THERMAL DESIGN OF LED LUMINAIRES

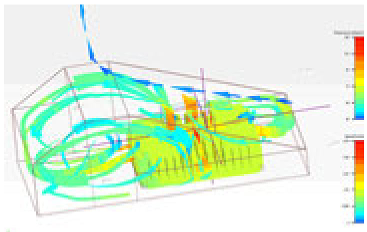


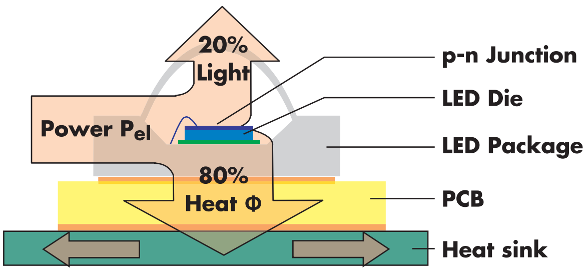
Photo: Leipziger Leuchten

As a modern source of light, LEDs open up a multitude of innovative lighting solutions. However, handling LEDs is still often characterised by misunderstandings and incorrect use of the associated semiconductor technology. In particular, the special thermal requirements of high-performance LEDs are often not given sufficient consideration. This flyer provides information on the special requirements of designing luminaires with LED technology with the aim of creating the requisite awareness for optimised thermal management design.

1. THERMAL BEHAVIOUR OF LED TECHNOLOGY

1.1 Specific Characteristics of LED Technology

LEDs are based on PCB technology and the high-performance variety is operated with currents of up to 3 A. As a result of the light generation process in the so-called p-n junction, up to 80% of the electrical energy LEDs is converted into heat. This increase in temperature during operation both negatively impacts light output and shortens the service life of LEDs. Continuously exceeding the maximum permissible p-n junction temperature will irreparably destroy the PCB.



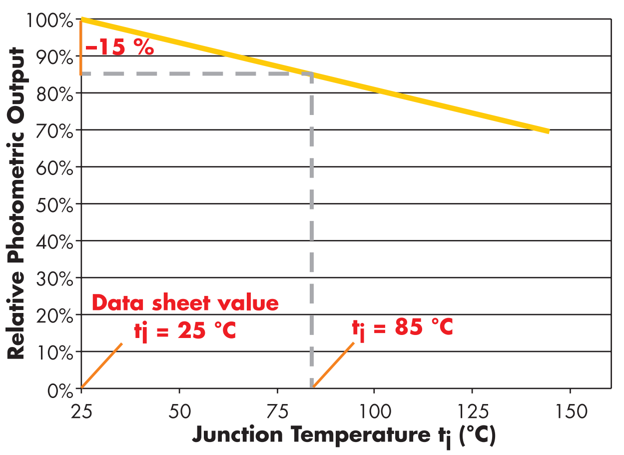
During operation, the PCB temperature quickly rises up to 100 °C and more. To achieve the desired properties of an LED luminaire in terms of brightness and service life, the p-n junction must be kept under a defined target temperature and the generated heat must be discharged from the chip to the luminaire body and from there to the ambient air. Suitably dimensioned cooling measures should therefore be taken into consideration when designing a luminaire from the outset.

1.2 Brightness and Service Life of LED Modules

Given favourable operating conditions, LEDs are characterised by the longest service life of all light sources. However, over time the physical properties of both the PCB and the conversion light emitter deteriorate. As a result, the LED degrades. To specify the decrease in luminous flux of its LED modules, VS uses the so-called Lx/By value (in acc. with IEC 62717 ed. 1). This value denotes that, given a nominal service life T (e.g. 50,000 hours), the decrease in luminous flux L must amount to no more than x%. The B index (y values) expresses how many of the installed LED modules are allowed to fall short of this limit value as a percentage. The value does not take total module failure into consideration.

Example: the L90/B10 value given for VS LUGA Shop modules indicates that after T = 50,000 hours, 90% of the original light output will be retained and that only 10% of the installed module population is permitted to fall short of this value. LED modules that fail to attain a lighting level defined by the respective application will have to be replaced. For that reason, a high L value (L90 or L70) plus a long service life are absolutely indispensable in the field of general lighting. In other fields of application, such as effect or auxiliary lighting, an L50 value is also acceptable.

The speed of the ageing process is highly dependent on the p-n junction temperature and will speed up over time. For that reason, service life values are only valid given certain p-n junction temperatures (tj). Service life values are based on statistical values that are determined by tests carried out by LED manufacturers; however, these statistical values do not reflect the precise behaviour of any one LED. The same applies to the brightness of LEDs. Due to the increase in temperature at the p-n junction, the light generation process becomes less efficient and a decrease in brightness becomes measurable. Some LED manufacturers typically quote the brightness of their LEDs given a tj of 25 °C, which does not correspond to realistic operating conditions. For instance, at tj = 85 °C, the decrease in light output already amounts to 15% in comparison to the starting value provided in the data sheet for tj = 25 °C.

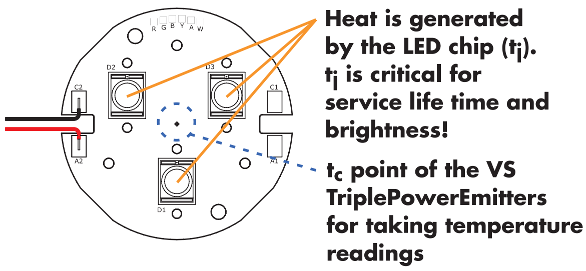


The cooler the p-n junction of an LED remains during operation, the better and longer the luminaire will perform. Accurately forecasting the service life and brightness of an LED luminaire therefore depends on knowing the p-n junction temperature, which is difficult to measure under real-life operating conditions

1.3 Defined Product Characteristics thanks to Stable Temperature at the tc/tp Point

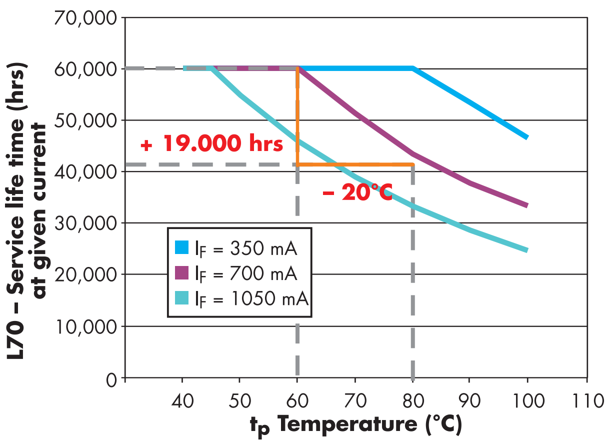
As it is extremely difficult to measure the temperature directly at the p-n junction (tj), VS LED modules feature a reference point (tc/tp) on the LED's PCB, which much simplifies this process. The temperature measured at this tc/tp point corresponds to the tj value and permits direct conclusions to be drawn about the behaviour of the LED. The tc/tp point is easy to reach with a temperature probe and measurements are easy to carry out.

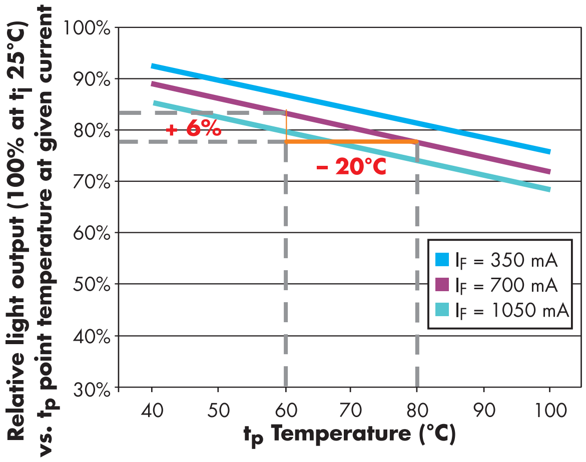
VS specifies the service life and brightness of its high-power modules with reference to the temperature at the tp point (performance temperature) and the associated operating current. The tc temperature denotes the maximum permissible temperature at the tc/tp point under normal operating conditions. The p-n junction of the LED can suffer irreversible damage if the tp value is permitted to attain or exceed the tc value. In turn, this can substantially shorten the service life of the LED or even lead to "sudden death". By defining the desired service life, the requisite tp temperature can then be determined and serve as a basis for the thermal design of an LED luminaire. Further information on service life and light degradation values can be found in the respective data sheets or can be made available on request.



The following applies as a basic rule: to improve all parameters, the tp temperature must be kept as low as possible.

Example: TriplePowerEmitter XR-E, operated at 700 mA
A 19,000-hour increase in the expected service life and 6% increase in brightness can be achieved by reducing the tp temperature from 80 °C to 60 °C.





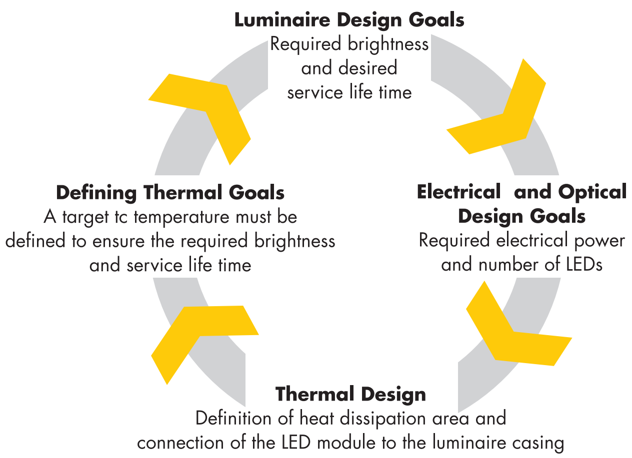
2. CHALLENGES ASSOCIATED WITH THERMAL MANAGEMENT

When designing an LED luminaire, care must be taken to ensure an optimum ratio of the applied electrical power to the cooling solution. This is the only way to ensure desired operational performance can remain stable over numerous hours. Depending on how much space is available for installation and also depending on the choice of material, the same brightness can either be achieved at a higher operating current and fewer LEDs (Case 1) or at a lower operating current and more LEDs (Case 2).

Given the same degree of cooling and identical operating conditions, 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 need to be set with regard to the design process since possible design targets in terms of

- electrical power,
- reducing the need for cooling measures and
- increasing light output

can be contrary to achieving the longest possible service life.

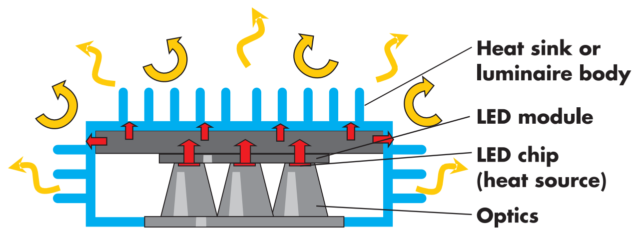


2.1 Thermal Design of LED Luminaires

Once the number of LEDs and the operating current have been determined as part of the electrical and optical design process, the thermal design of the LED luminaire must ensure that any generated heat is discharged from the p-n junction to the luminaire body and that the temperature at the tc/tp point always remains under the maximum permissible value, even under the most unfavourable circumstances. In the case of a suspended luminaire, this is the maximum permissible ambient temperature ta max..

Heat can only be discharged from a warmer to a cooler material. Three different processes are responsible for transferring heat

- Heat Conduction
  Heat transfer via media with direct physical contact with one another, but without there being a flowing medium, e.g. from the p-n junction through the LED casing to the PCB.
- Convection
  Combination of heat conduction and heat transfer via a moving medium that transports heated particles to cooler regions, e.g. a heat sink through which ambient air circulates.
- Heat Radiation
  Heat is transported via electromagnetic radiation without needing a medium. Radiation also functions in and through a perfect vacuum. A heat sink or LED luminaire casing radiates heat in the form of infrared (IR) radiation.



2.1.1 Internal Thermal Management

The transfer of heat from the p-n junction to the luminaire body or heat sink constitutes the internal thermal management of an LED luminaire. Heat conduction constitutes the most efficient heat transportation mechanism. The degree of heat conduction is highly dependent on the materials used and the geometry of the LED luminaire. Using materials with a low specific thermal resistance such as copper (0.0025 m·K) or aluminium (0.0043 m·K) can be seen as the most important factor.

To ensure the thermal resistance value (Rth) remains as low as possible over the entire heat transfer path from the LED module to the luminaire body, the thickness of materials that are poor heat conductors and through which heat must flow also has to be kept as thin as possible. Thermally conductive self-adhesive pads are available to enable tool-free attachment of LED modules to other components. VS provides matching thermally conductive self-adhesive pads for every LED module. As air is an extremely poor conductor of heat (38.5 m·K), it is critical to ensure that there are absolutely no air gaps in the heat transfer path.

2.1.2. External Thermal Management

This refers to the discharge of heat from the luminaire body or heat sink to the ambient air. In this case, the main processes involved are convection and heat radiation. The degree of convection is largely dependent on the speed of ambient air flow and the surface area around which air can circulate. A large surface area plus unhindered air circulation are critical. Heat radiation, on the other hand, is mostly dependent on the temperature and the surface area of the luminaire. The hotter and larger, the more heat can be given off in the form of IR radiation. Normally, this process only begins to be really noticeable upwards of a temperature of 50 °C. Highly polished metal surface radiate only little heat, while varnished surfaces enable very good heat radiation.

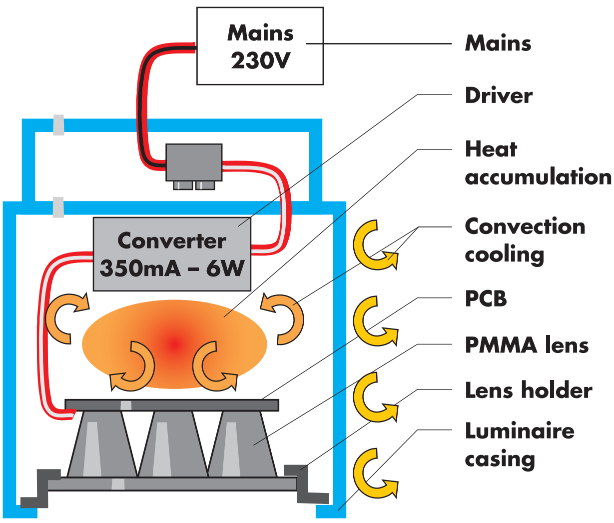
Example of a heat sink/ luminaire body with cooling fins for improved dissipation of heat to the ambient air

Once the LED module has been connected to the luminaire casing or heat sink in a thermally optimised manner, heat is mainly given off to the ambient air via convection. The amount of heat that can be discharged is influenced by the surface area provided by the luminaire or heat sink. As a rough guideline, a surface area of 25 cm^2 is required to discharge 1 Watt of thermal energy. This surface area can be increased by adding lamellae. Moreover, the degree of cooling can be improved by increasing the speed of air flow, e.g. with the help of fans.

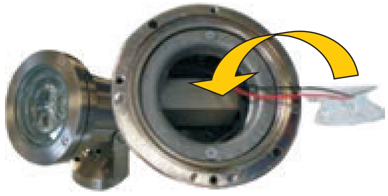
2.2 Examples of Thermal Design for LED Luminaires

2.2.1 Ineffective Thermal Design

In this luminaire, the LED module was integrated without ensuring a heat-conductive connection between the module and the luminaire body. As a result, the LEDs overheat. After 50 minutes of operation at only 350 mA, the tp temperature already reaches a critical 105 °C, which is considerably higher than the module's specified maximum tc temperature. This can cause component damage, e.g. to attached optics.



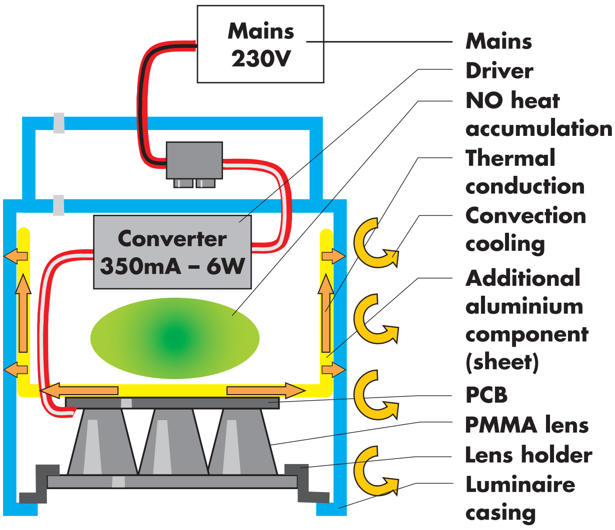
In this case, the main heat transportation mechanism within the luminaire is convection, which is insufficient to efficiently discharge the generated heat. The accumulated heat causes the LED module and the LED driver to overheat, which in turn substantially shortens their respective service lives.



Insufficient thermal connection of an LED module installed in a luminaire

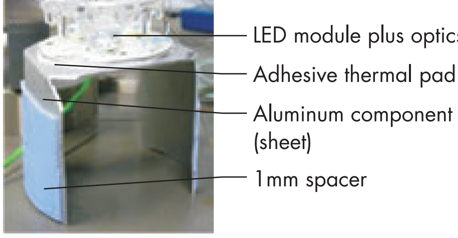
2.2.2 Effective Thermal Design

The thermal design of a luminaire can already be improved simply by ensuring a continuous thermal connection from the LED module to the metal luminaire body, which can be achieved by using an additional aluminium base to which the LED module is attached with a thermally conductive self-adhesive pad. The aluminium carrier is then integrated into the luminaire casing to ensure an optimum connection to the luminaire body. Thanks to being kept at a thermal equilibrium, the PCB temperature only reaches 46 °C after 45 minutes of operation in this case, which substantially improves the performance of the luminaire.



In this case, the main heat transfer process from the PCB to the luminaire body is heat conduction. This is the most efficient process for internal thermal design and permits heat to be optimally discharged via the luminaire body. As a result, neither the LED module nor the LED driver overheats.

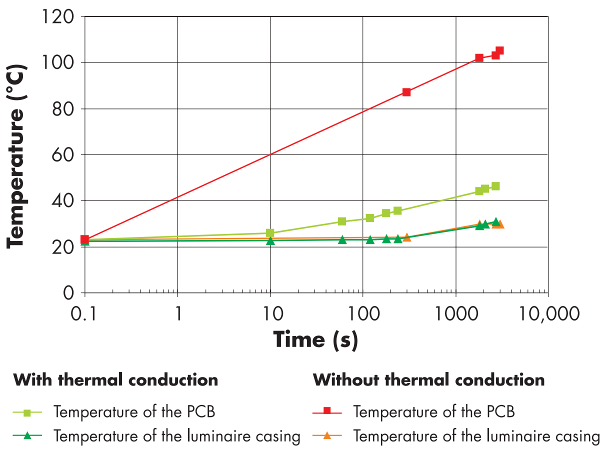
Improved Construction



Adding even a single highly thermally conductive component creates a heat path that can efficiently transfer heat from the LED modules to the outer skin of the casing. An accumulation of heat can thus be avoided.

2.2.2 Effective Thermal Design (cont.)

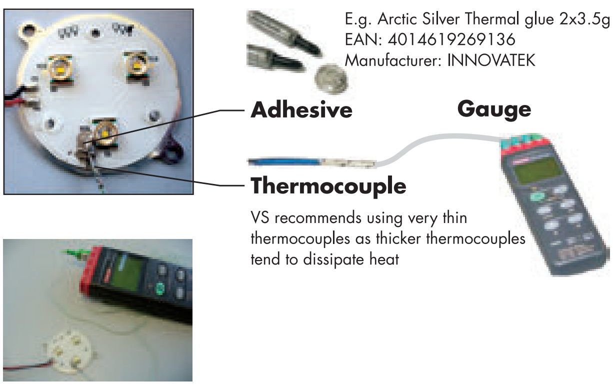
Given an identical luminaire casing temperature in both cases, reducing the temperature at the tc/tp point from 105 °C to 46 °C serves to increase service life to more than 60,000 hours and brightness by 17%. That means that improved internal thermal management does not cause the casing temperature of a luminaire to rise, but only serves to lower the p-n junction temperature of the luminaire. At the same time this also proves that when a luminaire casing feels cool to the touch, it does not signify effective thermal design. The temperature at the tc/tp point must be measured to gauge the effectiveness of a luminaire's thermal design.



2.3 How to Measure the Temperature at the tc/tp Point

Measuring the temperature at the tc/tp point must be carried out in a steady thermal state in accordance with EN 60598-1. To this end, a thermocouple or sensor must be used to take the tc/tp temperature of the LED module in the luminaire. In addition, a corresponding maximum ambient temperature must be simulated – e.g. using an oven – that reflects installation conditions.

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



2.4 Principles of Optimised Thermal Management

In summary, it can be said that the following thermal management principles should be observed during the design process to ensure the longest possible service life of an LED luminaire:

- Never operate LED luminaires without an appropriate degree of cooling.Minimise the temperature at the tc/tp point of the LED module by ensuring effective heat conduction inside the luminaire.
- Minimise the thermal resistance value (Rth) of the LED's PCB to the luminaire casing by using highly thermally conductive materials, e.g. aluminium or copper.
- Avoid air gaps in the heat path, e.g. by using thermally conductive self-adhesive pads or thermal paste.
- Maximise the surface area of the luminaire to optimise heat discharge via convection to the ambient air.
- Check the design by measuring the PCB temperature at the tc/tp point under the most unfavourable conditions (at the luminaire's ta max.).

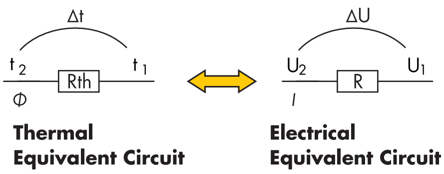
3. FURTHER FORMULAE AND CALCULATION EXAMPLES

In conclusion, the described mechanisms are briefly presented as physical formulae, which are then applied using a heat sink calculation as an example.

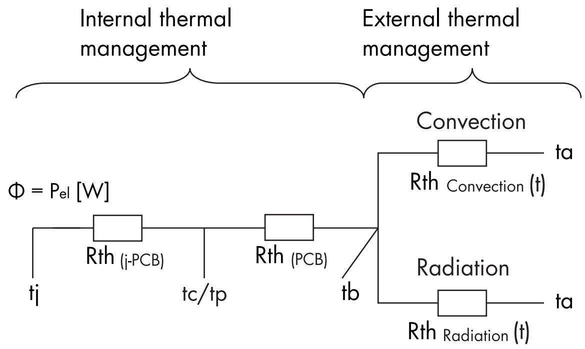
3.1 Analogy of a Basic Electrical Circuit to a Thermal Network

The analogy of an electrical circuit can be used for thermal calculation purposes. The same principles apply to connecting thermal resistors in parallel or series as do to electrical circuits.

Thermal Quantity	Elektrical Quantity
Absolute thermal resistance Rth [$\frac{K}{W}$]	Electrical resistance R [Ω]
Temperature difference Δt [K]	Electric voltage U [V]
Heat flow Φ [W]	Electric current I [A]
Thermal conductivity λ [$\frac{W}{mK}$]	Electrical conductivity σ [$\frac{s}{m}$]



3.2 Equivalent Thermal Circuit Diagram of a Luminaire



- Φ = Pel = thermal flow
  To simplify matters, this is assumed to equal the consumed electrical power.
- t_j = p-n junction temperature of the LED (Junction Temperature)
- t_p = PCB temperature (Performance Temperature)
- t_b = Temperature of the luminaire body or heat sink (Body Temperature)
- t_a = Ambient Temperature
- Rth (j-PCB) = thermal resistance of the p-n junction to the PCB
- Rth (PCB) = thermal resistance of the PCB to the luminaire body = sum of the thermal resistance found in this path
- $Rth_{Convection}$ (t) = temperature-independent thermal resistance in the convection path
- $Rth_{Radiation}$ (t) = temperature-independent thermal resistance in the radiation path

3.3 Thermal Transport and Thermal Resistance

$\Phi = \lambda \frac{A}{l} (t2 - t1) = \frac{\Delta t}{Rth}$ and thus $Rth = \frac{l}{\lambda A}$

λ [$\frac{W}{mK}$] = specific thermal conductivity of the material

A [m^2] = cross-section of material l

l [m]= length of material

t_2 [°C oder K] = higher temperature

t_1 [°C oder K] = lower temperature

Rth [$\frac{K}{W}$] = thermal resistance

Typical heat conduction values for common materials:

Material	Specific Thermal Conductivity λ [$\frac{W}{mK}$]
Copper	398
Aluminium	234
Silicium	148
Tin	67
Silver	429
Air	0,0261

3.4 Convection

- $\Phi = hA (t2 - t1) = \frac{\Delta t}{Rth_{Convection}}$ and thus $Rth_{Convection} = [\frac{1}{hA}]$
- h [$\frac{W}{m^2K}$] = thermal transfer coefficient, temperature-independent
  Typical values for the thermal transfer coefficient for heat transfer from heat sink to ambient air range between 3,5 and 35 $\frac{W}{m^2K}$
- A [m^2] = surface area
- t_2 [°C or K] = higher temperature
- t_1 [°C or K] = lower temperature

3.5 Heat Radiation

$\Phi = \sigma\varepsilon A (t_2^4 - t_1^4)$

Due to the 4th power of the temperature, a simplification in the form of $\Phi = \frac{\Delta t}{Rth_{Strahlung}}$ is not possible. At higher temperatures, the thermal resistance decreases in the radiation path and more heat is given off in the form of radiation.

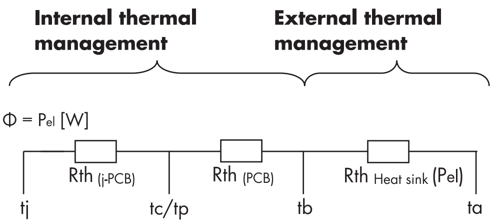
- σ = Stefan-Boltzmann constant = $5{,}670 \cdot 10^{-8} \frac{W}{m^2K^4}$
- ε = emission coefficient = factor between 0 and 1, depending on the surface finish of the heat sink.

Examples for 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
Ceramic, grey	0,9
Matte Black Coated Surface	0,97

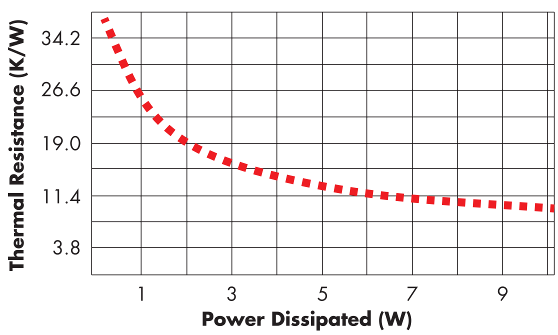
- A [m^2] = surface area
- t_2 [°C or K] = temperature of the heat source
- t_1 [°C or K] = ambient temperature

3.6 Thermal Resistance of Heat Sinks

Since the amount of heat that can be discharged via convection and radiation is dependent on the heat sink, manufacturers of heat sinks sum up the Rth of their products to an Rth value that is dependent on the amount of thermal energy that will have to be discharged. This is mostly presented in the form of a diagram. This makes it much easier to dimension cooling measures since the equivalent circuit diagram can be expressed as a connection in series. The lower the Rth value of a heat sink is, the more efficiently it will be able to conduct heat.



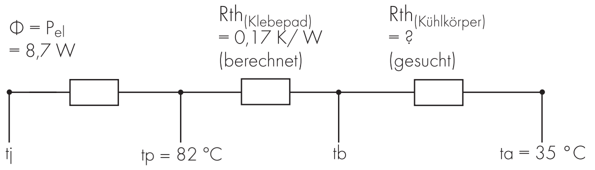
Example of an Rth curve for a heat sink:



3.7 Example for Dimensioning a Heat SinkA sample calculation will serve to demonstrate how to dimension a heat sink for a simple application. Specifically, the matching heat sink will be determined for operating a VS TriplePowrEmitter XR-E in cool white at 700 mA with a target service life of at least 40,000 hours. The TriplePowerEmitter is attached to the respective heat sink using an adhesive pad and is then operated while ensuring unhindered air convection at ta max. = 35 °C. No casing is used.
Underlying values:

- Φ = Pel max. at 700 mA = 8.7 W (data sheet details)
- Target tp temperature for the desired 40,000 hours: tp = 82 °C
- Ambient temperature ta max. = 35 °C

Equivalent Circuit Diagram::



Calculation:
$\Phi = \frac{\Delta t}{Rth}$ and thus $Rth = \frac{\Delta t}{\Phi}$
The temperature difference Δt results from t_p – ta.
The quantity of heat Φ to be discharged is known.
Two thermal resistors $Rth = Rth_{(adhesive\ pad)} + Rth_{(heat\ sink)}$ are connected in series between t_a and t_p

The thermal resistance of the adhesive pad can be calculated using the geometry of the article (see data sheet for details):

$\lambda = 0{,}8\ \frac{W}{mK}$, diameter ∅ 43 mm, thickness l = 0,20 mm and thus
$$Rth_{(adhesive\ pad)} = \frac{l}{\lambda A} = \frac{4l}{\lambda \pi d^2} = \frac{4 \cdot 0{,}0002\ m}{0{,}8 \frac{W}{mK} \cdot \pi \cdot (0{,}043\ m)^2} = 0{,}17 \frac{K}{W}$$

The following therefore applies to the required heat sink:
$$Rth_{(heat\ sink)} = \frac{(t_p - ta)}{\Phi} - Rth_{(adhesive\ pad)} = \frac{82°C - 35°C}{8{,}7\ W} - 0{,}17 \frac{K}{W}$$
$$= 5{,}40\ \frac{K}{W} - 0{,}17\ \frac{K}{W} = 5{,}23\ \frac{K}{W}$$

To ensure the tp temperature does not exceed 82 °C during operation at an ambient temperature of 35 °C, a heat sink is required with a thermal resistance value of 5.23 K/W at a power consumption of 8.7 W.