APPLICATION NOTE

CLD-AP94 REV 0

Cree® XLamp® XT-E LED PAR38 Reference Design



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INTRODUCTION

This application note details the design of a 150-watt equivalent PAR38 replacement lamp using Cree's XLamp XT-E LED. The XT-E offers industry-leading performance and reduces system cost.

Parabolic aluminized reflector (PAR) lamps are widely used in various indoor and outdoor applications, from residential and commercial recessed downlights, indoor retail spotlights and outdoor security lighting to stage lights, emergency-vehicle lighting and locomotive headlights. The high flux and efficacy offered by the XLamp XT-E LED make it a particularly strong candidate for use in a PAR38 lamp.

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DESIGN APPROACH/OBJECTIVES

In the "LED Luminaire Design Guide" application note, Cree advocates a 6-step framework for creating LED luminaires.[1] All Cree reference designs use this framework, and the design guide's summary table is reproduced below.

Step	Explanation
1. Define lighting requirements	• The design goals can be based either on an existing fixture or on the application's lighting requirements.
2. Define design goals	• Specify design goals, which will be based on the application's lighting requirements. • Specify any other goals that will influence the design, such as special optical or environmental requirements.
3. Estimate efficiencies of the optical, thermal & electrical systems	• Design goals will place constraints on the optical, thermal and electrical systems. • Good estimations of efficiencies of each system can be made based on these constraints. • The combination of lighting goals and system efficiencies will drive the number of LEDs needed in the luminaire.
4. Calculate the number of LEDs needed	• Based on the design goals and estimated losses, the designer can calculate the number of LEDs to meet the design goals.
5. Consider all design possibilities and choose the best	• With any design, there are many ways to achieve the goals. • LED lighting is a new field; assumptions that work for conventional lighting sources may not apply.
6. Complete final steps	• Complete circuit board layout. • Test design choices by building a prototype luminaire. • Make sure the design achieves all the design goals. • Use the prototype to further refine the luminaire design. • Record observations and ideas for improvement.

Table 1: Cree 6-step framework

THE 6-STEP METHODOLOGY

The goal of the design is an LED-based PAR38 lamp that shows the performance available from the XLamp XT-E LED.

1. DEFINE LIGHTING REQUIREMENTS

Table 2 shows a ranked list of desirable characteristics to address in a PAR38 lamp reference design.

Importance	Characteristics	Metric
Critical	Light intensity - center beam candle power (CBCP)	candelas (cd)
	Illuminance	footcandles (fc) / lux (lx)
	Beam angle - full width half maximum (FWHM)	degrees (°)
	Luminous flux	lumens (lm)
	Efficacy	lumens per watt (lm/W)
	Color uniformity	
	Form factor	

1 LED Luminaire Design Guide, Application Note AP15, www.cree.com/xlamp_app_notes/luminaire_design_guide

Importance	Characteristics	Metric
Important	Price	$
	Lifetime	hours
	Operating temperatures	°C
	Operating humidity	% relative humidity
	Correlated color temperature (CCT)	K
	Color rendering index (CRI)	100-point scale
	Manufacturability	
	Ease of installation	

Table 2: Ranked design criteria for PAR38 lamp

Table 3 summarizes the ENERGY STAR® requirements for all integral LED lamps.[2]

<table>
<tr><th>Characteristic</th><th>Requirements</th></tr>
<tr><td>CCT and Duv</td><td>Lamp must have one of the following designated CCTs (per ANSI C78.377-2008) consistent with the 7-step chromaticity quadrangles and Duv tolerances below.
<table>
<tr><th>Nominal CCT</th><th>Target CCT (K) and Tolerance</th><th>Target Duv and Tolerance</th></tr>
<tr><td>2700 K</td><td>2725 ± 145</td><td>0.000 ± 0.006</td></tr>
<tr><td>3000 K</td><td>3045 ± 175</td><td>0.000 ± 0.006</td></tr>
<tr><td>3500 K</td><td>3465 ± 245</td><td>0.000 ± 0.006</td></tr>
<tr><td>4000 K</td><td>3985 ± 275</td><td>0.001 ± 0.006</td></tr>
</table></td></tr>
<tr><td>Color maintenance</td><td>The change of chromaticity over the minimum lumen maintenance test period (6,000 hours) shall be within 0.007 on the CIE 1976 (u′, v′) diagram.</td></tr>
<tr><td>CRI</td><td>Minimum CRI (R_a) of 80. R_9 value must be greater than 0.</td></tr>
<tr><td>Allowable lamp bases</td><td>Must be a lamp base listed by ANSI.</td></tr>
<tr><td>Power factor</td><td>Lamp power < 5 W and low voltage lamps: no minimum power factor is required
Lamp power > 5 W: power factor must be ≥ 0.70
Note: Power factor must be measured at rated voltage.</td></tr>
<tr><td>Minimum operating temperature</td><td>-20 °C or below</td></tr>
<tr><td>LED operating frequency</td><td>≥ 120 Hz
Note: This performance characteristic addresses problems with visible flicker due to low frequency operation and applies to steady-state as well as dimmed operation. Dimming operation shall meet the requirement at all light output levels.</td></tr>
<tr><td>Electromagnetic and radio frequency interference</td><td>Must meet appropriate FCC requirements for consumer use (FCC 47 CFR Part 15)</td></tr>
<tr><td>Audible noise</td><td>Class A sound rating</td></tr>
<tr><td>Transient protection</td><td>Power supply shall comply with IEEE C62.41-1991, Class A operation. The line transient shall consist of seven strikes of a 100 kHz ring wave, 2.5 kV level, for both common mode and differential mode.</td></tr>
<tr><td>Operating voltage</td><td>Lamp shall operate at rated nominal voltage of 120, 240 or 277 VAC, or at 12 or 24 VAC or VDC.</td></tr>
</table>

Table 3: ENERGY STAR requirements for all integral LED lamps

Table 4 summarizes the ENERGY STAR requirements for replacement PAR lamps.[3]

2 ENERGY STAR Program Requirements for Integral LED Lamps Eligibility Criteria – Version 1.4, Table 4, www.energystar.gov/ia/partners/product_specs/program_reqs/Integral_LED_Lamps_Program_Requirements.pdf

3 Ibid., Table 7C

Criteria Item	ENERGY STAR Requirements
Definition	Directional lamp means a lamp having at least 80% light output within a solid angle of ∏ sr (corresponding to a cone with angle of 120°)
Minimum luminous efficacy	Lamp diameter < 20/8 inch: 40 lm/W Lamp diameter > 20/8 inch: 45 lm/W
Color spatial uniformity	The variation of chromaticity within the beam angle shall be within 0.006 from the weighted average point on the CIE 1976 (u′, v′) diagram.
Maximum lamp diameter	Not to exceed target lamp diameter
Maximum overall length (MOL)	Not to exceed MOL for target lamp
Minimum center beam intensity PAR and MR16 lamps	
PAR lamps	Link to online tool at www.energystar.gov/ia/products/lighting/iledl/IntLampCenterBeamTool.zip
Lumen maintenance	> 70% lumen maintenance (L_{70}) at 25,000 hours of operation
Rapid-cycle stress test	Cycle times must be 2 minutes on, 2 minutes off. Lamp will be cycled once for every 2 hours of L_{70} life.

Table 4: ENERGY STAR requirements for PAR lamps

As shown in Figure 1, we used the ENERGY STAR Center Beam Intensity Benchmark Tool to determine that a 150-W equivalent PAR38 lamp with a 15° beam angle needs to provide CBCP of 15,761 cd.

ENERGY STAR® Integral LED Lamp Center Beam Intensity Benchmark Tool

PAR Lamps

Target Incandescent/Halogen Lamp Parameters

Enter PAR type/value: **38** lamp diameter in ⅛ of inch
Enter Nominal Lamp Wattage: **150** watts
Enter Nominal Beam Angle*: **15** degrees

Minimum Center Beam Intensity: 15761 cd

Term	Coefficient	PAR Type	Nominal Wattage	Beam Angle	Predicted Log CBCP	Log CBCP Two-sigma Lower Bound	Predicted CBCP	CBCP Two-sigma Lower Bound
Intercept	5.5102112	38	150	15	9.968	9.665	21324	15761
PAR	0.1395448							
Watts	0.0448725							
Beam Angle	-0.088493							
PAR*Watts	-0.000521							
PAR*Beam Angle	-0.000719							
PAR^2	-0.001192							
$Watts^2$	-0.00005981							
Beam $Angle^2$	0.0008786							
Root Mean Square Error	0.151113							

*Nominal beam angle per ANSI C78.379-2006: American National Standard for electric lamps-- Classification of the Beam Patterns of Reflector Lamps.
See Section 4.1 Nominal beam angle classifications, and section 4.3 Beam angle tolerance of PAR and R lamps.

Figure 1: ENERGY STAR Center Beam Intensity Benchmark Tool output for 150-W equivalent PAR38 lamp with 15° beam angle

To demonstrate the capability and flexibility of the XT-E LED, we made two additional versions of the PAR38 lamp, with 18° and 35° beam angles. We used the ENERGY STAR Center Beam Intensity Benchmark Tool to determine that an 18° beam angle lamp needs to provide CBCP of 12,147 cd and a 35° beam angle lamp needs to provide CBCP of 3,743 cd.

2. DEFINE DESIGN GOALS

Table 5 shows the design goals for this project.

Characteristic	Unit	Minimum Goal	Target Goal
Light output	lm	1,600	> 1,600
CBCP - 15° beam angle	cd	15,761	16,000
CBCP - 18° beam angle	cd	12,147	12,500
CBCP - 35° beam angle	cd	3,743	4,000
Efficacy	lm/W	54	60
Power	W	30	< 30
CCT	K	3,000	3,000
CRI	100-point scale	75	80
Power factor	%	90	> 90

Table 5: XT-E PAR38 lamp design goals

3. ESTIMATE EFFICIENCIES OF THE OPTICAL, THERMAL & ELECTRICAL SYSTEMS

We used Cree's Product Characterization Tool (PCT) tool to determine the drive current for the design.[4] For the 1,600-lumen target, we estimated 90% optical efficiency and 85% driver efficiency. We also estimated a solder point temperature of 75 °C.

Current (A)	LED 1			
	Model	Cree XLamp XT-E {AWT}		
	Flux	Q4 [100]	Tsp (ºC)	75
	Price	$ -		
	SYS # LED	SYS lm tot	SYS W	SYS lm/W
0.100	55	1620.8	17.35	93.4
0.150	38	1625	18.26	89
0.200	29	1611.3	18.84	85.5
0.250	24	1628.8	19.74	82.5
0.300	21	1674.1	20.98	79.8
0.350	18	1640	21.22	77.3
0.400	16	1633.1	21.78	75
0.450	15	1689.2	23.2	72.8
0.500	14	1718.6	24.28	70.8
0.550	13	1722.9	25.01	68.9
0.600	12	1703.2	25.39	67.1
0.650	11	1660.9	25.41	65.4
0.700	11	1756.5	27.56	63.7
0.750	10	1681	27.03	62.2
0.800	10	1761.9	29.01	60.7

Figure 2: PCT view of the number of LEDs used and drive current

4 PCT is available at: pct.cree.com

The PCT shows that, at 600 mA, 12 XT-E LEDs provide sufficient light output to meet the design goals.

Thermal Requirements

For the PAR38 lamp in this reference design we decided to use a commercially available housing with an Edison screw base. The housing is part of a kit, shown in Figure 3, that includes a plastic optic-locking ring.[5] We also decided to use a commercially available heat sink, shown in Figure 4, to dissipate the thermal load.[6]

Figure 3: Housing kit components

Figure 4: Heat sink

We performed thermal simulations to verify this thermal design is sufficient. Figure 5 shows the thermal simulation results for the design. The simulated solder point temperature (T_{SP}) is 75 °C.

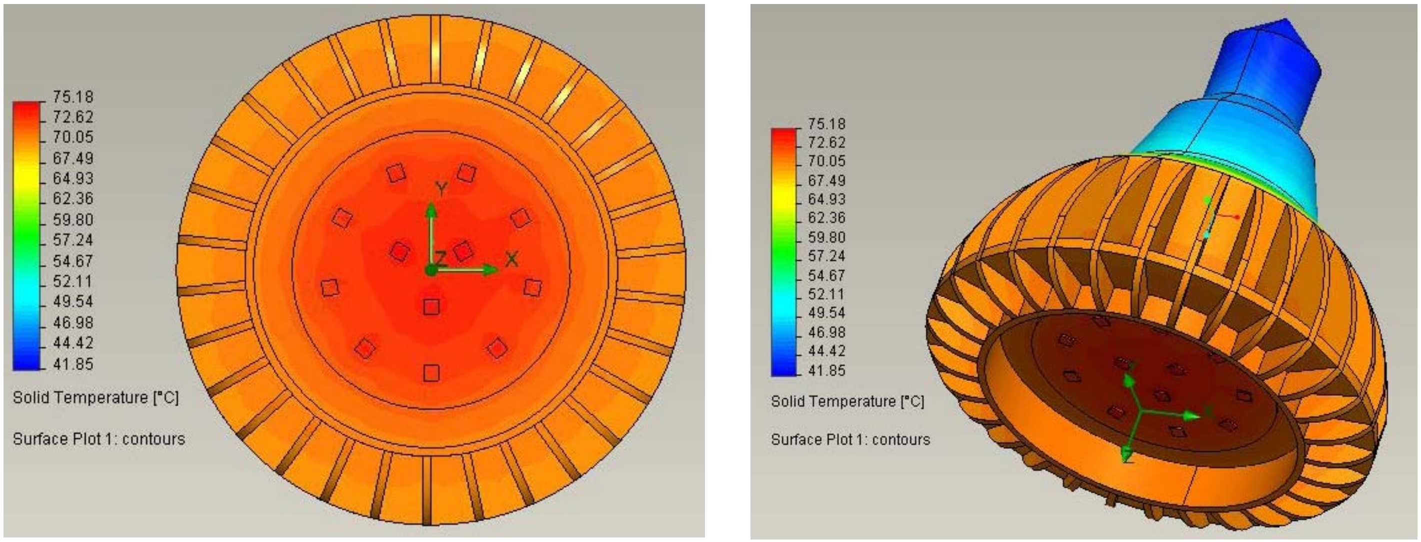


Figure 5: Thermal simulation of XT-E PAR38 lamp

5 PAR38 housing module, LedLink Optics, Inc., www.ledlink-optics.com/productsmodule.aspx
6 Ibid., Model PAR38

Driver

The driver for this PAR38 lamp must be located inside the lamp housing. We decided to use a market-ready constant-current driver that fits within the PAR38 form factor and matches the design's current and voltage range.[7]

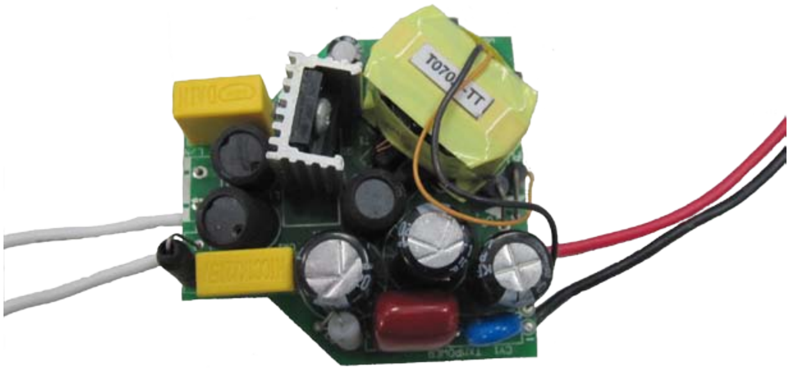


Figure 6: XT-E PAR38 driver

Secondary Optics

PAR38 lamps are commonly used as both spotlights and floodlights and are offered with a variety of beam angles. This XT-E PAR38 design addresses lamps with 15°, 18°, and 35° beam angles, each using a 12-in-1 lens optic, shown in Figure 7.[8] The optic is only design difference in the lamps.

Figure 7: Both sides of XT-E PAR38 optic

4. CALCULATE THE NUMBER OF LEDS NEEDED

Using Cree's PCT, we determined that 12 XLamp XT-E LEDs produce sufficient light to meet the 1,600-lm design goal.

7 Model TXM11-T0702-TT, TXM Power Co., www.ledpower.com.cn
8 LedLink Optics, Inc., www.ledlink-optics.com/productsmodule.aspx

5. CONSIDER ALL DESIGN POSSIBILITIES

There are many ways to design an LED-based PAR38 lamp. This reference design aims to show that the XT-E LED enables a PAR38 lamp offering superior performance.

The XT-E LED offers a wide range of color temperatures. As highlighted in Table 6, we selected a warm white LED for this PAR38 lamp design. By selecting an LED from a low-level flux bin, we ensured that this design meets its goals using an LED that is readily available.

Color	CCT Range		Base Order Codes Minimum Luminous Flux @ 350 mA (lm)		Order Code
	Min.	Max.	Group	Flux (lm)	
Warm White	2,600 K	3,700 K	Q5	107	XTEAWT-00-0000-00000LDE7
			Q4	100	XTEAWT-00-0000-00000LCE7
			Q3	93.9	XTEAWT-00-0000-00000LBE7

Table 6: XT-E order codes

6. COMPLETE THE FINAL STEPS

Using the methodology described above, we determined a suitable combination of LEDs, components and drive conditions for a PAR38 lamp. This section describes how Cree assembled the lamp and shows the results of the design.

Prototyping Details

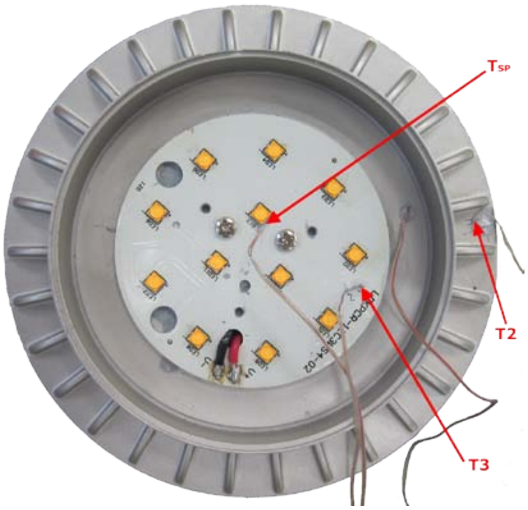
1. We verified the component dimensions to ensure a correct fit.
2. Following the recommendations in Cree's Soldering and Handling Application Note for the XT-E LED,[9] with an appropriate solder paste and reflow profile, we reflow soldered the LEDs to the metal core printed circuit board (MCPCB).
3. We soldered the input wires to the MCPCB.
4. We tested the connection by applying power to the LEDs and verified the LEDs lit up.
5. We applied a thin layer of thermal conductive compound to the back of MCPCB and attached it to the heat sink with screws.
6. We soldered the LED DC input wires to the driver DC output wires.
7. We fit the LED driver into the housing and secured it with screws.
8. We screwed the housing to the heat sink.
9. We placed the optic on the LED MCPCB, aligning the positioning tabs, and secured it to the heat sink with the plastic locking ring.
10. We performed final testing.

9 Cree XLamp XP and XT Family LEDs Soldering and Handling, Application Note AP25, www.cree.com/xlamp_app_notes/XP_XT_SH

Results

Thermal Results

Cree verified the board temperature with a thermocouple to confirm that the thermal dissipation performance of the heat sink aligns with our simulation. As shown in Figure 8, the measured solder point temperature was 78 °C, which is in close agreement with the simulation and shows that the heat sink is sufficient for this design.



T_{SP} Solder Point Temperature	T2 Heat Sink Temperature	T3 PCB Temperature
78 °C	62 °C	66 °C

Figure 8: Thermal measurement

Based on the measured solder point temperature of 78 °C, the junction temperature (T_J) can be calculated as follows.

$T_J = T_{SP}$ + (LED power * LED thermal resistance)
T_J = 78 °C + (2 W * 5 °C/W)
T_J = 88 °C

Estimated LED Lifetime

Since the XLamp XT-E LED is a new component, based on our experience with similar LED systems, we expect the lumen maintenance performance of the XT-E LED to be at least as good as that of the XLamp XP-E High Efficiency White (HEW) LED.

Figure 9 shows the calculated and reported lifetimes, determined using the TM-21 projection algorithm, for the XP-E HEW LED at a 700-mA input current at three solder point temperatures. The duration of Cree's XP-E HEW LM-80 data set is 6,000 hours at a 700-mA drive current. The TM-21 methodology limits the projection to six times the duration of the LM-80 data set.

LED	XLamp XP-E High Eff. White		
I	700 mA		
Data Set	1	2	3
Tsp	**45°C**	**55°C**	**85°C**
Sample Size	25	25	25
Test Duration	6,048 hrs	6,048 hrs	6,048 hrs
α	4.302E-06	5.332E-06	7.913E-06
β	1.024E+00	1.011E+00	1.015E+00
Calculated Lifetime	L70(6k) = 88,500 hours	L70(6k) = 68,900 hours	L70(6k) = 47,000 hours
Reported Lifetime	**L70(6k) > 36,300 hours**	**L70(6k) > 36,300 hours**	**L70(6k) > 36,300 hours**

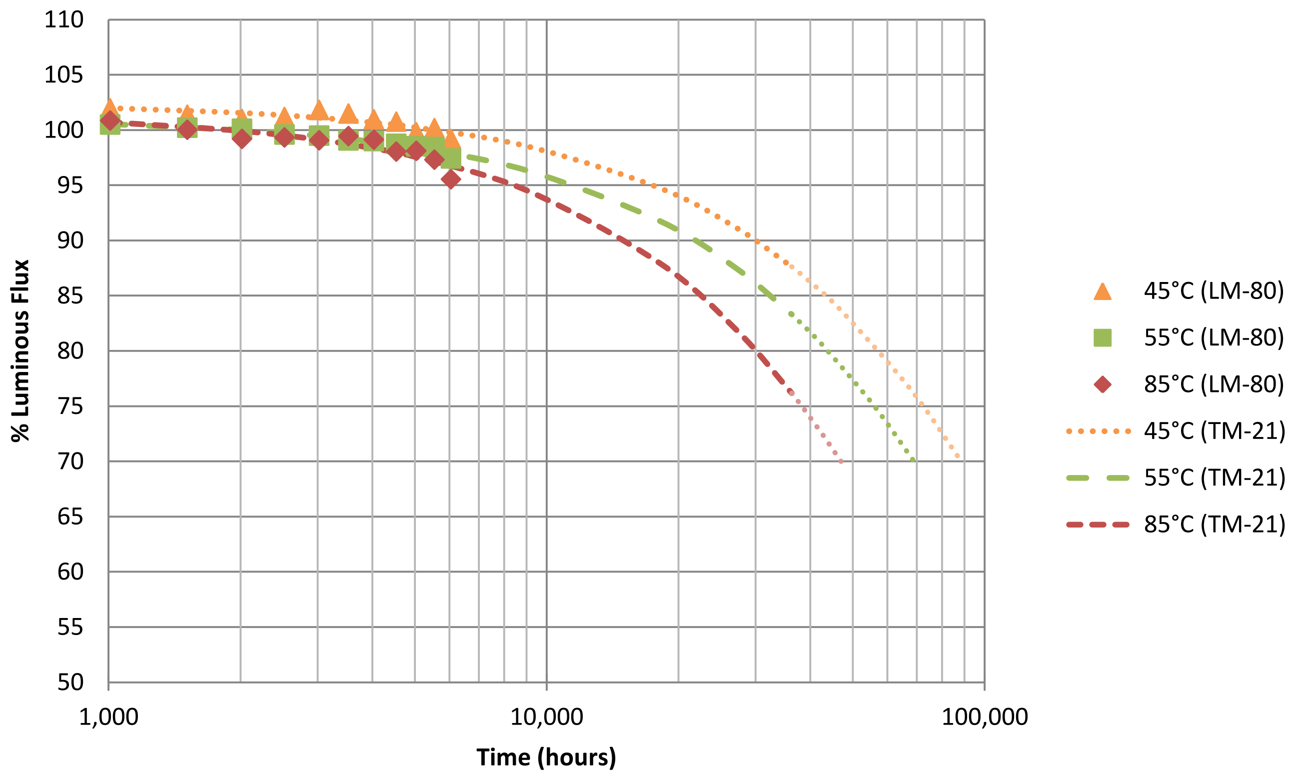


Figure 9: XP-E HEW TM-21 data

Figure 10 shows the calculated and reported lifetimes for the XP-E HEW LED, interpolated from the data shown in Figure 9, at the measured 78 °C T_{SP} for the XT-E LED in this design. With a reported L70(6k) lifetime greater than 36,300 hours and a calculated L70(6k) lifetime of 51,500 hours, we expect the lamp to easily meet the ENERGY STAR lumen maintenance requirement, > L70 at 25,000 hours.[10]

LED	XLamp XP-E High Eff. White		
I	700 mA		
	Ts1	Tsi (Interpolated)	Ts2
Tsp	**55°C**	**78°C**	**85°C**
Tsp	328.15 K	350.15 K	358.15 K
Ea/kB	1546.25		
A	5.9337E-04		
α	5.332E-06	7.170E-06	7.913E-06
β	1.011E+00	1.013E+00	1.015E+00
Calculated L70	L70(6k) = 68,900 hours	L70(6k) = 51,500 hours	L70(6k) = 47,000 hours
Reported L70	L70(6k) > 36,300 hours	**L70(6k) > 36,300 hours**	L70(6k) > 36,300 hours
Calculated Lifetime		L70(6k) = 51,500 hours	
Reported Lifetime		**L70(6k) > 36,300 hours**	

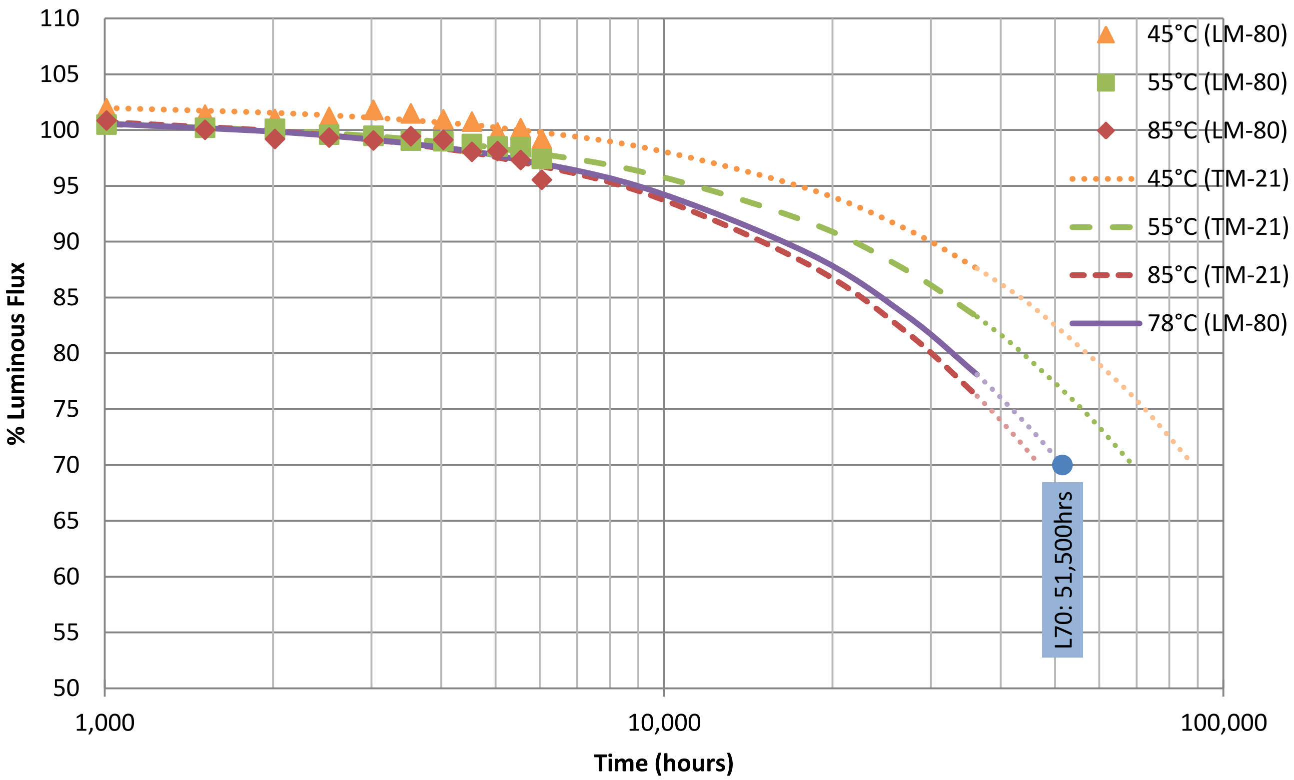


Figure 10: XP-E HEW TM-21 data with T_{SP} = 78 °C

10 That is, after 25,000 hours of operation, the LED will still deliver at least 70% of its initial luminous flux.

Optical and Electrical Results

We obtained the results in Table 7 and Table 8 by testing the PAR38 lamps in a 1.5-meter sphere after a 60-minute stabilization time.[11] As the tables show, the lamps exceed the 1,600-lm target using less than 30 W of power. The lamps also meet their CBCP goals. In addition, the PAR38 lamps meet the ENERGY STAR efficacy, power factor, CCT and CRI requirements.

The results in Table 7 are common to the three XT-E PAR38 lamps.

Characteristic	Unit	Result
Power	W	24.5
CCT	K	3,093
CRI	100-point scale	82
Power factor	%	99.2
Current	mA	600
Voltage (total)	V	38.7

Table 7: XT-E PAR38 lamp steady-state results

Table 8 shows optical results for the three individual XT-E PAR38 lamps.

Characteristic	Unit	Result		
Lens model		GK25	GK40	GK60
Beam angle	°	14	18	37
Light output	lm	1,679	1,815	1,738
CBCP	cd	16,802	12,936	3,903
Efficacy	lm/W	68.5	74	71

Table 8: XT-E PAR38 lamp optical results

We also tested the intensity distribution of the PAR38 lamps. Figures 11, 12 and 13 show an even intensity distribution for each beam angle.

11 Testing was performed in a type A goniometer at Cree's Shenzhen Technology Center. IES files for the PAR38 lamp are available at www.cree.com/xlamp_app_notes/XTE_par38_gk25_ies, www.cree.com/xlamp_app_notes/XTE_par38_gk40_ies and www.cree.com/xlamp_app_notes/XTE_par38_gk60_ies

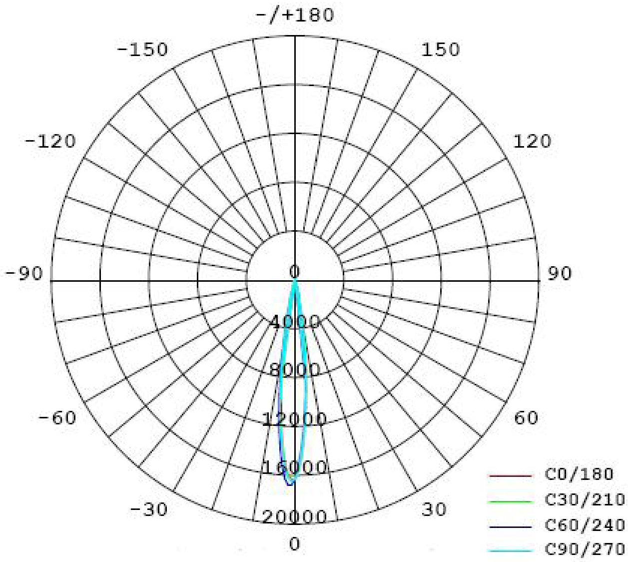


Figure 11: Angular luminous intensity distribution of XT-E PAR38 lamp - 14° beam angle

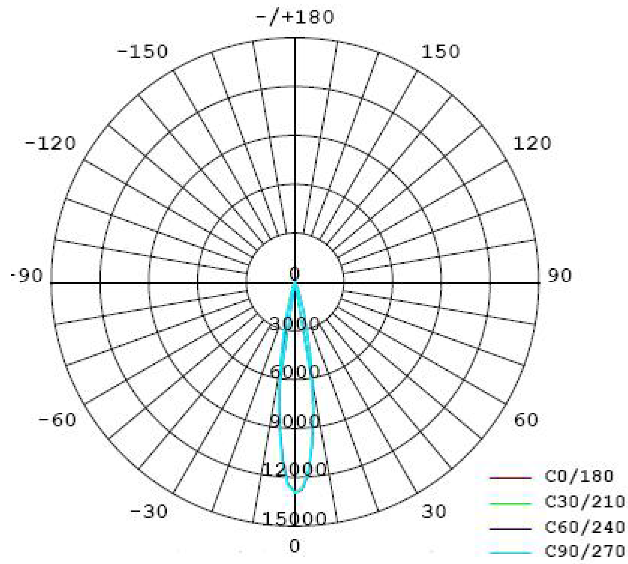


Figure 12: Angular luminous intensity distribution of XT-E PAR38 lamp - 18° beam angle

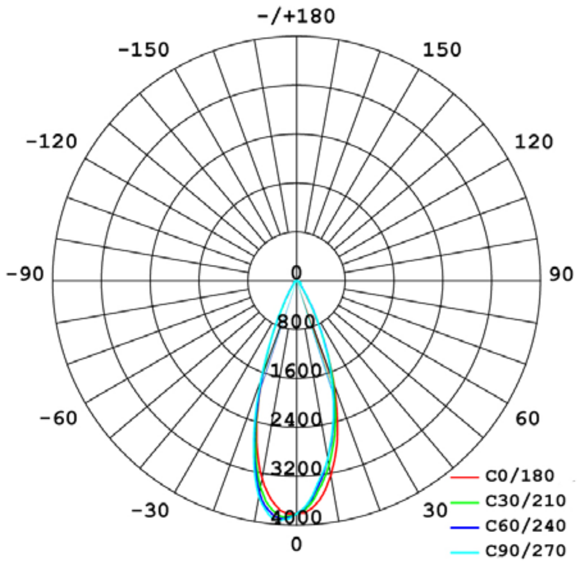


Figure 13: Angular luminous intensity distribution of XT-E PAR38 lamp – 37° beam angle

Figures 14, 15 and 16 show the illuminance of the XT-E PAR38 lamps at various distances from the light source.

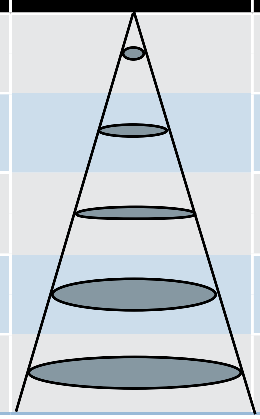
Height		Illuminance					Diameter	
		Eavg	Emax	Eavg	Emax			
1 m	3.3 ft	1010 fc	1604 fc	10,869 lx	172,631 lx		24.7 cm	0.8 ft
2 m	6.6 ft	252.4 fc	401.0 fc	2717 lx	43,161 lx		49.4 cm	1.6 ft
3 m	9.8 ft	112.2 fc	178.2 fc	1208 lx	19,181 lx		75.1 cm	2.4 ft
4.m	13.1 ft	63.1 fc	100.2 fc	679 lx	10,791 lx		98.7 cm	3.2 ft
5 m	16.4 ft	40.4 fc	64.2 fc	435 lx	691 lx		123.4 cm	4.1 ft

Figure 14: XT-E PAR38 illuminance – 14° beam angle

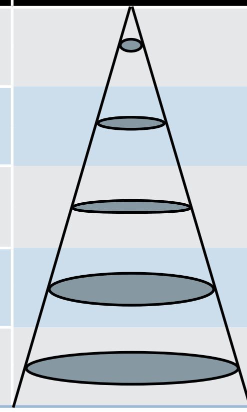
Height		Illuminance					Diameter	
		Eavg	Emax	Eavg	Emax			
1 m	3.3 ft	803.4 fc	1209 fc	8,648 lx	130,081 lx		32.0 cm	1.1 ft
2 m	6.6 ft	200.9 fc	302.1 fc	2,162 lx	32,521 lx		64.0 cm	2.1 ft
3 m	9.8 ft	89.3 fc	134.3 fc	960.9 lx	14,451 lx		96.1 cm	3.2 ft
4.m	13.1 ft	50.2 fc	75.5 fc	540.5 lx	813.0 lx		128.1 cm	4.2 ft
5 m	16.4 ft	32.1 fc	48.3 fc	345.9 lx3	520.3 lx		160.1 cm	5.3 ft

Figure 15: XT-E PAR38 illuminance – 18° beam angle

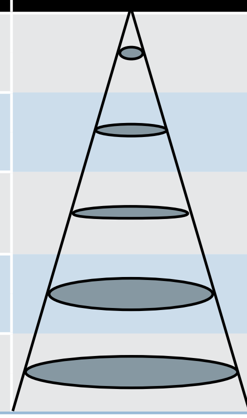
Height		Illuminance					Diameter	
		Eavg	Emax	Eavg	Emax			
1 m	3.3 ft	244.6 fc	349.7 fc	2,633 lx	37,641 lx		58.8 cm	1.9 ft
2 m	6.6 ft	61.2 fc	87.4 fc	658.2 lx	941.1 lx		117.6 cm	3.9 ft
3 m	9.8 ft	27.2 fc	38.9 fc	292.5 lx	418.3 lx		176.3 cm	5.8 ft
4.m	13.1 ft	15.3 fc	21.9 fc	164.5 lx	235.3 lx		235.1 cm	7.7 ft
5 m	16.4 ft	9.8 fc	14.0 fc	105.3 lx3	150.6 lx		293.9 cm	9.6 ft

Figure 16: XT-E PAR38 illuminance – 37° beam angle

CONCLUSIONS

This reference design illustrates the superior performance of a PAR38 lamp based on the Cree XLamp XT-E LED. The PAR38 lamp components are all commercially available, showing that an extremely capable lamp can be designed without the time and expense of developing custom parts. Demonstrating the flexibility of the XLamp XT-E LED, we made three excellent PAR38 lamps by changing only the optic. The lighting-class performance of the Cree XLamp XT-E LED makes it an attractive design option for an LED-based PAR38 lamp.