

IPC-7530A

2017 - March

Guidelines for Temperature Profiling for Mass Soldering Processes (Reflow and Wave)

Supersedes IPC-7530

May 2001

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Association Connecting Electronics Industries



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Developed by the Thermal Profiling Guide Task Group (5-22h) of the
Assembly & Joining Committee (5-20) of IPC

Supersedes:
IPC-7530 - May 2001

Users of this standard are encouraged to participate in the
development of future revisions.

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Acknowledgment

Any document involving a complex technology draws material from a vast number of sources across many continents. While the principal members of the Thermal Profiling Guide Task Group (5-22h) of the Assembly & Joining Committee (5-20) are shown below, it is not possible to include all of those who assisted in the evolution of this standard. To each of them, the members of the IPC extend their gratitude.

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Guidelines for Temperature Profiling for Mass Soldering Processes (Reflow and Wave)

1 SCOPE

This standard describes thermal profile guidelines and practical guidelines to meet requirements to produce acceptable solder joints in mass soldering processes, including but not limited to reflow and wave soldering.

Thermal profile is a unique temperature vs. time plot for each fully populated printed wiring board assembly (PWBA), using thermocouples attached with high-temperature solder or copper or aluminum tapes to selected representative components of the PWBA as it travels at a given belt speed (i.e., transport speed) through various temperature zones of an oven or soldering system.

1.1 Purpose The purpose of this standard is to provide useful and practical information for developing thermal profiles to produce acceptable SnPb and Pb-free electronics assemblies. This standard is for managers, design and process engineers and technicians who deal with mass soldering processes.

1.2 Background During mass soldering, it is important that all solder joints reach the minimum soldering temperature. Minimum soldering temperature is the minimum temperature necessary to ensure metallurgical bonding of the solder alloy and the base metals to be soldered. Metallurgical bonding requires that the surfaces to be soldered and the solder reach this minimum soldering temperature for a sufficient time to allow wetting of the solder surfaces and the formation of a layer(s) of intermetallic compound(s) of some of the base metal(s) with one or more constituents of the solder alloy.

As a practical matter, minimum soldering temperature is somewhat (~ 25 °C) above the liquidus temperature of the solder alloy. The solder joint on a given PWBA that is the last to reach minimum soldering temperature (typically on or underneath one of the components with the highest thermal mass) determines the temperature profile setting for a given PWBA and soldering process/machine. Developing a good profile is a balancing act for the process engineer, who also needs to make sure smaller and temperature-sensitive components do not overheat or become damaged.

Reflow soldering requires controlled rates of heating and subsequent cooling; however, too rapid a heating rate can damage PWBAs and components. High cooling rates can also damage components and result in temperature gradients of sufficient magnitude to warp PWBAs and larger components and also fracture solder joints. Because of this, appropriate temperature profiling is essential for ensuring high-quality solder joints.

Even though different products, based on their thermal mass, require different amounts of thermal input, all products must achieve the minimum temperature (temperature above liquidus) without exceeding the maximum temperature (without damage to any components) within a defined time period (thermal profile). This is the key reason for developing a unique profile for each product.

Thermal input is determined by temperature/gas flow settings in each zone, the number of zones and the belt speed, which stays the same in each zone. Establishing minimum temperature, maximum temperature and duration in a zone ensures formation of intermetallic bonding between the component leads and their corresponding footprint or land patterns on those pads. All components, even though their thermal masses are different, must meet the same minimum and maximum temperature requirements. This is the biggest challenge for developing a profile, so developing a thermal profile for a PWBA with very large thermal mass components (e.g., a large ball grid array (BGA)) and small thermal mass components (e.g., 0201 or smaller chip resistors and capacitors) is a balancing act. In addition, different heating and cooling rates will have various effects on a variety of defects, adding more complexity to the balancing act. For example, a slower heating rate will help reduce voids in a BGA, but it will increase the potential for head on pillow (HoP) in the same BGA.

1.3 Terms and Definitions Other than those terms listed below, the definitions of terms used in this standard are in accordance with IPC-T-50.

1.3.1 Thermal Profile A unique temperature vs. time plot for each fully populated PWBA, using thermocouples attached with high-temperature solder or copper or aluminum tapes to selected representative components of the PWB as it travels at a given belt speed through various temperature zones of an oven or soldering system. Each product requires unique oven settings and belt speed (recipe) to achieve the desired profile on the PWBA.

Thermal profile may also be known as reflow profile, wave profile, selective profile, laser profile or other soldering profiles.

1.3.2 Recipe A combination of oven settings and conveyor speed based on the thermal profile of a product. Sometimes also known as reflow program.

1.3.3 Pasty Range The semiliquid state between liquidus and solidus, as solder begins to solidify but is not yet completely solid and also when solder begins to melt but is not yet completely molten.

Figure 1-1 shows eutectic temperature, superheat and pasty range. Eutectic temperature is the lowest melting point possible for the alloy and is lower than the melting point of any of the metals in the alloy. Even though eutectic is an alloy, it behaves like a metal because it has only one melting point, just like a metal. The range can be very small or very large depending on the composition of the alloy. As seen in Figure 1-1, either to the left or right of eutectic temperature, the pasty range is very small, but it grows as the composition changes in either direction with changes in Sn or Pb content.

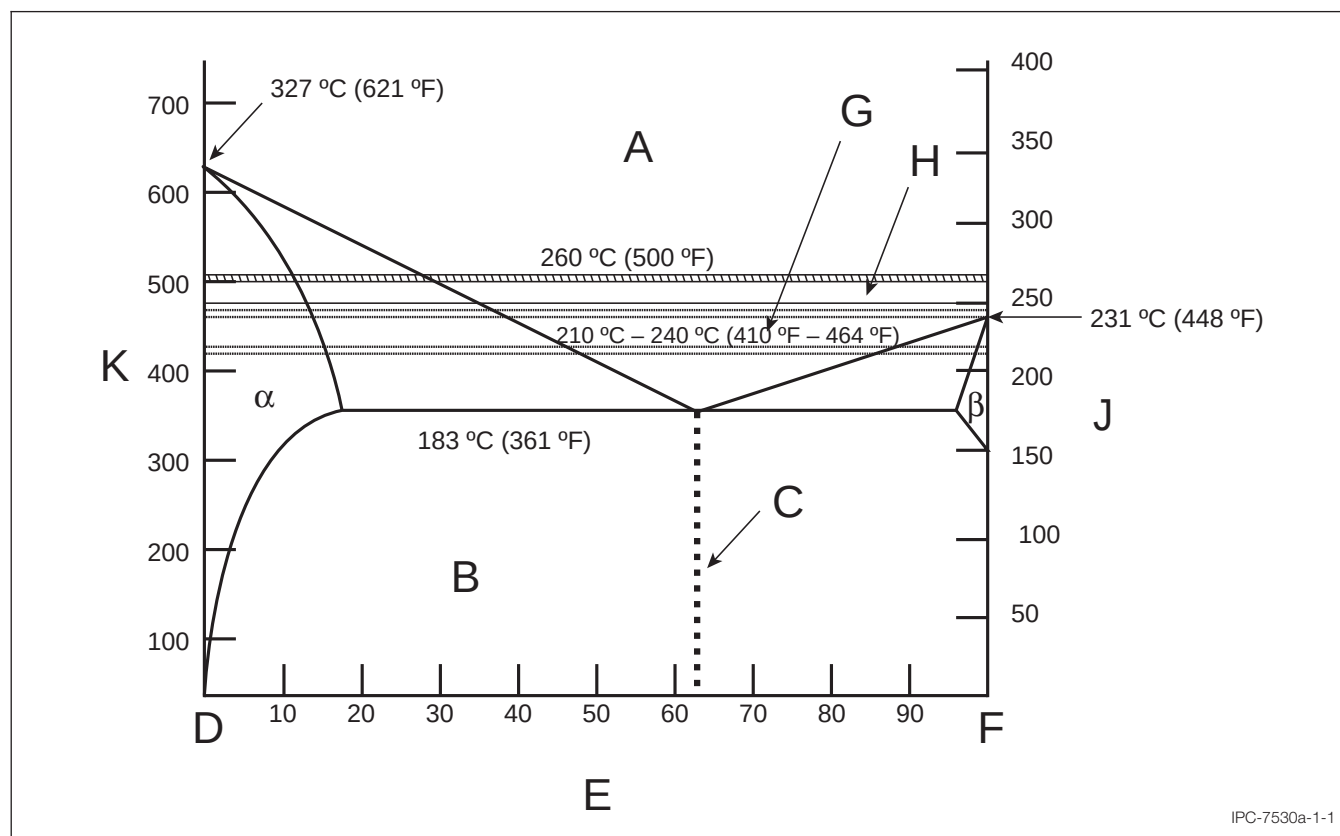


Figure 1-1 Phase Diagram for SnPb Solder

- | | |
|-----------------------------------|-----------------------------------|
| A – Liquid solder | F – Tin |
| B – Solid solder | G – Reflow soldering temperatures |
| C – Eutectic composition SN63Pb37 | H – Wave soldering temperatures |
| D – Lead | J – Temperature °C |
| E – Composition weight % tin | K – Temperature °F |

Figure 1-2 shows a SnAgCu (SAC) phase diagram. Since SAC alloy has an affinity for copper, this changes the total copper percentages in the diagram. The diagram addresses copper content from 0 % to 3 % by weight on the X-axis and silver content from 0 % to 8 % on the Y-axis. Due to the dissolution rate of copper in this alloy composition, the analysis has to be constantly monitored to verify good process controls. Typical SAC alloys are within the zone of < 1 % copper and 3.5 % to 4 % silver. However, SAC 305 with silver content of 3.5 % is the most commonly used alloy. It is rare to use 4 % silver due to higher cost and potential reliability concerns. Some mobile applications use 1 % silver to achieve better mechanical shock and vibration reliability.

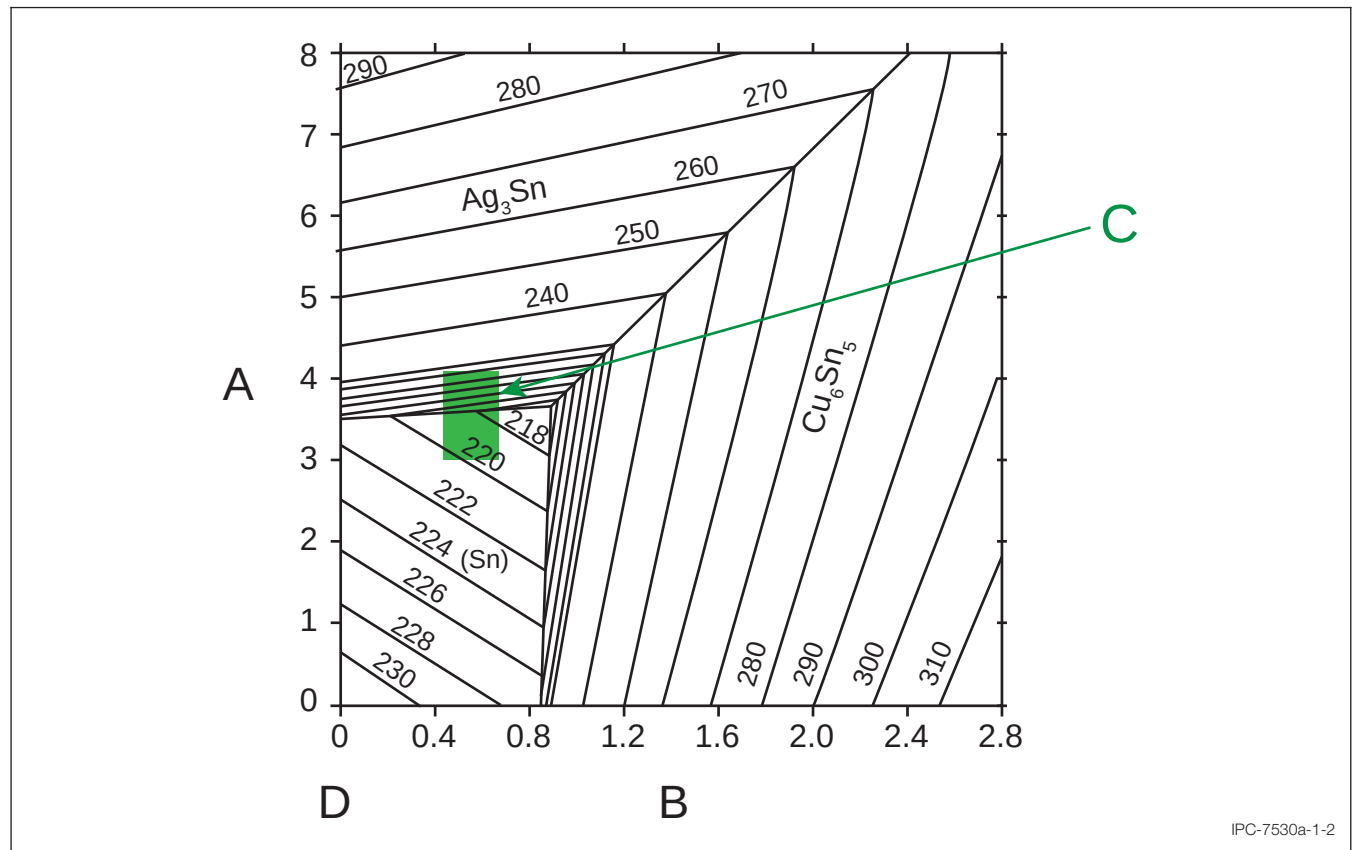


Figure 1-2 Pasty Range of SAC Solder

A – wt % Ag

B – wt % Cu

C – Composition region industry is using - Silver 3.5 % to 4 %, Copper 0.5 % to 0.7 %, remainder tin

D – Sn

1.3.4 Ramp Rate The net change in temperature divided by total time in that zone.

During soldering, the ramp rate is different in different zones (e.g., preheat zone, soak zone, reflow zone and cooling zone). Ramp rate is very high in the preheat zone and is very low in the soak zone.

1.3.5 Soak (Dwell) The time/temperature an assembly is held at a very low ramp rate in the reflow soldering process to allow all components to reach a desired stable temperature. In a reflow operation, the soak (dwell) also ensures the solder paste is fully dried before reaching reflow temperatures, and it acts as a flux activation zone for solder pastes.

1.3.6 Peak The maximum allowable temperature of the entire process. A portion of the reflow process where the temperature is raised sufficiently to cause the solder paste to reflow.

1.3.7 Melting Point The temperature at which a solder alloy starts to become liquid.

1.3.8 Liquidus The lowest temperature at which an alloy is completely liquid.

1.3.9 Solidus The highest temperature at which an alloy is completely solid.

1.3.10 Eutectic The temperature at which solidus and liquidus are the same. There is not a plastic range (material is malleable but not liquidus or solidus).

1.3.11 Time Above Liquidus (TAL) The time above liquidus (TAL) for solder, expressed at different liquidus temperatures. The higher the temperature, the shorter the TAL. When a specific temperature is not mentioned, TAL is assumed to be the time above melting point for solder.

In cases of eutectic alloys, TAL and time above melting point are the same. In cases of noneutectic alloys, TAL is less than time above melting point.

1.3.12 True TAL The solder joint on a PWBA that is above melting point for the shortest amount of time, or also known as the duration of time where all solder joints are above liquidus of solder.

True TAL is less than TAL of component(s) that are smaller in thermal mass. In the case of BGAs, True TAL is less than TAL of BGA balls on the periphery, which are in molten condition longer than BGA balls in the center of the package.

1.3.13 Delta T (Profile or Equipment) The largest temperature difference between two or more measurement points at a given point in time.

1.3.14 Phase Diagram An equilibrium diagram depicting thermodynamically distinct phases, with each phase possessing its own distinct physical, mechanical and electrical properties. In a metallurgical system (e.g., alloy), a phase diagram represents the relationship between temperature and composition.

1.3.15 Superheat The temperature difference between the peak reflow temperature and the liquidus of the alloy. Superheat is generally near 25 °C in SAC Pb-free and near 30 °C to 40 °C in SnPb or low-temperature Pb-free alloys.

1.3.16 Cooldown The amount of time necessary for a PWBA to return to ambient temperature after a soldering operation.

1.3.17 Preheat The section of the soldering equipment which establishes the ramp rate for an assembly before soak. It is a profile zone where the assembly is heated from room temperature to the beginning of the soak zone temperature and is characterized by the ramp slope measurement.

1.3.18 Class 1 Radiant IR-Dominant Systems Heating a PWBA predominantly by infrared (IR) radiation with little or no convection.

1.3.19 Class 2 Convection/IR Systems Heating a PWBA by a combination of IR radiation and convection in varying ratios.

1.3.20 Class 3 Convection-Dominant Systems Heating a PWBA predominantly by convection with little or no IR.

1.3.21 Profile Zones The profile is divided into distinct time periods which represent portions of the thermal process. Each zone is characterized by one or more measurements extracted from each zone (e.g., temperature, slope or time value).

1.3.22 Reflow Program See Recipe (1.3.2).

1.3.23 Liquidus Time Delay (LTD) The time difference between inner and outer balls becoming liquidus.

2 APPLICABLE DOCUMENTS

2.1 IPC¹

IPC-T-50 Terms and Definitions for Interconnecting and Packaging Electronic Circuits

IPC-A-610 Acceptability of Electronic Assemblies

IPC-CA-821 General Requirements for Thermally Conductive Adhesives

IPC-2222 Sectional Design Standard for Rigid Organic Printed Boards

IPC-7095 Design and Assembly Process Implementation for BGAs

IPC-7801 Reflow Oven Process Control Standard

1. www.ipc.org

2.2 Joint Industry Standards²

J-STD-001 Requirements for Soldered Electrical and Electronic Assemblies

J-STD-006 Requirements for Electronic Grade Solder Alloys and Fluxed and Non-Fluxed Solid Solders for Electronic Soldering Applications

J-STD-020 Moisture/Reflow Sensitivity Classification for Nonhermetic Solid State Surface Mount Devices

J-STD-075 Classification of Non-IC Electronic Components for Assembly Processes

2.3 JEDEC³

JEP 140 Beaded Thermocouple Temperature Measurement of Semiconductor Packages

3 CONVECTION REFLOW PROFILING

3.1 Thermal Profiles A solder profile, also known as a thermal profile, is a key variable in the manufacturing process that significantly impacts product yield, quality and reliability. Conveyor speed and zone temperature are two variables in solder profile development. Solder profile is not only product specific; it is also flux and solder alloy dependent. Different pastes require different profiles for optimum performance, so it is important to consult the paste manufacturer before developing the solder profile.

To develop the profile, a loaded PWBA is needed for which the profile is being developed. Begin with a given belt speed and then monitor the top-side PWBA temperature using thermocouples. Most new reflow ovens have built-in thermocouples and software packages to record the thermal profile. Also, commercial hardware and software packages make thermal profile development an easy task.

Use of such profilers has been important in SnPb and Pb-free assemblies. It is critical that such profilers be used on each product to achieve good yield without exceeding the temperature constraints imposed by different types of components. Table 3-1 provides key thermal profiles for SnPb, Pb-free and mixed-alloy assemblies (backward and forward compatibility profiles). Note that profiles for Pb-free and forward compatibility are the same. Table 3-2 provides profiles for SAC and low-temperature Pb-free alloys containing bismuth. Profiles for other alloys can be found in J-STD-006.

With SnPb, there has been general industry consensus about the composition of solder to be used: eutectic Sn63Pb37 with a melting point of 183 °C. With this composition, there is a big difference between melting point (183 °C) and peak temperature (210 °C to 220 °C). This difference, also known as superheat, varies from 30 °C to 40 °C, so it provides a very wide window (30 °C to 40 °C), and thermal profile development is much easier.

In Pb-free assembly, the commonly used SAC (SnAgCu) solders contain 3 % to 4 % silver, 0.5 % to 0.7 % copper and the remainder tin. These alloys have a melting point near 220 °C. A few components, such as some aluminum electrolytic capacitors, put restrictions on the maximum temperature and duration above 230 °C to which they can be subjected. Additional constraints will be dictated by low-cost laminates, plastic connectors and moisture-sensitive components.

To accommodate such constraints, the peak temperature in Pb-free assemblies should be maintained between 230 °C and 245 °C, a variation of only 15 °C, which is a tight process window. This is nearly a 60 % drop from the 35 °C variation with SnPb assemblies mentioned earlier. The difficulty in achieving a thermal profile to meet the defined process window is further increased if large components with high thermal mass are used on the same board with smaller, temperature-sensitive components. The reasons are simple. Large components with high thermal mass require a larger heat input to meet the process window requirements for peak temperature and TAL. However, this large heat input may result in smaller, temperature-sensitive components falling outside the process window requirements. To resolve this issue, very tight process control and narrow temperature bandwidth across the PWBA are necessary.

The problem can be further compounded by backward-compatibility issues in which some Pb-free components are used on a primarily SnPb PWBA. In such cases, the profile must accommodate both SnPb and Pb-free package requirements.

2. www.ipc.org
3. www.jedec.org

Table 3-1 Profile Comparison Between SnPb, SAC 305 and Mixed Alloys

Profile Topic	SnPb Alloy Profile	Mixed/Backward Compatibility Profile	Pb-Free Alloy (SAC 305)/Forward Compatibility Profile	Mixed SAC Alloy (SAC 305/SAC 105) Profile
Alloy solidus temperature	183 °C	183 °C	217 °C to 220 °C	217 °C to 227 °C ¹
Target alloy peak temp range	210 °C to 220 °C	228 °C to 232 °C ²	235 °C to 245 °C	240 °C to 245 °C
Absolute minimum peak reflow temperature ³	205 °C	228 °C ²	230 °C	235 °C
Component ramp-up rate	2 °C to 4 °C per second ⁴	2 °C to 4 °C per second ⁴	2 °C to 4 °C per second ⁴	2 °C to 4 °C per second ⁴
Component ramp-down rate	2 °C to 6 °C per second ⁴	2 °C to 6 °C per second ⁴	2 °C to 6 °C per second ⁴	2 °C to 6 °C per second ⁴
Soak or preheat activation temperature	100 °C to 150 °C ⁴	100 °C to 150 °C ⁴	150 °C to 200 °C ⁴	150 °C to 200 °C ⁴
Soak or preheat activation time	60 to 120 seconds ⁴	60 to 120 seconds ⁴	60 to 150 seconds ⁴	60 to 150 seconds ⁴
Dwell time above liquidus	60 to 90 seconds	60 to 90 seconds	60 to 90 seconds	60 to 90 seconds
Dwell time at peak temperature	20 seconds max	20 seconds min	20 seconds max	20 seconds min
Solder paste used	SnPb	SnPb	Pb-free (SAC 305)	Pb-free (SAC 305)
SMT component types	All SMT type SnPb and Pb-free, but not Pb-free BGA balls	All SMT type SnPb and Pb-free, including SAC Pb-free BGA balls	All components, including BGAs, are Pb-free, including BGAs with SAC 305 Pb-free BGA balls	All components, including BGAs, are Pb-free, but BGAs with SAC 105 Pb-free BGA balls, not SAC 305 BGA Balls
Reason for peak temperatures	Pb-free surface finishes on BGA parts have no problem melting at 205 °C All SnPb surface finishes have 90 % tin; Pb-free finishes have nearly 100 % tin with some other Pb-free elements like bismuth	A compromise temperature is needed so SnPb parts do not overheat Pb-free SAC BGAs with melting point of 217 °C to 220 °C can melt, collapse and fully mix with SnPb paste Lower peak temperatures will cause SAC BGA balls to not melt or to partially melt, increasing the incidence of HoP, opens and poor reliability	All components are Pb-free and can take higher heat Too high a peak temperature may cause BGA ball drops, opens, dewetting and PWBA warpage Large BGAs are tested for maximum of 245 °C for MSL-level rating	All components are Pb-free and can take higher heat Pb-free SAC BGAs with melting point of 227 °C can melt, collapse and fully mix with SAC 305 paste Lower peak temperatures will cause SAC 105 BGA balls to partially melt, increasing the incidence of HoP, opens and poor reliability Too high a peak temperature may cause BGA ball drops, opens, dewetting and PWBA warpage Large BGAs are tested for maximum of 245 °C for MSL-level rating

Note 1. When using SAC 105 BGA balls with melting point of 227 °C with SAC 305 solder paste with melting point of 217 °C to 220 °C.

Note 2. See IPC-7095 for details regarding mixed-alloy/backward compatibility soldering.

Note 3. Coolest temperature on the PWBA.

Note 4. Verify with component and/or solder paste supplier.

Table 3-2 Profile Comparison Between SAC Alloy, SnBi (Low-Temperature) Alloys and Resin-Containing SnBi Solder Pastes

Profile Topic	SAC 305 Solder Paste Profile	SnBi Low-Temperature Solder Paste Profile	Resin-Containing SnBi Low-Temperature Solder Paste Profile
Alloy solidus temperature	217 °C to 220 °C	139 °C to 140 °C	139 °C to 140 °C
Target alloy peak temperature range	235 °C to 245 °C	160 °C to 200 °C	160 °C to 180 °C
Absolute minimum peak reflow temperature ¹	230 °C	160 °C	160 °C
Component ramp-up rate	2 °C to 4 °C per second ²	1 °C to 3 °C per second ²	2 °C to 4 °C per second ²
Component ramp-down rate	2 °C to 6 °C per second ²	2 °C to 6 °C per second ²	2 °C to 6 °C per second ²
Soak or preheat activation temperature	150 °C to 200 °C ²	100 °C to 120 °C ²	None (to avoid premature curing of resin)
Soak or preheat activation time	60 to 120 seconds ²	30 to 90 seconds ²	None (to avoid premature curing of resin)
Dwell time above liquidus	60 to 90 seconds	30 to 90 seconds ²	60 to 210 seconds ²
Dwell time at peak temperature	20 seconds max	20 seconds max ²	Varies ³
Post-reflow resin-cure temperature	N/A	N/A	125 °C to 130 °C ³
Post-reflow resin-cure time	N/A	N/A	130 to 240 seconds ³
Solder paste used	Pb-free (SAC 305) paste	SnBi (eutectic or noneutectic) low-temperature paste without resin	SnBi (eutectic or non-eutectic) low-temperature paste with resin
SMT component types	All components, including BGAs, are Pb-free, including BGAs with SAC 305 Pb-free BGA balls	All components, including BGAs, are Pb-free, including BGAs with SAC 305 Pb-free BGA balls Do not use BGAs with SnPb solder balls	All components, including BGAs, are Pb-free, including BGAs with SAC alloy Pb-free BGA balls Do not use BGAs with SnPb solder balls

Note 1. The coolest component on PWBA.

Note 2. Verify with component and/or solder paste supplier.

Note 3. Some resin-containing solder pastes require extended time after the reflow phase in the thermal profile to cure the resin; others use TAL phase in the thermal profile to cure the resin.

Figure 3-1 shows a profile schematic. Figure 3-2 shows a real-world example for a SnPb profile. Figure 3-3 shows an example of a SAC 305 profile for a single-sided PWBA moving at 24 inches per minute. Figure 3-4 shows a profile for the same PWBA in Figure 3-3, but it is double-sided. Note almost the same oven temperature but a slower belt speed of 21 inches per minute.

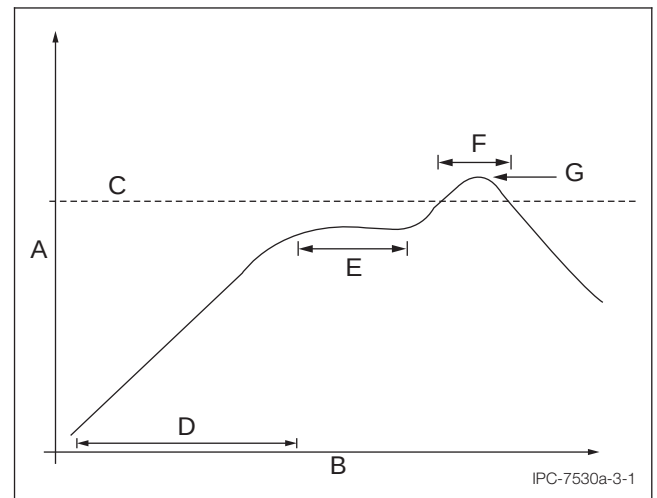


Figure 3-1 Thermal Profile Schematic

A – Temperature

B – Time

C – Alloy liquidus temperature

D – Preheat slope = temperature ramp rate

E – Preheat dwell = soak time

F – Time above liquidus

G – Peak temperature = maximum assembly temperature

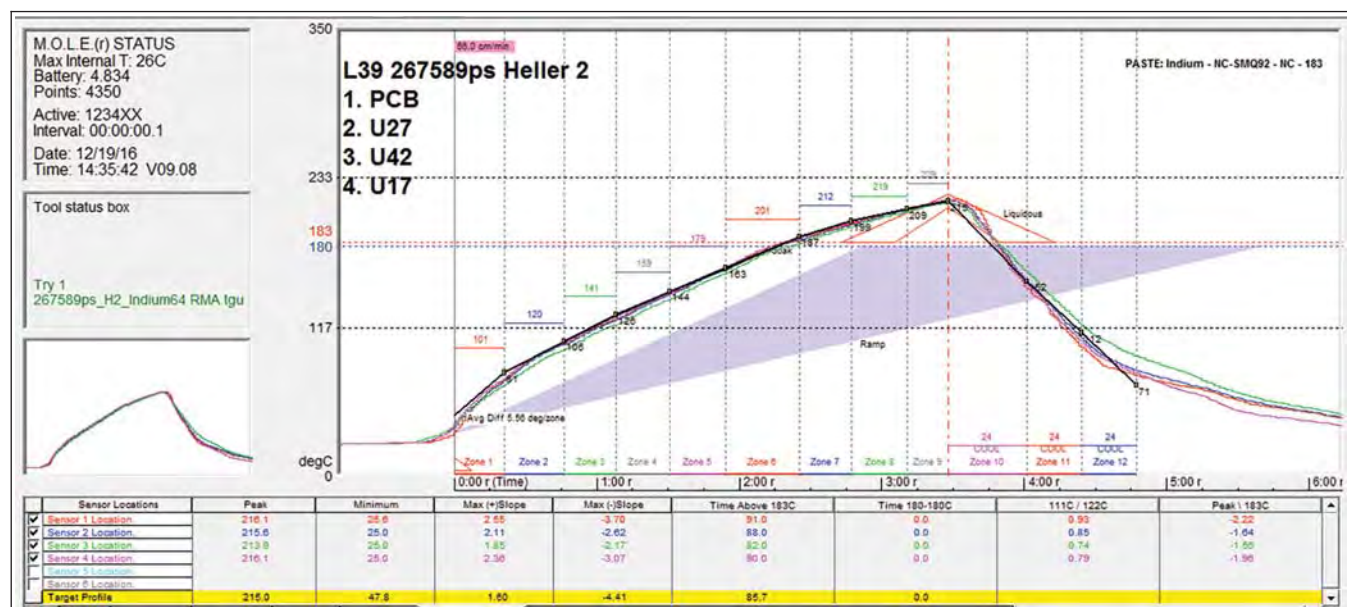


Figure 3-2 SnPb Profile With Multiple Thermocouples

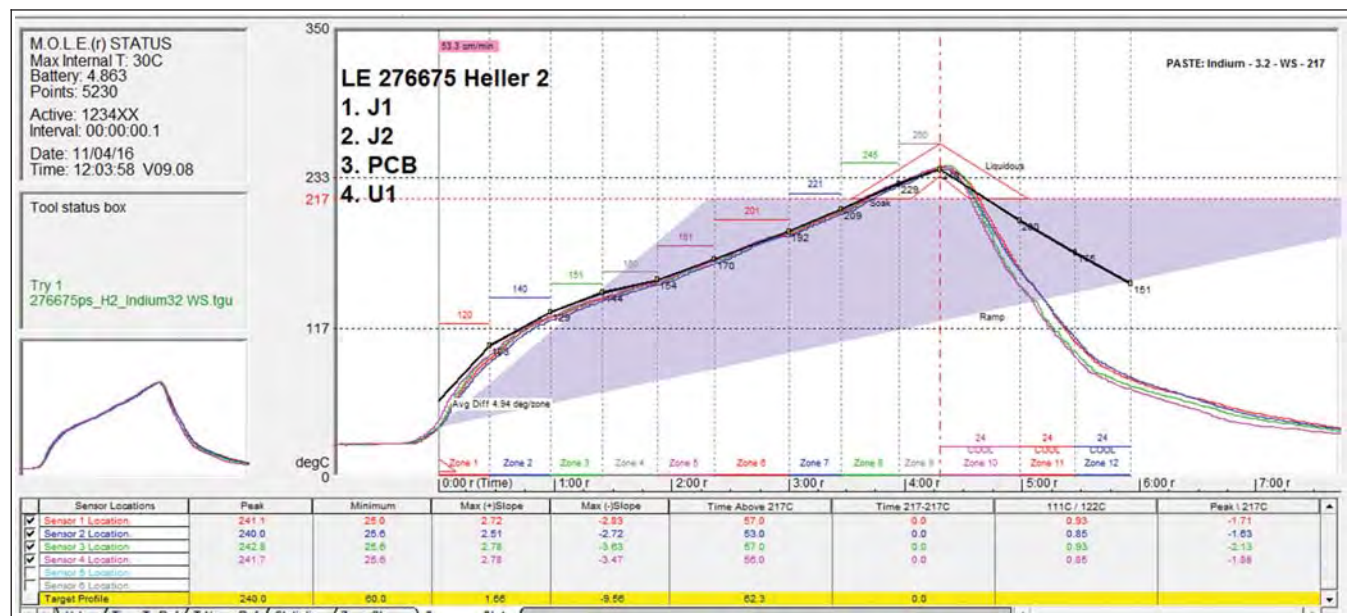


Figure 3-3 SAC 305 Profile for a Single-Sided PWBA (Belt Speed for Single-Sided PWBA 24 Inches per Minute)