



BSI Standards Publication

Study for the derating curve of surface mount fixed resistors - Derating curves based on terminal part temperature

National foreword

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TECHNICAL REPORT

Study for the derating curve of surface mount fixed resistors – Derating curves based on terminal part temperature

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

**STUDY FOR THE DERATING CURVE
OF SURFACE MOUNT FIXED RESISTORS –****Derating curves based on terminal part temperature****FOREWORD**

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IEC TR 63091, which is a technical report, has been prepared by IEC technical committee 40: Capacitors and resistors for electronic equipment.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
40/2502/DTR	40/2532/RVDTR

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "<http://webstore.iec.ch>" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

INTRODUCTION

Work began in 2012 to adopt the new derating curve suitable for the surface mount fixed resistors that use the terminal part temperature as the horizontal axis.

The derating curves for surface mount fixed resistors are defined in JIS C 5201-8:2014.

However, the principle of the derating curve was established when the resistors were cylindrically shaped, wired in the air and the heat was dissipated directly from the resistor body into the ambient environment. Therefore, it is not suitable for the surface mount fixed resistors that use the printed circuit boards as the main heat path.

It is necessary to fulfill the demands from the electric and electronic device manufacturers for raising the power ratings safely. Additionally, it is required to establish a new derating curve that is suitable for the surface mount fixed resistors so that they can be used safely in a high temperature environment, typically in automotive electronic devices.

Making a change of the temperature rule for evaluation of the fixed resistors from the ambient temperature to the temperature of the connection point (terminal part temperature of the resistor) will affect many defined contents of multiple standards in the IEC 60115 series. Additionally, it will mean changing the users' evaluation rules, so the impact will be enormous. Therefore, it has been decided to issue the Technical Report first to attract attention of the relevant market players and then, we will start working on changing the defined contents of the IEC 60115 series.

STUDY FOR THE DERATING CURVE OF SURFACE MOUNT FIXED RESISTORS –

Derating curves based on terminal part temperature

1 Scope

This Technical Report is applicable to SMD resistors with sizes equal or smaller than the RR6332M, including the typical rectangular and cylindrical SMD resistors mentioned in IEC 60115-8.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60115-1:2008, *Fixed resistors for use in electronic equipment – Part 1: Generic specification*

IEC 60115-8:2009, *Fixed resistors for use in electronic equipment – Part 8: Sectional specification: Fixed chip resistors*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <http://www.electropedia.org/>
- ISO Online browsing platform: available at <http://www.iso.org/obp>

3.1

terminal part temperature

T_t

temperature of terminal part of the resistor

3.2

rated terminal part temperature

terminal part temperature of the resistor at the time of the rated load life test

3.3

hotspot of the resistor

hottest part of the resistor that is caused by the Joule heat generated from the resistive element when the current is applied and is generally located inside resistor's body

3.4

hotspot temperature

T_{hs}

temperature of the internal hotspot of the resistor

3.5**surface hotspot of the resistor**

hottest part on the surface of the resistor generally near the hotspot

3.6**surface hotspot temperature** T_{shs}

temperature of the surface hotspot of the resistor

Note 1 to entry: Generally, the internal hotspot temperature is higher than the surface hotspot temperature.

3.7**thermal resistance of the resistor** R_{th}

restraint of the thermal flow from the resistor's hotspot to the environment

Note 1 to entry: Thermal resistance is calculated by dividing the difference between the surface hotspot temperature T_{shs} and the terminal part temperature T_t by the applied power P and usually expressed in K/W.

3.8**thermally sensitive point temperature** T_{sp}

temperature of the part the most sensitive to temperature rise in the resistor

3.9**maximum allowable temperature****MAT**

ideal maximum temperature at which the resistor is able to keep its function

3.10**maximum terminal part temperature****MTT**

maximum temperature of the terminal part of the resistor

4 Study for the derating curve of surface mount fixed resistors**4.1 General**

The electric/electronic device designers are reducing the power applied to the resistor below the level shown in the derating curves provided by the resistor manufacturer based on the ambient temperature of the unloaded resistor, but the ambient temperature of the board rises when they use SMD resistors.

But, the body temperature of the SMD resistor may become higher than the temperature verified in the test implemented by the resistor manufacturer even when this rule is observed. On the other hand, in some cases excessive derating is requested and an extremely large margin is set.

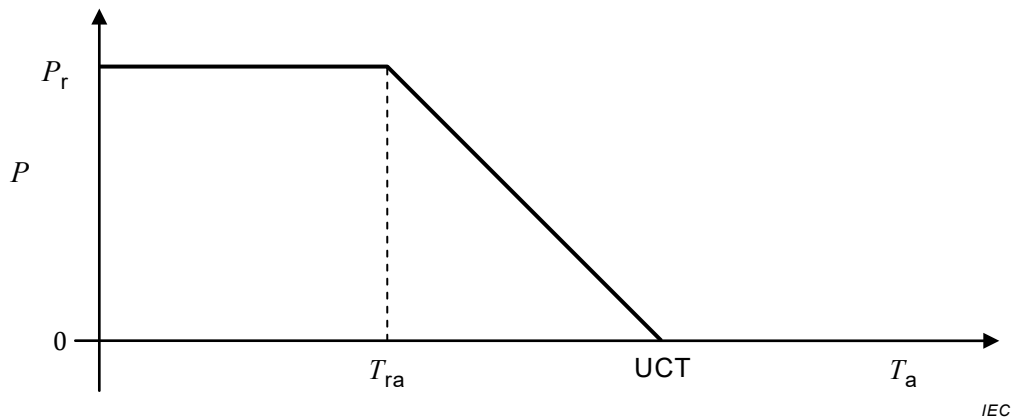
In this Technical Report, the reasons why the derating curves, which are defined in 2.2.4 of IEC 60115-1:2008 and in 2.2.3 of IEC 60115-8:2009, provided by the resistor manufacturers sometimes cannot be used by electric/electronic device designers in their design activity will be given, and the method of changing them into a practical designing tool will be suggested.

There are three key points. The first and most important point is to use the derating curve based on the terminal temperature instead of the ambient temperature. The second point is the measuring method of the terminal part temperature of the SMD mounted on the printed circuit board. The third point is the measuring method of the thermal resistance $R_{th,shs-t}$ of the

resistor terminal part to the surface hotspot. The second and third points are the issues that need to be defined in association with the first point.

4.2 Using the derating curve based on the terminal part temperature

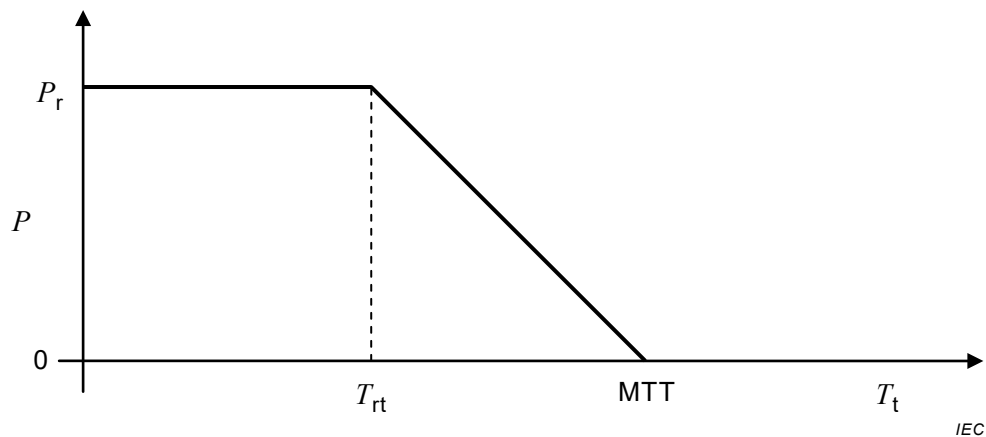
Using Figure 2 instead of Figure 1 is suggested for the design of high-power applications of the SMD resistors in excess of the conventional rated dissipation (e.g. 100 mW for RR1608M). The validity of using the derating curve based on the terminal part temperature is explained in Annex E.



Key

P	Applied power
P_r	Rated power
T_a	Ambient temperature
UCT	Upper category temperature
T_{ra}	Rated ambient temperature

Figure 1 – Existing derating curve based on ambient temperature



Key

P	Applied power
P_r	Rated power
T_t	Terminal part temperature
MTT	Maximum terminal temperature
T_{rt}	Rated terminal temperature

Figure 2 – Suggested derating curve based on terminal temperature

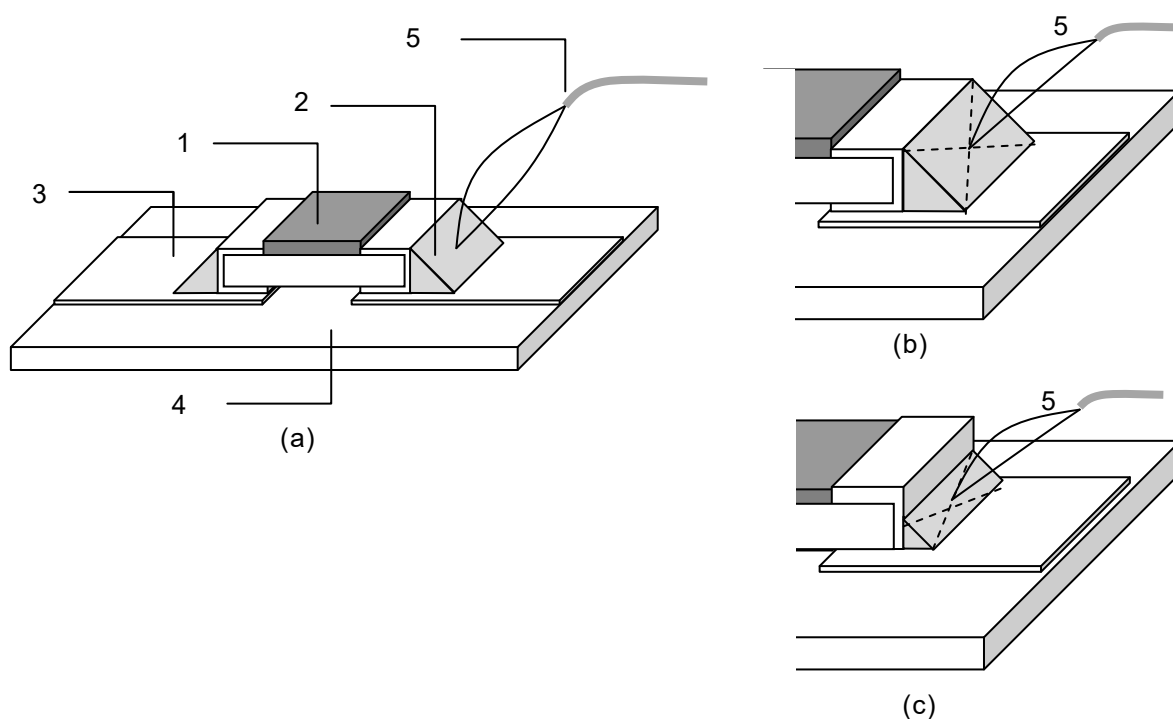
4.3 Measuring method of the terminal part temperature of the SMD resistor

The measurement will be done on the commonly-used printed circuit board, but the resistor manufacturer can replace it with the board defined in the standard. The temperature measurement position will be the centre part of the fillet regardless of the size. The measurement sensor will be the thermocouple. The measurement point is shown in Figure 3.

A type K thermocouple with a wire diameter (single wire) of 0,1 mm is recommended. As in Figure 4, the tips of the type K thermocouple should be spot-welded and pre-treated by applying suitable flux and dipped in melted solder so that it can be surely and directly soldered to the fillet of the target resistor.

This report is based on the use of type K thermocouples due to their low thermal conductivity. If other thermocouples are to be used, their thermal properties need to be considered, as shown for type T thermocouples in Annex I.

The measured value should be corrected as necessary by estimating the influence of the heat dissipation through the thermocouple. The method will be mentioned in Formula (1).

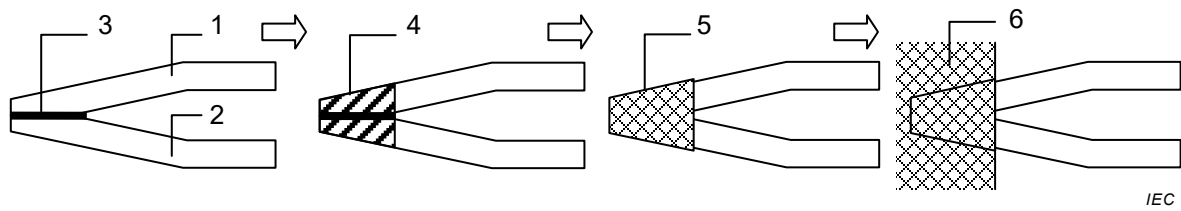


IEC

Key

- 1 Resistor
- 2 Solder fillet
- 3 Copper pattern
- 4 Printed board
- 5 Thermocouple (Tip is the measuring point)
- (b) Attachment position of the thermocouple when fillet is large (centre of solder meniscus)
- (c) Attachment position of the thermocouple when fillet is small (centre of solder meniscus)

Figure 3 – Attachment position of the thermocouple when measuring the temperature of the terminal part

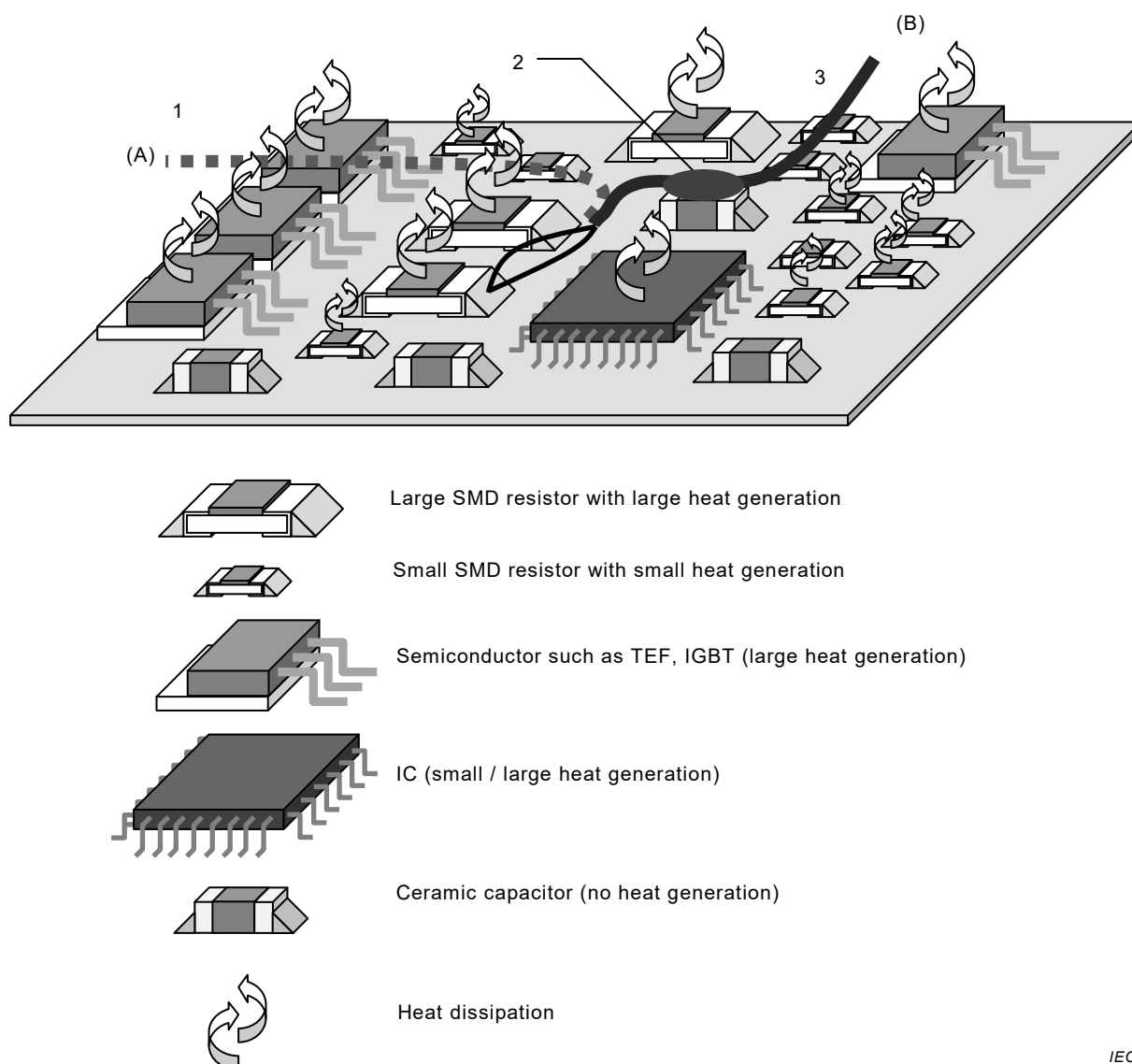


Key

- 1 Thermocouple wire (alumel wire)
- 2 Thermocouple wire (chromel wire)
- 3 Spot-welded part
- 4 Flux-coated part
- 5 Dipped in melted solder
- 6 Connected to the fillet

Figure 4 – Attaching type K thermocouples

The thermocouple connected to the measuring point will be wired along the isothermal line. When the isothermal line is unknown, make sure that the thermocouple is not affected directly by other heat-generating products on the board. The thermocouple should not be closely-attached with other products or the board, and they should be wired parallel to the board as shown in Figure 5.



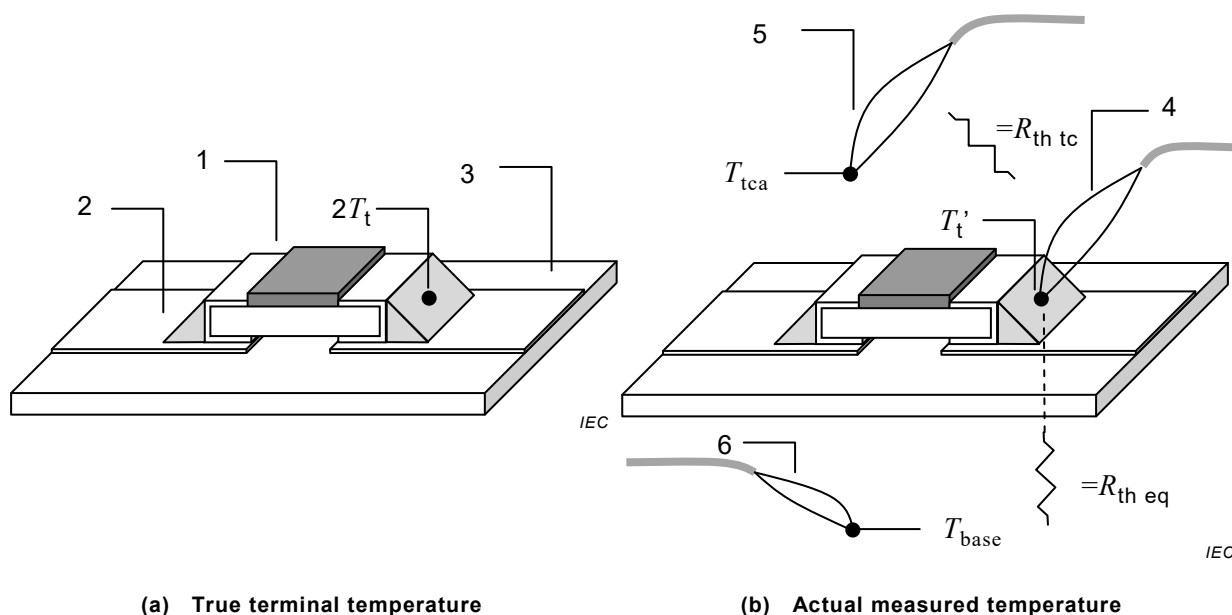
IEC

Key

- 1 Wiring close to the parts with large heat generation such as the dotted line shall be avoided.
 - 2 No mechanical strength when only the tip of the thermocouple is soldered, so fix the wiring and trunking onto the parts with no heat generation.
 - 3 Avoid the heat generating parts when wiring.
- (A) Inadequate wiring.
- (B) Suitable wiring.

Figure 5 – Wiring routing of the thermocouple

Next, the temperature drop caused by the heat dissipation from the thermocouple will be estimated by comparing the measured temperature T_t' and the true value T_t when there is no thermocouple connected. Each symbol will be shown in Figure 6 (refer to Figure 9 for the example of T_{base}).



Key

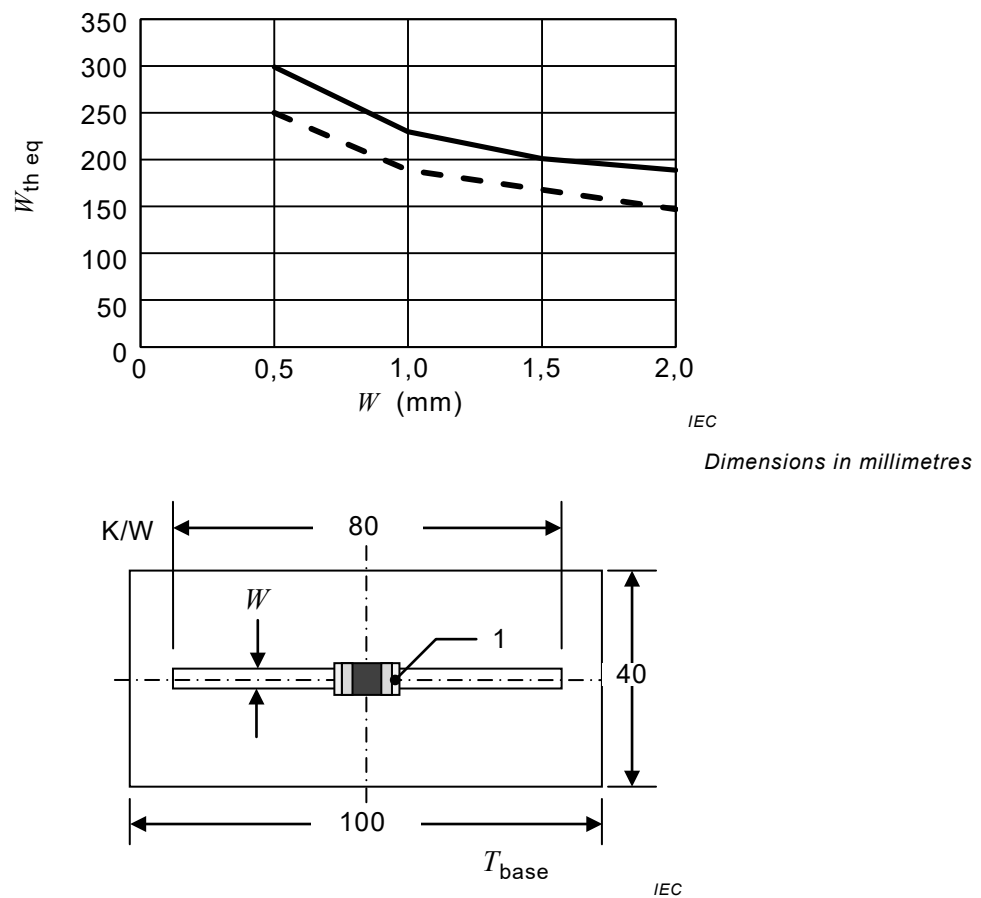
- 1 Resistor
- 2 Copper pattern
- 3 Printed board
- 4 Thermocouple for measuring the terminal part temperature
- 5 Thermocouple for measuring the heat dissipation space temperature
- 6 Thermocouple for measuring the standard temperature
- T_t Fillet temperature (centre part) before attaching the thermocouple = true terminal temperature
- T'_t Fillet temperature (centre part) after attaching the thermocouple = actual measured terminal part temperature
- T_{base} Temperature of the base position for measuring the temperature rise
- T_{tca} Temperature of the space where the thermocouple radiates and not always equivalent to T_{base}
- $R_{th\ tc}$ Thermal resistance when the thermocouple is presumed as a heatsink and the thermal resistance between the tip of the thermocouple and the heat dissipation space of the thermocouple (T_{tca} measurement position)
- $R_{th\ eq}$ Thermal resistance of the printed board viewed from the terminal part and the equivalent thermal resistance between the terminal part where the thermocouple is connected and the standard temperature measured space (T_{base} measurement position)

Figure 6 – The true value and the actual measured value of the terminal part temperature

The temperature that is actually measured by the thermocouple is T'_t and the T_t cannot be measured. But the difference $\Delta T = T_t - T'_t (\geq 0)$ can be calculated from Formula (1).

$$\Delta T = (T_t - T_{tca}) (R_{th\ eq} / R_{th\ tc}) \quad (1)$$

$R_{th\ eq}$ is the thermal resistance from the terminal part of the printed circuit board to the surrounding space, set as a standard, such as the spatial temperature in which the board is set. An example value is shown in Figure 7.

**Key**

- Pattern thickness 35 μm
- - - Pattern thickness 70 μm
- T_{base} Temperature standard (ambient temperature where the board is set)
- $R_{th eq}$ Equivalent thermal resistance of the printed board to the temperature standard T_{base}
- 1 Thermal resistance measuring point
- W Pattern width

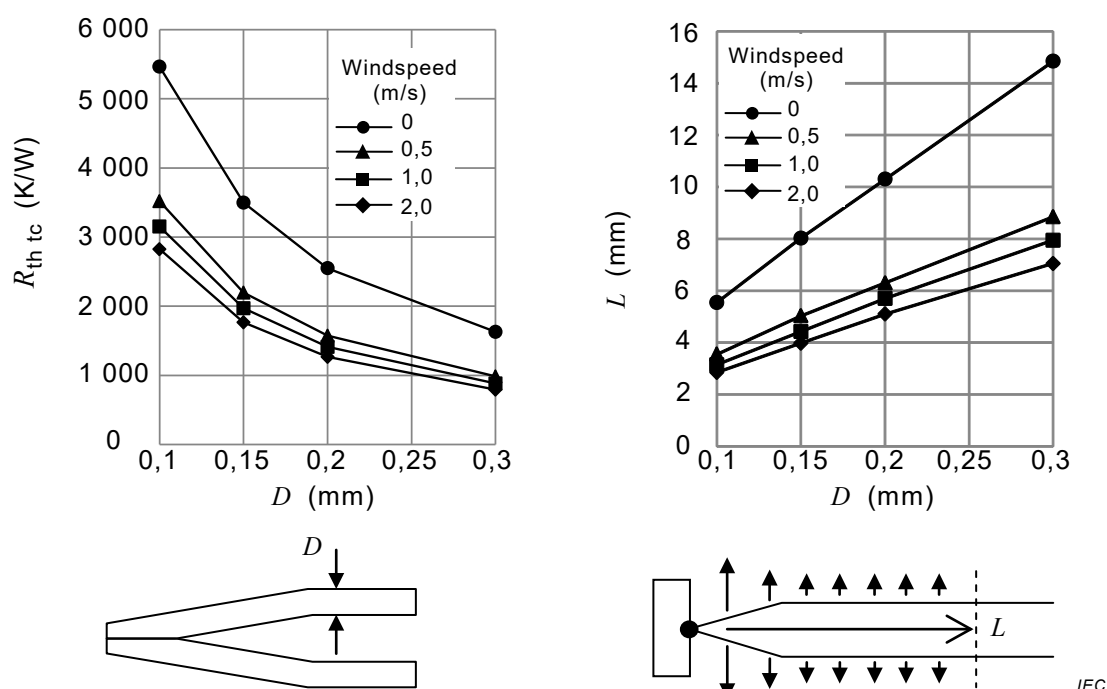
Figure 7 – Thermal resistance $R_{th eq}$ of the FR4 single side board (thickness 1,6 mm)

When calculating $R_{th eq}$ on the actual board for measuring the temperature, power P shall be applied only to the target resistor for measuring T_{base} and terminal part temperature T_t' with the thermocouple. Formula (2) shall be used.

$$R_{th \cdot eq} = (T_t' - T_{base}) / P \quad (2)$$

This is only an approximate estimate. However, there will not be a controversial error unless the thermal resistance between the terminals of the resistor itself is extremely large. Refer to Annex I for details.

The length of the thermocouple that causes the heat dissipation is indicated with L . This is the distance from the measuring point that causes 90 % of the heat dissipation from the thermocouple.



Key

- $R_{th\ tc}$ Thermal resistance when the thermocouple is regarded as a heatsink
- L Length from the measurement point that cause the heat dissipation of the thermocouple
- D Wire diameter of the thermocouple

Figure 8 – Length that cause the heat dissipation and the thermal resistance of the type-K thermocouple (calculated)

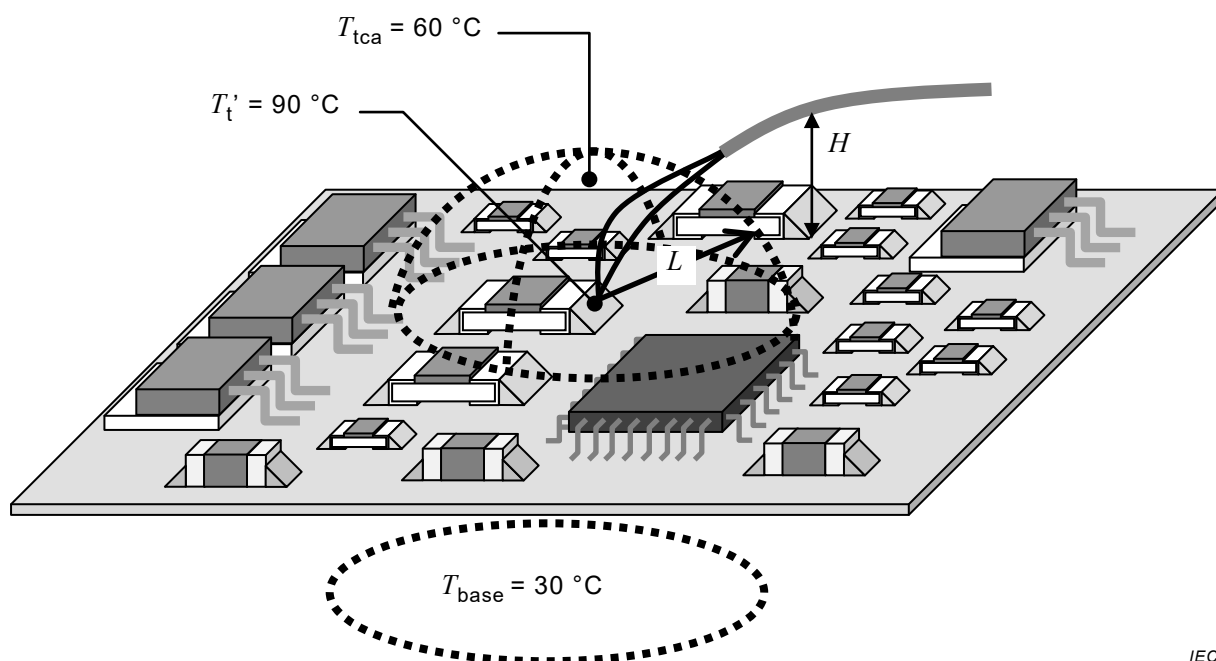
The air speed 0 m/s in Figure 8 means that the thermocouple is set horizontally in a space with no forced air and the heat dissipation is only by natural convection.

For the same type of thermocouples, the thinner the strand of wire diameter is, the higher the thermal resistance is and the length that causes the heat dissipation L gets shorter.

The measuring point of T_{tca} shall be within radius L of the target fillet. Read L from Figure 8. The height from the measuring point T_{tca} of the board will be the same as the height of the wired thermocouple (H in Figure 9) for measuring T_t' .

T_{tca} does not have to be measured one by one for the measuring points of T_t' . All the necessary T_t' should be measured, but only one typical point of the T_{tca} that is expected to have the lowest temperature needs to be measured.

The typical calculation result of ΔT is shown in Figure 9. The place where the board is set is assumed to be a natural convection environment. For the purpose of checking the operating temperature of the resistor, it is understandable when it is actually calculated that ΔT is negligible in most cases when a type K thermocouple of 0,1 mm in diameter is used.



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Calculation example

When $R_{th\ tc} = 5\ 500\ \text{K/W}$, $R_{th\ eq} = 300\ \text{K/W}$

$$\Delta T = (90 - 60) (R_{th\ eq} / R_{th\ tc}) = 1,64\ \text{K}$$

Key

- T'_t Fillet temperature (terminal part temperature) after connecting the thermocouple
- T_{tca} Ambient temperature for the heat dissipation of the thermocouple
- T_{base} Ambient temperature of the board
- L Length from the measurement point that cause the heat dissipation of the thermocouple
- H Height where the thermocouple will be wired

Figure 9 – Example of calculation of the measurement error ΔT caused by the heat dissipation of the thermocouple

However, when type K thermocouples with wires 0,2 mm in diameter or thicker are used, or when there is airflow, ΔT would become larger. It is necessary for the resistor manufacturer and electric/electronic device designers to take on the responsibility and perform the corrections.

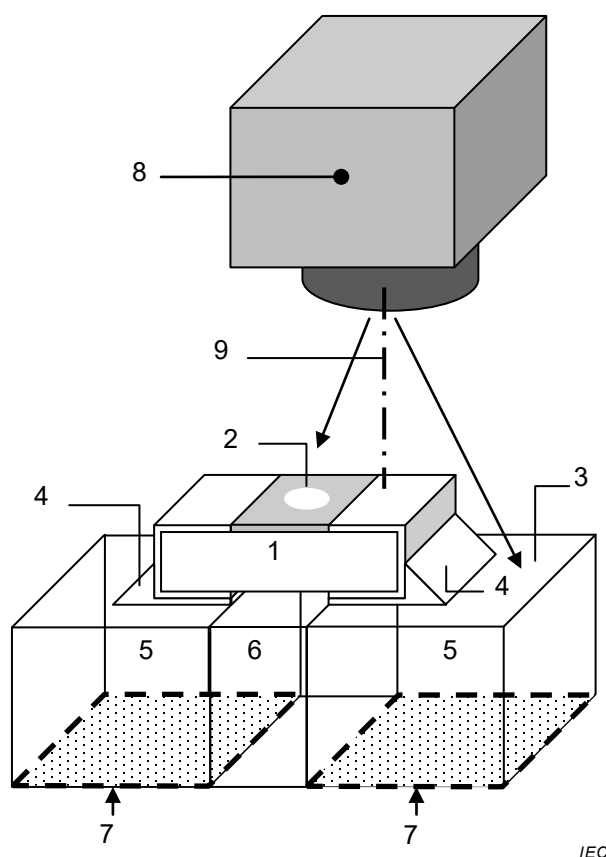
4.4 Measuring method of the thermal resistance $R_{th\ shs-t}$ from the terminal part to the surface hotspot

In this subclause, the measurement method for T_{shs} and T_{tn} will be explained. The difference between T_{shs} (surface hotspot temperature) and T_{tn} (terminal part temperature) divided by P (applied power) is used for calculating the proportional constant $R_{th\ shs-t}$. If T_{shs} and T_{tn} can be measured, $R_{th\ shs-t}$ can be calculated with Formula (3).

$$R_{th\ shs-t} = (T_{shs} - T_{tn}) / P \quad (3)$$

The recommended measuring system is shown in Figure 10.

The copper block on which the resistor is mounted will be an alternative to the idealized infinite heatsink.



Key

- 1 Resistor
- 2 Surface hotspot
- 3 Terminal part temperature measuring point
- 4 Solder fillet
- 5 Copper block larger than square 10 mm on a side rectangular cuboid, power will be applied to the resistor through the copper block
- 6 Insulator with good heat conduction
- 7 Downside of the copper block fixed to a certain temperature
- 8 Infrared thermograph
- 9 Infrared thermograph lens axis

**Figure 10 – Recommended measurement system
of T_{shs} and T_t for calculating $R_{th\ shs-t}$**

Measure the surface hotspot temperature T_{shs} and terminal part temperature T_{tn} directly with an infrared thermograph. The point at which to measure the terminal part temperature T_{tn} should be on the top surface of the copper block and close to the fillet of the resistor (within 3 mm from the fillet excluding the fillet). The points that should be considered during measuring are as follows.

- 1) The space resolution and the peak detection capability of the infrared thermograph is not the same. Select the lens with a magnification percentage that can measure the hotspot peak temperature correctly.
- 2) If the space resolution and hotspot peak detection capability of the infrared thermograph is not clarified, the data shall clearly state which lens was used for magnifying whatever μm per pixel.
- 3) The top surface of the copper block on which the target resistor is mounted and the temperature measured by the infrared thermograph should be coated evenly with black-body sprays to make a diffused surface with constant emissivity.

- 4) Lenses with large magnification have a short focus in general. Therefore, even a small misalignment of the focus could lead to a large error in the temperature measurement. Especially precise adjustment of the focus would be needed when measuring the hotspot of a small area.

4.5 Conclusions

There are 3 points to suggest in this Technical Report, as mentioned in the opening of this clause:

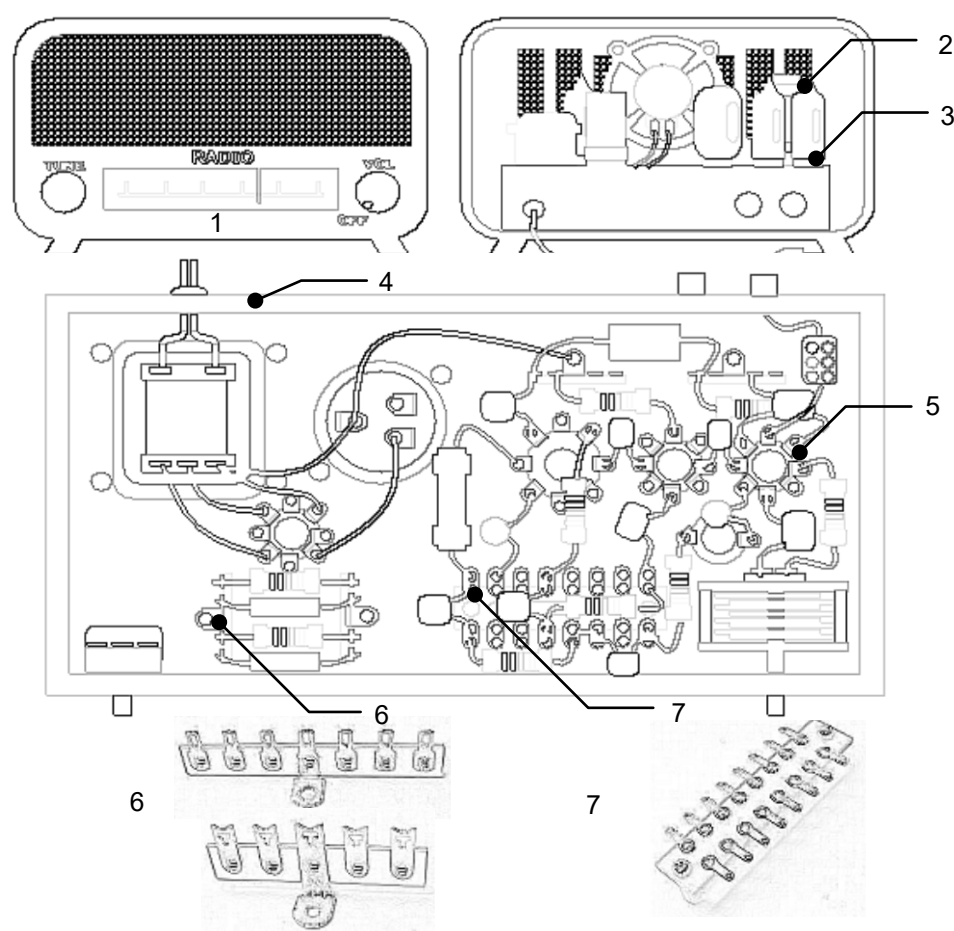
- 1) use of the derating curve based on the terminal temperature instead of the ambient temperature for the design of high power applications of the SMD resistors in excess of the conventional rated dissipation (e.g. 100 mW for RR1608M);
- 2) measurement method of the terminal part temperature of the SMD resistor mounted on the printed board;
- 3) measurement method of the thermal resistance $R_{th\ shs-t}$ from the terminal part of the resistor to the surface hotspot.

Annex A (informative)

Background of the establishment of the derating curve based on ambient temperature

A.1 Tracing the history of the mounting and heat dissipation figuration of resistors

The derating curve that uses the ambient temperature as the horizontal axis was established as a standard more than 50 years ago, at an era when vacuum tubes were being used. As shown in Figure A.1, the resistors in those days were mainly made with lead wires, and lug terminals were used for mounting.



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Key

- 1 Vacuum tube radio broadcasting receiver
- 2 Vacuum tube
- 3 Chassis
- 4 Rear side figure of chassis (image)
- 5 Vacuum tube socket
- 6 Lug terminal (vertical)
- 7 Lug terminal (horizontal)

Figure A.1 – Wired in the air using the lug terminal

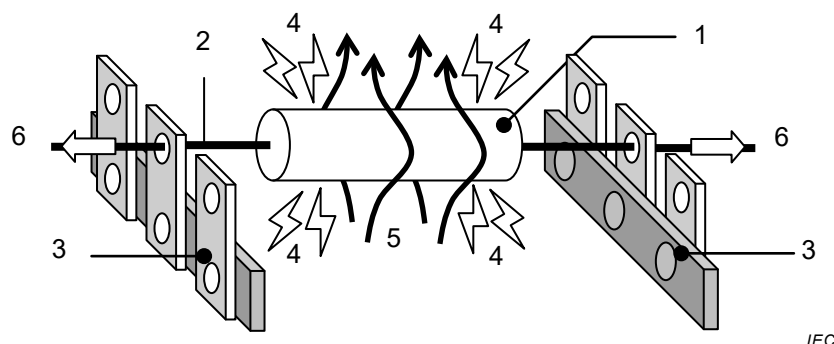
As shown in Figure A.2, all the heat generated in any kind of resistors will be released through the following three phenomena.

The first phenomenon is heat conduction. The heat is conducted through the connection part such as the lead wire to the lug terminals and other parts with lower temperatures.

The second phenomenon is heat transfer by convection to the ambient atmosphere of the resistor. The ambient air is expanded with the heat provided from the resistor and becomes less dense resulting in updraft. The rising air will siphon off the new cool air from the low surrounding to the ambient air of the resistor. By repeating this, an ascending current will consistently occur around the resistor and the heat will be transferred into the atmosphere. This is called heat dissipation by convection flow.

The third phenomenon is radiation by infrared.

Heat dissipation by either of the phenomena (heat conduction, convection and radiation) would be larger when the temperature difference between the resistor and the lead wire and the other parts connected is larger. For the resistors wired in the air by the lug terminal, the heat conduction via the lead wires are small compared with the heat dissipation by convection and radiation. The lead wires are mainly made with copper and the coefficient of thermal conductivity is high but the shape is narrow and long, so the thermal resistance will not be so low. In abbreviated calculation, the thermal resistance of the lead wire 0,8 mm in diameter and 38 mm in length will be 190 K/W, which is quite a large value. On the other hand, the heat dissipation is proportionate to the surface area of the resistor, so the heat dissipation performance from the surface of the cylindrical resistor to the atmosphere will be favourable and the calculated thermal resistance is surprisingly low.



Key

- 1 Resistor
- 2 Lead wire of resistor
- 6 Lug terminal (vertical)
- 4 Heat dissipation by radiation
- 5 Heat dissipation by convection
- 6 Heat dissipation by conduction

Figure A.2 – Heat path when wired in the air using the lug terminal

The numerical simulation was implemented for the heat dissipation ratio of each heat type (conduction, convection and radiation) in the resistor model. The simulation model is a cylindrical resistor of 24,5 mm in body length, 9 mm in body diameter, 0,8 mm in lead wire diameter and 38 mm in lead wire length. This sample was wired in the air under 25 °C with a no-airflow condition and 1 W will be applied. As a result, the heat dissipation ratio was 51 % from convection, 32 % from radiation and the remaining 17 % was from the conduction via the 38 mm lead wire. Since a large portion of the heat dissipation is implemented from the convection and radiation through the atmosphere, it is natural to set the ambient temperature as the standard of the operating resistor.

However, the resistor manufacturer is expected to implement load life tests to verify the characteristics of the resistor, especially the stability under operational condition. The method is to set the lead wire resistor horizontally as if it were floating in the air and apply the rated power in a test chamber with the temperature set at the predetermined value. The heat dissipation ratio is the same as the condition of the actual use by electric/electronic device designers.

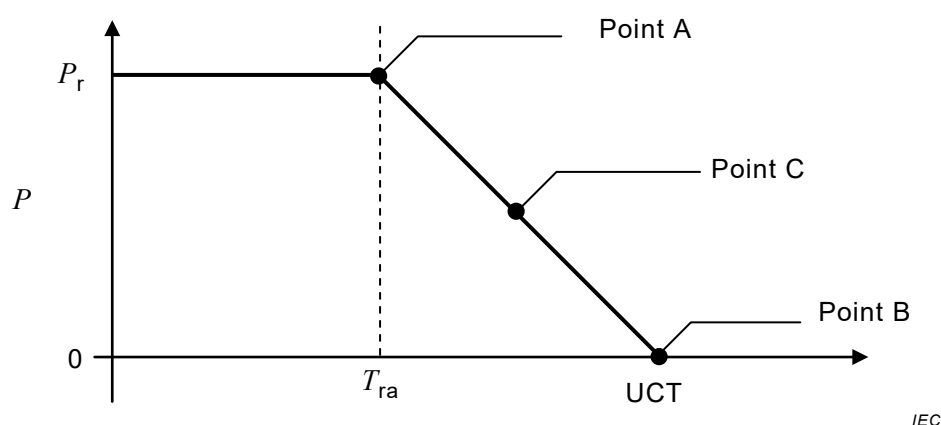
Therefore, introducing the ambient temperature around the resistor as the temperature index to correspond to the test conditions by the resistor manufacturer and the actual use conditions of electric/electronic device designers was reasonable for the mounting conditions of the resistors in those days. Since then, the mounting methods changed to lead wire resistors on printed circuit boards and then SMD resistors. At the same time, miniaturization of the resistor itself has advanced as well. Associated with a change in the mounting methods and miniaturization, the heat dissipation ratio of the heat generated in the resistor has changed. The ratio of the convection and radiation has decreased gradually and the conduction to the printed circuit board has increased. This change summarised in Annex J.

A.2 How to establish the high temperature slope part of the derating curve

A.2.1 General

It is necessary to have a good knowledge of the theoretical base of how the derating curves of resistors are established to understand the content of this technical report. Furthermore, this theoretical base is often misconceived with the analogy of the derating curve for semiconductors.

The derating curve for resistors is established to not exceed the temperature and heat stress that is tested by the resistor manufacturer. It is verified that the resistor can keep its function when the load is reduced as the ambient temperature rises according to the derating curve provided by the resistor manufacturer, even when the thermally sensitive part of the resistor is unknown.



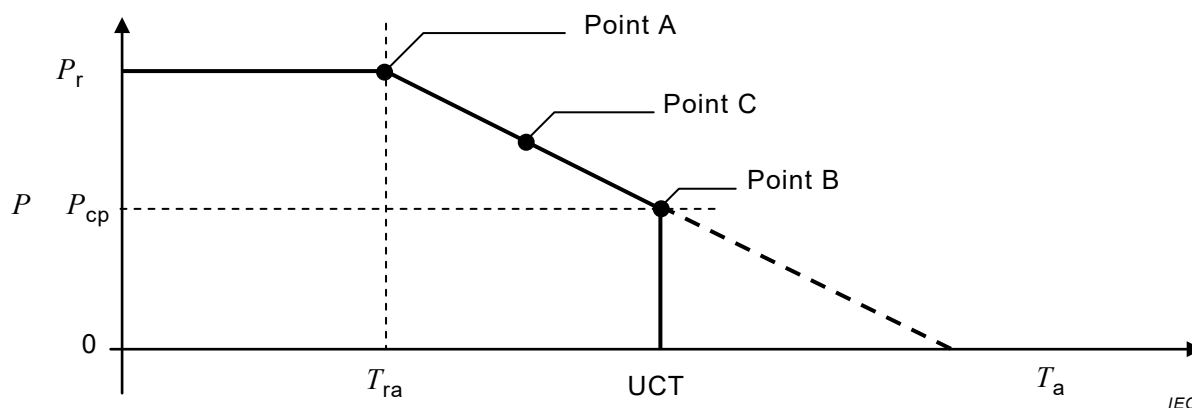
Key

P	Applied power
P_r	Rated power
T_a	Ambient temperature
T_{ra}	Rated ambient temperature (normally 70 °C)
UCT	Upper category temperature
Point A	Load life test condition
Point B	High temperature exposure test condition
Point C	Between Point A and Point B

Figure A.3 – Test condition for resistors with category power 0 W

In principle, the derating curve is established by connecting the two test conditions with a line, the load life test (rated load applied at ambient temperature) and the high-temperature exposure test (UCT without load as shown in Figure A.3) or the test condition of the UCT with the category power loaded as shown in Figure A.4.

Except for special cases, the resistor manufacturers do not test the middle conditions like Point C in Figure A.4. The reason why will be shown in A.2.3.



Key

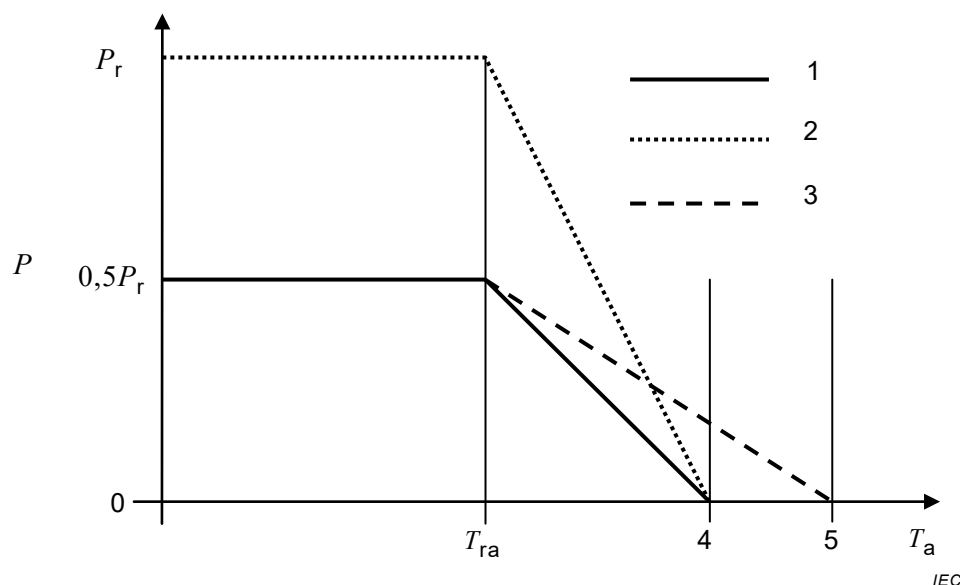
P	Applied power
P_r	Rated power
P_{cp}	Category power (percentage of the rated power)
T_a	Ambient temperature
T_{ra}	Rated ambient temperature (normally 70 °C)
UCT	Upper category temperature
Point A	Load life test condition
Point B	High temperature exposure test condition
Point C	Between Point A and Point B

Figure A.4 – Test condition for resistors with category power other than 0 W

However, it could be predicted that the line formed by 100 % rated power is the electrical limit but, it is possible to double the rated power by changing the test conditions even when using the same resistor as seen in Figure A.5. Therefore, it cannot be said that the present line shown is purely the electrical limit. When the applied power is at its maximum, the temperature difference inside the resistor will also become maximum. The heat stress caused by the temperature gap within the resistor becomes maximum. Therefore, it could be said that this line verified by the resistor manufacturer could be used under a certain condition. Verified under a certain condition means that, when the resistor is used under the condition described in the specification, the characteristics, such as the resistance value change, are kept within the tolerance values.

Additionally, the UCT is also not the genuine temperature limit of the material that makes up the resistor. The UCT is a test condition for rank classification of resistors. Therefore, there are resistors that have no effect on their characteristics even when it gets hotter than the category upper temperature. If the test condition is reviewed and the resistor with a maximum operating temperature of 125 °C is tested in a high temperature exposure test of 155 °C, and the characteristic is verified, it would be possible to change the maximum operating temperature to 155 °C. However, the characteristics of the construction material of each resistor part shall at least be resistant to the UCT.

It is important to know that the derating curve of the resistor is basically determined according to the test results.



Key

- P Applied power
- P_r Rated power
- T_a Ambient temperature
- T_{ra} Rated ambient temperature
- 1 Derating curve before reviewing the rated power
- 2 Derating curve when rated power is raised
- 3 Derating curve when maximum operating temperature is reviewed
- 4 Existing UCT
- 5 Reviewed high UCT

Figure A.5 – Example of reviewing the derating curve

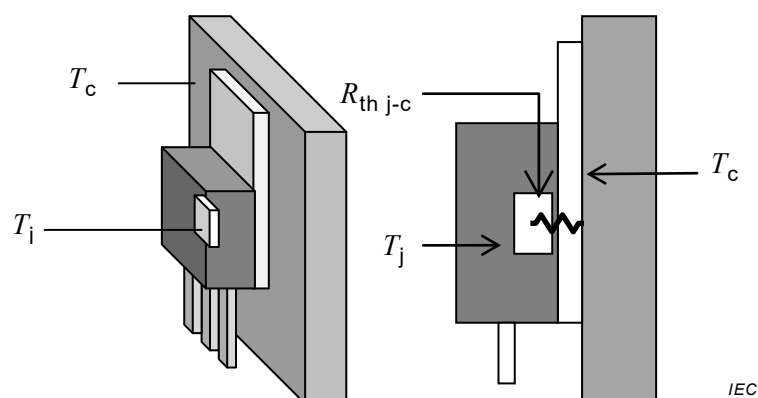
A.2.2 Derating curve for the semiconductors

Given their similar appearance, they are often misunderstood, but it is important to know that the derating curve for resistors and semiconductors are completely different. The semiconductor in the example is a transistor that is used by fitting on a heat sink. The rated power P_r of the transistor is a power that the temperature of the transistor sensitive point will reach the certain limited value when fixed to the heat sink set at 25 °C. The temperature of the sensitive point of the transistor shall not exceed the certain limited value under any circumstances.

The junction temperature of the bipolar transistor and the channel for the field-effect transistor would be the sensitive point that determines the operating temperature limit. The transistor cannot be used when the sensitive point temperature exceeds the defined temperature such as 150 °C (generally 150 °C but some are 175 °C). The sensitive point of temperature rise and the limited temperature are clearly determined for the semiconductors.

The relationship between the case temperature T_c , which the junction temperature T_j does not exceed, the limit temperature T_{j-max} , and the allowable power P that can be applied to the transistor under that case temperature will be considered, using the bipolar transistor as an example in Figure A.6.

The temperature rise ΔT_{j-c} of the case to the junction is assumed to be proportionate to the power P consumed by the transistor. This proportional constant shall be $R_{th\ j-c}$. This $R_{th\ j-c}$ is the thermal resistance between the junction and the case.



Key

T_c Heatsink temperature = case temperature

T_j Junction temperature

$R_{th\ j-c}$ Thermal resistance between the junction and the case including thermal interface material

NOTE $R_{th\ j-c}$ is the thermal resistance of the component

Figure A.6 – T_j , T_c and $R_{th\ j-c}$ of transistors

When power P is applied to the transistor at case temperature T_c , the junction temperature T_j would be calculated as shown in Formula (A.1).

$$T_j = T_c + R_{th\ j-c} P \quad (A.1)$$

This T_j shall always be lower than T_{j-max} . Therefore, the applied power P should be limited in that manner. And the applied power P would be shown as $P(T_c)$ as the function of T_c , as shown in Formula (A.2).

$$T_{j-max} \geq T_c + R_{th\ j-c} P(T_c) \quad (A.2)$$

Transform Formula (A.2) to the following Formula (A.3).

$$P(T_c) \leq (T_{j-max} - T_c) / R_{th\ j-c} \quad (A.3)$$

When $T_c = 25\ ^\circ\text{C}$, $P(T_c)$ is allowed up to the rated power P_r , it can be calculated in Formula (A.4). Then Formula (A.5) is transformed from Formula (A.4).

$$P_r = (T_{j-max} - 25) / R_{th\ j-c} \quad (A.4)$$

$$\Rightarrow R_{th\ j-c} = (T_{j-max} - 25) / P_r \quad (A.5)$$

From Formula (A.3) and Formula (A.5), Formula (A.6) is obtained.

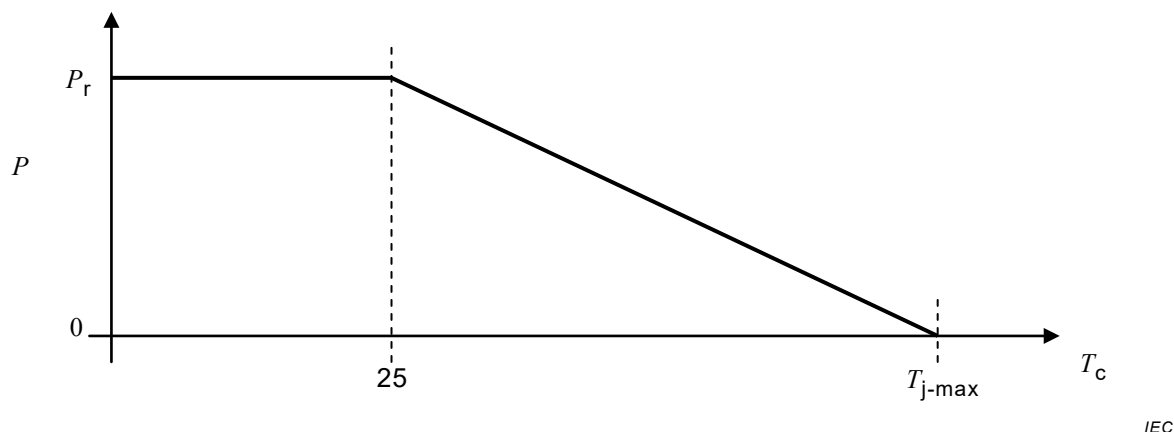
$$P(T_c) \leq P_r (T_{j-\max} - T_c) / (T_{j-\max} - 25) \quad (\text{A.6})$$

However, in the range of $T_c < 25\text{ °C}$, $P(T_c) > P_r$ could be possible in Formula (A.6), but in the document the applied power cannot exceed P_r .

The limited power that the transistor can have applied would be as shown in Formula (A.7) when the above conditions are considered.

$$\left. \begin{aligned} P(T_c) &= P_r (T_{j-\max} - T_c) / (T_{j-\max} - 25) & 25\text{ °C} \leq T_c \leq T_{j-\max} \\ P(T_c) &= P_r & \text{Lower limit of the transistor operating temperature} \leq T_c < 25\text{ °C} \end{aligned} \right\} \quad (\text{A.7})$$

The operating range of the transistor indicated from this formula would be shown as Figure A.7. This figure is often seen in the heat design textbooks for transistors. The transistor shall always be used under the condition that does not exceed the derating curve. This curve looks very alike to the derating curves for resistors.

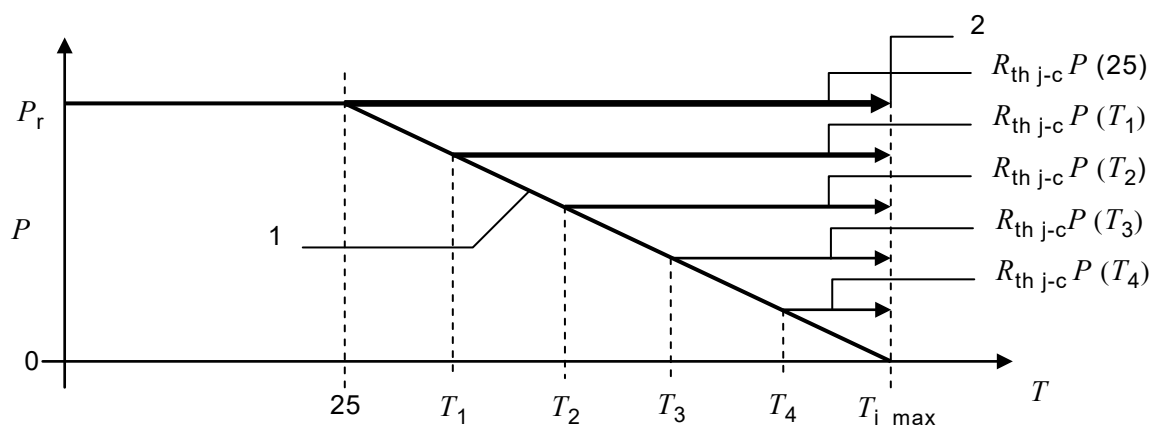


Key

P	Power that can be applied to the semiconductor
P_r	Rated power
T_c	Case temperature
$T_{j-\max}$	Junction upper temperature

Figure A.7 – Derating curves for transistors

The trajectory of T_j when $P(T_c)$ is derated according to the derating curve, along with the rise of T_c in the range of $25\text{ °C} \leq T_c \leq T_j$, is shown in Figure A.8.



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Key P Power that can be applied to the semiconductor P_r Rated power T Temperature

1 Case temperature

2 Trajectory T_j is the junction temperature

$$T_i = 25 + i(T_{j_max} - 25)/5$$

For $i = 1 \dots 4$ **Figure A.8 – Trajectory of T_j when P is reduced according to the derating curve**

$R_{th\ j-c} P(T_c)$ is the temperature rise from the T_c to the T_j by the derated power $P(T_c)$ according to the increased T_c and the sum with the T_c would always show T_{j_max} .

When the load power to the semiconductor is reduced according to the derating curve as the temperature rises, the thermally sensitive point (junction temperature T_j for bipolar transistors) would always be the certain limited temperature T_{j_max} , but this is because the derating curve is made to be so.

A.2.3 Derating curve for resistors

As described in this subclause, the derating curves for resistors are based on a different point of view. But, the derating curves for resistors and semiconductors are similar in shape, so they are often misinterpreted. The largest difference is that the temperature of the thermally sensitive point of the resistor will change when the power is reduced according to the derating curve. In contrast, the temperature of the thermally sensitive point of the semiconductor would be a constant temperature as shown in Figure A.8. However, the range of the change of the thermally sensitive point temperature including the heat stress caused by the temperature difference between the resistor parts would be kept below the limited temperature which is tested and verified by the resistor manufacturer.

As for the lead wire resistors, the heat dissipation through the lead wire by the heat conduction is small compared to the convection and radiation. Therefore, under the natural convection environment, the temperature rise against the ambient temperature T_a of each part of the resistor is approximately the applied power and the specific proportional constant of the resistor wherever the lead wire tip is connected.

In this example, the hotspot temperature T_{hs} will be used as the representative temperature of each part. The hotspot is the hottest part of the resistor as mentioned in the terms and definitions in Clause 3 and is generally located in the centre of the resistive element. The behaviour of the temperature of the hotspot temperature T_{hs} when the load is reduced, along

with the rise of the ambient temperature according to the derating curve based on Figure A.3, will be considered using the temperature rise ΔT_{hs-a} from the hotspot ambient temperature T_a .

The hotspot is only a representative example, so be aware that the hotspot temperature T_{hs} changes in a definite proportion against the temperature rise ΔT_{hs-a} from the hotspot ambient temperature T_a no matter which part of the resistor it is.

The rate of the temperature rise by self-heating from the applied power differs by each resistor, so two cases are to be considered. One is a small temperature rise, and the other is a large temperature rise from the applied power. In the graph in Figure A.9, the horizontal axis shows the temperature rise ΔT_{hs-a} from the ambient temperature T_a , the vertical axis shows the percentage of the applied power P_{rp} to the rated power. Figure A.9 shows the example of a small temperature rise, and Figure A.10 shows the example of a large temperature rise compared to the applied power ratio. Generally, if the applied power is the same, the temperature rise will be small when the constitution is large, and the temperature rise will be large when the constitution is small.

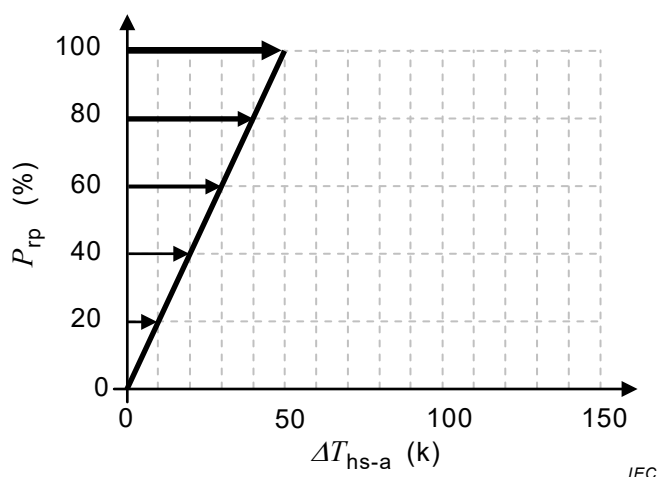
When the rated power is indicated with P_r (W), the thermal resistance $R_{th\ S}$ of the ambient temperature T_a to the hotspot for the resistors with a small temperature rise would be as shown in Formula (A.8).

$$R_{th\ S} = 50 / P_r \text{ (K/W)} \quad (\text{A.8})$$

And the thermal resistance $R_{th\ L}$ of the ambient temperature T_a to the hotspot for the resistors with a large temperature rise would be shown in Formula (A.9).

$$R_{th\ L} = 150 / P_r \text{ (K/W)} \quad (\text{A.9})$$

When the leaded resistors are wired in the air, most of the generated Joule heat T_a would be dissipated into the atmosphere, so the thermal resistance calculated from Formula (A.8) and Formula (A.9) would serve to show the characteristics of the resistor.

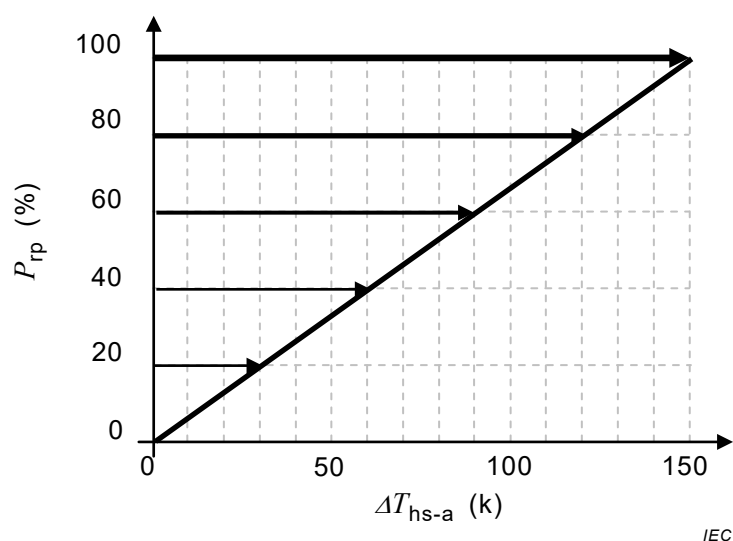


Key

P_{rp} Fraction of applied power to the rated power

ΔT_{hs-a} Temperature rise from the ambient temperature T_a to the hotspot temperature

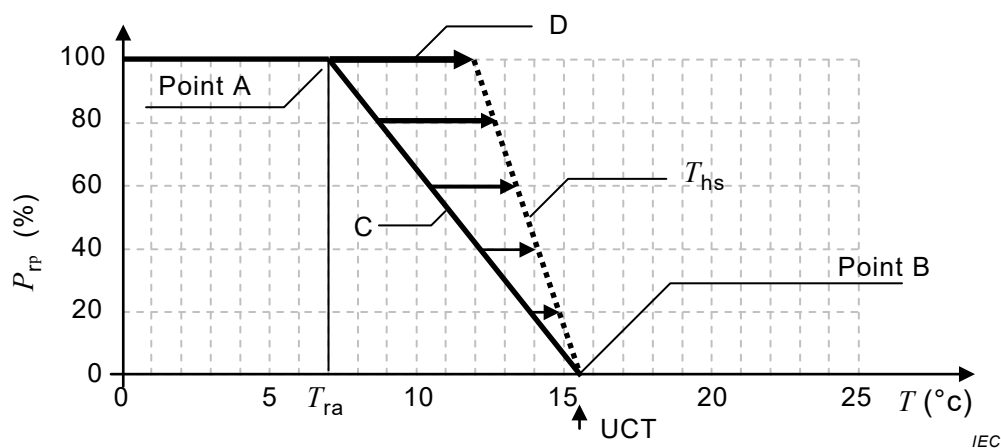
Figure A.9 – Leaded resistors with small temperature rise

**Key**

- P_{rp} Fraction of applied power to the rated power
 ΔT_{hs-a} Temperature rise from the ambient temperature T_a to the hotspot temperature

Figure A.10 – Leaded resistors with large temperature rise

First the trajectory of the hotspot temperature T_{hs} obtained from the Figure A.3 and Figure A.9 will be studied. The trajectory of T_{hs} can be calculated by simply adding the self-generated heat (temperature rise from the ambient temperature T_a to the hotspot ΔT_{hs-a}) shown in Figure A.9 to the derating curve shown in Figure A.3. The result would be as shown in Figure A.11.

**Key**

- T Temperature
 P_{rp} Fraction of applied power to the rated power
 T_{ra} Rated ambient temperature
 T_{hs} Hotspot temperature (trajectory when load is derated)
UCT Upper category temperature
Point A Load life test point
Point B High temperature exposure test point (T_{hs} will be maximum here)
C Derating curve made by the method in Figure A.3 (Horizontal axis is the ambient temperature T_a)
D Vector representation of temperature rise from the ambient temperature to the hotspot

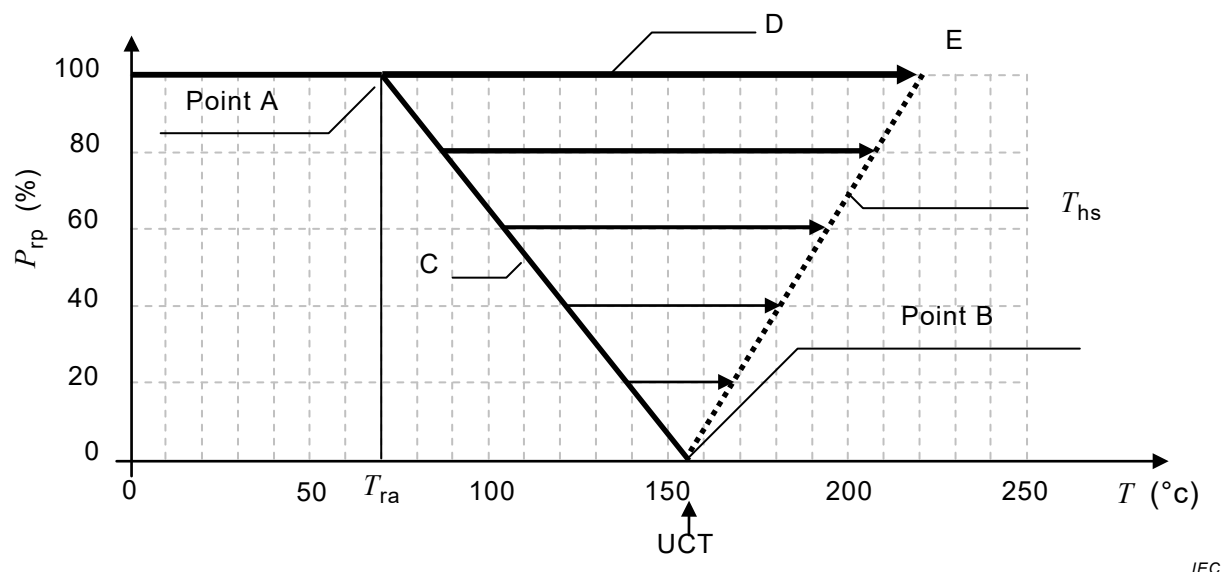
Figure A.11 – Trajectory of T_{hs} for the lead wire resistors with small temperature rise

In Figure A.11, the hotspot would reach the maximum temperature in the high-temperature exposure test, but the heat stress caused by the temperature difference inside the resistor will be the largest at the load life test. This is when the temperature difference between the ambient and the hotspot temperatures becomes maximal and when the rated power applied at T_a is equal to the rated ambient temperature.

This means, for example, that the temperature gradient becomes large at the point where the generated heat density is high, such as at the tip of the trimming line when the current is applied, and the heat stress will become locally large. The local heat stress can be the cause of degradation for some of the resistive elements.

The heat stress caused by the temperature rise of the entire resistor would be largest at the high-temperature exposure test when the entire resistor becomes uniformly the maximum temperature. On the derating curve, or within the entire area of the bottom left-hand side of the derating curve, unless under special conditions, the hotspot temperature and the heat stress will not exceed the above-mentioned maximum value. If the electric/electronic device designers used the resistors by reducing the power as the rise of the ambient temperature T_a according to the derating curve, the resistor will not be used under the conditions that exceed the maximum stresses (high temperature and heat stress) verified in the load life test and high-temperature exposure test implemented by the resistor manufacturer.

Next, for the resistor with a large temperature rise shown in Figure A.10, the power load ratio reduced as the temperature rises according to the derating curve made from the test in Figure A.3 will be considered. The hotspot temperature T_{hs} makes a trajectory as shown in Figure A.12.

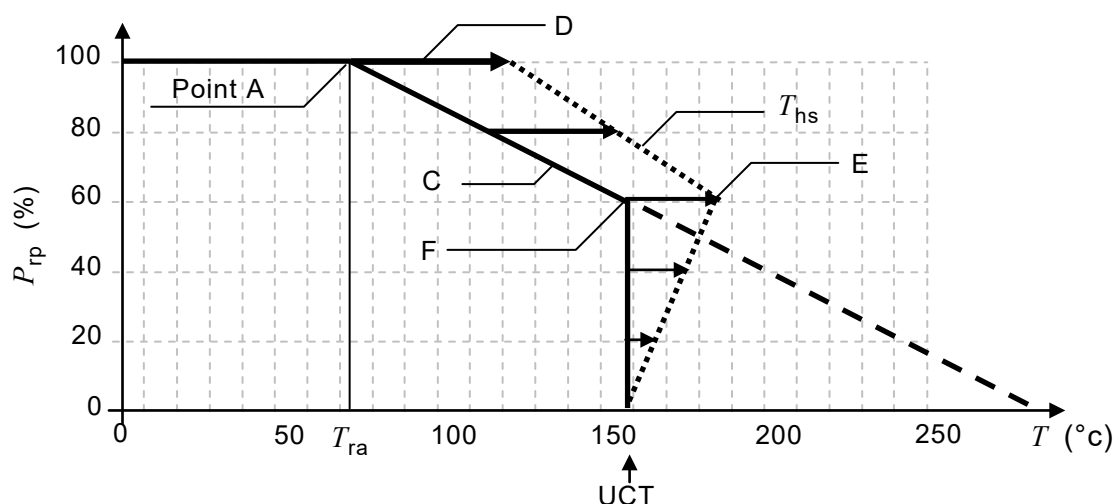
**Key**

T	Temperature
P_{rp}	Fraction of applied power to the rated power
T_{ra}	Rated ambient temperature
T_{hs}	Hotspot temperature (trajectory when load is derated)
UCT	Upper category temperature
Point A	Load life test point
Point B	High temperature exposure test point
C	Derating curve made by the method in Figure A.3 (horizontal axis is the ambient temperature T_a)
D	Vector representation of temperature rise from the ambient temperature to the hotspot
E	Point where the T_{hs} reaches the maximum temperature (at load life test)

Figure A.12 – Trajectory of T_{hs} for the lead wire resistors with large temperature rise

In this case, the hotspot temperature and the heat stress caused by the temperature difference inside the resistor becomes the largest during the load life test, which is when the rated power P_r is applied at the rated ambient temperature T_{ra} . It is not clear which condition, the load life test or the high-temperature exposure test, will make the heat stress caused by the temperature rise of the entire resistive element the largest. However, on the derating curve or within the entire area of the bottom left-hand side of the derating curve, the hotspot temperature and the heat stress will not exceed the above-mentioned maximum value. Therefore, if the electric/electronic device designers used the resistors by reducing the power according to the derating curve, the resistor will not exceed the maximum stress (high temperature and heat stress) verified in the load life test and the high-temperature exposure test implemented by the resistor manufacturer.

There may be strange feelings that there is a case that shows $T_{hs} > UCT$ but, this case exists. All the resistors that do not have the category power of zero have the operating range of $T_{hs} > UCT$. It could be easily explained by overwriting the temperature rise ΔT_{hs-a} (from the ambient temperature to the hotspot temperature T_{sh}) applicable to each power applied to the resistor on the derating curve as shown in Figure A.13. ΔT_{hs-a} is proportionate to the power applied to the resistor, so it is trivial without any specific data.



IEC

Key

P_{rp}	Fraction of applied power to the rated power
T	Temperature
T_{ra}	Rated ambient temperature
T_{hs}	Hotspot temperature (trajectory when load is derated)
UCT	Upper category temperature
Point A	Load life test point
C	Derating curve made by the method in Figure A.4 (horizontal axis is the ambient temperature T_a)
D	Vector representation of temperature rise from the ambient temperature to the hotspot
E	Point where the T_{hs} reaches the maximum temperature (at the test of UCT and category power)
F	Test point at UCT and category power

Figure A.13 – Trajectory of T_{hs} for resistors with category power other than 0 W

The UCT is just a segment to categorize the test conditions so they are not defined according to the upper temperature limit of the materials that constitute the resistor. This is why $T_{hs} > \text{UCT}$ is acceptable.

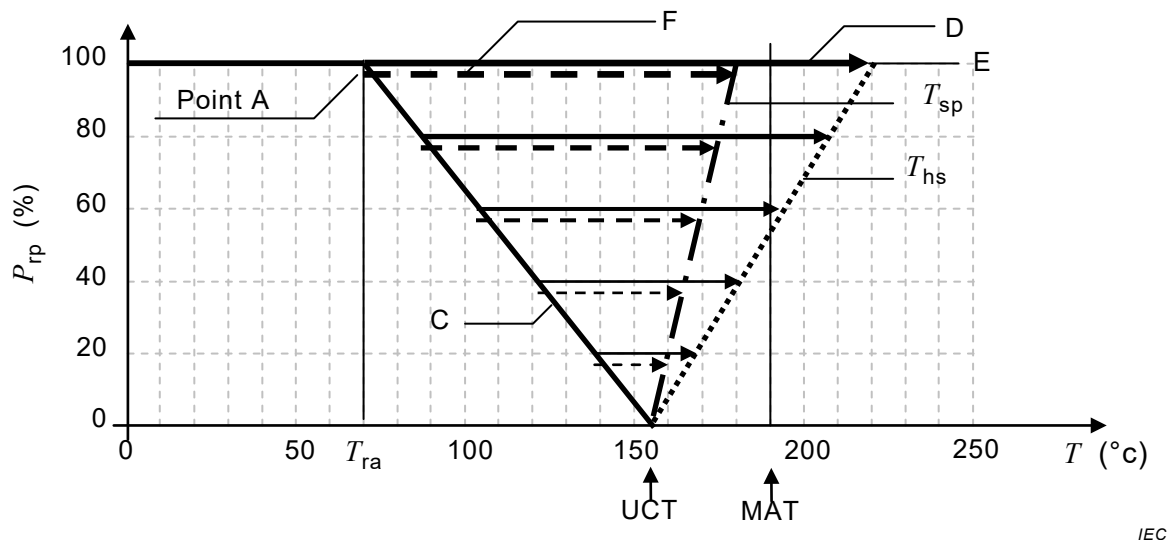
A resistor always has a thermally sensitive point that will lose function when the temperature becomes high. Therefore, if the thermally sensitive point temperature T_{sp} is set, the temperature just before the function of the resistor is lost would be the maximum allowable temperature (MAT). The condition for the resistor to function normally would be always $\text{MAT} \geq T_{sp}$. To pass the high-temperature exposure test, $\text{MAT} \geq \text{UCT}$ shall be true. Additionally, the highest temperature in the resistor is T_{hs} , so $T_{hs} \geq T_{sp}$ is trivial.

By introducing this idea of the thermally sensitive point temperature T_{sp} and the maximum allowable temperature (MAT) and showing it visually, it would be easy to explain the reason of the derating curve for resistors and the reason why $T_{hs} > \text{UCT}$ is acceptable in some cases. Figure A.14 shows Figure A.12 added with the T_{sp} and the MAT.

The MAT is the physical temperature upper limit of the thermally sensitive point and as shown in Figure A.14, T_{sp} cannot exceed the MAT at any time. If there is an area that is $T_{sp} > \text{MAT}$, then it will not be able to pass the load life test. On the other hand, $\text{MAT} > \text{UCT}$ would be obvious.

The important thing is that if the resistor passes the load life test, it inevitably accomplishes this relationship even when the thermally sensitive point against heat cannot be found and the temperature limit MAT is unknown.

However, in Figure A.14, this example shows a resistor that has a hotspot that is not the thermally sensitive point, but for most of the resistors, the hotspot is also the thermally sensitive point. In this case, $T_{hs} \leq MAT$ will be the condition in which this resistor can be safely used.



Key

P_{rp} Fraction of applied power to the rated power

T Temperature

T_{ra} Rated ambient temperature

T_{hs} Hotspot temperature

T_{sp} Thermally sensitive point temperature

UCT Upper category temperature

MAT Maximum allowable temperature

Point A Load life test point

C Derating curve made by the method in Figure A.3 (based on ambient temperature)

D (Solid arrow) temperature rise from the ambient temperature to the hotspot

E Point where the T_{hs} reaches the maximum temperature (at load life test)

F (Dash arrow) Temperature rise from the ambient temperature to the thermally sensitive point

Figure A.14 – T_{sp} and MAT for lead wire resistors with large temperature rise

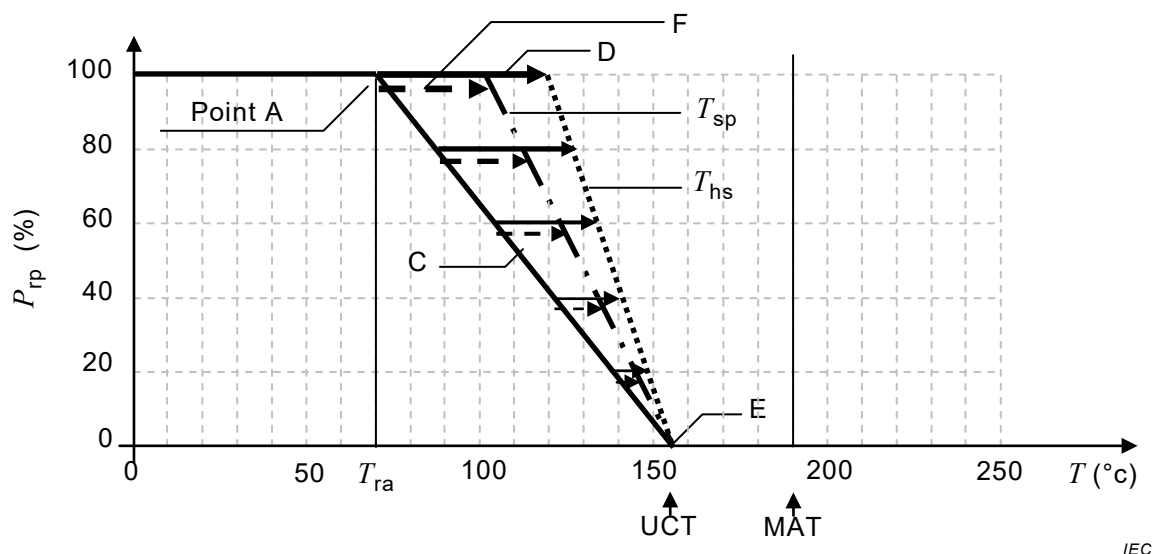
As shown in Figure A.15, the resistors with a small temperature rise as shown in Figure A.9 will also come into effect.

In this case, if the resistor passes the high-temperature exposure test, it inevitably accomplishes this relationship even when the thermally sensitive point cannot be found and the MAT is unknown.

From the above explanation, for resistors with large or small temperature rises, the derating curves can be established by implementing the tests shown in Figure A.3 or Figure A.4 if the load life test and the high-temperature exposure test are implemented and the determined index, such as the resistance value change rates, is both within the standard values.

If the power is reduced along with the rise of the ambient temperature according to the derating curves provided by the resistor manufacturer, the resistor will not be used in the electric/electronic devices under the thermal and heat-stress conditions that are more severe

than the tests implemented by the resistor manufacturer. This is the theoretical rationale that the method of establishing and using the present derating curve is correct.



Key

P_{rp} Fraction of applied power to the rated power

T Temperature

T_{ra} Rated ambient temperature

T_{hs} Hotspot temperature

T_{sp} Thermally sensitive point temperature

UCT Upper category temperature

MAT Maximum allowable temperature

Point A Load life test point

C Derating curve made by the method in Figure A.3 (Based on ambient temperature)

D (Solid arrow) Temperature rise from the ambient temperature to the hotspot

E Point where the T_{hs} reaches the maximum temperature (at load life test)

F (Dash arrow) Temperature rise from the ambient temperature to the thermally sensitive point

Figure A.15 – T_{sp} and MAT for lead wire resistors with small temperature rise

However, many of the hotspots of the resistors are the thermally sensitive points. For these kinds of resistors, Figure A.14 and Figure A.15 can be simplified as in Figure A.16.

From this point, the word "hotspot" will be used in place of "thermally sensitive points". Therefore, for the resistors that have thermally sensitive points other than hotspots, take "hotspot" to mean "thermally sensitive point".