SOLAIS
LIGHTING GROUP

LED Active Cooling - The Need for Advanced Thermal Management

For the Advancement of LEDs

Introduction to LEDs and Thermal Management

As LED technology pushes the boundaries of lighting performance and the spectrum of applications, thermal management continues to pose a challenge to LED development. To achieve their full potential for energy efficiency, cost efficiency, lumen output, efficacy and an overall higher-quality white light, LEDs require high-performance thermal management systems. In contrast to conventional lighting, such as incandescents that require heat to produce light, LEDs are hindered by high temperatures. Furthermore, a great deal of the energy that LEDs produce is heat, necessitating the implementation of innovative thermal management systems previously unneeded in the lighting industry.

Relative Power Conversion for "White" Light Sources

	Incandescent[1] (60W)	Fluorescent[1] (Typical Linear CW)	Metal Halide[2]	LED[3]
Visible Light	8%	21%	27%	20-30%
Infrared Light	73%	37%	17%	0%
Ultraviolet Light	0%	0%	19%	0%
Total Radiant Energy	81%	58%	63%	20-30%
Heat (Conduction+Convection)	19%	42%	37%	70-80%
Total	100%	100%	100%	100%

[1]IESNA Handbook
[2]OSRAM SYLVANIA
[3]Varies depending on LED efficacy. This range represents best currently available technology in color temperatures from warm to cool. U.S. Department of Energy's Solid State Lighting Multi-Year Program Plan (March 2009) calls for increasing extraction efficiency to more than 50 percent by 2025.

Adapted from U.S. DOE

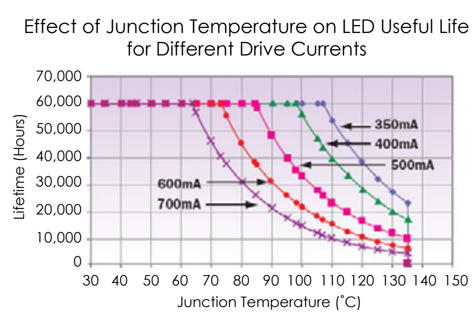
A particularly promising approach to the challenge of thermal management is active cooling. This white paper identifies and evaluates the current methods of LED thermal management to provide a greater understanding of the systems critical to the success and advancement of LED lighting technology.

The Importance of Thermal Management

Understanding LED Thermal Characteristics

The single most important factor in determining LED spectral and electrical performance is the temperature at the junction between the diode's positive and negative layers, which is influenced by the flow of electricity. This value is known as the "junction temperature" of the diode.

The ability of an LED thermal management system to dissipate heat is highly dependent on ambient temperature and airflow. For example, in recessed lighting applications, exchange of air between the interior of the housing and the room below is very limited. Even in a typical air-conditioned office space, the cool air has no impact on the temperature of the housing because the housing is located above the plane of the ceiling. These factors cause significant increases in junction temperature.



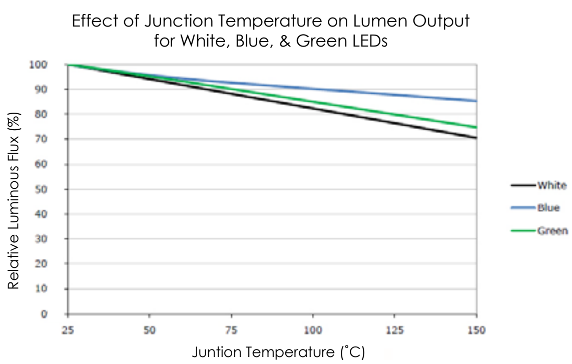
Adapted from Electronics Cooling

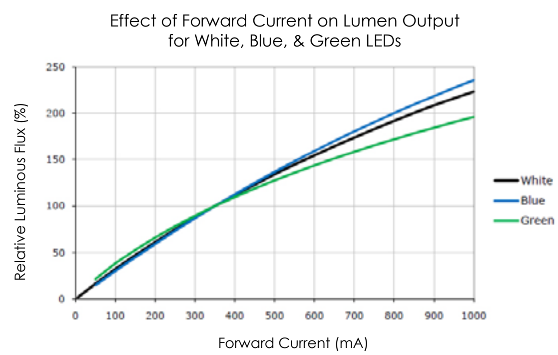
Effects of Heat on LEDs

High junction temperatures degrade LED performance, specifically useful life, color quality and lumen output. Every LED chip manufacturer tests and can provide junction temperature ratings for each of its products. This testing determines the maximum rated junction temperature, up to which expected lumen maintenance and performance can be sustained. Beyond this maximum rated junction temperature, the LED will experience a 30 to 50 percent decrease in its useful life for every 10˚C increase.

Increases in junction temperature also create a noticeable color shift toward the higher end of the spectrum. This is important with “white” light LED sources that typically use blue wavelengths (low end of the visible light spectrum) coupled with a phosphor. With heat causing a shift towards red wavelengths (high end of the visible light spectrum), the interaction with the phosphors is altered, resulting in a different color of “white”. Additionally, because most system modules are made up of LED arrays, which produce more heat than a single LED, maintaining consistent color across carefully matched multiple diode systems is an extremely important consideration in virtually all LED lighting products and applications.

The last major factor impacted by LED thermal management systems is lumen output (also known as luminous flux). Increases in electrical current generally produce increases in lumen output. However, higher current also increases thermal buildup within the LED. Because of this, the current must be reduced to optimize system performance and useful life. **As a result, most currently available LED replacement lamps do not provide the lumen output necessary to match their claimed incandescent equivalents.** Compounded with additional thermal variables (e.g., application), high junction temperatures pose a significant limitation.

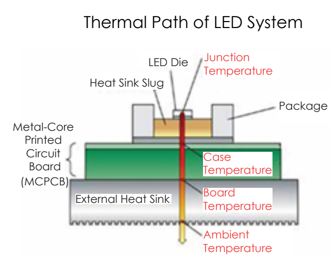




Adapted from CREE, Inc.

The Thermal Path of an LED System

The ability of an LED system to dissipate heat is ultimately described by its “thermal resistance,” which is a measure of a material’s ability to resist heat transfer (expressed in ˚C/W). In an LED, this value essentially represents the difficulty in transporting heat away from the junction of the diode, following the thermal path shown in the diagram to the right. Once it reaches the metal-core board, the heat must then be dissipated to the surrounding environment. The two main approaches to this final dissipation are heat sinking (passive cooling) and active cooling.



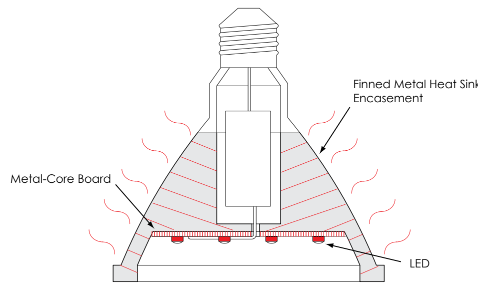
Adapted from PNNL

Heat Sinks and Passive Cooling

The Basics

Currently, the most common approach to thermal management in commercially available LED systems is heat sinking. Heat sinks are generally finned metal encasements that conduct accumulated heat away from the LED. In this type of thermal management system, the metal-core board is mounted inside the heat sink, so the heat can transfer to the fins and dissipate to the ambient environment. Without sufficient air movement, the metal fins lose their effectiveness and are only marginally better at dissipating heat than a solid block of metal of the same volume. Even in open-air applications, tightly spaced fins are ineffective because they restrict airflow between them. These characteristics render heat sinks impractical solutions for enclosed or high-output applications.

Heat Sink Thermal Management Diagram



In heat sinks, heat is transferred from diode to metal-core board, then transferred again to the finned metal heat sink encasement, where it is dissipated by the movement of the ambient air.

Appropriate Applications

In low-output applications, such as gimbal-ring track lighting and other open-air accent lighting, heat sinks are a suitable solution to thermal buildup because the thermal demands are not severe. But in high-output applications, the LED modules/arrays must be supplied with significantly more electrical current to achieve the lumen output levels necessary for replacing current incandescent sources. This increase in electrical current results in a commensurate increase in thermal production, requiring passively cooled systems to have very large and heavy heat sinks for heat dissipation. This, in turn, introduces a significant limitation, because the increased bulk and weight of the required heat sinks greatly restrict the potential application versatility. To avoid oversized and awkward heat sinks, the drive current must be lowered to prevent an increase in heat buildup, but this also lowers the light output of the lamp.

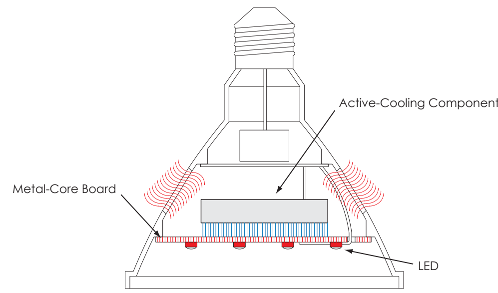
Why Passive Heat Sinks become Ineffective

Passive thermal management systems cool by conduction. In this type of system, the conduction of heat is a linear function of both temperature (which varies) and the thermal properties of the materials of the system's components (which remain constant). For high-output applications, where heat production reaches high levels, the material properties of the system's components do not allow for the necessary rate of cooling. This results in a runaway system in which the heat continues to build, and the junction temperature continues to rise. The optimal solution is to take an active approach to system cooling.

Additionally, many high-output applications, such as recessed downlights for general lighting, require the lamp to be in an enclosure. Such enclosures, even in low-output applications, are detrimental to heat sink systems because they cause further heat buildup around the diode. Given all of these potentially negative aspects of heat sinks, it is important to consider the intended application of the LED lamp when choosing between the different thermal management systems.

Active Cooling

Active-Cooling Thermal Management Diagram



In active cooling, heat is transferred from diode to metal-core board, where active-cooling components dissipate heat to ambient air.

The Basics

An emerging option for LED thermal management is active cooling. In these types of lamps, the cooling system is typically mounted on and aimed at the metal-core board. This means that the heat is dissipated directly from the metal-core board to the ambient environment. By eliminating the extra thermal transfer required in heat sinks (i.e., the transfer of heat from the metal-core board to the heat sink), actively cooled systems have less total thermal resistance than passively cooled systems.

Well-Proven Technology for High-Performance Systems

Many common high-end, highly sophisticated electronic devices (computers, televisions, stereo systems, processors, etc.) utilize active-cooling systems as their primary cooling solutions. Given that LEDs are also themselves electronic devices, the use of active cooling for LED systems is a logical evolution in design.

Succeeding Despite All Doubts

There are many types of active-cooling systems, including active heat sink cooling, water cooling, thermoelectric cooling, heat pipes and fan cooling. Most concerns with these approaches for use in LED lighting stem from the misconception that many of the mechanical components of these methods are prone to noise, friction, dust and dirt accumulation, and other general wear-and-tear issues that could possibly limit performance and useful life. The high quality of active-cooling devices used currently across the electronics industry has virtually eliminated all concerns regarding these technologies, rendering related concerns regarding LED systems unwarranted. The belief that fan-cooled LED systems are associated with loud system-operation noise is untrue. For example, unlike the fairly large, exhaust case fans in a computer tower, multiple smaller fans dedicated to individual components (e.g., the CPU, the graphics card) go unnoticed because they run at constant low speeds, making them inaudible. Many LCD and plasma television sets also use multiple fans to properly cool their components, yet do not suffer from audibility.

Active Cooling in Computer Graphics Card

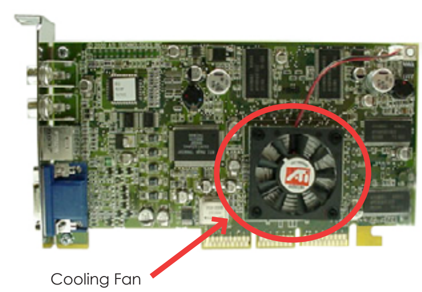


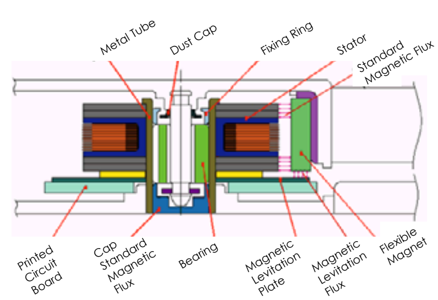
Photo from HowStuffWorks, Inc.

The Reliability of Active Cooling

Many of the fans used in electronic devices today feature magnetic levitation technology, which leverages magnetic forces to eliminate contact between the center shaft of the fan and the bearing surrounding it. As a result, the fan remains balanced during operation with zero swaying and limited friction, rendering it virtually free of all noise.

Due to the stable operation of these fans, core components can be sealed to prevent dust penetration, as well as to maximize retention of lubrication, thereby avoiding the buildup of friction. The exclusion of dust from the fan's interior components provides another

Magnetic Levitation Fan Structure



Adapted from Sunon

advantage over heat sinks; dust tends to collect on and between the fins of heat sinks, acting as an insulating layer and lowering the dissipation of heat to the ambient air. Additionally, zero friction also translates into limited additional heat generation – a key reason these fans have a rated life of more than 50,000 hours.

The Right Solution

The long life, robust application flexibility and overwhelming benefit of active cooling in LED systems render it the ideal thermal management system for high-output applications. With actively cooled systems, performance need not be compromised, because the necessary drive current to produce light output equivalent to incandescent sources can be utilized without requiring significant additional bulk or excess weight, while the system maintains maximum useful life. Because of this, these systems offer tremendous advantages over heat sink systems.

The Potential of LEDs

Lighting is the largest consumer of electrical energy in retail establishments and office buildings in the United States and accounts for nearly 20 percent of the world's total electric consumption. When clean, energy-efficient LED technology realizes its full technological and market potential:

Worldwide electricity consumption due to lighting will be decreased by more than 50 percent.
Total consumption of electricity will be decreased by more than 10 percent.
Carbon emissions and new capital infrastructure associated with electric power generation will decrease proportionately.
Hazardous waste that exists in today's conventional light sources, such as the mercury in fluorescent and high-intensity discharge (HID) lamps, will be eliminated.

Among the main factors preventing LED technology from reaching its full potential is sub-optimal thermal management systems. The development and implementation of advanced thermal management systems will not only provide higher-quality and higher-performance products, but will increase consumer acceptance and interest in LED lighting – a technology with tremendous potential to improve not only our daily lives but also our environment.

