Thermal Management in Solid State Lighting

Thermal Conduction and Convection in Passive Thermal Management

September, 2010

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Objective and Scope

Thermal management is critical to the long life of the LED's used in a Solid State Luminaire (SSL). This document provides the SSL consumer a fundamental knowledge of how the science of thermodynamic physics applies to the SSL, the methods used in SSL thermal management, and how effective thermal management directly relates to measurable LED performance over time.

Overview

The science of thermodynamics can be taken beyond the doctorate level. For purposes here, only the thermodynamic principles that relate to thermal management of the SSL will be covered.

The term "thermal management" applies to everything from the comfort of your home to preventing your car from overheating to the performance of superconductors. For purposes here, it directly relates to the light output and longevity of the LED. Specifically, our objective in SSL design is to insure the cool operation of the LED. Regardless of where the science is applied, the fundamental characteristics of heat-energy, how it acts and how it can be managed, are the same.

Complete thermal management of the SSL includes the power supply. However, to keep to a manageable size, this document is restricted to the effects of thermal management on the LED. We'll consider thermal management solely as it applies to the operating temperature of the LED's "P-N junction", referred to hereafter as *junction temperature* (Tj).

The P-N junction is located between the anode (+) and the cathode (-) of the LED, and contains the semiconductor material. The movement of electrons across the junction causes a release of energy and the emission of *photons*. Photons are in the ultraviolet band, beyond the visible spectrum of the human eye, however, when the photon hits a phosphor coating on the lens of the LED, it excites and causes the phosphor to emit light in our visible spectrum.

Though much more efficient than any traditional lighting technology, the photon-generation process in the LED is not perfect. As a result, a fraction of the total energy used is converted to heat. In order to keep the LED cool, sound thermal management will move heat away from the junction at a rate that exceeds the rate the heat-energy is being generated.

The lower the Tj, the longer the LED will maintain a high level of light output. The ability of the SSL to support this is defined by *lumen maintenance*.

Introduction to Thermodynamics

Heat is energy. Energy, by the laws of physics, can be transformed but never "disappears". Because of this, rather than "cooling", we need to think of thermal management in terms of moving heat-energy away from the junction (to a remote location). This process is called "heat transfer" or "thermal transfer" and is optimized using one or more of the *Three Laws of Thermodynamics*.

The objective of the SSL engineer is to combine commercially available materials in a chain of components that cost-effectively optimizes thermal transfer (to maintain an desired maximum Tj). Being effective in this requires an understanding of:

1. The principles of thermodynamics
2. The commercially available materials, their costs, benefits, and thermodynamic characteristics
3. The manufacturing technologies used to process the materials, the geometric and dimensional capability of those processes, and the effect of those processes on the materials
4. The effect of geometry as it relates to thermal transfer
5. The range and effect of environmental conditions in application

The First Law of Thermodynamics basically states that energy cannot be created or destroyed; it can only be transformed. Therefore, in the SSL, our objective is to *exchange* the heat-energy at the junction with a lesser heat-energy from elsewhere. In doing this, we're also observing the Second Law of Thermodynamics, which essentially states that *hot always moves to cold*[(1)].

Exchanging the heat-energy at the junction with that of the ambient environment means utilizing:

> Thermal Conduction: the transfer of thermal energy from one molecule to the next. There is *no physical movement* associated with conduction; it is an exchange of molecular energy or "molecule-swapping". Hot travels to cold in an effort to *equalize* thermal differences.
>
> Thermal convection: *the physical movement* of molecules between fluids. Whether through a liquid, a gas, or combination, thermal convection should be thought of as a *fluid process*.
>
> Thermal radiation: molecular heat-energy that is transferred in the form of electromagnetic radiation. Thermal radiation is *a result of physical movement*.

Thermal conduction and convection are critical (while thermal radiation is virtually non-existent) in SSL thermal management. For the sake of practicality, we'll consider thermal radiation beyond the scope of this document and focus solely on thermal transfer using conduction and convection.

Applying these two thermodynamic principles in the SSL is done using one of two types of thermal management; either *active* or *passive*.

Two Types of Thermal Management in the SSL

> Active thermal management (or active cooling[2]) encompasses technologies that *require an introduction of energy* to enhance the thermal transfer process. In solid state lighting, this might include fans, pumps, or other devices that force a fluid (air or liquid) into motion.
>
> Passive thermal management (or passive cooling[3]) relies on the thermodynamics of conduction and convection without an introduction of additional energy to enhance thermal transfer.

Active cooling is used where passive cooling cannot move heat at a high enough rate to support the thermal management needs of a given device. For example, a computer may use fans to move air over a CPU heat sink. For devices such as this, passive cooling does not move enough heat-energy to maintain the desired operating temperature (of the thermally managed device).

There are disadvantages to active cooling in SSL's. For one, few if any active cooling devices are proven to match the 100,000 plus hours[4] expected of a SSL. Additionally, the noise they introduce and the power they consume is undesirable.

In SSL's, though uncommon, there are applications where active cooling is necessary. For example, in recessed can lighting as well as in LED T8 tube replacements, the natural upward movement of heated air is prohibited by the housing. In order to introduce fresh air to exchange the heated air, the heated air must be inspired to move downward.

Like a hot air balloon, the heated air in these two applications is not sealed, but it is contained. The inherent desire of the heated air to escape upward is prevented and heat builds in the ambient air surrounding these SSL's. They end up baking in the very heat they created. With the elevated ambient, convection is reduced and Tj's run high causing degradation of color and output. While these products are ubiquitous, this inherent problem has not been addressed by the products presently on the market.

Passive cooling is clearly preferable when sufficient heat exchange can be facilitated without the need for active cooling. As it relies on physics, the elimination of the failure modes that are otherwise associated with active cooling devices means luminaire reliability is inherently improved.

Considering passive cooling a logical first choice, how do we know when it will be sufficient? And, when we can determine it is sufficient, how do we determine how much is enough?

The requirements of the cooling system are determined by a) the rate at which heat-energy is being introduced and b) the rate at which heat-energy can be transferred. These factors determine the required *capacity* of the thermal management system.

The LED is an efficient light source. The percentage of the total energy consumed that is converted to light, when compared to traditional technologies, is relatively high, and the percentage of energy that is converted to heat is relatively low. Nevertheless, the rate at which the portion of the supplied energy is converting to heat must be more than offset by the thermal management capacity of the SSL.

The rate at which heat-energy is introduced to the junction is referred to as the "load rate". The load rate sets the bar for our thermal management capacity. Thermal transfer rates (conduction and convection) must outpace the load rate (to prevent a buildup of heat).

Thermal Conductivity; the Path to Convection

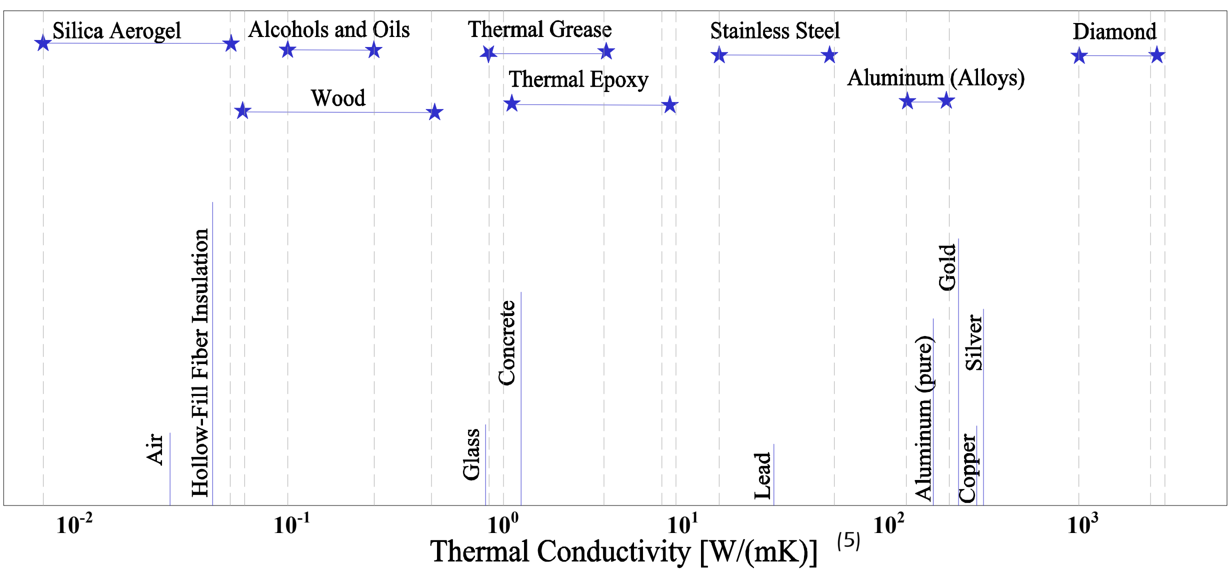
Conductivity starts at the junction and the heat-energy travels through a series of components to end at the convection surface(s). A goal of the SSL design engineer is to adjoin these components in a manner that maximizes the thermal conductivity (minimizes the thermal resistance) between the junction and the convection surface. This requires knowledge of materials science, an in-depth understanding of the associated processing technology's capabilities, and an arsenal of geometric shapes that enhance conductivity and convection.

Thermal Conductivity; Materials

The thermal conductivity of a material is measured in Watts per Kelvin per Meter [W/(mK)].

As mentioned, thermal conductivity is energy-swapping. Some materials do this more effectively than others and thermal conductivity is a measure of this effectiveness. Pure copper has a thermal conductivity of about 400W/mK while air is at about 0.025W/mK.

Aluminum is a commonly used heat sink material for a number of reasons. When reviewing the chart of thermally conductive materials (below), gold, silver, and copper are slightly higher on the list. We don't need to elaborate on why gold and silver are not used but copper, in addition to being more expensive as a base material, is also difficult to process. Sometimes, gold, silver, or copper are used in small amounts as conductors *to* an aluminum heat sink, but their use *as* a heat sink is impractical.



(5)

Besides being a cost-effective base material, aluminum is also easily workable using common machining, casting, and extrusion processes. Geometry, which we'll detail ahead, is a critical characteristic of the heat sink and the ease of converting aluminum into a shape conducive to thermal management adds to its suitability. Other factors that come into play (i.e. weight, corrosion-resistance, dimensional stability, creep resistance, tensile strength, etc.) make aluminum an excellent choice for heat sink material.

All of the materials in the path between the junction and the surrounding air, including those in the LED itself, are part of and important to thermal conductivity; any impediment in this chain of components will render the entire system ineffective. Too often, we see the poor choice of materials working against thermal conductivity.

For example, one product on the market utilizes a thermal chain where convection is blocked by powder coating over a die cast heat sink. Powder coating, with the thermal conductivity of epoxy, seals in air which acts as an insulator (contrary to the purpose of a heat sink). The published test results for the product show a Tj that is too high and leaves too little margin for real world performance.

Thermal conductivity can be maximized with sound materials (and associated manufacturing process) selection. For example, materials such as metal core circuit boards or thermally conductive interface materials support robust conduction. Anodizing a heat sink enhances thermal conductivity by displacing air. Materials that are intelligently selected will maximize function without sacrificing aesthetics or cost.

In many SSL designs, there is a direct interface between the heat sink and the LED circuit board. With this approach, imperfections in the surface finishes of the two components (heat sink and circuit board) determine how much air is trapped between them. Since air is a very poor thermal conductor, robust designs use a thermal epoxy or a thermally conductive material between the heat sink and the circuit board to compensate for surface finish irregularities and maximize surface contact (minimizing the air) between the components.

Selection of thermally conductive materials is important but, equally important are the methods used to manufacture these components. The density of the components in the conductive path is every bit as critical as the materials themselves. The associated processing technologies are a part of the structural integrity and density of the components; these directly relate to thermal conductivity. Additionally, different processes are capable of creating different part geometry which also enhances or inhibits the conduction (and convection) process.

Thermal Conductivity; Component Geometry

A fundamental of sound thermal design is applying a series of *ever-reducing cross sections (thicknesses)*. If heat is required to travel from a thick through a thin and back into a thick section, the thin section creates a *thermal restriction* and negates the benefit of the subsequent thick section(s).

As simple as it sounds, thermal restrictions can be elusive. Also since, in the SSL, we have *multiple points* where heat is introduced, we need to provide an adequate path to convection for each (LED). Common layouts, where LED's are crowded, make for a less expensive luminaire, but choke conductivity as the heat-energy from the multiple LED's competes for the same pathways to the convection surfaces. Space between LED's is one of the design considerations in the prevention of thermal restrictions.

Even more significant than thermal restrictions are *thermal barriers*. A common flaw in heat sink design is to incorporate too many components in the conductive path. Despite physical adjacency, surface imperfections between components trap air; since air is one-ten-thousandth as conductive as aluminum, even small amounts of trapped air create thermal barriers. Materials that compensate for these surface imperfections minimize the effect of the jump across these components, however, minimized part count will always be the preferred solution.

While minimizing the number of components is a design objective, in thermal management it is often said there is *no substitute for mass*. The greater the quantity of available molecules the more conductivity is accommodated. However, in our conductivity chain, material integrity, part count minimization, and geometric shape help to minimize the need for mass to achieve the necessary conductivity without excessive material (and its associated expense and waste). As detailed ahead, geometry, more than any of these other characteristics, plays a critical role in convection.

Thermal Conductivity; Manufacturing Methods

Even in the same material, different manufacturing processes render different thermal characteristics. Material selection must consider manufacturing processes that insure the conductive integrity of the components in the path to convection.

For example, compare an aluminum die casting to an aluminum extrusion. The extrusion process inherently creates a product with greater density (less air) than the die casting process. With the insulating properties of air and the conductive properties of aluminum being at such polar extremes, even the small amounts of air in die cast aluminum renders a significant reduction in thermal conductivity. Die castings, size for size, are 20-30% less thermally conductive than extrusions[6].

Combining sound materials selection with processing technologies that support the density of the components optimizes conductivity. Minimizing part count and utilizing a design with ever-reducing cross sections optimizes conductivity and eliminates thermal restrictions. These factors encourage the movement of heat-energy away from the junction using conduction.

The final step to the ambient environment uses the principle of convection. Convection uses the virtually infinite supply of surrounding (ambient) air to carry our heat-energy away from the heat sink in order to equalize with the surrounding environment. Without robust convection, the heat-energy will eventually saturate the heat sink mass (and back up into the LED).

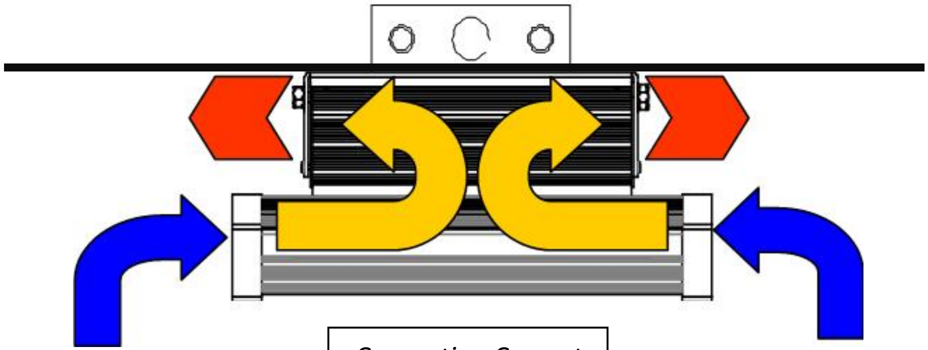
Convection

Convection is the fluid process, whether in air or liquid, in which heat-energy is transferred from one molecule to the next (causing the movement of the latter).

The greater the surface area, the more convection occurs and an objective of heat sink design should be to maximize convection surface area. “Cooling Fin” details are commonly used as they effectively increase surface area while remaining confined to a given footprint.

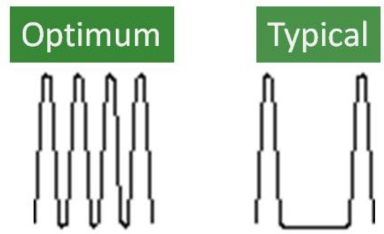
As mentioned earlier, convection is the *physical movement* of molecules. For our purposes, encouraging the movement of the ambient air, using the properties of thermodynamics, creates what is called *convection current*. Simply put, the convection current defines the flow of air into, through, and out of the heat sink surfaces. The manner in which we accommodate and encourage the convection current is called *plenum design*.

PLENUM DESIGN

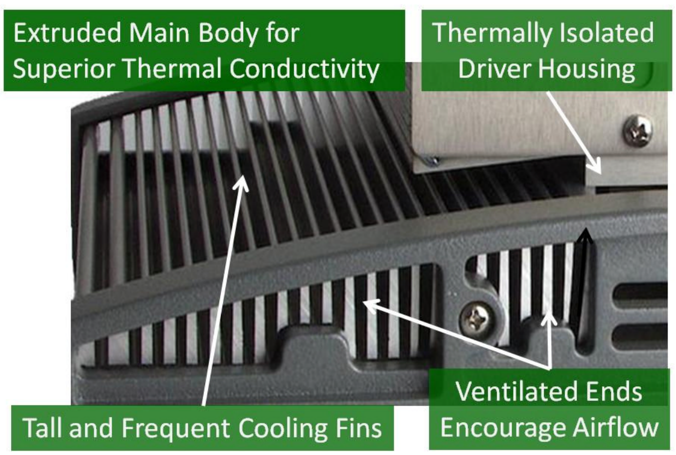


Convection Current

With passive cooling, plenum design relies on the basic principle that heat rises. Upward movement of heated air creates a low pressure that draws in fresh air to equalize the pressure. Robust plenum design provides an entry point for fresh air, a path through the convection surfaces, and an exit path for heated air to escape.



An additional feature of robust convection is surface area; the more the better. Tall and frequent cooling fins effectively maximize convective surface area (shown at right). LED manufacturers usually recommend a minimum of $6in^2$ per LED; the end result is achieved by the combination of the space between the LED's and the geometry (height and frequency) of the cooling fins.



Mentally stretching the heat sink flat and envisioning the final size provides a quick visual for comparing one heat sink to another. Better yet, ask the SSL manufacturer for the actual ratio of square inches of convection surface area per LED.

Many SSL manufacturers take the easy way out here. Incorporating tall and frequent fins makes production of the heat sink, through die casting or extrusion, more difficult.

Too often, we see plenum designs that do not inspire a strong convection current. Some do not provide an ample fresh air intake. Others ignore the space above the heat sink that allows the heated air to exit. In some cases, pre-heated air is re-introduced to the convective surface in a perpetual cycle. In severe cases, heat sinks are trapped inside housings, where the heat-saturated ambient temperature is too high to maintain a Tj conducive to longevity.

Convection current must flow. The SSL must breathe. A sound plenum design will accommodate this.

We know that conductivity and convection work together to achieve robust thermal management. But how do we know when we've achieved our goal? What measurement can we use to determine the effectiveness of our thermal design?

Thermal Resistance

As we know, the longevity of the LED is directly related to its junction temperature (Tj) in operation over time. To recap, the Tj, in operation, is directly proportional to the:

a) load- the rate of heat-energy the LED is generating and
b) capacity- the rate that heat-energy is transferred

In the solid state lighting industry, the measurement of *thermal resistance* encompasses both of these in a single *factor*. The load is directly proportional to the wattage being introduced in the luminaire. The capacity can be considered by the difference between the Tj and the ambient temperature (Ta).

Thermal resistance is calculated using the following formula:

$$\frac{\text{Junction Temperature } (^{o}\text{C}) - \text{Ambient Temperature } (^{o}\text{C})}{\text{System Watts (W)}} = \text{Thermal Resistance } (^{o}\text{C/W}).$$

In reality, there are a number of external factors that affect SSL operating temperature. However, to provide a means for comparison, we standardize these external variables. In a lab environment, we provide a standard ambient temperature of 25^{o}C (76^{o}F), insure a pure (contaminant-free) environment, and air movement is to be induced only by the luminaire.

Like a golf score, the lower the thermal resistance the better. A lower factor means there is a smaller difference between the junction temperature and the ambient temperature. Conversely, a large difference means that heat-energy is building up in and around the junction.

The Tj of an LED is impossible to properly measure *in situ*. So how do we obtain the actual junction temperature in the assembled luminaire?

In exactly the same way the SSL manufacturer calculates the thermal resistance of the luminaire, the LED manufacturer calculates the thermal resistance of the LED. This provides the SSL manufacturer the ability to measure case temperature (Tc) *in situ* (shown right). Then, combining the Tc with the known system watts, we can solve for Tj.

Thermal resistance essentially tells us how easily heat-energy is permitted to move. Once we understand that, we can determine the effectiveness of our design and how changes to various design parameters ultimately affect junction temperature (in a given luminaire).

Having measured the case temperature in situ and calculated the Tj, adding the Ta (ambient temperature), and total system watts, we have everything we need to calculate thermal resistance.

What does thermal resistance do for us? What useful information does it provide?

Applying the Thermal Resistance Factor

To reiterate, the formula for calculating thermal resistance is:

$$\frac{Tj - Ta}{\text{System Watts}} = \text{Thermal Resistance}$$

As in any algebraic equation, having three of the above four variables allows us to solve for the fourth. In application, this allows us to run a number of "what-if" scenarios.

For a simple example, let's say we've measured our thermal resistance. The Tj was 75^{o}C. The Ta was our standard 25^{o}C. Our total system wattage measured 100W. These are the only three parameters we need to know to calculate our thermal resistance.

Plugging these into the formula, we get:

$$[(75^{o}C - 25^{o}C)/100W)] = 0.50^{o}C/W.$$

Now, knowing our thermal resistance factor is 0.5, we can answer the following "what-if's":

- What will our Tj be if the average Ta is 30^{o}C (86^{o}F)?
  - Answer (solving for Tj),
    - ((x-30)/100) = 0.50 ; x = 80^{o}C.
- What if the average Ta increases to 50 ^{o}C (122^{o}F)?
  - Answer (again solving for Tj),
    - ((x-50)/100) = 0.50; x = 100^{o}C.
- How high can the average Ta be while maintaining a maximum Tj of 90^{o}C?
  - Answer, (solving for Ta),
    - ((90-x)/100) = 0.50; x = 40^{o}C (104^{o}F)
- How much power can we drive and have a maximum Tj of 110^{o}C if our average Ta is 30^{o}C (86^{o}F)?
  - Answer, (solving for Wattage)
    - ((110-30)/x)=0.50; x = 160W.

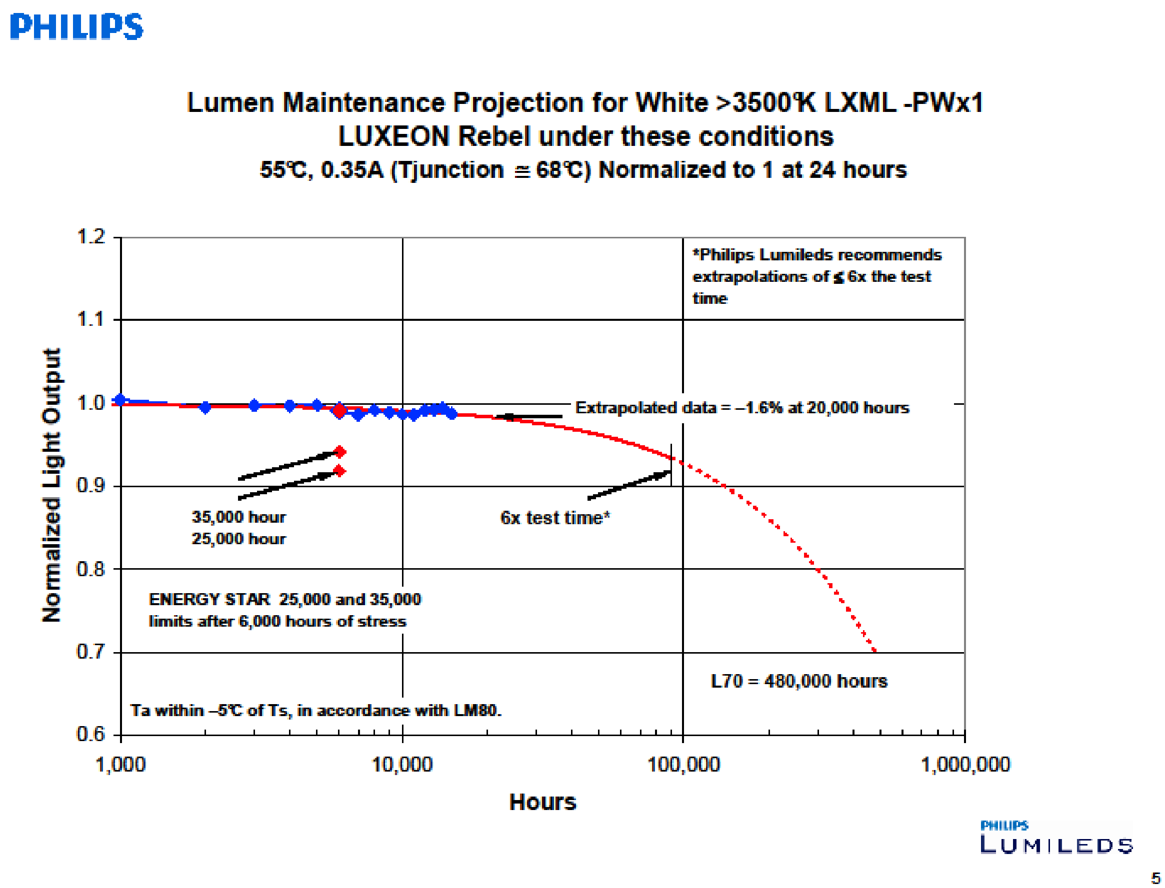
…and so on.

Now, since the Tj is the one variable we wish to manage, how do we decide what Tj is acceptable?

LM-80 Testing; Correlating Junction Temperature to Life Expectancy

To determine the life expectancy and output of a LED relative to Tj, LED manufacturers test their products to the Illuminating Engineering Society (IES) testing method known as LM-80. The results provide the ability to predict output over time relative to Tj.

To create a forecast of LED life expectancy, life cycle testing is performed at various junction temperatures. Each Tj tested provides a result like the following:

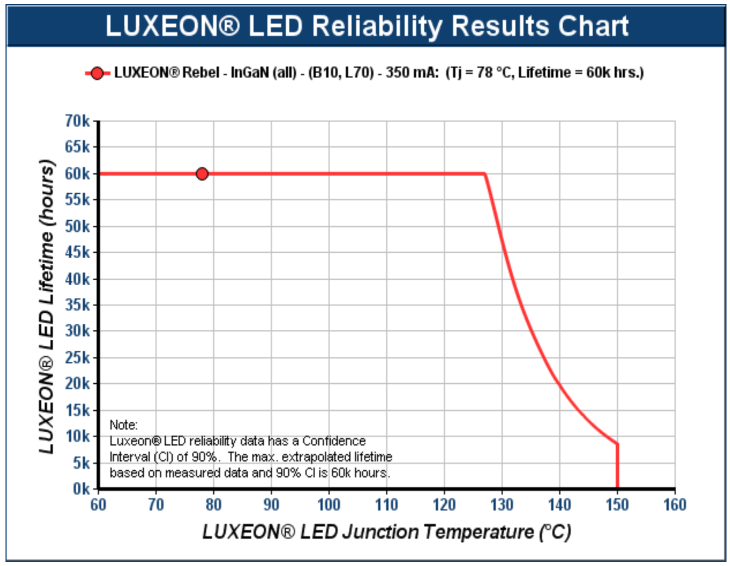


I draw back my bow and let my arrow fly. Though I don't know exactly where it will land, the speed and trajectory of its path (and a bit of Calculus) provide a reasonable guess. Additionally, since the LED has been in existence since 1962, the industry has historical data to draw upon.

In the above, the "6x test time" is where reputable manufacturers draw the line on their predictions. Up to that point, the statistical probability of the prediction is considered sound while predictions beyond that point are generally not accepted in the engineering community.

Since LED technology advances quickly, the LED's used in the high-powered SSLs on the market today haven't yet been in existence for very many hours. So, if the LED has only 10,000 hours of testing, and LM-80 testing accepts a 6x factor, where do the promises of 100,000 hour life expectancies come from? The consumer should ask that of any SSL manufacturer claiming greater than 60,000 hours and they should never be accepted if they are beyond those of LM-80 projections.

As you can see in the title bar of the chart on the previous page, that particular result is from testing at 68°C Tj. Tests are conducted at various Tj's to develop the chart shown at right. Here again, though logic says the curve will not hit a wall at 60,000 hours, there is no industry-accepted data to support a projection beyond the 6x testing. (As a result, the projection is capped at 60,000 hours.)



With this chart, we can see that, above 128°C Tj, life expectancy of the LED drops quickly. With this in mind, let's revisit thermal resistance.

Earlier, our second example showed us that the thermal resistance of our hypothetical luminaire allowed us to get to an ambient temperature of 50°C while maintaining a junction temperature of 100°C. Referencing the above chart, we can see that the life expectancy for a 100°C Tj is still beyond the 60,000 hour mark.

Also (still assuming the 0.5°C/W thermal resistance), with the ambient 25°C used in the chart, we can ask, "How much wattage can I drive and still maintain a Tj of 128°C"?

The answer: (128-25)/x = 0.5; x = 206W

We've determined we can drive our luminaire (in a Ta of 25°C) up to a maximum of 206W and be at a junction temperature of 128°C; at that Tj we still achieve our 60,000 hour life[7].

Just how much the real world environment affects thermal management is difficult to determine. We do know that various geographical locations will affect Tj differently, and that the most difficult environments are those that are hot and dusty (such as in the Southwest). For a SSL to perform well in those areas requires exceptional thermal management. This of course means overdesigning for the cooler climates or providing different products for different parts of the world. (Very few, if any, SSL manufacturers are willing to even consider the logistics associated with the latter.) As a result, every SSL should be designed for the most extreme environment in which they are to be used.

Determining if our SSL is suitable for extreme environments can only truly be achieved in field studies over time. Comparing the theoretical to the actual, we develop the relationship between the two. Once the SSL manufacturer understands this relationship and adjusts to a conservative safety margin, the importance of minimizing thermal resistance becomes all the more clear.

Summary

While there are numerous factors to be considered in SSL selection (i.e. price, quality, uniformity of light distribution, power consumption, etc.), robust thermal management assures one of the most important benefits of the technology, light output over time.

Thermal management of the SSL can be as simple or complex as we want. In practicality, it comes down to the manufacturer having selected materials and processes that render thermal integrity in a geometry that supports conduction and convection.

With the information outlined here, a lot of what makes a robust thermal design can be determined simply by looking at the SSL. Does the design provide a sufficient convection current (air flow) or are there limited fresh air vents? Are the LEDs well-spaced or crammed together? How tall and frequent are the heat sink fins, how many in^2 per LED? Does the product incorporate materials into components using thermally robust manufacturing processes? Is there sufficient heat sink mass?

Other factors can't be seen with the naked eye. Are metal core PCB's and/or thermally conductive pads/epoxies used? Which LED manufacturer's product is being used? Can I obtain their LM-80 data? What is the thermal resistance of the SSL?

The ability to recognize a thermally robust product design moves us one step closer to determining design quality. Optimally, since it is not feasible to expect the consumer to measure data (such as thermal resistance), in situ junction temperature testing and reporting should be an industry requirement. However, since it is not, understanding how thermal resistance is calculated, what we can do with the resulting factor (^{o}C/W), and cross-referencing that the LED manufacturer's LM-80 data, the consumer can separate the true from the unfounded longevity claims.

(1)Technically, there is no such thing as cold, only the absence of heat.

(2), (3) Though technically a form of heat transfer, these two types of thermal management are commonly referred to as *active cooling* and *passive cooling*.

(4) Though life expectancies should not be projected to more than 10x actual LED test hours, SSL's may run for 100,000 or more hours.

(5) Chart compiled from information found at www.wikipedia.org

(6) Computation based upon calculated specific gravity resulting from die casting and extrusion processes for like products.

(7) Laboratory results should not be construed as recommended for field applications. "Environmental conditions" encompass temperature, humidity, air movement, potential chemical contaminations, wildlife, and more.