications to the DLC testing requirements based on testing results.

- Mogul base LED replacement lamps are often longer, wider and heavier than the HID lamps they replace. Specifiers need to know the lamp size as well as the interior dimensions of the incumbent HID luminaire. However, the interior dimensions of the incumbent luminaire may not be easily determined, since these dimensions may not be listed on the luminaire's specification sheets. LRC found that lamp length was often a limiting factor to selecting a product, but this specification step could not be conducted until the interior dimensions of the pre-approved luminaire was known. The DLC technical requirements require a pre-approved base case luminaire in which to test the retrofit kit. The interior dimensions of these luminaires (with some tolerance) could be stated in the testing requirements and a requirement for the mogul base lamps to fit within these luminaires could be stated. Although this would not guarantee that the mogul base LED lamps would fit in all incumbent luminaires, it could potentially begin to address the over-size issue that was seen in Phases 1 and 2.
- Similarly, lamp weight is an important consideration. During the photometric testing, it was observed that several of the lamps sagged downwards when they were screwed into the mogul socket, and some were so heavy the end of the lamp rested on the flat lens of the luminaire when the luminaire was positioned in its application orientation (flat lens facing down for the roadway, area and wall pack luminaires).
- Several of the lamps tested have a "paddle" shape where the lamp has a flat surface on which the LEDs and optics are mounted. If these lamps are not oriented parallel to the flat lens of the luminaire, the reflector and housing may cut off part of the lamps integral optic distribution. (Lamp orientation is less of a factor for omnidirectional, HID and LED lamps). Several of the products tested could not be "locked" into position so that the flat portion of the lamp was parallel to the aperture of the luminaire. Some products could be screwed in tightly into the socket, but the lamp could still be freely rotated to align the optics with the luminaire aperture. While this mechanical rotation makes orienting the lamp easier initially, not being able to lock the lamp into place means that the lamp orientation may change, and subsequently the distribution may change, while the lamp is operating. Locking the lamp into position would also ensure that the lamp is installed, per the design intent, correctly into the luminaire.
- Some of the products tested in Phase 1 can be operated at line voltage (bypassing the magnetic ballast). The HID persistence testing task (Task 2) may indicate that there is a safety concern for these types of bypassed systems when input voltages of 277V or higher are used. Phase 3 of this project will test whether MH lamps exhibit non-passive failures when operated in a closed luminaire without a ballast on a 277V circuit employing a standard circuit breaker. One benefit of a LED retrofit kit over the mogul base LED replacement lamps is that HID lamps cannot be relamped into the retrofitted luminaire, as is possible with mogul base LED replacement lamps.

- Lamps of widely varying light output are claimed to be equivalent to the HID lamps they replace. Design performance metrics, such as brightness and application efficacy, allow the specifier to further compare product performance in a “base case” application.
- Information regarding relative light output under higher temperatures may be useful for certain applications.
- With regards to all of the recommended modifications listed above, manufacturers should indicate which pre-approved luminaire was used to test the retrofit kit products and replacement lamps. Performance in one pre-approved luminaire is not necessarily indicative of similar performance in a different luminaire.
- Four of the mogul base LED lamps tested, demonstrated significantly lower stabilized light output and power compared to the rated data on the specification sheet. We recommend that the photometric and electrical data submitted to DLC be within some given tolerance (TBD) of the rated data.