Originally published in the Proceedings of the 2009 SMTA PanPacific Microelectronics Conference, with minor additions herein.

ON THE USE OF 3 THERMOCOUPLES TO VERIFY A PRINTED CIRCUIT BOARD PROFILE DURING THE REFLOW OPERATION

Daryl L. Santos[1], Arun Ramasubramanian[1], and Laurence A. Harvilchuck[2]

[1]Systems Science and Industrial Engineering (SSIE) Department
Binghamton University
Binghamton, NY 13902-6000

[2]Advanced Process Laboratory
Unovis Solutions
Binghamton, NY

ABSTRACT

This paper presents the results of an initial evaluation study to determine if a printed circuit board's (PCB's) profile can be verified by using only 3 thermocouples (T/Cs). Herein, this paper describes two processes: a "characterization" process and a "verification" process.

It is important to mention that the techniques herein are not suggested to replace a thorough T/C procedure for initial product/process development and qualification. Instead, these techniques are geared for use in process monitoring once a process has been qualified. Also, while only one type of reflow oven is used in this experimentation, these techniques can be applicable to a wide variety of reflow ovens.

In the ***characterization*** process, a T/C is applied to a low-mass component (L), an intermediate/sensitive component (S), and a high-mass component (H). In the ***verification*** process, the 3 T/Cs (L1-L3) are placed on the laminate, along the top, leading-edge surface of the PCB.

This study uses a desktop computer's motherboard as the Test Vehicle (TV). A 20-channel temperature recorder (a.k.a., "M.O.L.E. ® Temperature Recorder") is used to attach 20 T/Cs to the TV – 3 attached along the top, leading-edge and the rest attached at various locations and components (sensitive/critical and non-critical) around the TV. A baseline, Pb-free profile is identified as the desirable profile and two response variables are studied: peak temperature and time above liquidus.

By simulating changes to the oven – performed by altering belt speeds and a temperature zone from the baseline profile – evidence shows that by putting tight specifications on the two response variables for the temperature profiles of the 3 T/Cs located on the surface of the laminate's leading-edge, one can effectively verify that the board's characterization profiles are still within specification.

Key words: Process verification, Pb-free, reflow, characterization.

INTRODUCTION

This paper presents the results of an initial study to determine if the use of only 3 thermocouples can be utilized to verify a PCB's profile during the reflow operation. In so doing, a thermal recorder, with the capability to measure up to 20 channels was used to thoroughly map a Test Vehicle. Three of the 20 were used to record the temperatures on the leading-edge of the PCB laminate, the other seventeen were distributed around the PCB in both critical and non-critical locations. Two techniques were conducted: a "characterization" technique and a "verification" technique.

In the characterization technique, a T/C is applied to a low-mass component (L), an intermediate/sensitive component (S), and a high-mass component (H). In the verification technique, the 3 T/Cs (L1-L3) are placed along the top, leading-edge surface of the PCB.

As such, the characterization technique can be graphically represented by applying the 3 T/Cs as demonstrated in Figure 1. This figure is representative, the locations of the components conceivably could be anywhere on the PCB.

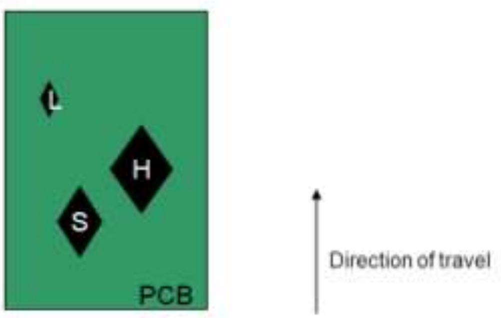

Figure 1. Demonstration of 3 T/Cs to Place for Characterization Technique.

Similarly, Figure 2 is used to demonstrate the locations of the 3 T/Cs in a verification technique. Here, the locations – left, center, and right – are fixed.

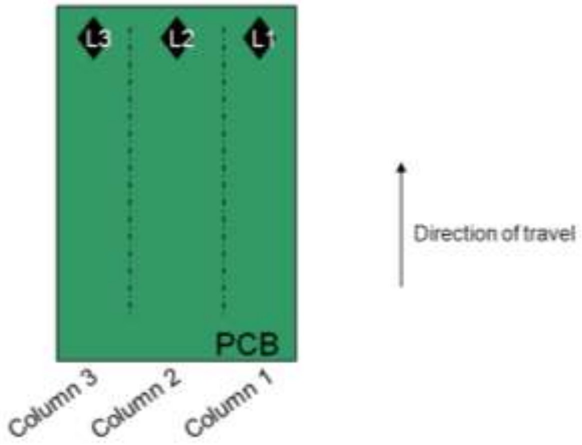

Figure 2. Demonstration of 3 T/Cs to Place for Verification Technique

The logic behind the placement/evaluation of these three locations is that the components with the smallest thermal mass – i.e., the most thermally sensitive components on the board – will not see profiles significantly different from these leading-edge locations.

EXPERIMENTAL

This section describes the Test Vehicle, how it is thermocoupled, the four different reflow profiles that are utilized in the experiment, and the procedure followed to collect the data.

Thermocoupling the Test Vehicle

The Test Vehicle (TV) is a desktop motherboard. The board measures 9.5" x 9.5". As a portion of the goal of this project is to allow the profiling to be done in a quick fashion, a "lick-and-stick" approach was taken for connecting the T/Cs to the TV. The T/Cs, in other words, were attached solely via Kapton® tape either on the surface of the board, or on or under components of interest. A more thorough R&D type of T/C attach – for example, drilling into a BGA sphere – was intentionally avoided to better reflect current practice in many "line-side" situations. A schematic of the 20 T/C locations appears in Figure 3, below; a photographic image of the TV appears in the Appendix.

Since a major focus of this work is to determine if 3 T/Cs located along the top, leading-edge of the PCB is sufficient for verifying product temperatures (profiles), the other 17 T/Cs available (via the use of the 20-channel thermal recorder) were attached to various locations on the TV.

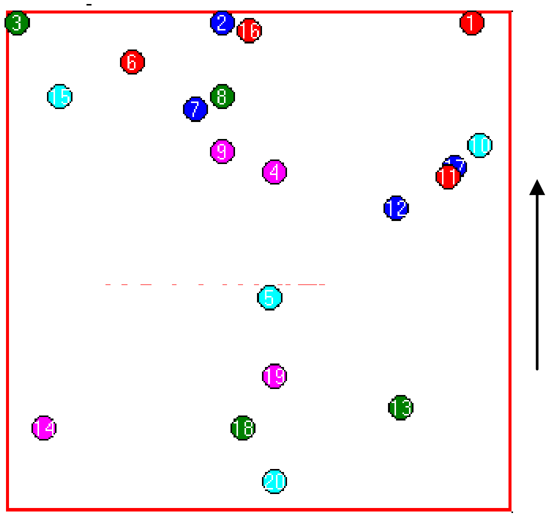

Figure 3. Schematic of 20 T/C Locations

T/Cs used for "Characterization" Technique

The locations/components identified for the characterization technique are the following:

- Location 18 – Identified as a component with low thermal mass (L)
- Location 8 – Identified as a component with intermediate/sensitive thermal mass (S)
- Location 19 – Identified as a component with large thermal mass (H). This location is arguably the most thermally sensitive on the assembly with the narrowest process window for acceptably reliable assembly.

T/Cs used for "Verification" Technique

The 3 T/Cs placed along the top, leading-edge of the PCB are those identified for the "verification" technique described in an earlier section. Refer to Figure 2. They are numbered locations 1, 2, and 3.

Reflow Profiles

In order to perform this initial study, 4 different Pb-free reflow profiles were planned: a baseline profile, and three other profiles that represent changes to the stability of the oven. A reflow oven with 6 heating zones and one cooling zone was used. A brief description of each of the profile settings is provided below; diagrams of each of the temperature profiles appear in [1].

- Profile 1: This profile is referred to as the "baseline" profile. It was selected as it provided a good Pb-free reflow profile for 3 critical components (4, 5, and 19). Locations 4, 5, and 19 are considered the most critical of the components as they correspond to the largest thermal masses on the board: the corner joints of a large ball grid array, and the processor socket joints. For this profile and for comparison purposes for the other profiles, the zone temperature settings (top zones and bottom zones set to be the same) are shown in the Appendix of this document; the belt speed for Profile 1 is 30cm/min.
- Profile 2: This profile is identical to Profile 1 in zone temperature settings; belt speed is 35 cm/min.
- Profile 3: This profile is identical to Profile 1 in zone temperature settings; belt speed is 40 cm/min.
- Profile 4: This profile is identical to Profile 1 except for one significant exception. The reflow zone (6) temperature was set much lower than it was in the other profiles. It is set at 220^{o}C whereas the reflow zone temperature is 260^{o}C for all other profiles.

The logic for changing the belt speed with regards to Profiles 2 and 3 was to determine if the 3 top, leading-edge T/Cs alone would be sufficient to depict a change in temperature recordings with regards to the ***response variables*** *of Peak Temperature and Time Above Liquidus (TAL). Profile 4 was an attempt to simulate a bad temperature zone without, for example, actually shutting down a fan and compromising the oven.*

PROCEDURE

The following steps were followed for each of the four profiles:

1. Set machine parameters (zone settings and belt speed);
2. Allow oven to stabilize;
3. Set mole to record;
4. Place TV on center of the conveyor belt and allow assembly to go through oven;
5. Upon exiting oven, stop recording on the mole;
6. Set TV aside to allow it to cool/stabilize – while keeping the oven running at current profile (this is done to mimic a production environment);
7. Disconnect mole from T/Cs;
8. Connect mole to computer and download the temperature readings;
9. After TV has cooled/stabilized for a one-hour period, reattach mole to the T/Cs;
10. Repeat Steps 3 through 9 until a total of 5 replicates have been accumulated for the current profile.

RESULTS

As two studies are conducted, one for characterization and one for verification, the results will be separated accordingly. Each study consists of a group of 3 T/Cs.

For each experiment/technique (characterization and verification), the data were analyzed first by looking at each individual T/C in the group and secondly by looking at the grouped behavior of the 3 T/Cs. In evaluating the profiles, the following two ***response variables*** are of interest:

- Peak Temperature
- Time Above 217^{o}C; aka, Time Above Liquidus (TAL)

In analyzing the response variables, a Oneway Analysis of Variance (Oneway ANOVA) was conducted. The purpose of which is to determine if Reflow Profile has an effect on the response variables. Also conducted was a Tukey-Kramer multiple comparisons test (MCT). The MCT was used to determine if the differences in the performance (readings) of the T/Cs between the different profiles are significant. The MCT is conducted at an α = 5% value (i.e., providing a 95% confidence). This paper is actually a summary of a 35+ page whitepaper technical document (Santos et al., 2008). Due to page restrictions, all data, graphs, tables, and statistical analyses cannot be presented. The interested reader is invited to contact the authors for a copy of the whitepaper.

Before the results are summarized, it is important that the reader have a fundamental understanding of how the data were analyzed.

Consider the following discussion with regards to Peak Temperature and T/C 1 – one of the T/Cs used in the verification experiment. In comparing the baseline (Profile 1), to Profiles 2 and 3, that have the same zone temperature settings but increasingly quicker belt speeds, we would expect that Peak Temperature will reduce from baseline to Profile 2, to Profile 3. We should also expect that in comparing the baseline to Profile 4 (where the belt speed is same as the baseline, but the reflow zone (6) is significantly reduced) that Peak Temperature will also reduce. Given this discussion, Figure 4 is a replica of a graph that appears in the aforementioned whitepaper [1] for T/C 1 (L1) and Peak Temperature.

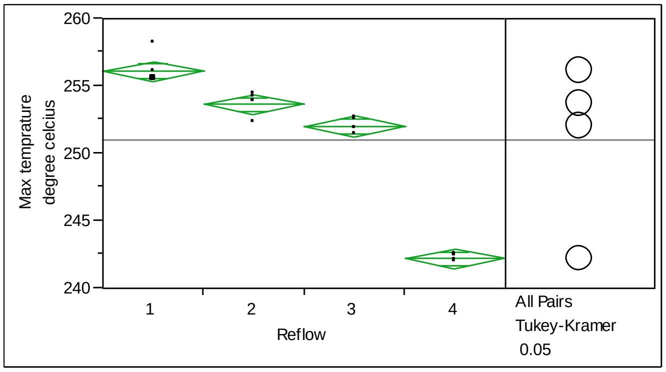

Figure 4. Peak Temperature - T/C 1 (L1)

Figure 4 indicates that the mean values of Peak Temperature (designated by the horizontal lines in each diamond figure) have decreased, as expected, from baseline (256.10°C) to all other profiles, respectively (253.64, 252.00, and 242.18°C). The circles on the right-most portion of the figure indicate the significance of the differences across the different profiles. For example, the circle related to the baseline (Profile 1), is separate from the circle of Profile 2. Since they do not overlap, the Peak Temperature of Profile 1 for T/C 1 can be said to be significantly different from that of all the other profiles.

A similar understanding/analysis can be made with the TAL data appearing in Santos et al. (2008). We should expect that the TAL in moving to Profiles 2 and 3, as compared to the baseline, will decrease. Profile 4, however, is a little more interesting. As Profile 4 is only different in one zone (6), but because that setting is still high (220°C) and the liquidus value is below that (217°C), there may not be as a large difference in TAL as comparing the baseline to Profile 4 as when comparing the baseline to Profiles 2 and 3. All of this is evidenced in Figure 5, below.

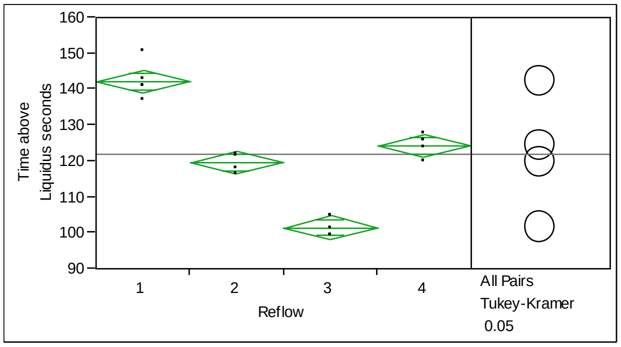

Figure 5. TAL - T/C 1 (L1)

Figure 5 indicates there are significant differences between the mean TAL values for the baseline as compared to all other profiles (the circle for the baseline does not intersect with any others). The mean values of TAL - T/C 1 for Profiles 1-4, respectively, can be found in [1] and are 142.12, 119.58, 101.46, and 124.26 seconds.

Now that an understanding of how some of the data/graphs were analyzed, summary results of the two experiments are now presented, beginning with the characterization experiment.

Characterization Experiment Summary Results

The 3 characterization T/Cs are locations 18, 8, and 19. These represent a low thermal mass component (L), an intermediate/sensitive component (S), and a high thermal mass component (H).

Tables 1 and 2, in the Appendix of this paper, present the mean Peak Temperature values and mean TAL values for each of the components in the characterization group. The values are presented for each of the reflow profiles (RP1-RP4). In addition, percent changes in moving from the baseline (RP1) to each of the other profiles (RP2, RP3, or RP4) are noted.

Verification Experiment Summary Results

The 3 verification T/Cs are those numbered 1-3 and are the 3 located on the laminate across the top, leading-edge of the TV. The whitepaper [1] provides the following for each of these T/Cs: an ANOVA analysis for Peak Temperature and an ANOVA analysis for TAL. The whitepaper also provides an ANOVA analysis for Peak Temperature for the combined (1, 2, and 3) thermocouples as well as an ANOVA analysis for TAL for the combined (1, 2, and 3) thermocouples.

Tables 3 and 4, in the Appendix of this paper, present the mean Peak Temperature values and mean TAL values for each of the components in the verification group. The values are presented for each of the reflow profiles (RP1-RP4). In addition, percent changes in moving from the baseline (RP1) to each of the other profiles (RP2, RP3, or RP4) are noted.

CONCLUSIONS

The two response variables of importance in this work are Peak Temperature and Time Above Liquidus (TAL). Lead-free guidelines for these two variables are typically listed as the following:

- Peak Temperature: Min 235°C, Max 260°C
- TAL: 60-120 sec

In looking at the two groups (characterization and verification groups), Tables 5 and 6, in the Appendix of this paper, provide the mean values of Peak Temperature and TAL.

Response Variables and Baseline Profile

Concerning the baseline profile (RP1), we see that regardless of group, mean peak temperature does not exceed the 260^{o}C specification, as desired. For TAL, the characterization group does not exceed 120 seconds, which is also desired. However, the verification group does exceed the 120 second threshold. *We offer that this is not necessarily a bad situation*. The reader should keep in mind that the baseline profile was developed while considering the 3 locations of highest thermal mass (locations 4, 5, and 19). In order to get those 3 locations up to temperature and for sustained (60-120 second) duration, it is not surprising that 3 thermocouples simply placed along the leading edge of the substrate have a TAL that exceeds 120 seconds. Furthermore, and to restate, the mean Peak Temperature does not exceed 260^{o}C in this group; nor does the mean Peak Temperature of any individual thermocouple in this group exceed this value (see Table 3).

To further support that this is not a necessarily bad situation, let us consider one of the most thermally sensitive components on the TV as measured by T/C 18 (see Tables 1 and 2). T/C 18's mean Peak Temperature is comfortably below 260^{o}C and its TAL is only slightly above 120 seconds.

Effect of Changing from Baseline Profile on the Response Variables

Even a casual evaluation of Tables 5 and 6 reveal that when changing to Profiles 2 or 3 – where the belt speed is increasingly quickened – both the characterization group and the verification group see decreases in Peak Temperature and TAL. These results are expected. In changing to Profile 4 – that simulates a bad reflow zone, both the characterization and verification groups also see decreases in Peak Temperature and TAL. Again, these results are expected, but it is even more important that the data support these expectations.

To restate an earlier point, this work represents but a subset of a 35+ page whitepaper that contains a wealth of additional statistical analysis, graphs, and tables. The interested reader is invited to contact the authors to obtain a copy of that whitepaper.

Interesting Ending Observation

In fact, by the very conducting of this study and focusing on only 3 T/Cs, there is evidence to support (studying the performance of T/C 3, alone – see Table 3) that the reflow oven utilized in this experiment may need to be serviced soon! In fact, an evaluation of T/Cs 14 and 15, relatively in the same plane of travel as T/C 3 also show (but not presented herein) non-statistically-separable performance (as did T/C 3) in Peak Temperature between Profile 1 (baseline) and Profile 2.

Concluding Remark

Paul Austen, of ECD, Inc., has reviewed the aforementioned whitepaper [1] and offers this opinion [2]: "The Binghamton University study has shown that, when done correctly by adhering to the original target profile, three-thermocouple profiling can be used to verify the original target profile that was achieved through the use of twenty thermocouples. Ideally, three-thermocouple profilers complement the traditional six-, twelve-, or twenty-channel thermal profilers that were used to characterize the PCB assembly and achieve the necessary target profile. Robust software will allow for the appropriate documentation verifying that the process was in spec with the OEM or paste manufacturer's required profile. It is in the ability to save production time, use all lines, and decrease product waste, while ensuring proper documentation of process verification, that we see tremendous benefits from oven profiling in the production environment."

ACKNOWLEDGEMENTS

We would like to extend our sincere appreciation to Unovis Solutions (Binghamton, NY) for allowing Mr. Larry Harvilchuck to participate in this study. Thanks also go out to Mr. Ashok Pachamuthu, graduate research assistant and student lab manager of Binghamton University's surface mount assembly laboratories. The authors would also like to thank ECD, Inc. for the use of the 20-channel temperature profiler utilized in this study. Finally, the authors would like to thank the Integrated Electronics Engineering Center (IEEC) and the S3IP Center at Binghamton University.

REFERENCES

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[2] Austen, P., "Oven vs. Board Profiling for the Production Environment," SMT Online Article, http://smt.pennnet.com/Articles/Article_Display.cfm?Sect

Originally published in the Proceedings of the 2009 SMTA PanPacific Microelectronics Conference, with minor additions herein.

ion=ONART&PUBLICATION_ID=35&ARTICLE_ID=343296&C=HMST&dcmp=rss, accessed December 14, 2008.

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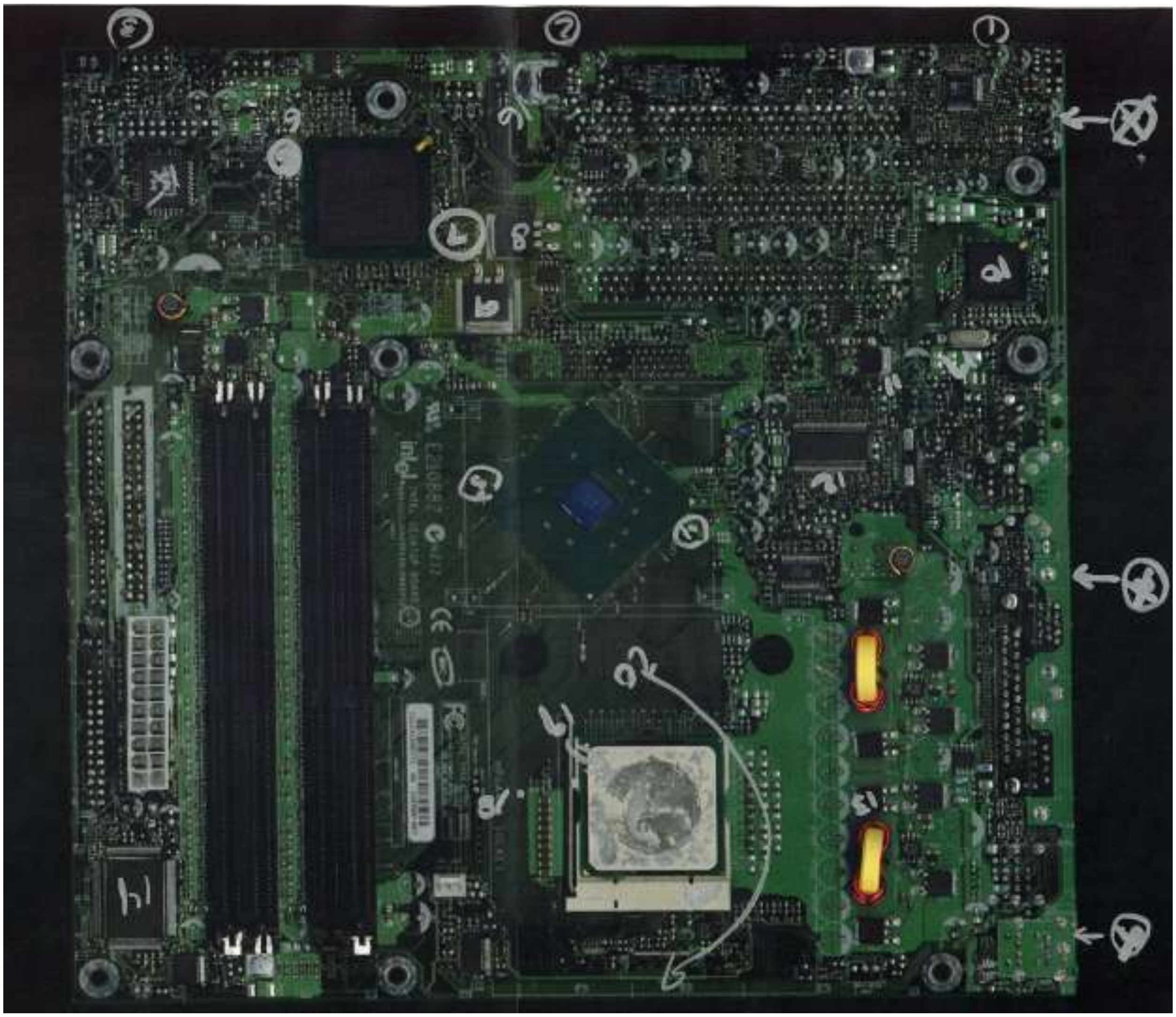
APPENDIX

Photograph of Thermocoupled Test Vehicle



Direction of travel through reflow oven

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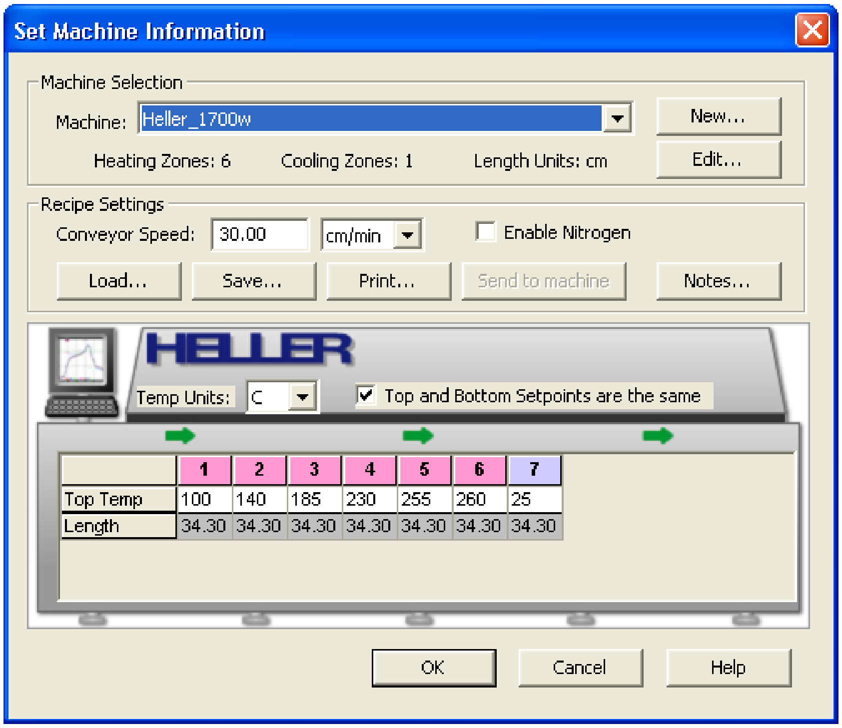
"Baseline" Profile 1: Oven Settings



Set Machine Information

Machine Selection

Machine: Heller_1700w

Heating Zones: 6 Cooling Zones: 1 Length Units: cm

Recipe Settings

Conveyor Speed: 30.00 cm/min

☐ Enable Nitrogen

Temp Units: C

☑ Top and Bottom Setpoints are the same

	1	2	3	4	5	6	7
Top Temp	100	140	185	230	255	260	25
Length	34.30	34.30	34.30	34.30	34.30	34.30	34.30

Profile 1: Results

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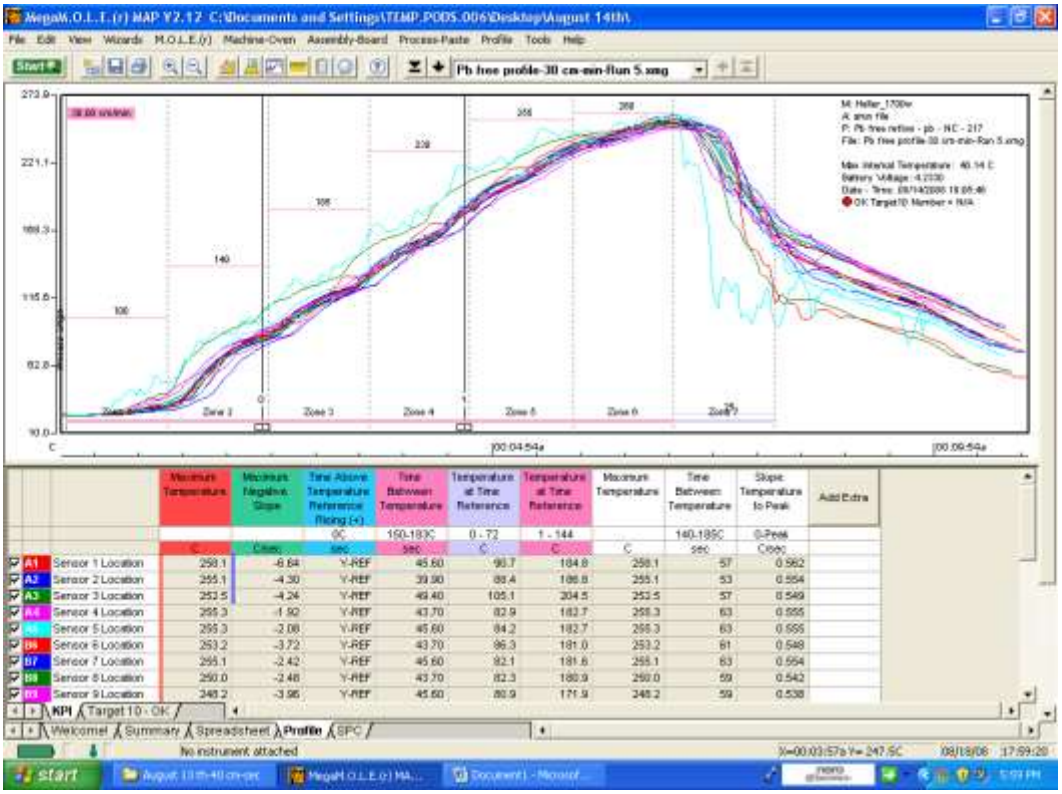

M: Heller_1700w
A: anun file
P: Pb-free reflow - pb - NC - 217
File: Pb free profile-30 cm-min-Run 5.xmg

Max Internal Temperature : 40.14 C
Battery Voltage : 4.2330
Date - Time: 08/14/2008 19:05:46
● OK Target10 Number = N/A

		Maximum Temperature	Maximum Negative Slope	Time Above Temperature Reference Rising (+)	Time Between Temperature	Temperature at Time Reference	Temperature at Time Reference	Maximum Temperature	Time Between Temperature	Slope Temperature to Peak	Add Extra
				0C	150-183C	0 - 72	1 - 144		140-185C	0-Peak	
		C	C/sec	sec	sec	C	C	C	sec	C/sec	
☑	A1 Sensor 1 Location	258.1	-6.64	Y-REF	45.60	90.7	184.8	258.1	57	0.562	
☑	A2 Sensor 2 Location	255.1	-4.30	Y-REF	39.90	88.4	186.8	255.1	53	0.554	
☑	A3 Sensor 3 Location	253.5	-4.24	Y-REF	49.40	105.1	204.5	253.5	57	0.549	
☑	A4 Sensor 4 Location	255.3	-1.92	Y-REF	43.70	82.9	182.7	255.3	63	0.555	
☑	A5 Sensor 5 Location	255.3	-2.08	Y-REF	45.60	84.2	182.7	255.3	63	0.555	
☑	B6 Sensor 6 Location	253.2	-3.72	Y-REF	43.70	86.3	181.0	253.2	61	0.548	
☑	B7 Sensor 7 Location	255.1	-2.42	Y-REF	45.60	82.1	181.6	255.1	63	0.554	
☑	B8 Sensor 8 Location	250.0	-2.48	Y-REF	43.70	82.3	180.9	250.0	59	0.542	
☑	B9 Sensor 9 Location	248.2	-3.96	Y-REF	45.60	80.9	171.9	248.2	59	0.538	

No instrument attached

X=00:03:57s Y= 247.5C   08/18/08   17:59:20

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Table 1. Mean Peak Temperature Values for the 3 Characterization T/Cs

	RP1	RP2	RP3	RP4	%Δ 1-2	%Δ 1-3	%Δ 1-4
T/C 18 L	250.76	245.42	241.5	232.5	2.13%	3.69%	7.28%
T/C 8 S	249.12	246.48	242.64	234.2	1.06%	2.60%	5.99%
T/C 19 H	248.04	243.56	238.86	230.88	1.81%	3.70%	6.92%

Table 2. Mean TAL Values for the 3 Characterization T/Cs

	RP1	RP2	RP3	RP4	%Δ 1-2	%Δ 1-3	%Δ 1-4
T/C 18 L	120.46	98.62	79.42	109.44	18.13%	34.07%	9.15%
T/C 8 S	123.5	99.18	82.84	117.42	19.69%	32.92%	4.92%
T/C 19 H	112.86	90.56	69.92	105.64	19.76%	38.05%	6.40%

Table 3. Mean Peak Temperature Values for the 3 Verification T/Cs

	RP1	RP2	RP3	RP4	%Δ 1-2	%Δ 1-3	%Δ 1-4
T/C 1	256.10	253.64	252.00	242.18	0.96%	1.60%	5.44%
T/C 2	253.92	250.70	248.86	239.08	1.27%	1.99%	5.84%
T/C 3	252.76	255.32	252.20	242.14	-1.01%	0.22%	4.20%

Table 4. Mean TAL Values for the 3 Verification T/Cs

	RP1	RP2	RP3	RP4	%Δ 1-2	%Δ 1-3	%Δ 1-4
T/C 1	142.12	119.58	101.46	124.26	15.86%	28.61%	12.57%
T/C 2	137.94	110.50	96.52	117.04	19.89%	30.03%	15.15%
T/C 3	142.12	123.76	106.02	125.78	12.92%	25.40%	11.50%

Table 5. Mean Peak Temperature Values (°C) by Group

	RP1	RP2	RP3	RP4	%Δ 1-2	%Δ 1-3	%Δ 1-4
Characterization Group	249.3	245.2	241.0	232.5	1.66%	3.33%	6.73%
Verification Group	254.3	253.2	251.0	241.1	0.41%	1.27%	5.16%

Table 6. Mean TAL Values (sec) by Group

	RP1	RP2	RP3	RP4	%Δ 1-2	%Δ 1-3	%Δ 1-4
Characterization Group	118.9	96.1	77.4	110.8	6.82%	34.93%	6.82%
Verification Group	140.7	118.0	101.3	122.4	16.19%	28.00%	13.05%