Cree® XLamp® A19 Reference Overview

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INTRODUCTION

Within the past year the LED industry has begun producing white, high power LEDs in sufficient volume that value-priced light bulbs are now practical consumer products. In North America many retailers now have LED bulbs as part of their inventory of lighting products.

Most LED replacement lamps or LED light bulbs pose significant design problems in managing thermal equilibrium. These problems were always less severe for gas discharge and filament lamps because these lamps are inherently convective and dissipate heat through the same path as the light. LEDs, whose thermal load is dissipated through conduction, must have a separate path and heat sink for thermal dissipation. Hence the design constraints that come with replacement lamps.

A great deal of interest and activity has centered on the E26/A19 form factor and there are many ways to approach the design and production of the classic A19 bulb. This application note reviews a variety of LED choices available from Cree to achieve attractive and cost effective warm white A19 bulbs or replacement lamps. This application note is different from other Cree application notes in that it reviews a spectrum of design choices rather than focusing on a particular implementation.

While most Cree reference designs or application notes use a 6-step framework, described in the "LED Luminaire Design Guide,"[1] this application note is largely about the many LED options and topologies that are available when designing A19 LED replacement lamps. As such we only visit a few of the steps in the framework.

A19 LIGHTING REQUIREMENTS

The most common form of A19 LED replacement lamps are often referred to as "snow cones." This moniker comes from the hemispheric dome that covers a circuit board of LEDs that sit atop a conic heat sink, which gives the visual impression of an ice cream cone or snow cone. The benefits of this approach come from a relatively large set of suppliers, delivering form-factor appropriate heat sinks, device drivers and molded diffusers. As such, this style of A19 bulb has rapidly become the dominant value-priced bulb. For many lighting applications the hemispheric distribution of luminous flux that comes along with the snow cone approach is sufficient – a very wide-angle flood lamp. But for applications that require a spherical or omnidirectional distribution of flux, the snow cone is not optimal.[2]

In order to achieve an omnidirectional flux distribution, other approaches to flux geometry must be used. Noteworthy or innovative examples of these designs include bulbs from GE, Philips and LSG, shown below.

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[1] LED Luminaire Design Guide, Application Note AP15, www.cree.com/~/media/Files/Cree/LED%20Components%20and%20Modules/XLamp/XLamp%20Application%20Notes/LED_Luminaire_Design_Guide.pdf. The guide advocates a 6-step approach consisting of:

1. Define lighting requirements
2. Define lighting goals
3. Estimate efficiencies of optical, thermal and electrical systems
4. Calculate the number of LEDs needed
5. Consider all the design possibilities and choose the best
6. Complete the final steps

[2] The US Environmental Protection Agency defines the omnidirectional requirements in ENERGY STAR® Program Requirements for Integral LED Lamps, www.energystar.gov/ia/partners/product_specs/program_reqs/ILL_prog_reqs.pdf. Table 4, p3, applies to all lamps; Table 6, p9, applies to "Non-Standard" Lamps – snow cone bulbs fall into this category, and Table 7A, p10, applies to omnidirectional lamps.

Figure 1: Omnidirectional Bubls from GE, LSG and Phillips[3]

The following table summarizes requirements to be met to be eligible to qualify for the Energy Star® Program.

Characteristic	Requirement
CCT	The lamp must have one of the following designated CCTs (per ANSI C78.377-2008) consistent with the 7-step chromaticity quadrangles below. 2700 K 3000 K 3500 K 4000 K
Color Maintenance	The change of chromaticity over the first 6,000 hours of luminaire operation shall be within 0.007 on the CIE 1976 (u', v') diagram.
CRI	Minimum CRI (Ra) of 80. R9 value must be greater than 0.
Dimming	Lamps may be dimmable or non-dimmable. Product packaging must clearly indicate whether the lamp is dimmable or not dimmable. Manufacturers qualifying dimmable products must maintain a Web page providing dimmer compatibility information.
Warranty	3-year warranty for luminaires with replaceable drivers.
Allowable Lamp Bases	Must be a lamp base listed by ANSI.
Power Factor (PF)	Lamp power < 5 W and low voltage lamps: no minimum PF Lamp power > 5 W: PF > 0.7
Minimum Operating Temperature	-20°C or below
LED Operating Frequency	LED operating frequency ≥ 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.

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[3] The illustration shows the GE Energy Smart LED Bulb, a 40-W equivalent LSG Definity A19 bulb and the Phillips Endura bulb.

Characteristic	Requirement
Electromagnetic and Radio Frequency Interference	Must meet appropriate FCC requirements for consumer use (FCC 47 CFR Part 15)
Audible Noise	Class A sound rating
Transient Protection	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.
Operating Voltage	Lamp shall operate at rated nominal voltage of 120, 240 or 277 VAC, or at 12 or 24 VAC or VDC.

Table 1: Energy Star requirements for all integral LED lamps

This table summarizes the Energy Star requirements for non-standard LED lamps.

Characteristic	Requirement
Minimum luminous efficacy	LED lamp power < 10 W: 50 lm/W LED lamp power > 10 W: 55 lm/W
Minimum light output	200 lumens
Luminous intensity distribution	No specific distribution is required. Must submit goniophotometry report showing luminous intensity distribution produced by the lamp.
Lumen maintenance	L70 > 25,000 hours
Rapid-cycle stress test	Cycle times must be 2 minutes on, 2 minutes off. Lamp will be cycled once for every 2 hours of required minimum L_{70} life.

Table 2:Energy Star requirements for non-standard LED lamps

The following table summarizes the Energy Star requirements for omnidirectional lamps.

Characteristic	Requirement	
Minimum luminous efficacy	LED lamp power < 10 W: 50 lm/W LED lamp power > 10 W: 55 lm/W	
Minimum light output	200 lumens	
	Nominal wattage of lamp to be replaced (watts)	Minimum initial light output of LED lamp (lumens)
	25	200
	35	325
	40	450
	60	800
	75	1100
	100	1600
	125	2000
	150	2600

Characteristic	Requirement
Luminous intensity distribution	Products shall have an even distribution of luminous intensity (candelas) within the 0° to 135° zone (vertically axially symmetrical). Luminous intensity at any angle within this zone shall not differ from the mean luminous intensity for the entire 0° to 135° zone by more than 20%. At least 5% of total flux (lumens) must be emitted in the 135°-180° zone. Distribution shall be vertically symmetrical as measured in three vertical planes at 0°, 45° and 90°.
Maximum lamp diameter	Not to exceed target lamp diameter as per ANSI C78.20-2003.
Maximum overall length (MOL)	Not to exceed MOL for target lamp as per ANSI C78.20-2003.
Lumen maintenance	L70 > 25,000 hours
Rapid-cycle stress test	Cycle times must be 2 minutes on, 2 minutes off. Lamp will be cycled once for every 2 hours of required minimum L70 life.
Color angular uniformity	The variation of chromaticity shall be within 0.004 from the weighted average point on the CIE 1976 (u’, v’) diagram.

Table 3: Energy Star requirements for omnidirectional lamps

The performance system performance requirements for non-standard and omnidirectional lamps, as shown in Tables 3 and 4, are essentially the same. The latter has defined luminous intensity distribution and minimum light output, which allow the lamps to be compared more readily to the incandescent lamps they replace.

DESIGN GOALS

To be familiar with the rapidly evolving product space for LED replacement lamps, application engineers at Cree have built at least a dozen different A19 lamp prototypes. Our team has experimented with a broad selection of XLamp LEDs, drivers and enclosures. We have developed a few examples as models as being the most cost-effective, for a variety of reasons. For example:

Constraint	Solution	Rationale
Maximize driver efficiency	XLamp MX-6S	High voltage LEDs in series all for more-efficient driver implementations
Minimize LED in bulb BOM	XLamp XP-E HEW	Extremely high lumen/$ ratio, optimized for diffused lighting applications
Minimize Production and inventory costs	XLamp CXA-2011	Reduced manufacturing complexity; simplified inventory

Table 4: A19 design goals and LED solutions

We will explore aspects of each of these designs.

Figure 2: A19 bulbs using a variety of Cree XLamp LEDs

The table below summarizes characteristics and goals from several bulb designs we review in this application note. All these designs use hemispheric distribution and are considered non-standard LED lamps in the Energy Star vernacular.

Characteristic	Unit	40-W-Equivalent "Value" Bulb	60-W-Equivalent Performance Bulb
Luminaire Light Output	Lm	450	800
Power	W	<10	<13
Efficacy	Lm/W	>50	65
Lifetime	Hours	25,000	
CCT	°K	3,000	3,000
CRI		80	80

Table 5: General A19 system goals

ESTIMATE EFFICIENCIES OF THE OPTICAL, THERMAL & ELECTRICAL SYSTEMS

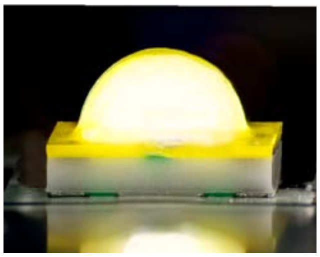
This section is an estimation exercise and discussion for a variety of LED configurations using Cree's Product Characterization Tool or PCT.[4] The PCT is tool that models basic LED and system performance to develop initial approaches for system design.

In all the cases we review here, we are assuming a 15% loss in the diffusing structures of the LED bulbs. This is a representative loss for the cast-plastic diffusive domes.

For a 40-W-equivalent LED bulb we have set up the PCT to compare system estimation information for three LEDs, the XLamp MX-6S, MX-6 and XP-E HEW. The settings of the PCT are to deliver 450 lumens with an 85%-efficient optical system and an 87%-efficient driver system. We also assume we have a heat sink that allows the system to maintain a 55° solder-point temperature.

We have configured the PCT display to focus on system-wide information, looking at the number LEDs required, lumens delivered, system wattage and efficacy.

XLamp MX-6 LED



XLamp XP-E HEW LED

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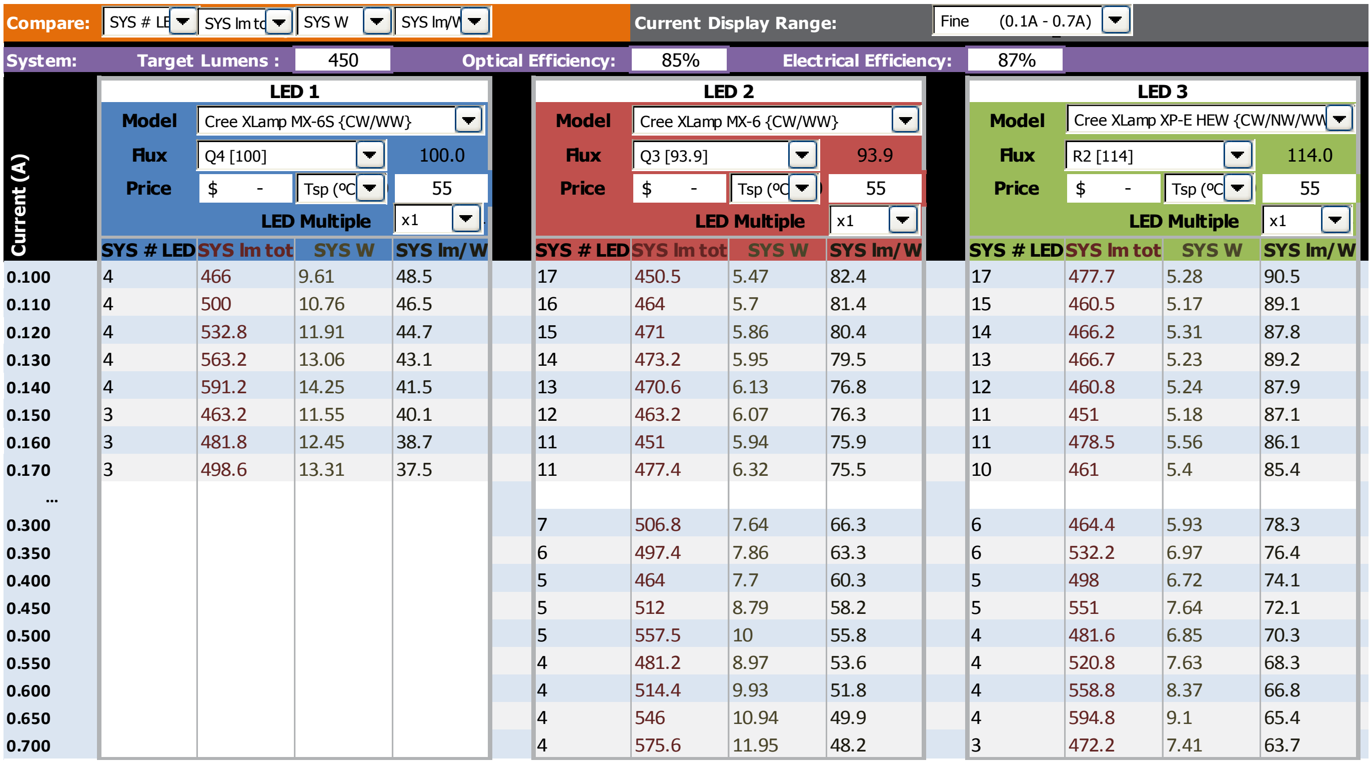
[4] pct.cree.com



Compare: SYS # LE | SYS lm to | SYS W | SYS lm/W

Current Display Range: Fine (0.1A - 0.7A)

System: **Target Lumens :** 450 **Optical Efficiency:** 85% **Electrical Efficiency:** 87%

LED 1 — **Model** Cree XLamp MX-6S {CW/WW}; **Flux** Q4 [100] 100.0; **Price** $ - Tsp (ºC 55; **LED Multiple** x1

LED 2 — **Model** Cree XLamp MX-6 {CW/WW}; **Flux** Q3 [93.9] 93.9; **Price** $ - Tsp (ºC 55; **LED Multiple** x1

LED 3 — **Model** Cree XLamp XP-E HEW {CW/NW/WW; **Flux** R2 [114] 114.0; **Price** $ - Tsp (ºC 55; **LED Multiple** x1

Current (A)	LED 1				LED 2				LED 3			
	SYS # LED	SYS lm tot	SYS W	SYS lm/W	SYS # LED	SYS lm tot	SYS W	SYS lm/W	SYS # LED	SYS lm tot	SYS W	SYS lm/W
0.100	4	466	9.61	48.5	17	450.5	5.47	82.4	17	477.7	5.28	90.5
0.110	4	500	10.76	46.5	16	464	5.7	81.4	15	460.5	5.17	89.1
0.120	4	532.8	11.91	44.7	15	471	5.86	80.4	14	466.2	5.31	87.8
0.130	4	563.2	13.06	43.1	14	473.2	5.95	79.5	13	466.7	5.23	89.2
0.140	4	591.2	14.25	41.5	13	470.6	6.13	76.8	12	460.8	5.24	87.9
0.150	3	463.2	11.55	40.1	12	463.2	6.07	76.3	11	451	5.18	87.1
0.160	3	481.8	12.45	38.7	11	451	5.94	75.9	11	478.5	5.56	86.1
0.170	3	498.6	13.31	37.5	11	477.4	6.32	75.5	10	461	5.4	85.4
...												
0.300					7	506.8	7.64	66.3	6	464.4	5.93	78.3
0.350					6	497.4	7.86	63.3	6	532.2	6.97	76.4
0.400					5	464	7.7	60.3	5	498	6.72	74.1
0.450					5	512	8.79	58.2	5	551	7.64	72.1
0.500					5	557.5	10	55.8	4	481.6	6.85	70.3
0.550					4	481.2	8.97	53.6	4	520.8	7.63	68.3
0.600					4	514.4	9.93	51.8	4	558.8	8.37	66.8
0.650					4	546	10.94	49.9	4	594.8	9.1	65.4
0.700					4	575.6	11.95	48.2	3	472.2	7.41	63.7

Figure 3: Product Characterization Tool analysis of a 450-lumen A19 bulb

This analysis shows us many approaches to delivering a 40-W-equivalent value bulb. In considering drive current and number of LEDs, at one end of the spectrum the four MX-6S LEDs can present an 85-V, 100-mA load, consume just under 10 watts of power and deliver just under 50-lm/W efficacy. Six MX-6 LEDs driven at 350 mA deliver over 63 lm/W while using under 8 watts of power. Four XP-E HEW LEDs, in the R2 flux bin, can deliver equivalent flux at an improved efficacy of just over 70 lm/W using 6.9 W of power.

The case for using MX-6S LEDs is particularly interesting and not well represented in Figure 3 because the high-voltage LEDs have the potential to allow for higher-efficiency device drivers. In an article in the April 2011 issue of *LEDs Magazine*, Matt Reynolds of National Semiconductor shows through a simple and elegant analysis that the use of high-voltage LEDs allows for lower operating temperatures of supporting driver electronics — capacitors, inductors and diodes.[5] The implication of his analysis includes the potential for drivers that are both more reliable (cooler operating temperatures for capacitors, for example) and more efficient. In our PCT analysis, an increase of 6% efficiency in drive electronics, from 87% to 93%, delivers an almost 7% improvement in efficacy.

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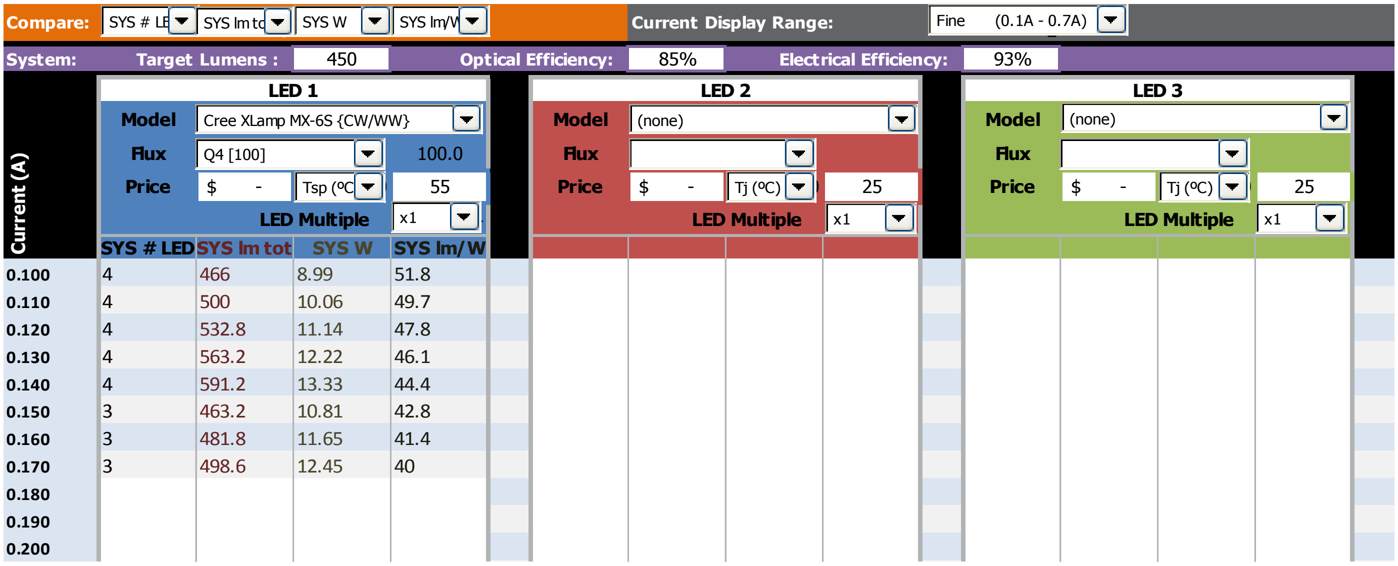
[5] Reynolds, Matthew, "High LED Drive Currents with Low Stack Voltages Creat Efficiency Challenges," LEDs Magazine, February, 2011, pp 53-59.



Compare: SYS # LE SYS lm to SYS W SYS lm/W

Current Display Range: Fine (0.1A - 0.7A)

System: Target Lumens : 450 Optical Efficiency: 85% Electrical Efficiency: 93%

LED 1: Model Cree XLamp MX-6S {CW/WW}; Flux Q4 [100] 100.0; Price $ -; Tsp (ºC 55; LED Multiple x1

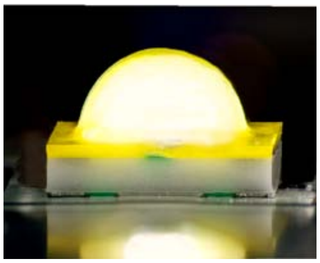
LED 2: Model (none); Flux; Price $ -; Tj (ºC) 25; LED Multiple x1

LED 3: Model (none); Flux; Price $ -; Tj (ºC) 25; LED Multiple x1

Current (A)	SYS # LED	SYS lm tot	SYS W	SYS lm/W
0.100	4	466	8.99	51.8
0.110	4	500	10.06	49.7
0.120	4	532.8	11.14	47.8
0.130	4	563.2	12.22	46.1
0.140	4	591.2	13.33	44.4
0.150	3	463.2	10.81	42.8
0.160	3	481.8	11.65	41.4
0.170	3	498.6	12.45	40
0.180				
0.190				
0.200				

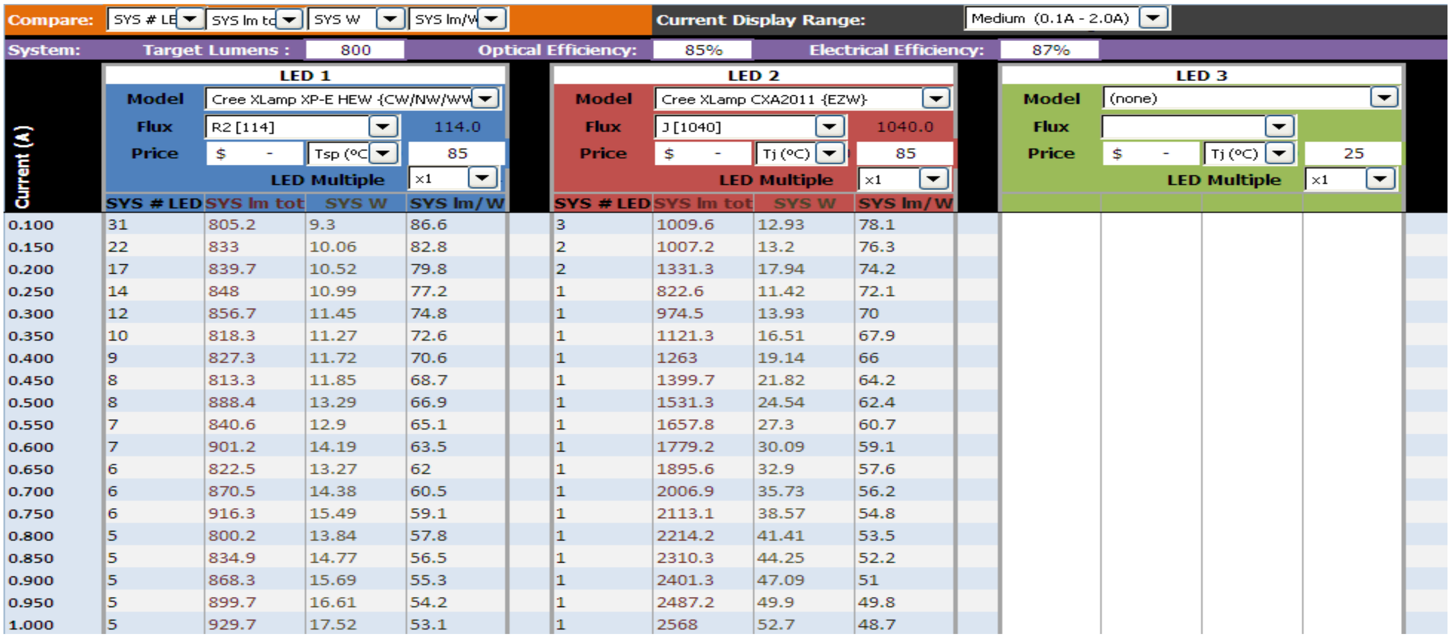
Figure 4: Improved driver performance for the MX-6S LED

The choices change when moving to the brighter 60-W-equivalent LED lamp. Very high efficacies can be achieved with large numbers of LEDs, but it is an impractical amount of money to be spent on LEDs, and the space constraints of the bulb will not permit it. In practice, the 800-lumen target is achieved with a few additional parts and with an increased thermal load in the system. For this part of the exercise, we are assuming a higher junction temperature of 85 °C. The two cost-effective LEDs for this bulb are the XP-E HEW and the CXA2011. The PCT is again configured to illustrate numbers of LEDs, system lumens, system power and efficacy.



XLamp XP-E HEW LED

XLamp CXA2011 LED



Compare: SYS # LE | SYS lm to | SYS W | SYS lm/W

Current Display Range: Medium (0.1A - 2.0A)

System: Target Lumens : 800 Optical Efficiency: 85% Electrical Efficiency: 87%

LED 1
Model: Cree XLamp XP-E HEW {CW/NW/WW
Flux: R2 [114] | 114.0
Price: $ - | Tsp (°C | 85
LED Multiple: x1

LED 2
Model: Cree XLamp CXA2011 {EZW}
Flux: J [1040] | 1040.0
Price: $ - | Tj (°C) | 85
LED Multiple: x1

LED 3
Model: (none)
Flux:
Price: $ - | Tj (°C) | 25
LED Multiple: x1

Current (A)	LED 1				LED 2			
	SYS # LED	SYS lm tot	SYS W	SYS lm/W	SYS # LED	SYS lm tot	SYS W	SYS lm/W
0.100	31	805.2	9.3	86.6	3	1009.6	12.93	78.1
0.150	22	833	10.06	82.8	2	1007.2	13.2	76.3
0.200	17	839.7	10.52	79.8	2	1331.3	17.94	74.2
0.250	14	848	10.99	77.2	1	822.6	11.42	72.1
0.300	12	856.7	11.45	74.8	1	974.5	13.93	70
0.350	10	818.3	11.27	72.6	1	1121.3	16.51	67.9
0.400	9	827.3	11.72	70.6	1	1263	19.14	66
0.450	8	813.3	11.85	68.7	1	1399.7	21.82	64.2
0.500	8	888.4	13.29	66.9	1	1531.3	24.54	62.4
0.550	7	840.6	12.9	65.1	1	1657.8	27.3	60.7
0.600	7	901.2	14.19	63.5	1	1779.2	30.09	59.1
0.650	6	822.5	13.27	62	1	1895.6	32.9	57.6
0.700	6	870.5	14.38	60.5	1	2006.9	35.73	56.2
0.750	6	916.3	15.49	59.1	1	2113.1	38.57	54.8
0.800	5	800.2	13.84	57.8	1	2214.2	41.41	53.5
0.850	5	834.9	14.77	56.5	1	2310.3	44.25	52.2
0.900	5	868.3	15.69	55.3	1	2401.3	47.09	51
0.950	5	899.7	16.61	54.2	1	2487.2	49.9	49.8
1.000	5	929.7	17.52	53.1	1	2568	52.7	48.7

Figure 5: LED configurations for a 60-W-equivalent, non-directional LED lamp

Running at these space-constrained and elevated temperatures, it takes eight XP-E HEW LEDs from the R2 flux bin, driven at 350 mA to deliver 810 lumens, at 12 watts of power with an efficacy of almost 68 lm/W. The single CXA2011 from the J flux bin, running at 250 mA delivers improved performance: 814 lumens, 11.3 watts and over 72 lm/W.

IMPLEMENTATIONS AND ANALYSIS

The most thorough analysis of a Cree LED A19 bulb comes from a collaboration with Marvell Semiconductor (www.marvell.com). The 40-watt-equivalent LED replacement lamp uses four Cree XP-E HEW LEDs and Marvell's 88EM8081 PFC controller. The system delivers 475 lumens at 3000 °K CCT, consuming 7.5 watts of power.[6] This implementation is in good correspondence with the PCT analysis in Figure 3.

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[6] Details on this design are available at www.marvell.com/green-technology/Marvell_Cree_A19LED_Reference_Bulb_platform_brief_PB001.pdf

Figure 6: 4 XP-E HEW LEDs in a 40-W-equivalent A19 lamp

In early 2011, Cree built a CXA20011-based A19 bulb. In fact, in analyzing some A19 replacement lamps on the market, we found one with a device driver that closely matched the CXA2011 voltage and current requirements, and as a first pass replaced the LED array with a CXA2011. Results from this first experiment were somewhat disappointing. At steady-state, the bulb produced 750 lumens and consumed 12.8 watts with a system efficacy of 58 Lm/W. Although this level of performance is Energy Star conformant, it was not in good correspondence with the PCT analysis shown in Figure 5. We believe refinements to the heat sink assembly and a more recent driver circuit could deliver a substantial improvement in performance.

Figure 7: A19 bulb with a CXA2011 LED

CONCLUSIONS

Because of their small size and lumen density, development of cost-effective and well-engineered LED replacement lamps presents tremendous challenges to every aspect of LED systems design. Experimentation and innovation are occurring throughout the LED replacement lamp ecosystem. Cree supports this ecosystem by delivering the broadest portfolio of LEDs in the industry and by maintaining a vigorous pace of product innovation to bring the best LED options to the replacement-lamp manufacturing community.