Thermal Management of High Brightness LEDs at the System Level

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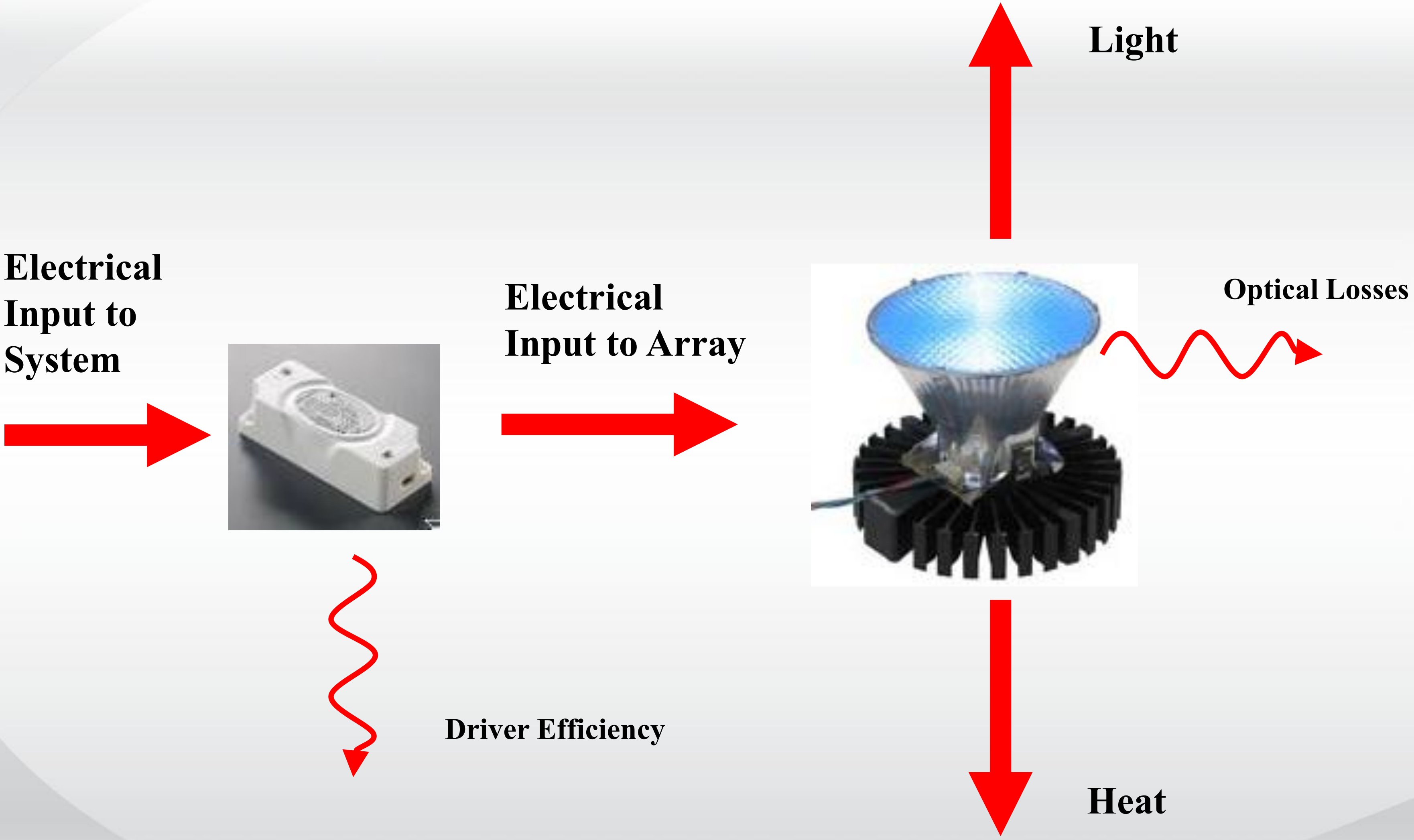
LEDs for Illumination – a paradigm shift

- Traditional incandescent light sources are very inefficient, however most of the wasted heat energy is radiated from the bulb

- LED light sources are very efficient, however most of the wasted heat energy is conducted from the package

System Energy Equation



Electrical Input to System

Electrical Input to Array

Light

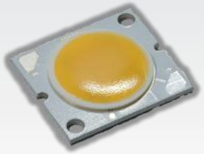
Optical Losses

Driver Efficiency

Heat

LED arrays vs. LED emitters – Thermal Perspective

- **Different thermal resistance**
  - In application, Bridgelux arrays have one less thermal interface that emitters
  - The thermal path (distance and thermal conductivity) are different due to different package construction
- **Different die to die spacing**
  - Smaller surface area for same lumen output with arrays
  - More concentrated heat source with arrays
- **Materials compatibility - coefficient of expansion**
  - Arrays use compatibility materials and wire bonding technology 'pre-engineered'
  - Emitters users must consider substrate materials and solder joint properties 'customer engineered'



vs.

Importance of Thermal Management

Most problems in an LED lighting solution are caused by poor thermal management

Importance of Thermal Management

- Flux changes with temperature ⬇
- Vf changes with temperature ⬇
- Color changes with temperature ⬆

To optimize the performance of a luminaire, proper thermal management is essential

The effect of case temperature on the LED operation AT LUMINARE OPERATING TEMPERATURE must be considered before finalizing the design

System Margins – Example

System Specification: Energy Star

575 lm Minimum	40 lm/W Minimum	15 W Maximum

	Best Case Scenario	Typical Case Scenario
Driver Efficiency	80%	75%
Optical Efficiency	90%	85%
Thermal Efficiency	90%	85%
Guard Band	0%	5%
Array Efficacy	60 lm/W	**75 lm/W**

There are MULTIPLE ways to achieve target specification.
The best designs aim to optimize ALL aspects.

Thermal Design Process

From the system requirement specification

1. Determine physical dimension constraints & aesthetic goals
2. Determine temperature constraints
3. Determine orientation
4. Calculate the power
5. Consider passive or active airflow designs
6. Select thermal interface material
7. Calculate system thermal resistance
8. Design heat sink
9. Perform computer simulation of design – verify within design limits
10. Build prototype
11. Test prototype – verify within design limits

1. Thermal Design Process: Physical Dimensions

Is there a pre-determined size?

Is the design intended for drop-in replacement of current fixture?

Is there a market standard? Ex. MR16, A19, PAR 30.

2. Thermal Design Process: Temperature Constraints

Efficacy considerations:

•Light output decreases with temperature

Lifetime:

- Lifetime decreases with increased temperatures
- Bridgelux recommends maintaining a Tcase below 70 °C

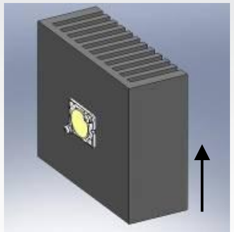
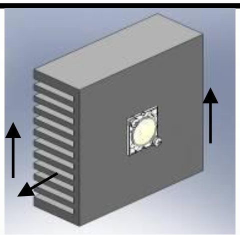
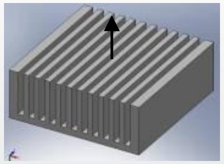
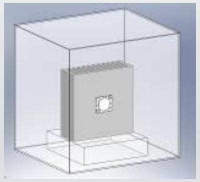
Color shift:

•CCT shifts slightly with temperature variations

Ambient:

- An accurate ambient temperature assumption is critical to proper thermal design

3. Thermal Design Process: Orientation

Fin Orientation	Illustration	Guideline
		Typical Relative Effectiveness
Vertical		100%
Horizontal		85%
Horizontal Down		60%
Vertical (Inside a 6 x 7 x 7 in^3 Non-Conducting Box)		–

4. Thermal Design Process: Power Calculation

Rule of Thumb:
The thermal management system should be designed for 85% of the total LED array input power

$$Q = (V_f * I_f) * 0.85$$

- Q is the thermal power dissipated (approximately the heat that needs to be managed)
- V_f is the forward voltage of the device
- I_f is the current flowing through the device

CAUTION: Other heat generating sources (i.e. Driver) may need to be considered and added into the total heat load.

4. Thermal Design Process: Typical Application Power Ranges

Application	Bulbs	Down Light	Street Light
LED Power Range	4 – 15W	12 – 50W	50 – 200W

5. Thermal Design Process: Passive Heat Sinks

In thermal design, SURFACE AREA should be defined as the sum of all thermally conductive surfaces which are exposed to the ambient environment.

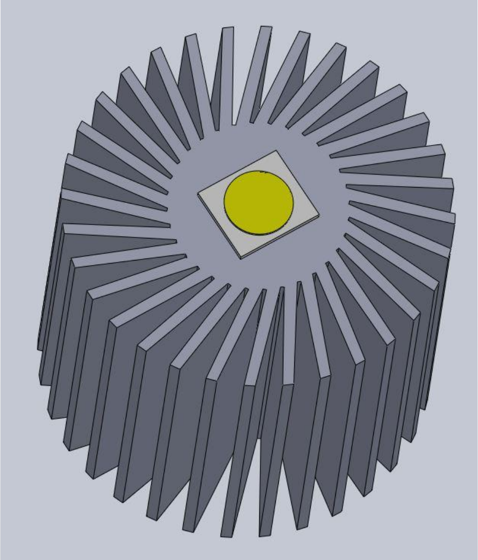
When relying on natural convection to transfer heat to the ambient the minimum required surface area for an aluminum heat sink is 10 in^2 per watt (or 64.5 cm^2 per watt) of dissipated power.

CAUTION!!!

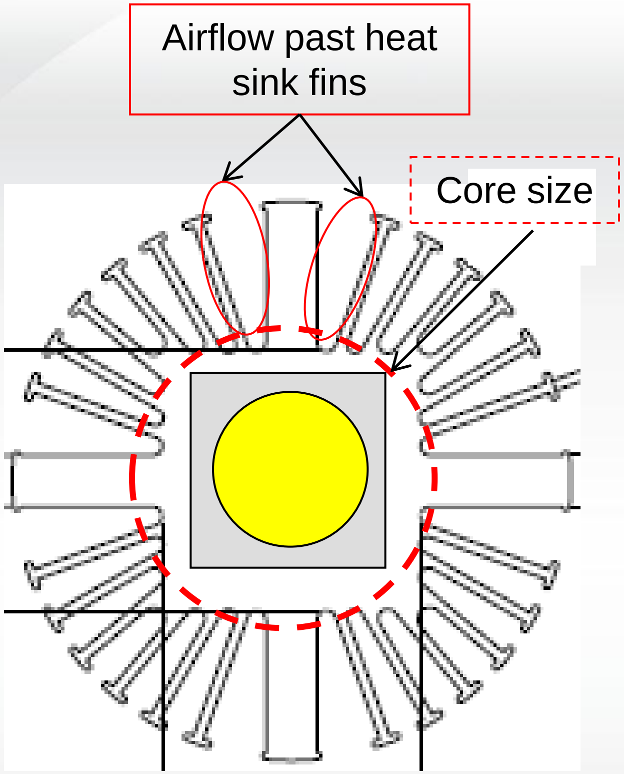
Without airflow, a heat sink fin is rendered useless.

3. Thermal Design Process: Radial Heat sinks

- Radial heat sinks allow for good airflow when lamps are placed in a vertical orientation.
- Utilizing a radial design can improve the efficiency of a thermal system and reduce cost



5. Thermal Design Process: Airflow



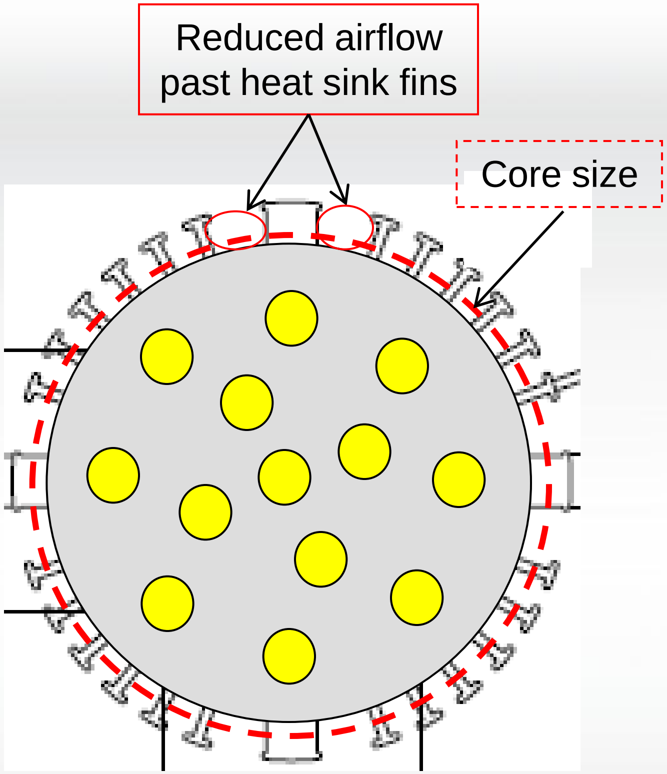
Airflow past heat sink fins

Core size

LED Array

Key Concepts

- A smaller source size leads to increased airflow
- Smaller source leads to a smaller heat sink core
- Heat sink cost reduction



Reduced airflow past heat sink fins

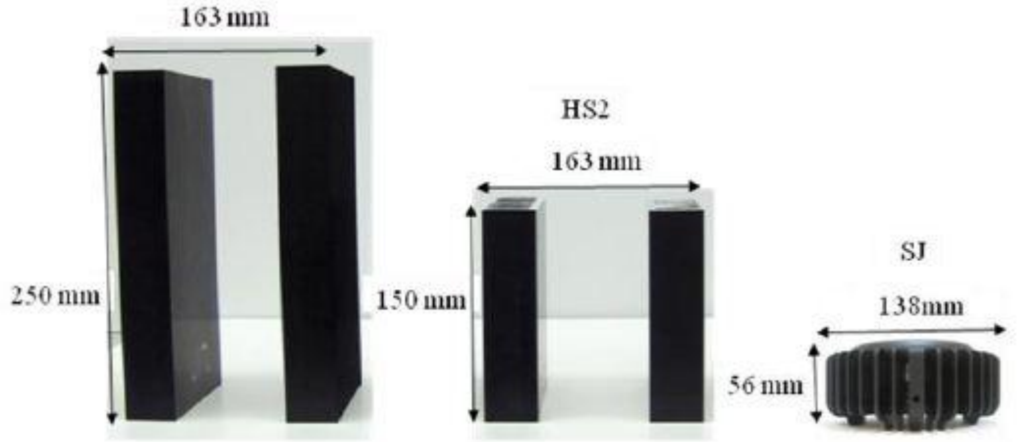
Core size

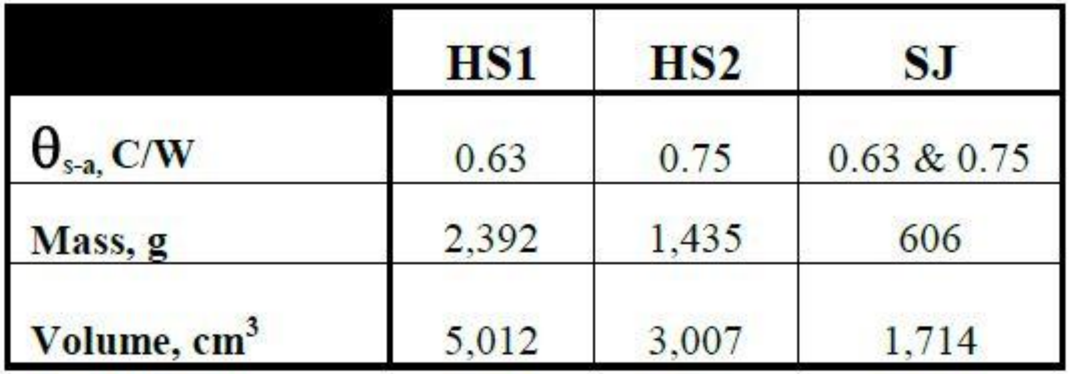
LED Emitter

5. Thermal Design Process: Forced Convection

KEY CONCEPTS:

- Physical dimension reduction
- Material volume reduction
- Cost parity with for high wattage systems





	HS1	HS2	SJ
$\theta_{s\text{-}a}$, C/W	0.63	0.75	0.63 & 0.75
Mass, g	2,392	1,435	606
Volume, cm^3	5,012	3,007	1,714

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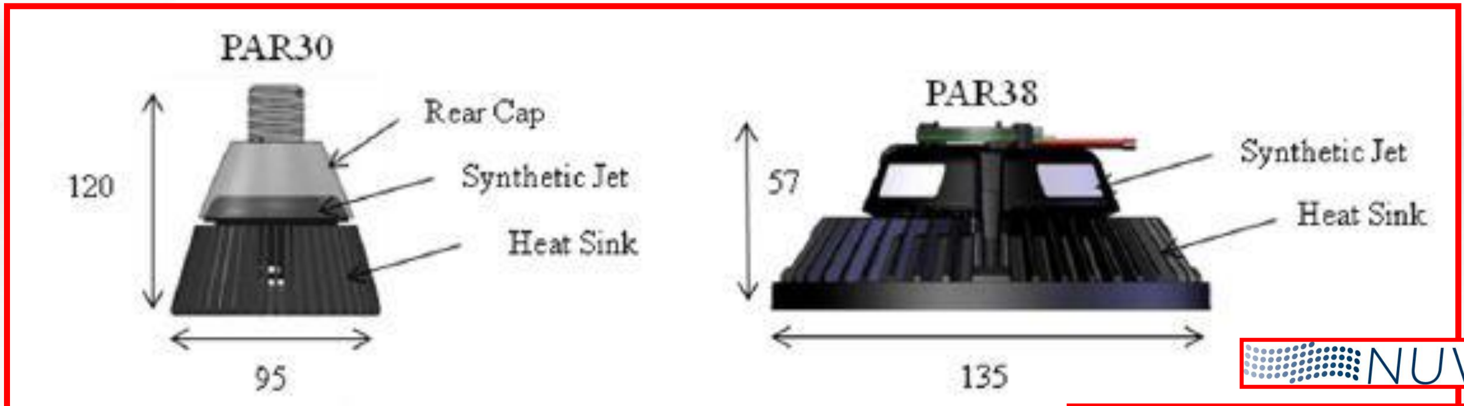
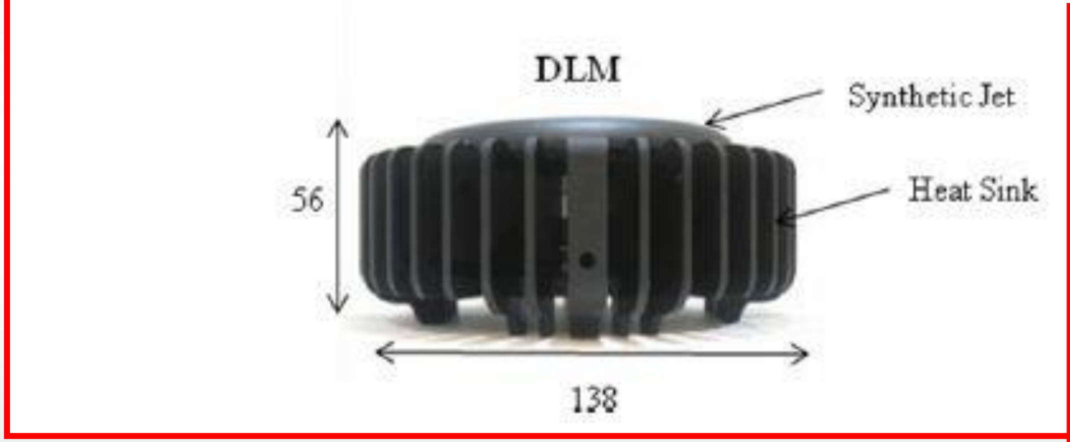
5. Thermal Design Process: Forced Convection





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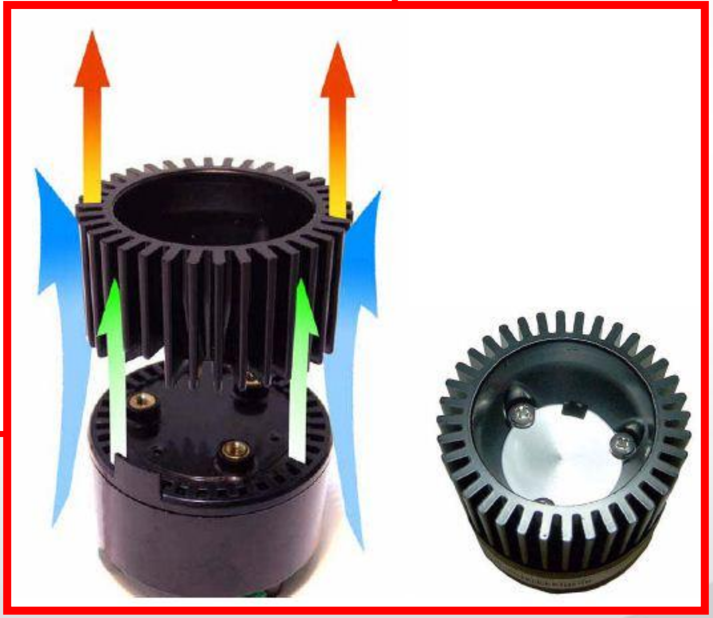
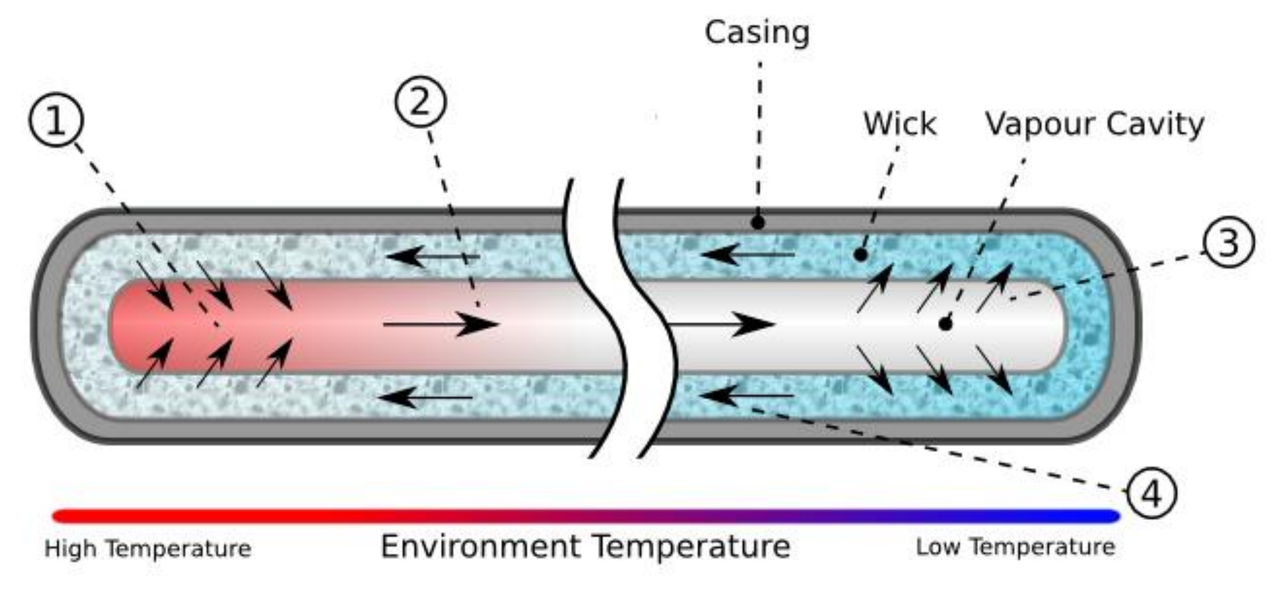


- Forced convection, aka “Active”, thermal systems increase airflow
- Increased airflow increases the convection properties of a system
- The result is a much smaller surface area requirement

5. Thermal Design Process: Heat Pipes

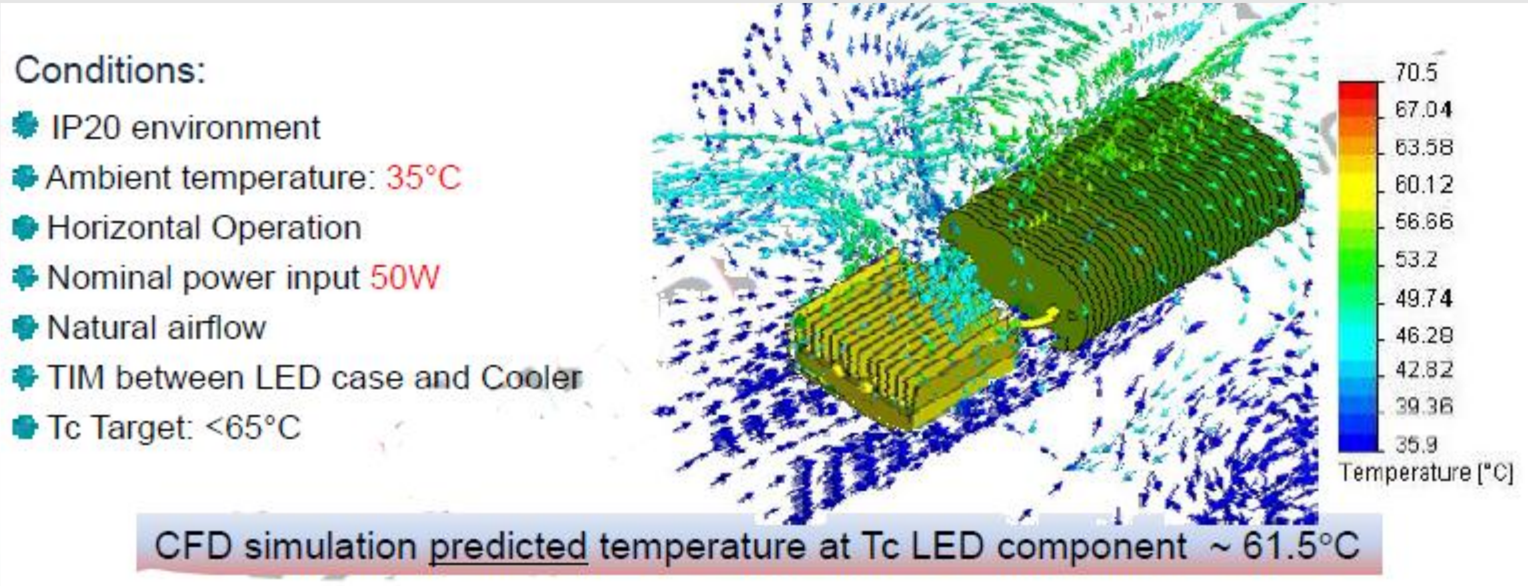
A **heat pipe** is a heat transfer mechanism that combines the principles of both thermal conductivity and phase transition to efficiently manage the transfer of heat between two solid interfaces



Heat Pipe Thermal Cycle

1. Working fluid evaporates to vapor absorbing thermal energy.
2. Vapor migrates along cavity to lower temperature end.
3. Vapor condenses back to fluid and is absorbed by the wick, releasing thermal energy.
4. Working fluid flows back to higher temperature end.

5. Thermal Design Process: Heat Pipes

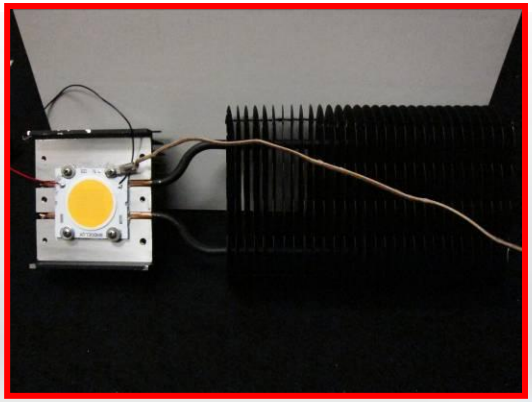


Conditions:

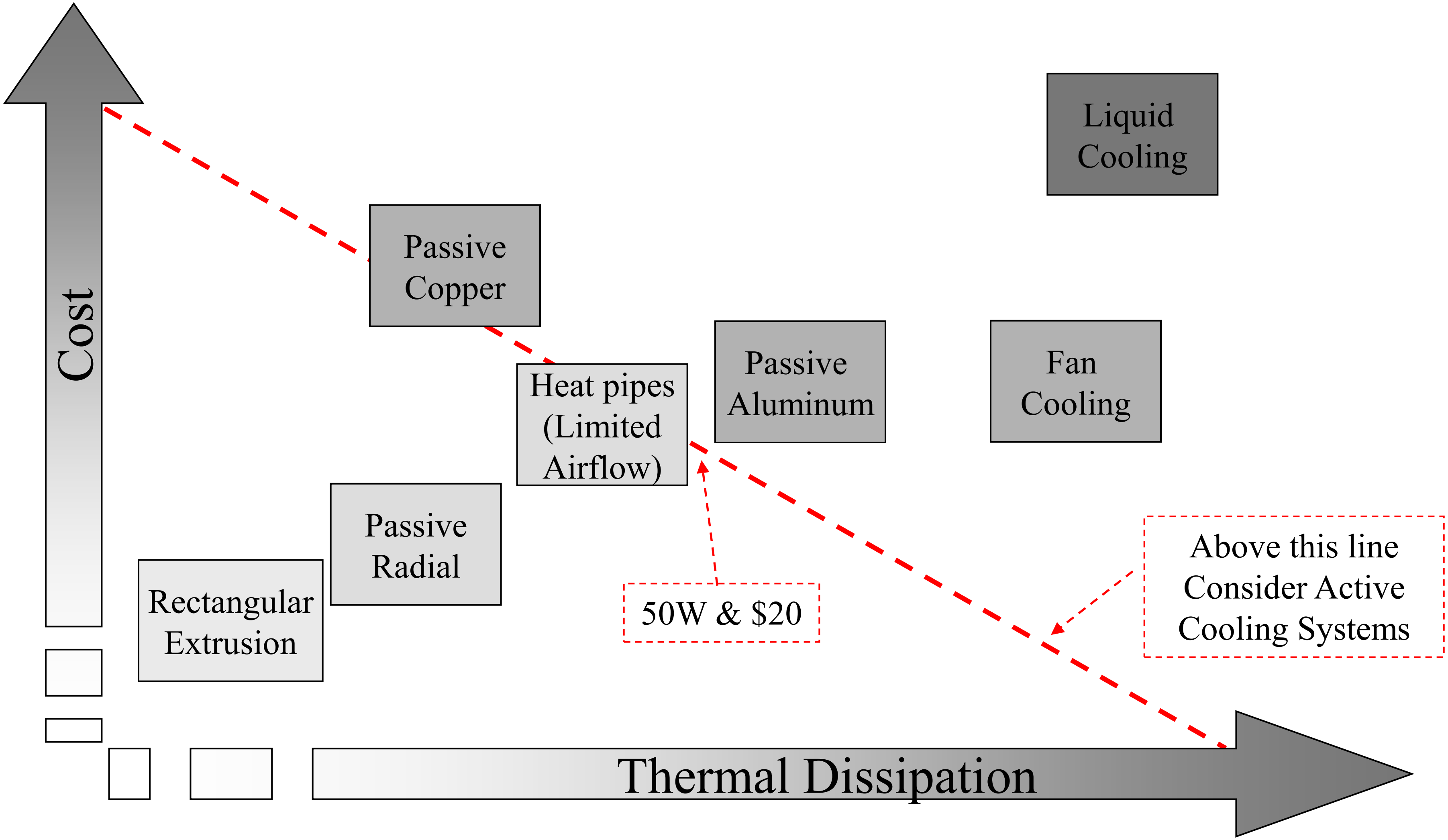
- IP20 environment
- Ambient temperature: 35°C
- Horizontal Operation
- Nominal power input 50W
- Natural airflow
- TIM between LED case and Cooler
- Tc Target: <65°C

CFD simulation predicted temperature at Tc LED component ~ 61.5°C

Bridgelux in-house testing confirms the thermal simulation above.



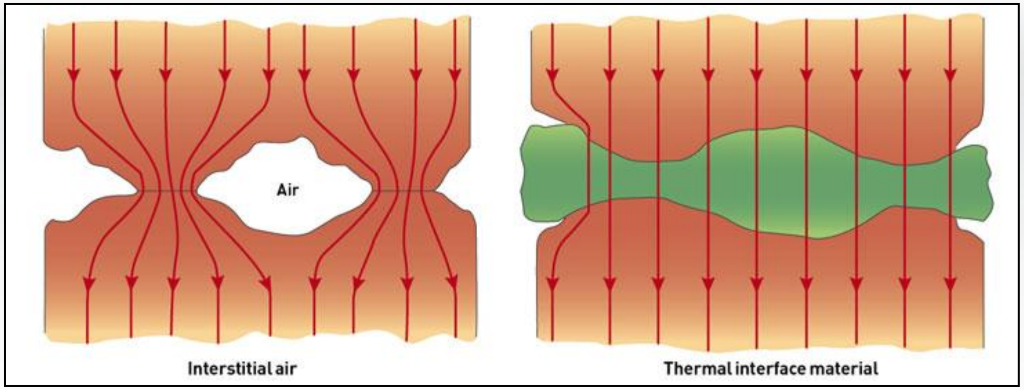
5. Thermal Design Process: Active and Passive Cooling



50W & $20

Above this line Consider Active Cooling Systems

6. Thermal Design Process: Interface Materials



- "A **Thermal Interface Material or Mastic** (aka **TIM**) is used to fill the gaps between thermal transfer surfaces, such as between microprocessors and heat sinks, in order to increase ***thermal transfer efficiency***."
  - http://en.wikipedia.org/wiki/Thermal_interface_material

- For all products except RS Array series products, flatness of the back surface of the LED Array is maintained at < 0.1 mm across the LED Array. For RS Array Series products, flatness is maintained at < 0.25 mm across the LED Array. A standard flatness for a manufactured heat sink is around 0.05 mm.

6. Thermal Design Process: Interface Material Comparison

	Pad	Thermal Adhesive	Thermal Grease	Thermal Grease Based Pad	Phase Changing Materials	Thermal Tape
Relative Thermal Conductivity	Various	High	High	High	High	Med
Electrical Isolation	Various	None	None	None	Various	Various
Cost	High	Med/High	Low	Low/Med	High	Med
Manufacturability	Custom stamping of rolls	Screen Printing / Messy	Screen Printing / Messy	Custom stamping of rolls	Custom stamping of rolls	Custom stamping of rolls
Reliability	Good	Good	Potential Long Term Silicone Oil Bleed	Potential Long Term Silicone Oil Bleed	Unproven: Thermal Cycling	Unproven: Peeling/Air gaps
Attachment	None	Permanent	None	None	None	Single or Dbl Adhesive
Other Concerns					Thermal Cycling	Air gaps
Recommended for Evaluation	High	High	Medium	Medium	Low	Low

7. Thermal Design Process: Thermal Resistance

Heat sinks can be defined by the thermal resistance required to maintain a specified array case temperature with knowledge of:

- Thermal power
- Thermal resistance of system
- Ambient temperature

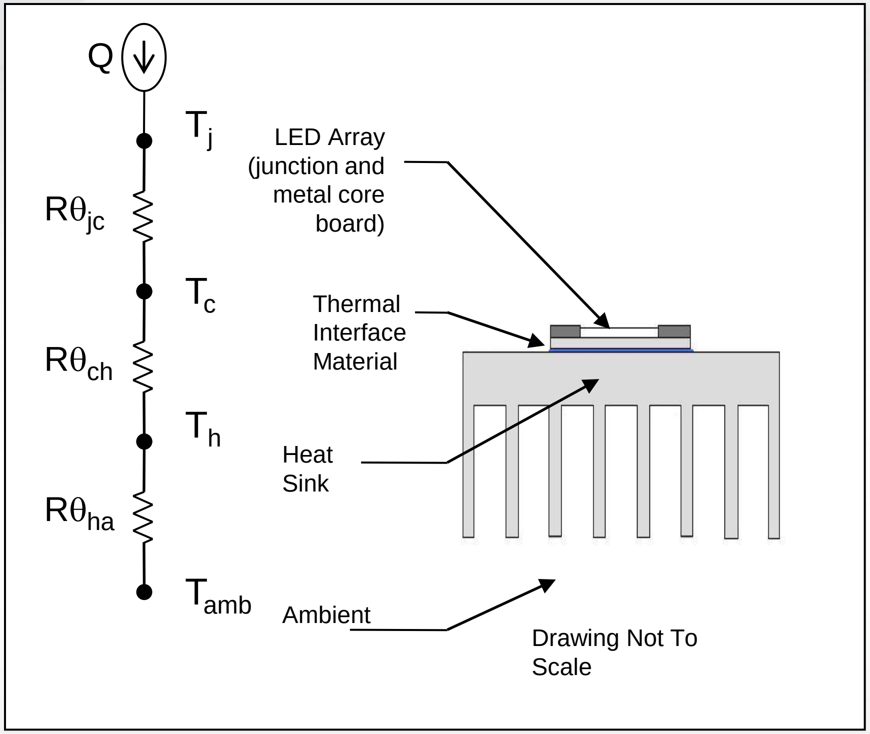
7. Thermal Design Process: Thermal Resistance Equation

$$R\Theta_{\text{system}} = (T_{\text{case}} - T_{\text{ambient}}) / Q$$

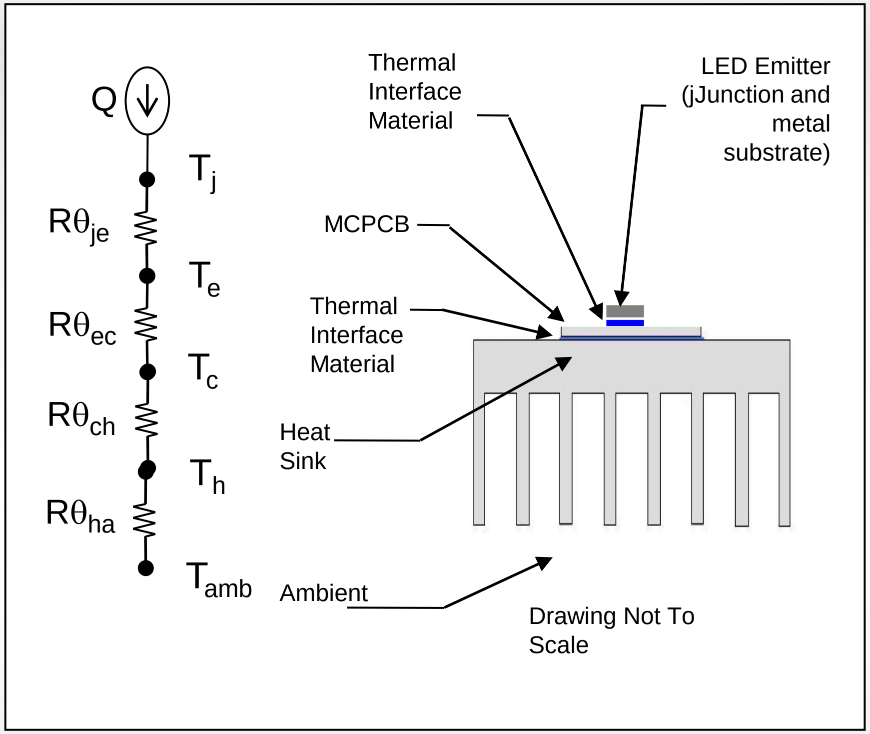
- $R\Theta_{\text{system}}$ is the thermal resistance from the case of the array to the ambient side of the heat sink.
- For a well assembled luminaire, $R\Theta_{\text{system}}$ is approximately the same as thermal resistance of the heat sink
- T_{case} is the required case temperature of the array
- T_{ambient} is the ambient temperature of the environment
- Q is heat flow

7. Thermal Design Process: Thermal Resistance Model

LED Array



LED Emitter



$$R\Theta_{ja} = R\Theta_{j\text{-}c} + R\Theta_{c\text{-}h} + R\Theta_{h\text{-}amb}$$

$$R\Theta_{ja} = R\Theta_{j\text{-}e} + R\Theta_{e\text{-}c} + R\Theta_{c\text{-}h} + R\Theta_{h\text{-}amb}$$

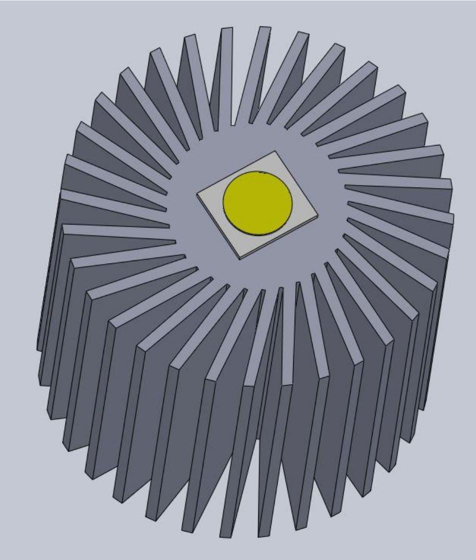
8. Thermal Design Process: Heat Sink References

- Many heat sink companies produce heat sink products (extrusions and castings) that are suitable for use with Bridgelux LED Arrays. These products can be procured quickly directly from the company or their distributor for expediting concept and prototype testing processes.

- Thermal Modeling Service Companies can be used by companies in need of thermal and mechanical engineering assistance during their design, prototype or manufacturing processes. These companies offer services ranging from mechanical design to thermal simulation.

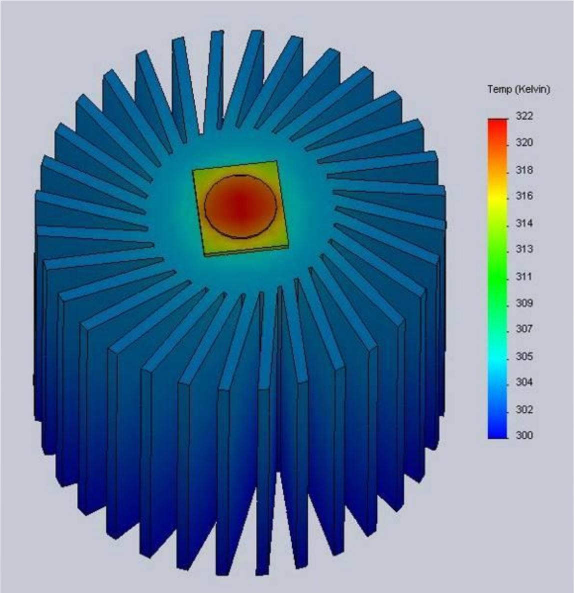
9. Thermal Design Process: Simulation

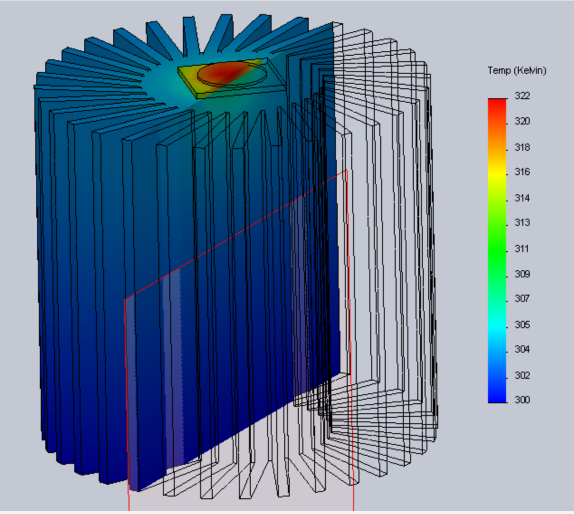
Thermal Simulation allows for cost and time reductions during the design and prototyping phases



Heat sink 3D Design

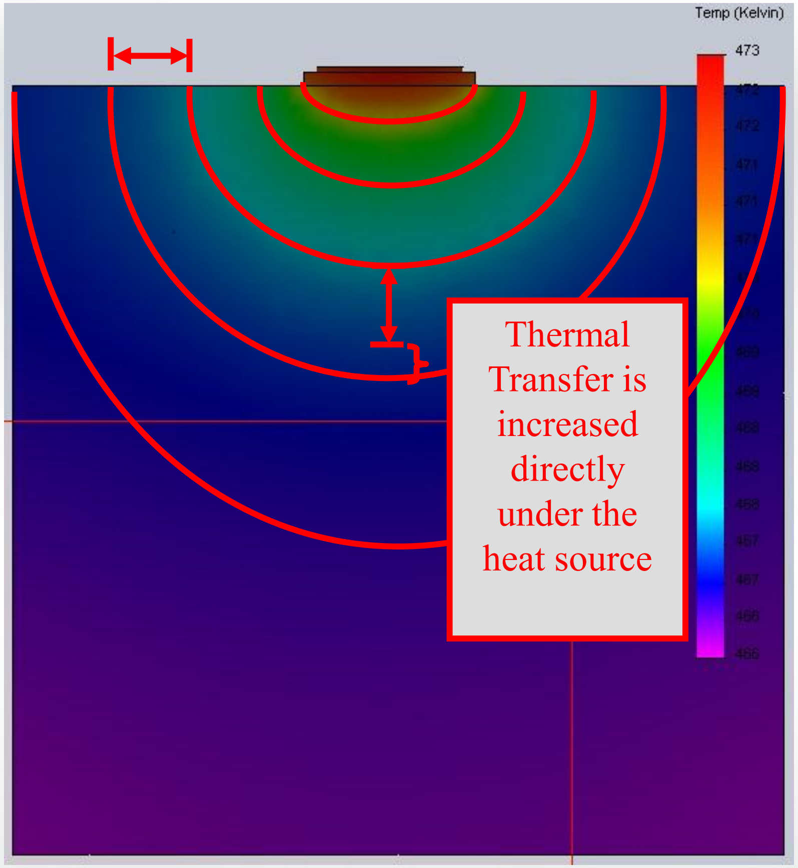
Thermal Simulation with Solidworks Simulation software



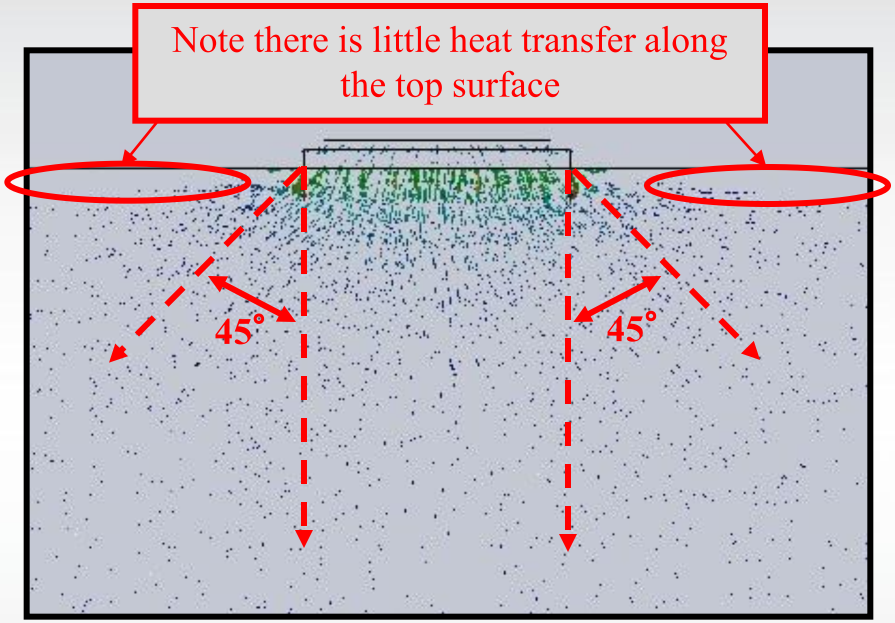


Analysis of Thermal Simulation

9. Thermal Design Process: Thermal Transfer



Thermal Transfer is increased directly under the heat source



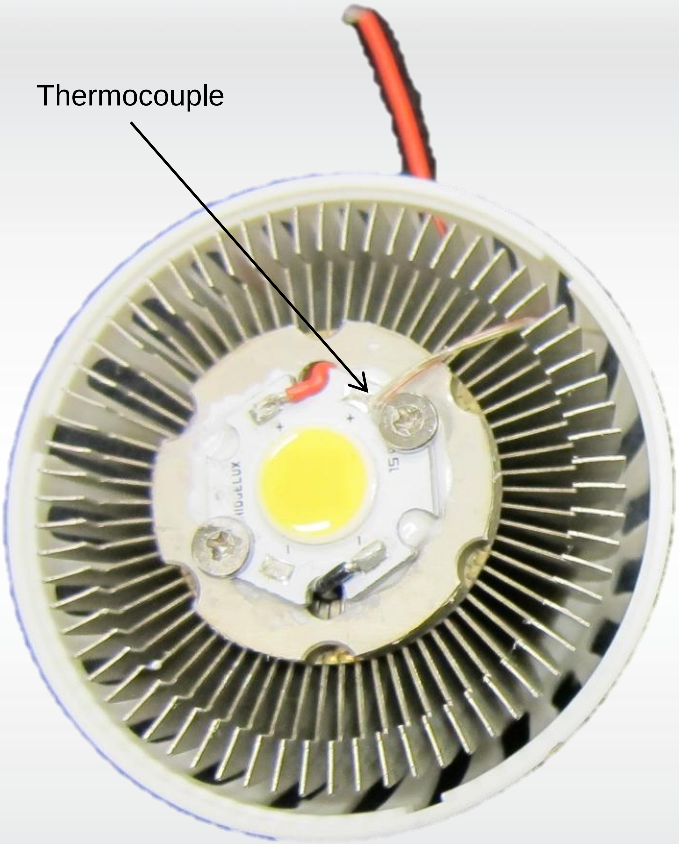
Note there is little heat transfer along the top surface

Thermal transfer is increased directly under the thermal source. Therefore, conduction vertically through the heat sink is critical in order to fully utilize any heat sink fin design.

Thermal transfer density:
As a rule of thumb, heat travels downward at 45° to the surface. Thus, increasing the surface area with a large heat spreader will not significantly improve the thermal design.

10. Thermal Design Process: Build Prototype

11. Thermal Design Process: Test Prototype



Key Tests

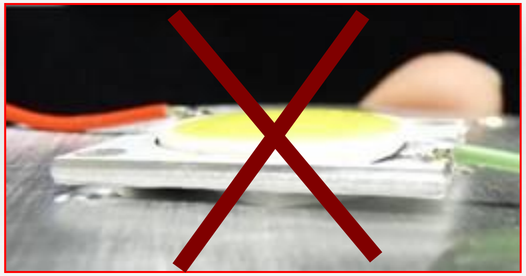
- Ambient temperature
- Case temperature
- Light output
- Color

TIP: To measure Case Temperature a thermocouple can be mounted under the head of a mounting screw. This is usually within 2 degrees of the case temp

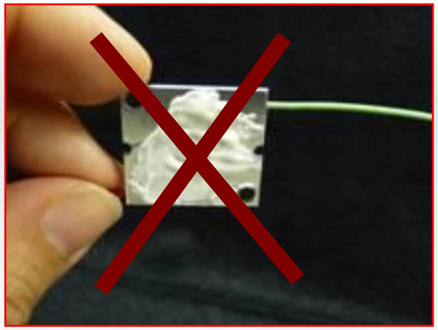
And don’t forget manufacturing

- Once you’ve designed a good thermal system solution, don’t forget to be sure it is implemented in production
  - TIM application
  - Mounting to heat sink
    - Correct screw torque

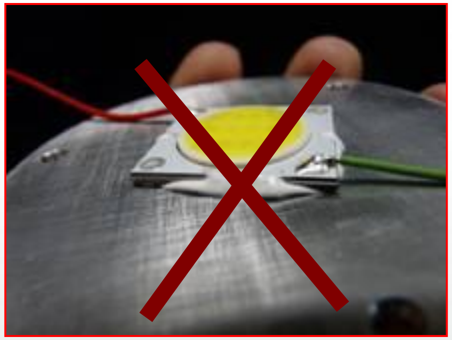
Thermal Interface Material – Greases/Epoxies



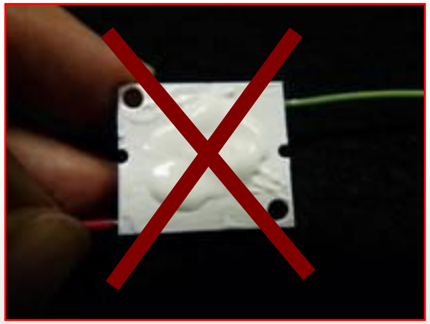
Bond-line too thick
Insufficient coverage



Insufficient thermal grease coverage



- Excessive amounts of thermal paste
- Thermal paste fillet too high and could cause electrical short

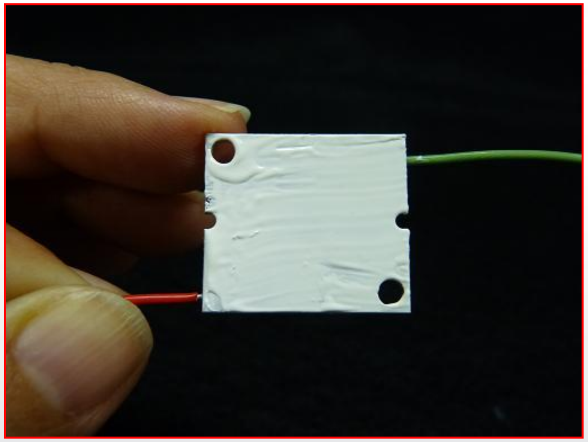


Excessive amounts thermal grease will result in a thick bond-line and possibly an excessive fillet height

Thermal Interface Material – Greases/Epoxies

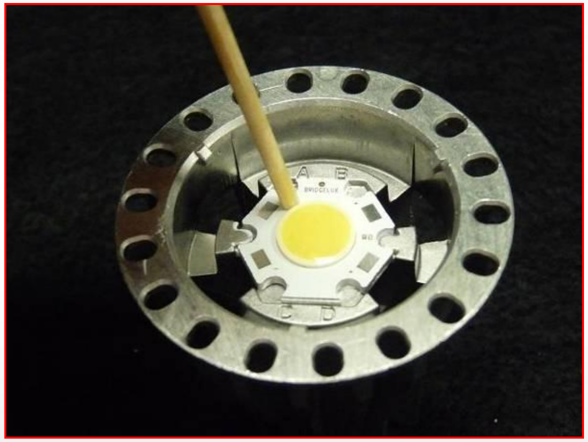
Proper Application Concepts

Ensure entire bottom of device is covered



Minimize bond-line thickness

Squeeze part on sides onto heat sink (Do not press down on yellow resin area)



Recap

- Most problems with LED applications are related to system level thermal considerations
- Good thermal design is critical
  - Simulate
  - Prototype
  - Test
- Accounting for thermal effects to light output, color and electrical properties are critical

Thank You!