IEC TR 60068-3-12

Edition 3.0 2022-10

TECHNICAL REPORT

colour inside

Environmental testing –
Part 3-12: Supporting documentation and guidance – Method to evaluate a possible lead-free solder reflow temperature profile

IEC TR 60068-3-12:2022-10(en)

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ELECTROTECHNICAL
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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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FOREWORD

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IEC TR 60068-3-12 has been prepared by IEC technical committee 91: Electronics assembly technology. It is a Technical Report.

This third edition cancels and replaces the second edition published in 2014. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) Extended purpose

Guidance is added on how to create a reflow profile considering the tolerances resulting from the accuracy of the measuring equipment, preparation method and specifications of the component manufacturers (components, PCB, solder paste, etc.).

b) Distinction from existing standards

The envelope profile given in this document does not represent a temperature-time profile for the qualification of materials but defines the reflow process limits for the soldering of electronic assemblies.

The schematic temperature-time-limit curves of the envelope profile are derived from generally valid findings (literature data). Additionally, tolerance considerations are given for all envelope points of the envelope profile.

In contrast to IEC TR 60068-3-12:2014, the creation of the envelope profile is not primarily linked to a concrete example.

c) Subclause 8.2 presents an approach for establishing a possible temperature profile for a lead-free reflow soldering process using SnAgCu solder paste that is taken from IEC TR 60068-3-12:2014.

d) Synergies with existing standards

Limit values and tolerances from standards and guidelines for the qualification of materials are included in this document and are listed as examples in the references.

The text of this Technical Report is based on the following documents:

Draft	Report on voting
91/1776/DTR	91/1804/RVDTR

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

The language used for the development of this Technical Report is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

A list of all parts in the IEC 60068 series, published under the general title *Environmental testing*, can be found on the IEC website.

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.

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INTRODUCTION

The enormous variety of materials and components processed in SMT requires to consider their thermal properties, especially in reflow soldering.

Since the second edition essentially limited its focus to lead-free soldering, there is a need to extend the contents in order to cover state of the art reflow soldering processes in general.

Reflow soldering is a joining process using an additional metal (solder) with a liquidus temperature of 450 °C or less, in which solder paste or preforms are reflowed (see ISO 857-2:2005).

Reflow soldering can be carried out with the technical processes of convection (air or nitrogen), condensation (vapour phase), radiation (e.g. infrared) or contact heat as well as with the help of low pressure (vacuum).

The goal of a qualified reflow soldering process is to create high quality and reliable solder joints at product level. It is important to avoid soldering defects and damage to components and printed circuit board.

In addition to the requirements for the formation of reliable solder joints, the specifications of the connection partners and the production requirements (temperatures, final layers, alloys, etc.), an adequate process control is an important factor. Primarily the resistance of the components and circuit boards to solder heat, as well as the specifications of the solder paste and/or flux, need to be considered. The sum of these physical limits is a theoretical temperature-time curve for a specific product (see DVS 2613).

This document is intended for engineers (e.g. development, manufacturing technology, work preparation) and operators (production) responsible for the creation and release of temperature-time (T-t) profiles for reflow soldering in surface mount technology.

This document initially was prepared by the German DKE GUK 682.2 "Thermal joining technology in electronics".

ENVIRONMENTAL TESTING –

Part 3-12: Supporting documentation and guidance – Method to evaluate a possible lead-free solder reflow temperature profile

1 Scope

This part of IEC 60068, which is a Technical Report, describes the creation of temperature-time profiles (in specific envelope profiles) for reflow soldering of electronic assemblies, considering tolerances resulting from the accuracy of the measuring equipment, preparation method and specifications of the manufacturers of components, circuit boards, solder paste, etc.).

The envelope profile given in this document does not represent a temperature-time profile for qualification but defines the reflow process window for the soldering of electronic assemblies. Qualification profiles can be found, for example, in IEC 60068-2-58 for resistance to soldering heat, or in IEC 60749-20, IEC 61760-4 and IPC/JEDEC J-STD-020E for moisture sensitivity classification of components.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

No terms and definitions are listed in this document.

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

4 Determination of an envelope reflow profile

4.1 Temperature-time-envelope curve

According to IEC 61191-1:2018, 8.2.2, manufacturers of electronic assemblies need to determine the parameters of a soldering process as follows:

> *"The process shall include, as a minimum, a reproducible time/temperature envelope including the drying/degassing operation (when required), preheating operation (when required), solder reflow operation, and a cooling operation."*

The necessary envelope points for the creation of a temperature-time-envelope curve result from the respective minima and maxima of the data for the solder heat resistance of the components and PCBs, their minimum solderability temperatures, as well as from the specifications of the solder paste and/or flux. The cycle time (time per electronic assembly) and the process time (T_0 to T_3 end) influence each other.

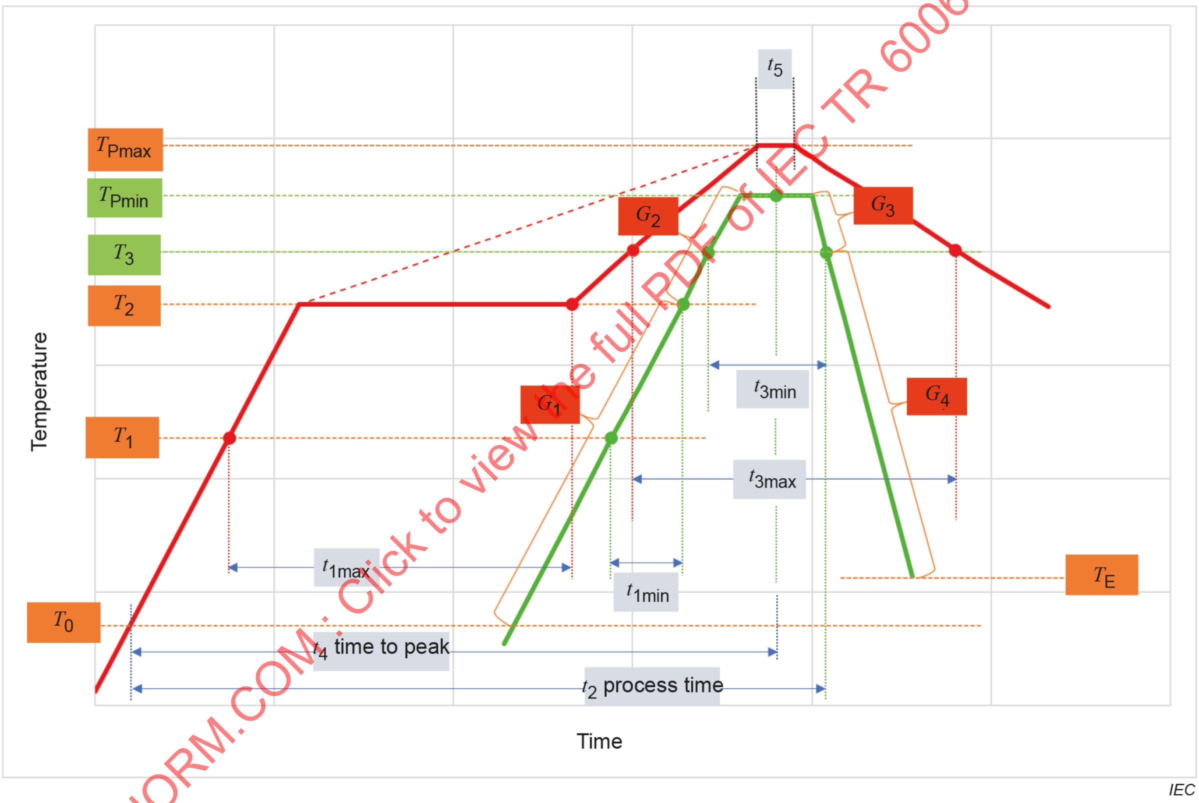
The temperature-time curve is described by the units in Table 1.

Table 1 – Temperature-time curve – Units

Physical quantity	Symbol	Units	Remark
Temperature	T	°C or K	ΔT, Temperature differences in kelvin (K) 1 K = 1 °C 0 °C = 273,15 K
Time	t	s or min	
Gradient	G	K/s	$\Delta T/\Delta t$

4.2 Diagram of a theoretical envelope reflow profile

Figure 1 shows the maximum (upper line in red) and minimum (bottom line in green) theoretical temperature-time curves for a reflow soldering process with all envelope points defining these two curves. The reflow soldering profile measured in each case is expected to be located within the boundaries of the envelope profile, as shown in Figure 1.



NOTE The calculation of gradients is described in 5.3.

Figure 1 – Schematic envelope reflow profile

4.3 Key parameters of the envelope reflow profile

Table 1 describes the main requirements for setting the envelope points for defining the upper and lower limits of an envelope reflow profile.

The envelope points take into account material-specific data, in particular the resistance to soldering heat, as well as findings for the reliable formation of the solder joints (alloy properties, microstructure formation, etc.). Therefore, there are, for example, temperature-time curves which are measured on the components (soldering heat resistance) and temperature-time curves which are measured on or in the solder joint (soldering). In addition, the manufacturing expectations regarding the cycle time of the individual product need to be taken into account.

The "Tolerance" column in Table 2 needs to be completed by the manufacturer of the electronic assemblies. The measurement errors are treated as "inset" limits, which means that the estimated measurement error (e.g. 5 K for the temperature measurement chain) is subtracted from the upper limit values, and added to the lower limit values. This is to ensure that the limit values cannot be exceeded.

In the "Comment" column in Table 2, corresponding notes are given for each parameter.

Table 2 – Envelope points of a reflow temperature-time-profile

Envelope point	Explanation	Typical value	Tolerance	Comment
***T*, temperature (y-axis)**				
T_0	Start temperature	T_0 > room temperature Typical: 50 °C		Reference temperature to determine the reflow profile. Temperature is significantly above room temperature – consider the production needs. Temperature at which the recording begins.
T_1	Lower preheating temperature		+5 K	Consider solder paste recommendations and needs of PCB-Assembly. IEC 61760-1:2020, 6.2.2 IPC/JEDEC J-STD-020E: $\mathrm{T}_{\mathrm{smin}}$ (s = soak)
T_2	Upper preheating temperature		−5 K	Consider solder paste recommendations and needs of PCB-Assembly. IEC 61760-1:2020, 6.2.2 IPC/JEDEC J-STD-020E: $\mathrm{T}_{\mathrm{smax}}$ (s = soak)
T_3	Liquidus temperature			Note the difference between solidus and liquidus temperature. The solder alloy is completely fluid (liquidus temperature). Consider solder paste recommendations. IEC 61760-1:2020, 6.2.2 IPC/JEDEC J-STD-020E): T_{L} (T_{L} = liquidus temperature
T_{Pmax}	Maximum peak temperature	T_{P} is below the classification temperature T_{C} (i.e. the max. soldering temperature T_4 of the component) $T_{\mathrm{pmax}} = T_{\mathrm{C}} - 5$ K		The maximum peak temperature is either the maximum allowed temperature at the termination (e.g. dissolution of metallization) or the maximum temperature measured on the package top side (e.g. moisture/reflow sensitivity of non-hermetic components). IEC 61760-1:2020, 6.2.2: T_4 IEC 60068-2-58:2015, 7.6.4.4: T_4 IPC/JEDEC J-STD-020E: T_{P} Consider: $T_{\mathrm{P}} = T_{\mathrm{C}} - 5\mathrm{K}$, T_{C}: classification temperature IPC TM 650 2.6.27A
T_{pmin}	Minimum peak temperature	T_3 + 15 K		The minimum peak temperature is normally the temperature at the termination of the component (solder joint). Reaching the minimum peak temperature enables the solderability. IEC 60068-2-58:2015, 6.6.5 IPC-7093, IPC-7095, IPC/JEDEC J-STD-020E $T_{\mathrm{pmin}} = (T_3 + 15\ \mathrm{K})$

Envelope point	Explanation	Typical value	Tolerance	Comment
T_E	End temperature			Reference temperature to determine the end of the reflow profile. Temperature is significantly below the solidus temperature. Consider the production needs. Temperature at which the calculation ends.
***t*, time (x-axis)**				
t_{1min}	Min. preheating time			Minimum time between T_1 and T_2 Consider that t_1 is part of the time to peak. Consider solder paste and component recommendations. IEC 61760-1:2020, 6.2.2
t_{1max}	Max. preheating time			Maximum time between T_1 and T_2 Consider that t_1 is part of the time to peak. Consider solder paste and component recommendations. IEC 61760-1:2020, 6.2.2
t_2	Process time from T_0 to T_3 (end of peak)			
t_{3min}	Min. time above liquidus temperature	Typical: ≥ 30 s		Time above T_3 Consider the solder alloy recommendations. t_2 in IEC 61760-1 and IEC 60068-2-58 t_L in IPC/JEDEC J-STD-020E Additional reference: DVS 2613
t_{3max}	Max. time above liquidus temperature	Typical: ≤ 90 s		Time above T_3 Consider the component recommendation. Additional reference: DVS 2613
t_4	Time to peak Process time from T_0 to T_P			Time between T_0 and T_P Consider the solder paste recommendation and component specification. t_4 in IEC 61760-1 and IEC 60068-2-58
t_5	Time on peak	Corresponding to the component specification (T_C)		Consider the component specification. The heat resistance of components limits t_5 . IPC/JEDEC J-STD-020E, Time (t_p)* within 5 K of the specified classification temperature (T_C) t_3 in IEC 61760-1 and IEC 60068-2-58
***G*, gradient $\Delta T/\Delta t$**				Ramp rate See the instructions of the component and material suppliers.
G_1	Max. heating gradient to T_2, preheating		−0,5 K/s	Consider the solder paste and component recommendation IEC 61760-1:2020, 6.2.2
G_2	Max. heating gradient from T_2 to T_4		−0,5 K/s	Consider the component recommendation IEC 61760-1:2020, 6.2.2, IPC/JEDEC J-STD-020E Max ramp-up rate (3 K/s)

Envelope point	Explanation	Typical value	Tolerance	Comment
G_3	Max. cooling gradient from T_4 to T_3		+0,5 K/s	The cooling gradient is negative therefore the tolerance is positive. Consider the component recommendation. IEC 61760-1:2020, 6.2.2, IPC/JEDEC J-STD-020E Max. ramp-down rate (−6 K/s)
G_4	Max. cooling gradient from T_3 to T_E		+1 K/s	The cooling gradient is negative therefore the tolerance is positive. Consider the component recommendation for cooling. The cooling gradient below liquidus temperature is not separately specified in IPC/JEDEC J-STD-020E and IEC 60068-2-58.

5 Temperature profile measurements

5.1 Determining the measurement locations

The temperature-time profile is measured product-specific on a real assembly (electronic assembly).

Figure 2 shows a schematic view of important measurement locations.

The following items are essential for the determination of the measurement locations.

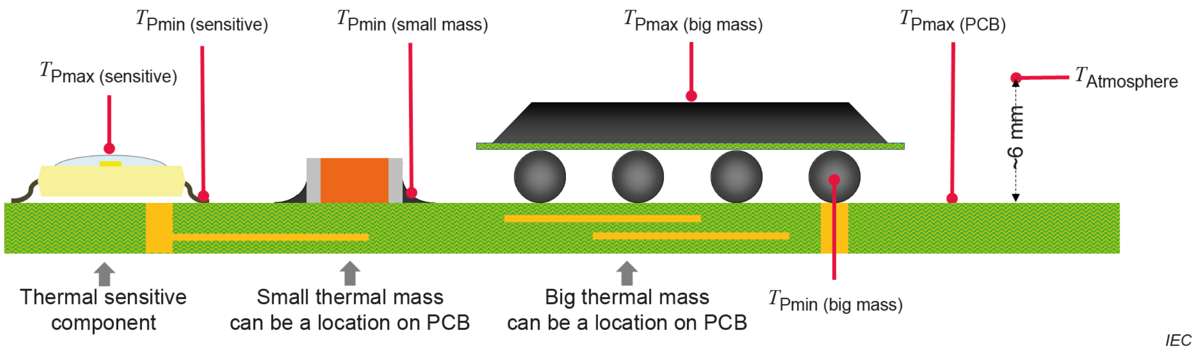
- Position of the large and small thermal mass.

  NOTE Here not only components are in focus, but also the areas on the test board with the largest and smallest thermal demands.
- Materials or components with critical solder heat resistance (e.g. electrolytic capacitors, optical components, sensors).
- The PCB material.
- Distinction between the solder joint and the position at the top of the package, which essentially describes the solder heat resistance.
- Thermocouples can be required on both sides of the measurement assembly, especially if the reflow soldering machine is equipped with top and bottom side heating.
- By means of the atmospheric temperature, information about the thermal interaction between the measuring assembly and the reflow soldering machine can be collected. However, it is not absolutely necessary for product profiling.
- Measuring points are limited to an essential number.
- The available channels of the data logger need to be considered.
- When contacting the thermocouples, the added thermal mass at the measurement location is minimized. This is especially important when testing small components.

Generally, the temperature drops near the transport chains, especially when measuring close to the CBS (centre board support).

PCB areas without components show the highest temperatures. This also applies for measurements on the package top side of the highest components.

To determine the position of the large and small thermal masses on the test board, a thermal imaging camera can be helpful. For this purpose, the test board is warmed up to a uniform temperature, e.g. 150 °C, by a heat chamber, and then the cooling behaviour of the board is observed. A large thermal mass will cool down more slowly than a small thermal mass.



Key

$T_{\text{Pmin (sensitive)}}$	temperature on solder joint on sensitive component
$T_{\text{Pmax (sensitive)}}$	temperature on the package top side
$T_{\text{Pmin (small mass)}}$	temperature on solder joint on smallest thermal mass
$T_{\text{Pmin (big mass)}}$	temperature on solder joint on biggest thermal mass
$T_{\text{Pmax (big mass)}}$	temperature on the package top side
$T_{\text{Pmax (PCB)}}$	maximum temperature on PCB surface
$T_{\text{Atmosphere}}$	temperature approximately 6 mm above PCB surface

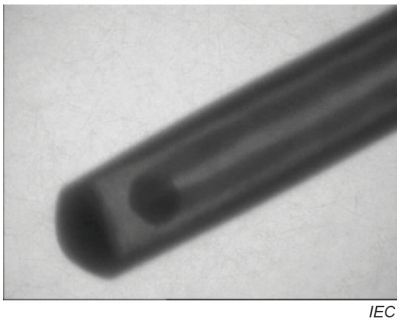
Figure 2 – Recommended temperature measurement locations on a test board

5.2 Selection and attachment of thermocouples

5.2.1 Types of thermocouples

For reflow measurement applications NiCrNi K-type thermocouples are typically used, with a limiting error of 1,5 K (see IEC 60584-1:2013, Table 12).

The use of sheath thermocouples can be a reasonable alternative to non-mantled types, which visibly consist of only one wire and are therefore much easier to apply (Figure 3). Since the components and their solder joints are becoming smaller and smaller, the thinnest possible wire diameters are preferred (e.g. sheath thermocouples ø0,25 mm), which also have shorter response times. The temperature resistance of the insulation material and connector material (often recognizable by the colour or colour coding), which needs to withstand multiple reflow passes in the soldering system, is also important, as well as sufficient strain relief. A clear labelling of the measurement location and of the thermocouple connector is of advantage.



SOURCE: Trainalytics GmbH, Lippstadt 2019. Reproduced with permission.

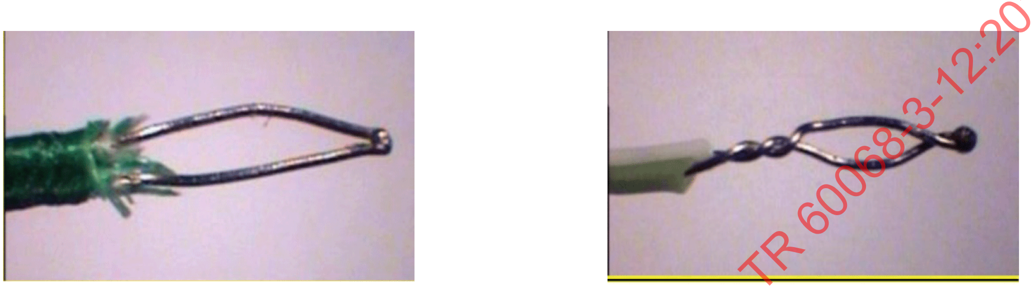
Figure 3 – X-ray of a sheath thermocouple

It is important that the size of the thermocouple (wire diameter, etc.) corresponds to the measurement location and that the thermocouple itself does not significantly distort the thermal mass at the measurement location (Figure 4).

5.2.2 Preparation of thermocouples

Prior to installation, the thermocouples need to be checked thoroughly to avoid damage during installation. For more information, see IPC-7801, Section 7.

It is important that the two exposed thermocouple wires do not touch each other up to the point of connection (weld). Twisting of the thermocouple wires would shift the measurement location and falsify the measurement results (Figure 4).



a) Good example **b) Rejectable because of twisted wires**

SOURCE: ERSA GmbH, Wertheim 2019. Reproduced with permission.

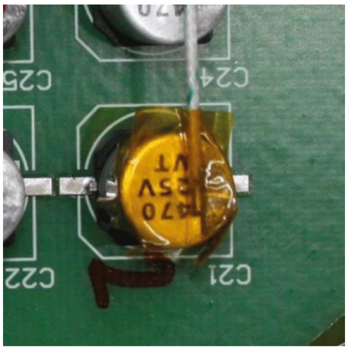
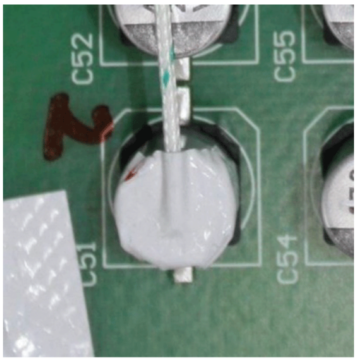
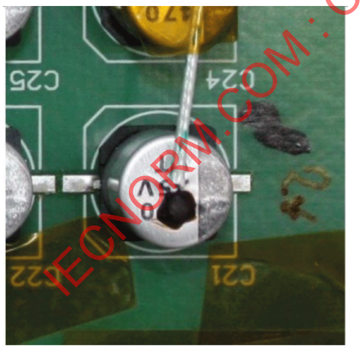
Figure 4 – Example of a) acceptable and b) unacceptable attachment of the thermocouples

5.2.3 Attachment of thermocouples

Both, DVS 2613, 3.3 Preparation and IPC-7801, 7.5 contain valuable information on fixing the thermocouples on the measuring assembly. Table 3 summarizes the main preparation methods with their advantages and disadvantages.

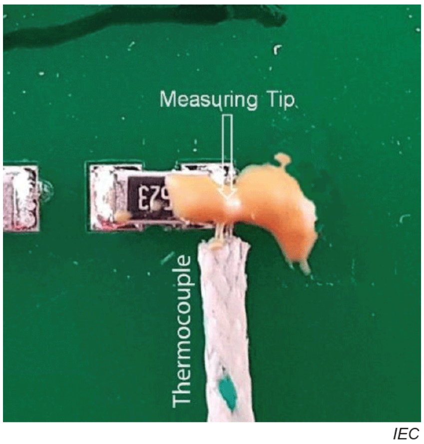
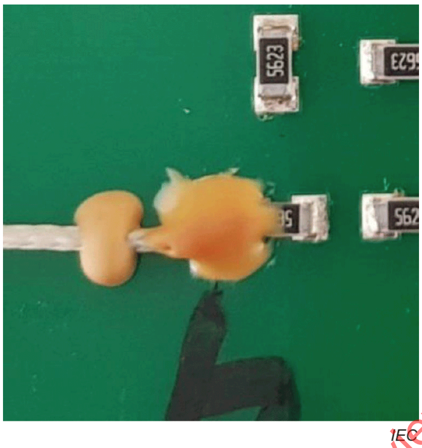
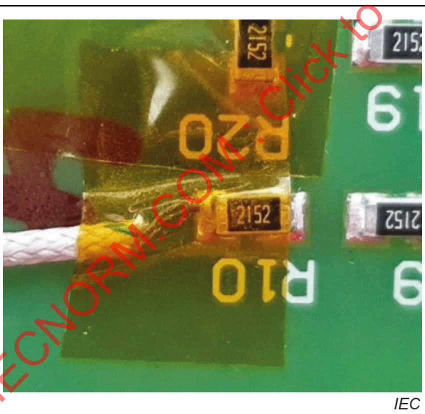
When using adhesives for thermocouple attachment, the thermal energy will most likely be conducted at least partially through the adhesive. The adhesive needs to be therefore thermally conductive itself so as not to falsify the measurement result, IPC-7530A. A minimum value of 0,4 W/mK is stated by the IPC-CA-82.

Table 3 – Thermocouple attachment methods

Preparation method	Advantages	Disadvantages
Polyimide tape  IEC	Fast preparation Multiple use of the thermocouples possible	Weak fixing, thermocouple usually holds only one reflow pass Big measurement errors to be expected
Aluminium tape  IEC	Fast preparation High adhesive force, therefore, several reflow passes possible Multiple use of the thermocouples possible Good measurement results to be expected	Expensive The thermal mass is additionally increased (especially for small components)
Thermal conductive paste	Good measurement results to be expected	Preparation requires practice and skill, thermocouples require additional fixing (e.g. wire) Paste not always available, and expensive
SMD adhesive  IEC	Good measurement results to be expected SMD adhesives mostly available High adhesive strength, therefore several reflow passes possible	Multiple use of the thermocouples hardly possible Too much adhesive falsifies the measuring results Preparation requires practice and skill
Soldering with high-temperature solder	Good measurement results to be expected Mechanically stable, therefore several reflow passes possible	Multiple use of the thermocouples hardly possible Preparation requires practice and skill High-temperature solder is not always available, and solderable surfaces are also required, which is hardly possible with thermocouples.

[SOURCE: Rehm, Thermal Systems GmbH, Blaubeuren 2019. Reproduced with permission.]

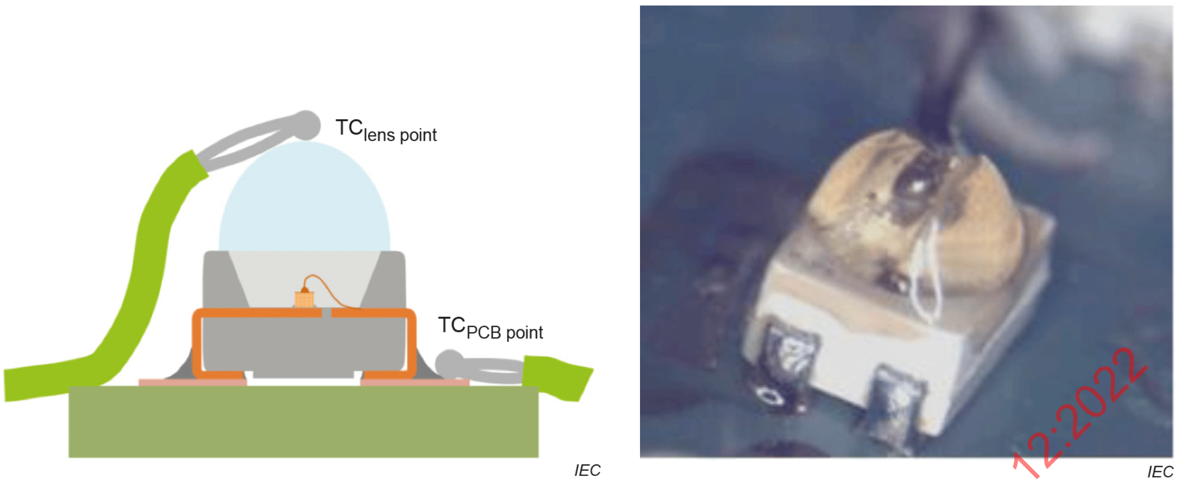
Figure 5 shows good and bad examples of how to fix thermocouples to the board with SMD adhesive and polyimide tape.

	Good example Because: 1) Thermocouple is in contact with measurement location 2) Thermocouple is at 90° to component axis on measurement location 3) acceptable amount of adhesive
	Bad example Because: 1) Excesive SMD adhesive 2) Thermocouple is attached in the axial component (or lead) direction on measurement location
	Bad example Because: 1) Thermocouple is not in contact with measurement location. 2) Thermocouple is attached in the axial component (or lead) direction on measurement point. 3) Twisted wires, see Figure 4. 4) Polyimide tape does not fit properly: too much space between the tape, thermocouple and PCB.

SOURCE: Rehm, Thermal Systems GmbH, Blaubeuren 2019. Reproduced with permission.

Figure 5 – Examples of good and bad thermocouple attachment

To fix thermocouples to LEDs demands special care. LED manufacturers provide important information on this in their LED specifications and accompanying documents. An example is shown in Figure 6.

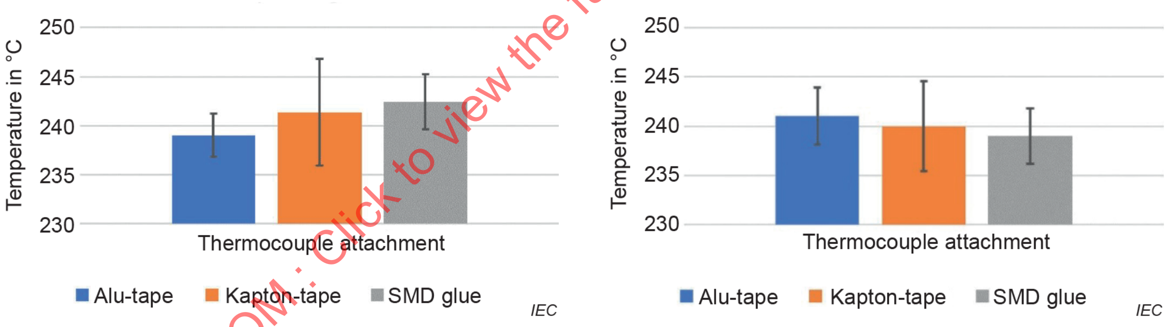


SOURCE: OSRAM, Measuring of the Temperature Profile during the Reflow Solder Process, Application Note, 2013. Reproduced with permission.

Figure 6 – Thermocouples (TC) fixed to an LED

5.2.4 Influence of attachment method and operator on measurement results

Figure 7 shows the results of field measurements of the same test board prepared by different persons with the respective methods.



a) measurement location on the package top side

b) solder joint of an electrolytic capacitor

Shown are mean values and standard deviations.

Samples were prepared by more than 100 persons.

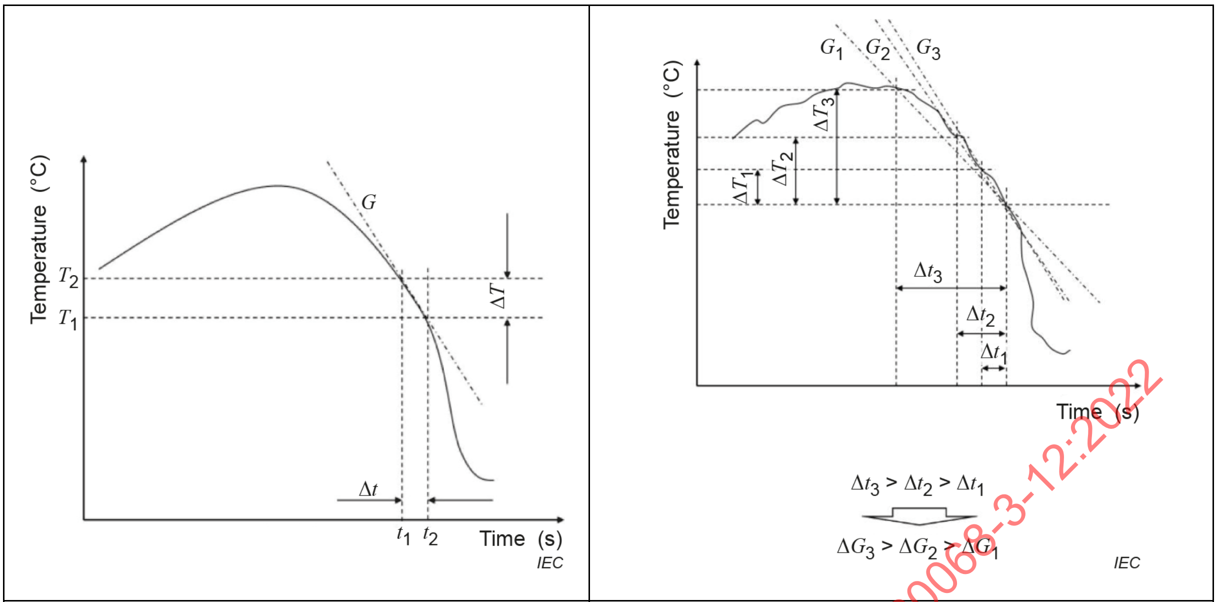
SOURCE: Rehm, Thermal Systems GmbH, Blaubeuren 2019. Reproduced with permission.

Figure 7 – Results of the same test board prepared by different methods

5.3 Temperature gradient

5.3.1 Gradient calculation

The principle of gradient calculation is shown in Figure 8.



The gradient G is the slope $\Delta T/\Delta t$ of the line through points (t_1, T_1) and (t_2, T_2)

The gradient changes with the change of the time interval Δt.

NOTE The time interval Δt can usually be set in the software of the data loggers used.

SOURCE: OSRAM, Measuring of the Temperature Profile during the Reflow Solder Process, Application Note, 2013. Reproduced with permission.

Figure 8 – Gradient calculation

Figure 9 shows an example of how the calculated gradient of a cooling curve changes when the time interval Δt is changed from 5 s to 10 s or 20 s. The maximum gradient of this curve is calculated for the point (339 s, 150 °C) and an interval length of 5 s. The calculations with the longer interval lengths result in flatter gradients of 5,7 K/s and 4,1 K/s.

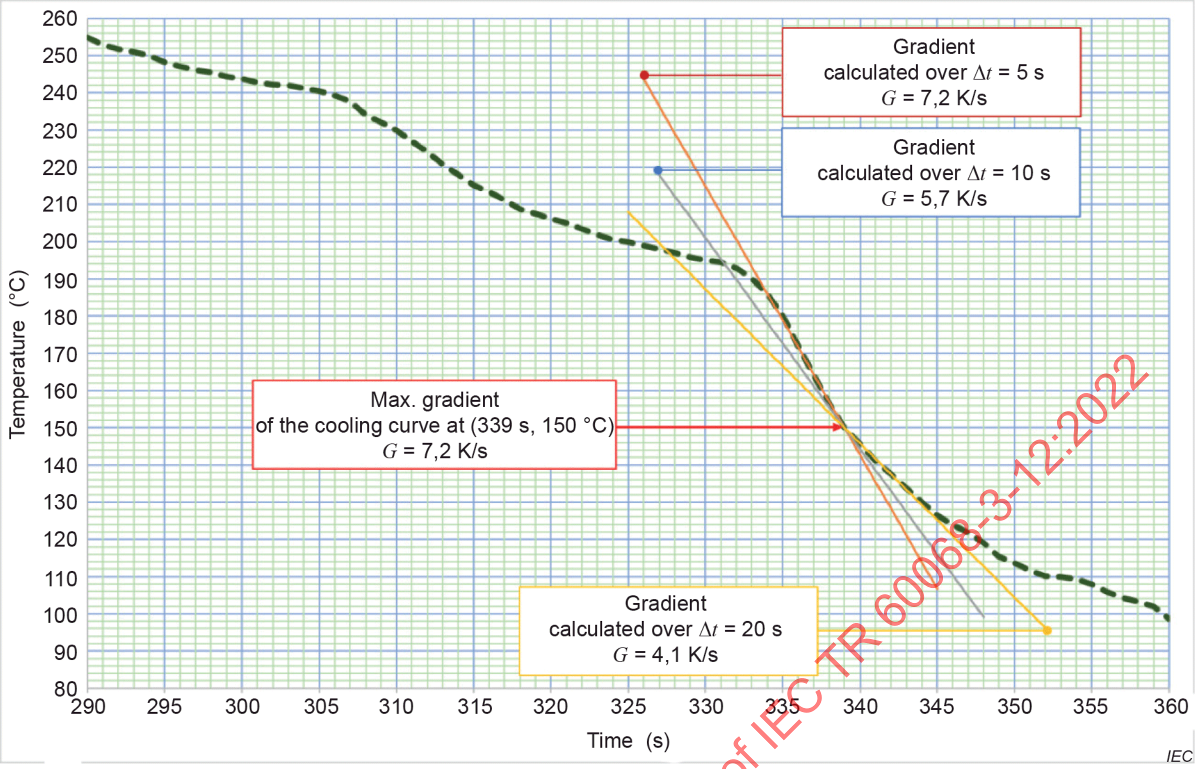


Figure 9 – Example of a gradient calculation on a temperature-time curve

5.3.2 Sampling rate

Electronic data loggers offer the possibility to set the sampling rate (measuring clock, measuring frequency, sampling interval) and the interval length. Changing these settings has consequences for the calculation of the gradient, as already shown in Figure 9.

By means of a correlation analysis it could be proven that an interval length Δt of 10 s is best suitable. 5 s is the lower reasonable limit. For an interval length of 5 s, a sampling rate of 0,1 s is best suitable. For an interval length of 10 s, an increase of the sampling rate from 0,1 s to 0,2 s is not critical. A sampling rate greater than 0,2 s is not advisable.

Conclusion: Interval length 10 s, sampling rate 0,1 s had best results.

This conclusion is based on the following assumptions.

- There is a proper fixing of the thermocouples. Otherwise, the measurement results would be close to an "air measurement".
- Systematic measurement errors, which are always present with thermocouples, are irrelevant in gradient determination and are not included here.
- There are no random measuring errors at the measuring device (data logger).
- Fluctuations of the reflow soldering system and/or heat transfer within the measuring interval remain unconsidered.

5.4 Analysis, comparison and overlay of different reflow profiles and best practice

The following examples demonstrate best practice when different reflow profiles need to be analysed.

If the starting point for all profiles is at a fixed point like the reflow oven entry, it is hard to compare the main profile features (see Figure 10).

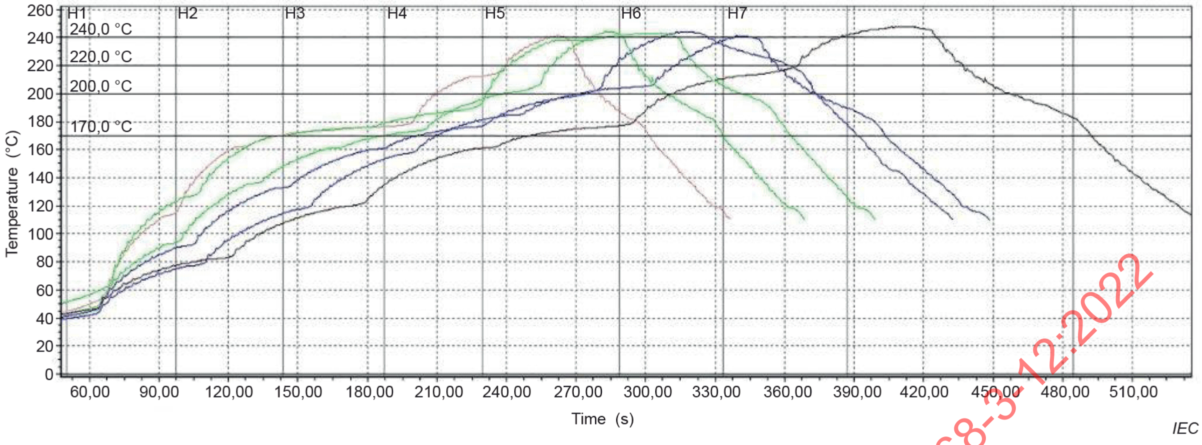


Figure 10 – Overlay of different reflow profiles (origin at oven entry)

When evaluating temperature-time profiles of several measurement location points of an electronic assembly, it is helpful for comparison to align these profiles according to their maximum temperature.

The different profile curves need to be shifted on the time axis to create an overlay in the peak temperature zones as shown in Figure 11.

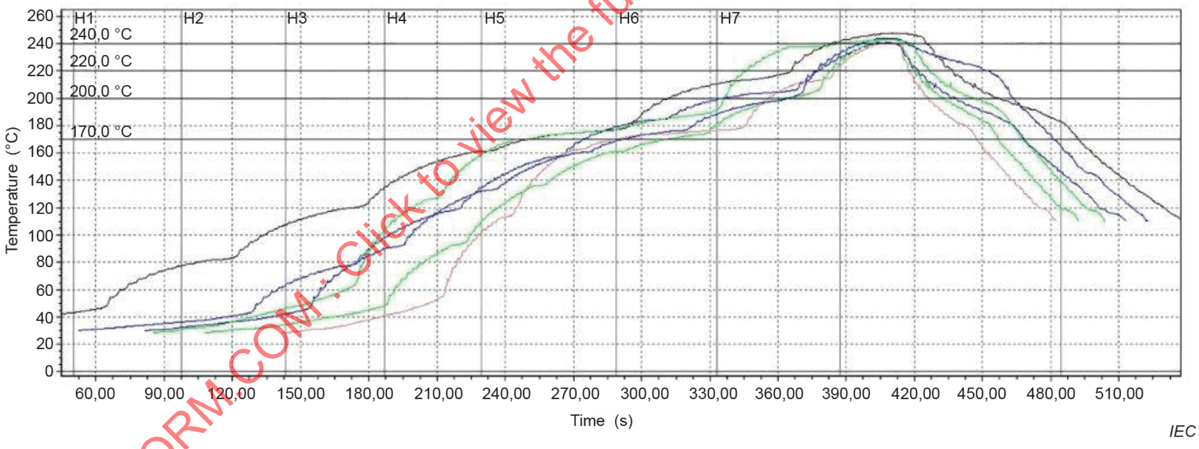


Figure 11 – Overlay of different reflow profiles (overlap at start of peak zone)

In this case it can be confirmed whether all temperature-time curves of the respective measurement locations are located within the defined envelope profile.

5.5 Measuring equipment

Requirements for thermocouples, data logger and accessories are described in IPC-7801.

6 Tolerance analysis of the measurement chain

The selected thermocouples create a continuous measurement chain with the data logger. A calibrated data logger is a pre-requisite. The requirements for the data logger are described in IPC-7801, Section 6, which requires an accuracy of the measuring equipment after calibration of ±2 K.

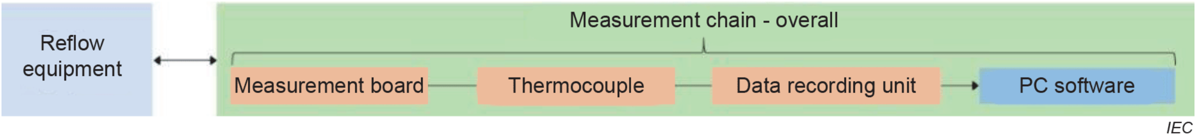


Figure 12 – Measurement chain

The entire measurement chain shown in Figure 12 is influenced by the following factors:

- the control behaviour of the reflow soldering system, which is a process fluctuation and cannot be influenced by the user. Strictly speaking, it is not part of the characterization of the measurement chain; however, it does result in fluctuations in heat transfer;
- the measuring system, which consists of the prepared test board, the attached thermocouples, and the connected data logger;
- the transfer of the data to a final PC software.

The respective tolerances are explained in Table 4.

Table 4 – Tolerances of the temperature measurement chain

Link of the measuring chain	Measurement differences in kelvin (K)		Remark, source
	Best case	Usual	
Reflow equipment			
Control behaviour	±0,5 K	±1 K	Field experience In IPC-7801, 10.4, ±2 K is required after calibration
Homogeneous heat transfer	±1,5 K	±2,5 K	Field experience and user specifications Mostly influenced by the so-called cross profile (measured over the transport width of the reflow soldering machine)
Test board			
Attachment of the thermocouple on the measuring assembly	±2,0 K	±5,0 K	Field experience Fixing of the thermocouple with SMD adhesive or aluminium tape
Thermocouple	±0,5 K	±1,5 K	IEC 60584-1:2013, Table 12, specifications and tolerances.
Data recording unit	±0,5 K	±0,5 K	General information of the manufacturers
PC software			Here, particular attention is paid to the radio transmission of the measuring data to complete data transfer.

Under best conditions (proper preparation of the test board, good – if possible calibrated – technique, reflow soldering equipment, data logger, etc.), the total tolerance of the temperature measurement chain (mean square deviation) is:

Best case	±2,6 K
Usual	±5,9 K

However, the fundamental requirement of IEC 61191-1:2018, 8.2.1 b) can be met:

> *"... maintain the soldering temperatures for the range of component thermal masses and solder joint sizes to within ±5 °C of their selected temperature profile, throughout the span of the required continuous soldering production run;".*

The process capability is determined under consideration of the required tolerance span.

NOTE The algorithms and requirements necessary for the calculation of process capability are described in IPC-7801, 9.1 "Cpk – Process Capability Index and Cp – Capability Performance".

7 Optimizing a temperature profile

7.1 General procedure

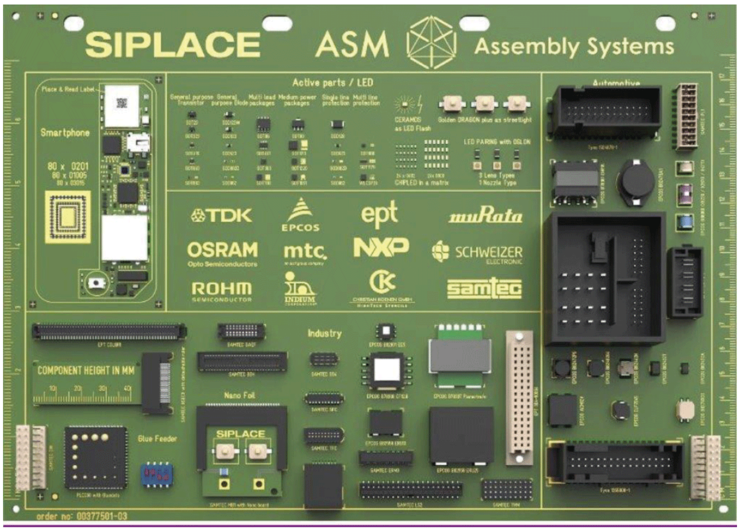
This Clause 7 describes by means of an example how to determine optimal reflow soldering machine parameters to meet the objectives of a temperature-time envelope profile for an electronic assembly.

1) Select a suitable test board and describe it as accurately as possible with regard to its assembly and material properties. Production targets consider, for example, cycle time.
2) Determine the temperature-time-envelope profile. A detailed knowledge of the solder heat resistance of the assembled components is necessary; see Clause 4).
3) Define measurement locations on the test board: soldering point of the smallest and largest thermal masses, on the package top side and, if necessary, further measuring points like top and bottom side of the assembly, etc. For the determination of the smallest and largest thermal masses, the use of a thermal imaging camera of the measuring assembly can be helpful. A thermocouple can be used to measure the atmospheric temperature (see Clause 5).
4) Select the reflow soldering system and describe it: number and dimensions of heating and cooling zones, top and bottom heating, etc.
5) If possible, perform a simulation of the temperature-time behaviour of the measuring assembly under the conditions of the selected reflow soldering machine to calculate the theoretically optimal reflow soldering machine parameters (settings) (knowledge of the heat transfer coefficient is needed for the simulation).
6) Perform real measurement with the test board in the selected reflow soldering system. Based on an established temperature profile, it is of advantage (according to general experience) to change only one factor in the following order during each further optimization run:
   a) transport speed;
   b) zone temperatures;
   c) convection rate.

If simulation results are available, verify them using the measurement results.

7.2 Description of a typical test board and the used reflow oven

Figure 13 shows the design of a test board used in the following example.



PCB:

- FR4
- One layer
- 206 mm and 290 mm
- Thickness 1,6 mm
- 35 µm Cu with iNiAu

Components:

- Passive down to 03015
- LEDs from Dragon to 0402,
- Smart components,
- Diverse connectors
- Power components,
- like ERU25
- Finishes: mostly Sn

Solder paste: SnAgCu305

SOURCE: Rehm, Thermal Systems GmbH, Blaubeuren 2019. Reproduced with permission.

Figure 13 – Description of a test board (electronic assembly)

This test board is used primarily to demonstrate the range of components that can be processed by reflow soldering. The wide range of components, especially their considerable differences in thermal masses, provides a particularly good basis for an example to demonstrate the steps required to determine the optimum reflow soldering system parameters.

Description of the used reflow soldering machine:

– System type:	Convection reflow soldering system
– Heated length:	3 000 mm
– Preheating:	5 zones of 350 mm each (top and bottom)
– Peak:	2 zones of 350 mm each (top and bottom)
– Cooling zones:	3 zones of 350 mm each (top)

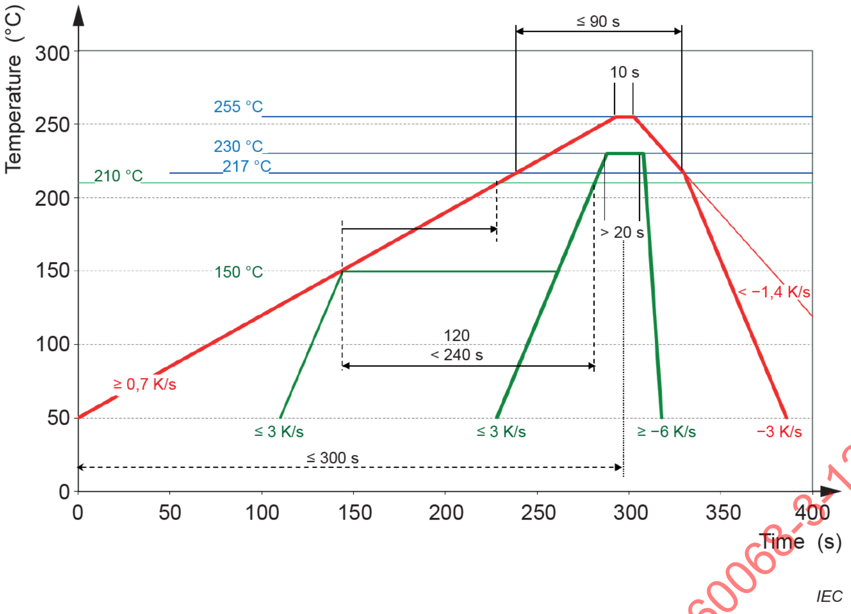
7.3 Schematic envelope reflow profile for the example board

As described in 7.1 2), the creation of an envelope profile is based on the knowledge of the properties of all materials and components used. Table 5 summarizes all envelope points and limits of the envelope profile of the selected sample assembly.

Table 5 – Envelope points at the envelope reflow profile for the test board

Envelope point	Explanation	Target	Source
T_0	Reference temperature to determine the reflow profile	50 °C	
Gradient 1 G_1	Max. heating gradient to T_2, preheating	3,0 K/s	Requirement IC components (acc. data sheet)
T_1	Min. preheating temperature	150 °C	Recommendation solder paste
$t_{1\text{max}}$	Max. preheating time	240 s	Recommendation solder paste
$t_{1\text{min}}$	Min. preheating time	120 s	Recommendation solder paste
T_2	Max. preheating temperature	210 °C	Recommendation solder paste
Gradient 2 G_2	Max. heating gradient from T_2 to T_P (peak)	3,0 K/s	Requirement IC components (acc. data sheet)
t_5	Time on peak	10 s	Requirement IC components (acc. data sheet)
T_{Pmin}	Min. peak temperature	230 °C	Experience value (solder joint)
T_{Pmax}	Max. peak temperature	255 °C	Data sheet critical component, measured on the package top side
Gradient G_3, G_4	Max. cooling gradient	–6,0 K/s	Requirement IC components (acc. data sheet)
$t_{3\text{min}}$	Min. time above liquidus	20 s	Experience value (solder joint)
$t_{3\text{max}}$	Max. time above liquidus	90 s	Requirement IC components (acc. data sheet) and recommendation solder paste
T_3	Liquidus temperature	217 °C	Alloy (solder paste SAC)
t_4	Time to peak	≤ 300 s	Requirement IC components (acc. data sheet)

Figure 14 shows the graphical visualization of the envelope profile limits defined in Table 5.



The red line indicates the upper line of the envelope profile.

The green line indicates the bottom line of the envelope profile.

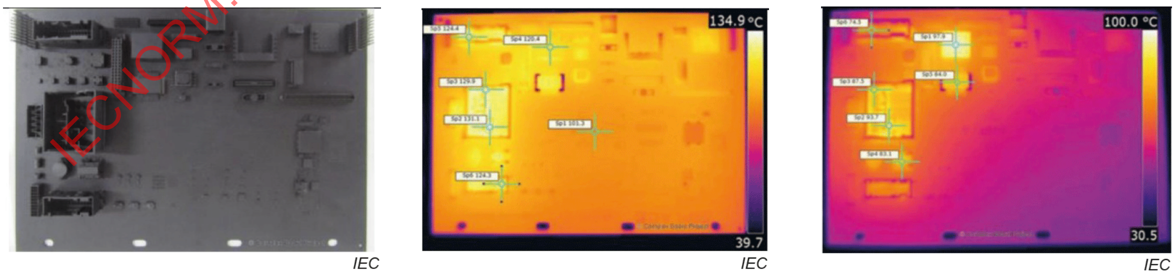
NOTE The temperature-time curves of the measuring locations are usually not symmetrical with respect to the maximum temperature T_{P}.

Figure 14 – Envelope reflow profile for the test board

7.4 Preparation of test board

To be able to provide evidence of the actual temperature-time reflow curves achieved, measuring points for attaching thermocouples need to be defined on a suitable measuring assembly (see 5.1). To determine the locations of the smallest and the largest thermal masses on the board, at which the minimum and maximum solder joint temperatures are measured, it is helpful to use a thermal imaging camera.

Figure 15 shows the thermal images of the examined test board. The transformer ERU25, with a mass of 31 g, was localized as the location of the largest thermal mass and the placement area of the 0201, 01005 and 03015 sized components as the location of the smallest thermal mass.



a) Initially blackened testboard

b) After 30 s cooling

c) After 300 s cooling

Figure 15 – Thermal images of the test board after cooling down from 150 °C

With these results and the information on the soldering heat resistance of the components (in each case from the corresponding data sheets), it was possible to determine the measurement locations on the sample assembly contained in Table 6.

Table 6 – Measurement locations on the sample assembly

No.	Measurement location
1	Automotive connector (large) pin top
2	Automotive connectors (large) package
3	Automotive connector (large) pin bottom
4	Shielding solder joint
5	Shielding top side
6	Atmosphere
7	ERU25 soldered joint
8	ERU25 top side
9	0201-chip solder joint

For simplification, only the ERU25 solder joint (largest thermal mass) and 0201-chip solder joint (smallest thermal mass) are discussed in the following. The temperature-time curves of all other solder joints are naturally in between. Furthermore, the temperature-time curves for, for example, measuring points on the package top side and their possible violations of the envelope profile are not explained in detail.

7.5 Possibility of temperature profiling optimization with simulation tools

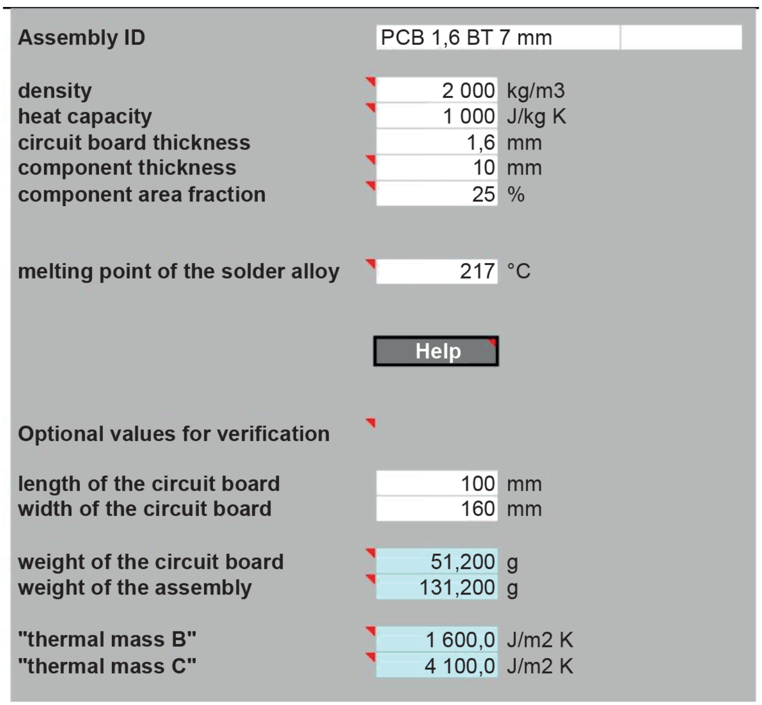
The temperature-time-profile setting preferably starts with a simulation (model calculation). This can save valuable working time and less experienced employees can be supported in optimizing reflow soldering programs. Simulation programs are offered by equipment manufacturers as well as manufacturers of measuring equipment and service providers.

Input parameters into the simulation are the geometrical and thermal parameters of the reflow soldering system (dimensions of the heating zones, heat transfer coefficients, etc.), a description of the assembly as exact as possible (especially the thermal mass and/or thickness of the components as well as their solder heat resistance) and the requirements of the solder paste. The simulation model uses these data to calculate the necessary setting values for the zone temperatures and the transport speed of the reflow soldering machine in order to optimize the temperature-time curve of the assembly. The transport speed can be set as a start parameter, based on the desired throughput of the boards (reciprocal value of the cycle time). The simulation calculation checks the temperature gradients and the maximum and minimum temperatures and times with respect to their compatibility with the given temperature-time envelope.

Ultimately, the simulation is based on estimates of the thermal mass of the assembly components and the heat transfer in the heating and cooling zones but provides instantaneous results from changes in the settings. Due to the estimated values, a measurement of the temperature curves at the exposed positions (largest and smallest thermal masses), as well as a thermocouple in the atmosphere (see Figure 2) is additionally necessary to verify the simulation and the actual zone temperatures. If necessary, the estimated input values such as the thermal masses and the heat transfer coefficients can then be adapted to the measurement. The simulation then provides without waiting time the effect of changes in the zone settings (settings of the reflow soldering machine) or the transport speed.

NOTE A simulation for reflow profile optimization with the help of numerical, analytical and empirical models always generates a prognosis, which reflects the actual temperature-time curves only with an approximation (uncertainty). However, the number of iteration steps in the reflow profile generation can be reduced.

The test board shown on Figure 13 was described as follows for the simulation variant used here (Figure 16).



Assembly ID	PCB 1,6 BT 7 mm	
density	2 000	kg/m3
heat capacity	1 000	J/kg K
circuit board thickness	1,6	mm
component thickness	10	mm
component area fraction	25	%
melting point of the solder alloy	217	°C

Help

Optional values for verification

length of the circuit board	100	mm
width of the circuit board	160	mm
weight of the circuit board	51,200	g
weight of the assembly	131,200	g
"thermal mass B"	1 600,0	J/m2 K
"thermal mass C"	4 100,0	J/m2 K

Density: circuit board material density from 1 600 kg/m^3 to 2 400 kg/m^3

Heat capacity: circuit board material heat capacity from 800 J/kg K to 1 200 J/kg K

Circuit board thickness

Component thickness: height of components, to use as a mean value or a maximum. Typical steps are 1 mm, 2 mm, 5 mm. Entering 0 means calculation without components.

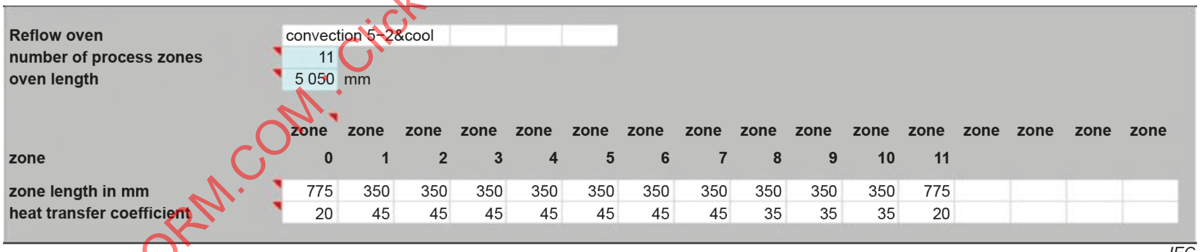
Component area fraction: area fraction covered with components, to use as a mean value or maximum. Typical values are 10 %, 25 %, 40 %. Entering 0 means calculation without components.

Length and width: Circuit board dimensions

Calculated from the input parameters are mass of circuit board and mass of the assembly, thermal mass of the circuit board (B) and of the components (C)

Figure 16 – Geometric and thermal description of the test board

In addition, the reflow soldering equipment needs to be described geometrically and thermally (with regard to its heat transfer coefficients) as precisely as possible (see Figure 17). The heat transfer coefficients can be obtained from the manufacturer of the reflow soldering equipment or can be measured by means of commercially available measuring boards. The program used here gives a range of heat transfer coefficients and suggests typical values, depending on the machine configuration. The value of 45 W/m^2 K used here reflects both-sided heating in the heating zones and one-sided cooling in the cooling zones.



Reflow oven	convection 5-2&cool	
number of process zones	11	
oven length	5 050	mm

	zone	zone	zone	zone	zone	zone	zone	zone	zone	zone	zone	zone	zone	zone	zone	zone
zone	0	1	2	3	4	5	6	7	8	9	10	11				
zone length in mm	775	350	350	350	350	350	350	350	350	350	350	775				
heat transfer coefficient	20	45	45	45	45	45	45	45	35	35	35	20				

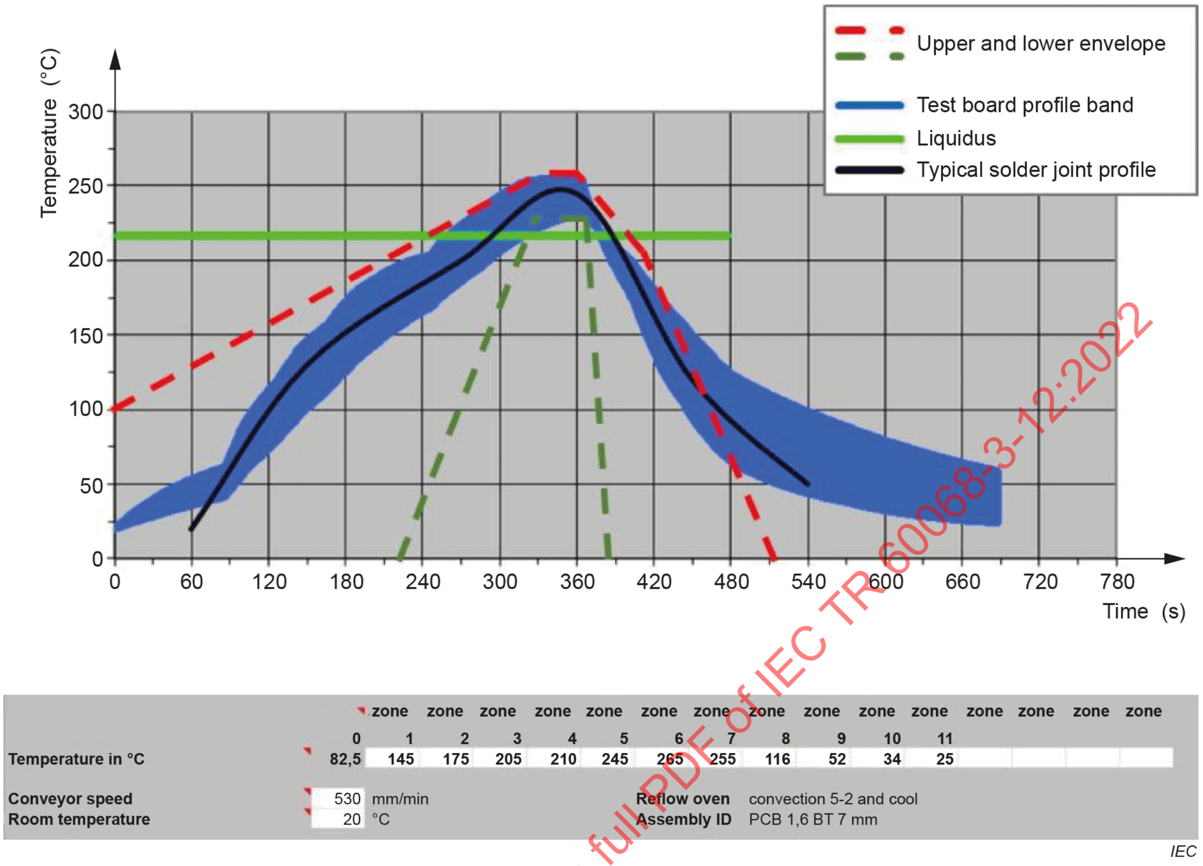
Figure 17 – Geometric and thermal description of the reflow soldering equipment

The envelope points of the desired envelope reflow profile, which are given for this example in Table 5, are also included in the simulation.

After entering the reflow soldering equipment settings for the zone temperatures and the transport speed, the simulation calculates the predicted reflow profile shown in Figure 18 for:

- the bare board, corresponds to the smallest thermal mass (0201 chip) on the example board = upper line of the blue band;
- the assembled test board (Figure 13), corresponds to the largest thermal mass (ERU25) on the test board = bottom line of the blue band;
- a typical solder joint profile on the test board, indicated by the black line;
- the liquidus temperature of the SAC solder, indicated in green;

– the envelope curve, indicated by the red and dark green dashed lines.



	zone 0	zone 1	zone 2	zone 3	zone 4	zone 5	zone 6	zone 7	zone 8	zone 9	zone 10	zone 11	zone	zone	zone
Temperature in °C	82,5	145	175	205	210	245	265	255	116	52	34	25			

Conveyor speed 530 mm/min
Room temperature 20 °C
Reflow oven convection 5-2 and cool
Assembly ID PCB 1,6 BT 7 mm

IEC

Figure 18 – Predicted reflow profile with help of simulation (blue band)

7.6 Iteration steps for finding reflow equipment setup

If results from a simulation are available, they can significantly shorten the iteration steps in manual reflow profile optimization. This means that the predicted reflow soldering equipment can be used directly during the first measurement. The first measurement after a simulation is generally called confirmation run.

If no simulation data are available, it is recommended to limit the iteration steps to the change of the transport speed at first and to adjust the temperatures of the heating and cooling zones according to empirical values.

For the selected test board, the following three iteration steps are discussed.

NOTE 1 The colour display of the measurement results in Table 8, Table 10 and Table 12 has the following meaning:

- green – there is no violation of the envelope profile;
- red – there is a violation of the envelope profile.

NOTE 2 The measurement results of all runs including the envelope profile are shown in Figure 19 for the 0201-chip solder joint and in Figure 20 for the ERU25 solder joint:

- red – at least one temperature-time curve violates the limits of the envelope;
- green – all temperature-time curves are within the limits of the envelope profile.

NOTE 3 Information on the limits of the envelope curve is given in Table 5.

1) Step 1: All settings of the reflow soldering machine were adjusted according to experience (see Table 7).

Table 7 – Settings according to experience

Zone	V1	V2	V3	V4	V5	P1	P2	K1	K2	K3
T_{upper} (°C)	145	160	175	190	205	235	340	97	35	26
T_{lower} (°C)	145	160	175	190	205	235	340	0	36	0
Transport speed	950 mm/min									

Table 8 – Measurement results for the settings from Table 7

Component type	Temperature, T_4 °C	Time above liquidus, t_3 s	Gradient, $G_{1,\,2}$ K/s
0201-chip solder joint	257	34	3,3
ERU25 solder joint	205	0	2,2

The results show that the solder joint of the 31 g ERU25 transformer cannot be soldered with these reflow soldering system parameters. The results from the first run indicate that too little heat was introduced into the assembly and therefore the ERU25 solder joint did not reach the minimum soldering temperature required. For this reason, the next step was to reduce the transport speed to increase the residence time of the assembly in the furnace and thus the heat input.

2) Step 2: Settings of the reflow soldering machine for the second run (see Table 9). These settings are taken from the simulation described in 7.5.

NOTE 4 The results from the first run provide a good basis for the optimization of the simulation model (e.g. adjustment of the heat transfer coefficients).

Table 9 – Settings for second run

Zone	V1	V2	V3	V4	V5	P1	P2	K1	K2	K3
T_{upper} (°C)	145	175	205	210	245	275	275	97	35	26
T_{lower} (°C)	145	175	205	210	245	275	275	0	0	0
Transport speed	530 mm/min									

Table 10 – Measurement results for the settings from Table 9

Component type	Temperature, T_4 °C	Time above liquidus, t_3 s	Gradient, $G_{1,\,2}$ K/s
0201-chip solder joint	260	124	2,7
ERU25 solder joint	238	84	1,6

The results of the second step show that especially for the 0201-chip soldering point there is a clear violation of time above liquidus t_3. In contrast, the soldering parameters for the ERU25 are already in the optimal range (see Figure 19 and Figure 20). As can be seen from the visualization of the measurement results in Figure 18, the time above liquidus at the 0201-chip solder joint is exceeded because the liquidus temperature of the solder is already reached in preheating zone 5. At the same time, the temperature of the 0201-chip solder joint at the end of preheating zone 5 is at the upper limit of the envelope profile. For this reason, the temperature in zone 5 is reduced by 35 °C.

3) Step 3: Adaptation of the heating zone temperatures (see Table 11).