

Thermal Design

of LED Luminaires



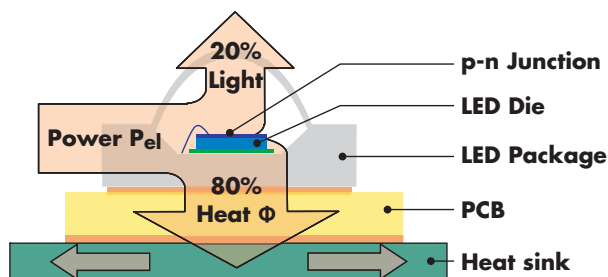
A New Lighting Experience

As the most modern source of light, LEDs open up a wealth of innovative lighting options. However, the way in which LEDs are handled is still often governed by misunderstandings and incorrect use of the associated semi-conductor technology. In particular, the special thermal requirements of high-performance LEDs are frequently largely ignored during installation. This information leaflet intends both to shed light on the special requirements governing luminaire design when using LED technology and create awareness for ensuring optimum thermal management.

1 Thermal Behaviour of LED Technology

1.1 Special Characteristics of LED Technology

LEDs are semi-conductor based devices that operate with currents of up to 1 A in the high-performance category. During the light generation process at the so-called p-n junction, up to 80% of the applied electrical energy is converted into heat, which in turn reduces both the light output and service life of LEDs. Continuously exceeding the maximum permissible temperature at the p-n junction will irreparably damage the semi-conductor.



During operation, the chip quickly reaches temperatures of 100 °C and more. To guarantee the desired properties of an LED luminaire in terms of lighting levels and service life, the p-n junction must be kept below a defined target temperature and any heat generated must be dissipated from the chip to the luminaire body and from there to the immediate environment. For that reason, attention should already be paid to ensuring an adequately dimensioned cooling path while designing an LED luminaire.

1.2 Brightness and Service Life of LED Modules

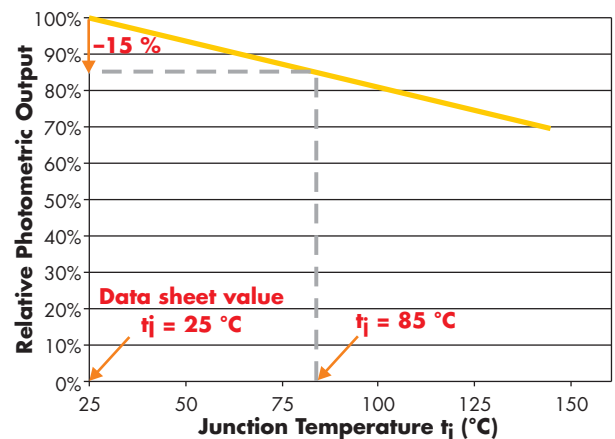
Although LEDs promise the longest service life of all types of lighting under favourable operating conditions, the physical properties of both the semi-conductor and inorganic fluorescent substances deteriorate over time, which leads to a degradation of the LED.

VS specifies the service life of its LED modules as L70 or L50 values. The L70 value, for instance, specifies the number of operating hours after which luminous flux amounts to 70% of the initial luminous flux value. LED modules should be replaced after this time. The specified L70 value is particularly relevant for general lighting applications. In other fields of application such as effect or auxiliary lighting, modules are only replaced when the luminous flux has dropped to half of the initial luminous flux value, i.e. L50.

The rate at which an LED module will age is highly dependent on the temperature at the p-n junction and will accelerate over time. As a result, service life values are only valid provided that certain p-n junction temperatures (t_j) are not exceeded. Service life values are statistical values determined during test runs undertaken by LED manufacturers and do not reflect the precise behaviour of individual LEDs.

The same applies to LED brightness values. The heat generated at the p-n junction impairs the efficiency of the light generation process and results in a measurable drop in brightness.

LED manufacturers typically specify LED brightness at a t_j of 25 °C, which is not a realistic reflection of the operating conditions found in a luminaire. For instance, compared to the value specified for $t_j = 25$ °C in the data sheet, a 15% drop in brightness is already measurable at $t_j = 85$ °C.



The cooler the p-n junction of an LED remains during operation, the better and longer the luminaire will function. Determining the precise service life and brightness of an LED luminaire therefore depends on the availability of accurate data regarding the temperature at the p-n junction during operation. However, this temperature is extremely difficult to measure in practice.

1.3 Defined Product Properties due to Stable Temperature at the t_c Point

Due to the complexities involved in taking direct readings of the temperature at the p-n junction (t_j), VS introduced the t_c reference point on its LED modules in an attempt to simplify matters.

This t_c point is situated on the LED PCB and the temperature measured at this point corresponds to the t_j value and makes it possible to predict the behaviour of the LED. The t_c point is readily accessible with a temperature sensor, thus making readings easy to take.

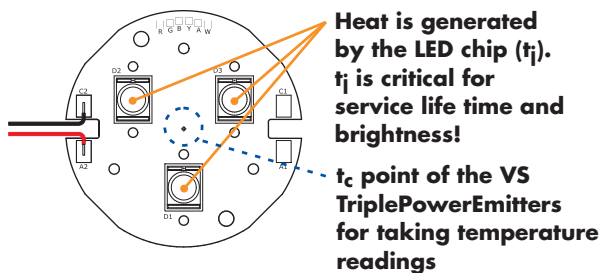
Thermal Design

of LED Luminaires



1.3 Defined Product Properties due to Stable Temperature at the t_c Point

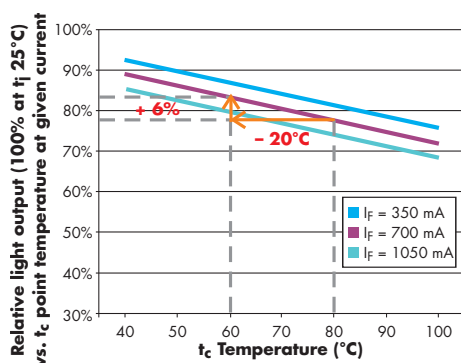
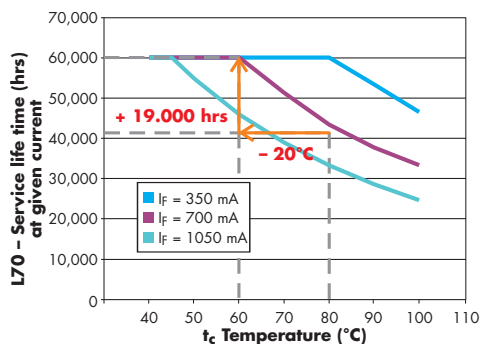
VS further specifies the service life and brightness of its high-power modules in relation to the t_c temperature and the operating current in a separate brochure entitled "Lifetime and Brightness dependent on t_c Point Temperature", which can be made available on request. The data specified in the brochure can thus be used to determine the max. t_c temperature to achieve a desired service life. This value can then be used as a key thermal design factor.



As a basic rule, keeping the t_c temperature as low as possible will optimise all parameters!

Example: a TriplePowerEmitter XR-E module operating on 700 mA

By reducing the t_c temperature from 80 °C to 60 °C the expected service life will increase by 19,000 hours and brightness by 6%!



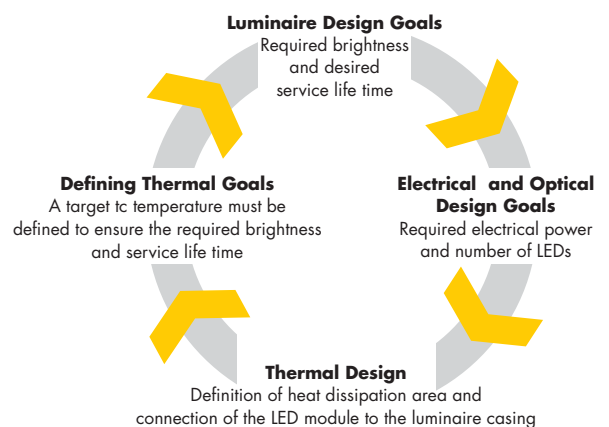
2 Thermal Management and its Challenges

When designing an LED luminaire, the thermal transfer path must be dimensioned to equal the applied power load. This is critical for ensuring that desired operating behaviour can remain stable over the long term. Depending on both how much space is available for installation and the material in question, the same brightness can be achieved with higher currents and fewer LEDs (Case 1) or lower currents and more LEDs (Case 2).

Given the same degree of cooling and identical operating conditions, the LEDs' service life will certainly be shorter in Case 1 than in Case 2. Depending on the intended use of an LED luminaire and its operating conditions, priorities must be set when deciding on design targets, as the possible objectives of

- electrical power,
- keeping the need for cooling as low as possible and
- increasing light output and service life

behave in different ways.



2.1 Thermal Design of LED Luminaires

Having determined the number of LEDs and the operating current as part of the electrical and optical design, the thermal management of an LED luminaire must guarantee that the generated heat is dissipated from the p-n junction to the luminaire body and that the desired temperature at the t_c point is not exceeded, even under the most unfavourable ambient conditions. In the case of a hanging luminaire, this is the maximum ambient temperature ($t_{a \max}$).




Thermal Design

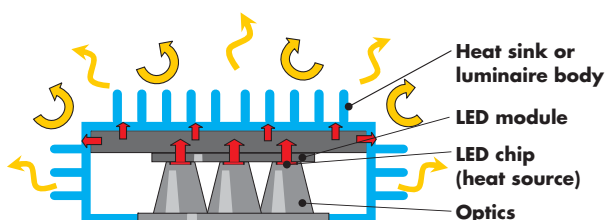
of LED Luminaires



2.1 Thermal Design of LED Luminaires

Heat can only be discharged from a warmer to a cooler material. Three different processes are involved in heat transfer:

- **Thermal Conduction**  Heat transfer through non-moving media in direct physical contact with one another, e.g. from the p-n junction through the LED casing to the PCB.
- **Convection**  Combination of thermal conduction and heat transfer through a moving medium. Hotter particles are transported to cooler regions. A heat sink, for instance, does this by transferring heat to the ambient air circulating around it.
- **Heat Radiation**  Heat transfer through electromagnetic radiation, i.e. not requiring a transfer medium. Radiation also works in and through a complete vacuum, e.g. a heat sink or LED luminaire casing will emit heat in the form of IR radiation.



2.1.1 Internal Thermal Management

The transfer of heat from the p-n junction to the luminaire body or heat sink can be understood as an LED luminaire's internal thermal management system.

The most efficient heat transfer mechanism is thermal conduction. The quality of thermal conduction is highly dependent on the materials used and the geometry of the luminaire. In this regard, ensuring the use of materials with low specific heat resistance, such as copper or aluminium, is key. To ensure low thermal resistance (R_{th}) along the entire thermal path from the LED module to the luminaire body, any materials that are poor thermal conductors and through which heat must flow should also be kept as thin as possible.

Heat-conducting adhesive pads are available for fixing LED modules to other components without needing further tools. VS provides suitable adhesive thermal pads for every LED module. As air is a very poor conductor of heat, care should be taken to avoid any air gaps along the thermal path.

2.1.2. External Thermal Management

This refers to heat dissipation from the luminaire body or heat sink to the ambient air. In this case, the main processes are convection and heat radiation. Convection is mainly dependent on the flow rate of the ambient air as well as the surface area around which air is circulating. A large surface area and free air circulation are the key criteria in this regard.

Heat radiation, on the other hand, is mainly dependent on the temperature and surface of the luminaire. The higher the temperature and larger the surface area, the more heat will be discharged in the form of IR radiation. As a rule, this process only really becomes noticeable above a temperature of 60 °C. Highly polished metal surfaces only radiate very little heat, while painted surfaces enable highly efficient heat radiation.



Example of a heat sink/ luminaire body with cooling fins for improved dissipation of heat to the ambient air

Having ensured an optimum thermal connection between an LED module and the luminaire casing, heat is then mainly dissipated to the ambient air via convection. The volume of heat flow is influenced by either the surface area of the luminaire or the heat sink.

As a general rule of thumb, a surface area of 25 cm² is needed to dissipate 1 Watt of thermal load.

The available surface area for ensuring thermal transfer can be increased by adding fins. Increasing the rate of air circulation, e.g. by fans, will further improve cooling efficiency.

Thermal Design

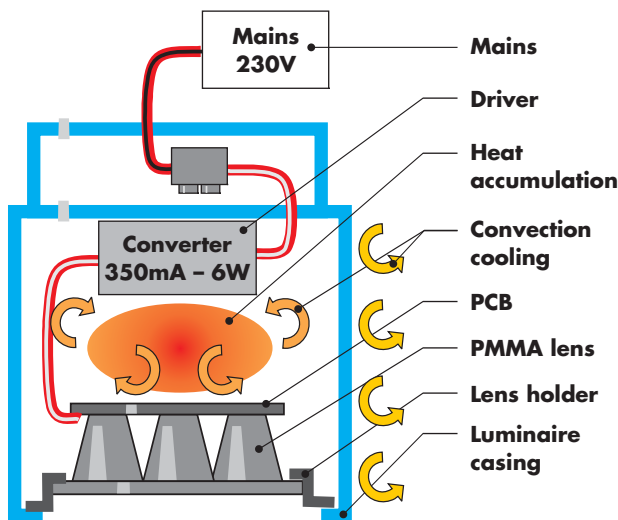
of LED Luminaires



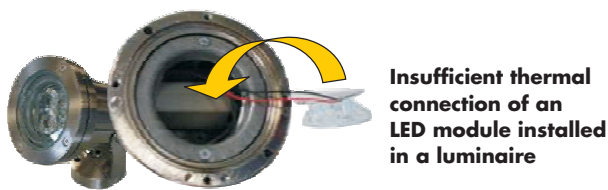
2.2 Examples of Thermal Design of LED Luminaires

2.2.1 Poor Thermal Design

In this luminaire, the LED module was installed without ensuring a heat-conducting connection between the module and the luminaire body. As a result, the LEDs will overheat. After 50 minutes of operation at only 350 mA, the t_c temperature already reaches a critical 105 °C, which clearly exceeds the specified maximum module temperature. This can damage other components, such as any attached optics.

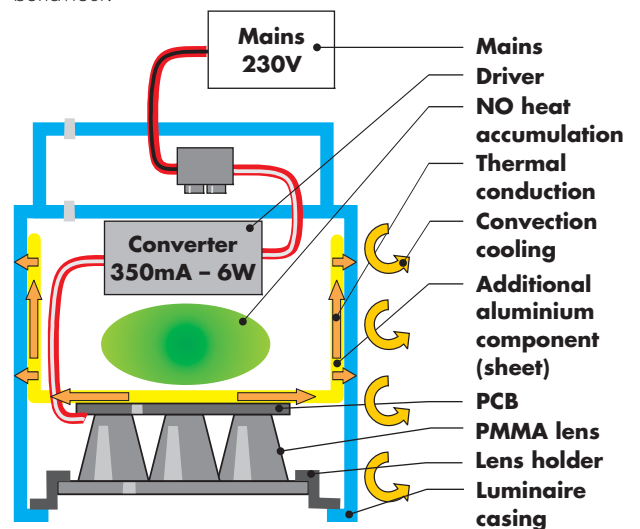


In this case, the main thermal transfer process within the luminaire is convection, which is insufficient to ensure effective heat dissipation. Instead, heat accumulates and overheats both the LED module and the LED driver, which considerably shortens the service life of the module.

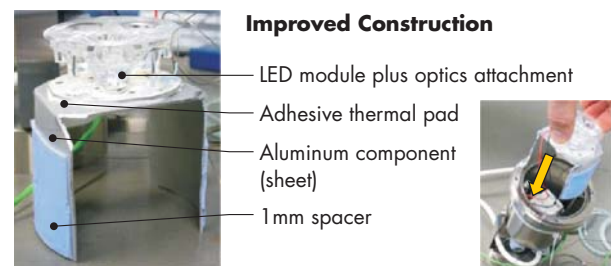


2.2.2 Good Thermal Design

The thermal design of a luminaire can be improved simply by ensuring a continuous thermal connection from the LED module to the metal luminaire body. This can be achieved by using an additional aluminium component (sheet) to which the LED module is attached with a heat-conducting adhesive pad. The aluminium component is then fitted into the luminaire to ensure a good connection to the luminaire body. Due to the thermal balance achieved in this case, the PCB temperature only reaches 46 °C after 45 minutes of operation, which in turn considerably improves the luminaire's operating behaviour.



As a result, the main heat process occurring from the PCB to the luminaire body is thermal conduction. This constitutes the most efficient process for internal thermal design as it ensures optimum heat dissipation through the luminaire body. In this case, neither the LED module nor the LED driver overheats.



Adding a highly heat-conducting component creates a thermal conduction path that ideally transfers heat from the LED module to the outer surface of the luminaire casing, thus preventing heat accumulation.

Thermal Design

of LED Luminaires

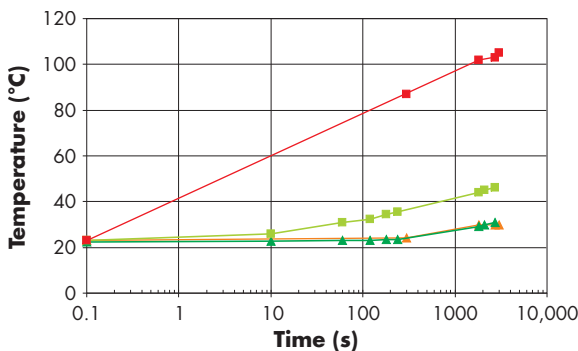


2.2.2 Good Thermal Design

Reducing the t_c point temperature from 105 °C to 46 °C will lengthen the service life of the module to more than 60,000 hours and increase brightness by 17%.

The casing temperature of the luminaire is identical in both cases, meaning that improved internal thermal management does not cause the casing temperature to increase, but rather the temperature at the p-n junction of the luminaire to decrease.

At the same time this proves that if the luminaire casing "feels" cool this does not necessarily point to good internal thermal design. For this reason, it is essential to always actually measure the t_c temperature.



With thermal conduction **Without thermal conduction**
—■— Temperature of the PCB —■— Temperature of the PCB
—▲— Temperature of the luminaire casing —▲— Temperature of the luminaire casing

2.4 Rules of Optimum Thermal Management

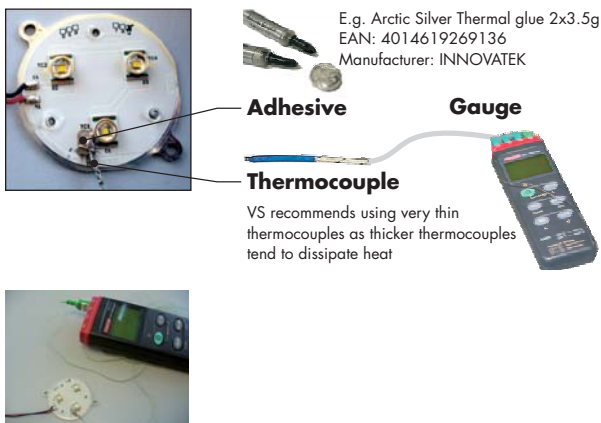
In summary, the following basic thermal management rules should be observed during the development process to ensure a long service life for the LED luminaire:

- LED luminaires should never be operated without appropriate cooling.
- If possible, the luminaire should be operated with low operating currents so that heat generation is minimised.
- The t_c temperature of the LED module should be minimised by ensuring good thermal conduction within the luminaire.
- Thermal resistance (R_{th}) from the LED PCB to the luminaire casing should be minimised by using highly heat-conducting materials, e.g. aluminium.
- Air gaps should be avoided along the thermal transfer path, e.g. by using heat-conducting adhesive pads.
- The surface area of the luminaire should be maximised to ensure optimum thermal transfer to the ambient air through convection.
- Luminaire design should be checked by taking a reading of the PCB temperature at the t_c point under the worst possible operating conditions (at the luminaire's $t_{a,max}$ temperature).

2.3 Measuring the Temperature at the t_c Point

Thermal readings at the t_c point must be taken when the module is in a steady thermal state in accordance with EN 60598-1. A thermocouple or sensor must be used to measure the t_c point temperature of the LED module inside the luminaire. In addition, an appropriate maximum ambient temperature that corresponds to real-life installation conditions must be simulated – e.g. by placing the LED luminaire in a suitably pre-heated oven.

Attaching a Thermocouple to the t_c Point of the LED Module using Heat-conducting Adhesive



Thermal Design

of LED Luminaires



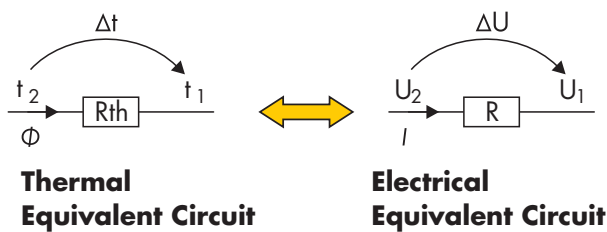
3 Further Formulae and Calculation Examples

In the following, the processes described above are summarised in physical formulae, which are then applied using a heat sink calculation as an example.

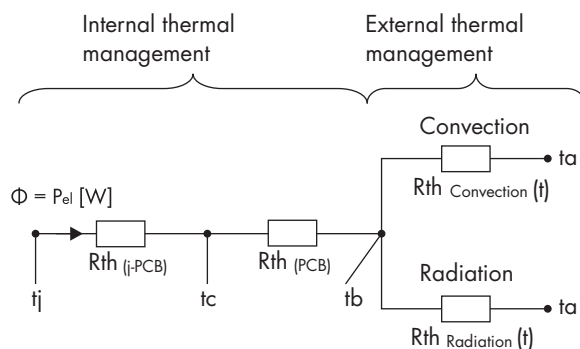
3.1 Analogy of a Basic Electric Circuit and a Thermal Network

The analogy of an electric circuit is useful for the purpose of performing a thermal calculation, as the same principles applicable to an electric circuit, wired either in series or parallel, also apply to thermal resistance.

Thermal Quantity	Electrical Quantity
Absolute thermal resistance $R_{th} [\frac{K}{W}]$	Electrical resistance $R [\Omega]$
Temperature difference $\Delta t [K]$	Electric voltage $U [V]$
Heat flow $\Phi [W]$	Electric current $I [A]$
Thermal conductivity $\lambda [\frac{W}{mK}]$	Electrical conductivity $\sigma [\frac{S}{m}]$



3.2 Thermal Equivalent Circuit of a Luminaire



- $\Phi = P_{el}$ = Heat flow
For the sake of simplicity, heat flow can be equated to electrical power consumption.
- t_j = Temperature at the LED's p-n junction
- t_c = PCB temperature (casing temperature)
- t_b = Temperature of the luminaire body or heat sink (body temperature)
- t_a = Ambient temperature (ambient temperature)

- $R_{th}(j \text{ PCB})$ = thermal resistance of the p-n junction to the PCB
- $R_{th}(\text{PCB})$ = thermal resistance of the PCB to the luminaire body = sum of all thermal resistance values along this path
- $R_{th \text{ Convection}}(t)$ = temperature independent thermal resistance along the convection path
- $R_{th \text{ Radiation}}(t)$ = temperature independent thermal resistance along the radiation path

3.3 Thermal Transfer and Thermal Resistance

- $\Phi = \lambda \frac{A}{l} (t_2 - t_1) = \frac{\Delta t}{R_{th}}$ and thus $R_{th} = \frac{l}{\lambda A}$
- $\lambda [\frac{W}{mK}]$ = Specific thermal conductivity of the material
- $A [m^2]$ = Cross-section of the material
- $l [m]$ = Length of the material
- $t_2 [^\circ C \text{ or } K]$ = Higher temperature
- $t_1 [^\circ C \text{ or } K]$ = Lower temperature
- $R_{th} [\frac{K}{W}]$ = Thermal resistance

Typical thermal conductivity values of common materials:

Material	Specific Thermal Conductivity $\lambda [\frac{W}{mK}]$
Copper	350
Aluminium	221
Silicon	148
Tin	67
Silver	429
Air	0.0261

3.4 Convection

- $\Phi = hA (t_2 - t_1) = \frac{\Delta t}{R_{th \text{ Convection}}}$ and thus $R_{th \text{ Convection}} = \frac{1}{hA}$
- $h [\frac{W}{m^2K}]$ = Heat transfer coefficient, temperature dependent
Typical values for the heat transfer coefficient for thermal transfer from the heat sink to air are 3.5 to 35 $\frac{W}{m^2K}$
- $A [m^2]$ = Surface
- $t_2 [^\circ C \text{ or } K]$ = Higher temperature
- $t_1 [^\circ C \text{ or } K]$ = Lower temperature

Thermal Design

of LED Luminaires



3.5 Thermal Radiation

$$\Phi = \alpha \epsilon A (t_2^4 - t_1^4)$$

Simplification to $\Phi = \frac{\Delta t}{R_{th\text{Radiation}}}$ is not possible due to the 4th power of the temperature. Thermal resistance along the radiation path decreases at higher temperatures, which allows more heat to be dissipated via radiation.

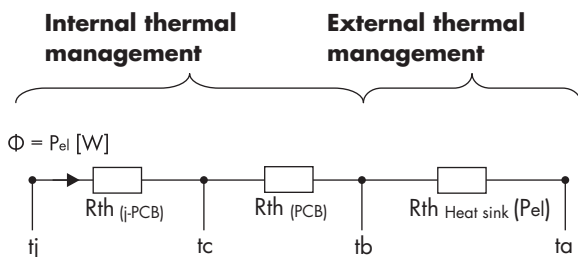
- σ = Stefan-Boltzmann constant = $5.610 \cdot 10^{-8} \frac{W}{m^2K^4}$
- ϵ = Emission coefficient = Factor between 0 and 1, depending on the surface finish of the heat sink.

Examples of the Emission Coefficient ϵ	
Aluminium, polished	0.038
Aluminium, untreated	0.09
Aluminium, anodized	0.8
Cast iron, polished	0.21
Mild steel / Stainless steel	0.2
Copper, polished	0.04
Ceramics, grey	0.9
Surface painted matt black	0.97

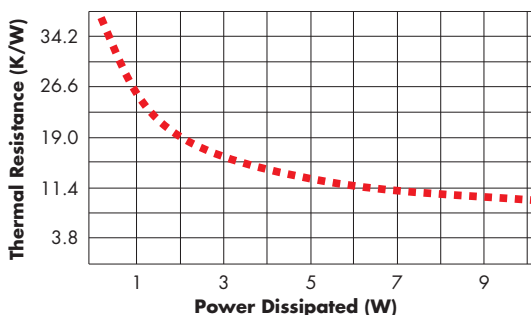
- $A [m^2]$ = Surface
- $t_2 [^\circ C \text{ or } K]$ = Temperature of the heat source
- $t_1 [^\circ C \text{ or } K]$ = Ambient temperature

3.6 Thermal Resistance of Heat Sinks

As the heat dissipated via convection and radiation is dependent on the temperature of the luminaire body, heat sink manufacturers summarise the R_{th} values of heat sinks and present them as a single R_{th} value in relation to the thermal load requiring dissipation. A diagram is mostly used to show these values, which considerably simplifies the process of dimensioning the thermal path because the equivalent circuit can be condensed to a circuit connected in series. The lower the R_{th} of a heat sink the higher the ability of heat dissipation.



Example of an R_{th} curve for a heat sink:



3.7 How to Dimension a Heat Sink

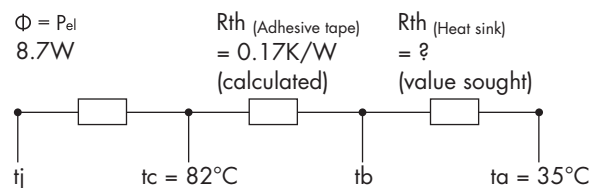
The following calculation provides an example of how to dimension a heat sink required for a simple application.

The aim is to quantify the heat sink needed for operating a cool white VS TriplePowerEmitters XR-E with 700 mA for a minimum of 40,000 hours. The TriplePowerEmitter is attached to the respective heat sink using an adhesive thermal pad and operated at a max. $t_a = 35^\circ C$ using freely flowing air for convection cooling. No casing is used.

Basic data:

- $\Phi = P_{el}$ max. at 700 mA = 8.7 W (data sheet value)
- Target t_c -temperature for the targeted 40,000 hours: $t_c = 82^\circ C$
- Max. ambient temperature $t_a = 35^\circ C$

Equivalent circuit:



Calculation:

$$\Phi = \frac{\Delta t}{R_{th}} \text{ and thus } R_{th} = \frac{\Delta t}{\Phi}$$

$t_c - t_a = \text{temperature difference } \Delta t$

Two thermal resistors are connected in series between t_a and t_c : $R_{th} = R_{th(\text{Adhesive pad})} + R_{th(\text{Heat sink})}$.

The heat quantity requiring dissipation Φ is known.

The thermal resistance of the adhesive pads can be calculated on the basis of the geometry of the product (see data sheet for details):

$$\lambda = 0.8 \frac{W}{mK}, \text{ diameter } \varnothing 43 \text{ mm, thickness } l = 0.20 \text{ mm}$$

$$\text{and thus } R_{th(\text{Adhesive pad})} = \frac{l}{\lambda A} = \frac{4l}{\lambda \pi d^2} = \frac{4 \cdot 0.0002m}{0.8 \frac{W}{mK} \cdot \pi \cdot (0.043m)^2} = 0.17 \frac{K}{W}$$

The following therefore applies for the required heat sink:

$$R_{th(\text{Heat sink})} = \frac{(t_c - t_a)}{\Phi} - R_{th(\text{Adhesive pad})} = \frac{82^\circ C - 35^\circ C}{8.7W} - 0.17 \frac{K}{W}$$

$$= 5.40 \frac{K}{W} - 0.17 \frac{K}{W} = 5.23 \frac{K}{W}$$

Given a power consumption of 8.7 W, a heat sink with a thermal resistance of 5.23 K/W is required to ensure the t_c temperature does not exceed $82^\circ C$ at an ambient temperature of $35^\circ C$.