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Triacs: How to calculate power and predict Tjmax

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Application note

Document information

Info	Content
Keywords	Triac, Silicon Controlled Rectifier, power, thermal resistance, heatsink, $T_j$max, knee voltage, slope resistance
Abstract	This Application Note describes how to calculate the power dissipation for triacs and Silicon Controlled Rectifiers. Thermal calculations are also included to help the circuit designer to predict the maximum junction temperature or calculate the required heatsink thermal resistance. Four worked examples ensure that all the power and thermal questions that arise during the design process are covered.

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Revision history

Rev	Date	Description
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1. Introduction

Triacs are used to control AC mains loads. In the majority of applications, the triac will dissipate sufficient power to make thermal considerations necessary. The size of heatsink must be calculated and the maximum junction temperature must be predicted. Such thermal design procedures must be followed if long-term reliability of the application is to be assured. **Thermal design and analysis form an essential part of the design and development process.**

The thermal design requires several stages of calculation involving power, thermal resistance and temperature rise. This Application Note introduces those calculations. Worked examples are included, the data for which is derived from the customer's application or the triac's data sheet.

2. Calculating triac power

Triac power dissipation is influenced by the load current. Full sine wave current (full wave conduction) is assumed, since it presents the worst-case condition of maximum triac power dissipation. It also makes for the easiest calculations. If calculations are required for half wave conduction (e.g. for an SCR), please refer to the following subsection: "How to calculate $I_{T(RMS)}$ and $I_{T(AVE)}$ for half wave conduction".

$$P = V_o \times I_{T(AVE)} + R_s \times I_{T(RMS)}^{\ 2} \qquad (1)$$

P – triac power dissipation (W).

V_o – triac knee voltage (V). This value is given in Philips data sheets on the I_T / V_T curve. If the value is not available, it can be obtained from the I_T / V_T curve as described in the following subsection: "How to calculate V_o and R_s".

$I_{T(AVE)}$ – average load current (A). This value is calculated from the application's RMS load current using equation 2. (This assumes full wave conduction and sinusoidal load current, which will give worst-case power dissipation.)

$$I_{T(AVE)} = \frac{2 \times \sqrt{2} \times I_{T(RMS)}}{\pi} \qquad (2)$$

R_s – triac slope resistance (Ω). This value is given in Philips data sheets on the I_T / V_T curve. If the value is not available separately, it can be obtained from the I_T / V_T curve as described in the following subsection: "How to calculate V_o and R_s".

$I_{T(RMS)}$ – RMS load current (A). This value is measured in the application.

2.1 How to calculate $I_{T(RMS)}$ and $I_{T(AVE)}$ for half wave conduction

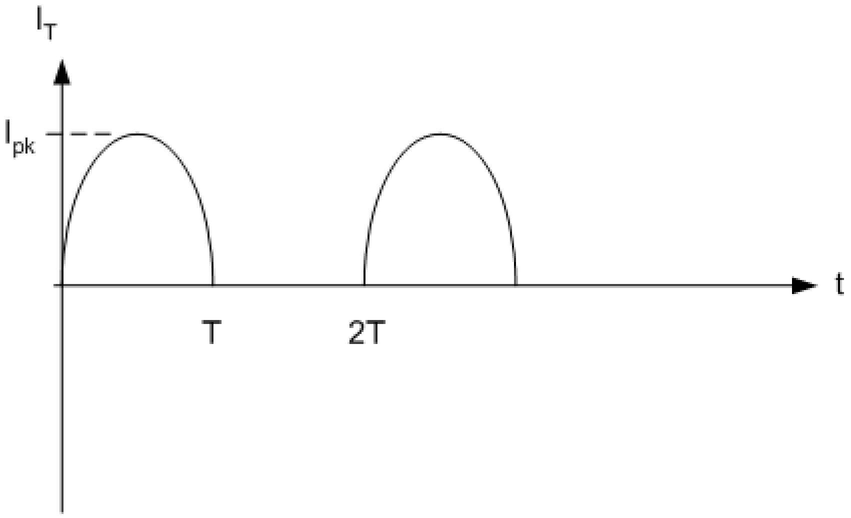

Fig 1. Half wave conduction – e.g. SCR at full power on AC mains.

$$I_{T(AVE)} = \frac{2 \times I_{pk} \times T}{\pi \times 2T} = \frac{I_{pk}}{\pi} \tag{3}$$

$$I_{T(RMS)}{}^2 = \frac{I_{pk}{}^2 \times T}{2 \times 2T} = \frac{I_{pk}{}^2}{4} \tag{4}$$

$$\therefore I_{T(RMS)} = \frac{I_{pk}}{2} \tag{5}$$

2.2 How to calculate V_o and R_s

If values for V_o and R_s are not given in the data sheet, you will have to generate the data yourself. This is easy to do.

1. Make an enlarged photocopy of the I_T / V_T curve.
2. Draw a tangent to the max V_T @ $T_j$max curve at the rated current of the triac.
3. The point where the tangent crosses the V_T axis gives you V_o.
4. The slope of the tangent V_T / I_T gives you R_s.

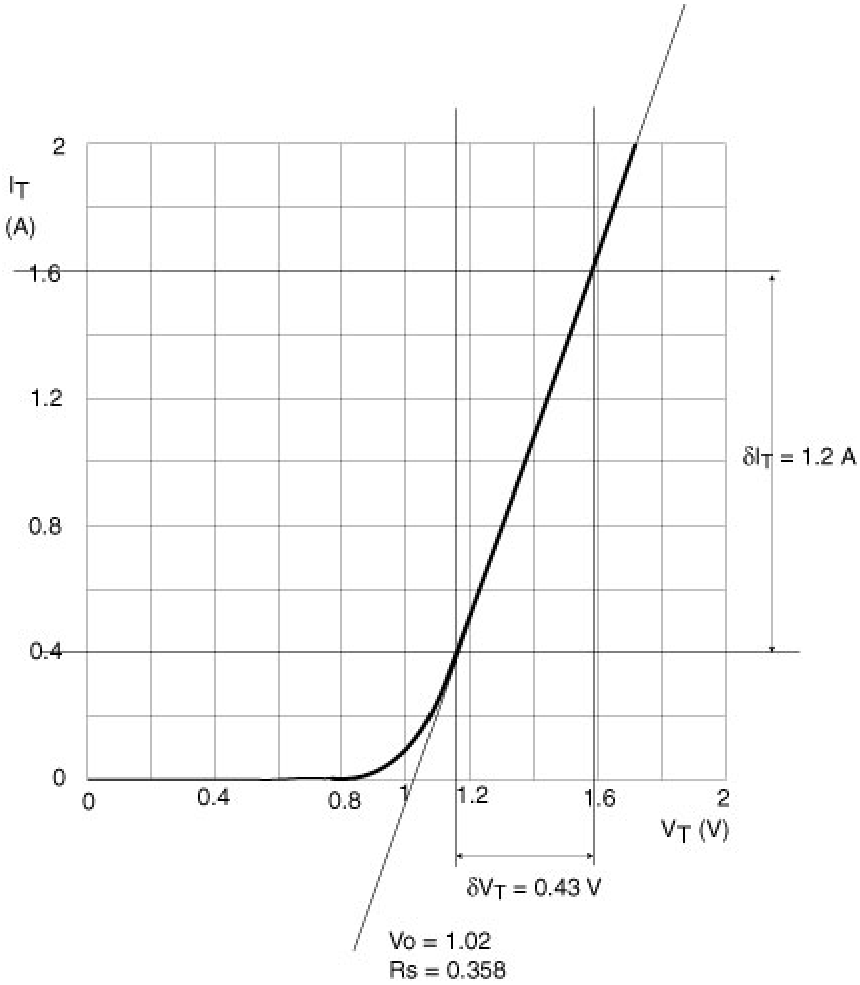

Fig 2. Using the tangent method to calculate V_o and R_s. (Note: For worst-case conditions and a hot triac, always use the "max V_T @ $T_j$max" curve.)

3. Calculating $T_j$max

$T_j$max is influenced by ambient temperature, triac power dissipation and the thermal resistance between junction and ambient. For this Application Note, only the steady state condition will be considered. [In the short-term transient condition, transient thermal impedance (Z_{th}) applies. This will always be lower than the steady-state thermal resistance (R_{th}). The transient condition is a lot more complicated and beyond the scope of this guide.]

$$T_j = T_a + P \times R_{thj-a} \quad (6)$$

T_j – junction temperature (°C).

T_a – ambient temperature (°C).

P – triac power dissipation (W).

$R_{th\,j\text{-}a}$ – junction-to-ambient thermal resistance (°C/W).

3.1 Analysis of $R_{th\ j\text{-}a}$

Thermal resistance is similar to electrical resistance in that the total resistance can be broken down into several smaller resistances in series. For the most popular package (TO220), $R_{th\ j\text{-}a}$ is composed of the following resistances:

$$R_{thj-a} = R_{thj-mb} + R_{thmb-hs} + R_{thhs-a} \quad (7)$$

Figure 3 shows thermal resistance broken down in pictorial form.

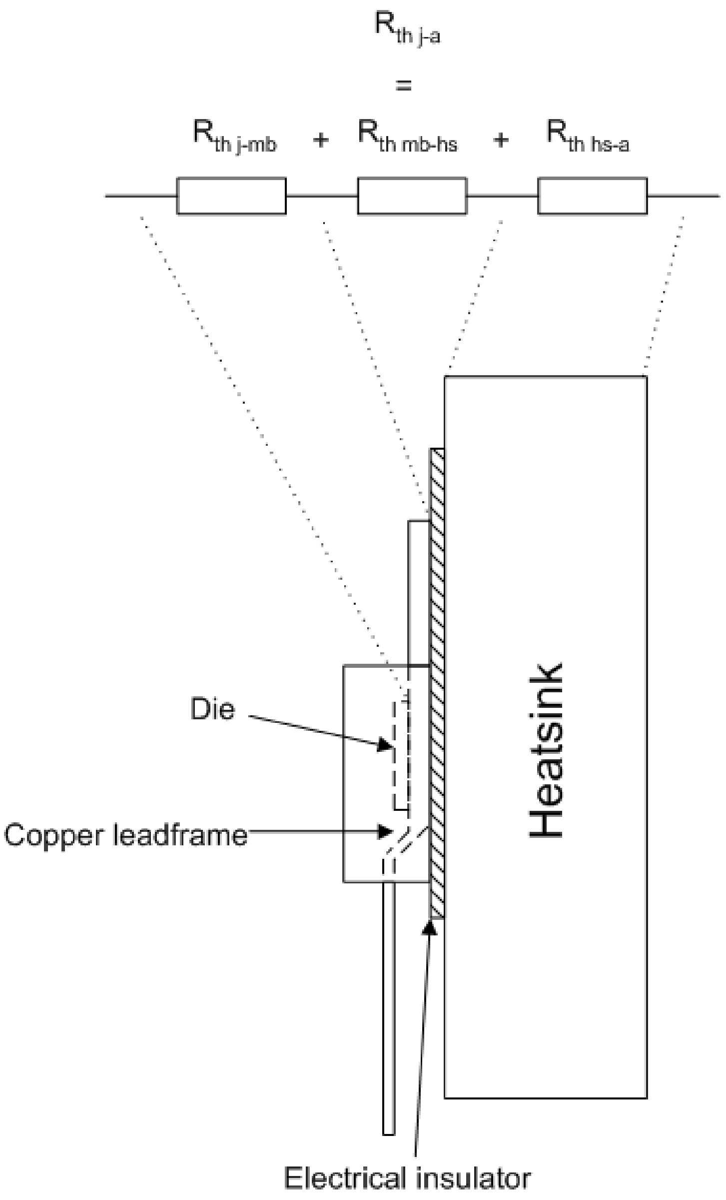

Fig 3. Composition of thermal resistance for the TO220 package.

$R_{th\ j\text{-}mb}$ – junction-to-mounting base thermal resistance (°C/W). This is fixed and governed by the device as it is influenced by die size. Refer to the relevant data sheet for the exact value.

$R_{th\ mb\text{-}hs}$ – mounting base-to-heatsink thermal resistance (°C/W). This is controlled by the equipment manufacturer because it is governed by the mounting method – e.g. with or without thermal grease, screw or clip mounted, insulating pad material, etc.

$R_{th\ hs\text{-}a}$ – heatsink-to-ambient thermal resistance (°C/W). This is governed by the application and is under the sole control of the equipment manufacturer.

Please note that there are some important caveats in the way the thermal resistance is specified because it depends on the package type and the practicality of isolating a metallic thermal reference point.

1. For plastic packages without a metal mounting base, $R_{th\ j\text{-}mb}$ + $R_{th\ mb\text{-}hs}$ is replaced by a single spec of $R_{th\ j\text{-}hs}$, since the heatsink is the nearest metallic reference point.
2. For low power plastic packages where a heatsink would not be used, only $R_{th\ j\text{-}lead}$ is specified, since the leads are the nearest metallic reference point. Most of the heat would be conducted through the leads to the PCB, with a little radiated directly from the package to ambient. For these packages we would specify a total $R_{th\ j\text{-}a}$ with certain assumptions about how the device is mounted on the PCB, which represent typical use.
3. For some surface mount packages without a mounting base but a *solder point* instead, $R_{th\ j\text{-}mb}$ is replaced by $R_{th\ j\text{-}sp}$. For these packages we would specify a total $R_{th\ j\text{-}a}$ when the device is mounted onto a PCB with a specified area of copper.

Table 1 lists the Philips triac packages and the means of specifying their thermal resistance. Thermal resistance values are given wherever they are fixed by the package type or mounting method. If the thermal resistance is influenced by the triac die, the correct value can be obtained from the data sheet.

Table 1: Philips triac packages and their thermal resistance specs.

Package type	Thermal resistance spec	Value (°C/W)
SOT54 (TO92)	$R_{th\ j\text{-}lead}$ $R_{th\ j\text{-}a}$ (PCB mounted, lead length = 4 mm)	60 150
SOT78 (TO220)	$R_{th\ j\text{-}mb}$ $R_{th\ mb\text{-}hs}$ (clip, with grease, no insulator) $R_{th\ mb\text{-}hs}$ (screw, with grease, no insulator) $R_{th\ mb\text{-}hs}$ (clip, no grease, no insulator) $R_{th\ mb\text{-}hs}$ (screw, no grease, no insulator) $R_{th\ mb\text{-}hs}$ (clip, with grease, 0.1 mm mica insulator) $R_{th\ mb\text{-}hs}$ (clip, with grease, 0.25 mm alumina insulator) $R_{th\ mb\text{-}hs}$ (screw, with grease, 0.05 mm mica insulator) $R_{th\ mb\text{-}hs}$ (screw, no grease, 0.05 mm mica insulator) $R_{th\ j\text{-}a}$ (free air without heatsink)	See data sheet 0.3 0.5 1.4 1.4 2.2 0.8 1.6 4.5 60
SOT82	$R_{th\ j\text{-}mb}$ $R_{th\ mb\text{-}hs}$ (clip, with grease, no insulator) $R_{th\ mb\text{-}hs}$ (clip, no grease, no insulator) $R_{th\ mb\text{-}hs}$ (clip, with grease, 0.1 mm mica insulator) $R_{th\ mb\text{-}hs}$ (clip, no grease, 0.1 mm mica insulator) $R_{th\ j\text{-}a}$ (free air without heatsink)	See data sheet 0.4 2.0 2.0 5.0 100
SOT186A (plastic TO220)	$R_{th\ j\text{-}hs}$ (with grease) $R_{th\ j\text{-}hs}$ (no grease) $R_{th\ j\text{-}a}$ (free air without heatsink)	See data sheet See data sheet 55
SOT223	$R_{th\ j\text{-}sp}$ $R_{th\ j\text{-}a}$ (free air, minimum pad area, FR4 PCB)	See data sheet 150 typ.
SOT404 (D^2PAK)	$R_{th\ j\text{-}mb}$ $R_{th\ j\text{-}a}$ (free air, minimum pad area, FR4 PCB)	See data sheet 55 typ.
SOT428 (DPAK)	$R_{th\ j\text{-}mb}$ $R_{th\ j\text{-}a}$ (free air, minimum pad area, FR4 PCB)	See data sheet 75 typ.

4. Worked examples

4.1 Vacuum cleaner

A triac is used in a phase control circuit to control the speed of a vacuum cleaner motor. Confirm by calculating for worst-case conditions that the triac's $T_j$max of 125 °C will not be exceeded.

Application information:

Motor power = 1.2 kW max.

Mains supply = 230 V RMS.

$$\therefore I_{T(RMS)} = \frac{P}{V} = \frac{1200}{230} = 5.22A$$

The triac is clamped to the die-cast metal housing of the turbine, without thermal grease, for heatsinking purposes. Therefore an insulated triac package is required.

Maximum heatsink temperature is 80 °C.

Calculations:

A 12 A Hi-Com triac is recommended to cope with the inrush current, which can be very high in this application. The suggested triac is BTA212X-600B, which uses the isolated SOT186A package, suitable for heatsinking directly to the turbine housing. Its I_{GT} of 50 mA is well matched to the drive circuit.

Using equation 2,

$$I_{T(AVE)} = \frac{2 \times \sqrt{2} \times I_{T(RMS)}}{\pi} = \frac{2 \times \sqrt{2} \times 5.22}{\pi} = 4.70A$$

From the data sheet, V_o = 1.175 V and R_s = 0.0316 Ω.

Using equation 1,

$$P = V_o \times I_{T(AVE)} + R_s \times I_{T(RMS)}{}^2 = 1.175 \times 4.70 + 0.0316 \times 5.22^2 = 6.38W$$

Using equation 7,

$$R_{thj-a} = R_{thj-mb} + R_{thmb-hs} + R_{thhs-a}$$

From the data sheet, $R_{th\ j\text{-}hs}$ = 5.5 °C/W without heatsink compound.

$R_{th\ hs\text{-}a}$ can be regarded as zero, since the turbine housing acts as an infinite heatsink with a maximum temperature fixed at 80 °C under worst-case airflow conditions.

Therefore Rth j-a is 5.5 °C/W.

Using equation 6,

$$T_j = T_a + P \times R_{thj-a} = 80 + 6.38 \times 5.5 = 115°C$$

This is below $T_j$max of 125 °C, therefore acceptable.

4.2 Refrigerator compressor

A triac is used in an electronic thermostat that controls the ON-OFF switching of a refrigerator compressor. What maximum heatsink thermal resistance is allowed to keep the triac's junction temperature within its $T_j$max of 125 °C?

Application information:

Steady state motor current = 1.4 A RMS.

Maximum inrush current = 17 A peak in the first half cycle.

Mains supply = 230 V RMS.

A surface mounted triac is required for direct soldering to the controller PCB.

Maximum ambient temperature is 40 °C.

The triac gate is triggered from a microcontroller with 20 mA current sink capability.

Calculations:

An 8 A Hi-Com triac is recommended to cope with the inrush current. The suggested triac is BTA208S-600E, which uses the SOT428 (DPAK) package. Its I_{GT} of 10 mA is well matched to the drive capability of the microcontroller.

Using equation 2,

$$I_{T(AVE)} = \frac{2 \times \sqrt{2} \times I_{T(RMS)}}{\pi} = \frac{2 \times \sqrt{2} \times 1.4}{\pi} = 1.26A$$

From the data sheet, V_o = 1.264 V and R_s = 0.0378 Ω.

Using equation 1,

$$P = V_o \times I_{T(AVE)} + R_s \times I_{T(RMS)}^{\;2} = 1.264 \times 1.26 + 0.0378 \times 1.4^2 = 1.67W$$

Using equation 6,

$$T_j = T_a + P \times R_{thj-a}$$

We already know that T_a = 40 °C and P = 1.67 W, and in this case, $T_j = T_j$max = 125 °C.

Rearranging the equation gives

$$R_{thj-a} = \frac{T_j - T_a}{P} = \frac{125 - 40}{1.67} = 51°C/W$$

Using equation 7,

$$R_{thj-a} = R_{thj-mb} + R_{thmb-hs} + R_{thhs-a}$$

From the data sheet, $R_{th\ j\text{-}mb}$ = 2 °C/W. We need to find $R_{th\ mb\text{-}a}$.

Rearranging the equation gives

$$R_{thmb-a} = R_{thj-a} - R_{thj-mb} = 51 - 2 = 49°C/W$$

This is effectively the “heatsink” thermal resistance, since the PCB is our heatsink in this case.

As an approximate guide, this thermal resistance can be obtained with a copper pad area of 500 mm^2 (refer to Philips Application Note “Surface mounted triacs and thyristors”, document order number 9397 750 02622).

Please note that the actual thermal resistance will be reduced by other, non-dissipating components in close proximity to the triac, while it will be increased by any components that dissipate power in the presence of the triac. It is essential therefore to measure the prototype to discover the true thermal performance.

4.3 Top-loading (Vertical Axis) washing machine

The machine uses a reversing induction motor that's controlled by two triacs. Will the triacs' $T_j$max of 125 °C be exceeded if they are operated without a heatsink?

Application information:

Full load motor power = 300 W.

Mains supply = 230 V RMS.

$$\therefore I_{T(RMS)} = \frac{P}{V} = \frac{300}{230} = 1.3A$$

Isolated triac package is required.

Maximum ambient temperature is 40 °C.

Calculations:

This application requires 1000 V triacs to withstand the high AC mains voltage that the motor imposes across them. A three-quadrant design is mandatory for maximum immunity to false triggering. The BTA208X-1000C or BTA208B-1000C is recommended. These are 8 A, 1000 V, Hi-Com triacs with I_{GT} of 35 mA. They use the SOT186A all-plastic insulated package and SOT404 (D^2PAK) surface mount package respectively.

Using equation 2,

$$I_{T(AVE)} = \frac{2 \times \sqrt{2} \times I_{T(RMS)}}{\pi} = \frac{2 \times \sqrt{2} \times 1.3}{\pi} = 1.17A$$

From the data sheet, V_o = 1.216 V and R_s = 0.0416 Ω.

Using equation 1,

$$P = V_o \times I_{T(AVE)} + R_s \times I_{T(RMS)}{}^2 = 1.216 \times 1.17 + 0.0416 \times 1.3^2 = 1.49W$$

Using equation 6,

$$T_j = T_a + P \times R_{thj-a}$$

We already know that T_a = 40 °C and P = 1.49 W.

From the data sheet, $R_{th\,j\text{-}a}$ for the SOT186A package in free air is 55 °C/W.

$$\therefore T_j = 40 + 1.49 \times 55 = 122°C$$

This is below the $T_j$max of 125 °C. Therefore the triacs can be operated without heatsinks.

4.4 Power tool

A heavy-duty electric drill uses a universal (brush) motor whose speed is controlled by a half-wave phase control circuit. Calculate the maximum power dissipation in the Silicon Controlled Rectifier and calculate the heatsink thermal resistance required to maintain the junction temperature below $T_j$max.

Application information:

Maximum peak value of motor current = 5 A.

A surface mounted triac is required for mounting within the trigger switch.

Maximum ambient temperature is 50 °C.

The SCR is air-cooled from the motor cooling fan.

Calculations:

The BTH151S-650R is recommended. Its 12 A RMS rating and ruggedised internal construction provide a high repetitive surge guarantee for the best reliability in repetitive overload situations. It uses the SOT428 (DPAK) package.

Using equation 3,

$$I_{T(AVE)} = \frac{I_{pk}}{\pi} = \frac{5}{\pi} = 1.59A$$

Using equation 5,

$$\therefore I_{T(RMS)} = \frac{I_{pk}}{2} = \frac{5}{2} = 2.5A$$

From the data sheet, V_o = 1.06V and R_s = 0.0304Ω.

Using equation 1,

$$P = V_o \times I_{T(AVE)} + R_s \times I_{T(RMS)}{}^2 = 1.06 \times 1.59 + 0.0304 \times 2.5^2 = 1.88W$$

Using equation 6,

$$T_j = T_a + P \times R_{thj-a}$$

We already know that T_a = 50°C and P = 1.88W, and in this case, T_j = $T_j$max = 125°C.

Rearranging the equation gives

$$R_{thj-a} = \frac{T_j - T_a}{P} = \frac{125 - 50}{1.88} = 39.9°C/W$$

Using equation 7,

$$R_{thj-a} = R_{thj-mb} + R_{thmb-hs} + R_{thhs-a}$$

From the data sheet, $R_{th\ j\text{-}mb}$ = 1.8°C/W. We need to find $R_{th\ mb\text{-}a}$.

Rearranging the equation gives

$$R_{thmb-a} = R_{thj-a} - R_{thj-mb} = 39.9 - 1.8 = 38.1°C/W$$

This “heatsink” thermal resistance covers the steady-state condition and is easily achievable with a small degree of airflow through the switch module.

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6. Contents

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