Thermal Management of Cree® XLamp® LEDs

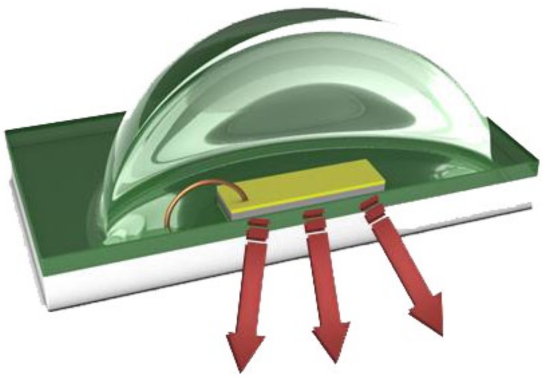

Figure 1: Thermal path of a Cree XLamp® LED

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INTRODUCTION

Cree XLamp® power LEDs lead the industry in brightness and reliability, enabling the LED lighting revolution with energy-efficient, environmentally friendly light. To take full advantage of the benefits of Cree's XLamp LEDs, proper thermal management must be understood and employed. This application note explains the importance of thermal management, discusses basic thermal fundamentals and details some general guidelines and design recommendations. A basic overview of methods to measure and simulate thermal performance is also provided.

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IMPORTANCE OF PROPER THERMAL MANAGEMENT

A main cause of LED failures is improper thermal management. Many performance characteristics of LED components are influenced by the operating temperature, so LED system designers need a basic understanding of thermal design and performance. All Cree XLamp LED product data sheets detail the performance characteristics that are impacted by temperature. Also, Cree's internally developed software, the Product Characterization Tool (PCT), can be used to calculate the specific responses to thermal effects. Some performance characteristics experience a recoverable change, such as light output, color and voltage, while others, such as lifetime, can experience a non-recoverable degradation due to high operating temperatures. However, exceeding the maximum operating temperature specification, which is typically a 150 °C junction temperature, can cause permanent and/or catastrophic damage to XLamp LEDs, so care must be taken to operate LEDs below this limit.

Light output

Elevated junction temperatures cause recoverable light output reduction, which is plotted on each of Cree's XLamp LED data sheets. As the junction temperature increases, the light output of the LED decreases, but recovers when the LED cools. Below in Figure 2 is a chart showing the relative flux versus junction temperature from the Cree XLamp XB-D LED data sheet. The XB-D LED, among many other new Cree XLamp LEDs, is binned at 85 °C, so the relative flux data is based on 100% light output at an 85 °C junction temperature.

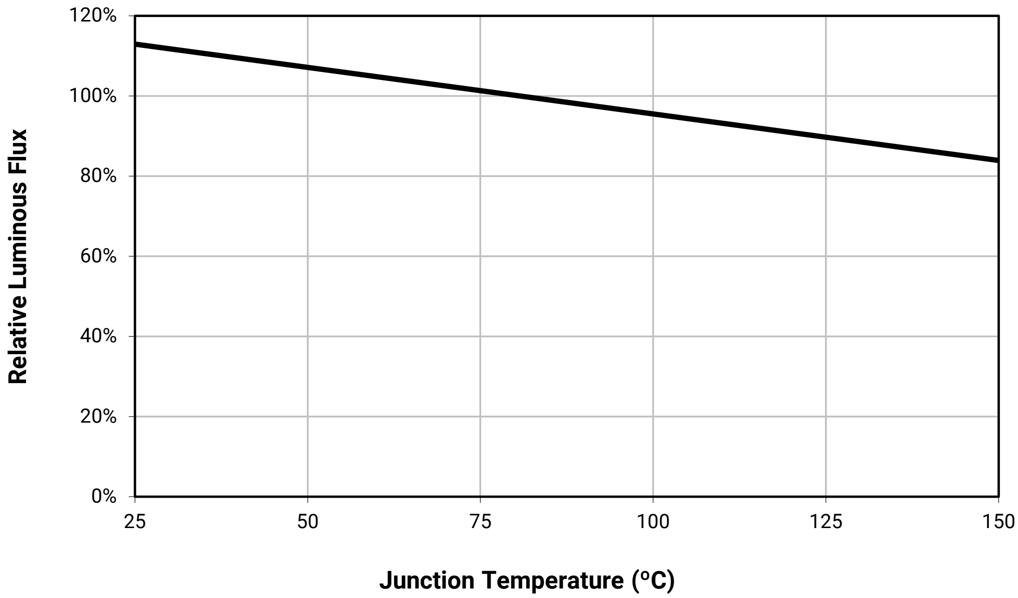


Figure 2: XLamp XB-D LED relative flux vs. steady-state junction temperature

Color

With increasing junction temperatures, the color of all LEDs shifts. While Cree manufactures the industry's best components with the smallest amount of color shift, this effect needs to be understood for proper system design. Shown below in Figure 3, again from the XB-D data sheet, are the CCx and CCy shifts relative to solder point temperature (T_{SP}). It is worth noting that the data in this plot shows that there is less than a 0.004 shift in either direction for the full range of operating temperatures. This will not be the case with most of Cree's competitor's LEDs on the market which typically shift drastically further than this.

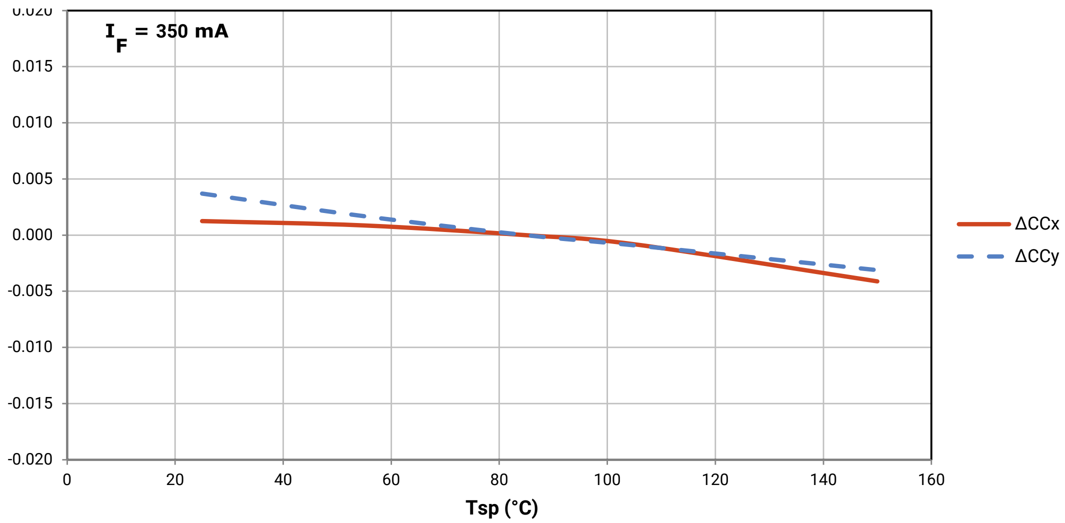


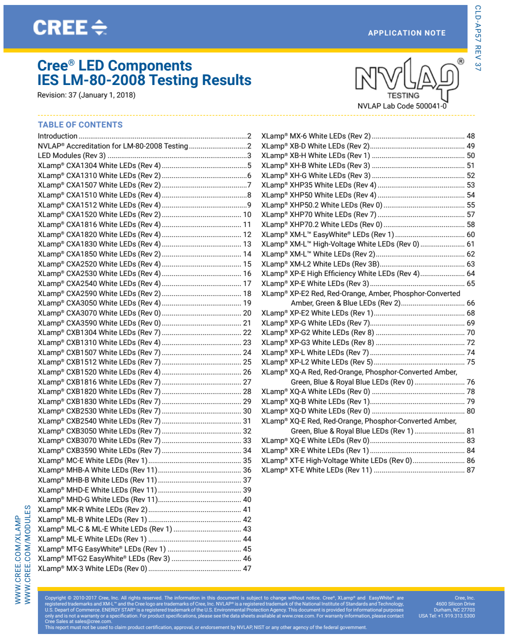
Figure 3: XLamp XB-D LED color shift vs. solder point temperature

Voltage

Forward voltage decreases as the junction temperature of an LED increases. This is shown on each of Cree's XLamp LED data sheets as the temperature coefficient of voltage, and varies slightly depending on the color and package type. This value varies from approximately -1 to -4 mV/°C per LED. It is important to understand the full operating conditions for an LED system so the driver can accommodate the potential range of drive voltages over the operating temperature of the system. An example of this is shown later in this document.

Reliability

The reliability of any LED is a direct function of junction temperature. The higher the junction temperature, the shorter the lifetime of the LED. Data from an IES LM-80-08 report can be used to predict the lumen maintenance of an LED under various temperature and drive current operating environments. Cree has published an LM-80 summary for its XLamp LEDs and full LM-80 data can be obtained by contacting a sales representative.



CREE

APPLICATION NOTE

CLD-AP57 REV 37

Cree® LED Components
IES LM-80-2008 Testing Results

Revision: 37 (January 1, 2018)

NVLAP® TESTING
NVLAP Lab Code 500041-0

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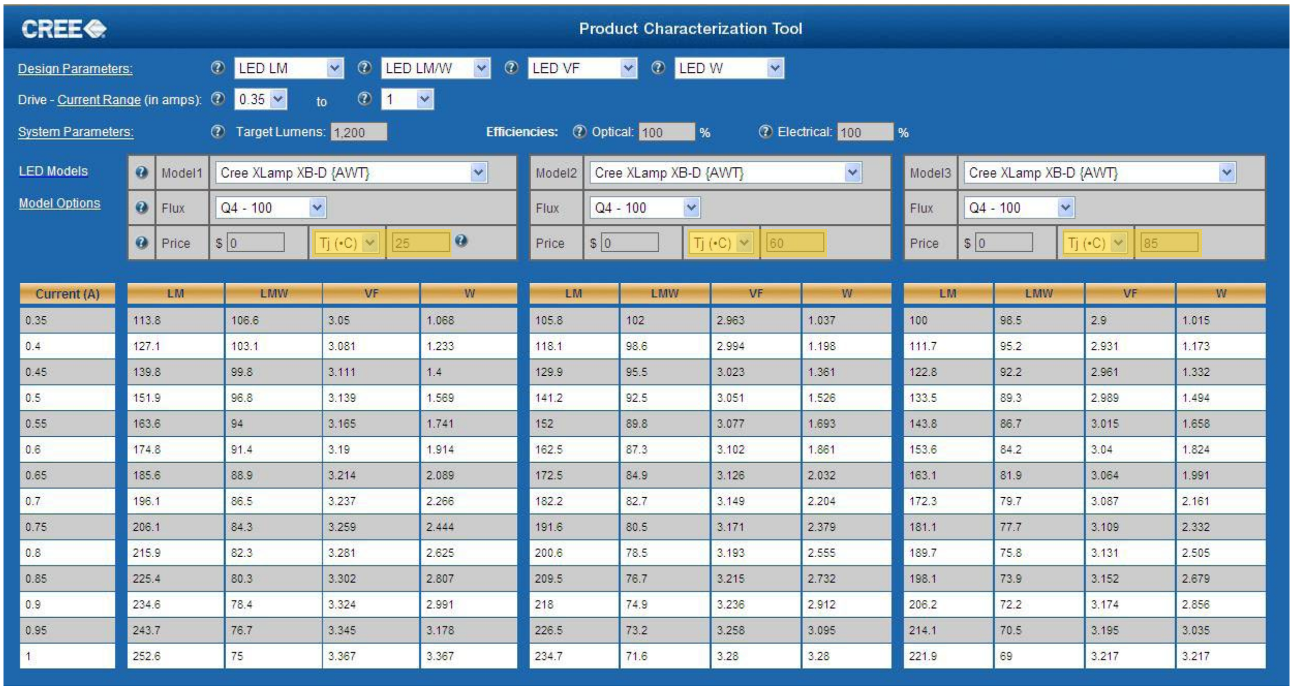
Figure 4: Cree XLamp LED LM-80 summary

A TM-21 calculator from the Environmental Protection Agency (EPA) can be used with the LM-80 data to predict lumen degradation and expected lifetime under specific operating conditions.

Cree Product Characterization Tool

In addition to using data from plots on Cree's data sheets, another extremely useful and accurate method to determine performance versus junction or solder point temperature is to use the PCT developed by Cree. Shown below in Figure 5 is the output of the PCT, showing the variability of lumens and voltage versus three different junction temperatures. Highlighted in yellow in Figure 5 are fields in the display where the temperature inputs are set.



Current (A)	LM	LMW	VF	W	LM	LMW	VF	W	LM	LMW	VF	W
0.35	113.8	106.6	3.05	1.068	105.8	102	2.963	1.037	100	98.5	2.9	1.015
0.4	127.1	103.1	3.081	1.233	118.1	98.6	2.994	1.198	111.7	95.2	2.931	1.173
0.45	139.8	99.8	3.111	1.4	129.9	95.5	3.023	1.361	122.8	92.2	2.961	1.332
0.5	151.9	96.8	3.139	1.569	141.2	92.5	3.051	1.526	133.5	89.3	2.989	1.494
0.55	163.6	94	3.165	1.741	152	89.8	3.077	1.693	143.8	86.7	3.015	1.658
0.6	174.8	91.4	3.19	1.914	162.5	87.3	3.102	1.861	153.6	84.2	3.04	1.824
0.65	185.6	88.9	3.214	2.089	172.5	84.9	3.126	2.032	163.1	81.9	3.064	1.991
0.7	196.1	86.5	3.237	2.266	182.2	82.7	3.149	2.204	172.3	79.7	3.087	2.161
0.75	206.1	84.3	3.259	2.444	191.6	80.5	3.171	2.379	181.1	77.7	3.109	2.332
0.8	215.9	82.3	3.281	2.625	200.6	78.5	3.193	2.555	189.7	75.8	3.131	2.505
0.85	225.4	80.3	3.302	2.807	209.5	76.7	3.215	2.732	198.1	73.9	3.152	2.679
0.9	234.6	78.4	3.324	2.991	218	74.9	3.236	2.912	206.2	72.2	3.174	2.856
0.95	243.7	76.7	3.345	3.178	226.5	73.2	3.258	3.095	214.1	70.5	3.195	3.035
1	252.6	75	3.367	3.367	234.7	71.6	3.28	3.28	221.9	69	3.217	3.217

Figure 5: Cree PCT

Performance example

An XLamp XB-D LED from the Q4 flux bin (100 lm at 350 mA, 85 °C) is sourced at 700 mA in an initial ambient temperature of 25 °C and heated to a 60 °C junction temperature. At what lumen output and voltage did the lamp start and end?

This can easily be determined from the PCT output above, and is shown below in Table 1.

Table 1: Performance characterization vs. temperature

Temperature	Luminous Flux (lm)	Voltage (V)	Efficacy (lm/W)
85 °C (binned)	172.3	3.087	79.7
25 °C (initial room temperature)	196.1	3.237	86.5
60 °C (steady state)	182.2	3.149	82.7

A few lessons can be learned from this example, including the drop in lumens and lumens per watt as the temperature increases. Additionally, the decrease in voltage can become significant when a large number of LEDs are included in a system, especially in very low initial ambient temperatures. When designing luminaire systems, all of this needs to be considered for proper final designs.

HEAT GENERATION

LEDs generate visible light when current passes across the junction of the semiconductor chip. However, LEDs are not 100% efficient; much of the power running through an LED is output as heat, which thus needs to be dissipated. Cree royal blue XLamp LEDs are over 50% efficient and white XLamp LEDs are over 40% efficient. That is, under normal operating conditions, approximately 50% to 60% of the input power is output as heat, while the rest of the input power is converted to light. To be conservative, assume LEDs convert 25% of the input power to light and output 75% of the input power as heat. This estimate varies depending on current density, brightness and component, but is a good estimate for thermal design. Equation 1 below shows how to calculate the thermal power.

$$P_t = 0.75 \; V_f \; I_f$$

Equation 1: Thermal power calculation

where:

P_t is the thermal power (W)
V_f is the forward voltage of the LED (V)
I_f is the source current to the LED (A)

The V_f and I_f can be measured directly or calculated from the PCT, so the thermal power can easily be calculated. This is the amount of power the system/heat sink must dissipate.

FUNDAMENTALS OF HEAT TRANSFER

There are three basic modes of heat transfer: conduction, convection and radiation. Each plays a role in LED performance and final system design and must be understood for proper thermal management.

Conduction

Conduction is the transfer of heat through a solid material by direct contact. This is the first mode of heat transfer to get thermal power from the LED junction to the heat sink. Metals are typically the best conductors of heat. The heat conduction potential of all materials can be expressed as thermal conductivity, typically abbreviated as k. Equation 2 below shows how to calculate the quantity of heat transferred via conduction.

$$Q_{cond} = -k \; A \; \frac{\Delta T}{\Delta x}$$

Equation 2: Fourier's law of heat conduction

where:

Q_{cond} is the amount of heat transferred through conduction (W)
k is the thermal conductivity of the material (W/m K)
A is the cross sectional area of the material through which the heat flows (m^2)
ΔT is the temperature gradient across the material (°C)
Δx is the distance for the heat must travel (m)

Convection

Convection is the transfer of heat through the movement of fluids and gases. In LED systems, this is typically the transfer of heat from the heat sink to the ambient air. There are two sub-categories of convection: natural and forced. Natural convection occurs with no artificial

source of field movement and is due to the buoyancy forces induced by thermal gradients between the fluid and solid. Forced convection occurs when an external instrument such as a fan, pump, or other device is used to artificially move the fluid or gas. In LED cooling systems, convection is the main mode of heat transfer to remove the generated heat from the LED system and heat sink. Equation 3 below shows how to calculate the quantity of heat transferred via convection.

$$Q_{conv} = h \ A \ \Delta T$$

Equation 3: Newton's law of cooling (convection)

where:

Q_{conv} is the amount of heat transferred through convection (W)

h is the heat transfer coefficient (W/m^2K)

A is the surface area (m^2)

ΔT is the temperature gradient across the material (°C), typically the difference between the surface temperature and ambient air temperature

The fundamental challenge in calculating the heat transfer via conduction is determining and computing the heat transfer coefficient (h). Typical values for h can vary significantly depending on boundary conditions, geometry and many other factors. However, for natural convection h will usually be in the range of 5-20 W/m^2K, while for forced convection h can be as high as 100 W/m^2K for air and up to 10,000 W/m^2K for water. Typically, for natural convection in air, a value of 10 W/m^2K is a good assumption for an initial rough calculation.

Radiation

The transfer of thermal energy through an electromagnetic field is the third component of heat transfer, radiation. The magnitude of radiation heat transfer is based on the emissivity of the material, which is the ratio of how closely the surface approximates a blackbody. In an LED system, radiation typically has a very small effect on the net system heat transfer since the surface areas are typically fairly small and surface temperatures are relatively low, to keep the LED junction temperatures below the maximum rated temperature of 150 °C. Equation 4 below shows how to calculate the quantity of heat transferred via radiation.

$$Q_{rad} = \varepsilon \ \sigma \ A \ (T_s^4 - T_f^4)$$

Equation 4: Radiative heat transfer equation

where:

Q_{rad} is the amount of heat transferred through radiation (W)

ε is the emissivity of the surface (dimensionless)

σ is the Stefan-Boltzmann constant (5.67×10^{-8} W/m^2K^4)

A is the surface area (m^2)

T_s is the surface temperature of the material (°C)

T_f is the fluid temperature of the medium (°C), typically referenced to the ambient air temperature

THERMAL PATH/MODEL

The thermal path of an LED system can be illustrated by a simple resistor network similar to an electrical circuit. Thermal resistances are represented by the resistors, the heat flow is approximated by the electrical current, and the corresponding temperatures within the system correspond to the electrical voltages. Below in Figure 6 is a resistor network representation of a multiple-LED system on a printed circuit board (PCB) mounted to a heat sink in ambient air.

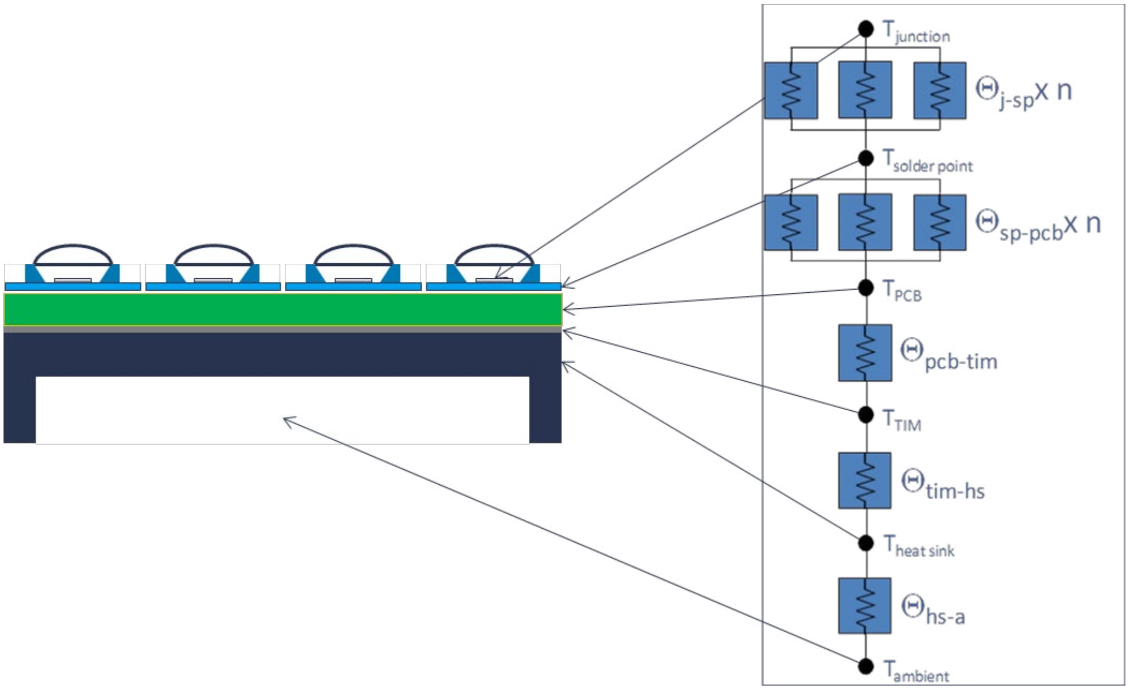


Figure 6: Thermal circuit of an LED array (not to scale)

where:

T is the temperature at each corresponding location (°C)

Θ_{a-b} is the thermal resistance from point a to point b (°C/W)

n is the number of LED components on a single PCB

To summarize the heat path illustrated in the Figure 6 above, heat is conducted from the LED junctions through the LED components to the PCB, through the thermal interface material (TIM) to the heat sink and then convected and radiated to the ambient air.

The nodes in the circuit represent the individual sections within the system and the locations where temperatures may be measured. For example, the solder point temperature ($T_{solder\ point}$) represents the location on the board, as specified in the corresponding data sheet for each Cree XLamp LED, where the temperature on the top of the PCB can be measured. This can be used to calculate the junction temperature, which is detailed in a later section.

The resistors represent the thermal resistances of the individual contributors. For example, Θ_{J-SP} represents the thermal resistance of the LED component from junction to solder point.

The system is divided into a network of parallel connections for the multiple LEDs and series connections for the singular components. If the system includes only one LED, or n =1 in Figure 5, the entire thermal path is simply in series.

The individual thermal resistances described above can be calculated from Equation 5 below.

$$\Theta_{a\text{-}b} = \frac{T_a - T_b}{P_t}$$

Equation 5: Individual thermal resistance calculation

where:

$\Theta_{a\text{-}b}$ is the thermal resistance from point "a" to point "b" (°C/W)
T_a is the temperature at point "a" (°C)
T_b is the temperature at point "b" (°C)
P_t is the thermal power as calculated in Equation 1

The thermal resistance of the entire system can also be compared to an electrical circuit in series, where the system thermal resistance can be calculated as shown below in Equation 6.

$$\Theta_{sys,a\text{-}z} = \Theta_{a\text{-}b} + \Theta_{b\text{-}c} + \ldots + \Theta_{y\text{-}z}$$

Equation 6: System thermal resistance calculation

where:

$\Theta_{sys,a\text{-}z}$ is the system thermal resistance from point "a" to point "z" (°C/W)
$\Theta_{a\text{-}b}$ is the thermal resistance from point "a" to point "b" (°C/W)
$\Theta_{b\text{-}c}$ is the thermal resistance from point "b" to point "c" (°C/W)
$\Theta_{y\text{-}z}$ is the thermal resistance from point "y" to point "z" (°C/W)

In an LED system, the total system-level thermal resistance is typically defined as "junction to ambient", or $\Theta_{J\text{-}A}$. This quantifies how well each component transfers thermal power. Each Cree XLamp LED has a current de-rating curve in its data sheet that gives the maximum drive current versus ambient temperature for a few system thermal resistances, or $\Theta_{J\text{-}A}$. Shown below in Figure 7 is the current de-rating curve for an XLamp XB-D LED from the XB-D data sheet.

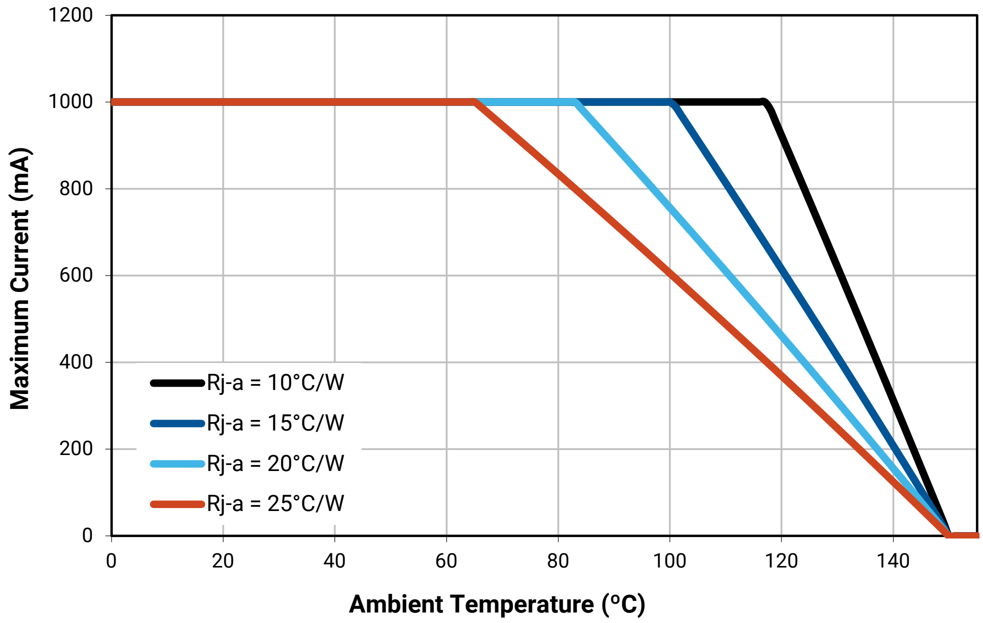


Figure 7: XB-D current de-rating curve

To use the current de-rating curve in Figure 7, the system-level thermal resistance must be calculated, as detailed above in Equation 6. The ambient temperature must also be known, and from this, the maximum drive current for this thermal design can be determined from the graph in Figure 7.

THERMAL STACK

For purposes of thermal analysis, an LED system typically consists of a multi-component assembly, called a thermal stack, in which all components contribute in varying degrees to the total system thermal performance. In a typical system, the LED is soldered to a PCB, either metal core or FR4, which is then usually attached to a heat sink. It is critical to maximize heat transfer between the heat sink and PCB, so a good TIM is needed to fill any air voids. The best method to enhance the thermal path is to minimize the number of materials in the thermal stack and use the most thermally conductive materials available. Below is a description of this typical LED system with some suggestions and comments to consider for each element.

XLamp LED component

Heat is generated at the junction of the LED chip within the XLamp LED component. The amount of heat can be calculated from Equation 7 below based on the measured T_{SP} and the thermal resistance of the LED, as stated on its data sheet.

$$T_J = T_{SP} + \Theta_{th}\ P_{total}$$

Equation 7: Junction temperature calculation

where:

- T_J is the junction temperature (°C)
- T_{SP} is the measured solder point temperature (°C)
- Θ_{th} is the thermal resistance of the component (°C/W)
- P_{total} is the total power (W) input to the LED (I_f x V_f)

All Cree XLamp LEDs must not exceed their maximum junction temperature of 150 °C, as specified on each data sheet.

Printed circuit board

Most Cree's XLamp LEDs are required to be mounted on a PCB to provide electrical and mechanical connections to additional components such as the driver and heat sink. The thermal effect of the PCB can be significant, so care must be used when choosing or designing a PCB. Cree has published a technical article, "Optimizing PCB Thermal Performance" that details PCB design recommendations and offers tips. Please consult this article for further information and advice.

Thermal interface material

The thermal interface material can play a large role in the system thermal performance, depending on the design choices made. TIMs are critical to minimize the air gaps between the heat sink and the PCB. TIMs not only provide a thermal interface between the PCB and the heat sink, but depending on the application these can have other functions as well, such as electrical insulation or making a mechanical connection. Many types of TIMs are used in LED systems including greases, tapes, pads, and epoxies. Each has its advantages and disadvantages depending on the application. Table 2 below shows some of the benefits and drawbacks of various materials.

Table 2: Relative properties of TIMs[1]

TIM	Property					
	Bulk Conductivity	Thermal Resistance	Bond Line Thickness	Production Automation	Reworkability	Stress Relief
Adhesive films	Good	Poor	Fair	Fair	Poor	Fair
Adhesives	Good	Good	Excellent	Excellent	Poor	Fair
Compounds	Good	Excellent	Excellent	Excellent	Good	Excellent
Encapsulants	Excellent	Good	Good	Excellent	Good	Good
Gap fill pads	Excellent	Fair	Poor	Fair	Excellent	Good
Gels	Good	Good	Good	Excellent	Good	Excellent
Phase changes	Excellent	Excellent	Fair	Excellent	Good	Excellent

Many characteristics must be considered when selecting a TIM, not just the thermal conductivity. Often overlooked is the bond line thickness of the material, and as shown below in Equation 8, the thermal resistance of the material is highly dependent on this thickness. The TIM manufacturer will provide these basic characteristics on their own data sheet, and it is important to understand how all the characteristics work together and to decide which is the most important for each specific application.

Sometimes a thinner TIM with poor thermal conductivity has a lower thermal resistance than a thicker TIM with better thermal conductivity. Both these attributes must be considered when selecting a TIM and their relative effects can be quantified with Equation 8 below. However, though a TIM may have better thermal conductivity than air, its conductivity will not be nearly as good as metal's, so the approach is not to add material between metal components but rather to fill the voids that are typically occupied by air. Just remember, thin to win!

$$\Theta_{TIM} = \frac{L}{k\ A}$$

Equation 8: TIM thermal resistance calculation

where:

Θ_{TIM} is the thermal resistance of the TIM
L is the thickness of the TIM (m)
k is the thermal conductivity of the TIM (W/m K)
A is the contact area (m^2)

Heat sink

The heat sink is the last and most influential part of the thermal stack, and is needed to first conduct heat away from the LEDs and then to convect and radiate heat to the ambient air. Thus, the first task of the heat sink necessitates that the heat sink be fabricated from a high thermal conductivity material to conduct heat away. The second task requires that the heat sink have a large surface area to convect heat to ambient and also have good emissivity so it can radiate heat away. In some cases, heat sinks are coupled to other heat dissipating devices such as housings, enclosures, etc. For this document, we group these devices under the general term "heat sink", but this should not be overlooked in system design as it can contribute significantly to the performance of the entire LED system.

Table 3 below shows the thermal conductivity of some common materials as well as a rough range of their emissivity, which can vary significantly depending on the material finish. Choosing the highest thermal conductivity and/or emissivity is obviously not always

1 www.dowcorning.com/content/etronics/etronicswet/relativepropertiespop.asp?popup=true

possible because of other factors that must be considered such as weight, cost, and manufacturability. Each of these must be evaluated for each application to determine the best material and manufacturing process.

Cast or forged aluminum is typically used for heat sinks. Anodizing aluminum gives a heat sink a much higher (to about 0.8) emissivity than standard aluminum and helps with radiative heat transfer to the environment.

Table 3: Thermal conductivity and emissivity for various materials at 25 °C

Material	Thermal Conductivity (W/m K)	Approximate Emissivity
Acrylic	0.2	0.94
Air	0.024	Not applicable
Aluminum	120 - 240	0.02 - 0.9 (depending on finish)
Ceramics	Alumina: 15 - 40 Aluminum nitride: 100 - 200	0.4 - 0.7 0.9
Conductive polymers	3 ~ 20	Not applicable
Copper	401	0.05 - 0.8 (depending on finish)
Diamond	2000	1.0
FR4	0.2	0.7 - 0.8
Glass	1.05	0.6 - 0.97
Silicon	150	0.6
Silicon carbide	350	0.85
Silver	429	0.02 - 0.074
Stainless steel	16	0.1 - 0.9 (depending on finish)
Thermal grease/epoxies/pads	0.1 ~ 10	Not applicable
Water	0.58	0.85 - 0.99
Wood	0.17	0.8 - 0.9

Heat sink design can be very complicated and limited by many restrictions such as space constraints, cost, weight, manufacturability and countless other requirements. There is no one right answer to heat sink design and each application must be approached on a case-by-case basis, but the following general guidelines can help in the design process.

- Maximize the surface area of the heat sink to maximize its ability to convect heat away from the LED source.
- A rough estimate of approximately 5-10 in^2 of heat sink surface area per watt of heat can be used for a first-order estimate of heat sink size.
- Do not restrict the airflow between the fins. Understand the orientation of the heat sink in the application in which it will be used and maximize the airflow through the heat sink and around as much surface area as possible.
- Choose a material that has good thermal conductivity to spread heat away from the LEDs.
- Use high surface emissivity heat sinks to maximize thermal radiation heat transfer. Anodizing dramatically increases the emissivity of an aluminum heat sink.
- Passive (natural convection) heat sinks are always preferred for many reasons, but if appropriate, actively cooled heat sinks can significantly improve performance.
- Use of thermal modeling can alleviate repetitive prototyping and indicate design deficiencies and potential areas of improvement early in the design process.

A key aspect of heat sink design to account for is the manufacturing method that will be used. These methods vary significantly and can produce extremely different heat sinks, which can serve different applications and their specific needs. Some aspects of the more common processes are compared below in Table 4.

Table 4: Heat sink manufacturing process comparison

Heat Sink Aspect	Bonded	Cast	Extruded	Folded	Forged	Skived	Stamped
Maximum fin height	6.0 in	3.0 in	3.0 in	2.0 in	5.0 in	1.5 in	2.0 in
Minimum fin thickness	0.032 in	0.070 in	0.040 in	0.010 in	0.020 in	0.016 in	0.007 in
Maximum aspect ratio	60:1	10:1	10:1	40:1	35:1	16:1	4:1
Type	Straight	Any	Straight Cross-cut	Straight	Any	Not perfectly straight	Straight
Cooling factor	0.8x	1.4x	x	0.7x	1.5x	1.2x	1.4x
Base cost factor	1.3x	0.8x	x	1.2x	1.3x	1.2x	0.7x
Tooling cost factor	1.5x	4.0x	x	1.8x	3.0x	1.2x	2.8x
Material type	Al6063 Cu1100	Al356	Al6063	Al6063 Cu1100	Al6063 Cu1100	Al6063 Cu1100	Al6063 Cu1100

Fans/active cooling

When the thermal load of an LED system is too high to be properly dissipated by passive means, active cooling may be the only solution. There are many types of actively cooled systems, from fans to liquid cooling to heat pipes to other exotic methods. The effectiveness, reliability, noise, cost, added power (and thus lower system efficiency) and maintenance of these devices need to be weighed against the benefits of an actively cooled system. Very few active cooling devices can equal the long LED lifetimes of many thousands to hundreds of thousands of hours, so care must be taken to not compromise system lifetime with inept active cooling solutions. An LED system is only as good as its weakest link, and active cooling can be this link without careful selection. Table 5 below briefly summarizes aspects of several active cooling systems.

Table 5: Active cooling examples[2]

Type	Thermal Dissipation Power	Details	Example Image
Fan sink	< 40 W	Fan mounted directly on heat sink. Additional power needed, therefore less lm/W. One big negative: if the fan fails, the entire unit must be replaced.	
Heat pipe	< 140 W	Heat pipes do not dissipate heat; they move it to another location, so a heat sink is still needed elsewhere.	
Liquid cooling	< 200 W	High heat flux applications. Expensive, typically 10 times the cost of a heat pipe solution.	
Peltier devices	< 80 W	Inefficient, limited cooling, expensive. Additional power needed, therefore less lm/W.	
Synthetic jet cooling	< 80 W	Cooling possibilities similar to a fan, but less noise and better reliability. Special heat sink design needed to best utilize this technology.	

THERMAL MEASUREMENT

Accurate temperature measurements are required to appropriately design a thermal system and to evaluate and assess an existing design. Whether for a final design or a prototype, the measurement process is the same and requires due diligence to make sure realistic and accurate measurements are made. LED reliability is a major advantage compared to traditional light sources, so proper and realistic measurement procedures should be used so this benefit is not jeopardized.

When performing thermal measurements, it is critical to set up the test subject as close as possible to the real-life, worst-case scenario to which the system may be subjected. Ensure that the measurement setup accounts for similar airflow, material properties, orientation, ambient conditions and any additional heat sources such as power supplies or contributory heat loads. This ensures that the temperatures measured correspond to real-world, worst-case scenarios and could identify potential problems that best-case scenarios may miss.

2 www.vettecorp.com/support/downloads/presentations/HeatSink_Basics_Cisco_Core_v6.pdf
qats.com/cms/2011/06/22/how-to-use-synthetic-jets-for-local-thermal-management/

Another factor to note is the time required for the system to thermally stabilize. Depending on the size of the heat load and the mass and effectiveness of the heat sink, some systems take only a few minutes to stabilize while others take hours. It is best to monitor the thermal stability and wait one hour at the very least for each thermal measurement. It is also recommended to monitor the ambient temperature and look exclusively at the difference between the measurement point and ambient temperature, as any change in ambient will be reflected in the measured data.

Various methods to measure temperature exist, and for LED systems the most common methods are simple thermocouples, infrared (IR) microscopes, and pulsed voltage/transient response monitoring. The latter two methods require expensive, accurate and specific tools that are beyond the scope of this document. Simple thermocouples are the most common and simplest method to obtain accurate data and are recommended for precise absolute LED system measurements.

Thermocouples

The soldering and handling application note Cree publishes for each XLamp LED details the location and process for attaching a thermocouple. Below in Figure 8 is an image from the XLamp XB-D LED Soldering and Handling document showing the proper location for a thermocouple. The general guideline for thermocouple attachment is to place the thermocouple as close to the LED as possible, mounted directly on a metal pad connected to the neutral thermal trace, if possible. Thermally conductive epoxy or solder is recommended to ensure good heat transfer from the board to the thermocouple. All thermocouples must be out of the optical light path or photons will interfere with the readings, giving extremely inaccurate results.

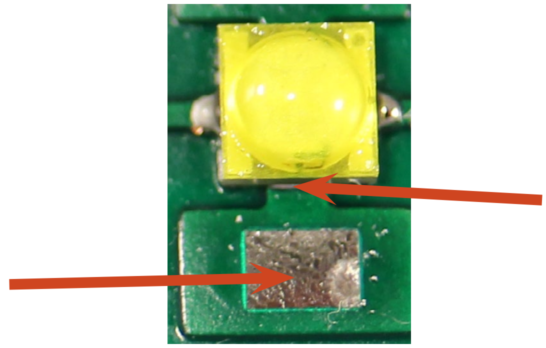


Figure 8: XB-D T_{SP} measurement location

Infrared camera

IR camera measurements can be useful to get a quick visual representation of the heat spreading through an LED system to see any potential hot spots and for other relative comparisons. However, using an IR camera for absolute temperature measurements can be very complex and lead to inaccurate results. Knowing the exact emissivity of the material is crucial for accurate results, and this often is not precisely known. One way to get this is to take a measurement with a thermocouple and then adjust the emissivity setting on the IR camera to match these results.

Figure 9 shows the same IR image captured with four different emissivity values, all within a normal small range for typical materials. The upper left image has an emissivity setting of 0.95, the upper right has 0.8, the lower left has 0.7 and the lower right has 0.5. The same point on the LED board has a temperature of 86.0 °C, 95.7 °C, 104 °C and 129 °C, respectively. Thus, a huge difference in temperature is seen with just a small emissivity difference.

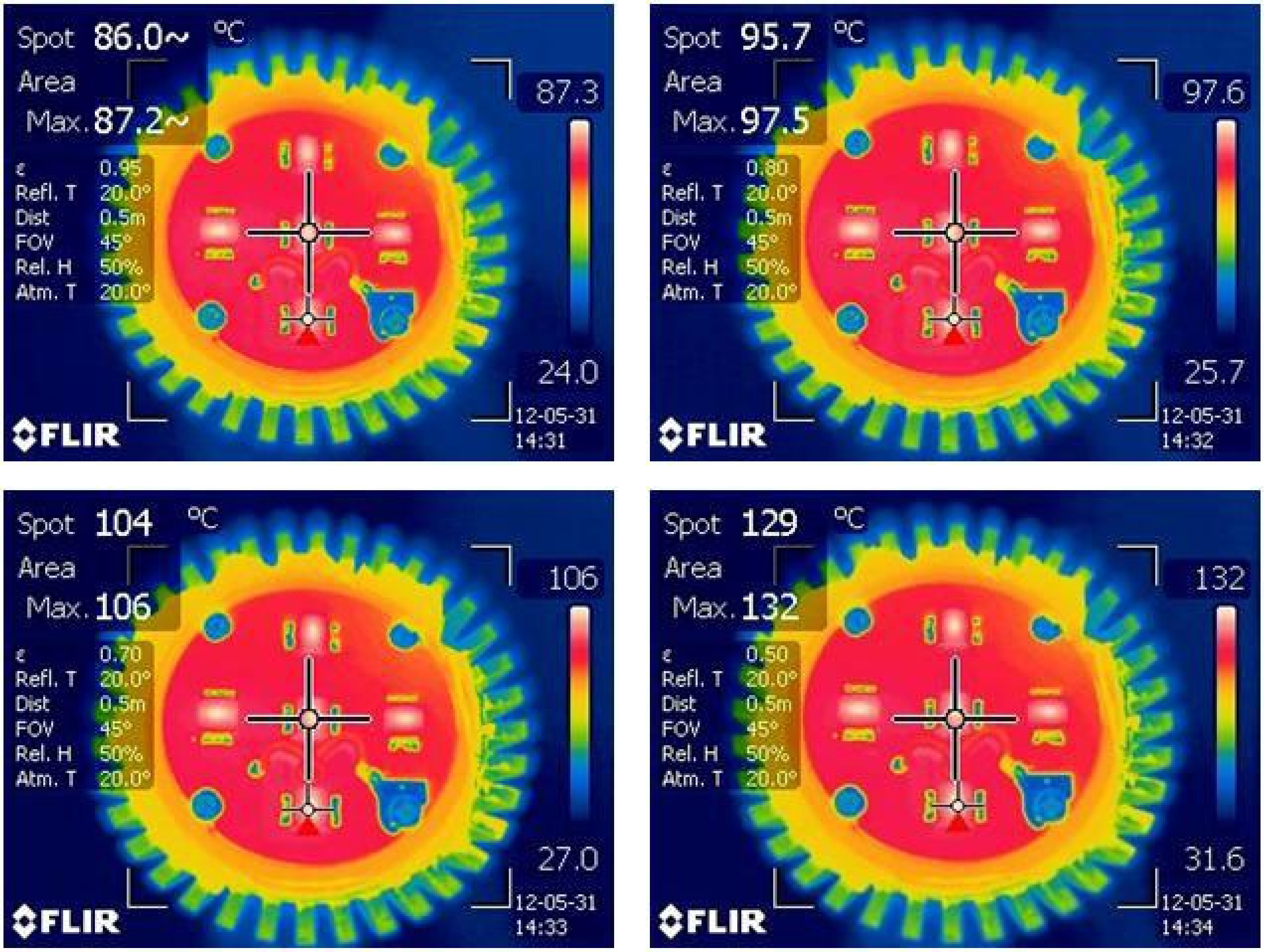


Figure 9: Same IR image with different emissivity values
Upper left: 0.95, upper right: 0.8, lower left: 0.7, lower right: 0.5

THERMAL SIMULATIONS

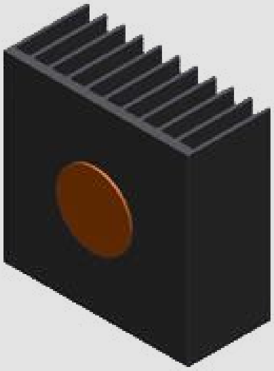
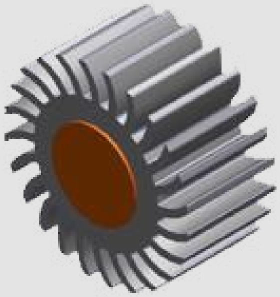
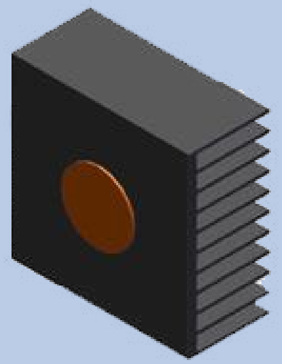
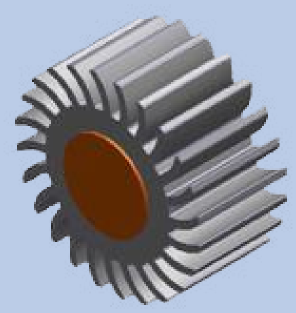
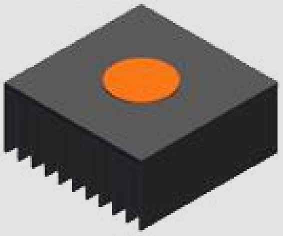
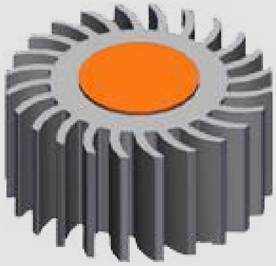
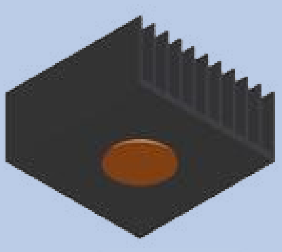
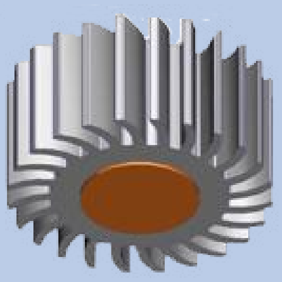
For early design validation, before investing in expensive prototyping and multiple design revisions, it is highly recommended to perform thermal simulations. Cree Services offers thermal simulation through its Thermal, Electrical, Mechanical, Photometric and Optical (TEMPO) service options. Thermal simulations can show problematic areas and hot spots within a design and can allow for iterative design adjustments to address problems and optimize the system. Computational fluid dynamics (CFD) analysis further enhances thermal simulations by solving for conduction, convection, whether natural or forced, and radiation to fully evaluate the total system design and the effect of the fluid flow around the system. Simulations are good for quick and inexpensive design adjustments and give a good visual representation of spreading, potential bottlenecks, and thus possible areas of improvement.

Care must be taken when performing thermal simulations as many assumptions must be made and operating conditions must be known and understood. A simulation will always give an answer; however, depending to the approach taken, it may not always be the right answer. After simulating a system and optimizing a design, building a final prototype to accurately measure its performance is always

recommended. However, thermal simulations can be used to minimize the iterative steps of seemingly infinite prototyping by proactively reducing the number of options and focusing the design work instead of investing in prototypes, testing and repeating.

Below in Table 6 are results from CFD simulations of comparative performances of two different types of heat sinks versus their orientation. An extruded heat sink shows significantly inferior performance when the fins are oriented perpendicular to gravity (Horizontal - 90° case), but comparable performance in the Horizontal - 0° and Vertical - Down cases in which the airflow is not restricted and is allowed to flow upward along the fins away from the source. Due to their symmetry, the radial heat sinks show identical performance when mounted horizontally, and much better performance when mounted vertically so that the air around the fins can flow upward. Remember, heat rises, so always try to orient a heat sink's fins such that the airflow is not impeded in the upward direction, opposite gravity.

Table 6: Heat sink orientation effects computed by thermal simulation

Source Orientation	Extruded Heat Sink		Radial Heat Sink	
	Thermal Resistance (Scaled to Source Orientation Horizontal - 0°)	Image	Thermal Resistance (Scaled to Source Orientation Horizontal - 0°)	Image
Horizontal - 0°	1.00 x		1.00 x	
Horizontal - 90°	2.15 x		1.00 x	
Vertical - Up	1.23 x		0.74 x	
Vertical - Down	1.03 x		0.74 x	

CONCLUSION

Thermal management of LEDs is extremely critical and understanding it is essential when designing and developing LED systems. To prolong their lifetime and improve their performance, LEDs must be kept cool under all drive and operating conditions. The fundamentals of heat transfer and a full understanding of the heat path and thermal stack is needed to properly design an LED system. Thermal simulations and testing should be used to optimize and measure the performance of each LED system.

RESOURCES

Below are some web links for various heat management resources. These are not explicitly recommended by Cree nor is this intended to be an all-encompassing list, but rather offers some resources for thermal design assistance.

Heat Sink Companies	
Aavid Thermalloy	www.aavid.com/
Advanced Thermal Solutions, Inc.	www.qats.com/
Asia Vital Components Co. (AVC)	www.avc-europa.de/
Cooler Master Ltd., Inc.	odm.coolermaster.com/
Cooling Source Inc.	www.coolingsource.com/
Huizhou Taisun Precision Parts Co., Ltd.	www.hztaisun.com/en/index.asp
Nuventix, Inc.	www.nuventix.com/
Wakefield Solutions, Inc.	www.wakefield.com/
Wisefull Technology Ltd.	www.wisefull.com/

TIM Companies	
3M	solutions.3m.com/wps/portal/3M/en_US/AdhesivesForElectronics/Home/Products/ThermalSolutions/
Arctic Silver, Inc.	www.arcticsilver.com/
Bergquist Company	www.bergquistcompany.com/thermal_materials/index.htm
Chomerics	www.chomerics.com/products/thermal/index.html
Dow Corning Corporation	www.dowcorning.com/content/etronics/etronicspadsfilm/ www.dowcorning.com/content/etronics/etronicswet/default.asp
GrafTech International Ltd.	www.graftech.com/MARKETS/Lighting-Thermal-Management.aspx
Indium Corporation	www.indium.com/TIM/
Laird	www.lairdtech.com/Products/Thermal-Management-Solutions/Thermal-Interface-Materials/
Shin-Etsu Chemical Co., Ltd.	www.silicone.jp/e/products/notice/heat/index.shtml
TIMtronics	www.timtronics.com/

PCB Companies	
Bergquist Company	www.bergquistcompany.com/thermal_substrates/index.htm
Copper Wave, Inc.	www.copperwavepcb.com/
Milplex Circuit Inc.	www.milplexcircuit.com/
Multilayer Prototypes, Inc.	www.mpi-pcb.com/
Saturn Electronics Corporation	saturnelectronics.com/thermalmanagement.htm

Thermal Simulation Companies	
Advanced Thermal Solutions, Inc.	www.qats.com/
ANSYS, Inc.	www.ansys.com/
Autodesk, Inc.	www.autodesk.com/simulation-cfd
Informative Design Partners (IDP)	www.informativedp.com/
ThermoAnalytics, Inc.	www.thermoanalytics.com/