XICATO

# Application Note - Heatsink Design

*Version 20120529*

## *Background*

Thermal management is a crucial ingredient in the design of a luminaire used in solid state lighting (SSL). Light output, reliability, and lifetime increase as LED junction temperature ($T_j$) decreases. Module case temperature ($T_c$) has been correlated to $T_j$, and therefore, it is very important to keep $T_c$ of the Xicato module below 90ºC. To assist with thermal management, Xicato has designed several reference heatsinks (HS) that customers can integrate into their design. See the Thermal Class Matrices on the 'Members Lounge' at www.xicato.com for more information on pairing different Thermal Classes with various standard HS.

It is also possible, however, to design the luminaire such that the luminaire itself acts as the HS. When designing a luminaire that also acts as HS, several factors must be taken into consideration, including:

1. Natural convection flow patterns
2. Luminaire orientation
3. Operating environment
4. Material selection

In order to assist in the thermal design, Xicato can run thermal simulations on the luminaire and provide feedback and recommendations for improvement, if necessary. See "Thermal Simulation Request Form" on the 'Members Lounge' or contact your Xicato representative for more information.

## *Modes of Heat Transfer*

The three modes of heat transfer are conduction, convection, and radiation. All three modes play an important role in the thermal management of LEDs.

Conduction is the transfer of heat between adjacent molecules, usually within a solid. Conduction through a solid is described by the following.

Equation 1: $q=k\cdot A\cdot \Delta TcondL$

Where: q is the rate of heat transfer [W]

k is the thermal conductivity of the solid [W/m·K]

A is the cross sectional surface area [$m^2$]

$\Delta T_{cond}$ is the temperature delta across the solid [K]

L is the distance heat is traveling through the material [m]

The higher the thermal conductivity (k), the more heat is transferred across the solid.

Material recommendations are made later in this report. Also note that as the length (L) gets longer, the rate of heat transfer reduces. **<u>This implies that long narrow heatsinks are less effective than short wide heatsinks.</u>**

Convection is the transfer of heat from one place to another by the movement of a fluid. In a luminaire application, the heat is transferred from a solid (the HS) to a fluid (usually air). Convective heat transfer is governed by the following equation.

Equation 2: $q=h\cdot As\cdot \Delta Tconv$

Where: h is the heat transfer coefficient [W/m$^2$·K]

$A_s$ is the surface area of the heat being transferred [m$^2$]

$\Delta T_{conv}$ is the temperature delta between the solid and the surrounding air [K]

Rearranging, it is clear that as q (or heat load) increases, $A_s$ must also increase in order to maintain the same $\Delta T_{conv}$, assuming a constant heat transfer coefficient. **<u>Thus, the surface area of the heatsink is very important in order to extract the heat out of the HS.</u>** Rearranging Equation 2, surface area can be described as:

Equation 3: $As=qh\cdot \Delta Tconv$

Thermal radiation is energy emitted by matter that is at a finite temperature. Radiative exchange between bodies is complicated and difficult to solve analytically. The following describes a simplified equation for "gray bodies", or a body that obeys Kirckoff's Law ($\varepsilon=\alpha$).

Equation 4: $q=\varepsilon\cdot\sigma\cdot A\cdot Ts4-Ta4$

Where: $\varepsilon$ is surface emissivity

$\sigma$ is the Stephan-Boltzmann Constant, $5.6703\cdot 10^{-8}$ [W/m$^2$·K$^4$]

$T_s$ is the surface temperature [K]

$T_a$ is the surrounding ambient temperature [K]

Emissivity provides a measure for how a surface emits energy compared to a blackbody (100% emitter). Because the Stephan-Boltzmann Constant is so small, the difference between $T_s$ and $T_a$ must be large in order for radiation to be a large contributor to heat transfer. **<u>Typically, radiation is not a large factor to heat transfer in LED cooling applications.</u>**

## *Design Considerations*

### *Natural Convection*

Natural convection occurs in the absence of forced fluid flow, such as wind, HVAC, or an active thermal solution such as a fan. Natural convection is heat transfer that occurs due to fluid flow that is induced by buoyancy forces that arise from density differences caused by temperature variations in the fluid.

In simple terms, it is heat transfer due to fluid flow (in our case, typically air) that is generated by the difference in density of air at different temperatures. Warm air is lighter (less dense) than cool air. As the air heats up around the HS, it becomes lighter and rises. As it moves away from the HS, it cools down, becomes heavier, and sinks. It then gets heated by the HS again, and the cycle continues. All the while, the HS and module are cooled as heat is transferred to the air. This cycle is shown in Figure 1.

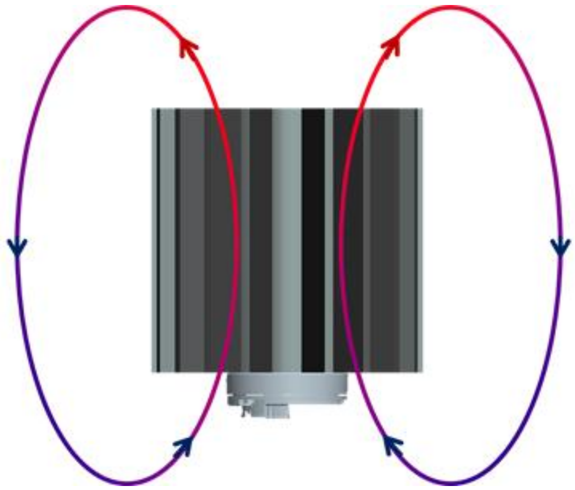

*Figure 1 – Natural convection*

Since natural convection is greatly affected by air density, and density is a function of gravitational pull, contact your Xicato representative when designing a luminaire for use in atmospheres other than Earth.

Fins are used in order to increase the surface area available for heat transfer. As can be seen in Equation 2, for the same heat transfer coefficient and temperature difference ($T_s$ heatsink to $T_a$ ambient) $\Delta T$, the higher the surface area, the more heat is transferred across the $\Delta T$. Up to a point, increasing surface area of a HS leads to decreased module case temperature. However, for a finned HS, increasing surface area can decrease heat transfer coefficient due to the restriction in the amount of fluid that can pass between the fins i.e., fins spacing is too close. Thus, surface area and heat transfer coefficient must be balanced in order to design an effective HS. Xicato can help achieve this balance through thermal simulation.

### *Forced Convection*

Forced convection occurs in the presence of forced fluid flow, typically induced by a fan or some other air-moving device. Since forced convection, or active cooling, is complicated in its own right, and requires different design considerations than systems cooled by natural convection, a separate Application Note has been written to cover active cooling. Refer to the Application Note “Designing Around an Active Heatsink” for more information on active cooling solutions.

### *Luminaire Orientation*

HS orientation is critical to module case temperature as the following demonstrates.

In order for heat to be effectively transferred from the HS to the air, the HS should be designed such than the HS fins run parallel to the airflow (or in other words, parallel to gravity). This is not always possible, and if the luminaire is able to rotate to different orientations, the fins may not be parallel to gravity for all orientations. The goal, however, should be to align the fins as close as possible to the vertical direction.

To demonstrate this point, consider the downlight in Figure 2. The left view is of the HS in a 0° orientation (parallel to gravity), which is the best-case orientation for this design. More airflow passes through the fins in this orientation because the fin channels are aligned parallel to gravity. The center and right views are of the HS in a 90° orientation (fin channels aligned perpendicular to gravity). Only the lower fins received good airflow in this orientation.

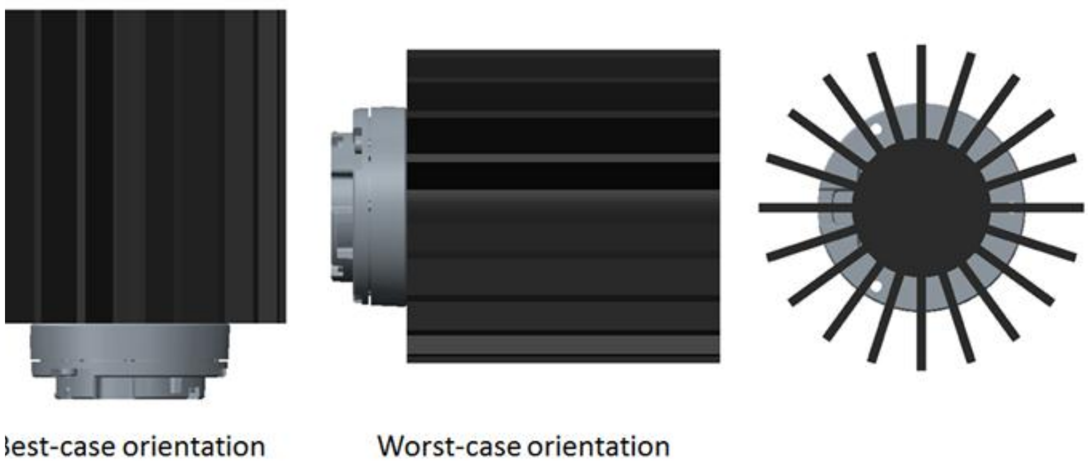


*Figure 2 – Preferred fin direction for 0° orientation*

Figure 3 is an example of a poor HS design for a 0° orientation (relative to the vertical plane). The fins are aligned to be perpendicular to gravity and a significant amount of air will not flow in between the fins. Therefore, this HS design does not take advantage of its entire surface area.

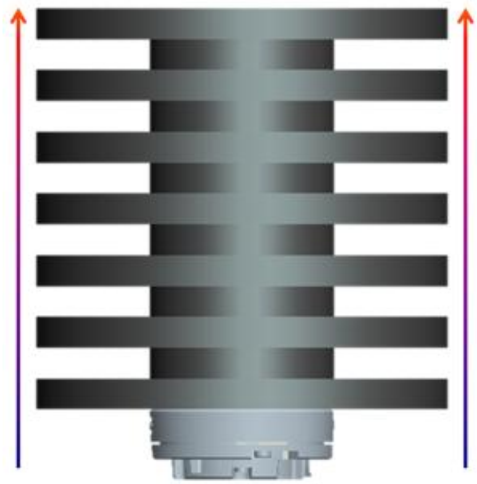

*Figure 3 – Poor fin design for 0° orientation*

If the HS were to be oriented 90° to vertical, it would be a much better HS design, as shown in Figure 4. Note that this is not to say that the HS oriented at 0° will not work thermally, but it is less likely to do so, and would result in a higher $T_c$ than in the 90° orientation.

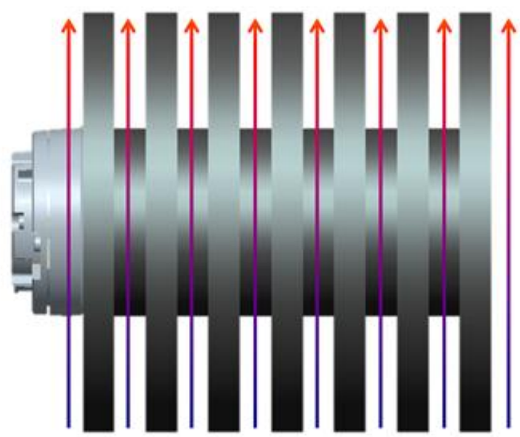

*Figure 4 – Good fin design for 90° orientation*

Figure 5 shows that this HS design may be good for a 45° orientation. Air would flow up into the channels between fins and remove heat as it rises. Thermal analysis or testing would need to be performed to determine whether or not the HS would pass in this and all orientations.

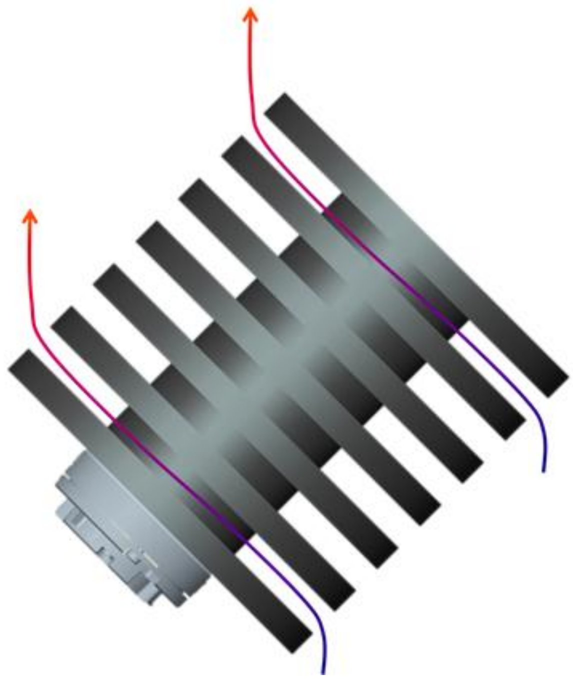

*Figure 5 – Possible good design for 45° orientation*

Depending on the most common orientation, a HS like that in Figure 4 **may** be preferred over the HS in Figure 2 for a 90° orientation, or vice versa in a 0° orientation. When a HS has a wide range of orientation, it is best to consider the worst-case orientation for luminaire validation.

Another type of HS design is the pin-fin HS. Figure 6 shows a typical pin-fin HS design. Based on research of the pin-fin HS market, HS heights above 50mm are usually not available without special ordering a taller design.

Pin-fin heatsinks typically have a worst-case orientation of 0°, while 90° is actually the best-case orientation. The reason for this is due to the fin design. In a 0° orientation, very little air flows into the center fins, reducing the effectiveness of these fins. In a 90° orientation, air flows through all fin channels very easily. Because of this, the more the heatsink tilts from vertical, the better the heatsink performs, which is the exact opposite behavior of a typical extruded heatsink. Pin-fin heatsinks can be a great choice for adjustable luminaires but usually are not the best choice for a fixed downlight, though the difference in case temperature between best and worst-case orientation is typically not as dramatic as it is with extruded heatsinks.


*Figure 6 – Pin-Fin heatsink orientation*

### *Operating Environment*

Another factor that must be considered is ambient temperature. The ambient temperature is the temperature of the air around the HS. An increase in ambient temperature increases case temperature by essentially the same amount. For example, say the module $T_c$ is equal to 85ºC at a 35ºC ambient. If the ambient increases to 40ºC, the module $T_c$ would increase to 90ºC.

The ambient temperature in an open environment is typically not dramatically affected by the heat that is dissipated from the module. If, however, the luminaire is located inside an enclosed box, the ambient temperature will increase as the module runs. If a HS is inside an enclosed box, it may be beneficial to thermally couple the HS to the box. In other words, make the box a part of the HS by having a physical connection between the module and the box. Another possible solution is to vent the box so that air can flow in and out of the confined space. These are not always possible, but may help reduce module $T_c$.

Another alternative is to design the HS to be larger than it would otherwise be if it were no in an enclosure. For more information on designing in an enclosure, see the Application Note “Heatsinking in an Enclosure”.

The typical environment designed to is a 40ºC ambient temperature. Your specific requirement may or may not be 40ºC. Supporting an ambient higher than 40ºC is possible with a carefully designed luminaire. Supporting 50ºC or higher may be possible as well, with an appropriately designed HS.

### *Material Selection*

Several factors should be considered when selecting a HS material, including (1) thermal conductivity, (2) weight, (3) cost, (4) ease of fabrication, and (5) surface finish.

Table 1 shows thermal conductivity for various materials.

| Material | Thermal Conductivity (W/m·K) | Density ($kg/m^3$) |
|---|---|---|
| Stainless Steel | 15 | 8055 |
| Iron, Pure | 80 | 7870 |
| Aluminum A380 Cast | 96 | 2700 |
| Aluminum ADC6 Cast* | 130 | 2700 |
| Aluminum 6063* | 200 | 2700 |
| Copper, Pure | 401 | 8933 |

* Recommended by Xicato

*Table 1 – Thermal conductivity of some materials*

Copper has a high thermal conductivity but it is also much more expensive and heavier than aluminum. Because aluminum is less expensive than copper and still has a relatively high thermal conductivity, it is the most common material choice in HS design. Additionally, aluminum is light, strong, and accepts many finishes (for aesthetic and radiative heat transfer purposes).

Two types of fabrication processes are common for HS design: extrusion and casting. Extrusion is the process of creating objects of a fixed cross sectional profile by pushing a material through a die of the desired cross section. Casting is a manufacturing process where a hot liquid is poured and subsequently cooled in a mold that contains a hollow cavity of the desired shape.

The extrusion process is ideal when the HS has a constant cross sectional profile. It is most common, however, that a luminaire that also acts as HS will not have a common cross section, making casting the more popular method.

Al 6063 is the recommended material for an extrusion. Al ADC6 Cast is recommended when casting is used. Note that there can be a significant difference between generic cast aluminum and one that is carefully selected for its thermal properties. For example, compare the thermal conductivity of Al ADC6 and A380 (see Table 1). Also compare the thermal conductivity of Al ADC6 and 6063. Because the thermal conductivity of Al 6063 is higher than that of Al ADC6 and other cast alloys, extruded heatsinks usually perform better from a thermal standpoint than a similar size cast HS.

Lastly, surface finish should also be considered. Table 2 shows a wide range of emissivity for several common aluminum surface finishes. A high emissivity surface may reduce module case temperature by a few degrees at high enough temperatures.

| Finish | Emissivity |
|---|---|
| Polished | 0.04 |
| Rough | 0.07 |
| Painted | 0.27 – 0.67 |
| Anodized | 0.77 |
| Blackbody (ideal) | 1 |

*Table 2 – Emissivity of common Aluminum surface finishes compared to the blackbody*

## Heatsink and Luminaire Design

### Reference HS Design

The HS shown in Figure 1 is one of Xicato's reference HS designs (XSA-38). As an example, a thermal simulation was run for a Thermal Class G module at a 45° orientation and 40ºC ambient temperature[1]. The results from this simulation are shown below.

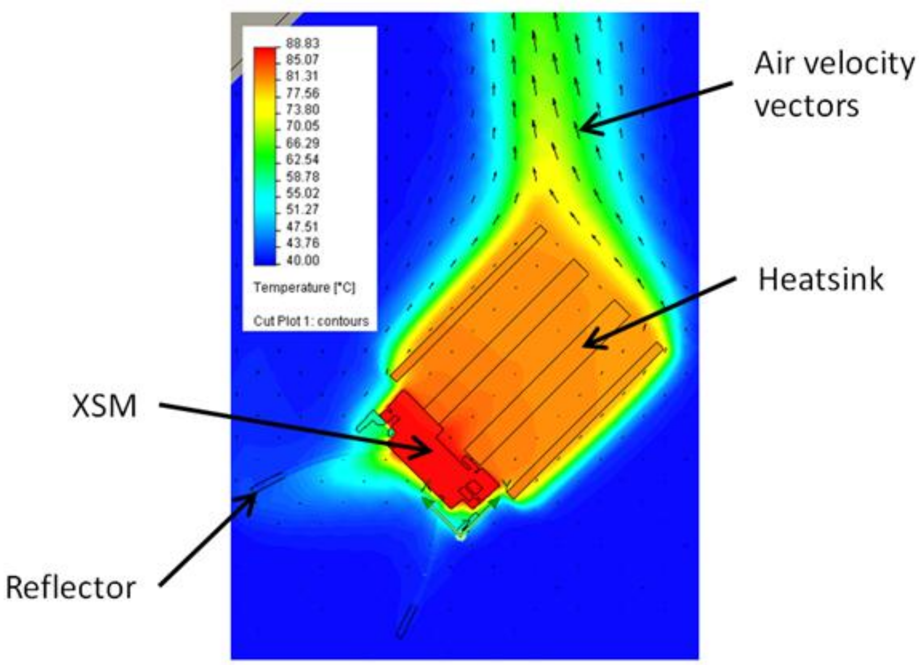


*Figure 7 – Temperature distribution and air velocity for Xicato reference HS*

The case temperature is just below the 90ºC maximum $T_c$ specification, and this module is supported by the XSA-38 HS.

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[1] For more information on Thermal Classes, contact your Xicato representative.

### *Example Luminaire as Heatsink Design*

As mentioned previously, the luminaire can be designed such that it acts as the HS, eliminating the need for the reference HS. The design is shown in Figure 8.

*Figure 8 – Example Luminaire as HS design*

The airflow pattern for this HS is shown below.

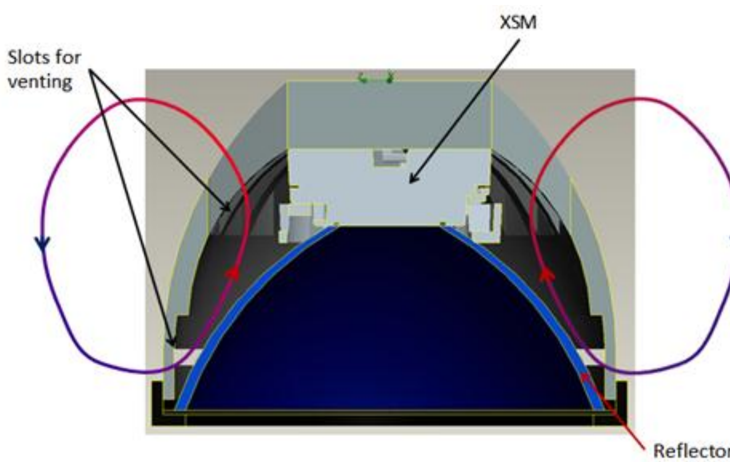


*Figure 9 – Airflow pattern for example luminaire*

Notice that the slots in the luminaire serve to create fins that improve HS thermal performance. Also note that an opening in the bottom of the luminaire is needed to allow fresh air to travel into the HS. If the slots at the bottom of the luminaire were not present, this would be a poor HS design, as very little air would flow through the fins and cool the module.

The HS was simulated for a Thermal Class G module at a 45° orientation and a 40ºC ambient temperature. The results are shown below.

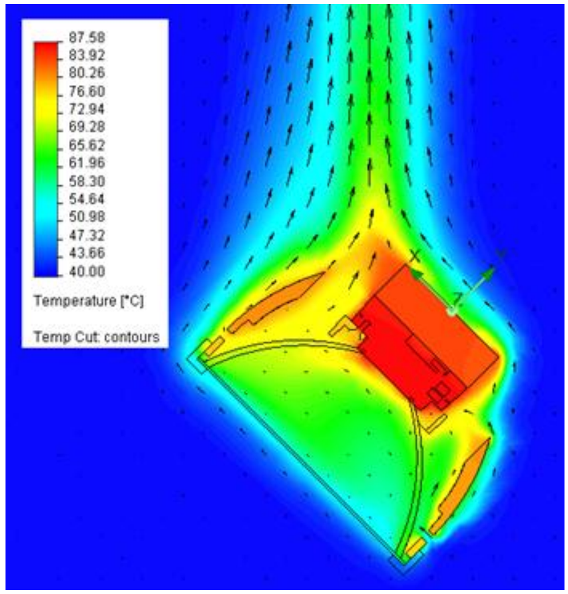


*Figure 10 – Temperature distribution and velocity for example luminaire*

The results for this HS are similar to those of the Xicato reference HS XSA-38. This luminaire meets thermal requirements, and is a suitable design for a Thermal Class G module.

Note that the luminaire described in this section is a simplified luminaire and is only shown as an example of how to incorporate thermal management into the luminaire design. An actual luminaire may be much more complicated, as mechanical, aesthetic, size envelope, and other factors need to be taken into consideration. Xicato encourages our partner fixture manufacturers to work directly with us via thermal simulation to optimize luminaire designs.

## *Fin Blockage*

The Xicato reference heatsinks were designed to meet the maximum XSM $T_c$ for optimal flow through the fins. When using a reference HS, care should be taken to ensure that the top and bottom of the HS is open to the environment. In the example below, a cover was placed over the top of XSA-38 and a thermal simulation was conducted with a Thermal Class G module.

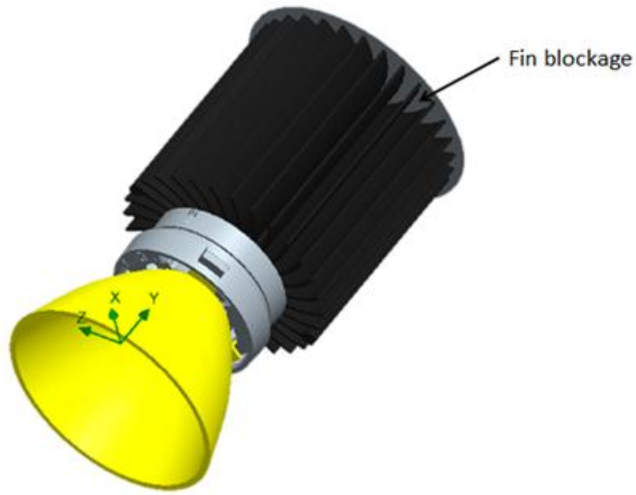


*Figure 11 – HS with top covered*

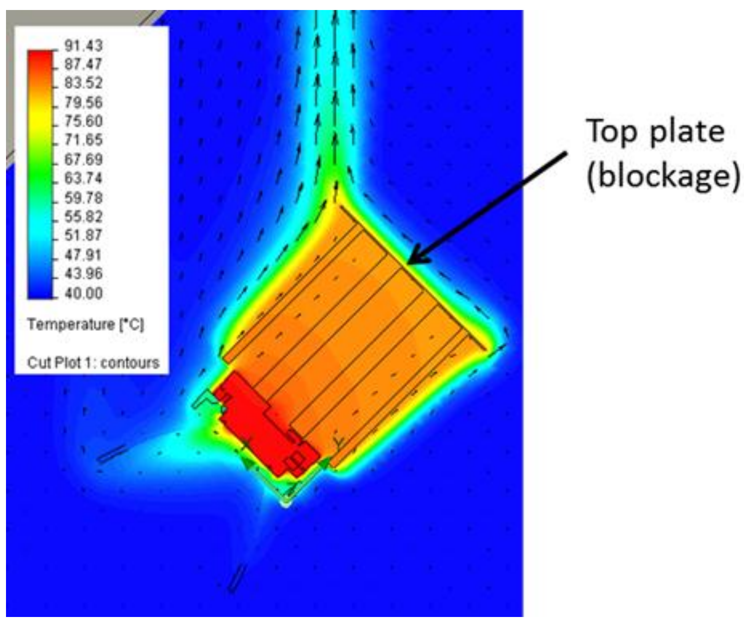


*Figure 12 – Temperature distribution and velocity for Xicato HS w/ top covered*

The module case temperature shown in Figure 12 covered is almost 3ºC higher than that in Figure 7, which is the same HS without any blockage. Tc is significantly impacted, and the module potentially goes from passing to failing under the guidelines set by Xicato's Luminaire Validation Program[2]. If a top plate is absolutely necessary, cutting slots or drilling holes to allow hot air to escape may reduce module temperature.

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[2] For more information on the Luminaire Validation Program, visit the 'Members Lounge' or contact your Xicato Representative.

## *Heatsinking Inside an Enclosed Track Luminaire*

Often, the heatsink, module, and reflector are placed inside a 'can'. This is typical of a track spot application. Airflow patterns through the heatsink are quite different when in free-air and when installed inside a 'can'. See the following figure for an example.

*Figure 13 – Module, heatsink, and reflector in free-air and inside a can*

When wrapping the heatsink inside a 'can', air cannot easily flow into the heatsink fin channels. Since airflow is critical to heatsink performance, it is essential that venting is created on the front-end and the back-end of the 'can'.

On the front-end, it is recommended to add a gap between the inner diameter of the 'can' and the outer diameter of the reflector. Additionally, venting can be added to the side of the 'can' at the front of the luminaire as shown below.

On the back-end, venting should also be added. The simplest way to do this is to allow the back to be completely open. If this is not feasible, for aesthetic or other reasons, venting can be accomplished by creating a grated venting pattern similar to that shown in the following figure.


*Figure 14 – Possible venting options for an enclosed track spot luminaire*

There are many different options available for venting, depending on personal preference. One way or the other, venting must be incorporated into the design.

Another option is to make the ‘can’ a part of the heatsink. This is described above in the section “Example Luminaire as Heatsink Design”.

## *HS in an enclosure*

Special design considerations must be taken into account when designing a luminaire inside of an enclosure (e.g., an IC fixture or an fixture inside a concrete enclosure). Because of the added complexity of designing with an enclosure, see the Application Note “Heatsinking In An Enclosure” for more details.

## *Thermal Interface Material*

In order to improve thermal contact between the module and the heatsink, a thermal interface material (TIM) should be used between these two surfaces. All Xicato products (XSM, XPM, and XLM) are shipped from the factory with a thermal pad pre-attached. This provides for an easy, clean, and reliable thermal interface between the module and the surface to which the module is attached.

For reference, Xicato uses eGRAF HT-1205A. The product data sheet can be found on the ‘Members Lounge’, or alternatively at www.egraf.com.

## Heatsink Surface Flatness

Because the eGRAF thermal pad is of finite thickness, care needs to be taken in order to ensure appropriate contact between the module and the heatsink.

Suppose that the difference in surface flatness between the module and the heatsink is greater than the thickness of the thermal pad. The thermal pad is 5 mil (0.005" or 0.127mm). If the difference in flatness is greater than 5 mil, there is the potential that the heatsink and the module don't make contact with each other in all places. If this were to happen, thermal performance could be greatly impacted, resulting in higher than expected Tc. To avoid any such possibilities, it is recommended that the surface flatness of the heatsink be no greater than 50 micron.

Note that the surface flatness callout on all Xicato reference heatsinks is 50 micron.

## Conclusions

Thermal management is critical to the design of SSL luminaires. To assist in the thermal design, a Xicato reference HS can be used in conjunction with the Thermal Class Matrix.

Additionally, the luminaire itself can be designed such that it is used as part of the thermal solution. To summarize, the three most important factors to consider when designing a luminaire that uses a passive thermal solution are:

1. Orientation and natural convection flow patterns
    a. Proper fin alignment
    b. Proper ventilation
2. Operating environment
3. Material selection
    a. Thermal conductivity
    b. Weight
    c. Cost
    d. Fabrication
    e. Surface finish

Once an initial luminaire has been designed, Xicato can run a thermal simulation and determine pass/fail and provide feedback for design improvement. In order to submit a simulation request, download the Thermal Simulation Request and Definition Form from the 'Members Lounge' and submit to thermal.sim@xicato.com.