Application Note 101

LED-Driver Thermal Design Considerations in LED-Based Fixtures - Part 1

The Importance of Driver Thermal Design in LED-Based Fixtures

Abstract:

The thermal design of an LED fixture affects its light output, efficiency, cost, lifetime and reliability. LED based fixture designers and managers who are concerned about any of the above lighting fixture parameters are highly recommended to consider the practical simple concepts outlined in the following series of "Thermal Design Considerations" application notes. Thermal management should be considered up front at the product definition phase. Unfortunately, most often thermal design is an afterthought once the LED and LED-driver design is finished. A good thermal design must be an integral part of the overall system design along with the LED and driver design. The following series of thermal design related application notes are targeted for both beginner and advanced LED fixture designers and managers.

Typically, fixture designers pay a great deal of attention to lowering the solder point temperature (Tsp) or case temperature (Tc) of the LED, however not much attention is paid to lowering the Tc of the driver. The facts are that there are considerably more electronics components in the driver that are much more susceptible to heat than the LED itself. In the advent of major process technology improvements in LED technologies, assuming that high quality LEDs are used from reputable LED companies, typically the life of the LED fixture is determined by the life of the driver.

In recent years, LED technology has made great progress such that they can run at fairly high temperatures with a respectable LED lifetime (L70). For example, Cree offers LEDs, like XHP50 and XHP70, with published LM80 data at 105°C and 125°C. In fact, due to great reliability and LED technology improvements, some reputable LED manufacturers have been known to encourage their customers to drive the LEDs hard at high temperatures to lower the system cost.

Typically, the lifetime of a driver is controlled by the life of the electrolytic capacitor. It is well known that the life of the electrolytic capacitor is halved for every 10°C increase in temperature. That is one of the main reasons that driver thermal design must be considered very seriously, otherwise the fixture life will be jeopardized by a large margin. It doesn't make much sense to design an elaborate and costly heatsink system for the LEDs and ignore the driver thermal design which is more susceptible to failure due to heat. A fixture designed for LED lifetime of +100 k hours and only 10 k hours of driver lifetime, is an extremely poor design and a disaster waiting to happen. A good thermal design should start by protecting the most susceptible element of the system, the driver, and then the LED boards. Most often LED drivers are operating at their maximum load, "pedal to the metal", where LEDs are typically operating at a fraction of their maximum spec drive current. For example, a 1.5 A LED is typically driven at no more than 1A. Both the driver and LED should be equally protected from heat, considering their life at a certain operating temperature, to yield the most optimum life with a given cost, size and weight of the heatsink. Please note that a good thermal design must have a goal of improving the performance, life, reliability and cost of the entire system rather than a portion of it. Interestingly a poor thermal design of the LED will affect the life of the driver and vice versa. If heat generated by the LED is not managed properly, it will increase

January 2017

the Tc of the driver. They are all interrelated and one clearly affects the other.

What makes matters worse for the driver is the fact that aside from its own generated heat, due to driver efficiency loss, the driver is typically in close proximity to the LED board where over 80% of the driver output power is converted to heat by the LED. Only a small percentage of driver output power is converted to photonic energy by the LEDs. The overwhelming majority of the power is converted to heat by the LED. Therefore, the driver is exposed to an extremely high amount of heat, almost equivalent to its entire rated output power!

The fact that the overwhelming majority of LED fixture field failures are due to driver failures (and not due to the LED failures) is another reason that more attention must be paid to thermal design of driver.

Driver Thermal Basics:

Good thermal management will include reducing the total amount of generated heat and conducting it away from the driver and LED to the ambient air as effectively as possible, with the least amount of thermal resistance at the lowest cost.

If the efficiency of the driver and LED were 100% then no heat would be generated and there wouldn't be a need for any thermal design and LED based fixtures would last an extremely long period of time. Although great strides have been made to improve the driver and LED efficiencies in recent years, unfortunately we are far from that utopian world; hence we must come up with a good thermal design if the goal is to have a reliable system with a long life.

The input power of a LED driver, typically from an AC outlet, is converted to DC voltage at a certain current, typically constant current, to drive the LED load. Since all power conversions are lossy, a portion of the input power is lost as heat as shown below in Figure 1.
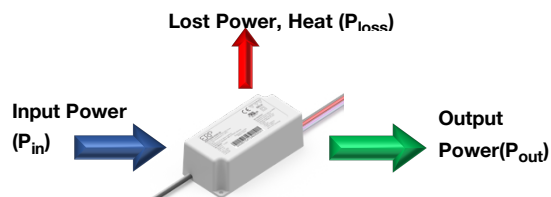

Figure 1. Graphical Representation of Driver Efficiency and Power Loss as Heat

Efficiency (η) is defined as the ratio of Output Power to Input Power and is always less than 1.

$$\eta = P_{out} / P_{in} \qquad Equation\ 1$$

Most of the input power is delivered to the LED load and some is lost as heat, as shown in the below equation.

$$P_{in} = P_{out} + P_{loss}$$

By replacing the P_{in} in the above efficiency Equation 1:

$$\eta = P_{out} / (P_{out} + P_{loss})$$

Rearranging the above equation results in the formula for calculating the power dissipated as heat, P_{loss}, as shown in Equation 2. The following simple formula could be used for driver or LED power loss calculations:

$$P_{loss} = Pin\ x\ (1-\eta) \qquad Equation\ 2$$

Where:
P_{loss} = Dissipated or Lost Power as Heat
P_{in} = Input Power
P_{out} = Output Power
η = Efficiency of the Driver (or LED)

For the sake of simplicity, the driver and LED losses are assumed to be entirely converted to heat. For example, a 150 W driver with 80% efficiency yields a whopping 30W loss of power which is all converted to heat (102.36 btu/hr).

Therefore, using Equation 2 we can calculate the driver power that is converted to heat as driver efficiency loss:

$$P_{loss} = 150\ W\ x\ (1 - 0.8) = 30\ W$$

More efficient drivers obviously generate much less heat and the Tc will be lower, therefore at a given LED and thermal design the more efficient driver can last considerably longer than a less efficient driver. As an example, an ERP driver at 90% efficiency at the same 150 W power level will have only 15 W of power converted to heat.

$$P_{loss\ Draco} = 150\ W\ x\ (1 - 0.90) = 15\ W$$

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A 90% efficient driver generates only 1/2 of the heat that was generated by the above mentioned less efficient driver at 80% efficiency. In other words, a 10% reduction in driver efficiency generates double the heat in the driver.

At a given design, considering all other parameters being the same, a more efficient driver will last considerably longer than a less efficient driver.

With a good thermal design, the driver will operate more efficiently at a lower Tc which will yield a longer driver life and a more reliable system. Additionally, the LED will operate more efficiently at lower temperatures, therefore yielding higher lumen output, higher LPW (Lumen Per Watt) and resulting in a longer fixture life.

Below are some system design examples demonstrating the above concepts, using Cree's free PCT tool which is available on their website at the link below.
http://pct.cree.com/dt/index.html

To demonstrate the effect of more efficient LEDs and drivers on thermal load, please see the below 3 Cree XPG2 based designs, as shown in Figures 2, 3 and 4. As a side by side comparison, in each figure, the blue header "LED 1" uses XPG2 R3 flux bin and the red header "LED 2" uses a much more efficient S4 flux bin XPG2 device. All designs are targeting a 12,000 lumens fixture. Driver Efficiency is shown as "Electrical Efficiency" in the below figures.
Each LED design is highlighted at three different drive currents 350 mA (green), 700 mA (yellow) and 1000 mA (orange).
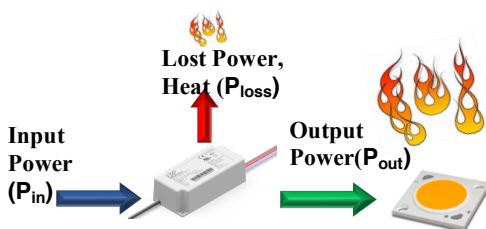

Figure 1.1 Most of the System Power is Converted to Heat by the LED

As represented in Figure1.1, 75% to 80% of the power delivered to the LED is converted to heat. Therefore, fixture designers should take precautions to lower the power delivered to the LEDs by using as efficient LEDs as possible to lower the thermal load of the system.

As shown in Figure 2, Design #1, driving both types of LEDs (R3 and S4 flux bins) at 1000ma, the more efficient S4 based system will consume 113Watts of system power where the same design at a less efficient LED of R3 flux bin will use ~153 W of system power to produce the same 12,000 lumens. In both cases the same type of driver at 90% efficiency is used and optical efficiency is assumed to be 90% and Tsp (LED Solder Point Temperature) is assumed to be at 85°C. In this design example the less efficient LED design will consume 35% more power, therefore generating considerably more heat (~40 W or 136.49 btu/hr) in the system. Please note that the R3 and S4 flux bin performance comparison illustrates an extreme case and typically the performance difference due to flux bin will not be as pronounced.
In reality, at a given heatsink design, the Tsp for the more efficient LED design will be lower. However, for the sake of simplicity that additional benefit is ignored.

Figure 2. Design #1: The Effect of Using More Efficient LEDs (R3 to S4)

In Figure 3, Design #2, all design parameters are kept the same except the driver has been changed to an 80% efficient driver, versus the previous case of a 90% efficient driver.

Please note that moving from a 90% to 80% efficient driver, using the same efficient S4 flux bin LEDs, the system power consumption increases from 113 W to 127 W at 1000 mA drive current. That is an increase of 12.4% or 14 W more heat that needs to be dealt with.

Figure 3. Design #2: The Effect of Using More Efficient Driver (80% to 90%)

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As shown in Figure 4, Design # 3, the Driver Efficiency is returned to 90%, however the optical efficiency is reduced to 60%. This is to demonstrate the fact that optics design also plays a major role in heat generation in the system and should be carefully controlled along with other system parameters. A less efficient optical design reduces the lumen output of the LEDs and forces the system designer to drive them at higher currents, or dramatically increase the number of LEDs, to compensate for the lumen loss and maintain the desired light output. Both cases increase the power consumption and consequently the thermal load.

Please note that when using the same efficient S4 flux bin LEDs, the system power dramatically increases from 113 W to 170 W at 1000 mA to generate the same 12,000 lumens; all other system parameters are kept the same. That is an additional 57 W of power consumption or 50.4% more heat that needs to be managed.

Current (A)	LED 1				LED 2				
Compare:	SYS lm tot	SYS lm/W	SYS # LED	SYS W			Current Display Range:	0.150A -	
System:	Target Lumens :	12,000	Optical Efficiency:	60%	Electrical Efficiency:	90%			
	Model	Cree XLamp XP-G2 {BWT}			Model	Cree XLamp XP-G2 {BWT}			
	Flux	R3 [122]		122.0	Flux	S4 [164]		164.0	
	Price	$ -	Tsp (°C) .0	85	Price	$ -	Tsp (°C) .0	85	
	ΔVf	0.000	Multiple x1		ΔVf	0.000	Multiple x1		
	SYS lm tot	SYS lm/W	SYS # LED	SYS W	SYS lm tot	SYS lm/W	SYS # LED	SYS W	
0.150	12006	73.07	366	164.3	12038	98.22	273	123	
0.200	12040	71.37	279	168.7	12008	95.95	207	125	
0.250	12031	69.78	226	172.4	12022	93.8	168	128	
0.300	12044	68.28	191	176.4	12037	91.79	142	131	
0.350	12054	66.85	166	180.3	12007	89.87	123	134	
0.400	12043	65.5	147	183.9	12004	88.05	109	136	
0.450	12011	64.21	132	187	12109	86.32	99	140	
0.500	12079	62.99	121	191.8	12078	84.68	90	143	
0.550	12037	61.83	111	194.7	12099	83.11	83	146	
0.600	12032	60.7	103	198.2	12091	81.6	77	148	
0.650	12001	59.64	96	201.2	12099	80.17	72	151	
0.700	12103	58.62	91	206.5	12157	78.8	68	154	
0.750	12109	57.65	86	210	12113	77.49	64	156	
0.800	12019	56.7	81	212	12168	76.22	61	160	
0.850	12155	55.8	78	217.8	12149	75.01	58	162	
0.900	12067	54.93	74	219.7	12057	73.84	55	163	
0.950	12083	54.09	71	223.4	12125	72.71	53		
1.000	12044	53.28	68	226.1	12143	71.62	51	170	
1.100	12007	51.73	63	232.1	12042	69.54	47		
1.200	12010	50.28	59	238.9	12040	67.59	44	178	
1.300	12098	48.9	56	247.4	12197	65.73	42	186	
1.400	12093	47.59	53	254.1	12268	63.97	40	192	
1.500	12236	46.32	51	264.1	12255	62.27	38	197	

Case 3: Difference is Optical Efficiency

By less efficient optics system power increases by 50.4%! 113W vs 170W

Figure 4. Design #3: The Effect of Using More Efficient Optics (60% to 90%)

Please note that in each of the above 3 cases the LEDs can be driven at a lower drive current, e.g. 350 mA, as highlighted in green, and generate significantly less heat. An additional benefit to this approach would be a much higher system LPW. The drawback of this approach is that it will require more LEDs and will increase the system cost.

Therefore, as demonstrated in the above three simple design examples, any LED fixture design is a balancing act between lumen output, LPW, cost, system life and thermal management.

If one ignores the entire system design analysis and proper thermal design of the driver and the LED boards, the outcome is going to be, at worst, disastrous or, at best, an undesirable and non-optimized system, much like throwing a dart in the dark.

Less heat and a better thermal design yield more lumens, higher system efficiency, longer driver and LED lifetime and a more reliable system.

ERP performs detailed temperature analysis on various driver components as part of the design verification and characterization of each product. The temperature of multiple components, specially the temperature of the electrolytic capacitor, directly affects the predicted life of the driver. Below is an example of ERP ESS040-900-42 lifetime vs Tc (driver case temperature) and Ta (ambient temperature observed by the driver) from the ESS datasheet. If the Tc is at 70°C, then the lifetime is 155,000 hours and if Tc is increased to 90°C then lifetime drops to 28,500 hours.

ESS040W-0900-42 (37.8 W, 900 mA @ 42 V max)
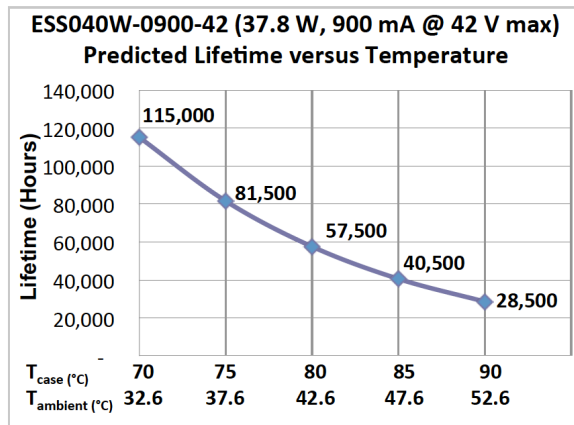Predicted Lifetime versus Temperature

Table 2: Predicted Driver Lifetime vs. Case Temperature

As shown in Table 2, the driver life is directly related to Tc. As part of the thermal design of the fixture, every effort must be made to reduce the total amount of heat generated and conducted away to ambient air as efficiently as possible, hence lowering the Tc. In the above ESS driver example, by lowering the driver Tc by 20°C the predicted lifetime of the driver is dramatically increased by a factor of 4x, from 28,5000 hours to 115,000 hours.

The above concept directly applies to LEDs as well. Obviously more efficient LEDs will produce less heat for a given design. Therefore, for a given fixture lumen output, drivers and LEDs that are more efficient will yield a longer lifetime.

For example, in a certain application if 120,000 hours of life is not needed and only 50,000 hours is acceptable, then another way of taking advantage of more efficient LEDs and drivers is to drive them harder and operate them at higher temperatures, the same as their less efficient counterparts. This will reduce the overall system cost at the same lifetime. By driving the LEDs harder, at the same desired lumens, the number of LEDs will be reduced, hence lowering the system cost. Please see this concept illustrated in the above PCT tables highlighted in orange.

In conclusion, LED fixture system parameters are all interrelated and should all be considered to yield the desired outcome. It would be a total waste of money on a good LED and heatsink design that will last over 100,000 hours if the system is going to last only 10,000 hours due to poor driver thermal management. Driver and LED thermal design must be considered at the fixture conceptual design phase and be carried out at every step of the design phase in order to come up with the desired fixture that meets all of the system requirements, including driver Tc and fixture life.

Courtesy of Cree For Some of The Content

For additional information, please also refer to the series of videos posted at: https://youtu.be/FJ5KR4n7uCY, https://youtu.be/n6ft5xUGCYE, https://youtu.be/9HB2nsR9SYU, https://youtu.be/NMVPHUDnk7g, https://youtu.be/bA1XDa6ADkw

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