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Edition 1.0 2017-05

TECHNICAL REPORT

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

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CONTENTS

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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- withdrawn,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
$\boldsymbol{T_t}$
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
$\boldsymbol{T_{hs}}$
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.

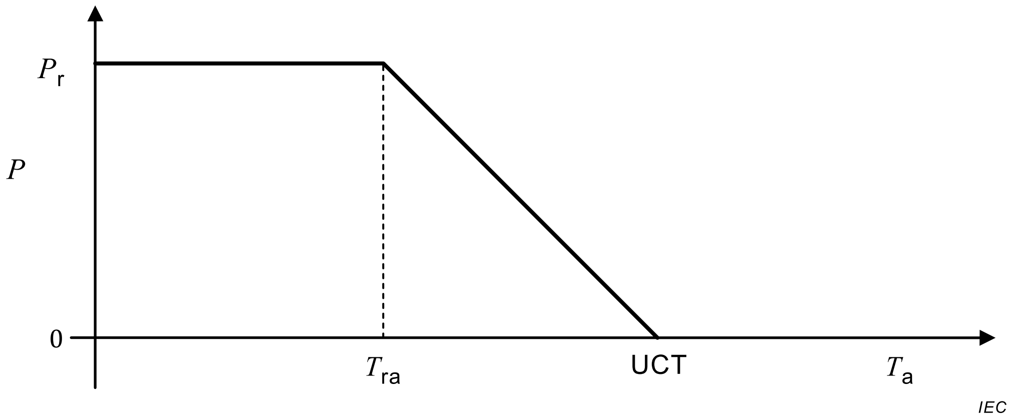
But, the body temperature of the SMD resistor may become higher than the temperature verified in the test implemented by the resistor manufacturer even when this rule is observed. On the other hand, in some cases excessive derating is requested and an extremely large margin is set.

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 $R_{\mathrm{th\ shs\text{-}t}}$ 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

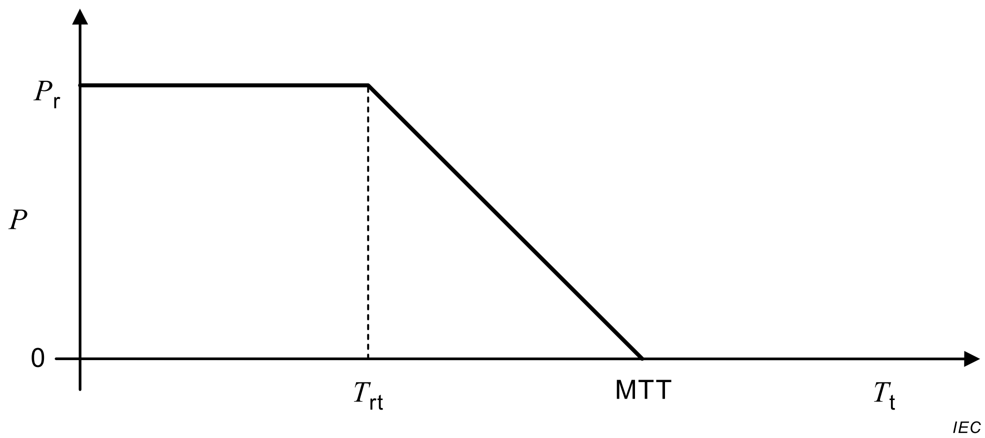
Using Figure 2 instead of Figure 1 is suggested for the design of high-power applications of the SMD resistors in excess of the conventional rated dissipation (e.g. 100 mW for RR1608M). The validity of using the derating curve based on the terminal part temperature is explained in Annex E.



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

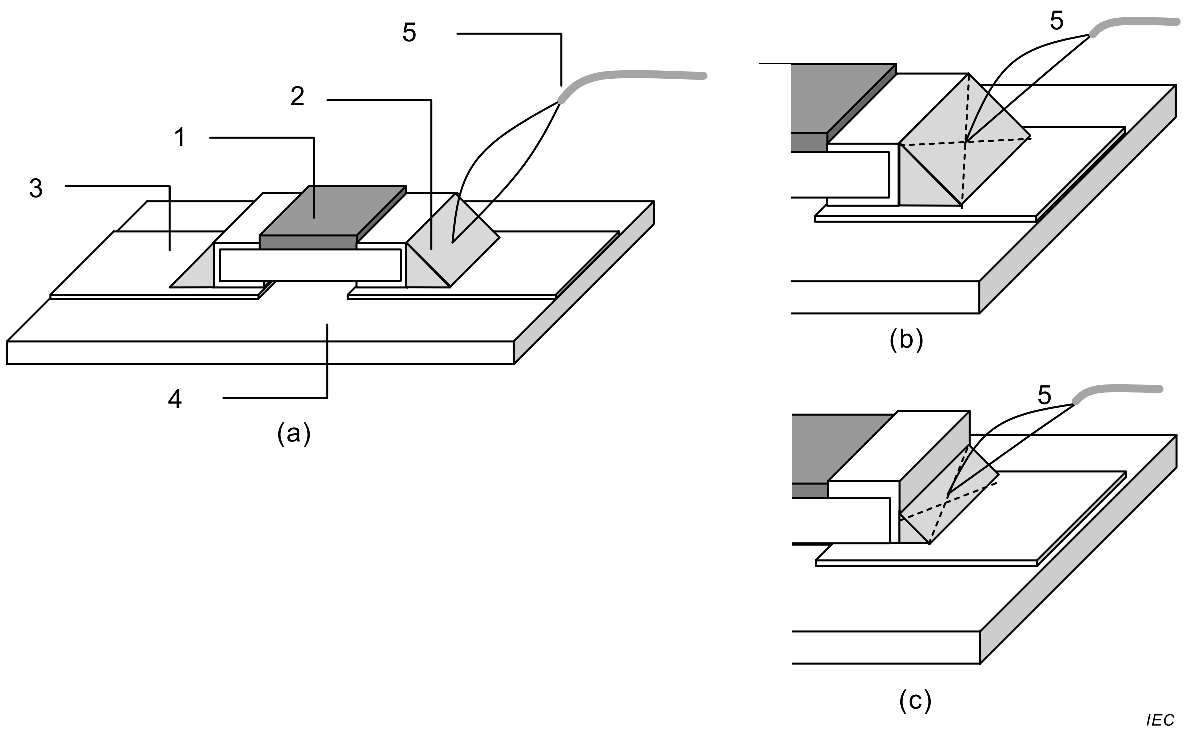
4.3 Measuring method of the terminal part temperature of the SMD resistor

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).



Key

1 Resistor

2 Solder fillet

3 Copper pattern

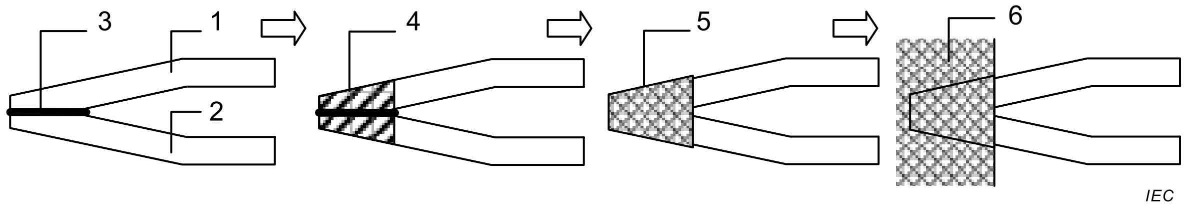
4 Printed board

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

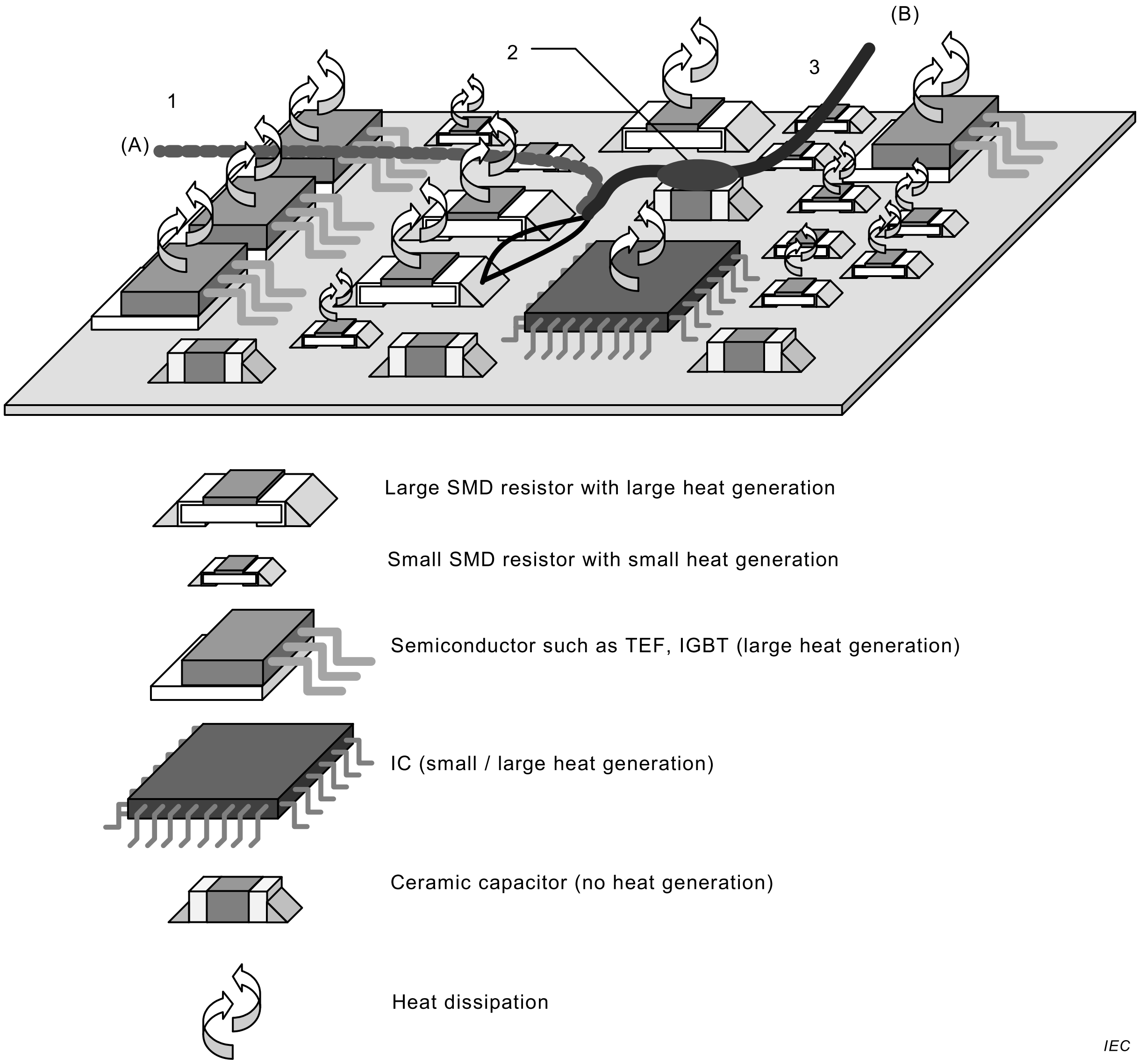
4 Flux-coated part

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.



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.

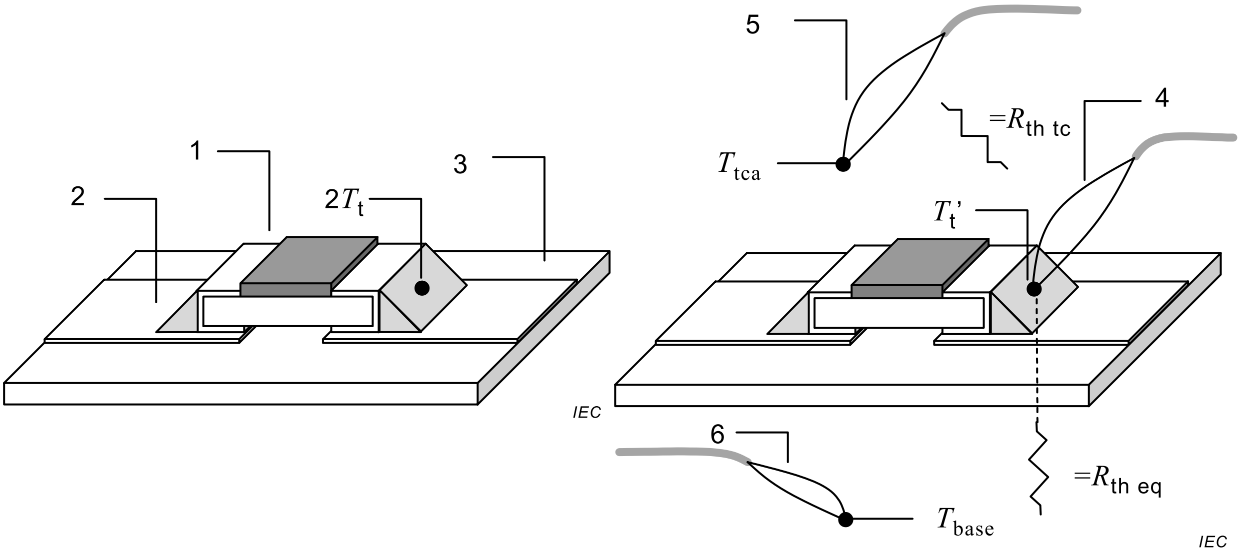
3 Avoid the heat generating parts when wiring.

(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}).



(a) True terminal temperature **(b) Actual measured temperature**

Key

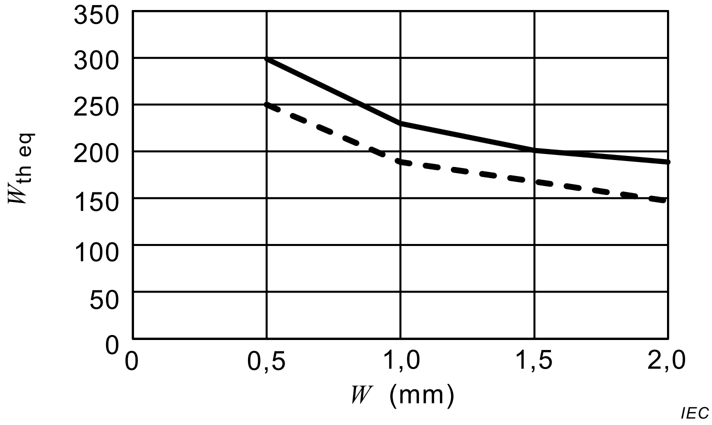
1	Resistor
2	Copper pattern
3	Printed board
4	Thermocouple for measuring the terminal part temperature
5	Thermocouple for measuring the heat dissipation space temperature
6	Thermocouple for measuring the standard temperature
T_t	Fillet temperature (centre part) before attaching the thermocouple = true 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

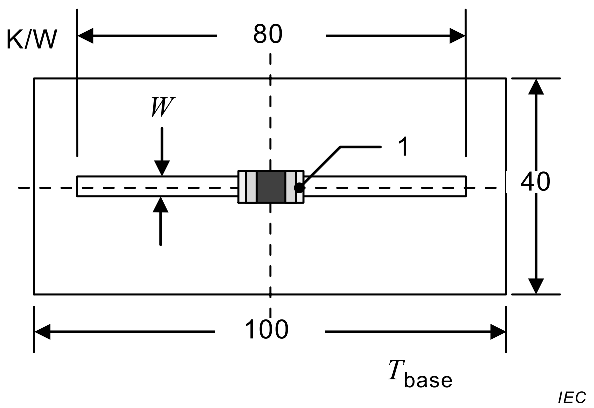
The temperature that is actually measured by the thermocouple is T_t' and the T_t cannot be measured. But the difference $\Delta T = T_t - T_t'$ (≥ 0) can be calculated from Formula (1).

$$\Delta T = \left(T'_{\mathrm{T}} - T_{\mathrm{tca}}\right)\left(R_{\mathrm{th \cdot eq}} / R_{\mathrm{th \cdot tc}}\right) \qquad (1)$$

$R_{th\ eq}$ 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.



Dimensions in millimetres



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

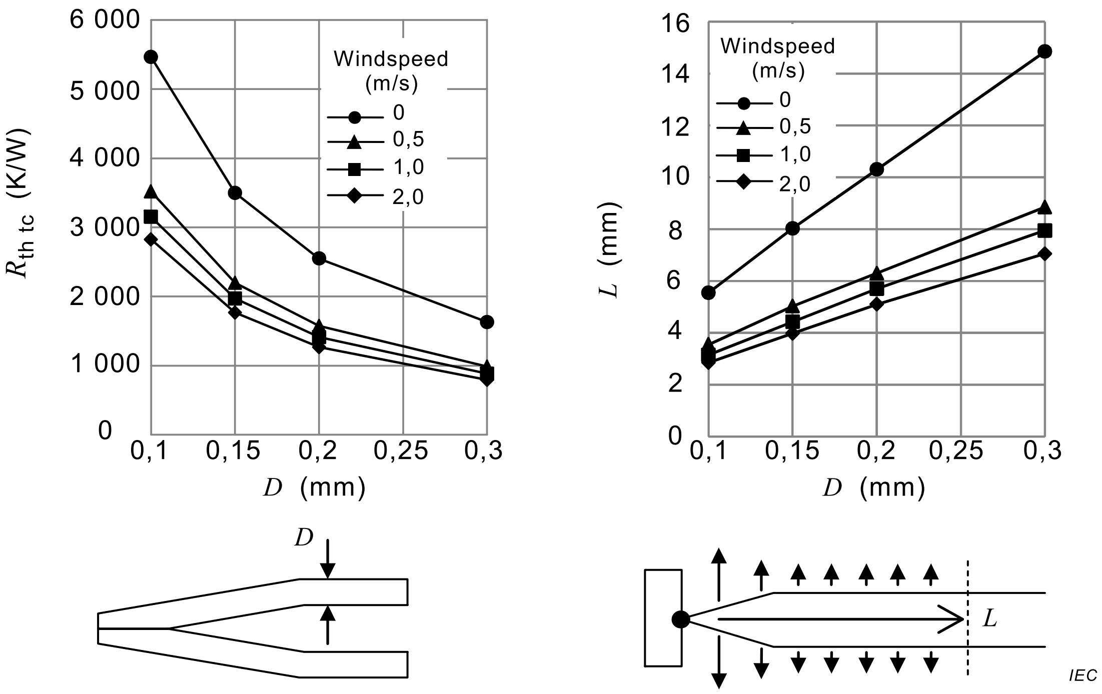
Figure 7 – Thermal resistance $R_{th\ eq}$ of the FR4 single side board (thickness 1,6 mm)

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.

$$R_{th \cdot eq} = \left(T'_t - T_{base}\right) / P \qquad (2)$$

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

$R_{\text{th tc}}$ 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)

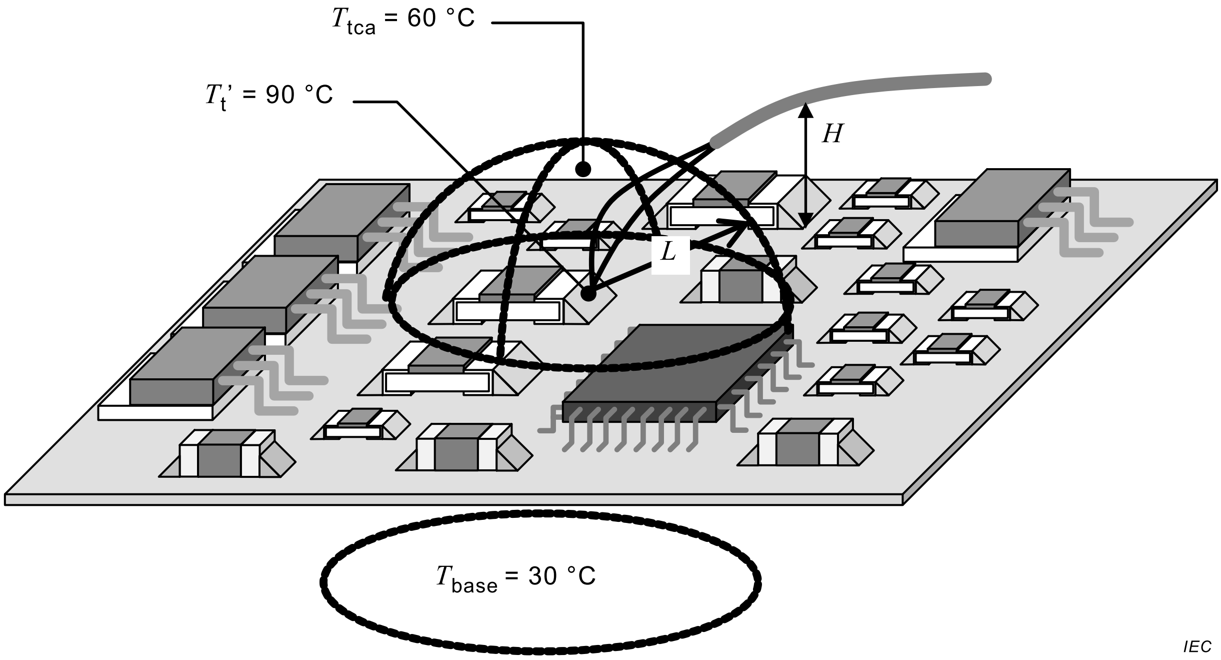
The air speed 0 m/s in Figure 8 means that the thermocouple is set horizontally in a space with no forced air and the heat dissipation is only by natural convection.

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.



Calculation example

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

ΔT = (90 – 60) ($R_{th\ eq}$ / $R_{th\ tc}$) = 1,64 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.

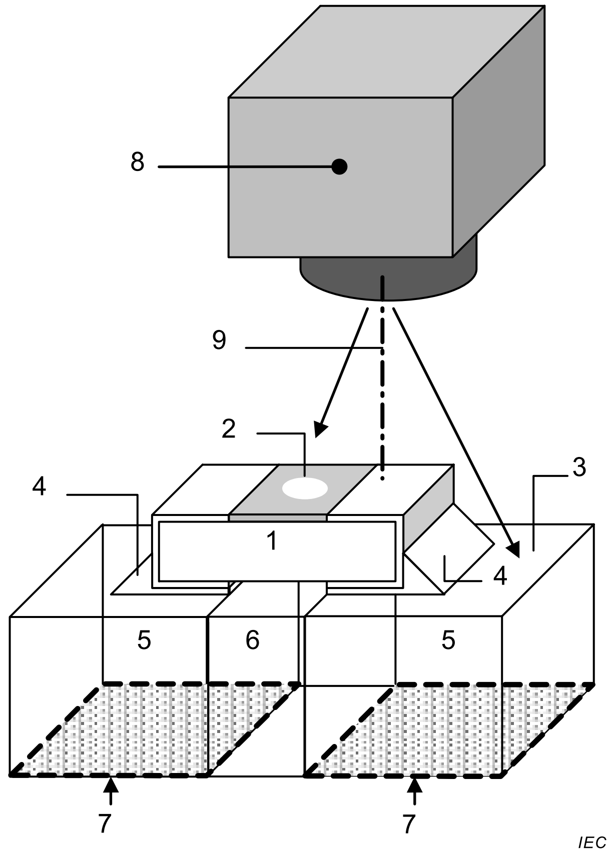
4.4 Measuring method of the thermal resistance $R_{th\ shs\text{-}t}$ from the terminal part to the surface hotspot

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 $R_{th\ shs\text{-}t}$. If T_{shs} and T_{tn} can be measured, $R_{th\ shs\text{-}t}$ can be calculated with Formula (3).

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

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 $R_{\mathrm{th\ shs\text{-}t}}$

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:

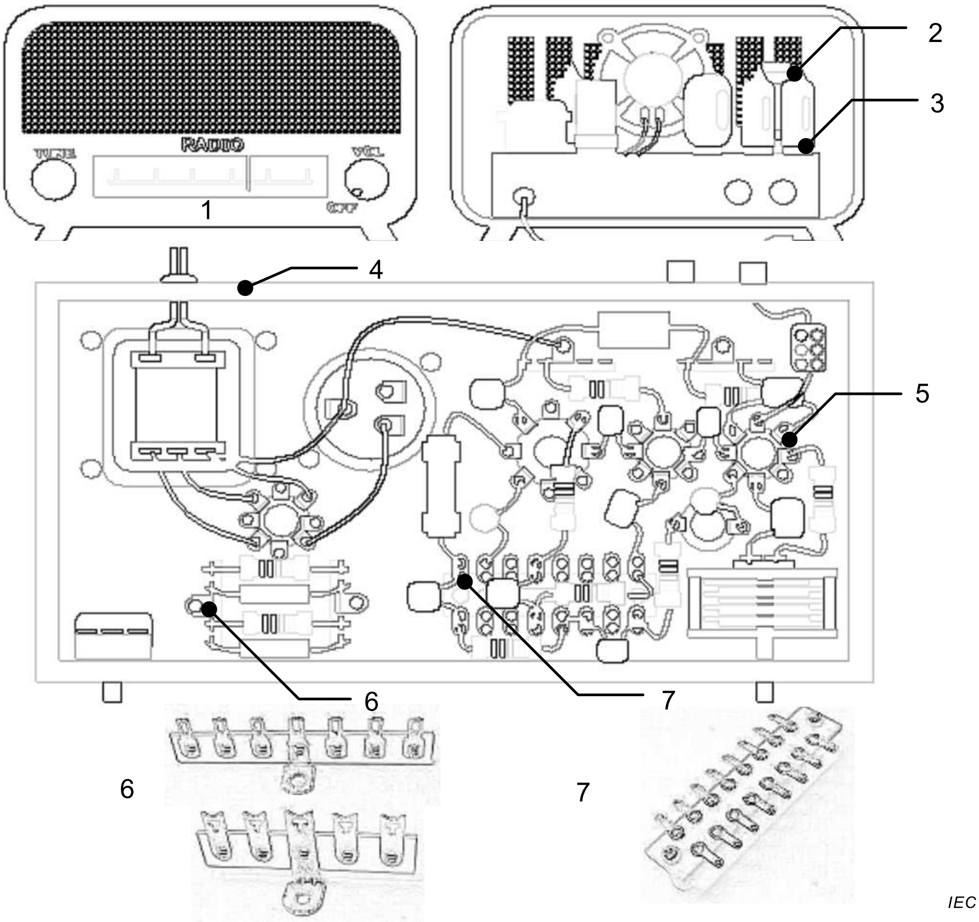
1) use of the derating curve based on the terminal temperature instead of the ambient temperature for the design of high power applications of the SMD resistors in excess of the conventional rated dissipation (e.g. 100 mW for RR1608M);
2) measurement method of the terminal part temperature of the SMD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



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

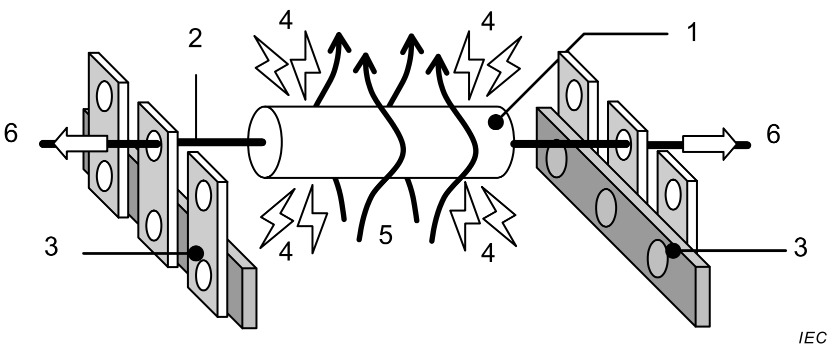
As shown in Figure A.2, all the heat generated in any kind of resistors will be released through the following three phenomena.

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.

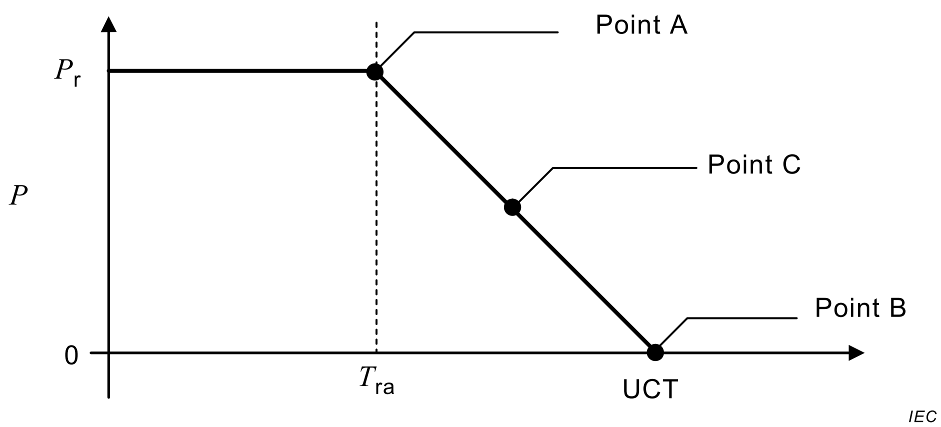
Therefore, introducing the ambient temperature around the resistor as the temperature index to correspond to the test conditions by the resistor manufacturer and the actual use conditions of electric/electronic device designers was reasonable for the mounting conditions of the resistors in those days. 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.



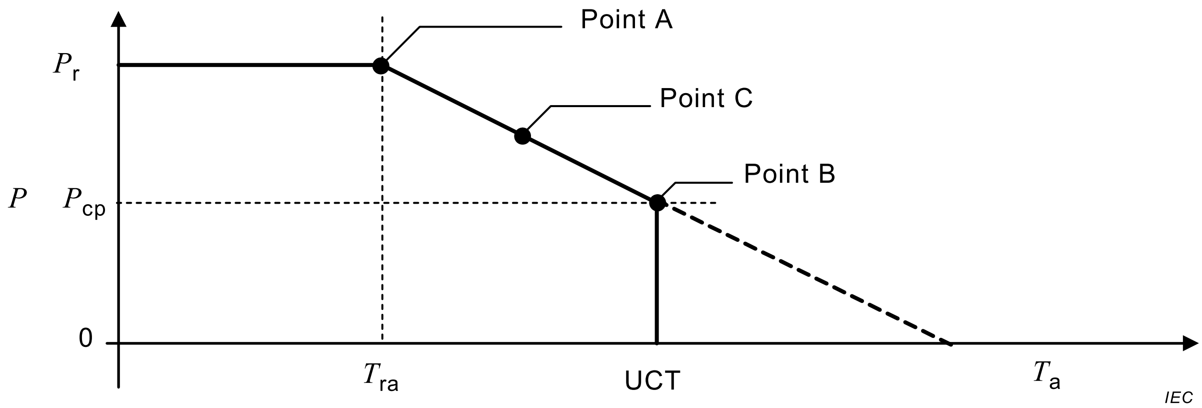
Key

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

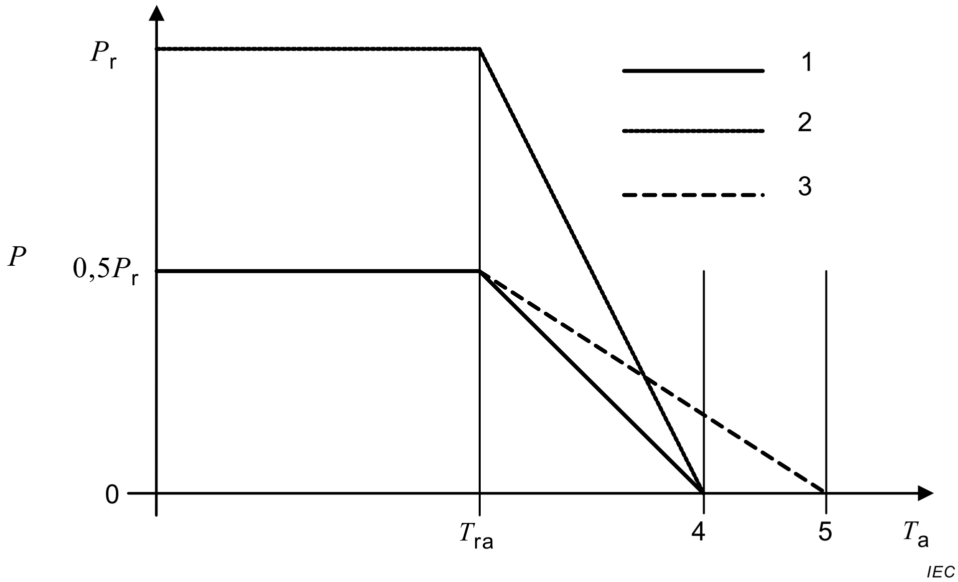
P	Applied power
P_r	Rated power
P_{cp}	Category power (percentage of the rated power)
T_a	Ambient temperature
T_{ra}	Rated ambient temperature (normally 70 °C)
UCT	Upper category temperature
Point A	Load life test condition
Point B	High temperature exposure test condition
Point C	Between Point A and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

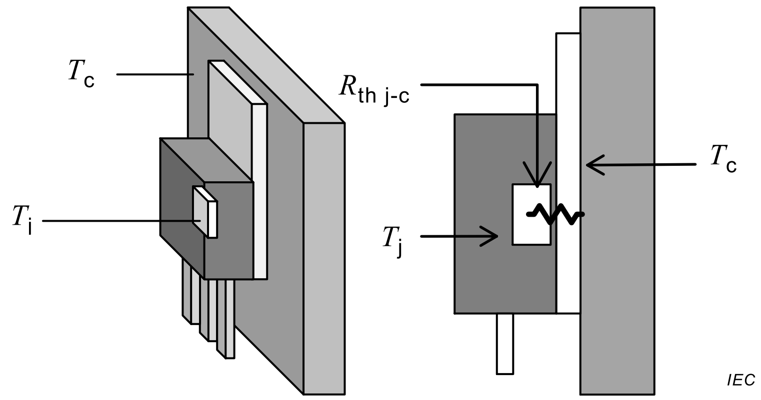
A.2.2 Derating curve for the semiconductors

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 $T_{j\text{-max}}$, 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 $\Delta T_{\text{j-c}}$ of the case to the junction is assumed to be proportionate to the power P consumed by the transistor. This proportional constant shall be $R_{\text{th j-c}}$. This $R_{\text{th j-c}}$ is the thermal resistance between the junction and the case.



Key

T_c Heatsink temperature = case temperature

T_j Junction temperature

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

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

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

$$T_j = T_c + R_{\text{th}\cdot\text{j-c}} P \tag{A.1}$$

This T_j shall always be lower than $T_{\text{j-max}}$. 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).

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

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

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

When T_c = 25 °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).

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

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

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

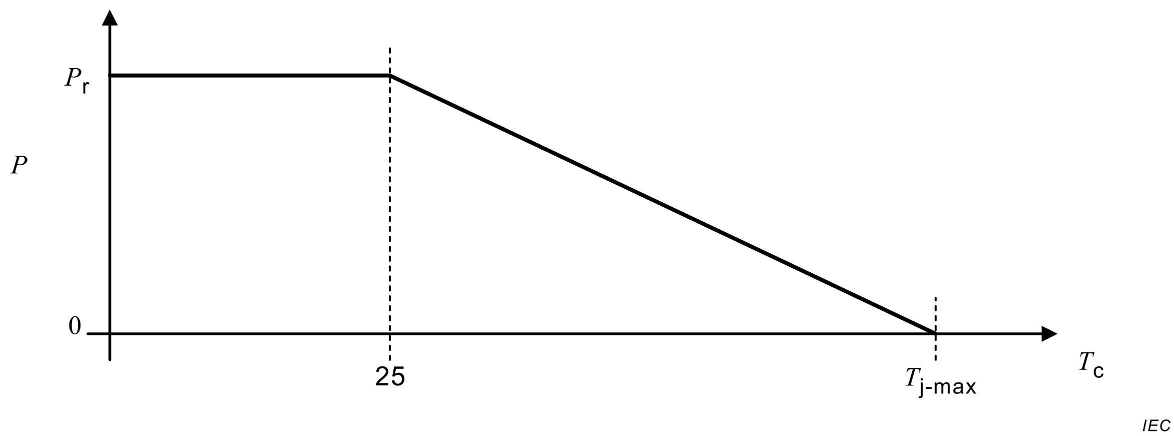
$$P(T_c) \leq P_r(T_{j-max} - T_c)/(T_{j-max} - 25) \tag{A.6}$$

However, in the range of T_c < 25 °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.

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

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.

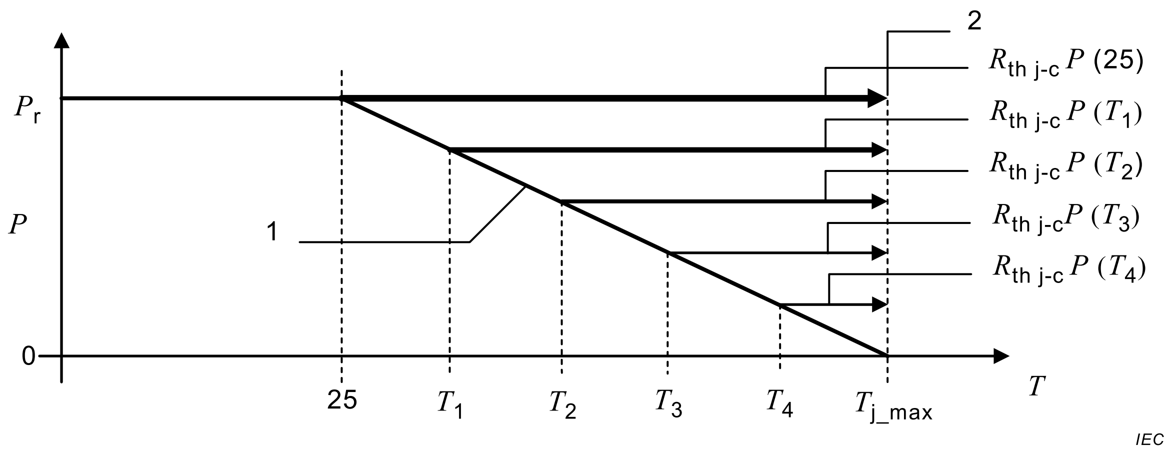


Key

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 °C ≤ T_c ≤ T_j, is shown in Figure A.8.



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($T_{\text{j-max}}$ – 25)/5

For i = 1...4

Figure A.8 – Trajectory of T_j when P is reduced according to the derating curve

$R_{\text{th j-c}}\,P(T_c)$ 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 $T_{\text{j-max}}$.

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 $T_{\text{j-max}}$, 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 $\Delta T_{\text{hs-a}}$ 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 $\Delta T_{\text{hs-a}}$ 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 $\Delta T_{\text{hs-a}}$ 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.

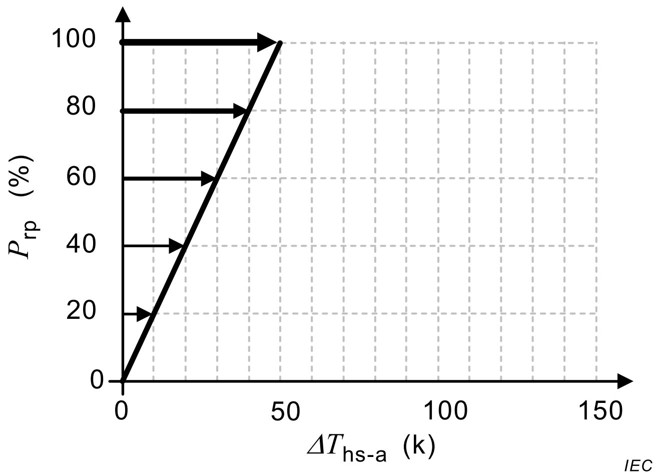
When the rated power is indicated with P_{r} (W), the thermal resistance $R_{\text{th S}}$ of the ambient temperature T_{a} to the hotspot for the resistors with a small temperature rise would be as shown in Formula (A.8).

$$R_{\text{th}\cdot\text{s}} = 50 / P_{\text{r}} \ \text{(K/W)} \tag{A.8}$$

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

$$R_{\text{th}\cdot\text{L}} = 150 / P_{\text{r}} \ \text{(K/W)} \tag{A.9}$$

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.

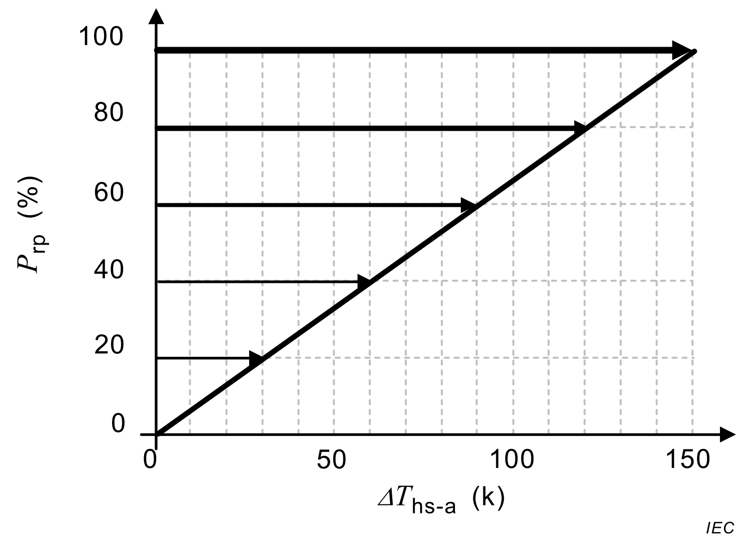


Key

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

$\Delta T_{\text{hs-a}}$ Temperature rise from the ambient temperature T_{a} to the hotspot temperature

Figure A.9 – Leaded resistors with small temperature rise



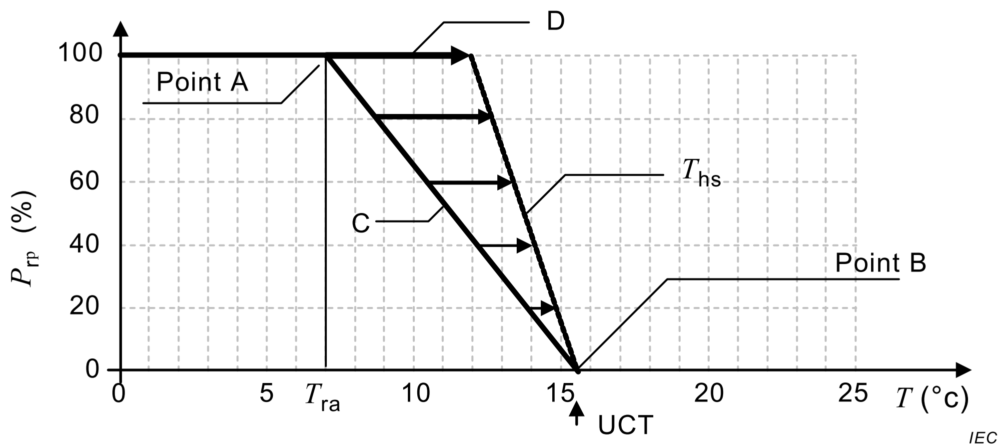
Key

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

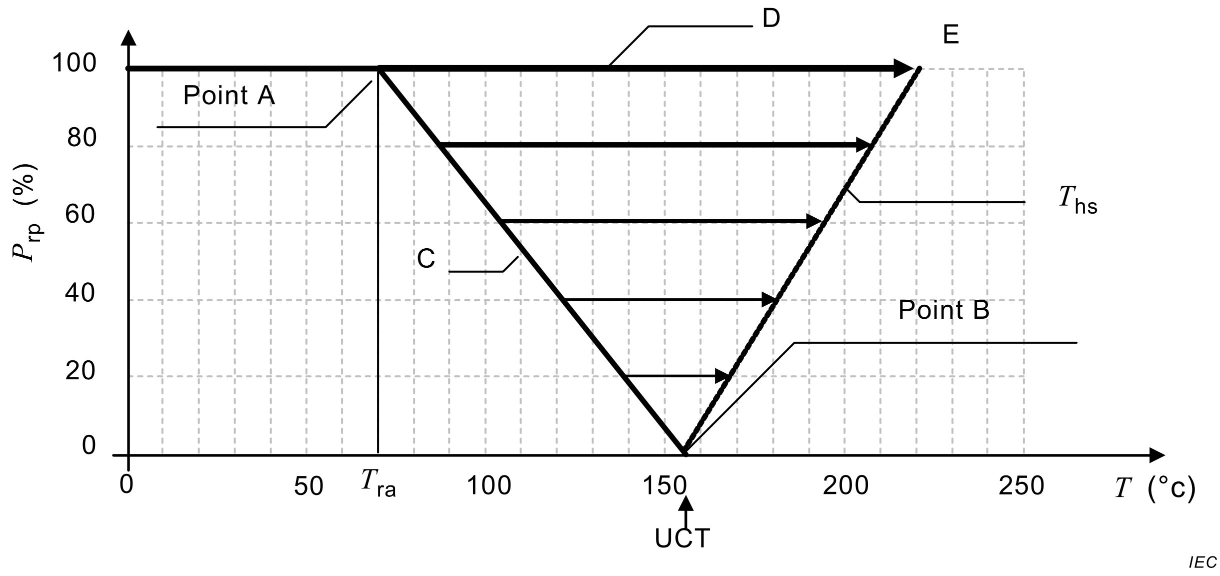
Figure A.11 – Trajectory of T_{hs} for the lead wire resistors with small temperature rise

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.



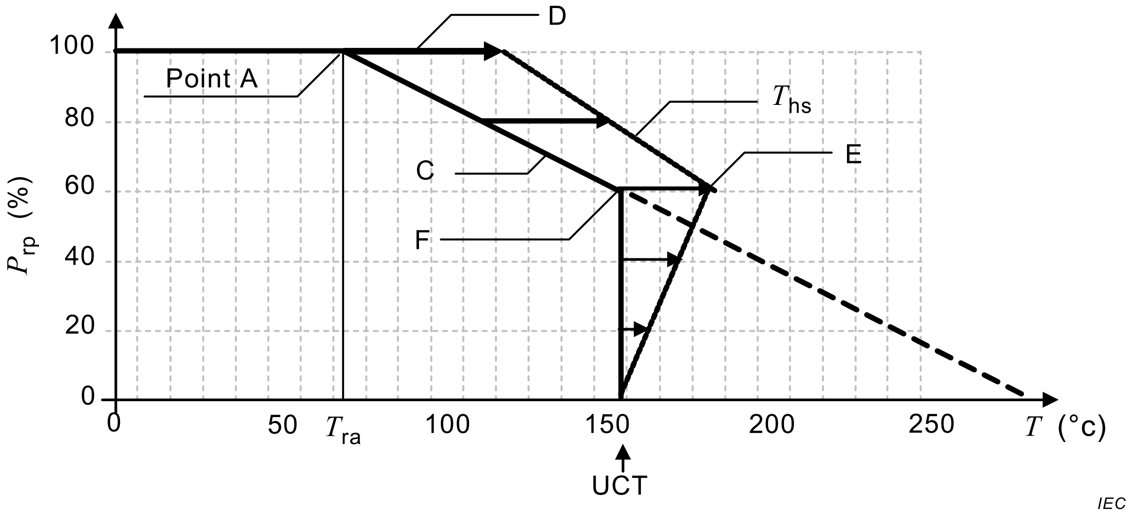
Key

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 $\Delta T_{hs\text{-}a}$ (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. $\Delta T_{hs\text{-}a}$ is proportionate to the power applied to the resistor, so it is trivial without any specific data.



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} > UCT is acceptable.

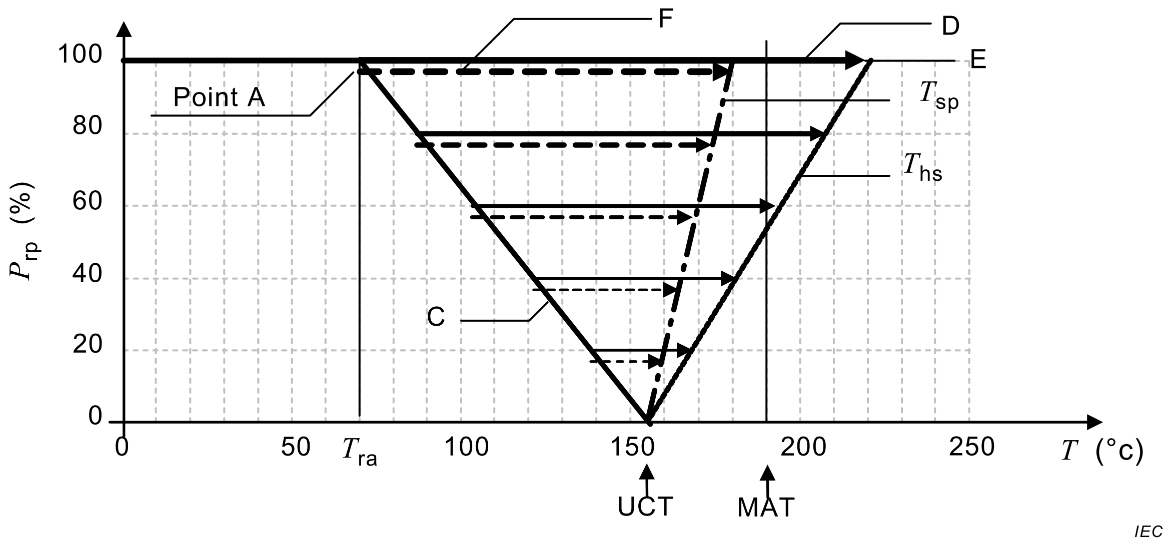
A resistor always has a thermally sensitive point that will lose function when the temperature becomes high. Therefore, if the thermally sensitive point temperature T_{sp} is set, the temperature just before the function of the resistor is lost would be the maximum allowable temperature (MAT). The condition for the resistor to function normally would be always MAT ≥ T_{sp}. To pass the high-temperature exposure test, MAT ≥ 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} > 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} > MAT, then it will not be able to pass the load life test. On the other hand, MAT > 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} ≤ 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

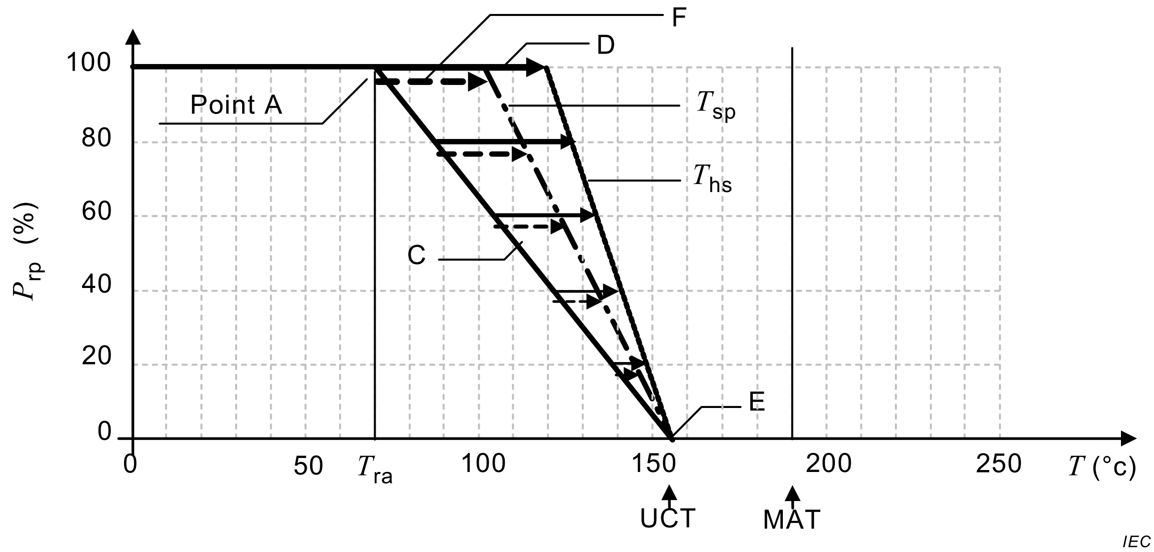
Figure A.14 – T_{sp} and MAT for lead wire resistors with large temperature rise

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

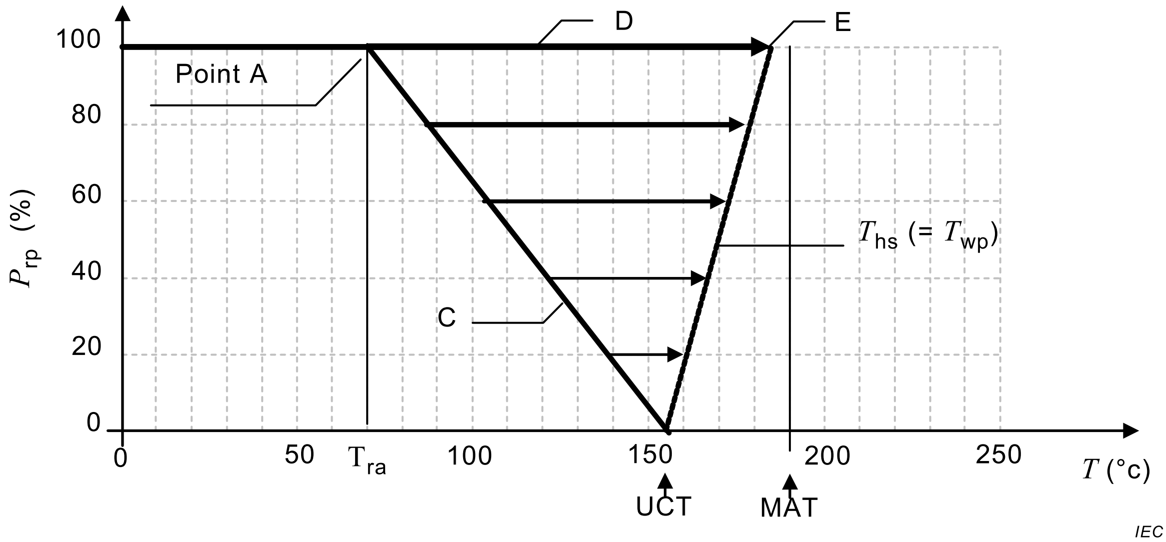
E Point where the T_{hs} reaches the maximum temperature (at load life test)

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

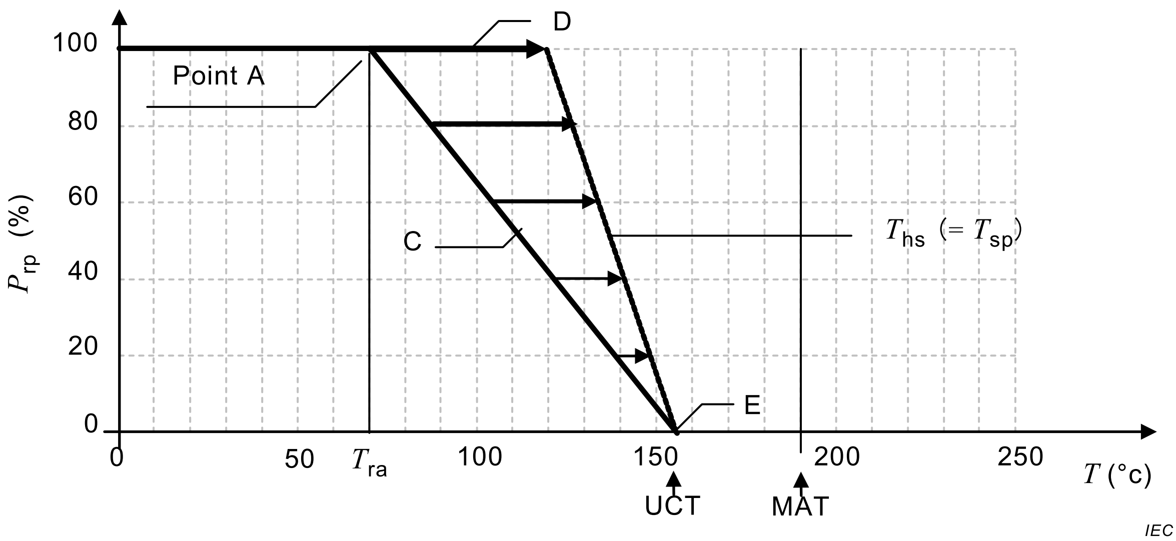
Figure A.15 – T_{sp} and MAT for lead wire resistors with small temperature rise

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".



a) Case A: Resistor with large temperature rise



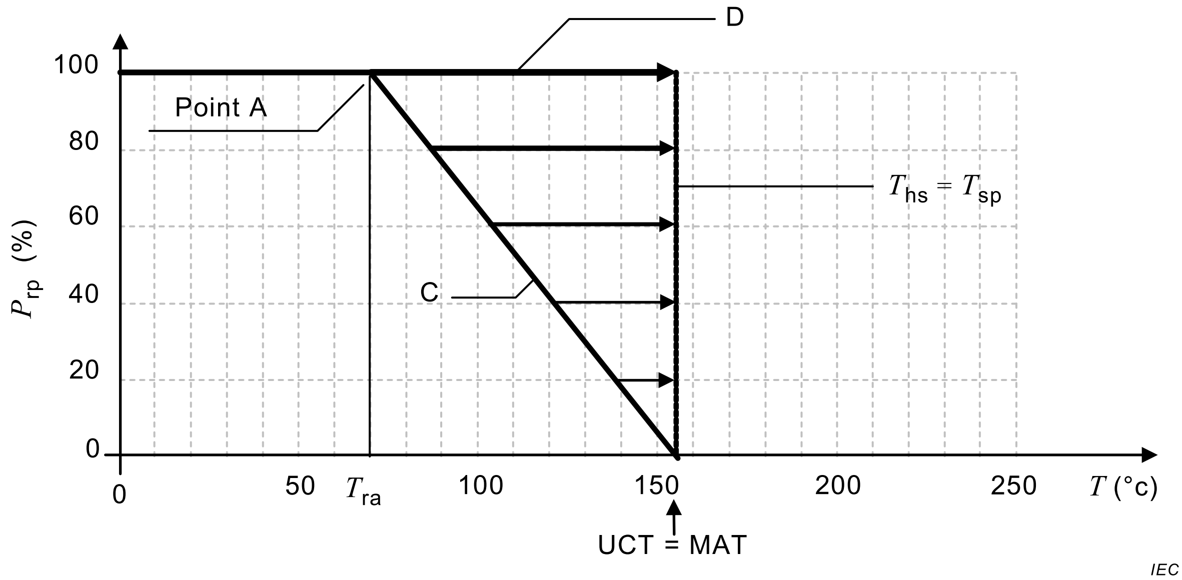
b) Case B: Resistor with small temperature rise

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	Temperature rise from the ambient temperature to the hotspot
E	Point where T_{hs} = T_{sp} becomes maximum temperature

Figure A.16 – Resistors for which the hotspot is the thermally sensitive point

A resistor that is like the one shown in Figure A.17 can exist on rare occasions. This resistor has a hotspot temperature T_{hs} during the load life test that corresponds with the UCT. In this case, when the power is reduced as the ambient temperature T_a rises in accordance with the derating curve, the trajectory of T_{hs} would always be a constant value of UCT. When the hotspot of this resistor is the thermally sensitive point and additionally UCT = MAT, this derating curve will have a very similar meaning as that of the derating curves for the semiconductors.



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	Temperature rise from the ambient temperature to the hotspot

Figure A.17 – Resistor that have derating curve similar to the semiconductor

The common mistake that electric/electronic device designers make is to think that all the resistors have the characteristics as shown in Figure A.17 by analogy with the derating curves for semiconductors. If all resistors have these kinds of characteristics, the meaning of the derating curve will be very simple and, in a way, ideal. But, the core elements of materials and structures that make up the resistors are not as uniform as those of the semiconductors. The material and structure varies. As for the resistors, it is difficult to identify the thermally sensitive point and the MAT in most cases. Therefore, it is very difficult to intentionally create a resistor that has a derating curve as shown in Figure A.17 and, moreover, even if it is developed, there is no advantage over the current derating curves.

If there was a resistor that has a derating curve as shown in Figure A.17 and a hotspot (thermally sensitive point) that can be observed easily, the derating curve for this resistor would be unnecessary. The conditions for use that would be provided to electric/electronic device designers would be:

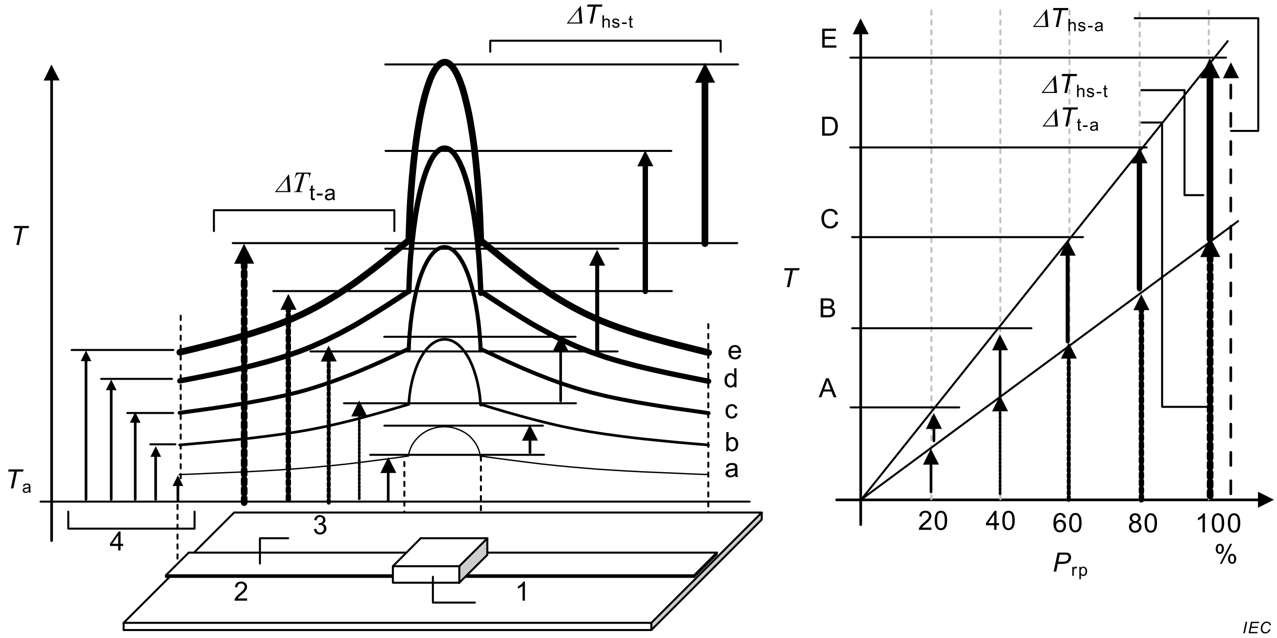
1) the applied power shall be less or equal to the rated power P_r, and
2) hotspot temperature T_{hs} shall be less or equal to the UCT; this simplification will be the advantage.

Annex B
(informative)

The temperature rise of SMD resistors and the influence of the printed circuit board

B.1 Temperature rise of SMD resistors

SMD resistors are always directly mounted on the printed circuit board for use. In this case, it will be explained that the hotspot temperature of the resistor (the thermally sensitive point temperature T_{sp} explained in Annex A is more important, but to prevent this from being complicated, it will be represented by the hotspot temperature T_{hs}) is not unambiguous even when the ambient temperature T_{a} and the applied power is defined. Figure B.1 is a diagram of the temperature distribution of a resistor including the board when the applied power to the SMD resistor mounted on the board is escalated from 0,2 P_{r} to P_{r} by 20 % for the rated power P_{r}. The graph on the right-hand side of Figure B.1 is a graph with the rated power ratio P_{rp} (%) plotted on the horizontal axis and temperature rise $\Delta T_{\mathrm{hs\text{-}a}}$ plotted on the vertical axis. The left and right graphs of Figure B.1 are adjusted to the height of the starting point and end point of the temperature rise vector $\Delta T_{\mathrm{t\text{-}a}}$ (dashed arrow) and $\Delta T_{\mathrm{hs\text{-}t}}$ (solid arrow).



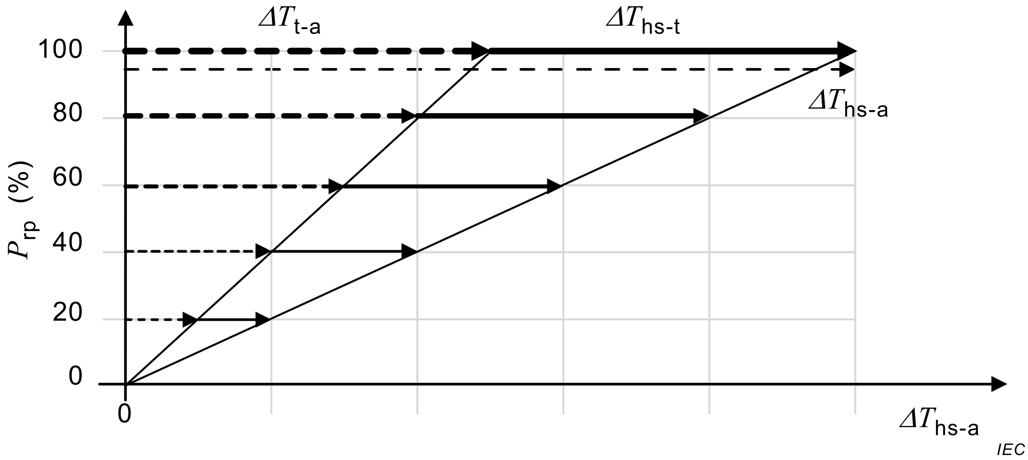
Key

T	Temperature rise of each part
T_a	Ambient temperature
P_{rp}	Fraction of applied power to the rated power
1	Resistor
2	Printed board
3	Pattern
4	Temperature of the edge of the board
a	Temperature distribution (Rated power × 0,2)
b	Temperature distribution (Rated power × 0,4)
c	Temperature distribution (Rated power × 0,6)
d	Temperature distribution (Rated power × 0,8)
e	Temperature distribution (Rated power × 1,0)
$\Delta T_{t\text{-}a}$	Temperature rise (dashed line) from the ambient to the terminal
$\Delta T_{hs\text{-}t}$	Temperature rise (arrowed line) from the terminal to the hotspot
$\Delta T_{hs\text{-}a}$	Temperature rise (arrowed chain line) from the ambient to the hotspot, always $\Delta T_{t\text{-}a}$ + $\Delta T_{hs\text{-}t}$
A	When 0,2 times the rated power is applied to $\Delta T_{hs\text{-}a}$
B	When 0,4 times the rated power is applied to $\Delta T_{hs\text{-}a}$
C	When 0,6 times the rated power is applied to $\Delta T_{hs\text{-}a}$
D	When 0,8 times the rated power is applied to $\Delta T_{hs\text{-}a}$
E	When 1,0 time the rated power is applied to $\Delta T_{hs\text{-}a}$

Figure B.1 – Temperature distribution of the SMD resistors mounted on the board

The temperature rise from the terminal to the hotspot $\Delta T_{hs\text{-}t}$ is the inherent value of the resistor, which is determined unambiguously by the thermal resistance (described in Annex F) of the resistor and the applied power. However, beware that the temperature rise from the ambient temperature to the terminal $\Delta T_{t\text{-}a}$ can differ largely from the board material, pattern, size and air flow.

The vertical axis and horizontal axis of the right-hand graph of Figure B.1 is switched as shown in Figure B.2 to add on the derating curve.



Key

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

$\Delta T_{t\text{-}a}$ Temperature rise (arrowed dashed line) from the ambient to the terminal

$\Delta T_{hs\text{-}t}$ Temperature rise (arrowed line) from the terminal to the hotspot

$\Delta T_{hs\text{-}a}$ Temperature rise (arrowed chain line) from the ambient to the hotspot, always $\Delta T_{t\text{-}a} + \Delta T_{hs\text{-}t}$

Figure B.2 – Temperature rise of the SMD resistors from the ambient temperature

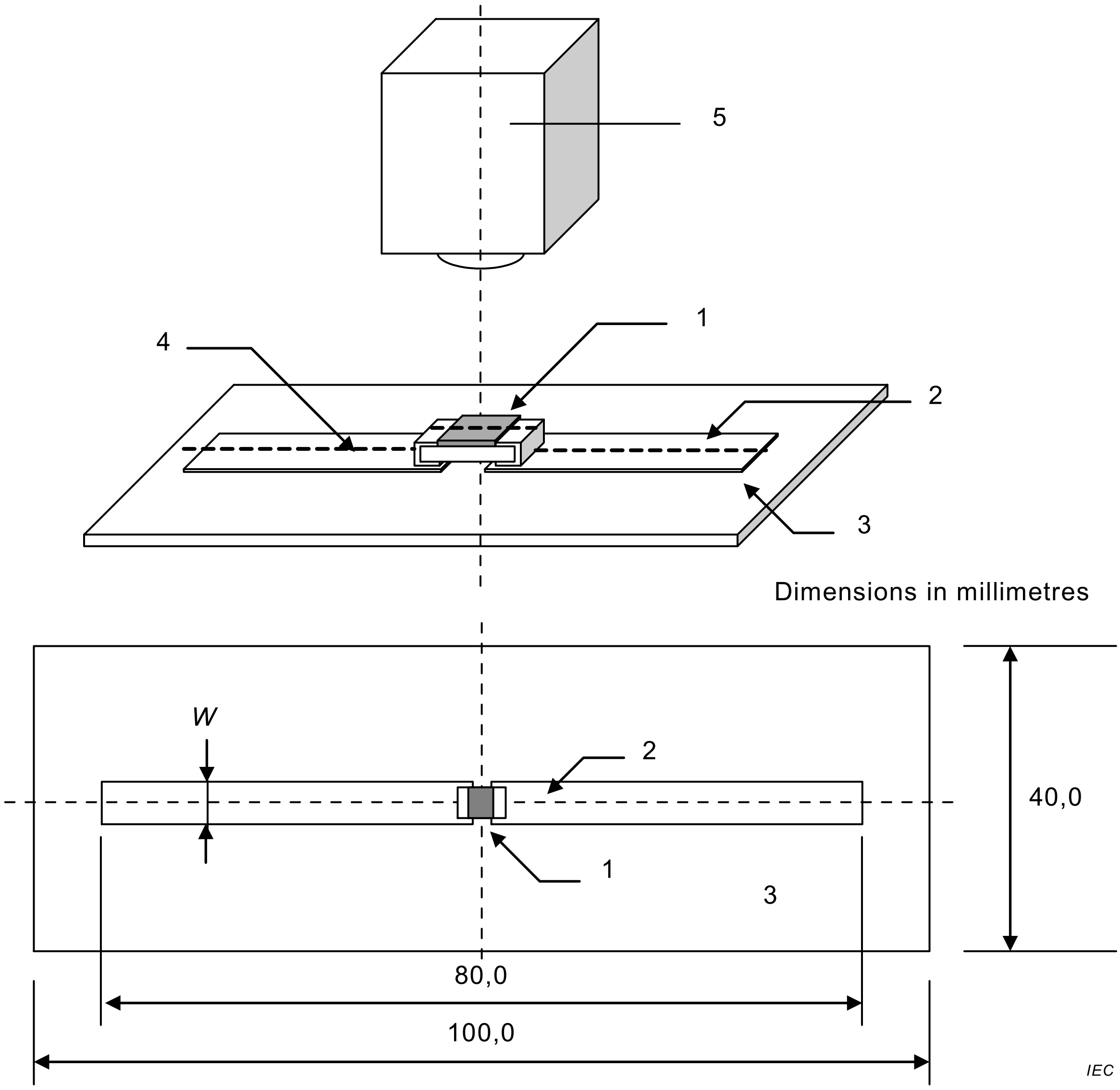
SMD resistors are different from the lead wire resistors, so not all of the heat generated at the resistive element is directly radiated into the atmosphere from the surface of the resistor. Most of the heat generated at the resistor (over 90 % of the heat for the resistors RR6332M or smaller, the smaller it gets the rate approaches 100 %) first goes through the terminal part into the board pattern and raises the board temperature around the resistor. And then the larger area of the board is heated, and then the heat is dissipated into the atmosphere. So, the board acts as the heat sink of the resistor. Therefore, when the heat conduction of the board is good and the heat transfer into the atmosphere is also good, the $\Delta T_{t\text{-}a}$ will be small. But when the heat conduction of the board is poor and the airflow around the board is bad, and the heat transfer into the atmosphere is poor, the $\Delta T_{t\text{-}a}$ will be large.

On the other hand, most of the heat generated at the resistor will conduct to the terminal part so the $\Delta T_{hs\text{-}t}$ is constant and does not depend on the board.

However, when strong forced air cooling is implemented, heat dissipation directly into the atmosphere from the SMD resistor surface will become unignorable, so $\Delta T_{hs\text{-}t}$ will be smaller than the value under the no-wind condition. But, the amount of heat dissipation is very small compared to the decrease of $\Delta T_{t\text{-}a}$ caused by the forced air cooling of the board under the same wind speed condition, so the decrease of $\Delta T_{t\text{-}a} + \Delta T_{hs\text{-}t}$ when the forced air cooling is implemented would be mostly the decrease of $\Delta T_{t\text{-}a}$.

When the change of $\Delta T_{t\text{-}a} + \Delta T_{hs\text{-}t}$ and $\Delta T_{t\text{-}a}$ are compared, it is permissible to ignore the change of $\Delta T_{hs\text{-}t}$.

The heat path of SMD resistors differ greatly from the lead wire resistors that were connected in the air and radiate directly into the atmosphere as mentioned in Clause 4. The heat dissipation of SMD resistors depends largely on the board. Figure B.3 shows the measurement system and data. Figure B.4 and Figure B.5 are the data.



Key

1: RR2012M resistor 0,25 W applied

2: Copper pattern, 2 kinds (thickness 35 µm and 70 µm)

3: Thickness1,6 mm FR4 board (set horizontally, above 40 mm from the desk)

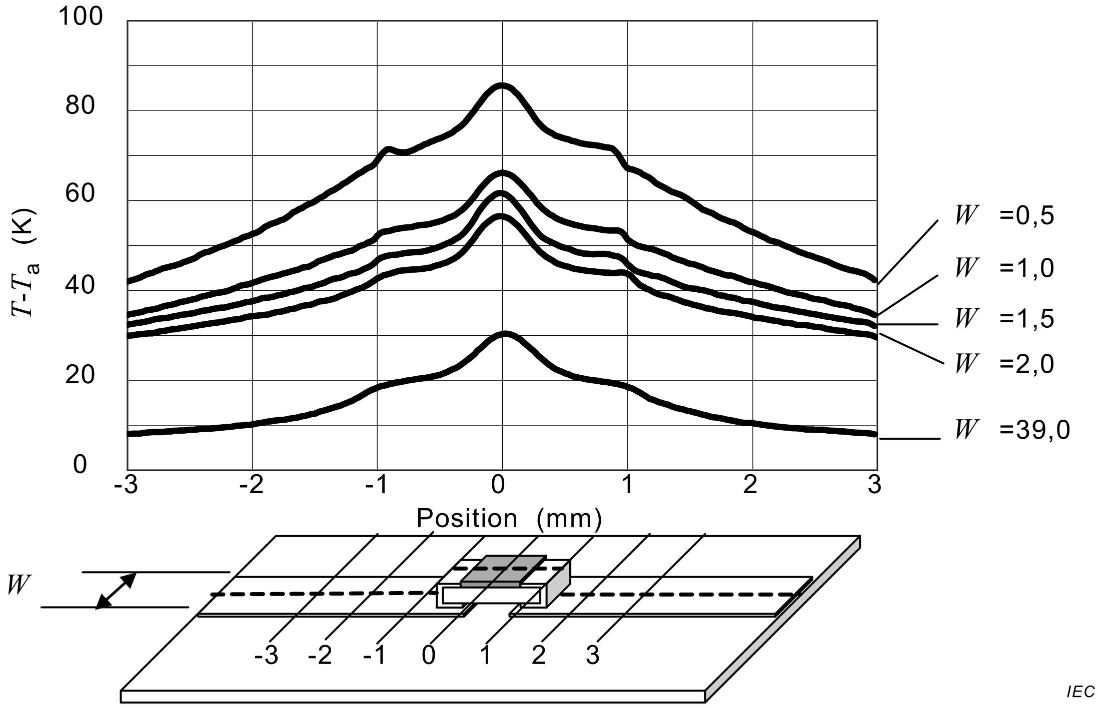
4: Measure temperature rise from the ambient temperature of the dotted line area

5: Infrared thermograph (magnification lens of 50 µm per pixel)

W: Pattern width, 5 kinds (0,5 mm, 1,0 mm, 1,5 mm, 2,0 mm and 39,0 mm)

Figure B.3 – Measurement system layout and board dimension

$T - T_a$ in Figure B.4 and Figure B.5 are both temperature rises. So, for example, when T_a = 25 °C, add 25 °C to the value read from the graph to obtain the actual temperature. When the same power is applied to the same resistor, but the width and thickness of the pattern is different, the surface hotspot temperature T_{shs} and temperatures of the other parts will change. T_{shs} will become 110 °C when T_a = 25 °C, pattern width 0,5 mm and thickness 35 µm. On the other hand, it will not even reach 50 °C when T_a = 25 °C, pattern width 39 mm and pattern thickness 70 µm.



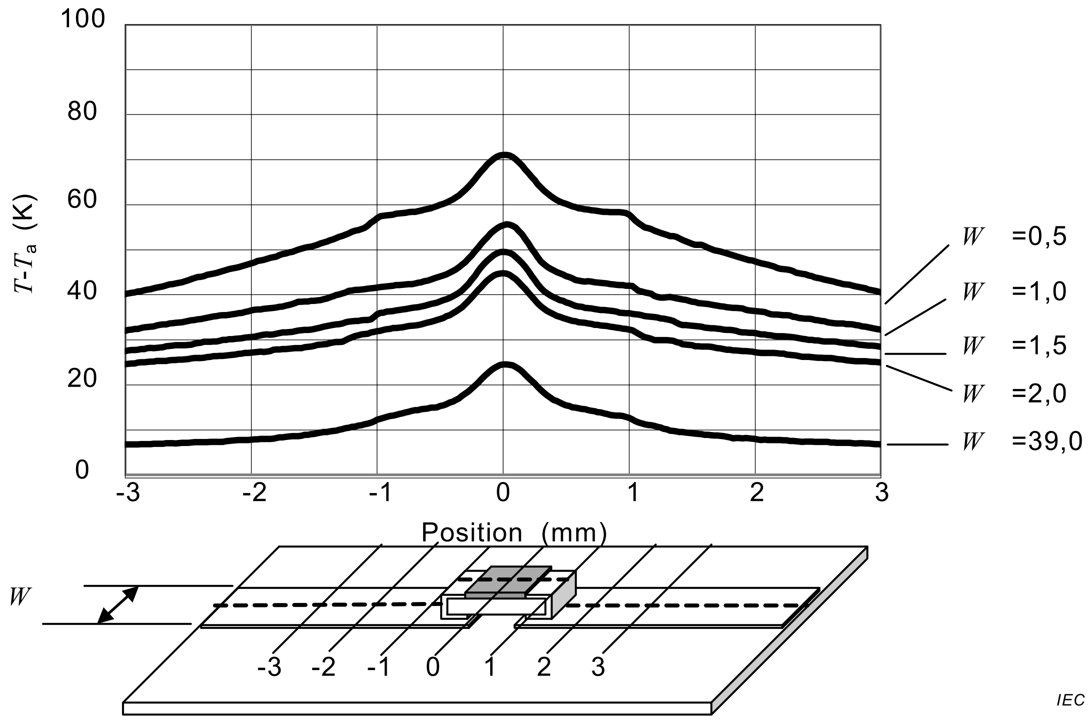
Key

T Each part temperature

T_a Ambient temperature

W Pattern width

Figure B.4 – Temperature rise of RR2012M (thickness 35 µm, 0,25 W applied)



Key

T Each part temperature

T_a Ambient temperature

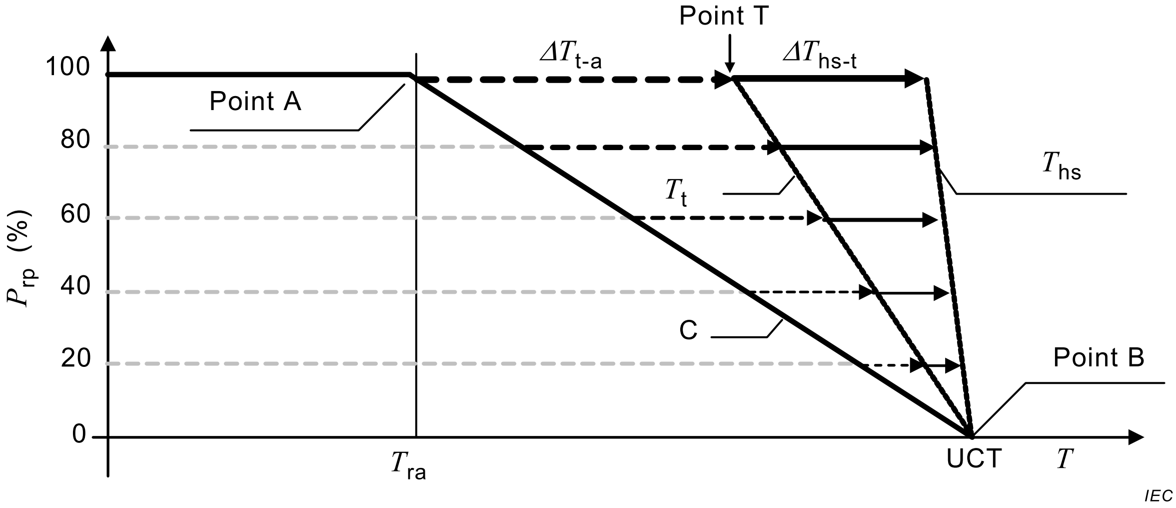
W Pattern width

Figure B.5 – Temperature rise of RR2012M (thickness 70 µm, 0,25 W applied)

B.2 The influence of the printed circuit boards

Suppose that the resistor manufacturer mounted the SMD resistors on the board and established the derating curve according to Figure A.3 and the methods mentioned in Annex A. Presume that the SMD resistors used here are the ones in which the hotspot temperature T_{hs} of the load life test do not exceed the high temperature exposure test temperature (UCT), such as the leaded resistors with a small temperature rise shown in Figure A.9.

And then, think about what would happen to the hotspot temperature when the applied power to the resistor is reduced according to the derating curve as the ambient temperature rises, on the exact same board. Figure B.6 shows the temperature rise from ambient to hotspot temperature ΔT_{hs-a} described in Figure B.2 by the sum of ΔT_{hs-t} (temperature rise from the terminal part to the hotspot) and ΔT_{t-a} (temperature rise from the ambient to the terminal part).



Key

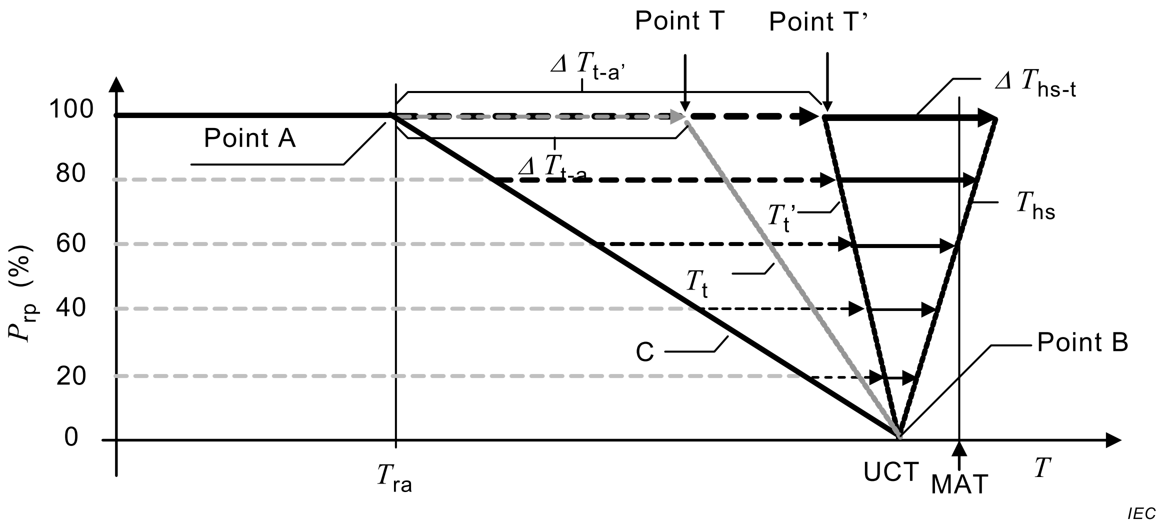
P_{rp}	Percentage of applied power to the rated power
T	Temperature
T_{ra}	Rated ambient temperature
T_{hs}	Hotspot temperature
UCT	Upper Category Temperature
Point A	Load life test point
Point B	High temperature exposure test point
C	Derating curve based on the ambient temperature T_a
$\Delta T_{t\text{-}a}$	Temperature rise from the ambient to the terminal part
$\Delta T_{hs\text{-}t}$	Temperature rise from the terminal part to the hotspot
Point T	Terminal part temperature of the resistor at the load life test
T_t	Terminal part temperature

Figure B.6 – Trajectory of the terminal part and hotspot temperature of the SMD resistors

In this case, the condition at which the resistor is set would be completely the same as the test condition at which the derating curve was established so the maximum temperature will not exceed the UCT. This would be the same idea with the leaded components. Additionally, the heat stress would not exceed $\Delta T_{hs\text{-}t}$ of the maximum value of the load life test.

But next, it is necessary to think about the correspondence between the actual usage condition of the SMD resistors in the electric/electronic devices and the derating curve defined by the resistor manufacturer. Of course, the actual boards used in the electric/electronic devices are not the same boards that are used in the load life test implemented by the resistor manufacturer. There might be many heat-generating components other than resistors mounted on the board, or the resistors might be densely mounted. For a brief explanation, suppose that the actual boards used in the devices have the same board and layout as the boards used in the load life test, but with a narrow wiring pattern width.

In this case, Figure B.6 would change as shown below.



Key

P_{rp}	Percentage of applied power to the rated power
T	Temperature
T_{ra}	Rated ambient temperature
T_{hs}	Hotspot temperature
UCT	Upper Category Temperature
Point A	Load life test point
Point B	High temperature exposure test point
C	Derating curve based on the ambient temperature T_a
ΔT_{t-a}	Temperature rise from the ambient to the terminal part (Test board at manufacturer)
ΔT_{t-a}'	Temperature rise from the ambient to the terminal part (Board with narrow pattern)
ΔT_{hs-t}	Temperature rise from the terminal part to the hotspot
Point T	Original terminal part temperature of the resistor at the load life test
Point T'	Terminal part temperature of the resistor at the rated load, rated ambient temperature on the narrow pattern board
T_t	Terminal part temperature (when the load is derated on the test board of the manufacturer)
T_t'	Terminal part temperature (when the load is derated on the board with narrow pattern)
MAT	Maximum Allowable Temperature

Figure B.7 – Operating temperature of the resistor on the board with narrow patterns

ΔT_{t-a} is expected to be larger than Figure B.6 on the boards with narrow patterns, as shown in the samples of Figure B.4 and Figure B.5. To discriminate the ΔT_{t-a} in Figure B.6, it is described as $\Delta T_{t'-a}$ in Figure B.7. When the rated power is applied, the terminal temperature moves from point T in Figure B.6 to point T' in Figure B.7 for $\Delta T_{t'-a} - \Delta T_{t-a}$ to the high temperature side. The temperature rise from the terminal part to the hotspot ΔT_{hs-t} does not change if the applied power is the same, even when the pattern width is different. As a result, even if the load is reduced along with the rise of the ambient temperature according to the derating curve established by the method in Annex A and shown in Figure A.3, the hotspot temperature of the resistor will exceed the temperature verified in the test implemented by the resistor manufacturer if the board is using a narrow pattern. In Figure B.6, there is a possibility of exceeding the UCT, or even the MAT. In this case, it is impossible to achieve the reliability which the resistor manufacturer assures even if the electric/electronic device designers used the resistor according to the derating curve.

This disadvantage is caused only because the electric/electronic device designers used a board with a narrower pattern than the resistor manufacturer used. The high temperature of the terminal part as shown in Figure B.7 can occur by just placing heat-generating components close by or when the copper pattern thickness is thinner.

Recently, in automotive applications, the design of electric/electronic devices for use under high temperature, and high-density mounting for miniaturization has advanced. From these demands, requests for raising the rated power are escalating against resistor manufacturers. In this situation, the ambiguity of the derating curves will not only confuse the equipment design of the electric/electronic device designers, but increase the risk of causing actual accidents.

The point is made that the current derating curves provided by resistor manufacturers for SMD resistors with the ambient temperature on the horizontal axis is too ambiguous, and they cannot be used directly in design activities. This recognition needs to be shared between the electric/electronic device designers and the resistor manufacturer.

Annex C
(informative)

The influence of the number of resistors mounted on the test board

C.1 General

There are other disadvantages to using the traditional derating curves based on the ambient temperature in addition to the points mentioned in Annex B.

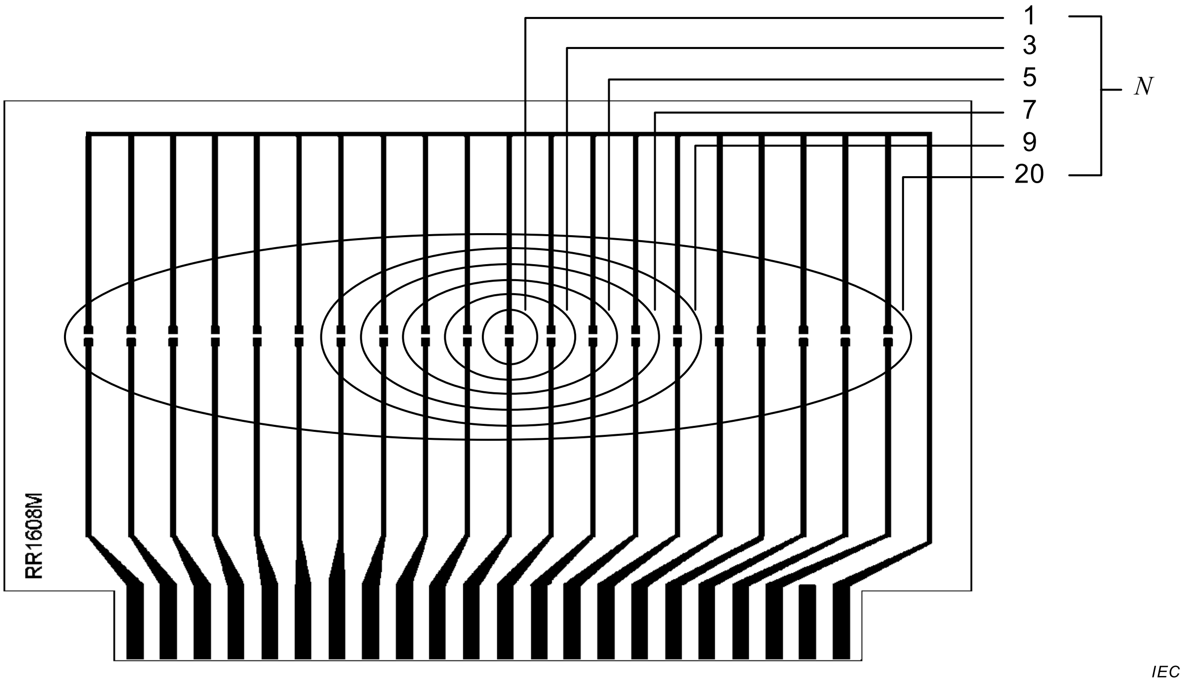
There is a possibility that the temperature of the resistor body during the load life test implemented by the resistor manufacturer may vary, even when they are set in the test chambers under the same ambient temperature of 70 °C.

There are three reasons for this. The first reason is that the number of mounting components and the coefficient of thermal conductivity of the board is not defined in the test boards of IEC 60115-8. The second reason is that there is no test board defined for the SMD resistors other than the specific types defined in IEC 60115-8. The third reason is that it is difficult for the resistor manufacturers to use a completely natural convection test chamber for the load life test.

The first and second reasons will be explained in this Annex C, and the third reason will be explained in Annex D.

C.2 The influence of the number of resistors mounted on the test board

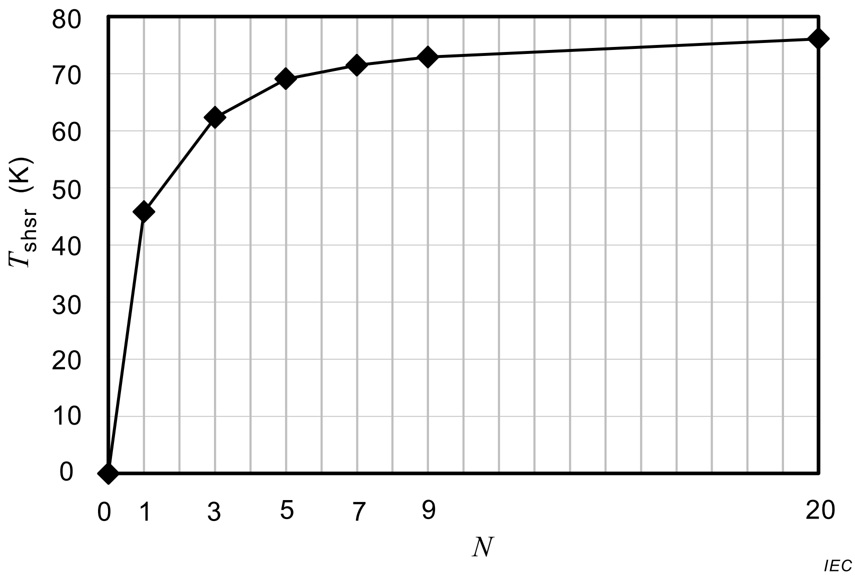
The load life test board for the specified shape SMD resistors are basically defined in the IEC 60115-8. In particular, the minimum pattern length, pad size and pitch for the board material, resistor type and size are defined. Therefore, at a glance, it looks as if any resistor manufacturer can develop the board and mount resistors and set at the same ambient temperature and apply the same power to each resistor and define the temperature of the resistor. But in reality, they cannot. It is because the number of samples mounted and the coefficient of the thermal conductivity of the board are not defined, so the $\Delta T_{\text{t-a}}$ in Figure B.6 cannot be unified. This is quite simple. Figure C.1 shown below is the test board compliant with IEC 60115-8. Figure C.1 is the comparison of the actual measured value of the temperature rise with 1, 3, 5, 7, 9 and 20 samples mounted on the test board. The power distribution is increased from the centre. The power for each resistor is set at 0,25 W to clearly make the difference in temperature rise influenced by the number of samples mounted. There are individual differences, but it is clear that the temperature rise is larger when there are more samples, as shown in Figure C.2 and Figure C.3.



Key

N Number of samples to which power is applied

Figure C.1 – Test board compliant with the IEC standard for RR1608M

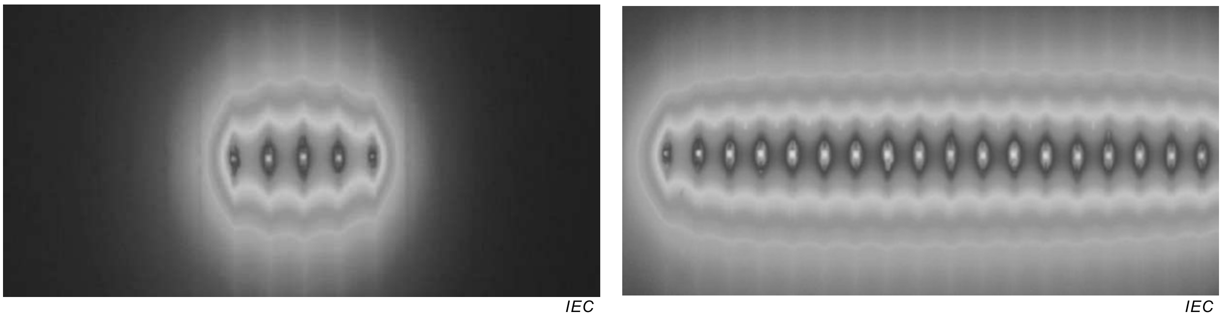


Key

T_{shsr} Surface hotspot temperature rise

N Number of samples to which power is applied

Figure C.2 – Relation between the number of samples and the surface hotspot temperature rise



a) 5 samples **b) 20 samples**

Figure C.3 – Infrared thermograph image in the same scale when power is applied to 5 samples and 20 samples

C.3 The delay of correspondence for current products with nonstandard dimensions

The second reason will be explained. Currently, many uniquely-shaped SMD resistors are developed and are sold with large rated powers. However, there is no common standard about the test board for these uniquely-shaped SMD resistors. As mentioned in Annex B, Figure B.3 and Figure B.4, SMD resistors use the patterns as a heat-sink, so if the resistor is required to have the largest rated power possible under the test environment with the same ambient temperature, it is necessary to use a test board with a wide-width pattern and to reduce the temperature rise from the ambient environment of the resistor.

Annex D
(informative)

Influence of the air flow in the test chamber

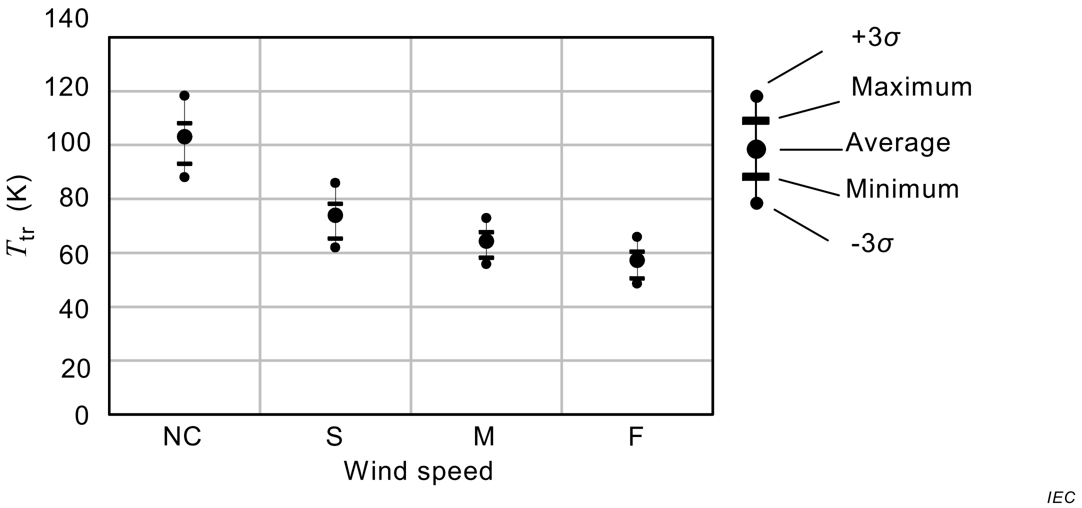
D.1 General

Figure D.1 shows the relation between the temperature rise of the terminal part of RR6332M and wind speed. It shows that the temperature rise of the resistor will drop much more than with natural convection, even with a faint airflow. The airflow is caused by the agitation fan which is set to keep the temperature inside the test chamber uniform. The power applied to the resistor would be the same even when the airflow condition changes. Ten samples of the RR6332M were mounted on the test board and 1 W was applied to each sample. The vertical axis is the rise from the ambient temperature to the terminal part temperature, but the hotspot temperature would be the terminal part temperature plus the certain offset temperature $\Delta T_{\text{hs-t}}$ according to the applied power, regardless of the wind speed. Therefore, the trend of this graph would be the same for the hotspot temperature as well. The reason why the hotspot temperature would be the terminal part temperature plus the certain offset temperature was mentioned in Annex B. SMD resistors have small surface areas, so the heat dissipation by heat transfer from the resistor surface to the atmosphere would be extremely small regardless of the airflow compared with the heat dissipation via the terminal part by heat conduction. The board compliant with IEC 60115-8 is used in the experiment. The board used for the RR1608M is shown in Figure C.1. The number of samples mounted is shown in Table D.1. There are 10 samples mounted for the large products and 20 samples for the small products.

D.2 Influence of the wind speed

The terminal temperature is measured with a type K thermocouple of 0,1 mm in wire diameter. The temperature measurement errors by the thermocouple will be mentioned later, but even when measurement errors are considered, it is possible to observe the large decrease of the temperature rise when there is a faint breeze of about 0,4 m/s to 0,7 m/s compared with the conditions with only natural convection.

Figure D.2 shows the test system for the natural convection flow and Figure D.3 shows the test system with air flow.



Key

T_{tr} Temperature rise of terminal part

NC Natural convection (horizontally set)

S 0,4 m/s to 0,8 m/s

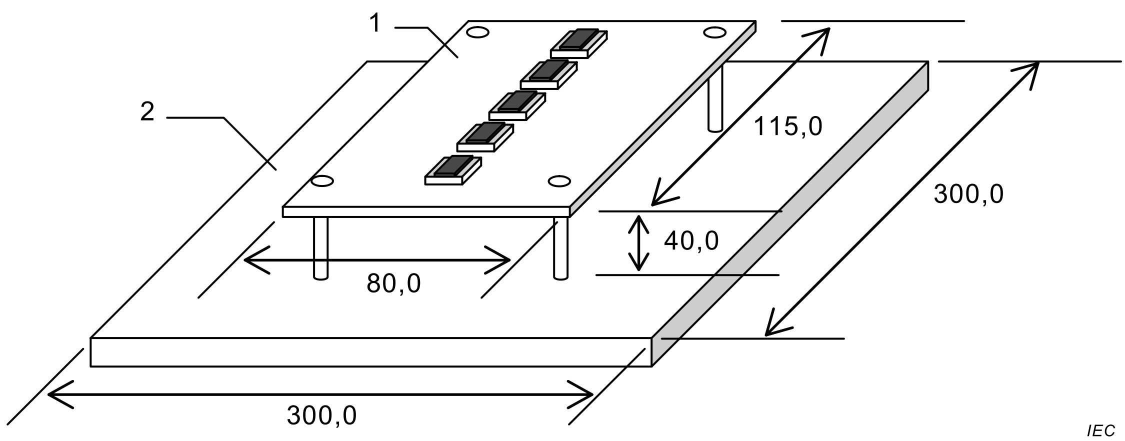
M 0,7 m/s to 1,4 m/s

F 1,4 m/s to 2,3 m/s

σ Standard deviation

Figure D.1 – Wind speed and the terminal part temperature rise of the RR6332M

Dimensions in millimetres



Key

1 Test board (set in the centre of the platform)

2 Platform

Figure D.2 – Test system for the natural convection flow

The test was implemented to products other than the RR6332M as well. The test boards are compliant with IEC 60115-8 just like the boards used in Figure C.1. The dimension of the entire board is 115 mm wide and 80 mm long for all resistor sizes, and the pattern width and the mounting pitch are all stated in IEC 60115-8. The number of samples mounted and the applied power for each sample is shown in Table D.1.

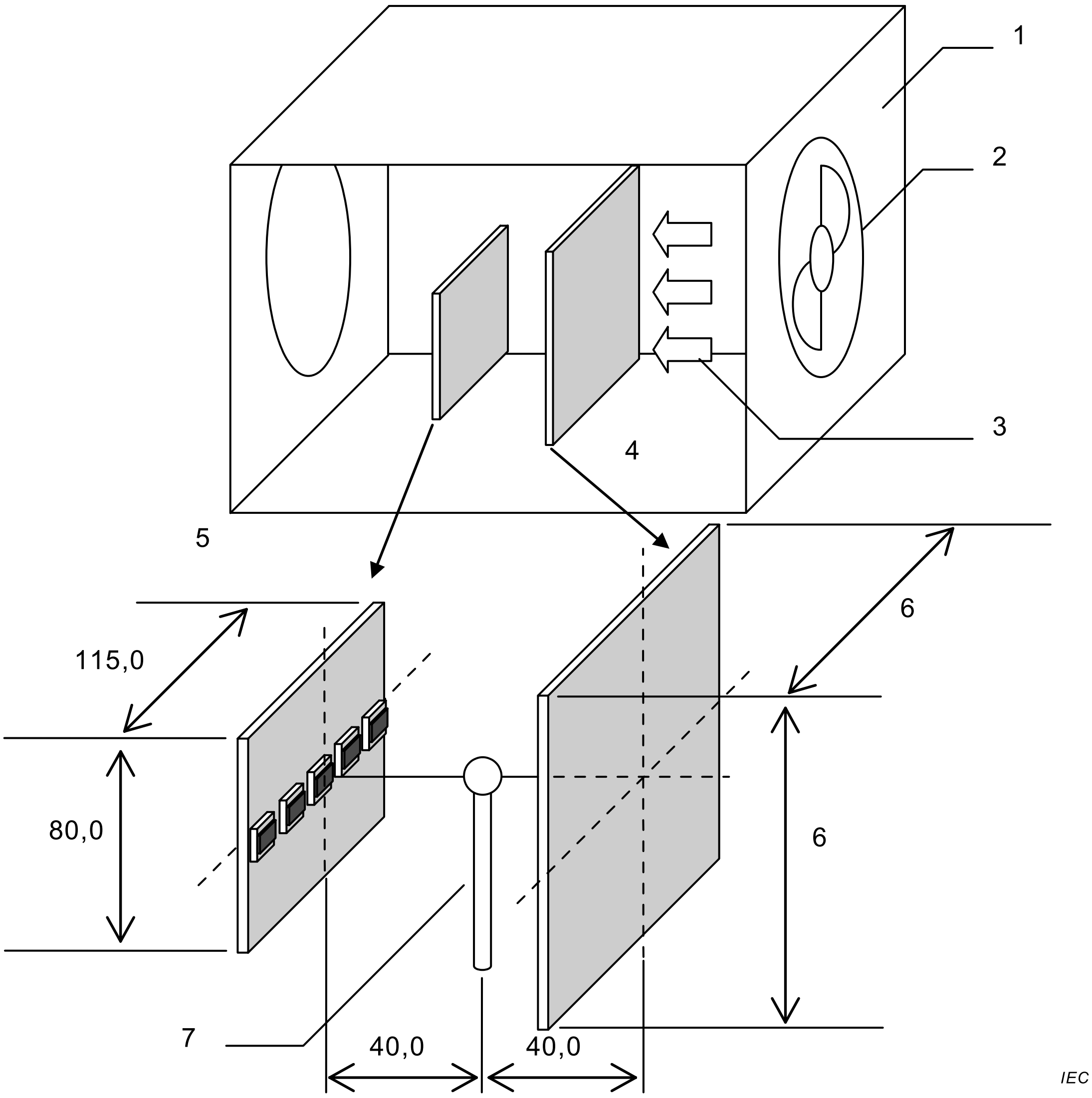
The thermocouple for the three sizes RR6332M to RR3225M are directly soldered to one side of the resistor terminal part (centre of the solder fillet) for all 10 samples mounted on one test board. The thermocouple for the four sizes RR3216M to RR1005M are directly soldered to one side of the resistor terminal part (centre of the solder fillet) to every other sample, in total 10 samples out of the 20 resistors mounted on the test board.

The results are shown in Figure D.4, Figure D.5, Figure D.6, Figure D.7, Figure D.8 and Figure D.9.

Table D.1 – Number of samples mounted and the applied power

Size	Number of samples mounted on one board	Applied power for each resistor W
RR6332M	10	1
RR5025M	10	0,75
RR3225M	10	0,5
RR3216M	20	0,25
RR2012M	20	0,125
RR1608M	20	0,1
RR1005M	20	0,063

Dimensions in millimetres



Key

1 Constant temperature chamber

2 Agitation fan

3 Agitation wind

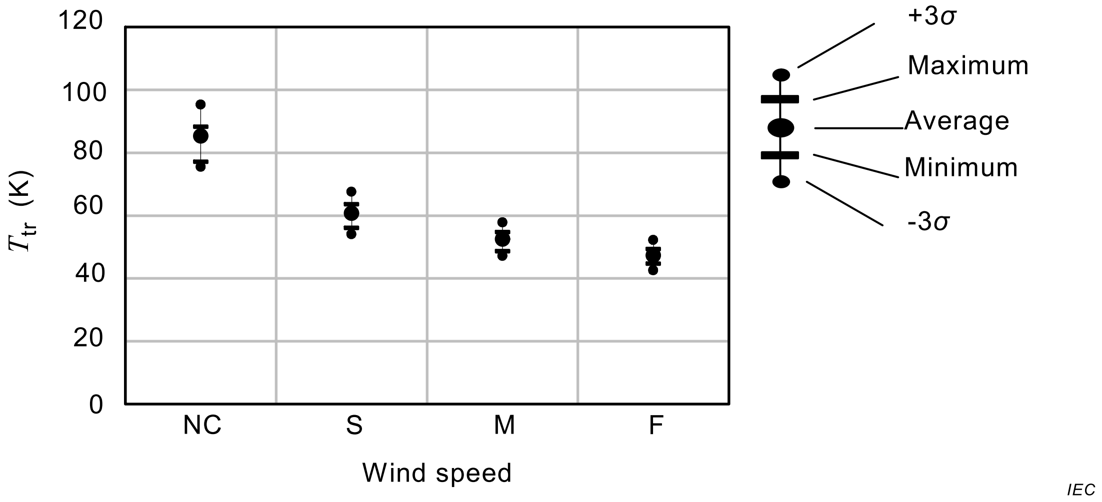
4 Partition

5 Test board

6 Size of the partition is changed to adjust the wind speed

7 Anemometer probe

Figure D.3 – Observing the influence of the agitation wind in the test chamber

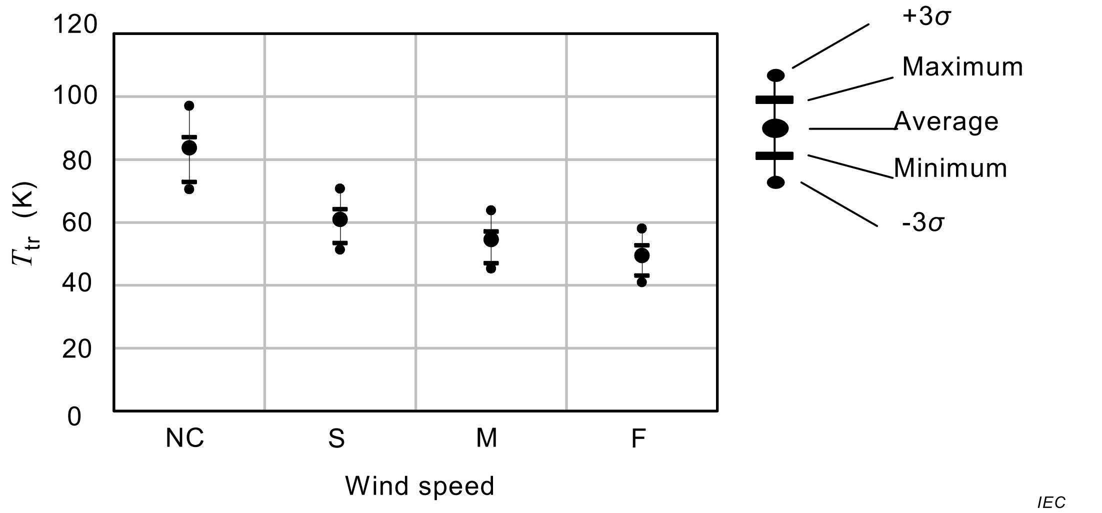


The following shows the test results of other sizes.

Key

T_{tr}	Temperature rise of terminal part
NC	Natural convection (Horizontally set)
S	0,4 m/s to 0,8 m/s
M	0,7 m/s to 1,4 m/s
F	1,4 m/s to 2,3 m/s
σ	Standard deviation

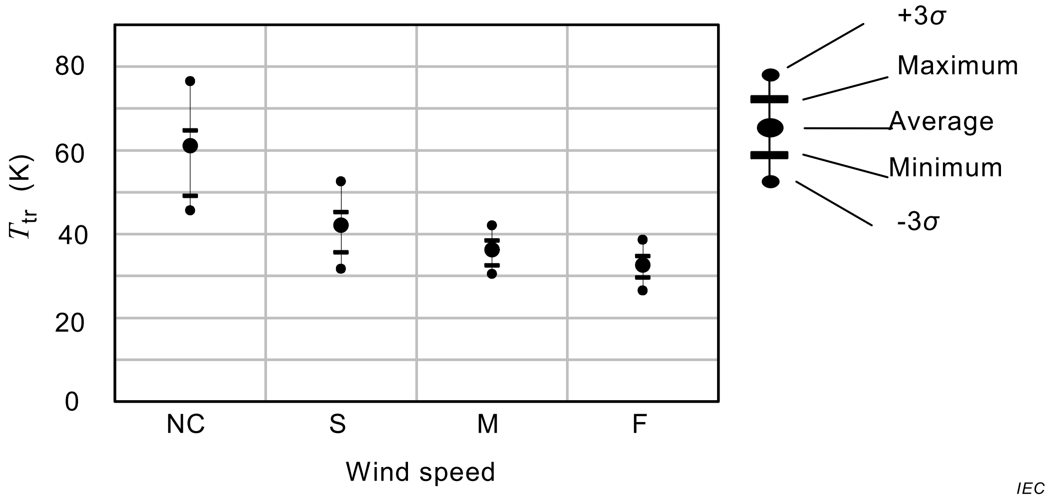
Figure D.4 – Wind speed and the terminal part temperature rise of the RR5025M



Key

T_{tr}	Temperature rise of terminal part
NC	Natural convection (Horizontally set)
S	0,4 m/s to 0,8 m/s
M	0,7 m/s to 1,4 m/s
F	1,4 m/s to 2,3 m/s
σ	Standard deviation

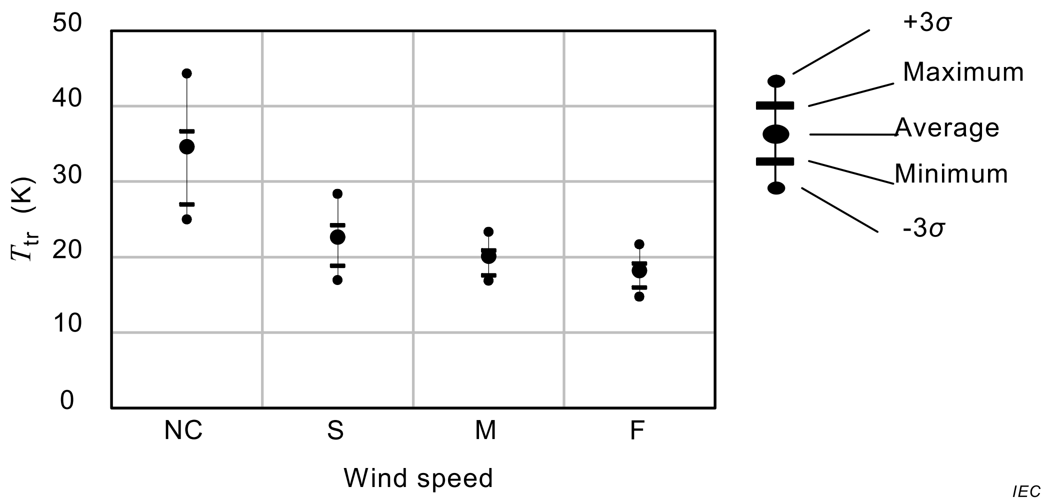
Figure D.5 – Wind speed and the terminal part temperature rise of the RR3225M



Key

T_{tr}	Temperature rise of terminal part
NC	Natural convection (Horizontally set)
S	0,4 m/s to 0,8 m/s
M	0,7 m/s to 1,4 m/s
F	1,4 m/s to 2,3 m/s
σ	Standard deviation

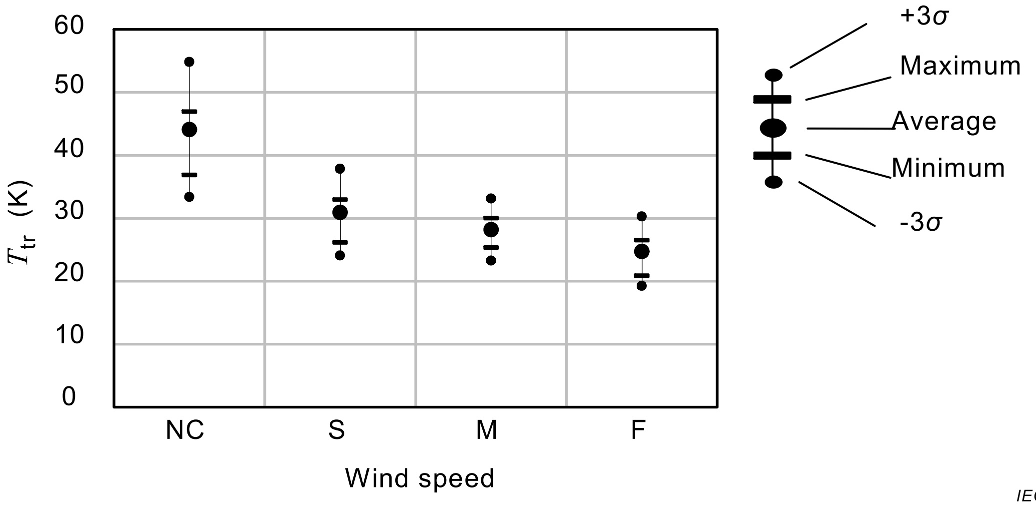
Figure D.6 – Wind speed and the terminal part temperature rise of the RR3216M



Key

T_{tr}	Temperature rise of terminal part
NC	Natural convection (Horizontally set)
S	0,4 m/s to 0,8 m/s
M	0,7 m/s to 1,4 m/s
F	1,4 m/s to 2,3 m/s
σ	Standard deviation

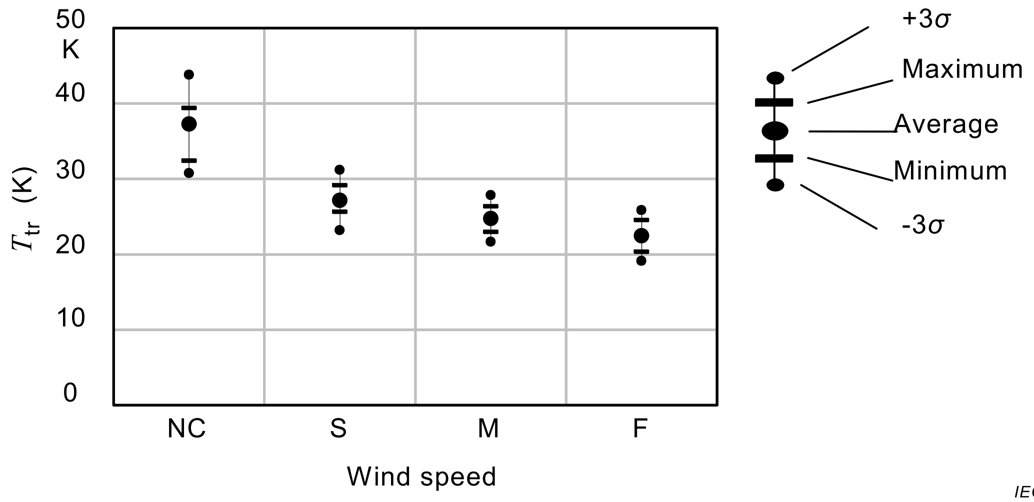
Figure D.7 – Wind speed and the terminal part temperature rise of the RR2012M



Key

T_{tr}	Temperature rise of terminal part
NC	Natural convection (Horizontally set)
S	0,4 m/s to 0,8 m/s
M	0,7 m/s to 1,4 m/s
F	1,4 m/s to 2,3 m/s
σ	Standard deviation

Figure D.8 – Wind speed and the terminal part temperature rise of the RR1608M



Key

T_{tr}	Temperature rise of terminal part
NC	Natural convection (Horizontally set)
S	0,4 m/s to 0,8 m/s
M	0,7 m/s to 1,4 m/s
F	1,4 m/s to 2,3 m/s
σ	Standard deviation

Figure D.9 – Wind speed and the terminal part temperature rise of the RR1005M

It is obvious that the temperature drops largely compared with the natural convection when there is even a faint airflow in all the sizes. If all of the resistor manufacturers implemented a load life test using only the test chamber with complete natural convection, at least the temperature difference of the test condition between each manufacturer caused by the agitation airflow in the chamber would be resolved. This would be ideal for some sides, but it would be impossible because of the cost. The important part is that the resistor manufacturers need to find a method that is able to provide electric/electronic device designers with rated power and derating curves that can be used in design activities even when the load life test for SMD resistors are implemented in test chambers with agitation airflow.

However, the temperature under the condition of the horizontal airflow against the board on which the resistor is mounted is also measured. It will be shown in Annex K. The same trend can be seen, but the temperature difference between the natural convection and with air flow is slightly smaller. The cause is thought to be as follows. When the airflow is set horizontally against the board surface on which the resistor is mounted, the experiment will be implemented in a wind tunnel, and the printed circuit board will be set in the direction in which the airflow will not be interfered, so it will be a laminar airflow. When it is a laminar airflow, the thermal boundary layer becomes thick, so, generally, the heat transfer coefficient becomes low compared with the turbulent airflow. When the board is set as shown in Figure D.3, the wind will become a turbulent airflow and the thermal boundary layer does not get thick, and the heat transfer coefficient becomes higher than the laminar airflow, so these results can be seen even when the wind speed is the same.

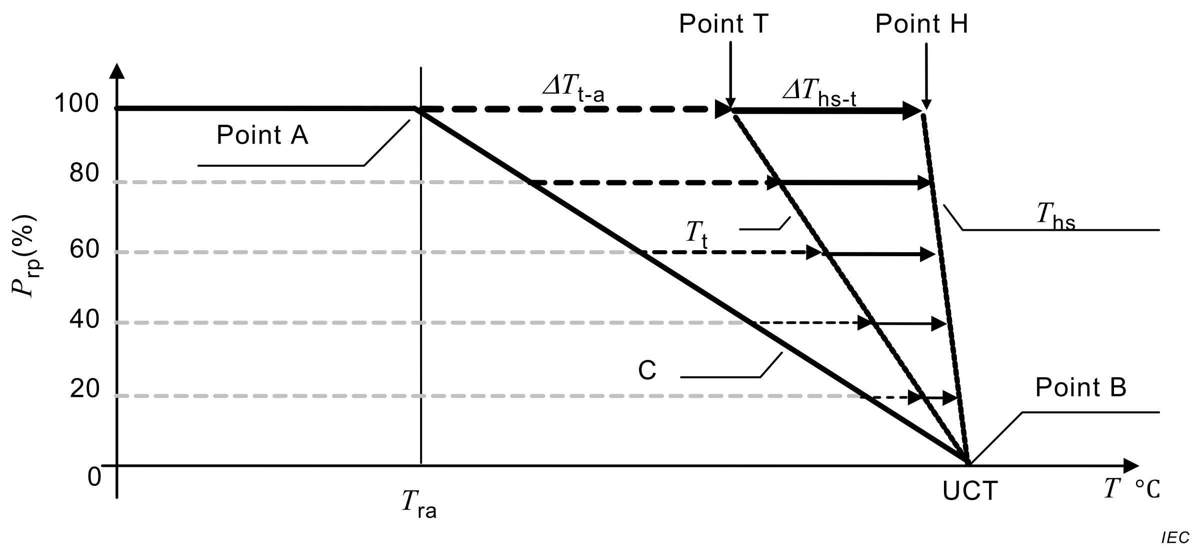
When a load life test using the test chamber is implemented by the resistor manufacturer, a partition is often used to prevent the agitation airflow from directly blowing onto the printed board and reducing the wind speed, but this has a high probability of making a turbulent airflow, so the temperature drop can become larger than the laminar airflow even when the wind speed close to the board is the same.

Annex E
(informative)

Validity of the new derating curve

E.1 Suggestion for establishing the derating curve based on the terminal part temperature

The derating curve that can resolve the disadvantages mentioned in Annex B, Annex C and Annex D will be studied. The answer is to establish a derating curve using the temperature of the point where the temperature of the resistor is reflected correctly at the load life test implemented by the resistor manufacturer. The first candidate would be the hotspot temperature, or the thermally sensitive point temperature. From here on, "thermally sensitive point" will be referred to as "hotspot temperature" to prevent confusion.



Key

P_{rp}	Percentage of applied power to the rated power
T	Temperature
T_{ra}	Rated ambient temperature
T_{hs}	Hotspot temperature
UCT	Upper Category Temperature
Point A	Load life test point
Point B	High temperature exposure test point
C	Derating curve based on the ambient temperature
ΔT_{t_a}	Temperature rise from the ambient to the terminal part
$\Delta T_{hs\text{-}t}$	Temperature rise from the terminal part to the hotspot
Point T	Terminal part temperature at the load life test
T_t	Terminal part temperature
Point H	Hotspot temperature at the load life test

Figure E.1 – Derating conditions of SMD resistors on the resistor manufacturer test board

Figure E.1 is Figure B.6 shown again. The derating curve defined with the hotspot (or thermally sensitive point) means that, in concrete terms, the derating part is a straight line drawn from point H to the UCT. In this case, the horizontal axis T would be the hotspot temperature.

The electric/electronic device designers should measure the temperature of the hotspot of the resistor and confirm that the power consumption ratio against the rating is under the derating curve that is defined with the hotspot temperature. From this verification, the usage condition of the electric/electronic device designers would be surely within the maximum temperature and maximum heat stress confirmed by the test implemented by the resistor manufacturer.

But, unfortunately, there are flaws in this derating curve using the hotspot temperature as the horizontal axis. The defects are shown below.

The resistors that have a hotspot that can be observed from the outside are limited. The hotspot does not mean that it is the thermally sensitive point of the resistor. Therefore, it cannot be said that it is OK to just control the hottest part of the resistor.

Even if there were a resistor whose hotspot was its thermally sensitive point that needs to be controlled, and it was able to be observed from the outside, the method would be a problem. The first piece of equipment that would come to mind to measure the hotspot temperature from the surface would be the infrared thermometer. But, the infrared thermometer can only measure the temperature of an area that can be seen from the outside. It would be impossible to measure and control the hotspot temperature of the resistor directly when it is inside the chamber during the test. Additionally, it would be also impossible for electric/electronic device designers to measure the hotspot of the resistors that are mounted on the board and set inside the chassis and operated. The details would be explained in Annex G but to measure the extremely small hotspot of a small-size SMD resistor would need a close-set magnifier with sufficient spatial resolution. This means that these kind of lenses need to be set very close (in the order of a few centimetres) to the object for it to be measured. From this point of view, it would be impossible to measure the direct hotspot temperature under the conditions of the load life test carried out by the resistor manufacturer and the actual operating conditions at the electric/electronic device designer side.

This is only a presumption that there is a resistor that has a hotspot that can be observed from the outside, and this hotspot is the only point that needs to be controlled. The method that would be appropriate when making assumptions about the hotspot temperature of the resistor that is under test in the test chamber by the resistor manufacturer should be considered. First, set the board used in the test on the table under the thermally neutral environment and the temperature rise from the ambient temperature to the hotspot $\Delta T_{\text{hs-a}}$ will be measured. Next, add the $\Delta T_{\text{hs-a}}$ to the set temperature of the test chamber and predict that it is the hotspot temperature of the resistor under test in the test chamber. This seems correct, but it is wrong.

It is impossible for all the resistor manufacturers to implement the test in a completely natural convection test chamber. In reality, there is airflow in the test chambers. As mentioned in Annex D, even a faint breeze of 0,4 m/s to 0,7 m/s would interrupt the temperature rise compared with the temperature rise $\Delta T_{\text{hs-a}}$ under the natural convection environment.

The same thing could be said of the actual usage conditions from the electric/electronic designer's side. For example, suppose that the electric/electronic designer opened the chassis or took out the printed board from the chassis and set it in open space and operated the equipment and measured the hotspot temperature of the resistor T_{hs}. At the same time, suppose that the base point is set somewhere on the board and measured as T_{ref} with an infrared thermograph. Then, attach a thermocouple to the point where T_{ref} was measured, and put it back into the chassis and activate the equipment and measure the base point temperature T'_{ref} with the thermocouple. In this case, the hotspot temperature T'_{hs} of the resistor inside the chassis will not become $T'_{\text{ref}} + (T_{\text{hs}} - T_{\text{ref}})$. If T_{ref} was very close to the resistor, such as the terminal part of the same component, it may happen, but when the measured point of T_{ref} and the place where the resistor is mounted becomes farther, the difference between T'_{hs} and $T'_{\text{ref}} + (T_{\text{hs}} - T_{\text{ref}})$ will get larger. This is because the temperature distribution on the board set inside the chassis will not become the same as the temperature distribution of the board alone or with a part of the chassis opened, unless the chassis is extremely large compared to the board. Besides, if a fan is used for air cooling, this method cannot be used.

The above problems are all hard to resolve, so it is difficult for the resistor manufacturer to provide the derating curves based on the hotspot. Even if it were possible, the index would become something that electric/electronic device designers would find difficult to use for verification of use.

However, the surface hotspot temperature can be calculated if the applied power, the thermal resistance between the surface hotspot of the resistor and the terminal part $R_{\text{th shs-t}}$, and the terminal part temperature could be measured. Even if resistors that could be derated by the surface hotspot are developed, it would be necessary to measure the terminal part temperature for operation.

Figure E.1 will be reviewed to see which point would be optimum for the horizontal axis of the derating curve.

The temperature rise from the terminal part to the hotspot $\Delta T_{\text{hs-t}}$ is the inherent value of the resistor when the applied power is defined. The thermal resistance from the terminal part to the hotspot of the resistor would be $R_{\text{th hs-t}}$. The hotspot temperature would be T_{hs}. The terminal part temperature would be T_{t}. The power applied to the resistor would be P. The formula to calculate the hotspot temperature is shown in Formula (E.1).

$$T_{\text{hs}} = T_{\text{t}} + \Delta T_{\text{hs-t}} = T_{\text{t}} + R_{\text{th}\cdot\text{hs-t}}P \quad \text{(E.1)}$$

Actually, the $R_{\text{th hs-t}}$ would be the characteristic value of the resistor. To avoid confusion, the formula is omitted. As already explained, when the hotspot is not the thermally sensitive point, the hotspot should be read as the thermally sensitive point.

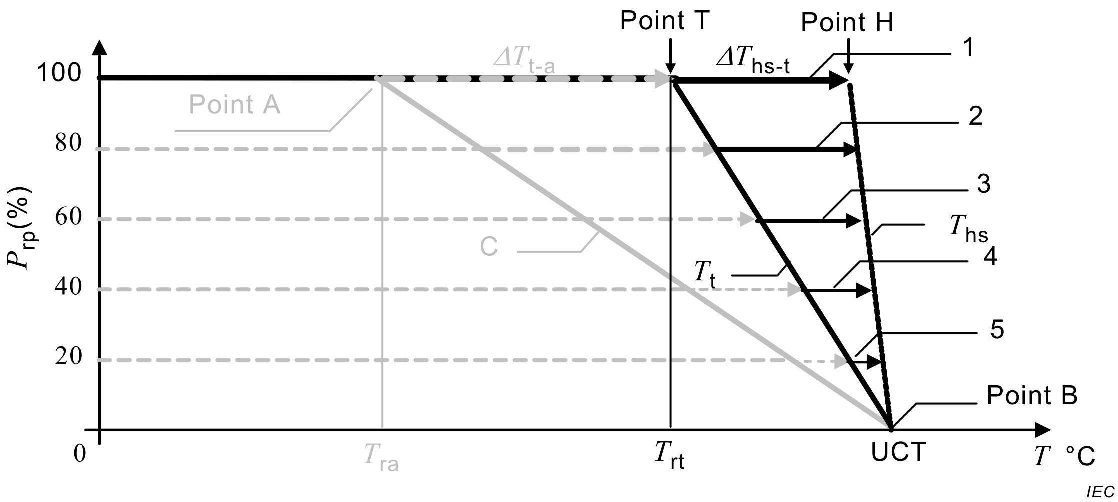
What if the terminal part temperature T_{t} is set as the horizontal axis of the derating curve and uses this temperature as the temperature measurement point common to both resistor manufacturer and the electric/electronic device designers? It means using the trajectory of the terminal part temperature (straight line connecting the Point T and UCT) in Figure E.1 as the derating curve

This derating curve will be called the derating curve based on the terminal part temperature. From here on, the traditional derating curve would be called the derating curve based on the ambient temperature for discrimination.

The $\Delta T_{\text{hs-t}}$ to power ratio is $R_{\text{th hs-t}}\,P$, so it would be reduced in proportion to power. Figure E.2 shows the relationship between $\Delta T_{\text{hs-t}}$, applied power and hotspot temperature when derating is implemented according to the derating curve based on the terminal part temperature.

Of course, the hotspot temperature would conform to the derating curve based on the hotspot temperature (line connecting point H and UCT).

Reducing the load according to the derating curve based on the terminal part temperature is equivalent to reducing the load according to the derating curve based on the hotspot temperature.



Key

P_{rp}	Percentage of applied power to the rated power
T	Temperature
T_{ra}	Rated ambient temperature
T_{rt}	Rated terminal part temperature
T_{hs}	Hotspot temperature
UCT	Upper Category Temperature
Point A	Load life test point
Point B	High temperature exposure test point
C	Derating curve based on the ambient temperature T_{a}
$\Delta T_{\text{t-a}}$	Temperature rise from the ambient to the terminal part
$\Delta T_{\text{hs-t}}$	Temperature rise from the terminal part to the hotspot
Point T	Terminal part temperature at the load life test
T_{t}	Terminal part temperature
Point H	Hotspot temperature at the load life test
1	$\Delta T_{\text{hs-t}} = R_{\text{th hs-t}} \times 1{,}0 \times P_{\text{r}}$
2	$\Delta T_{\text{hs-t}} = R_{\text{th hs-t}} \times 0{,}8 \times P_{\text{r}}$
3	$\Delta T_{\text{hs-t}} = R_{\text{th hs-t}} \times 0{,}6 \times P_{\text{r}}$
4	$\Delta T_{\text{hs-t}} = R_{\text{th hs-t}} \times 0{,}4 \times P_{\text{r}}$
5	$\Delta T_{\text{hs-t}} = R_{\text{th hs-t}} \times 0{,}2 \times P_{\text{r}}$

Figure E.2 – New derating curve provided by the resistor manufacturer to the electric/electronic designers

It is possible to measure the terminal part temperature by using a thermocouple during the load life test by the resistor manufacturer or under the operating condition when the electric/electronic designer mounted the resistor on the board inside the chassis. This is the important advantage of the derating curve based on the terminal part temperature.

The most important advantage of the derating curve based on the terminal part temperature is that it is theoretically equivalent to the derating curve based on the hotspot temperature. Even when the hotspot position or the limit value is unknown, the electric/electronic device designers can be sure that they are using the resistor below the maximum temperature and heat stress confirmed by the resistor manufacturer, as long as the power ratio is reduced below the derating curve as the terminal temperature rises. Introducing the derating curve based on the terminal part temperature as shown in Figure E.3 is the only method to resolve all the mentioned disadvantages.

Therefore, a suggestion is made for the resistor manufacturers to provide the derating curve based on the terminal part temperature by measuring the terminal part temperature of the SMD resistor during the load life test using the thermocouple. The electric/electronic device designers are recommended to use the SMD resistors by reducing the loads according to the derating curve based on the terminal part temperature.

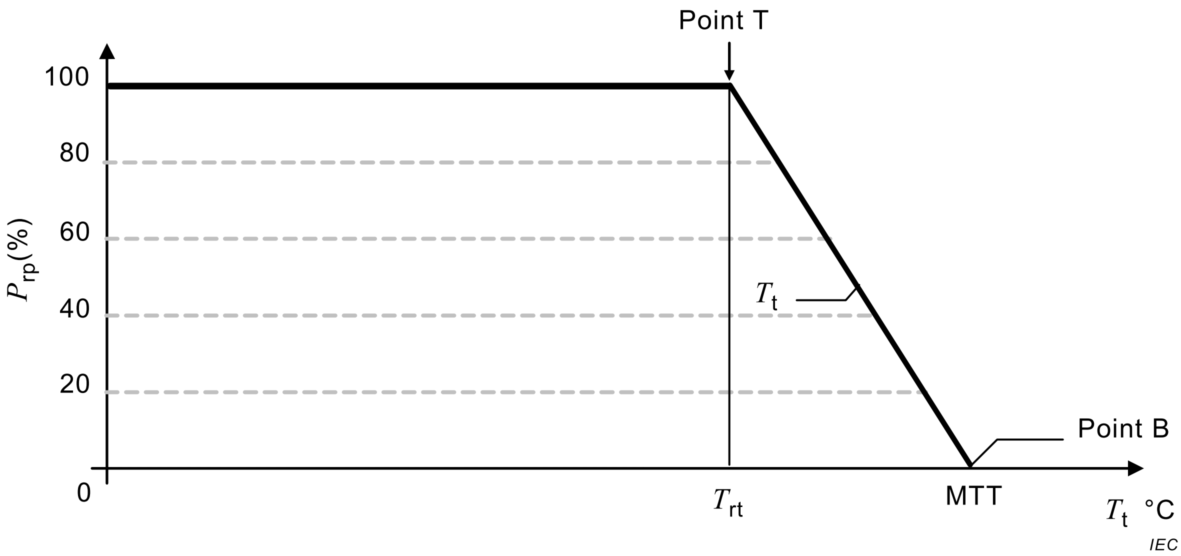
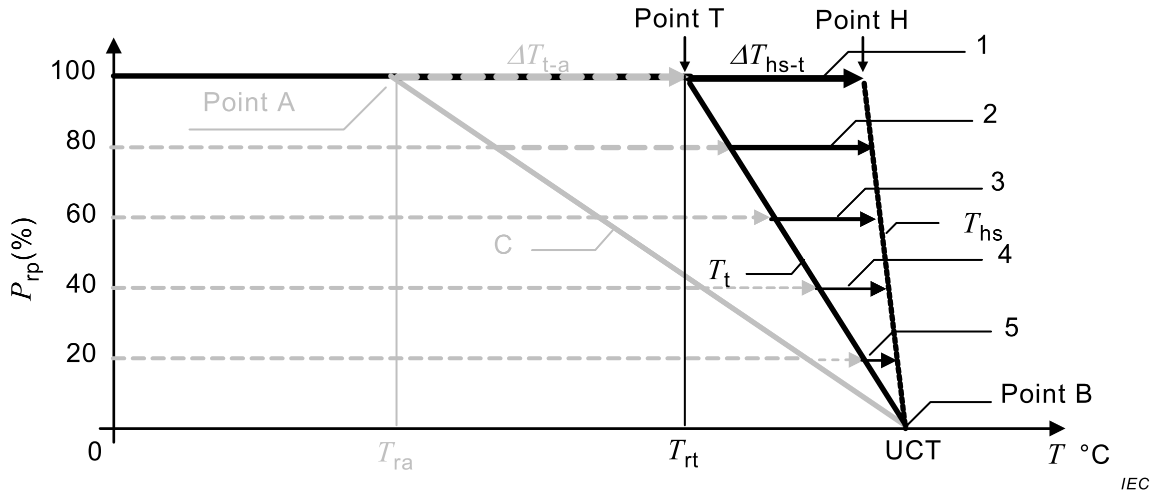


Figure E.3 – Derating curve based on the terminal part temperature

Eventually, the derating curves that would be provided by the resistor manufacturers to the electric/electronic device designers would have the terminal part temperature as the horizontal axis as shown in Figure E.4.



Key

P_{rp}	Percentage of applied power to the rated power
T_t	Terminal part temperature
T_{rt}	Rated terminal part temperature
MTT	Maximum terminal part temperature
Point T	Terminal part temperature at the load life test
Point H	Hotspot temperature at the load life test
Point B	High temperature exposure test point

Figure E.4 – Derating curve based on the terminal part temperature

E.2 Conclusion

The derating curves for resistors based on ambient temperature were established and the methods were defined more than 50 years ago, during the era of vacuum tubes, when large resistors with lead wires were connected to lug terminals. In those days, the heat generated in the resistor was radiated into the ambient atmosphere by radiation and convection. So, the resistor body temperature was the sum of the ambient temperature and the temperature rise by self-heating. Therefore, it was reasonable for the ambient temperature to be the standard for the derating curve defining the thermal approach in the use of resistors.

However, the heat path for SMD resistors is mainly the heat conduction through the printed board, and heat dissipation from the resistor body to the ambient atmosphere by radiation and convection is very low. SMD resistors are using the printed boards as a heatsink. When the printed boards intervene in the heat path, various disadvantages occur to the derating curve based on the ambient temperature.

The largest disadvantage would be when the same power is applied to the same SMD resistor. The temperature of the resistor will change drastically depending on the heat dissipation capability of the printed board, even when the ambient temperature is the same. Under such circumstances, the electric/electronic device designers cannot use the derating curves in their design activity even if they were established by the resistor manufacturers by implementing tests using the printed boards that conform to the standard. The reason is the heat dissipation capability of the printed boards used in the test implemented by the resistor manufacturer and the printed boards that the electric/electronic device designers actually use are different. Especially when watching the recent trends of the market, such as requests for raising the rated power and prolonging operating life, the current derating curves based on the ambient temperature are inadequate as design tools for the appropriate use of SMD resistors by electric/electronic device designers.

Therefore, establishing a new derating curve for SMD resistors is an urgent need so that the electric/electronic device designers can use them in their design activity. The first idea was to use the derating curve based on the hotspot temperature of the resistor. But, the resistors that need to control only the hotspot temperature are rare and measuring the accurate hotspot temperature is difficult. As a result of reviewing from various angles, using the derating curve based on the terminal part temperature of the resistor is suggested.

However, the derating curve for resistors is often misconceived with the analogy of the derating curve for semiconductors. The derating curve for semiconductors is determined to prevent the thermally sensitive point from exceeding a certain temperature, such as the junction temperature. On the other hand, the derating curve for resistors is a curved line that is determined in the test for which the resistor can be used if the load is derated according to the curve along with the temperature rise. Before the use of the derating curves for resistors, the difference with the derating curves for semiconductors should be recognized.

Annex F
(informative)

The thermal resistance of SMD resistors

The thermal resistance of the ambient temperature of the surface hotspot of the resistor $R_{\text{th shs-a}}$ is the sum of the thermal resistance of the ambient temperature to the terminal part of the resistor $R_{\text{th t-a}}$ and the thermal resistance of the surface hotspot to the terminal part $R_{\text{th shs-t}}$. The additional characters mean the following:

- "shs" means "surface hotspot",
- "a" means "air", and
- "t" means "terminal".

The thermal resistance of the ambient temperature to the surface hotspot of the resistor $R_{\text{th shs-a}}$ only has the meaning of an inherent value for the resistor. This is because the thermal resistance of the ambient temperature to the surface hot spot $R_{\text{th t-a}}$ is largely different from the mounted board material, pattern, components mounted close by, the fixing method of the board to the chassis and the presence of airflow. Formula (F.1) shows that the thermal resistance $R_{\text{th shs-t}}$, which is an inherent value of the resistor, is the temperature difference between the surface hotspot and the terminal part of the resistor divided by the applied power.

$$R_{\text{th}\cdot\text{shs}-\text{t}} = \left(T_{\text{shs}} - T_{\text{t}}\right) / P \tag{F.1}$$

Where

T_{shs} is the surface hotspot temperature,

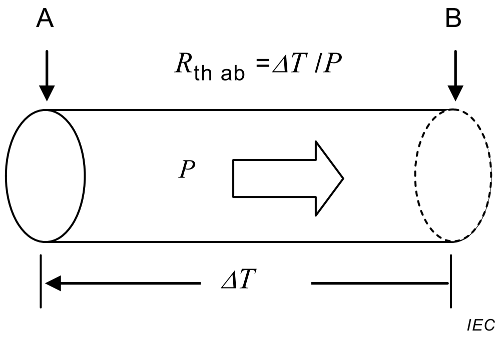
T_{t} is the terminal part temperature,

P is the power applied to the resistor.

However, the thermal resistance defined here is not the thermal resistance in a strict sense. The thermal resistance in a strict sense would be as follows. The thermal resistance between A and B ($R_{\text{th ab}}$) would be defined as below when there is temperature difference ΔT between surface A and surface B in the thermal path of heat P as shown in Figure F.1.

$$R_{\text{th}\cdot\text{ab}} = \Delta T / P \tag{F.2}$$

Formula (F.2) is based on the presumption that A is a homogeneous high-temperature part and B is a homogeneous low-temperature part, and the whole of P must be flowing from A to B.



Key

A Isothermal surface of the high temperature side

B Isothermal surface of the low temperature side

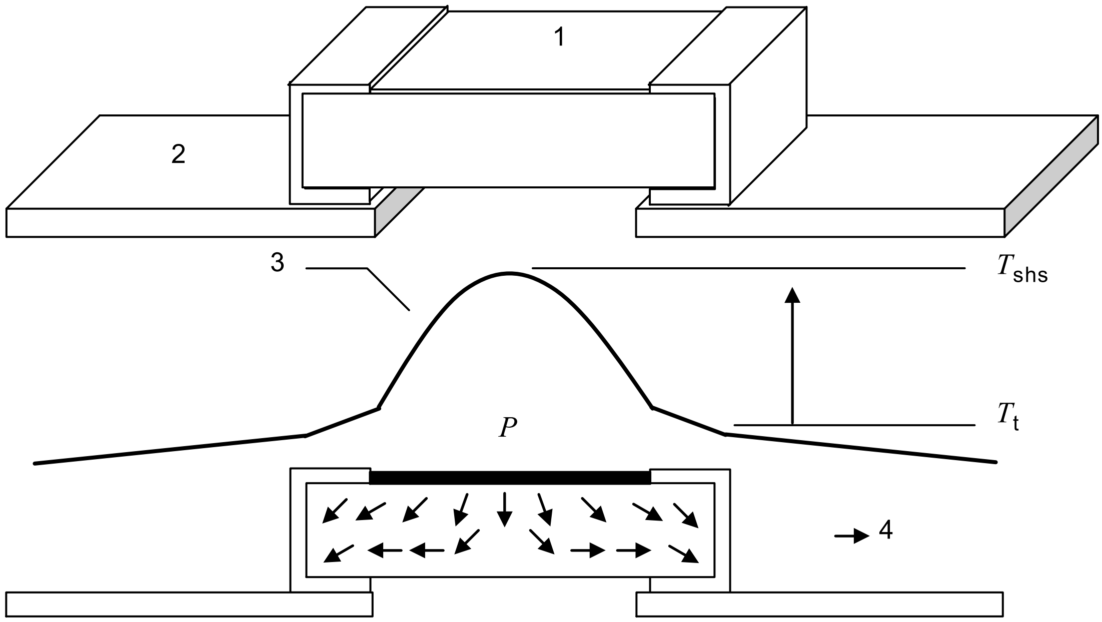
ΔT Temperature difference between A and B

P Thermal flow from surface A to surface B

$R_{\text{th ab}}$ Thermal resistance between surface A to surface B

Figure F.1 – Definition of the thermal resistance in a strict sense

On the other hand, the heat source of the resistor is the whole part of the resistive body (the example is the flat chip resistor). The heat flows from each heat-generating point to the terminal part through the base material (mainly the alumina ceramic) along various routes. The terminal part temperature T_{t} can be fixed as point B shown in Figure F.1, but the temperature of the resistive body would give a distribution like a nearly parabolic shape with the surface hotspot T_{shs} as the peak if it was observed from the surface of the resistor. This is shown in Figure F.2.



$R_{th\ shs\text{-}t} = (T_{shs} - T_t)/P$

IEC

Key

1	Resistive element of the resistor
2	Pattern
3	Temperature distribution
4	Heat flux
P	Heat flow
T_{shs}	Surface hotspot temperature
T_t	Terminal part temperature
$R_{th\ shs\text{-}t}$	Thermal resistance of resistor

Figure F.2 – Thermal resistance of the resistor

P is not generated only from T_{shs} and does not flow into one T_t. In this case, the meaning of the thermal resistance is different from the case shown in Figure F.1.

The power P of a resistor is the total heat generated in the whole resistive element. Not only the hotspot, but the low-temperature parts also generate heat and the temperature of the inner hotspot is higher than that of the surface hotspot. But, to derive the thermal resistance of the resistor, the surface hotspot T_{shs} that can be observed is often used as the typical high-temperature part. The heat of P should be divided to both terminals, but it would be treated as one as if it were the typical low-temperature part. In reality, there is a difference between the proper thermal resistance and the thermal resistance of the resistor. But, it is true that the difference between the surface hotspot temperature T_{shs} and the terminal part temperature T_t is proportionate to the power P. Therefore, by measuring

$$R_{th\ shs\text{-}t} = (T_{shs} - T_t)/P$$

and defining that this is the thermal resistance of the resistor, it would be convenient to derive the surface hotspot temperature from

$$T_{shs} = R_{th\ shs\text{-}t}\ P + T_t$$

by setting the terminal part temperature T_t and applied power P. On the other hand, it is possible to derive the terminal part temperature from

$$T_t = T_{shs} - R_{th\ shs\text{-}t}\,P$$

by setting the hotspot temperature T_{shs} and applied power P. This would be the purpose of defining, measuring and providing the thermal resistance from the terminal part to the surface hotspot $R_{th\ shs\text{-}t}$ to the electric/electronic device designers.

For example, when the electric/electronic device designers apply coatings to the printed board with resin, they need to keep the surface temperature of the resistor below the temperature at which the coating resin can survive. If $R_{th\ shs\text{-}t}$ is provided, the hotspot temperature can be easily predicted from the power consumption P and the terminal part temperature by using the thermocouple, even when it is set inside the chassis and cannot directly measure the surface hotspot with the thermograph.

It is often the case that electric/electronic device designers need to estimate the temperature of the surface of the printed board and verify that it does not exceed the upper temperature limit of the printed board. Especially in recent years, SMD resistors that have the resistive elements on the board side, so-called reverse mount resistors, have appeared on the market. For these kinds of resistors, the board side of the resistor where the resistive element is located, which cannot be observed from the surface, can reach a higher temperature than the observable side. The detail of the recommended measurement method of $R_{th\ shs\text{-}t}$, which uses the copper block, will be explained in Annex H. For reverse mount resistors, they should be flipped over and then mounted on the copper block so that the resistive element side can be observed when $R_{th\ shs\text{-}t}$ is measured. If $R_{th\ shs\text{-}t}$ is provided to the electric/electronic device designers, they can verify if the temperature exceeds the upper limit of the printed board or not under the operating conditions.

However, for all resistors, including the reverse mount resistors, the temperature of the resistor's surface facing the printed board can be estimated by measuring $R_{th\ shs\text{-}t}$ with the recommended measurement method using the copper block as shown in Annex H and Formula (F.3).

$$T_{shs} = R_{th \cdot shs-t} P + T_t \tag{F.3}$$

When Formula (F.3) is used, excess margins could be set because the heat of the surface hotspot that faces the printed board will be dissipated via the atmosphere to the printed board, so there is a high possibility that the temperature will be lower than the calculated value. The measurement or the estimation of the temperature of the printed board just under the resistor is a future subject which is explained in Annex M.

The following situations may also happen. The electric/electronic device designers cannot set thermocouples to all the resistor fillets and verify the temperature under the operating conditions (printed boards set inside the chassis and activated) at the equipment design phase. They need to determine which resistor terminal needs to be measured. In this case, the electric/electronic device designers need to find out the relevant resistor fillet to measure with a thermocouple by taking out the printed board from the chassis to make it possible to observe the surface directly and use the infrared thermograph and directly measure the terminal part temperature under the operating condition. It would be simple if the fillet temperature could be measured from the temperature distribution images of the infrared thermograph, but it is not that easy. Since the terminal part is formed with solder which has low emissivity, and also the target surface is a fillet and it is not horizontal against the board surface, the emissivity cannot be adjusted unless the entire board is coated with black body spray. Even if the board can be coated, the infrared thermograph will be focused on the surface hotspot which is hotter than the terminal part. Therefore, it would be difficult to identify the terminal part from the temperature distribution images. If $R_{th\ shs\text{-}t}$ is provided at this point, the electric/electronic device designers can predict the terminal temperature from the surface hotspot temperature T_{shs} which is easier to measure since it is focused in the thermal distribution image of the infrared thermograph. This would help define which resistor fillet needs to be measured with the thermocouple.

However, the infrared thermograph that the electric/electronic device designers normally use cannot measure the correct T_{shs} because it does not have the sufficient spatial resolution. The method of estimating the terminal part temperature using the infrared thermograph will be explained in Annex I.

If the determination of whether the resistor can be used or not is possible by the surface hotspot temperature T_{shs} and power limitation of some kind, the submission of $R_{\text{th shs}}$ to the electric/electronic device designers would be necessary. This means estimating the surface hotspot temperature under the operating condition inside the device. As mentioned before, the surface hotspot temperature of the resistor inside the chassis cannot be measured by the infrared thermograph. If $R_{\text{th shs}}$ is provided, T_{shs} can be derived from Formula (F.3) by measuring the terminal part temperature T_{t} with the thermocouple.

Annex G
(informative)

How to measure the surface hotspot temperature

G.1 Target of the measurement

The meaning of measuring the surface hotspot temperature is mainly to measure the thermal resistance of the resistor, $R_{\text{th shs-t}}$.

Of course, if the determination of whether the resistor can be used or not is possible by the surface hotspot temperature and the applied power, the measurement of the surface hotspot temperature would be to define the use, but, as mentioned in this annex, when using the infrared thermograph and directly measuring the temperature, the lens magnification percentage and the peak detection capability needs attention.

G.2 Recommended measuring equipment

Basically, an infrared thermograph is recommended for measuring the surface hotspot. But by using the ultra-fine thermocouple with a special wire diameter of 25 µm, or an ultra-thin thermocouple with a thickness of 20 µm (for example manufactured by ANBE SMT Co.[1]), the hotspots with the size around 100 µm in diameter can be measured with a comparatively fine precision.

G.3 Points to be careful when measuring the surface hotspot of the resistor with an infrared thermograph

G.3.1 General

The details of basic precautions and points when using the infrared thermograph, such as fitting the emissivity and adjusting the focus correctly, are not stated in this annex.

However, the method of coating the resistor surface with black-body coating whose emissivity is already known is recommended for the adjustment of the emissivity instead of measuring the surface emissivity of the resistor and entering the value in the infrared thermograph. The surface of SMD resistors are already coated with insulators, so the emissivity is over 0,8 in the first place. So, if the emissivity is raised up to 0,98 by the black-body coating, the heat flow that is radiated from the resistor surface into the atmosphere is very small even for the RR6332M with a large area as shown in the following formula. There will be no large measuring errors for most cases. In fact, when the black-body spray is not used, the risk of mistaking the measurement of emissivity will be larger.

Premise of calculation:

- ambient temperature 25 °C,
- surface temperature of resistor 125 °C,
- surface area of resistor 0,0063 m × 0,0032 m

Radiation heat flow when,

(Emissivity 0,80) = $0{,}80 \times 5{,}67 \times 10^{-8} \times \{(125 + 273{,}15)^4 - (25 + 273{,}15)^4\} \approx 0{,}0158$ W

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[1] This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of the product named. Equivalent products may be used if they can be shown to lead to the same results.

(Emissivity 0,98) = $0{,}98 \times 5{,}67 \times 10^{-8} \times \{(125 + 273{,}15)^4 - (25 + 273{,}15)^4\} \approx 0{,}0193$ W

where, $5{,}67 \times 10^{-8}$ W/(m^2 K^4) is the Stefan-Boltzmann constant.

The difference between heat dissipation heat flow when the emissivity is 0,98 and 0,80 works out to be 0,0035 W.

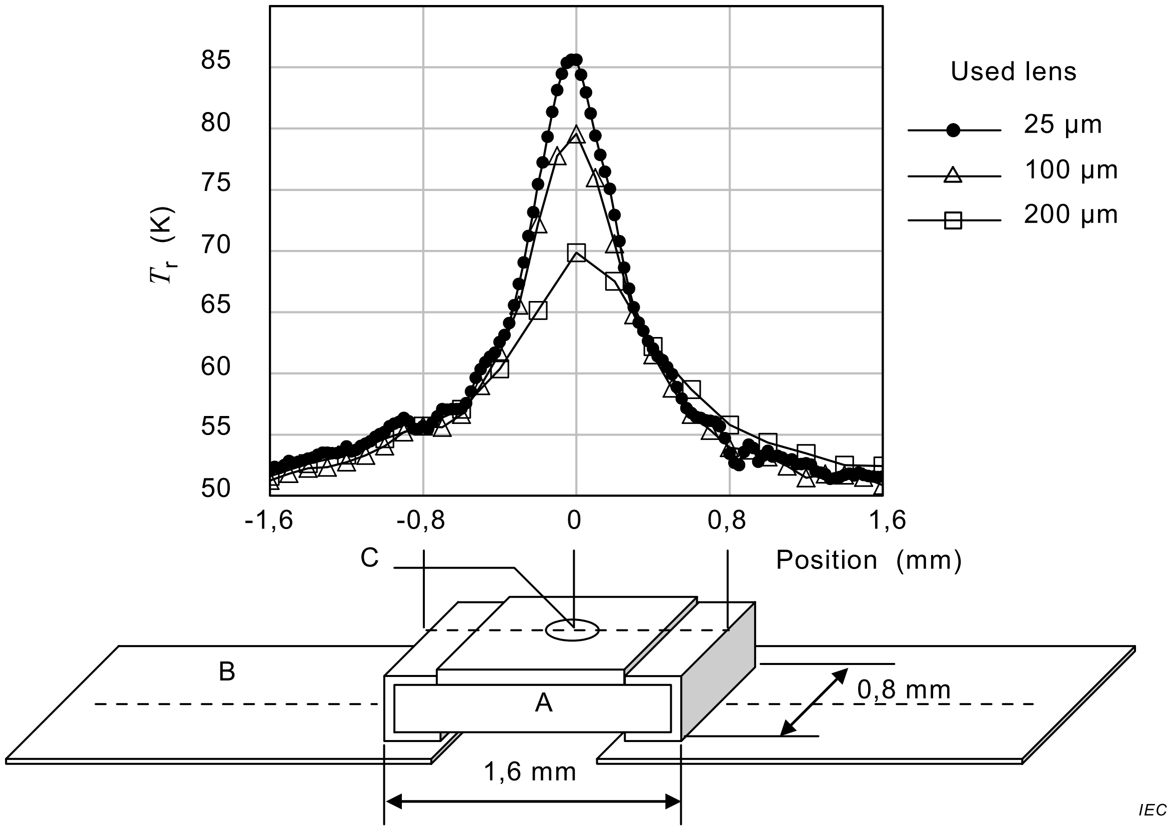
The error that is caused by the spatial resolution and angle between the measured surface and the light axis of the lens, which are easily-overlooked when using the infrared thermograph, will be mentioned.

G.3.2 Spatial resolution and accuracy of peak temperature measurement

The false perceptions that many users have about the spatial resolution of the infrared thermograph will be considered. The standard lenses that come with a general infrared thermograph have a magnification showing a square of 200 × 200 µm as 1 pixel, even for relatively high-spec products. Hotspots that are smaller than 100 µm for small size SMD resistors are predictable. Therefore, it is necessary to exchange the standard lenses with optional close-up magnification lenses to measure the surface hotspot temperature of small-size SMD resistors.

The magnification percentage of the close-up magnification lens is usually indicated as how many µm is shown as 1 pixel. For example, a lens that will show 25 × 25 µm as 1 pixel will be called the 25-µm lens. And a lens that will show 100 × 100 µm as 1 pixel will be called the 100-µm lens.

A common mistake is when it is thought that the peak of the surface hotspot temperature that is only around 100 µm in diameter can be measured correctly when the 100-µm lens is used. Figure G.1 shows the RR1608M thick film resistor with 0,25 W applied, and the resistor and the pattern surface temperature rise is actually measured by the infrared thermograph equipped with lenses of various magnification percentages. Large power compared to the size is applied to the resistor, but this is to define the difference. However, it is obvious that the raising of rated power in the near future would make this problem become more or less certain.



Key

A SMD resistor

B Pattern

C Surface hotspot

T_r Temperature rise of each part

Figure G.1 – Difference of the measured hotspot temperature caused by the spatial resolution

By cross-checking with the result of the simulation using the finite element method, a possibility was found that the surface hotspot peak temperature of the resistor in Figure G.1 cannot be measured even when the 25-µm lens is used. But the supposed error is under 1 °C so, the value measured with the 25-µm lens will be considered as the true value in this annex.

Figure G.1 shows that the peak value measured with the 100-µm lens is considerably low compared with the average of the four points measured by the 25-µm lens in the same area measured with the 100-µm lens. A similar trend can be seen with the values measured with the 200-µm lens and the 100-µm lens. This phenomenon is caused by the influence of the MTF (modulation transfer function) of the infrared thermograph. In other words, it is the degradation of the high-frequency component of the spatial frequency.

Generally, the clear guideline that defines what magnification percentage lens is suitable for measuring the peak temperature according to the area is not provided by the infrared thermograph manufacturer. However, from interview, document investigation and independent research, when the target area is presumed to be a square, it has become clear that the lens needs to have the ability to enlarge 1/3 to 1/4 of the target length as one pixel. It means that if the surface hotspot is a square of 100 × 100 µm, then a 25-µm lens to 33-µm lens should be used to measure the peak temperature of the surface hotspot of the resistor.

As for an SMD cylindrical resistor with spiral trimming, the power deposition would be made at both edges of the spiral trimming. The hotspot would be established broadly in the centre part of the resistive element, so it could be measured quite accurately with a relatively low spatial resolution lens (about 1/3 of the diameter).

The important point for the resistor manufacturer is to correctly understand the size of the surface hotspot of their products and verify that the thermograph used for the measurement has the sufficient spatial resolution to catch the peak of the surface hotspot temperature. If this fails, it will mean that electric/electronic device designers may be provided with incorrect information.

Additionally, electric/electronic device designers need to understand the spatial resolution of the thermograph and the accuracy of the peak temperature measurement.

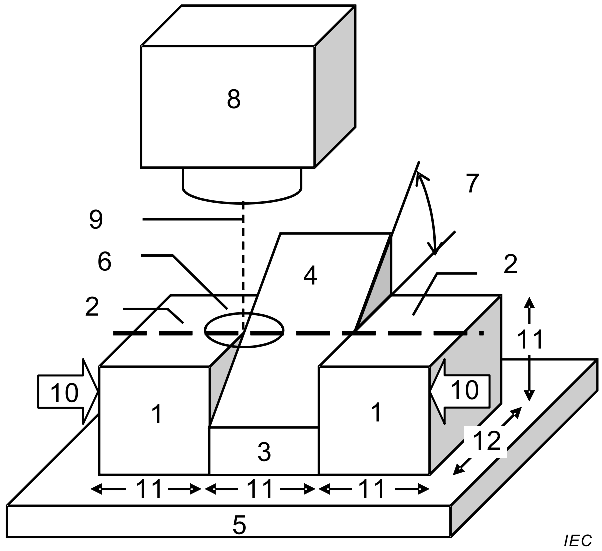
The verification method of the spatial resolution of the thermograph and the accuracy of the peak measurement will be mentioned in Annex L.

G.3.3 Influence of the angle of the measurement target normal line and the infrared thermograph light axis

The error caused by the angle of the optical axis and the target surface will be explained. Essentially, the light axis of the lens should be set vertically against the temperature measurement surface, but not all conditions allow that. Additionally, it is necessary to figure out the limit of the tilt for which the error could be ignored. This is the basic information that is needed for the measurement.

The measurement system for the error caused by the angle of the optical axis and the target surface will be shown in Figure G.2. Three copper blocks will be set on the hot plate that is heated to 100 °C. The top surface of the blocks at both ends will be set so that the light axis of the lens fits the normal line. The top surface of the centre block will be set with a specific angle against the other two blocks. In this test system, the top surface of the blocks at both ends will be called the horizontal surface, and the top surface of the centre block will be called the slope face. The heat conductivity of the copper is very high and it is 400 W/(m·K). Pressure is applied to the three copper blocks from both sides so they are rigidly linked thermally. All three copper blocks will be at 100 °C, which is the same temperature as the hotplate. The important part is that there is no temperature difference between the horizontal surface and the slope surface where it is the area that will be measured by the thermograph. When the horizontal surface and the slope surface is measured by the infrared thermograph beyond the boundary line, essentially it should be measuring the same temperature, but the difference in the centre slope surface will be larger as the angle gets larger. This is the error caused by the angle of the optical axis and the target surface.

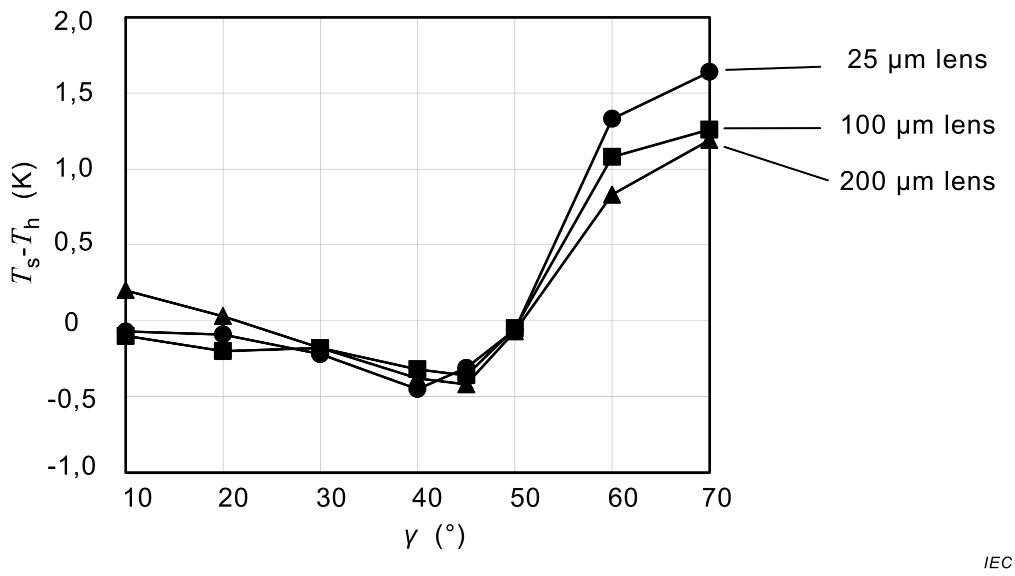
The 25-µm, 100-µm and 200-µm lenses are used. Additionally, to verify the difference of the zero air flow condition and the convection flow of hot air between the infrared thermograph and the target, the measurement test was implemented with zero airflow and 0,3 m/s wind from the side and ventilated. The results are shown in Figure G.3 and Figure G.4.



Key

1 Copper block (top surface is parallel)
2 Horizontal surface (orthogonal face to the light axis)
3 Copper block (top surface is a slope face)
4 Slope face (inclined face against the light axis)
5 Hotplate (heat up to 100 °C)
6 Measured area
7 Angle of the slope surface
8 Infrared thermograph
9 Light axis of the infrared thermograph lens
10 Pressure to contact each copper block
11 Dimension of copper block: 10 mm
12 Dimension of copper block: 15 mm

Figure G.2 – Measuring system for the error caused by the angle



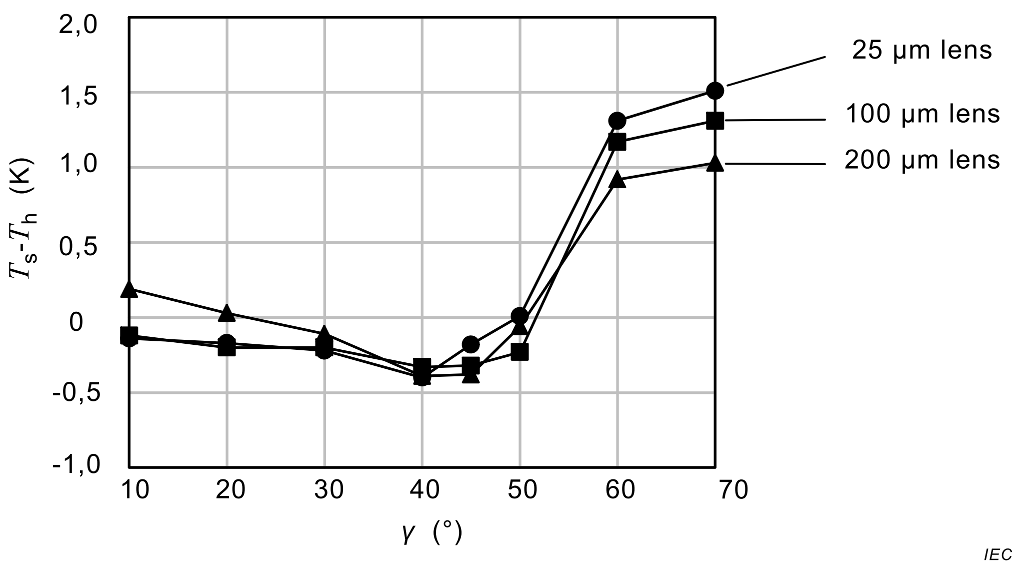
Key

T_h Horizontal surface temperature

T_s Slope face temperature

γ Angle of the thermograph light axis to the normal line over the slope surface

Figure G.3 – Error caused by the angle of the optical axis and the target surface (natural convection)



Key

T_h Horizontal surface temperature

T_s Slope face temperature

γ Angle of the thermograph light axis to the normal line over the slope surface

Figure G.4 – Error caused by the angle of the optical axis and the target surface (0,3 m/s air ventilation from the side)

When measuring the high emissivity and rough surface, for example the surface at which the emissivity is adjusted to more than 0,95 by a black-body coating, as long as the angle of the lens axis to the normal line is below 60°, there will be no large error.

However, when measuring a surface with metallic lustre (low emissivity), the angle dependency of the measured value by the infrared thermograph will become very large, so attention is needed. For example, when the emissivity of the solder fillet without any coating treatment is measured and the value is set to the infrared thermograph, the correct temperature cannot be measured unless the light axis of the lens on the thermograph is vertical against the target surface.

Annex H
(informative)

How the resistor manufacturers measure the thermal resistance of resistors

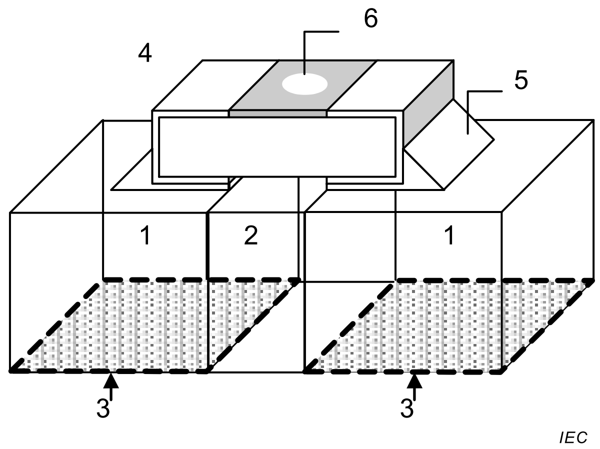
H.1 The measuring system

The thermal resistance of the resistor $R_{\text{th shs-t}}$ is explained in Annex F. It is the temperature difference between the surface hotspot and the terminal part divided by the power applied to the resistor. The precaution for the infrared thermograph when measuring the surface hotspot temperature is mentioned in Annex G. In this annex, the method of determining the terminal part temperature that is used to calculate the heat resistance from the terminal part to the surface hotspot, which will be provided to electric/electronic device designers by resistor manufacturers, will be stated.

First, the temperature distribution close to the terminal part when the SMD resistors are mounted on a standard printed board will be shown. Then, the variation of the thermal resistance from the surface hotspot to the terminal part calculated from each of the measured temperatures of the terminal parts will be shown. From these two points, it will be explained that the reproducible measurement of the thermal resistance is difficult when mounted on a printed board. The temperature distribution is estimated by using the finite element method simulator.

Next, a reproducible method will be verified by using the finite element method simulator.

The final results will be shown below. As shown in Figure H.1, establishing the measurement system will be necessary. Solder the SMD resistor as it connects the two copper rectangular cuboid electrodes (from here on "copper block") which are at least 10 mm long on one side. Then set the under surface of the copper block to a constant temperature and apply voltage between the two copper blocks and apply power to the resistor. The copper block surface temperature that is within 3 mm from the resistor fillet is recommended to be set as the terminal part temperature T_{tn} in order for the resistor manufacturer to calculate the thermal resistance.



Key

1 Rectangular cuboid copper block with square 10 mm on a side

2 Insulator with good heat conduction

3 Downside of the copper block fixed to a certain temperature

4 Resistor

5 Solder fillet

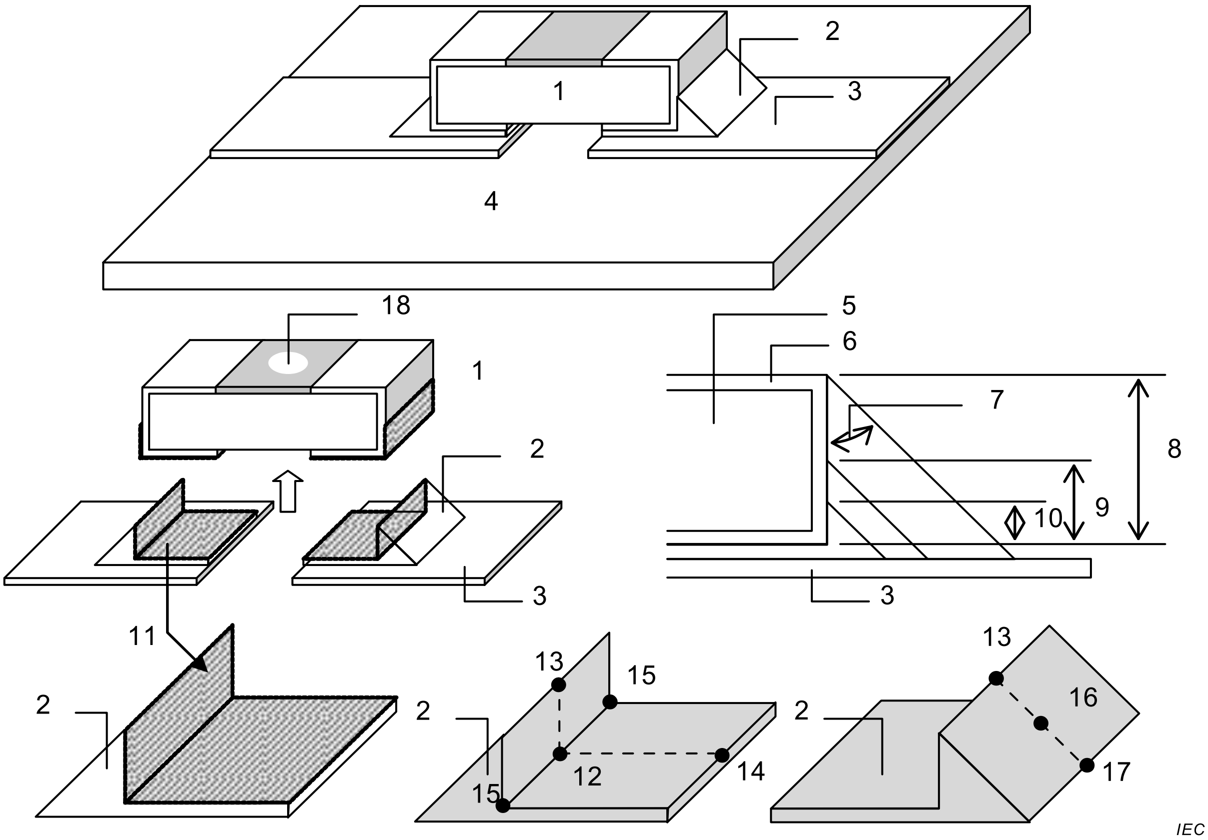
6 Surface hotspot

Figure H.1 – Measuring system for calculating the thermal resistance between the surface hotspot and the terminal part

Additionally, along with the SMD resistors, the copper block should also be coated with black-body spray whose emissivity is close to one, and measuring the hotspot and the terminal part temperature (copper block surface temperature) with the same infrared thermograph is recommended.

H.2 Definition of the two kinds of temperatures

In this annex, two kinds of temperature used in this report will be defined: the broad sense of the term temperature T_{n} and the narrow definition of the term temperature T_{tn}. From here on, the difference between T_{n} and T_{tn} and the reason why T_{tn} was introduced for use as the terminal part temperature when calculating the thermal resistance between the surface hotspot and the terminal part by the resistor manufacturer will be explained. The temperature distribution of the boundary surface of the resistor and the board (here means the boundary of the solder) is not uniform when the general printed board with thin copper foil is used. The example of the temperature distribution estimated by the finite element method simulation is shown in Table H.1. Figure H.2 is a model used in the simulation. The target resistor is RR2012M and it is mounted on an FR4 board of 80 mm × 80 mm and 1,6 mm thick. The applied power is 0,25 W. The temperature bounds are cooled with a wind speed of 0,5 m/s of 25 °C parallel to the board. Three conditions of the solderability are considered: solder comes up to the resistor's top surface (large fillet), up to half of the height of the resistor (medium fillet) and up to a quarter of the height of the resistor (small fillet). The solder thickness underneath the terminal of the resistor after mounting is set at 20 µm. The fillet angle is presumed to be 45°. The nonlinearity of the physical property is not considered in the simulation.



Key

1 Flat chip resistorRR2012M

2 Solder fillet

3 Copper pattern

4 Printed board (FR4)

5 Resistor base material

6 Resistor terminal

7 Fillet angle 45deg.

8 Fillet (Large)

9 Fillet (Medium) 1/2 of height 8

10 Fillet (Small) 1/4 of height 8

11 Area for calculating the temperature average inside the fillet T_{11}

12 Temperature of the inside centre part of the fillet T_{12}

13 Temperature of the fillet top part T_{13}

14 Temperature of the inside fillet of the centre part of the resistor T_{14}

15 Temperature of the inside edge of the fillet T_{15}

16 Temperature of the surface centre part of the fillet T_{16}

17 Temperature of the surface bottom part of the fillet T_{17}

18 Surface hotspot temperature T_{18} (T_{shs})

Figure H.2 – Simulation model

Table H.1 – Results of the fillet part temperature simulation (calculated value)

Pattern thickness µm	Pattern width mm	Fillet size	Calculated temperature °C								
			T_{11}	T_{12}	T_{13}	T_{14}	T_{15}	T_{16}	T_{17}	T_{18} T_{shs}	T_{18} − T_{12}
35	1,2	Large	86,7	86,2	87,5	87,0	86,2	86,1	84,2	94,6	8,34
		Medium	87,1	86,9	88,0	87,8	86,8	86,7	85,6	95,7	8,84
		Small	87,5	87,1	87,9	88,1	87,0	87,0	86,2	96,2	9,11
	10	Large	49,7	49,4	50,6	50,0	48,9	49,4	48,2	57,6	8,16
		Medium	49,9	49,7	50,8	50,5	49,1	49,7	48,9	58,3	8,55
		Small	50,0	49,9	50,5	50,7	49,2	49,8	49,3	58,7	8,78
70	1,2	Large	72,4	72,0	73,3	72,5	71,9	72,0	70,7	80,3	8,30
		Medium	72,4	72,2	73,3	72,9	72,2	72,2	71,4	80,9	8,72
		Small	72,6	72,3	73,0	73,0	72,2	72,2	71,8	81,2	8,95
	10	Large	44,3	44,0	45,3	44,5	43,7	44,1	43,3	52,2	8,18
		Medium	44,3	44,1	45,2	44,7	43,8	44,2	43,6	52,7	8,55
		Small	44,3	44,2	44,8	44,8	43,8	44,2	43,8	52,9	8,74

The temperature measurement positions in Table H.1 are where the symbols are shown in Figure H.2. Hereafter, the two-digit numbers indicating the position will mean the numbers shown in Figure H.2. The measurement positions 13, 16 and 17 of Table H.1 is the top, middle and bottom of the fillet slope, so the temperature can be measured directly with the thermocouple, but it is impossible for the other positions to be measured from a practical point of view. "18 − 12" will mean the temperature difference between the surface hotspot and the centre part inside the solder fillet.

As shown in Table H.1, this is important because the temperature of the centre part inside the solder fillet 12 and the centre part surface of the fillet 16 are relatively close. As shown in Figure H.4, it is estimated that many SMD resistors have these trends. Therefore, the basic measurement position of the terminal part temperature for SMD resistors mounted on the printed board is set at the centre of the fillet.

– Maximum/minimum measured temperature values, pattern thicknesses and pattern widths of the measurable positions 13, 16 and 17 can be organised as shown in Table H.2. The temperature measurement position in Table H.2 is the symbol shown in Figure H.2. The difference between the maximum and the minimum means the maximum value of T_{13}, T_{16}, or T_{17} minus the minimum value of T_{13}, T_{16}, *or* T_{17}, so the minimum value of the temperature rise equals the minimum value of T_{13}, T_{16}, or T_{17} minus the ambient temperature of 25 °C which is presumed in the simulation.

Table H.2 – Simulation result of the fillet part's temperature where it is measurable (calculated value)

Pattern thickness µm	Pattern width mm	Max. (T_{13}, T_{16}, T_{17}) °C	Min. (T_{13}, T_{16}, T_{17}) °C	Difference between max. and min. °C	Temperature rise min. °C
35	1,2	88,0	84,2	3,8	59,2
	10	50,8	48,2	2,6	23,2
70	1,2	73,3	70,7	2,6	45,7
	10	45,3	43,3	2,0	18,3

H.3 Errors in the measurement

If only measuring the terminal part temperature from the comparison of the difference between the maximum and minimum temperatures, no matter which of the positions 13, 16, or 17 it is, and even regardless of the fillet size, there will be no error that would be a practical issue.

However, suppose the surface hotspot temperature could be measured by some kind of method. Then, measure the fillet temperature and then subtract it from the surface hotspot temperature and divide by the applied power, 0,25 W, and calculate the thermal resistance of the surface hotspot to the terminal part temperature. In this case, the measured temperature error of the fillet measuring position will cause a large error to the calculated thermal resistance value.

Subtract each basic temperature measurement position temperature from the hotspot temperature of measurement position 18 in Table H.1. Then divide this by the applied power 0,25 W. This will be the thermal resistance between the surface hotspot and each basic temperature measurement position as shown in Table H.3. The thermal resistance section of "18 − x" shown in Table H.3 is the thermal resistance calculated by subtracting the temperature of the measurement position x from the measurement position 18 (surface hotspot) and dividing it by the applied power 0,25 W. The measuring position x is inside the centre of fillet 12, and the top, middle and bottom on the slope of the fillets 13, 16, and 17.

The percentage error calculated from the thermal resistance "18 − 12" as the true value in Table H.3 means literally that the thermal resistance calculated from "18 − 12" is the true value, and the differences between the surface hotspots and the thermal resistances of each of the measurement positions 13, 16 and 17 are expressed as percentages.

Table H.3 – Simulation result of the fillet part's temperature where it is measurable (calculated value)

Pattern thickness µm	**Pattern width** mm	**Fillet size**	**Thermal resistance** K/W				**Error when 18−12 is supposed to be the true value %**		
			18−12	**18−13**	**18−16**	**18−17**	**18−13**	**18−16**	**18−17**
35	1,2	Large	33,36	28,4	34,0	41,6	−15,22	2,24	24,14
		Medium	35,36	30,8	36,0	40,4	−13,06	1,42	14,73
		Small	36,46	33,2	36,8	40,0	−8,29	1,51	9,65
	10	Large	32,62	28,0	32,8	37,6	−14,48	0,98	14,72
		Medium	34,21	30,0	34,4	37,6	−11,94	0,69	9,87
		Small	35,11	32,8	35,6	37,6	−7,55	0,81	6,64
70	1,2	Large	33,20	28,0	33,2	38,4	−15,74	0,13	15,15
		Medium	34,89	30,4	34,8	38,0	−12,86	0,11	9,12
		Small	35,79	32,8	36,0	37,6	−7,95	0,53	5,87
	10	Large	32,72	27,6	32,4	35,6	−15,34	−0,85	8,97
		Medium	34,19	30,0	34,0	36,4	−12,20	−0,41	6,02
		Small	34,95	32,4	34,8	36,4	−7,38	0,22	4,18

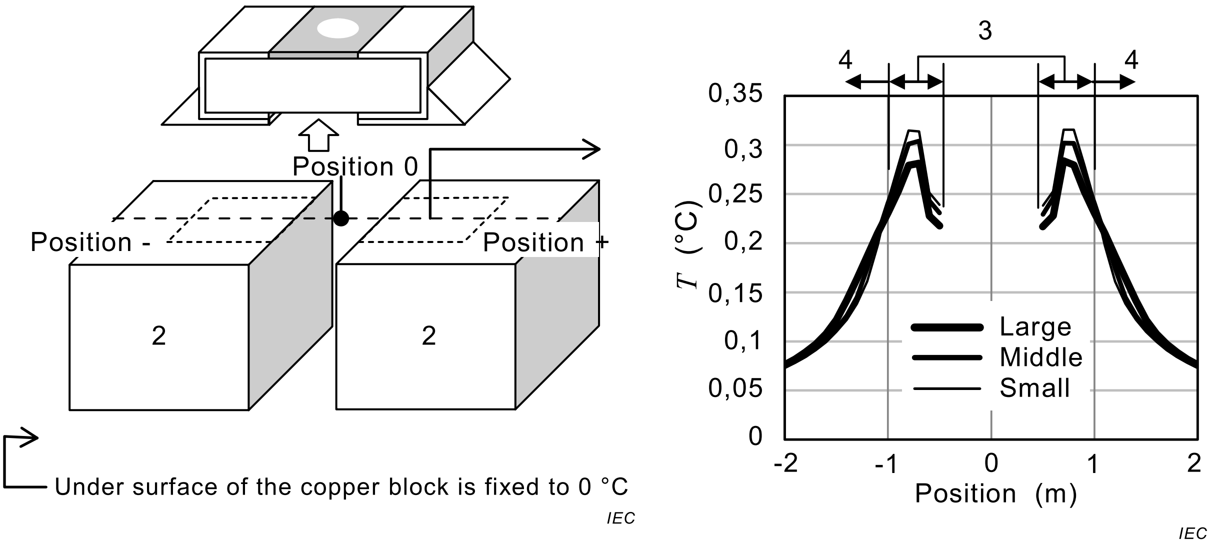
From Table H.3, when the measured position of the terminal part temperature is presumed to be 16 (centre of fillet), then the calculated thermal resistance becomes relatively stable. However, if the measured position is displaced to the top part of fillet 13, or to the lower part of fillet 17, the thermal resistance changes greatly. Therefore, if the resistor industry defined that the terminal part temperature for measuring the thermal resistance is that at the centre of the fillet, there will be some problems with reproducibility.

To improve the reproducibility of the measurement of the thermal resistance, the method of directly soldering the SMD resistor onto the copper block, which has very high heat conductivity as shown in Table H.1, and forcibly fixing the terminal part temperature of the resistor to the copper block temperature, has been suggested from the early times.

The simulation of the method shown in Figure H.1 was verified to see how stable the measured value would be compared with mounting on the printed board. The simulation model is Figure H.1 in its entirety, in which the printed board shown in Figure H.2 is changed to a copper block. As for the environmental conditions, the under surface of the copper block is set at 0 °C. If the copper block is set at 25 °C, then the temperature absolute value of the simulation result just shifts by 25 °C and the results of the thermal resistance will not change. The standard thickness of the solder under the terminal of the resistor is 20 µm, but simulations for the extremely thick, 50 µm, and extremely thin, 5 µm, are implemented as well.

The result of the simulation is shown in Figure H.3 and Table H.4.

Figure H.3 shows the temperature distribution of the top surface of the copper block when the solder thickness under the resistor terminal is 20 µm. Even though it is a copper block, the temperature does not become completely uniform: the temperature underneath the terminal of the resistor is less than 0,5 °C, but it is still higher than the rest of the block. But, when defining some kind of a base level for terminal part temperatures when measuring the thermal resistance between the surface hotspot and terminal part, the surface of the copper block would be realistic and appropriate.



(a) Copper block **(b) Temperature distribution**

Key

1	SMD resistor
2	Copper block
3	Underneath the terminal
4	Fillet
T	Temperature on the chain line of the copper block
Position	Position on the chain line
Large	Fillet size large, fillet top reaches the terminal top surface
Middle	Fillet size medium, Fillet top reaches up to1/2 of the terminal
Small	Fillet size small, Fillet reaches up to 1/4 of the terminal

Figure H.3 – Temperature distribution of the copper block surface (calculated)

Table H.4 – Thermal resistance simulation results between the surface hotspot and the terminal part based on the copper block temperature (calculated value)

Solder thickness (µm)	Fillet Size	Temperature		Thermal resistance			
		T_{shs} °C	T_{12} °C	$R_{th\ shs\text{-}12}$ K/W	$R_{th\ shs\text{-}Cu}$ K/W	$R_{th\ shs\text{-}Cu}$ %	Notes
5	Large	8,43	0,249	32,74	33,73	−4,83	
	Medium	8,75	0,262	33,96	35,01	−1,22	
	Small	8,91	0,267	34,58	35,65	0,58	
20	Large	8,52	0,294	32,92	34,09	−3,81	
	Medium	8,86	0,315	34,18	35,44	0,00	Standard of difference
	Small	9,04	0,324	34,86	36,16	2,01	
50	Large	8,66	0,385	33,12	34,66	−2,22	
	Medium	9,04	0,423	34,46	36,16	2,01	
	Small	9,24	0,442	35,18	36,95	4,24	

T_{shs} in Table H.4 is the surface hotspot temperature and "12" is the same code indicated in Figure H.2 and it is the temperature of the centre part inside the fillet. $R_{th\ shs\text{-}12}$ is the thermal resistance of the surface hotspot to the terminal part. This is calculated from the temperature of the centre part inside the solder fillet as the terminal part temperature. $R_{th\ shs\text{-}Cu}$ is the thermal resistance of the surface hotspot to the terminal part. This is calculated from the copper block temperature as 0 °C as the terminal part temperature. $R_{th\ shs\text{-}12}$ and $R_{th\ shs\text{-}Cu}$ can be said to have very close values.

"$R_{th\ shs\text{-}Cu}$ difference" is the change expressed in percentage calculated from the assumed basis, which is solder thickness 20 µm, solderability medium condition, $R_{th\ shs\text{-}Cu}$ for other solder thickness or fillet condition.

In the following explanation, the numbers 18, 13, 16, and 17 are the same numbers used in Figure H.2. 18 is the resistor surface hotspot; 13, 16, and 17 are top, middle and bottom of the fillet surface, respectively.

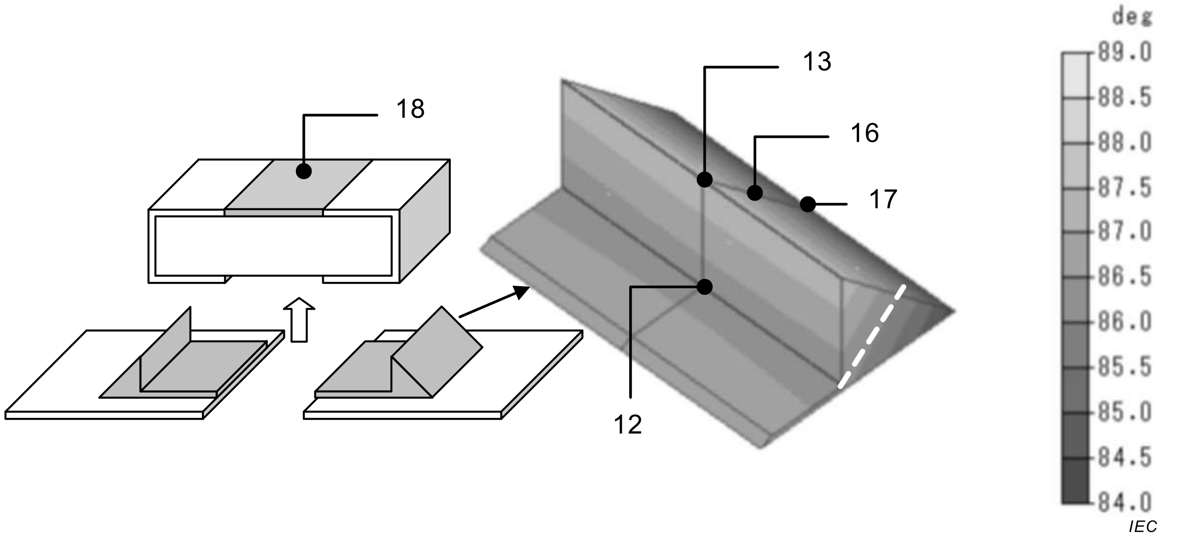
The thermal resistance $R_{th\ shs\text{-}Cu}$ obtained from the temperature of the copper block as the terminal part temperature has a value close to the thermal resistance "18 − 16" calculated from the temperature of the centre part of the solder fillet in Table H.3 as the terminal part temperature. The simulation was implemented for the resistor size RR2012M, but the same trend can be seen more or less for the other sizes.

The reason is that the terminal part temperature (centre of the fillet surface) used to calculate the thermal resistance "18 − 16" in Table H.3 will become the same temperature just underneath the resistor terminal as seen in the example shown in Figure H.4 when the isothermal line is considered. It is estimated that, when the copper block method is used, the temperature just underneath the resistor terminal will be forcibly fixed to a certain value from the excellent heat conduction of the copper block.

However, not all the thermal resistance $R_{th\ shs\text{-}Cu}$ calculated from the copper block surface is conformable with the thermal resistance "18 − 16" based on the centre of the fillet that is mounted on the general printed board. But even if they are not conformable, the purpose of measuring the position 16 (centre part of the solder fillet) that is mounted on the printed board, as shown in Figure H.2, is to verify what the temperature of the terminal part is. Therefore, in this use, a certain amount of error would be no problem.

Figure H.4 is one of the results of the simulation models of Figure H.2. The conditions are copper thickness 35 µm, pattern width 1.2 mm, and with large solder fillet. From this result, the details of the temperature distribution of the solder fillet can be observed. The dotted line is the isothermal line of 86 °C. It can be observed that the temperature of the centre part of the fillet surface reflects the bottom surface of the terminal part.

On the other hand, the thermal resistance "18 − 17" has set the terminal part temperature at the point very close to the hotspot of the resistor, so the calculated value is relatively low. And the thermal resistance "18 − 17" has set the terminal part temperature at the point far from the hotspot of the resistor, so the measured value is relatively high.



Key

12 Inside centre part of the fillet T_{12} = 86,2 °C

13 Top part of fillet T_{13} = 87,5 °C

16 Centre part of fillet T_{16} = 86,1 °C

17 Bottom part of fillet T_{17} = 84,2 °C

18 Surface hotspot T_{18} = 94,6 °C

Figure H.4 – Isothermal line of the fillet part (calculated)

In Figure H.3, there is temperature distribution on the copper surface, but the heat conduction of the thick copper block is extremely high, so the difference would be only a single digit compared with the difference between 16 and 17, so they can be ignored.

By referring the results obtained in the simulation of Figure H.3, setting the measurement point of the copper block surface temperature at 2 mm to 3 mm from the fillet of the target resistor would not be of any practical issue.

The point that needs to be carefully measured is when the method for measuring the surface hotspot and the terminal part is different, such as when the surface hotspot of the resistor is measured by an infrared thermograph and the terminal part is measured by a thermocouple. In this case, first, both of the methods should measure the target with the same temperature, and then understand the offset between the two measurement methods. After that, the offset caused by the different methods should be cancelled when calculating the difference between the surface hotspot and the terminal part temperature. To skip the complicated procedures, which can be the cause of the error, the above-mentioned surface hotspot of the resistor and the terminal part temperature is recommended to be measured with the same infrared thermograph.

Additionally, the surface of the copper without any coating has a very low emissivity, so measuring the emissivity of the copper and entering the value into the infrared thermograph can be the cause of a very large error. Therefore, coating with the black-body spray to forcibly fix the emissivity before measuring the copper surface temperature is necessary. It is already explained in Annex G but, unless the temperature of the resistor becomes extremely high compared to the ambient temperature, the hotspot temperature will not be low even when the black-body spray is coated on the entire resistor or the fillet. Therefore, coating the resistor with black-body spray uniformly and entirely is recommended.

Annex I
(informative)

Measurement method of the terminal part temperature of the SMD resistors

I.1 Measuring method using an infrared thermograph

When the derating curve of the resistor is based on the terminal part temperature, it is necessary for the electric/electronic device designers to measure the terminal part of the resistors in the designing process of their electric/electronic devices. However, in reality, it would be impossible to measure all the temperatures of the resistors by connecting thermocouples to every single terminal since they would be one of the most-used electronic devices. They need to distinguish which fillet of the resistor needs to be connected to the thermocouple and measured. This annex shows electric/electronic device designers how to use the derating curves based on the terminal temperature in their design activities.

An infrared thermograph has some points to be aware of, such as the fact that it can only measure the temperature where it can be observed directly, the need to consider the spatial resolution, and the need to adjust the emissivity. However, for the use of measuring the rough temperature rise of the terminal part when the printed board is not inside the chassis under operating condition at the step of defining where to connect the thermocouples, the infrared thermograph would be the first choice.

The surface of the SMD resistor is generally covered with insulators such as epoxy resin and glass. The emissivity of the insulator is usually around 0,85. As shown in Figure F.2, with the relatively low spatial resolution of 200-µm standard lenses, the true peak temperature of the surface hotspot cannot be observed. Usually, the intermediate temperature of the true peak and the terminal part will be observed as the quasi-peak temperature. If electric/electronic device designers can presume the difference between the quasi-peak temperature and the terminal part temperature as the design margin, the hotspot temperature of the resistor observed by the 200-µm lens can be considered as the terminal part temperature. For example, using the 200-µm lens in Figure F.2, the peak temperature is 70 °C and the terminal part temperature is 55 °C, so the 15 K difference may be considered as a margin.

Generally, the standard lens of the infrared thermograph can expand the area of the corresponding one pixel of light receiving element into a square of 300 × 300 µm or 400 × 400 µm and so on by adjusting the distance of the thermograph and target. If the area of one pixel is extended, the observed peak temperature of the resistor moves closer to the terminal part temperature. It will be possible to read the hotspot temperature observed by the infrared thermograph with a low spatial resolution lens as the terminal part temperature if this behaviour is used. However, to improve the accuracy of the infrared thermograph, the relationships between the equivalent area of the pixel for the light-receiving element and the peak temperature of the target SMD resistor and the terminal part temperature need to be estimated beforehand.

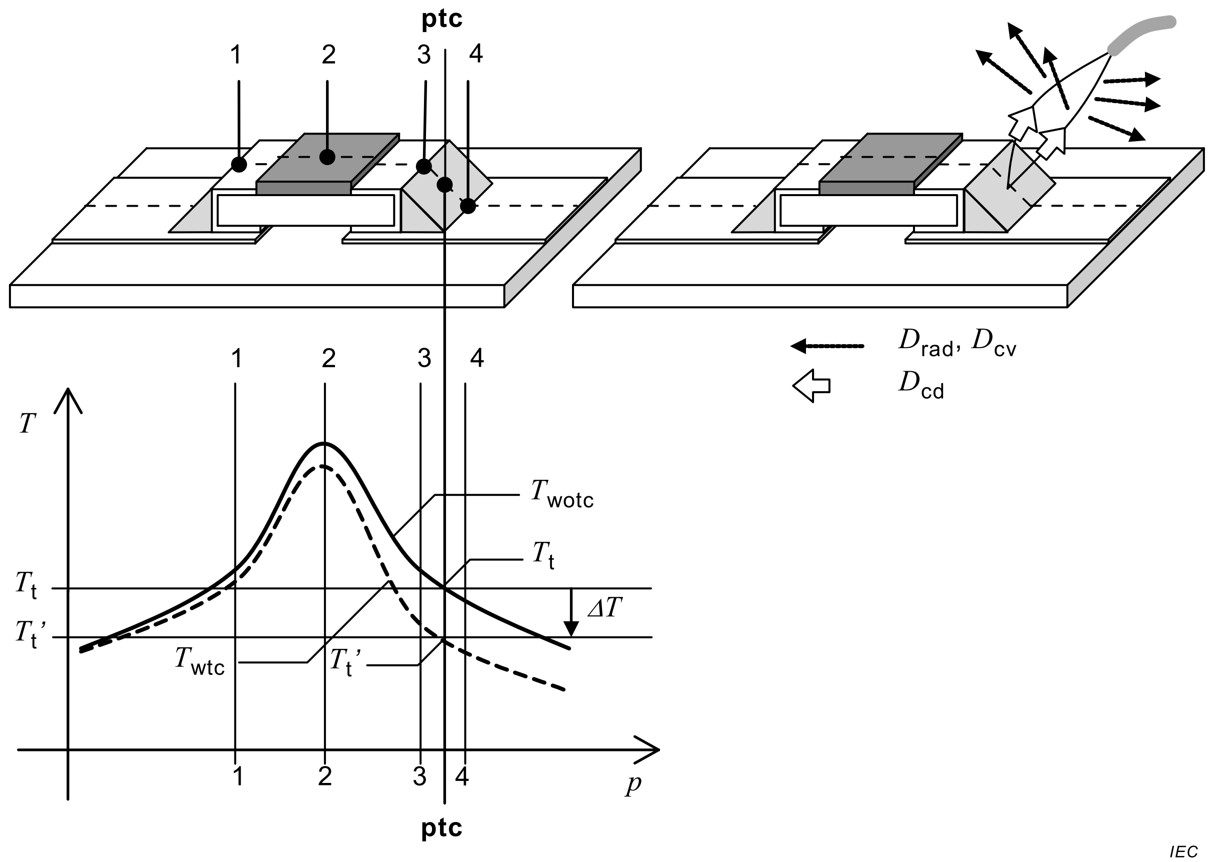
When the emissivity of the resistor is not clear, it can be set at relatively high values, such as 0,9 or 0,95, because the measured temperature will be higher than the actual value and this could be the design margins for the equipment. However, if an excessive value is set, the margins will become excessive, so it is preferable to set the value as accurately as possible.

If the board with the devices mounted can be entirely coated with black-body sprays and also be operated, it is possible to use an infrared thermograph and directly measure the terminal part temperature whose light axis of the lens is within 60°, as explained in Annex G. Since the solder fillet is made of metal and has low emissivity, it will be influenced largely by the light axis of the lens of an infrared thermograph and the target surface. Therefore, if the coating cannot be implemented, direct measurement of the solder fillet by an infrared thermograph would be impossible.

I.2 Measuring method using the thermocouple

The basic and simple measurement of the terminal part temperature is possible by using an infrared thermograph as shown in Figure I.1. But the only method to directly measure the terminal part of SMD resistors that cannot be observed from the outside is to use thermocouples. The resistor manufacturers will be using them when measuring the terminal part of the resistor in the test chamber while it is tested. Electric/electronic device designers will be using them when measuring the terminal part temperature of the resistor with small margins with the board set inside the chassis and operated.

When measuring the temperature of a micro part such as the terminal part of the RR2012M resistor with a thermocouple, the presumable largest contributing factor of an error is the temperature drop of the target part caused by the thermocouple behaving like a radiator as seen in Figure I.1.



Key

1 to 4 Position
ptc Position where the thermocouple is connected
D_{rad} Dissipation by radiation
D_{cv} Dissipation by convection
D_{cd} Dissipation by conduction
T Temperature
P Position
T_{wotc} Temperature distribution when there is no thermocouple
T_{wtc} Temperature distribution when there is thermocouple
T_t Temperature of the fillet centre part without thermocouple
T_t' Temperature of the fillet centre part with the thermocouple
ΔT Temperature drop by connecting the thermocouple

Figure I.1 – Temperature drop caused by the attached thermocouple

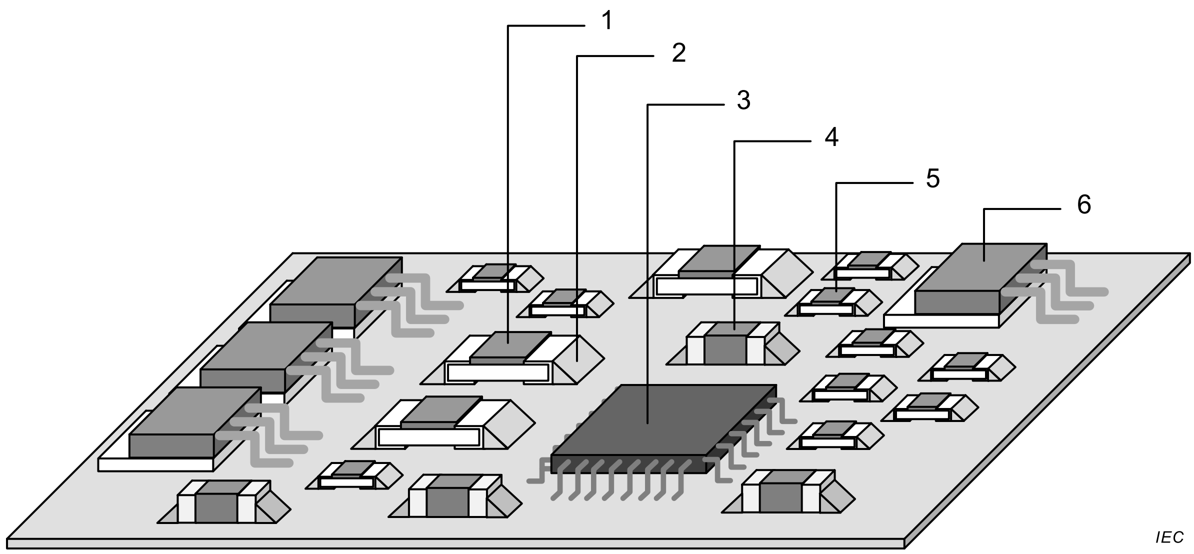
The terminal part temperature without the thermocouple would be T_t, and the temperature drop caused by the attachment of the thermocouple would be ΔT. Then, the actual temperature that the thermocouple will measure would be $T_t' = T_t - \Delta T$. If ΔT can be estimated, then $T_t = T_t' + \Delta T$, so the true temperature T_t can be calculated. However, if the heat dissipation effect of the thermocouple is small enough and $T_t' > \Delta T$, then the temperature drop caused by the thermocouple could be ignored.

I.3 Estimating the error range of the temperature measurement using the thermal resistance of the thermocouple

I.3.1 General

The thermal resistance of the thermocouple can be calculated. There are several methods for calculating the thermal resistance of the thermocouple. Here, the calculated results will be used to estimate the range of errors of temperature measurement by the thermocouple.

Many other devices other than the target resistor, on which the terminal is planned to be measured, are mounted on the printed board as shown in Figure I.2.



Key

1 Target resistor

2 Measure the terminal temperature (centre part of the fillet)

3 IC

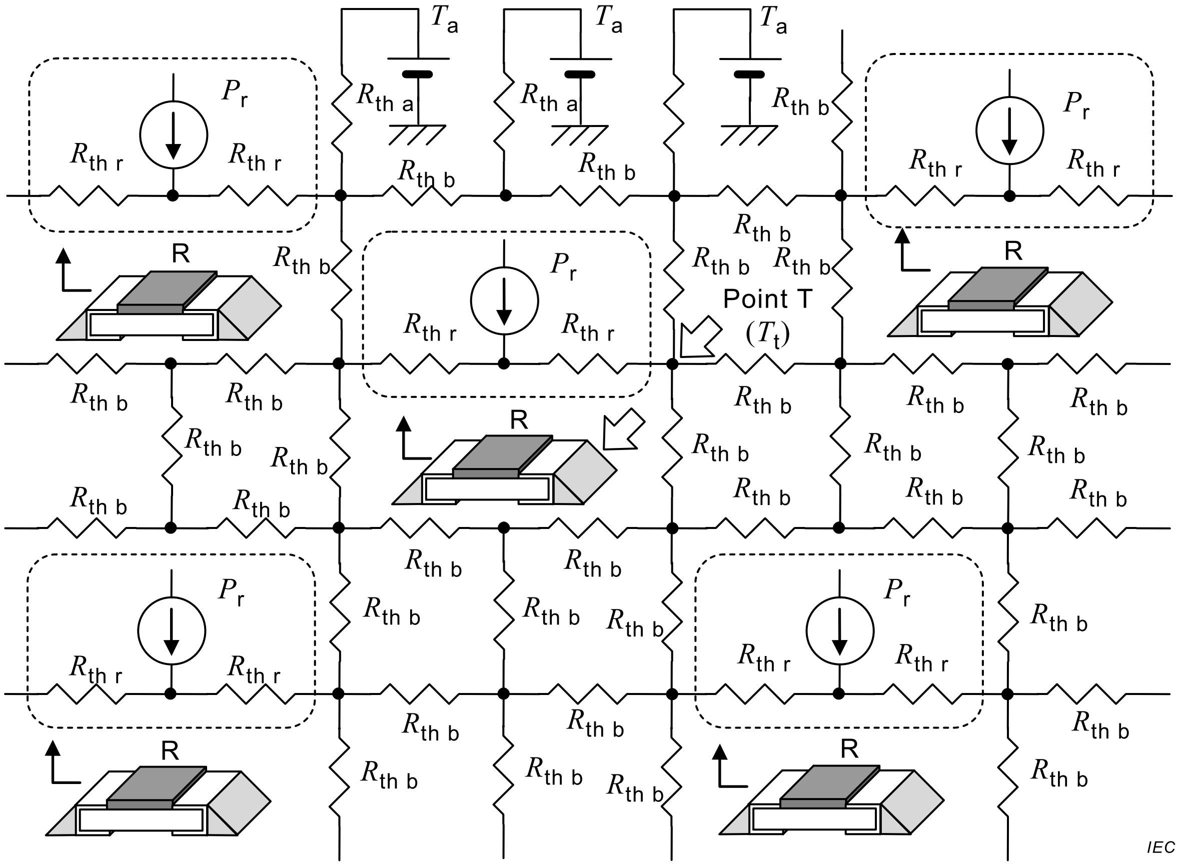
4 Capacitor (no self-heating)

5 Other resistors (with self-heating)

6 Semiconductors (with self-heating)

Figure I.2 – Example of the printed board

The relationship between the heat generation of each device mounted on the printed board and the temperature distribution can be considered with the thermal network as seen in Figure I.3. This thermal network is not the true reproduction of Figure I.2. It is only a clipped out image. The thermal resistance is shown with the old electric resistor symbol which is still often used in the heat-transfer engineering field.



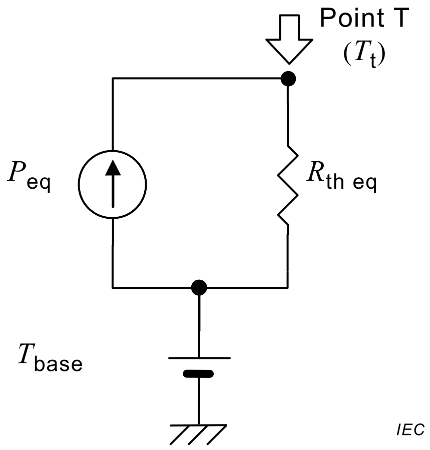
Key

R	Resistor
$R_{th\ r}$	Inner thermal resistance of resistor
P_r	Applied power to the resistor
$R_{th\ b}$	Thermal resistance of printed board wiring and base material
$R_{th\ a}$	Thermal resistance from the printed board to the atmosphere
T_a	Temperature of the atmosphere
Point T	Target terminal part of resistor
T_t	Target terminal part temperature

Figure I.3 – Printed board shown with the thermal network

Each of the thermal resistances, power and temperatures of the atmosphere in Figure I.3 are shown with the same symbols, but have different values. To prevent complications, $R_{th\ a}$ and T_a are all connected to the contact points. The heat-generating devices other than the target resistors, such as the IC and FET, are indicated with the resistance symbols since they do not influence the system when they are replaced with resistors as shown in Figure I.3.

The actual thermal network of the electrical circuit is a lot more complicated than the thermal network in Figure I.3. But when reviewing the temperature drop of the target resistor terminal part when it is connected to the thermocouple, it should be able to show in a simple diagram as shown in Figure I.4. This is the result of applying Norton's theorem used in the electrical circuit field to the thermal network. The thermal resistance of each part, which constitutes the thermal network, shows nonlinearity from the dependence to temperature. Therefore, it only works out in narrow temperature ranges and small power increases and decreases. However, it is sufficient enough for getting the approximate value of the temperature change.



Key

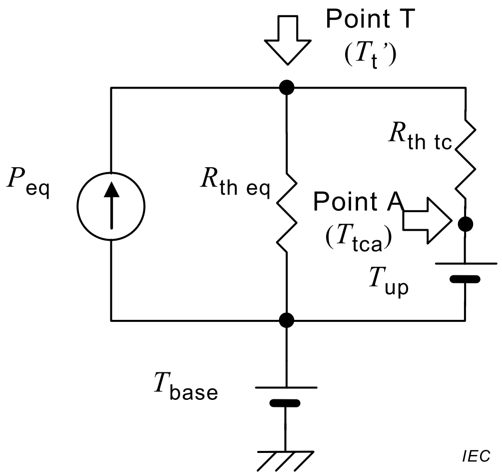
Point T	Target terminal part of resistor
T_t	Target terminal part temperature
P_{eq}	Equivalent heat source
$R_{th\ eq}$	Equivalent thermal resistance from the terminal part to T_{base}
T_{base}	Temperature to be set as standard (ambient temperature of the set)

Figure I.4 – Equivalent circuit of the printed board shown with the thermal network

From Figure I.4, the temperature T_t of the terminal part T of the target resistor will be indicated as in Formula (I.1).

$$T_t = P_{eq} \times R_{th \cdot eq} + T_{base} \tag{I.1}$$

The thermally equivalent circuit when the thermocouple is connected to the terminal part Point T will be approximately as shown in Figure I.5.



Key

Point T	Terminal part of target resistor
T_t'	Terminal part temperature of target resistor (after connecting thermocouple)
P_{eq}	Equivalent heat source
$R_{th\ eq}$	Equivalent thermal resistance
T_{base}	Temperature to be set as standard (ambient temperature of the set)
$R_{th\ tc}$	Thermal resistance when the thermocouple is regarded as a heatsink
T_{tca}	Ambient temperature of the thermocouple
T_{up}	Temperature rise of T_{tca} from T_{base}

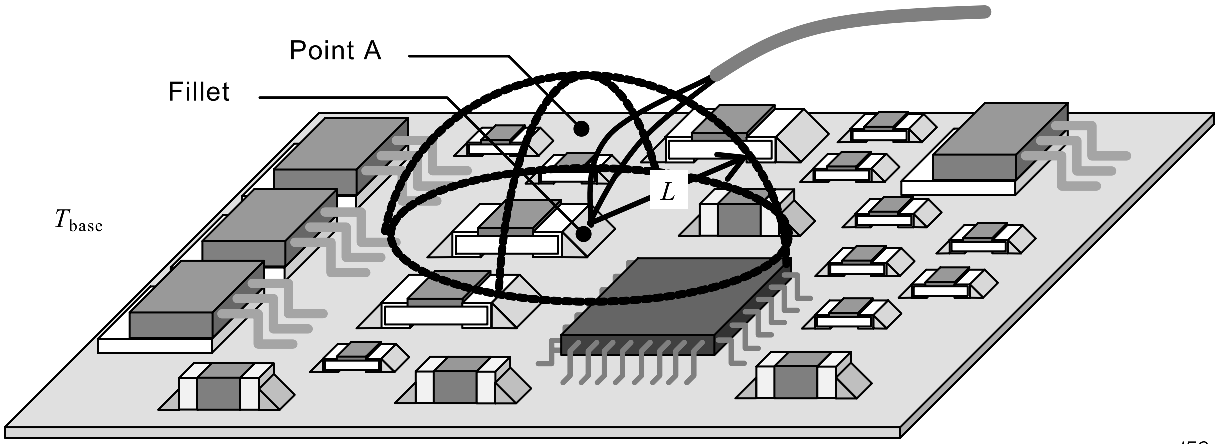
Figure I.5 – Equivalent circuit when the thermocouple is connected

The difference between T_{base} and T_{tca} is explained in Figure I.5.

The T_{base} can be the ambient temperature of the board or, when the board is set inside the chassis, it can be the external temperature of the equipment.

T_{tca} is the temperature of the atmosphere for the thermocouple when it behaves as a radiator as shown in Figure I.6. And 10 mm from the connecting point of the solder fillet will function as a radiator when the wire diameter is 0,1 mm, a type K thermocouple is connected but the rest of the part will not contribute to the heat dissipation. The temperature within the range of 10 mm from the connecting point should be much higher than the board's ambient temperature and the chassis' ambient temperature T_{base} because of the heat generation of other devices mounted on the board. The temperature rise is T_{up}. If the temperature of the heat dissipation space is set as T_{base} when estimating the temperature drop of the solder fillet caused by connecting the thermocouple, the temperature drop will be overestimated. To estimate the heat dissipation of the thermocouple properly, it is necessary to calculate the heat dissipation amount under the same condition of the temperature at which the thermocouple is set.

The spatial Point A for measuring T_{tca} will differ depending on the type and wire diameter of the thermocouple used, but for the wire diameter of 0,1 mm of the type K thermocouple, it should be around 5 mm to 10 mm in radius from the connection point of the thermocouple.

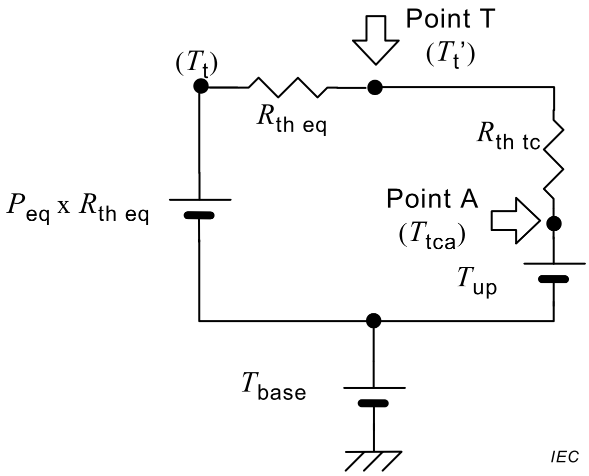


Key

Fillet	Solder fillet which the terminal part temperature will be measured
T_{tca}	Ambient temperature for heat dissipation of the thermocouple, equal to T_{up} + T_{base}
T_{up}	Temperature rise of T_{tca} from T_{base}
T_{base}	Temperature to be set as standard (ambient temperature of the set)
Point A	Place to measure the T_{tca}
L	Length from the measurement point that cause the heat dissipation of the thermocouple; heat dissipation is determined by the temperature in this range

Figure I.6 – Ambient temperature and the space need for the heat dissipation of the thermocouple

When the heat source P_{eq} in Figure I.5 is replaced to temperature difference P_{eq} $R_{th\ eq}$, it would be as shown in Figure I.7. In between the formula $P_{eq} \times R_{th\ eq}$ and $R_{th\ eq}$ expressed by the symbol of the electromotive force, the temperature of Point T before connecting the thermocouple T_t is entered. This is the temperature shown by Formula (I.1).



Key

Point T	Target terminal part of resistor
T_t'	Terminal part temperature of target resistor (after connecting thermocouple)
T_t	Terminal part temperature of target resistor (before connecting thermocouple)
P_{eq}	Equivalent heat source
$R_{th\ eq}$	Equivalent thermal resistance of printed board
T_{base}	Temperature to be set as standard (ambient temperature of the set)
$R_{th\ tc}$	Thermal resistance when the thermocouple is regarded as a heat-sink
T_{tca}	Ambient temperature of thermocouple
T_{up}	Temperature rise of T_{tca} from T_{base}

Figure I.7 – Equivalent circuit when the thermocouple is connected

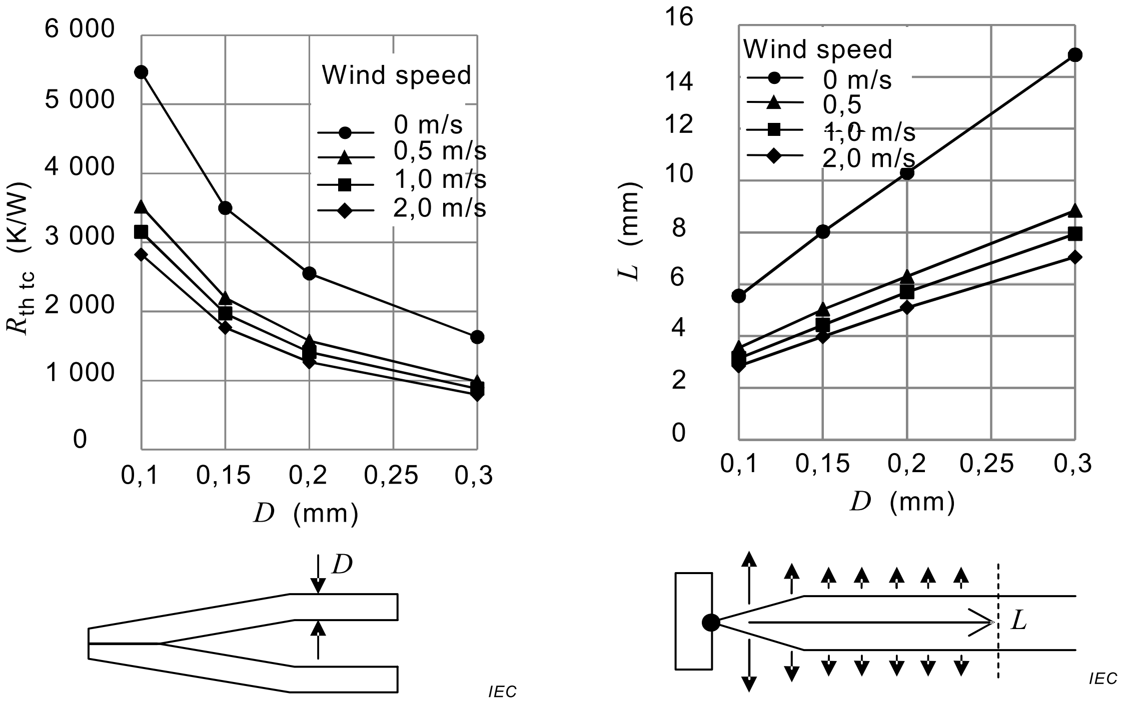
When T_t − T_t' = ΔT is calculated, it will be as shown in Formula (I.2).

$$T_t - T_t' = \Delta T = \left(T_t - T_{tca}\right) / \left\{1 + \left(R_{th \cdot tc} / R_{th \cdot eq}\right)\right\} \tag{I.2}$$

Substitute T_t = T_t' + ΔT to the above formula. It would be as shown in Formula (I.3).

$$\Delta T = \left(T_t' - T_{tca}\right) \times \left(R_{th \cdot eq} / R_{th \cdot tc}\right) \tag{I.3}$$

The actual values will be entered into this formula and the temperature drop caused by the thermocouple ΔT will be calculated. The theoretical value of the thermal resistance of the thermocouple $R_{th\ tc}$ is calculated based on Figure I.8, which shows the thermal resistance and the length that causes heat dissipation of a type K thermocouple with a tip temperature of 100 °C, T_{tca} is 50 °C. The length that causes heat dissipation of the thermocouple shows the length of the thermocouple to dissipate 90 % of the entire heat. However, the thermal resistance of the thermocouple does not change so much even when the tip temperature and T_{tca} change. For example, when the condition is tip temperature = 100 °C, T_{tca} = 90 °C, the thermal resistance rises only less than 3 % compared with the tip temperature = 100 °C, T_{tca} = 50 °C, and drops only less than 10 % compared with the tip temperature = 100 °C, T_{tca} = 200 °C.



(a) Wire diameter **(b) Wire length**

Key

$R_{th\ tc}$ Thermal resistance when the thermocouple is regarded as a heat-sink

L Length from the measurement point that cause the heat dissipation of the thermocouple

D Wire diameter of the thermocouple

Figure I.8 – Length that causes the heat dissipation and the thermal resistance of the type K thermocouple (calculated)

Figure I.8 shows that when the thermocouple has a wire diameter of 0,1 mm and under natural convection (air speed 0 m/s), the thermocouple will behave as a heatsink with a thermal resistance around $R_{th\ tc}$ = 5 500 K/W.

On the other hand, the thermal resistance of the board $R_{th\ eq}$ will largely depend on the material of the printed board, pattern width, pattern density and number of layers. For example, a single-sided FR4 board with a board thickness of 1,6 mm and with a copper thickness 35 µm will have 200 K/W to 300 K/W, even with one relatively narrow pattern as shown in Figure I.10. This value will decrease as the copper layer and copper foil thickness increases.

Presume that $R_{th\ eq}$ is 300 K/W and the resistor fillet temperature is measured with a thermocouple of wire diameter 0,1 mm type K thermocouple ($R_{th\ tc}$ = 5 500 K/W), and the value were 90 °C. If the spatial temperature close to the thermocouple were 60 °C, then the temperature drop of the fillet caused by the connected thermocouple ΔT would be calculated from Formula (I.3).

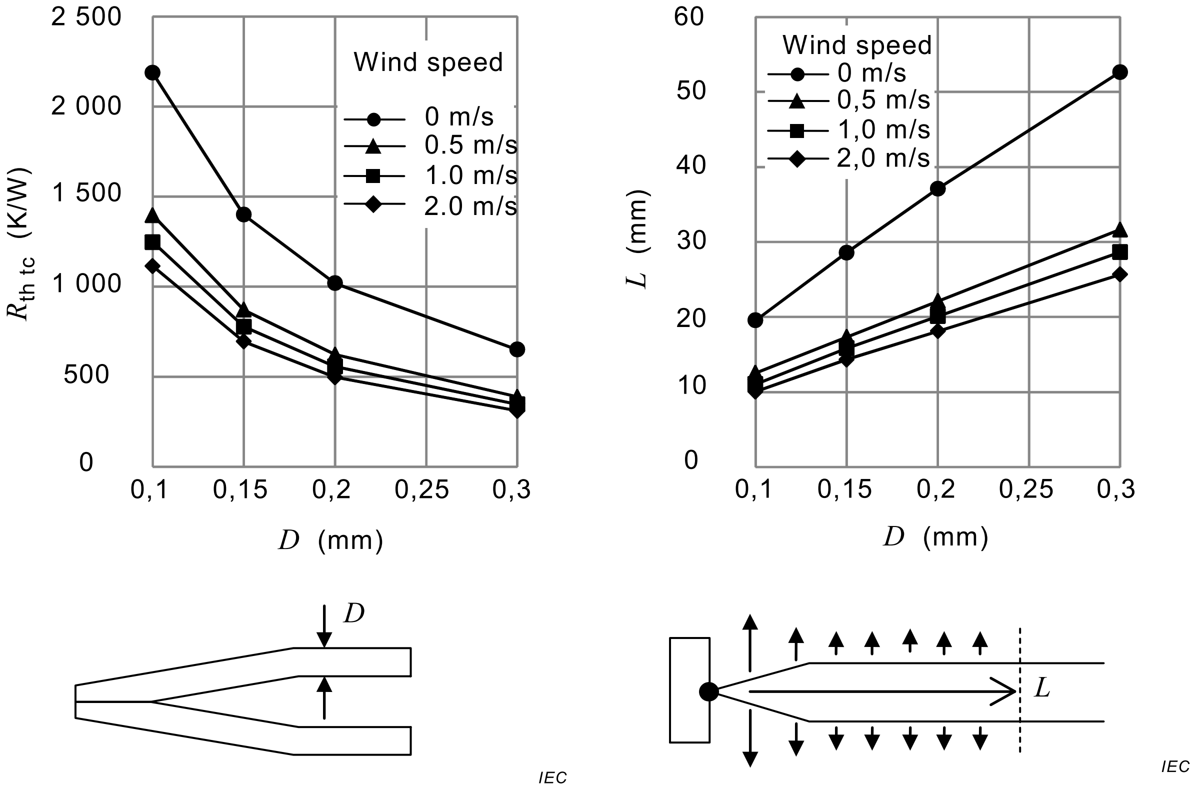
$$\Delta T = (90\ °\mathrm{C} - 60\ °\mathrm{C})(300\ \mathrm{K/W} / 5500\mathrm{K/W}) \approx 1{,}64\ °\mathrm{C}$$

The temperature without the thermocouple can be estimated to be 91,64 °C. This small influence caused by the thermocouple can be ignored when measuring the operating environmental condition of a resistor. $R_{th\ tc}$ = 5 500 K/W is a value calculated from the condition with some space for the air to move freely underneath the thermocouple and it is calculated on the small side, so the actual error would be smaller. The actual measured value when the board is horizontally set against the ground is $R_{th\ tc}$ = 10 000 K/W. So, when the type K thermocouple with a 0,1-mm wire diameter is used for measuring the fillet temperature, it can be said for most cases that a value close to the true value without an error can be achieved.

I.3.2 When using the type T thermocouples

Figure I.9 shows the thermal resistance and the length needed to radiate the heat of a type T thermocouple with tip temperature = 100 °C, T_{tca} = 50 °C. $R_{\text{th tc}}$ of the type T thermocouple becomes half of type K even when the wire diameter is the same as shown in the figure, so this needs attention. Additionally, the length needed to radiate the heat is very long compared to the type K. The reason is because one of the wires used in the type T thermocouples is made of copper, which has high heat conductivity.

The type T thermocouples have low thermal resistance, so the error caused by the heat dissipation is large. However, the stability and accuracy of the thermocouple itself is better than that of type K. Therefore, use the thermocouple properly according to the application.



(a) Wire diameter **(b) Wire length**

Key

$R_{\text{th tc}}$ Thermal resistance when the thermocouple is regarded as a heat-sink

L Length from the measurement point that cause the heat dissipation of the thermocouple

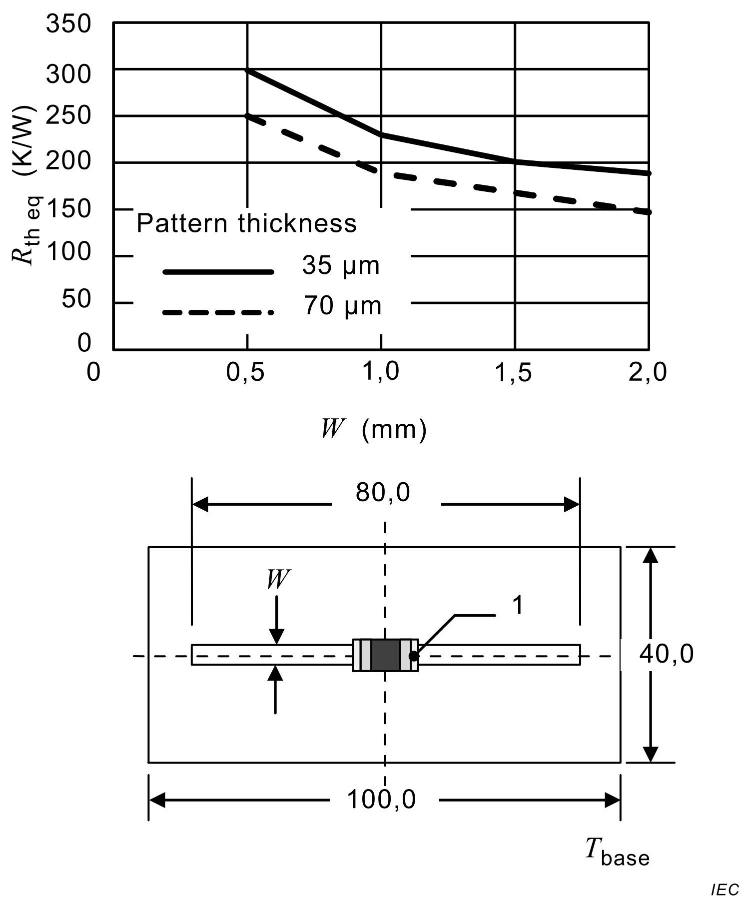
D Wire diameter of the thermocouple

Figure I.9 – Length that cause the heat dissipation and the thermal resistance of the type T thermocouple (calculated)

I.4 Thermal resistance of the board

The thermal resistance of Figure I.10 is calculated from the actual temperature measurement and the method is shown in Figure I.11.

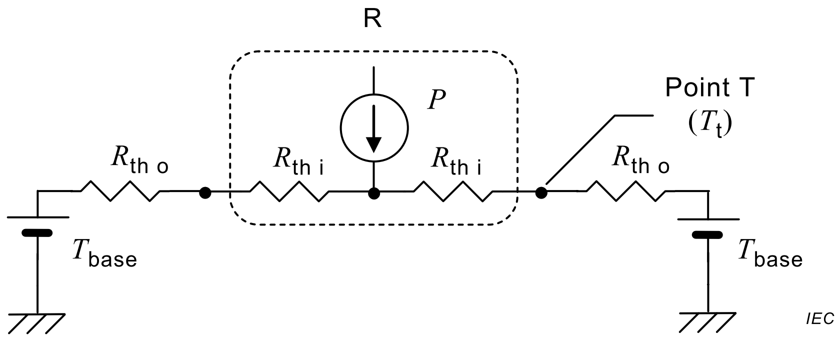
The equivalent circuit of the printed board and resistor in Figure I.10 can be simplified as in Figure I.11. In the actual printed board, except under special circumstances, the thermal resistance $R_{\text{th o}}$ from each of the terminals of the resistor to T_{base} do not become the same value, but this is an explanation of the principle, so it is presumed that they are the same.



Key

T_{base}	Temperature standard (temperature of the ambient where the board is set etc.)
$R_{\text{th eq}}$	Thermal resistance between the terminal part and T_{base}
1	Thermal resistance measuring point
W	Pattern width

Figure I.10 – Thermal resistance $R_{\text{th eq}}$ of the FR4 single side board (thickness 1,6 mm)



Key

R	Resistor
P	Power applied to the resistor
$R_{th\ I}$	Thermal resistance inside the resistor
$R_{th\ o}$	Thermal resistance of board of one side terminal
Point T	Measurement point of temperature
T_t	Measured temperature
T_{base}	Temperature standard such as the ambient

Figure I.11 – Calculating the thermal resistance of the board from the fillet side

The thermal resistance $R_{th\ o}$ of the board (single-sided terminal), which is from Point T to the ambient temperature, can be calculated from Formula (I.4) if the temperature drop caused by the heat dissipation of the thermocouple can be ignored. When the type K thermocouple with a wire diameter thinner than 0,15 mm is used, the error would be small enough to ignore.

$$R_{th{\cdot}o} = (T_t - T_{base})/(P/2) \tag{I.4}$$

The thermal resistance $R_{th\ eq}$ of Point T to T_{base}, which includes the thermal resistance of the board on the other side ($R_{th\ o}$) and the thermal resistance inside the resistor (2 $R_{th\ i}$), will be calculated as shown in Formula (I.5).

$$R_{th{\cdot}eq} = R_{th{\cdot}o}(R_{th{\cdot}o} + 2R_{th{\cdot}i})/(2R_{th{\cdot}o} + 2R_{th{\cdot}i}) \tag{I.5}$$

The value of the 2 $R_{th\ i}$ can only be calculated by the resistor manufacturer, but it can be supposed that it would be about 100 K/W to 200 K/W for the ceramic-based flat chip resistors. The general value for RR2012M, which is 140 K/W, is used for the calculation in Figure I.10.

When $R_{th\ o}$ is high, for example, more than 4 times the value of 2 $R_{th\ i}$, there will be no large error even when the value of the 2 $R_{th\ i}$ is ignored and calculated with Formula (I.6).

$$R_{th{\cdot}eq} = R_{th{\cdot}o}/2 = (T_t - T_{base})/P \tag{I.6}$$

For example, in the case of $R_{th\ o}$ = 480 K/W, 2 $R_{th\ I}$ = 140 K/W and the Formula (I.5) is used, it will be $R_{th\ eq}$ = 270 K/W. But when Formula (I.6) is used, it will be $R_{th\ eq}$ = 240 K/W in abbreviated calculation.

When the Formula (I.6) is used, $R_{\text{th eq}}$ will be about 10 % lower. But the purpose of calculating $R_{\text{th eq}}$ is to estimate the temperature drop caused by the thermocouple, so this level of error can be ignored.

Therefore, when a type K thermocouple with a wire diameter of 0,1 mm is used, the terminal part temperature can be measured without large error, and when the wire diameter increases and the thermal resistance of the thermocouple $R_{\text{th tc}}$ drops, then use Formula (I.3) and correct the measured value.

I.5 Conclusion of this annex

The infrared thermograph is unfavourable for electric/electronic device designers to accurately measure terminal temperatures. However, it is useful to figure out and identify which terminal part of the resistor it is necessary to measure with thermocouples when the surface peak temperature of the resistor is determined by using the limit of the spatial resolution, and the surface peak temperature can be converted into the terminal part temperature.

When the thermocouple is used to measure the terminal part of the micro devices, the thermocouple behaves as a heatsink and the target measuring point temperature drops. But, if the drop amount can be perceived, it would be a preferred method to measure the terminal part temperature. Furthermore, the drop amount can be perceived easily. And if type K thermocouples with a wire diameter of 0,1 mm can be used, the temperature drop caused by the heat dissipation from the thermocouple can be practically ignored.

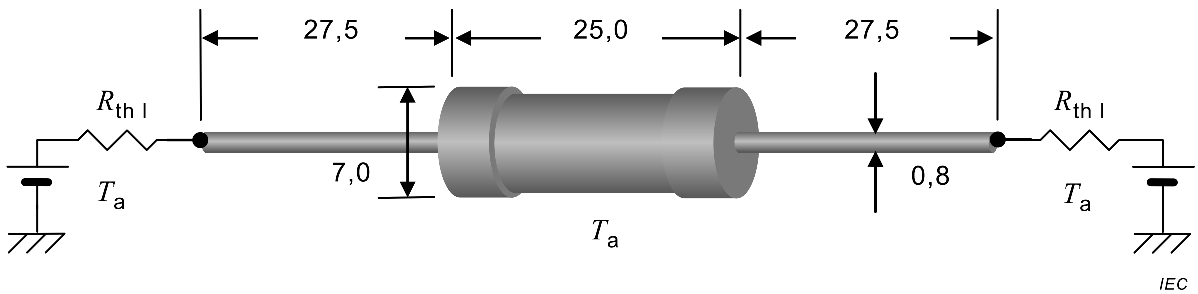
Annex J
(informative)

The variation of the heat dissipation fraction caused by the difference between the resistor and its mounting configuration

J.1 Heat dissipation ratio of cylindrical resistors wired in the air

ANSYS CFD[2] thermo-fluid analysis software is used to derive the heat dissipation percentage when wired in the air. The simulation model is shown in Figure J.1. The emissivity of the resistor body surface is presumed to be 0,85 and the emissivity of the surface of the leaded wire is presumed to be 0,1. Suppose that there are 30 mm of lead wires from both ends of the resistor body. Then, connect the thermal resistance of the ambient space as the boundary condition to the tip of the lead wire.

Dimensions in millimetres



Key

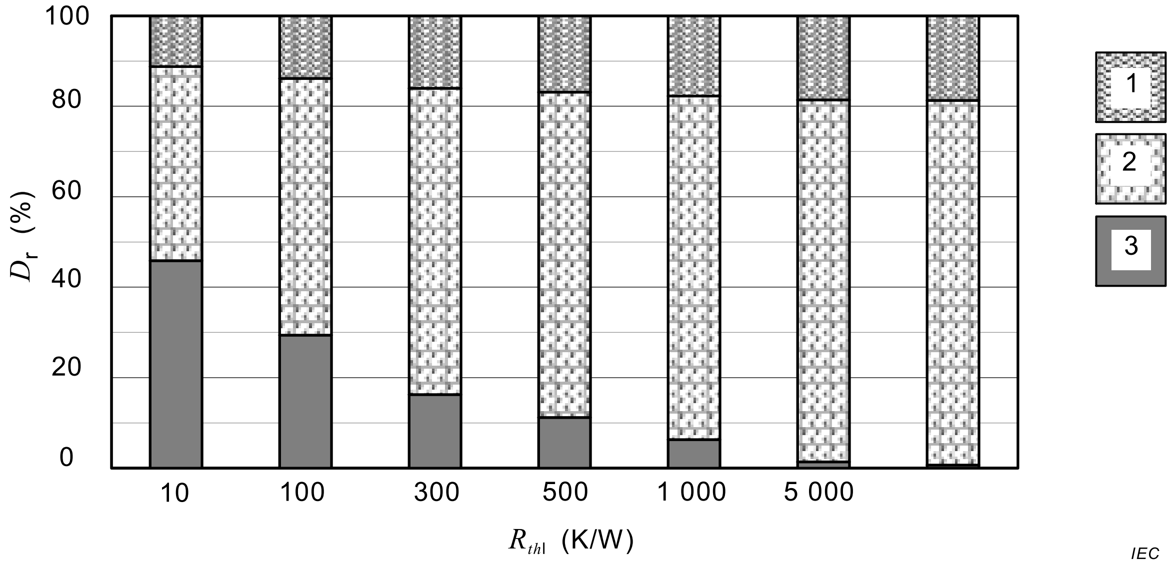
T_a Ambient temperature (presumed 25 °C)

$R_{th\ l}$ Thermal resistance from the tip of the lead wire to the ambient temperature (boundary condition)

Figure J.1 – Simulation model of the lead wire resistors wired in the air

2 ANSYS CFD is the trade name of a product supplied by ANSYS. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of the product named. Equivalent products may be used if they can be shown to lead to the same results.

Dimensions in millimetres



Key

D_r Percentage of heat path

$R_{th\ l}$ Thermal resistance from the tip of lead wire of resistor through the wiring to the atmosphere

1 Dissipation by radiation to the atmosphere

2 Dissipation by convection to the atmosphere

3 Dissipation by conduction from the tip of lead wire through thermal resistance $R_{th\ l}$

Figure J.2 – Heat dissipation ratio of the leaded cylindrical resistors (calculated)

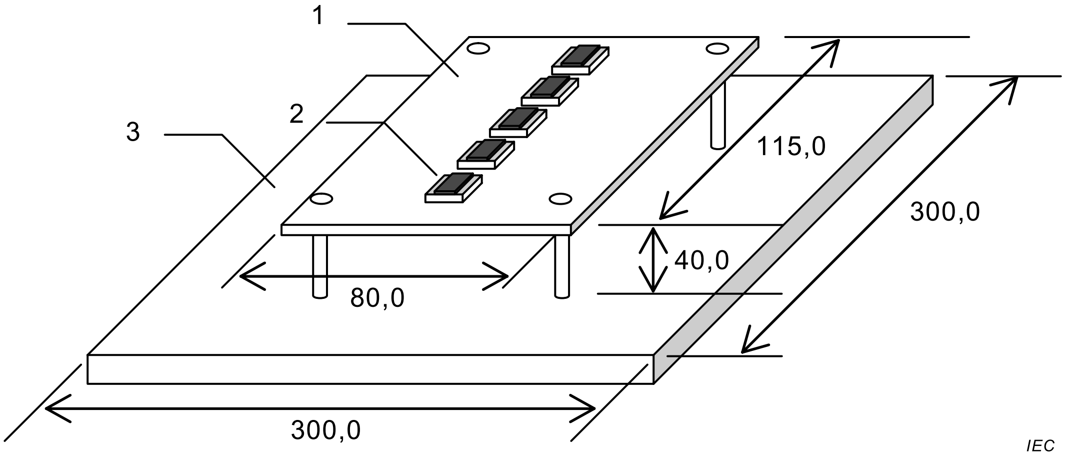
1,5 W is applied to the resistor and it is verified that the centre part of the resistor reaches around 100 °C under the ambient temperature T_a = 25 °C, and that it corresponds to the actual measured value including the temperature distribution. The simulation result is shown in Figure J.2.

J.2 Heat dissipation ratio of SMD resistors mounted on the board

The heat dissipation ratio is defined from the heat transfer to the atmosphere by radiation and convection calculated from the actual temperature measurement value of each part when resistors of each sizes RR6332M, RR5025M, RR3225M, RR3216M, RR2012M, RR1608M, RR1005M are mounted on boards that conform to IEC 60115-8 and set as shown in Figure J.3 and the power is applied.

The temperature measurement of each part is implemented by an infrared thermograph that has sufficient spatial resolution and the necessary temperature accuracy. The surface temperature of the board before the power is applied is used as a substitute of the ambient temperature.

Dimensions in millimetres



Key

1 Board compliant with IEC 60115-8, set in the centre of table

2 Resistor

3 Table

Figure J.3 – Measurement system of the heat dissipation ratio of SMD resistors mounted on the board

When the SMD resistors are mounted on the board and the power is applied, the surface hotspot will be formed close to the centre of the resistor's surface and the ambient temperature will be lower than the surface hotspot. The target of this clause is to verify that the heat dissipation of the SMD resistor is mainly implemented by heat conduction via the board. Therefore, the condition when the heat dissipation ratio based on radiation and convection becomes the largest will be supposed. In particular, when calculating the heat dissipation amount of the heat transfer by radiation and convection, the entire top surface of all the resistor size is presumed to be the same temperature as the observed surface hotspot.

The heat dissipation amount by radiation Q_{rad} (W) is calculated from Formula (J.1).

$$Q_{\text{rad}} = \varepsilon\delta\left\{(273{,}15 + T_{\text{shs}})^4 - (273{,}15 + T_{\text{a}})^4\right\}S \quad \text{(J.1)}$$

Where

ε is the emissivity (0,85 presumed);

δ is the Stefan-Boltzmann constant (5,67 × 10^{-8} (W $\text{m}^{-2}\text{K}^{-4}$));

T_{shs} is the observed surface hotspot temperature (°C);

T_{a} is the observed ambient temperature of the board (°C);

S is the top area of the resistor (m^2).

The heat dissipation amount by convection Q_{cv} (W) is approximately given by Formula (J.2).

$$Q_{\text{CV}} = 2{,}51 \times 0{,}96 \times \left\{(T_{\text{shs}} - T_{\text{a}})/L\right\}^{0{,}25}(T_{\text{shs}} - T_{\text{a}})S \quad \text{(J.2)}$$

Where

T_{shs} is the observed surface hotspot temperature (°C);

T_{s} is the observed ambient temperature of the board (°C);

S is the top area of the resistor (m^2);

L is the representative short side length of the chip resistor (m).

The coefficient 0,56 in Formula (J.2) is the value originally applied to the perpendicular plane, but it is used to estimate the heat dissipation amount of the outside.

The values actually measured and the results of the calculations are shown in Table J.1.

Table J.1 – Analysis result of the heat dissipation ratio of SMD resistors (calculated value and value actually measured)

Size	RR6332M	RR5025M	RR3225M	RR3216M	RR2012M	RR1608M	RR1005M
P (W)	1	0,75	0,5	0.25	0,125	0,1	0,063
T_{shs} (°C)	177,67	151,33	135,27	106,99	71,88	84,14	74,42
T_a (°C)	28,5	28,8	27,2	26,7	23,7	25,8	25,1
Q_r (mW)	27,506	11,641	5,219	2,171	0,445	0,320	0,097
Q_{cv} (mW)	53,238	25,626	12,047	5,946	1,380	1,078	0,369
Radiation (%)	2,75	1,55	1,04	0,87	0,35	0,32	0,15
Convection (%)	5,32	3,42	2,41	2,38	1,10	1,08	0,59
Conduction (%)	91,93	95,03	96,55	96,75	98,54	98,60	99,26

From Table J.1, it is clear that more than 90 % of the heat is dissipated by the heat conduction via the board.

J.3 Heat dissipation ratio of the cylindrical resistors mounted on the through-hole printed board

After the age of vacuum tubes with lead wired cylindrical resistors that were connected to lug terminals and before the appearance of SMD resistors, there were long years of mounting lead-wired cylindrical resistors on through-hole-boards. The heat dissipation percentage of this intermediate period is predicted to be in between the results shown in J.1 and J.2. This means that the percentage of heat dissipation through conduction was indispensable along with the radiation and convection.

As shown in Formula (J.1) and Formula (J.2) in J.2, the heat dissipation amount of the radiation and convection depends largely on the area. The larger the area becomes, the larger the percentages of radiation and convection will get. When the lead-wired cylindrical resistors were first mounted on the printed boards, the heat conduction to the board was not small enough to ignore, but still the percentages of the radiation and convection were high when considering the entire heat dissipation. However, the transistors which were introduced around the same years as the printed boards reduced the size and power consumption of the amplifying elements beyond comparison. From this trend, the miniaturization and power saving of electric/electronic devices advanced quickly. As a result, small passive components including resistors became the mainstream. Even for the lead-wire resistors, as the size gets smaller, the surface area becomes smaller and the heat dissipation amount by radiation and convection will decrease and they will be mounted on printed board patterns with shorter leads, so the percentage of heat dissipation by heat conduction to the printed boards will increase.

The leaded resistors just before the appearance of the SMD resistors such as 1/4 W and 1/6 W probably had as close a percentage of heat dissipation to the board as the present SMD resistors. Therefore, for the lead-wire small-size cylindrical resistors that are supposed to be mounted on printed boards, the derating curves with ambient temperature as the horizontal axis were already a mere facade.

Annex K
(informative)

Influence of airflow on SMD resistors

K.1 General

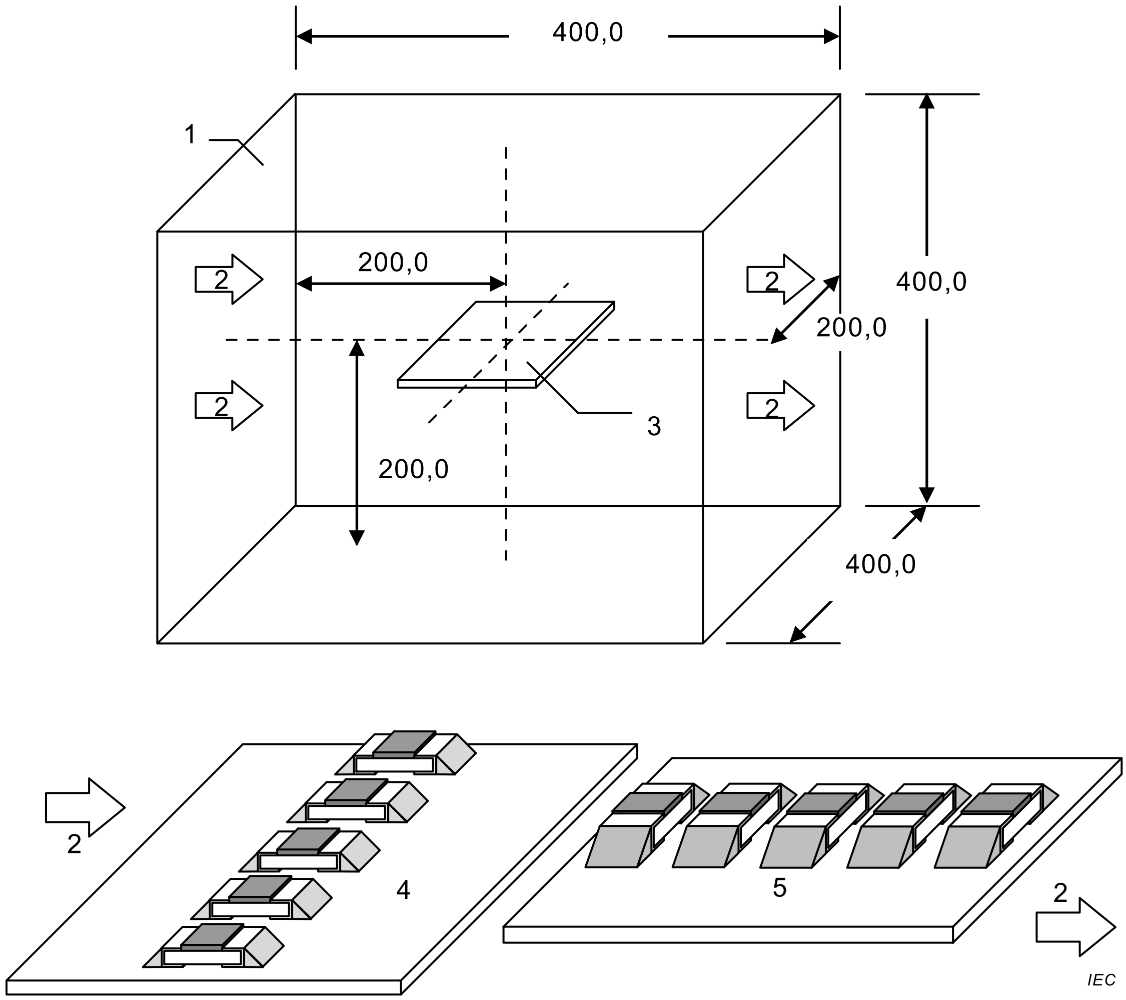
In Annex D, the temperature drop of the terminal part when the turbulent flow is applied to the board was shown. In this annex, the temperature drop of the terminal part will be shown for each size when parallel laminar flow is applied.

K.2 Measurement system

The measurement instrument will be the wind tunnel as shown in Figure K.1. The board is set parallel to the airflow to make the laminar airflow.

The test board size is 110 mm × 80 mm and they are the same boards that are mentioned in Annex D. There are two board layouts. One is set so that the wind direction and the resistor set in line will cross orthogonally and the other will be set parallel. The latter case is set to observe the degraded leeward cooling efficiency caused by the boundary layer. The thermocouple used to measure the terminal part temperature is a type K with a wire diameter of 0,1 mm. The thermocouple is directly soldered to the centre of the fillet.

Dimensions in millimetres



Key

1 Wind tunnel

2 Wind direction

3 Sample board position

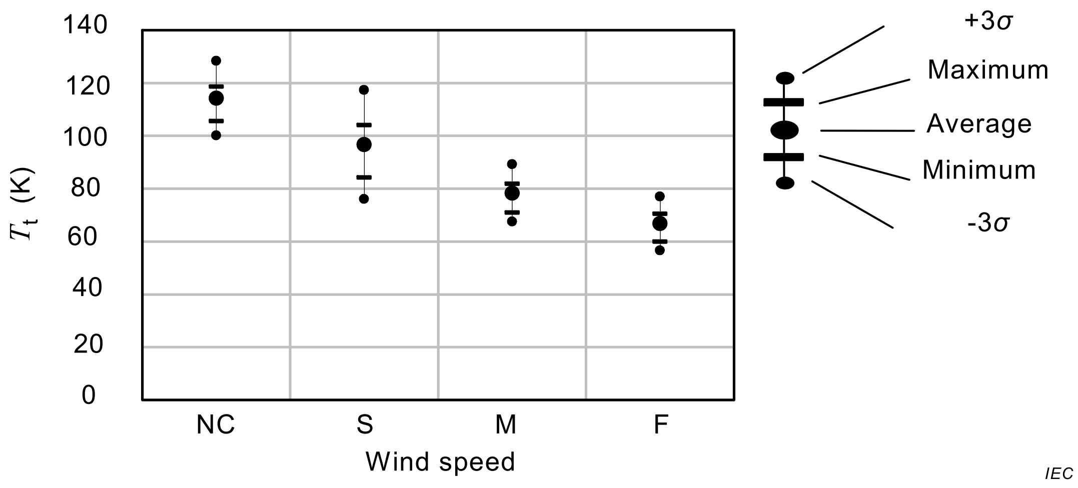
4 Sample board (resistor set orthogonal to the wind direction)

5 Sample board (resistor set parallel to the wind direction)

Figure K.1 – Measurement system

K.3 Test results (orthogonal)

The results are shown in Figure K.2, Figure K.3, Figure K.4, Figure K.5, Figure K.6, Figure K.7 and Figure K.8.



Key

T_{tr} Terminal part temperature rise

NC Normal convection (flat)

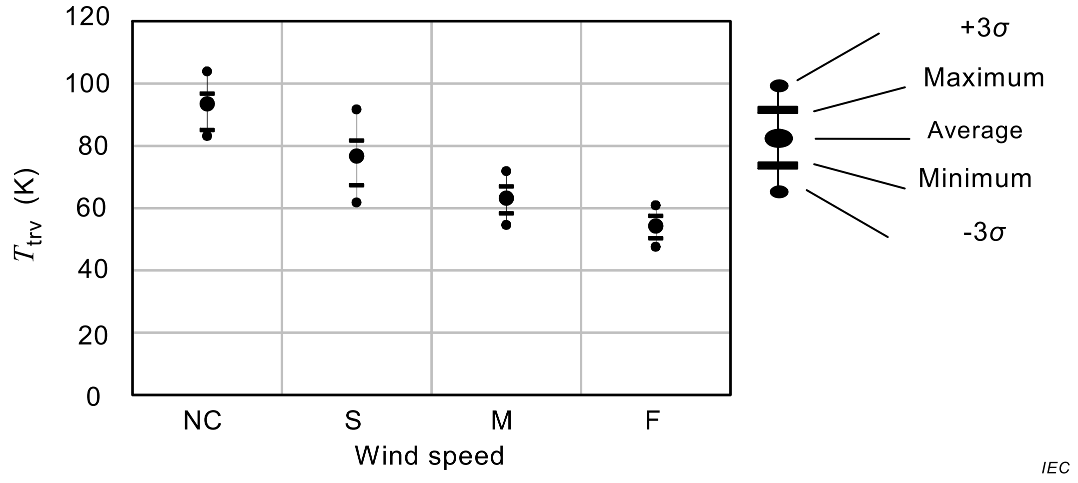
S 0,3 m/s to 0,6 m/s

M 0,7 m/s to 1,2 m/s

F 1,6 m/s to 2,4 m/s

σ Standard deviation

Figure K.2 – Relationship between the terminal part temperature rise and the wind speed for the RR6332M (orthogonal)



Key

T_{tr} Terminal part temperature rise

NC Normal convection (flat)

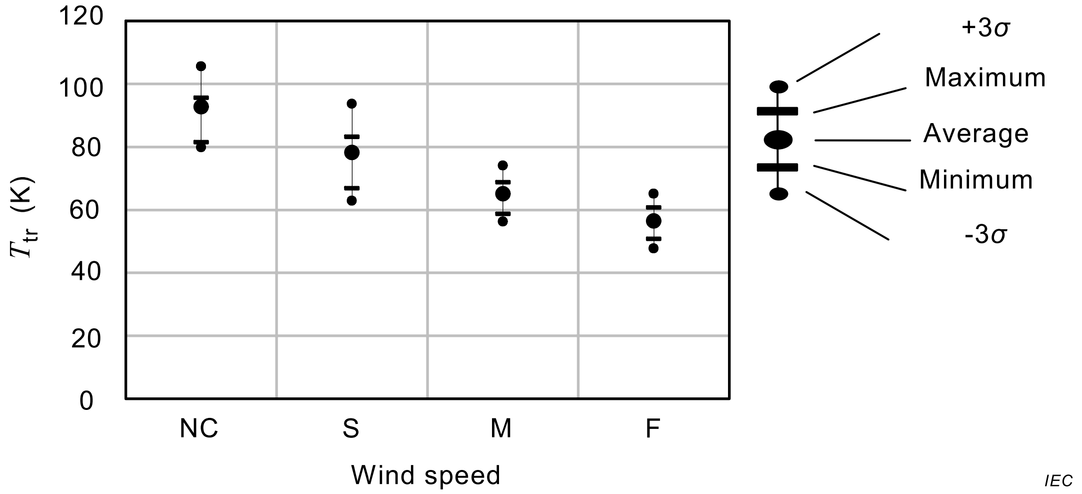
S 0,3 m/s to 0,6 m/s

M 0,7 m/s to 1,2 m/s

F 1,6 m/s to 2,4 m/s

σ Standard deviation

Figure K.3 – Relationship between the terminal part temperature rise and the wind speed for the RR5025M (orthogonal)



Key

T_{tr} Terminal part temperature rise

NC Normal convection (flat)

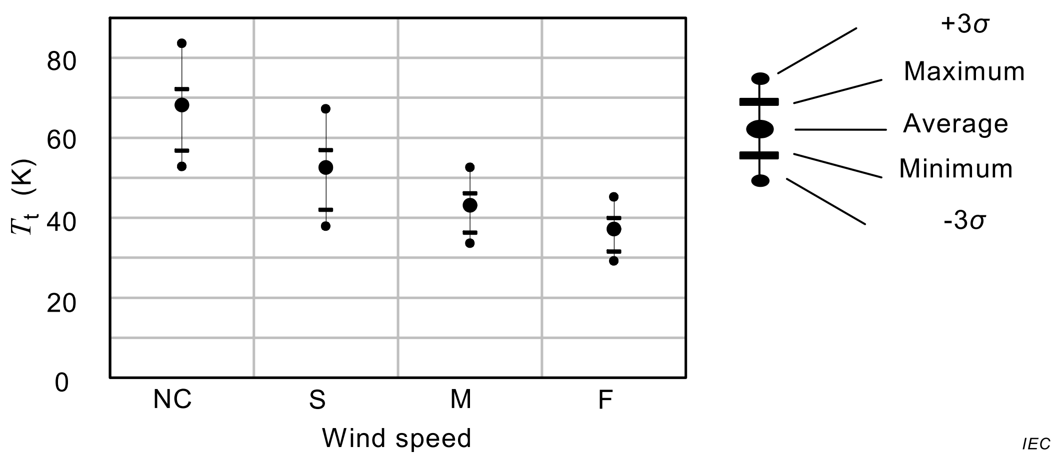
S 0,3 m/s to 0,6 m/s

M 0,7 m/s to 1,2 m/s

F 1,6 m/s to 2,4 m/s

σ Standard deviation

Figure K.4 – Relationship between the terminal part temperature rise and the wind speed for the RR3225M (orthogonal)



Key

T_{tr} Terminal part temperature rise

NC Normal convection (flat)

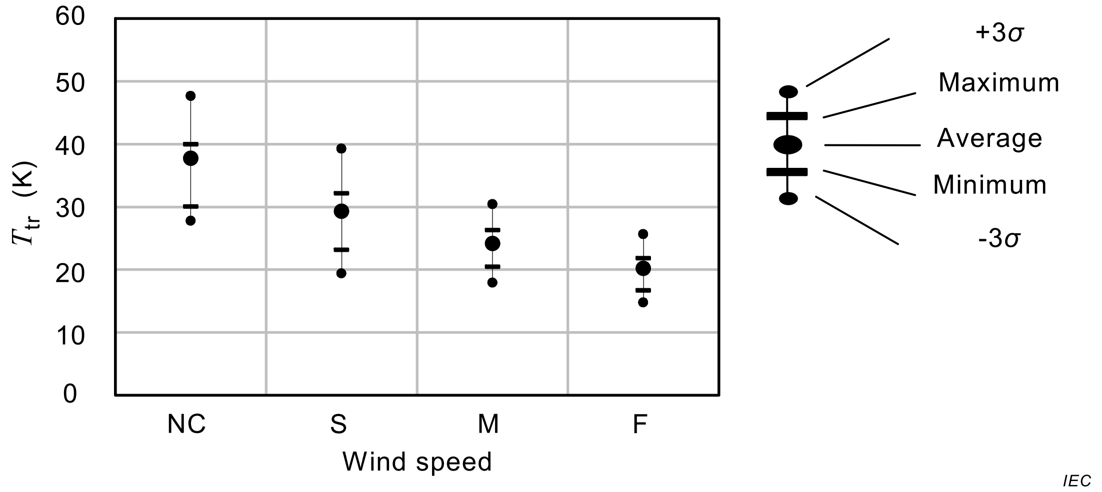
S 0,3 m/s to 0,6 m/s

M 0,7 m/s to 1,2 m/s

F 1,6 m/s to 2,4 m/s

σ Standard deviation

Figure K.5 – Relationship between the terminal part temperature rise and the wind speed for the RR3216M (orthogonal)



Key

T_{tr} Terminal part temperature rise

NC Normal convection (flat)

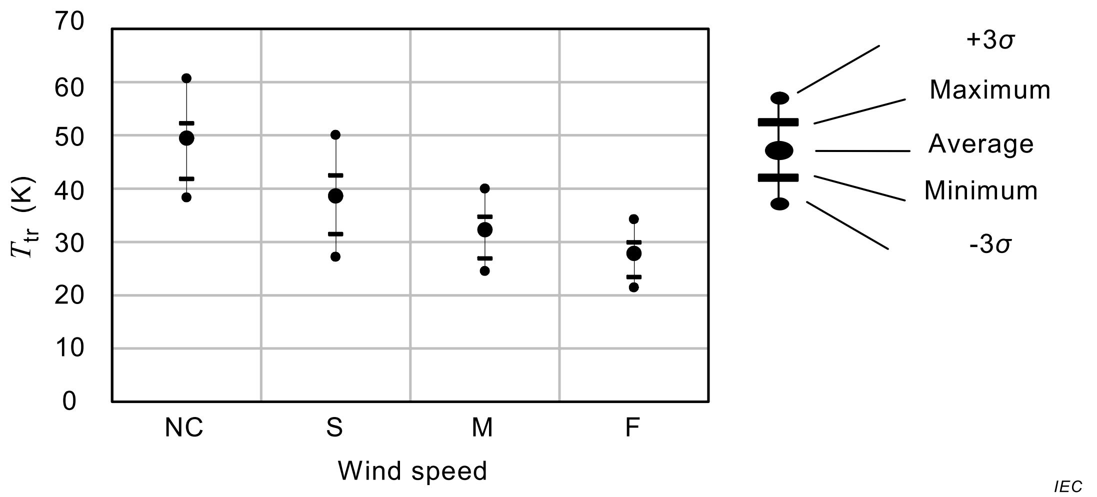
S 0,3 m/s to 0,6 m/s

M 0,7 m/s to 1,2 m/s

F 1,6 m/s to 2,4 m/s

σ Standard deviation

Figure K.6 – Relationship between the terminal part temperature rise and the wind speed for the RR2012M (orthogonal)



Key

T_{tr} Terminal part temperature rise

NC Normal convection (flat)

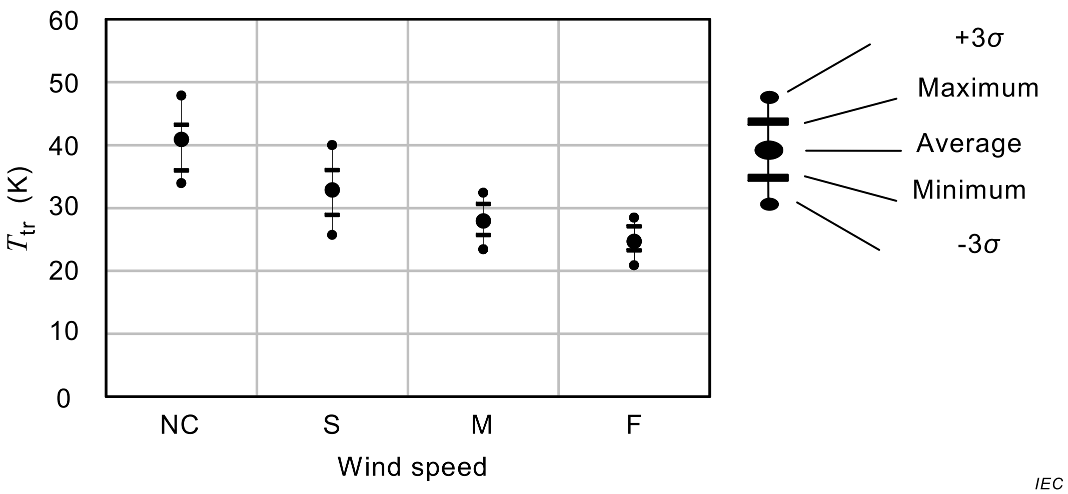
S 0,3 m/s to 0,6 m/s

M 0,7 m/s to 1,2 m/s

F 1,6 m/s to 2,4 m/s

σ Standard deviation

Figure K.7 – Relationship between the terminal part temperature rise and the wind speed for the RR1608M (orthogonal)



Key

T_{tr} Terminal part temperature rise

NC Normal convection (flat)

S 0,3 m/s to 0,6 m/s

M 0,7 m/s to 1,2 m/s

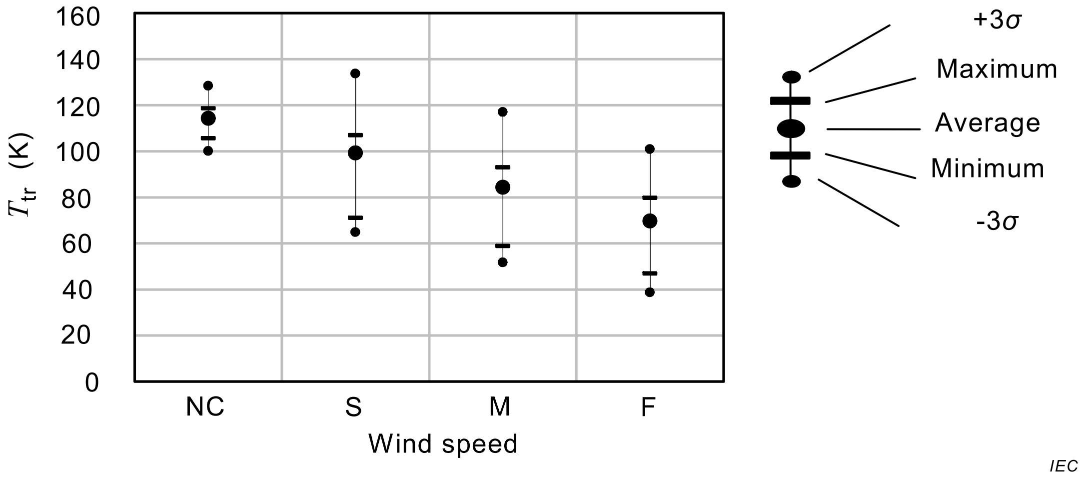
F 1,6 m/s to 2,4 m/s

σ Standard deviation

Figure K.8 – Relationship between the terminal part temperature rise and the wind speed for the RR1005M (orthogonal)

K.4 Test results (parallel)

The results are shown in Figure K.9, Figure K.10, Figure K.11, Figure K.12, Figure K.13, Figure K.14 and Figure K.15.



Key

T_{tr} Terminal part temperature rise

NC Normal convection (flat)

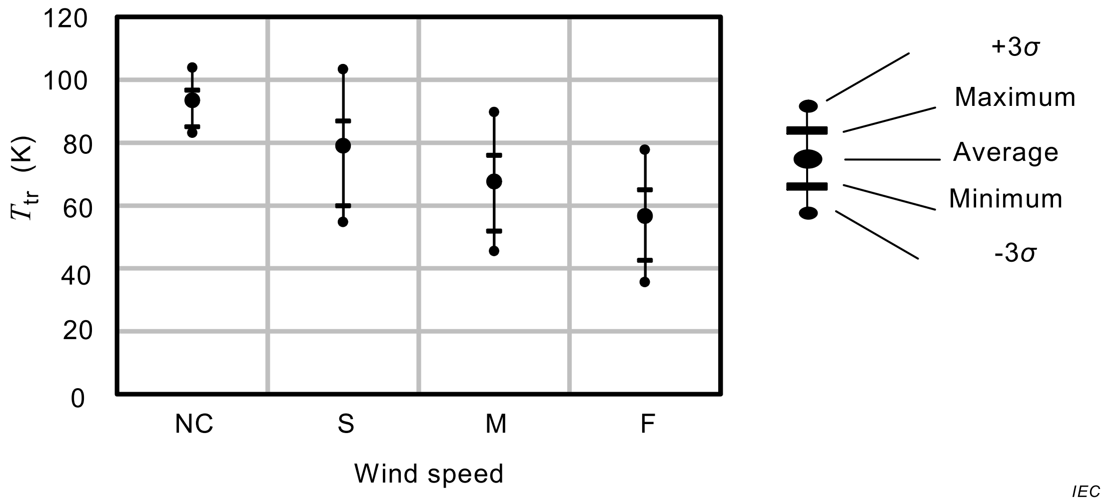
S 0,3 m/s to 0,6 m/s

M 0,7 m/s to 1,2 m/s

F 1,6 m/s to 2,4 m/s

σ Standard deviation

Figure K.9 – Relationship between the terminal part temperature rise and the wind speed for the RR6332M (parallel)



Key

T_{tr} Terminal part temperature rise

NC Normal convection (flat)

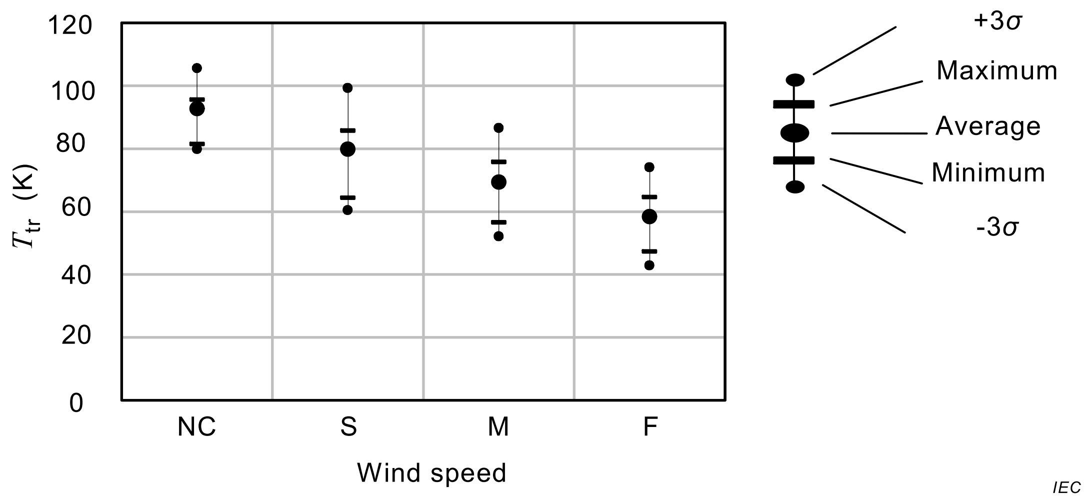
S 0,3 m/s to 0,6 m/s

M 0,7 m/s to 1,2 m/s

F 1,6 m/s to 2,4 m/s

σ Standard deviation

Figure K.10 – Relationship between the terminal part temperature rise and the wind speed for the RR5025M (parallel)



Key

T_{tr} Terminal part temperature rise

NC Normal convection (flat)

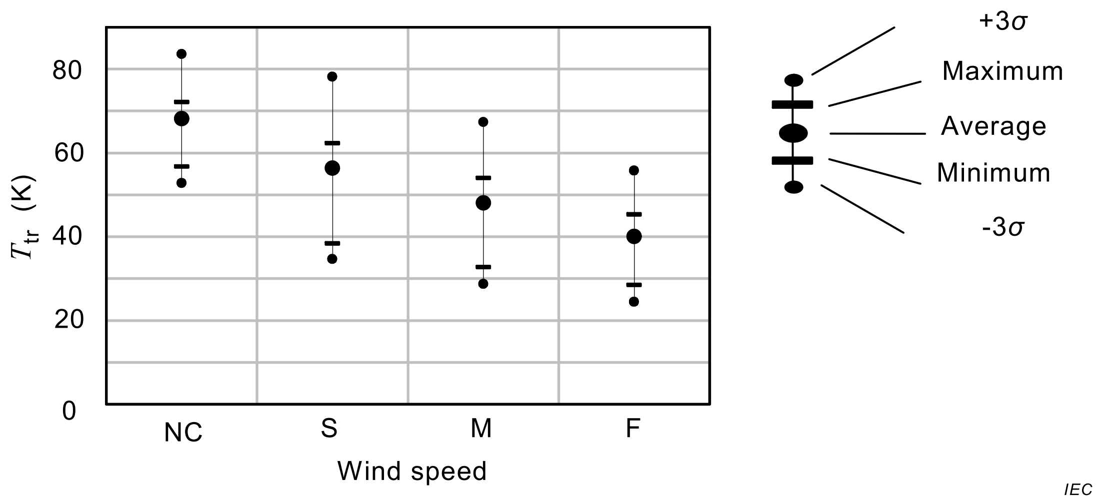
S 0,3 m/s to 0,6 m/s

M 0,7 m/s to 1,2 m/s

F 1,6 m/s to 2,4 m/s

σ Standard deviation

Figure K.11 – Relationship between the terminal part temperature rise and the wind speed for the RR3225M (parallel)



Key

T_{tr} Terminal part temperature rise

NC Normal convection (flat)

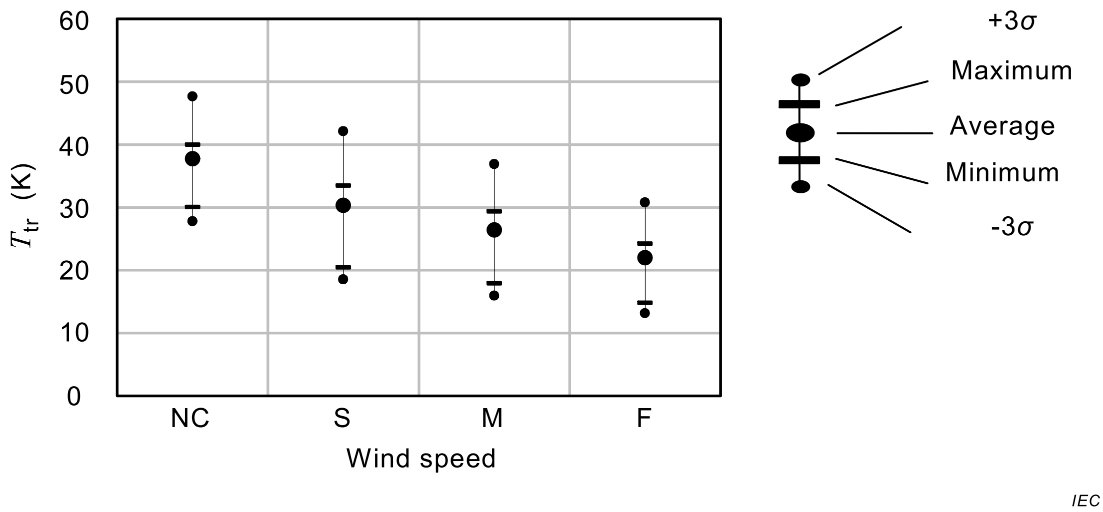
S 0,3 m/s to 0,6 m/s

M 0,7 m/s to 1,2 m/s

F 1,6 m/s to 2,4 m/s

σ Standard deviation

Figure K.12 – Relationship between the terminal part temperature rise and the wind speed for the RR3216M (parallel)



Key

T_{tr} Terminal part temperature rise

NC Normal convection (flat)

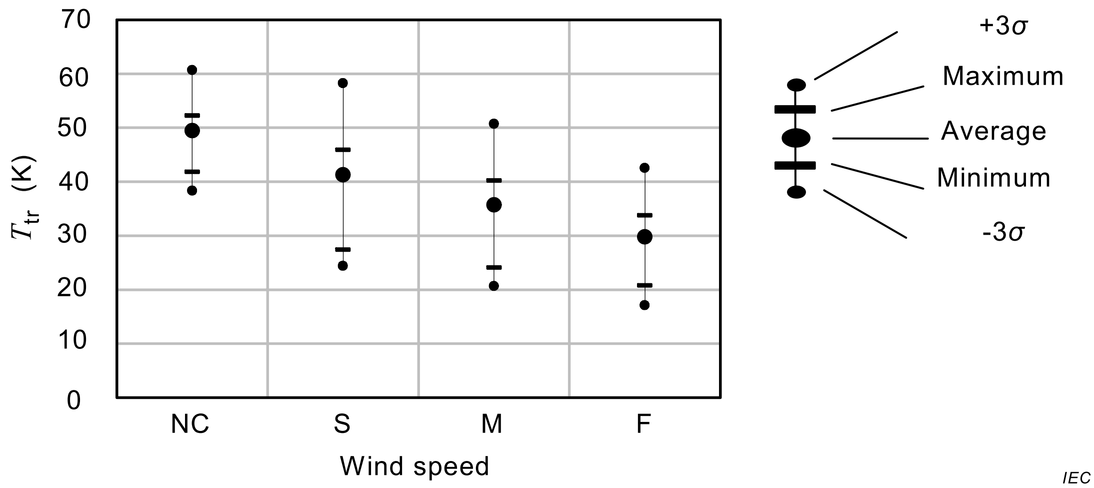
S 0,3 m/s to 0,6 m/s

M 0,7 m/s to 1,2 m/s

F 1,6 m/s to 2,4 m/s

σ Standard deviation

Figure K.13 – Relationship between the terminal part temperature rise and the wind speed for the RR2012M (parallel)



Key

T_{tr} Terminal part temperature rise

NC Normal convection (flat)

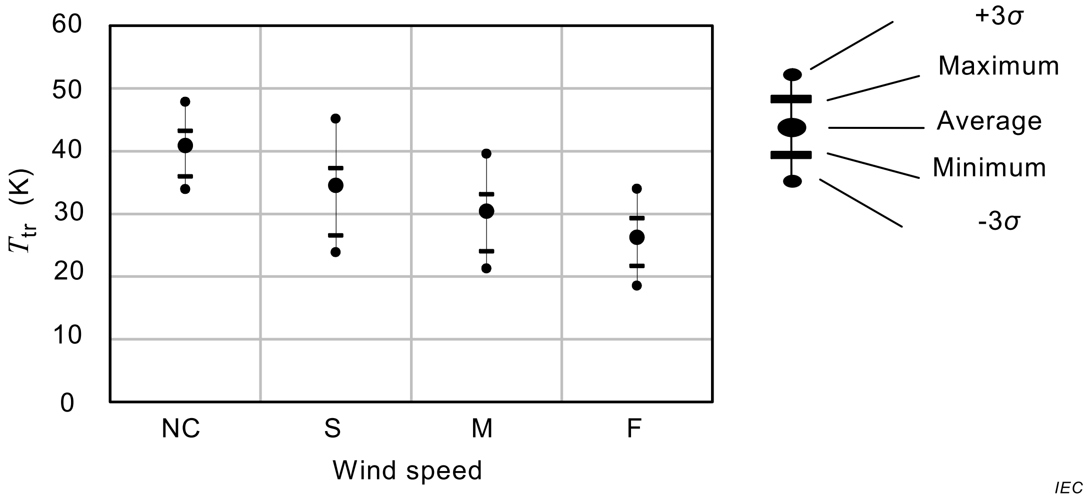
S 0,3 m/s to 0,6 m/s

M 0,7 m/s to 1,2 m/s

F 1,6 m/s to 2,4 m/s

σ Standard deviation

Figure K.14 – Relationship between the terminal part temperature rise and the wind speed for the RR1608M (parallel)



Key

T_{tr} Terminal part temperature rise

NC Normal convection (flat)

S 0,3 m/s to 0,6 m/s

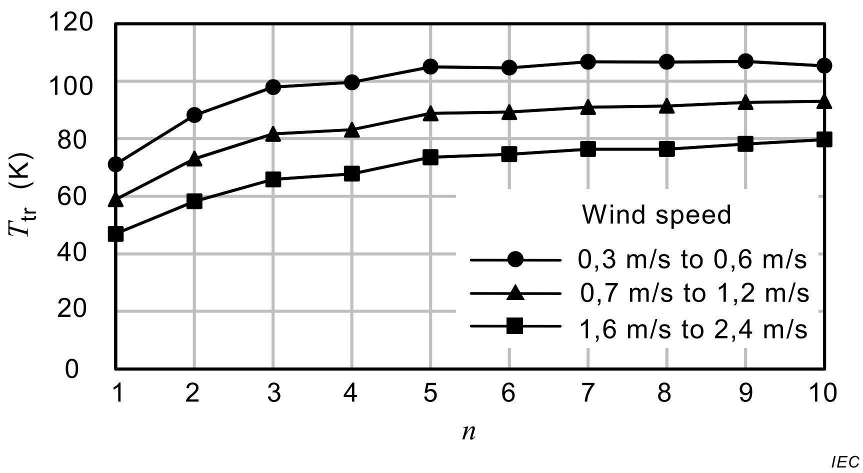
M 0,7 m/s to 1,2 m/s

F 1,6 m/s to 2,4 m/s

σ Standard deviation

Figure K.15 – Relationship between the terminal part temperature rise and the wind speed for the RR1005M (parallel)

By comparing the orthogonal and parallel airflow applied to the resistor set in a line, the resistors with large rated power (RR6332M, RR5025M and RR3225M) had large differences between their maximums and minimums. From this, it can be observed that windward resistors have lower temperature than those leeward and their heat dissipation efficiency is degraded because of the development of the thermal boundary layer on the board from the windward to the leeward sides. Figure K.16 is the temperature distribution of the RR6332M and the smaller sample numbers are positioned windward.



Key

T_{tr} Temperature rise from normal temperature

N Sample number (small numbers are windward)

Figure K.16 – Terminal part temperature rise of RR6332M, difference between the windward and leeward sides when placed parallel

Annex L
(informative)

The influence of the spatial resolution of the thermograph

L.1 The application for using the thermograph when measuring the temperature of the SMD resistor

There are two purposes for using the infrared thermograph to measure the resistor's temperature. The first purpose is to observe the board's surface directly with the thermograph and verify that the SMD resistors are used under suitable temperature at the electric/electronic designing step: without setting the printed board inside the chassis, turn it on and operate. In this case, to observe the entire printed board, the field of view needs to be widened so the area corresponding to one pixel would be limited to around a square of 200 × 200 µm. However, the aim is to ascertain the rough temperature, so accuracy is not required.

The second purpose is for the resistor manufacturer to measure the terminal part temperature and surface hotspot temperature to calculate the thermal resistance $R_{\text{th shs-t}}$ from the terminal part to the surface hotspot where the resistor becomes the hottest. The main reason for the resistor manufacturer to measure $R_{\text{th shs-t}}$ and provide it to the electric/electronic device designers is explained in Annex F. But, to serve the objectives, $R_{\text{th shs-t}}$ should be as accurate as possible.

The terminal part temperature mentioned here is the narrowly-defined terminal part temperature that was explained in Annex H. This means that it is the surface temperature of the copper block and it has a large area. So as long as the emissivity is adjusted, almost any kind of infrared thermograph can measure quite accurately. The more difficult temperature measurement would be that of the surface hotspot.

The surface hotspot of a small size SMD resistor that is around 100 µm in diameter is very common. To measure it, the standard lens of the thermograph (applicable to large targets such as buildings, but can only magnify up to a square of 200 × 200 µm as 1 pixel) should be exchanged into the fixed focus close-up magnification lens that can magnify a square of 25 × 25 µm as 1 pixel and the resolution capability will be enhanced. The point to be aware of is when the close-up magnification lens that magnifies the square of 25 × 25 µm as 1 pixel is used, a high temperature part of a square of 25 × 25 µm cannot be measured accurately. This is caused not only by the position gap of the pixel and target part, but because of many other elements such as the MTF (modulation transfer function) of the lens. Before measuring, the minimum area of the temperature peak that can be observed according to the combination of the infrared thermograph and the close-up magnification lens should be verified.

In this annex, the method of simply estimating how accurately the temperature of the microscopic area can be measured by the infrared thermograph will be suggested.

However, electric/electronic device designers generally do not use a thermograph with a high magnification close-up lens in their design process. This is because thermographs with high magnification close-up lenses have very narrow fields of view, such as a few square centimetres and, additionally, they have a very short focus. Therefore, it is impossible to measure the temperature of large areas and have uneven surfaces because of the mounted devices on the printed board, and they need to sweep and focus on each and every device.

L.2 The relation between the minimum area that the accurate temperature could be measured and the pixel magnification percentage

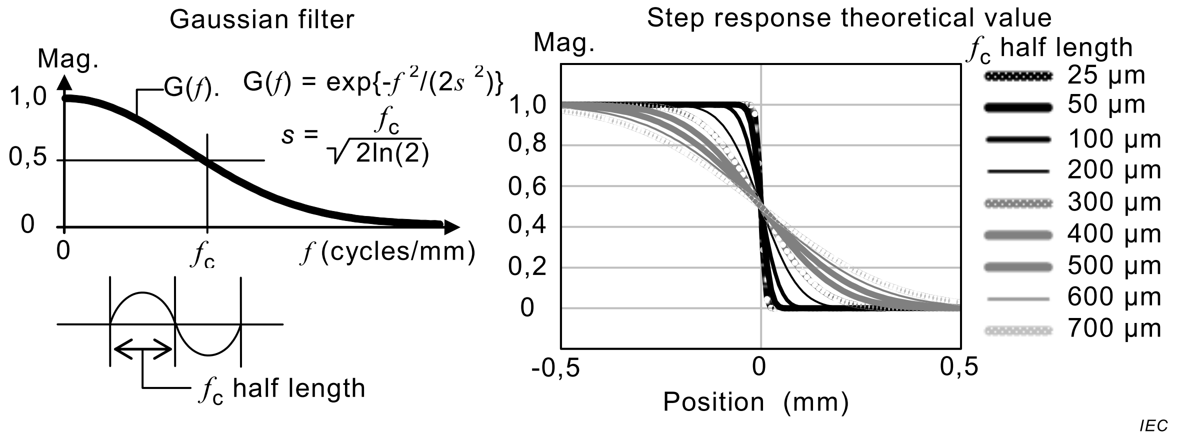
The magnification percentage of the close-up magnification lens is usually indicated as how many µm of the measured surface is shown as one pixel of the infrared light receiving element. For example, a 25-µm lens would have an optical magnification percentage that will make a square of 25 × 25 µm as 1 pixel. The standard lens can also adjust the pixel to a suitable size, so, in this subclause, the lens that can magnify a square of $A \times A$ µm as 1 pixel will be called the A-µm lens.

In this annex, the method of simply estimating how accurate the temperature of the microscopic area can be measured by using the spatial frequency characteristic of the measurement system as an index will be introduced and suggested.

[Step 1]

For the one-dimensional step temperature change shown in Figure L.1, the reply when it goes through the Gaussian filter with various cut-off spatial frequencies f_c (cycles/mm) will be calculated and made into a graph in advance. The parameter of the graph of the theoretical value of the step response is the Gaussian filter cut-off frequency f_c that is operated on the ideal step wave. However, to make it comparable with the pixel A (µm), it will be described as X (µm) of the half wavelength f_c and the explanatory note title is f_c half length. The relationship between the f_c (cycles/mm) and X (µm) is shown as the following: f_c = 1 000 / (2X).

In Figure L.1, the characteristic of the Gaussian filter which would be the parameter shown as X (µm) and would be the half wavelength of the cut-off spatial frequency.

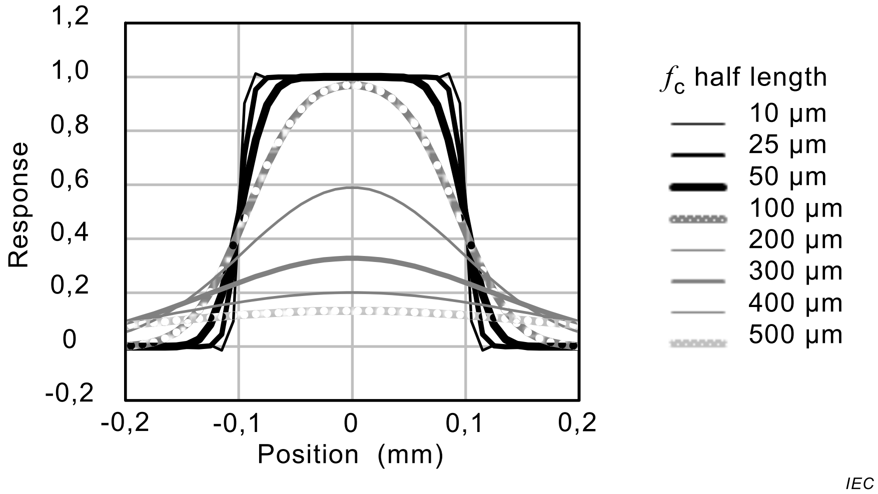


Key

Gaussian filter	Filter for transfer function G(f)
f_c	Cut-off spatial frequency
Position	Distance from the boundary of high temperature 1 and low temperature 0
Step response	Response wave form through the Gaussian filter of various f_c in the step down temperature change from the ideal 1 to 0
f_c half length	Gaussian filter cut-off spatial frequency in half wavelength X (µm)

Figure L.1 – Step response of the Gaussian filter of the various cut-off spatial frequencies (calculated)

For the material that has a part with high temperature only inside the diameter D (mm) defined beforehand, the two-dimensional reply when it goes through the Gaussian filter with various cut-off spatial frequency f_c (cycles/mm) will be calculated and made into a graph. Figure L.2 is a calculation example for 0,2 mm in diameter. This processing can be done by anyone who has the basic knowledge of the discrete Fourier transform.



Key

F_c half length Gaussian filter cut-off spatial frequency in half wavelength X (μm)

Figure L.2 – Temperature distribution (cross-section) when measuring the object that becomes high temperature only in the range of 0,2 mm in diameter

[Step 2]

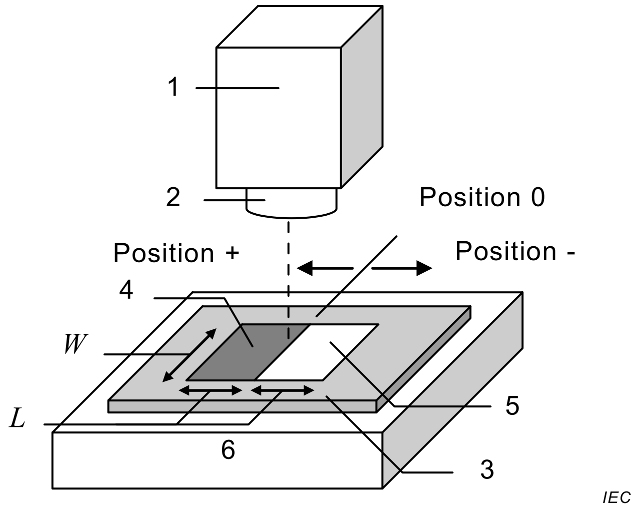
As shown in Figure L.3, attach the A (μm) lens to the thermograph and observe the temperature distribution of the boundary of the surface covered with insulators, such as the epoxy resin part and the solder mask part of the printed board, and the exposed metal part such as the pads.

The emissivity of the insulator is over 0,8 and relatively high, but the metal part is extremely low. Therefore, the step response can be measured from the temperature distribution image of the printed board of the same temperature.

When observing, the physical dimension of the exposed part of metal and the insulator part should be, when the lens is A (μm), over 10 times A in both length and breadth, and additionally the boundaries should be a clear straight line.

However, when measuring the temperature, it is preferable to set the entire printed board at more than 50 K higher than the room temperature, such as through heating with a hot plate. Even at room temperature, the temperature difference between the solder mask part and the exposed metal part can be observed because of the difference in emissivity, but, by raising the temperature, the difference becomes larger and the accuracy of the measurement of step response will improve.

This step 2 can be easily implemented by the resistor manufacturers and electric/electronic device manufacturers.



Key

1	Infrared thermograph
2	A (µm) lens
3	Printed board
4	Solder resist coating surface
5	Metal exposed surface
6	Hotplate
Position	Distance from the boundary of high and low temperature
W	Width of the observed surface, recommended to be longer than 10 times of lens magnification rate A
L	Length of observed surface, recommended to be longer than 10 times of lens magnification rate A

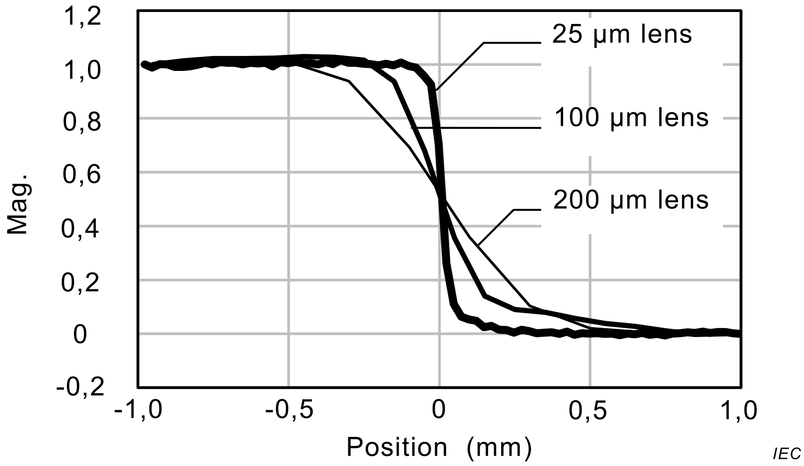
Figure L.3 – Measuring system of spatial frequency filter of the infrared thermograph

[Step 3]

Normalize the temperature difference in the vertical axis from 0 to 1 in the temperature distribution, which is actually measured in Step 2 as seen in Figure L.4, and overlap with Figure L.1. The overlapped image is shown in Figure L.5. By comparing the value actually measured and the calculated value, it would be possible to estimate the cut-off spatial frequency of the MTF of an infrared thermograph with an A-µm lens, when the MTF is a Gaussian filter. In this example, the 25-µm lens has the responsive equivalent to the pass through of the cut-off spatial frequency converted to half wavelength of a 50-µm to 100-µm Gaussian filter, and the 200-µm lens has the responsive equivalent to the pass through of the f_c half wavelength 600-µm Gaussian filter. It is omitted in this study, but it is found that the 100-µm lens has the responsive equivalent to the pass through the f_c half wavelength 300-µm Gaussian filter.

[Step 4]

If the cut-off spatial frequency of the Gaussian filter of the measurement system can be estimated, it is possible to estimate from Figure L.2 at which micro area the peak temperature can be measured accurately.

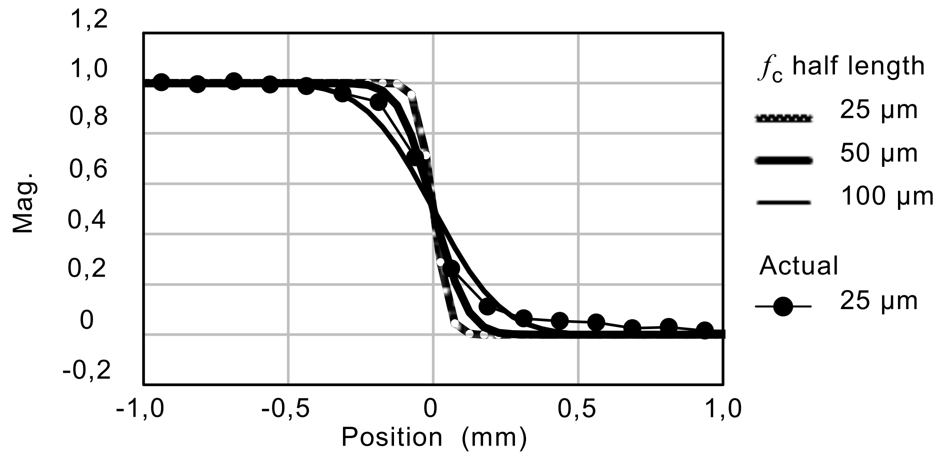


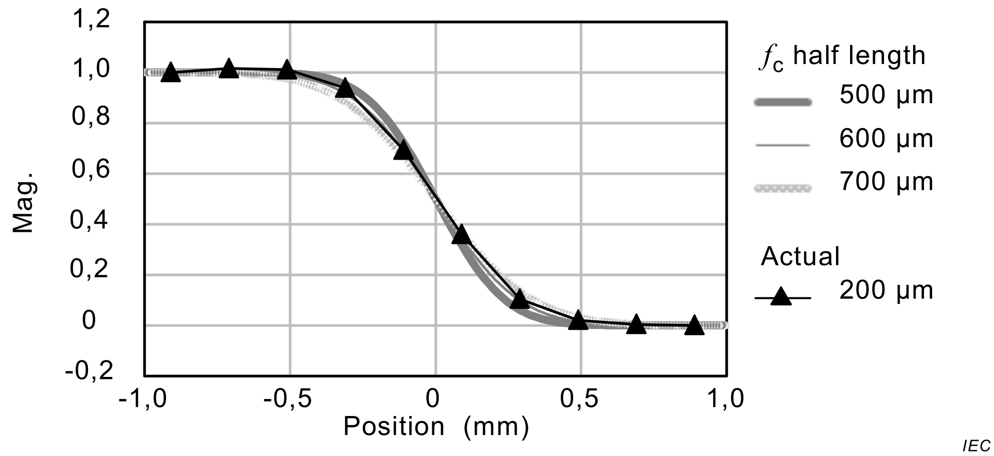
Key

Position 0 is the boundary and minus side is high temperature and plus side is low temperature

Mag. Normalize the high and low temperature by 1 to 0

Figure L.4 – Actual measured value of the step response of various magnifier lenses





Key

Position	Position < 0 is high temperature. Position > 0 is low temperature. Position = 0 is transitional regime
Mag.	Normalize the high and low temperature by 1 to 0
f_c half length	Gaussian filter cut-off spatial frequency in half wavelength shown in X μm
Actual	Actual measurement value when magnification rate A (μm) lens is used

Figure L.5 – Comparison of the actual measured value and the calculated value (step response)

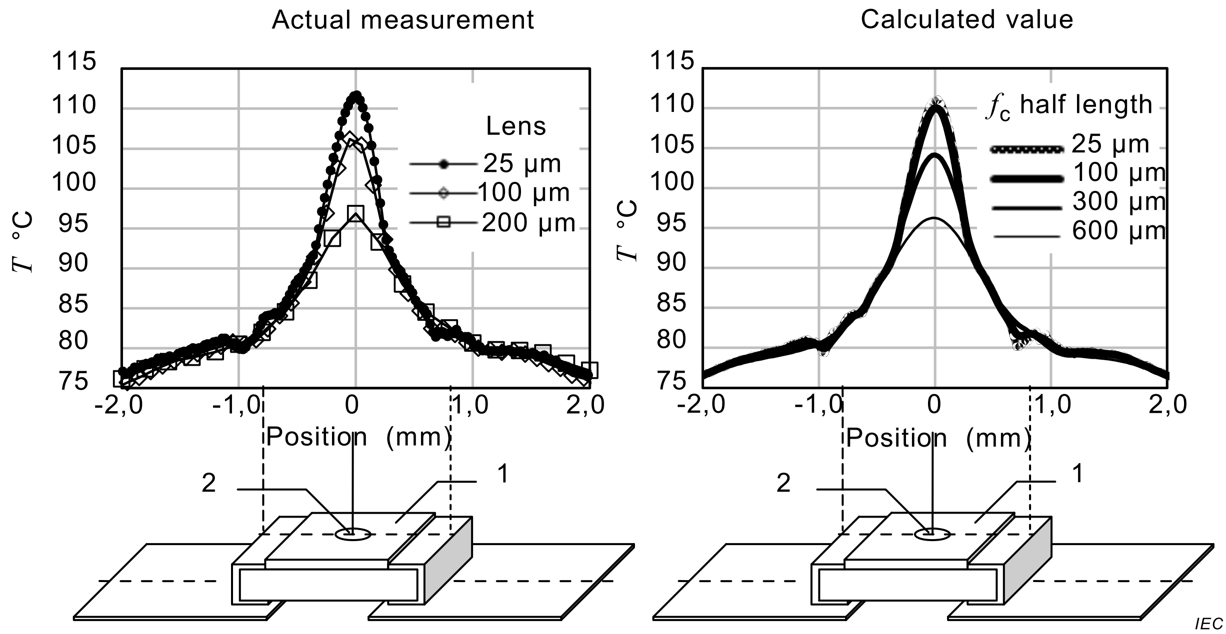
From the result of Step 3 and Figure L.2, even when it is the 25-μm lens, and the part of 0,2 mm in diameter is only the hot or cold part, measuring the peak temperature is very close to the limit. The cut-off spatial frequency half wavelength of the Gaussian filter of the 200-μm lens is 600 μm, so from Figure L.2, the measurement by the 200-μm lens may only show 10 % of the actual peak temperature.

L.3 Example of the RR1608M SMD resistor hotspot's actual measurement

Apply 0,25 W to the RR1608M thick-film rectangular chip resistor (metal-glaze resistive element) and let it self-heat. Measure the surface hotspot with the 25-μm lens, the 100-μm lens and the 200-μm lens. Suppose that the result measured by the 25-μm lens is the true value. Then compare this true value (2-dimensional temperature distribution image) with the calculated result put through the Gaussian filter with various cut-off spatial frequencies f_c.

Figure L.6 shows the result. It shows that the actual measured value of the 100-µm lens is equivalent to the f_c half wavelength 300 µm, and the 200-µm lens is equivalent to the f_c half wavelength 600 µm of the Gaussian filter. This conforms to the results in step 3.

From the results of the measurement system this time, the response when the A (µm) lens is used will be around $X = 3 \times A$ (µm) when indicated in the f_c half wavelength X of the Gaussian filter.



Key

1	Resistor
2	Surface hotspot
Position	Hotspot centre is 0 (mm) and the distance in lengthwise direction of the resistor
T	Temperature
f_c half length	Gaussian filter cut-off spatial frequency in half wave length X (µm)
Lens	Lens used

Figure L.6 – Comparison of the actual measured value and the calculated value (surface hotspot of the resistor)

L.4 Conclusion

Even when the centre of the pixel of the infrared thermograph is set on the hotspot of an A µm in diameter, the temperature cannot be measured accurately by an infrared thermograph with an A-µm lens. In this annex, the method of estimating MTF's approximate value by using the commonly-available printed boards and hotplates is shown.

The important point for resistor manufacturers is to provide the right information to electric/electronic device designers. Therefore, it is necessary for resistor manufacturers to know the surface hotspot size accurately and verify that the infrared thermograph has the sufficient performance to measure the surface hotspot temperature of that size when measuring their in-house products.

However, it is necessary for electric/electronic device designers to understand the spatial resolution and peak temperature detection capabilities of the infrared thermograph that is used to measure the resistor or the board temperature.

Annex M
(informative)

Future subjects

SMD resistors are mounted on the printed board when used, but when the temperature of the resistor substrate surface, which faces the printed board (back side) is high, the temperature of the printed board may rise from the radiation and heat conduction via the atmosphere. The limit of this temperature rise is to the temperature of the resistor substrate surface which faces the printed board (back side), but, usually, the temperature of this surface cannot be measured.

When using SMD resistors, electric/electronic device designers need to estimate the temperature rise of the printed board surface in some way and verify that the printed board can resist that temperature.

The method of estimating the temperature rise of the printed board surface underneath the SMD resistor is a future subject for resistor manufacturers.

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