QUALITY AND RELIABILITY TESTING OF CIRCUIT BOARDS ASSEMBLED WITH LEAD FREE COMPONENTS, FINISHES, SOLDERING MATERIALS AND PROCESSES IN SIMULATED PRODUCTION CONDITIONS

Sammy Shina, Ph.D., University of Massachusetts, Lowell, MA, USA
Greg Morose, Sc.D., Massachusetts Toxics Use Reduction Institute (TURI), Lowell, MA, USA
Richard Anderson Ph.D., and Helena Pasquito, Cobham, Lowell, MA, USA
Bob Farrell, Benchmark Electronics, Hudson, NH, USA
Don Longworth and Wendi Boger, DDi Incorporated, Anaheim, CA, USA
Ken Degan, Teradyne Inc., North Reading, MA, USA
Donald Abbott, Ph.D., Texas Instruments, Attleboro, MA, USA
David Pinsky, Karen Ebner, and Amit Sarkhel,
Raytheon Company, Tewksbury, MA, USA
Michael Miller and Louis Feinstein, Textron Systems, Wilmington, MA, USA
Deb Fragoza, Eric Ren, EMC, Hopkinton, MA, USA
Charlie Bickford, Wall Industries, Exeter, NH, USA

The New England Lead-free Electronics Consortium is a collaborative effort of New England companies spanning the electronics supply chain, created by the University of Massachusetts Lowell in 1999 and sponsored by the Toxics Use Reduction Institute and the U.S. EPA. The consortium has completed and published the results of three phases of manufacturing and testing of lead-free Printed Wiring Boards (PWBs) with the goal of achieving zero-defect lead-free soldering processes with comparable or superior reliability to that of leaded solder processes.

In this fourth phase of testing, which began in 2007, several simulated conditions of assembly and rework processes were evaluated in a matrix of multiple levels of components, PWB lead free surface finishes and solders, and compared to a baseline of leaded equivalent materials and processes. Both Through Hole (THT) and Surface Mount (SMT) Technologies were evaluated. The assembly portion of the testing and rework is completed and the long term reliability and vibration is ongoing.

All quality and reliability testing was performed with industry standard methodologies, using specially trained production inspectors for the quality evaluation, and extreme thermal cycling for reliability testing.

Our results indicate that with proper selection of currently available (2008) materials and finishes and careful control of the assembly processes, successful lead free assembly and rework can be achieved. Comparison of different strategies for rework, and recommendations for least copper dissolution for THT technology processes are discussed in the published book by the paper authors. Reliability testing to date showed interesting inflection points for leaded versus lead free reliability that has to be resolved by additional thermal cycling, to be published when completed in 2009, together with vibration testing.

Key words: Lead Free, Visual Inspection, Rework, Reliability testing, Thermal Cycling, Design of Experiments.

INTRODUCTION

In January 2003, The European Union (EU) published Directives 2002/96/EC on Waste Electrical and Electronic Equipment (WEEE) and 2002/95/EC on the Restriction of the use of certain Hazardous Substances in electrical and electronic equipment (RoHS). These emerging directives have been the primary drivers for a global movement toward lead free electronics.

NEW ENGLAND LEAD-FREE CONSORTIUM

The consortium has been very successful in maintaining a synergistic and close working relationship between its ever changing and expanding member companies since 1999. The unique success of its endeavors is due to the fact that the member companies volunteer expertise and knowledge of their personnel and supply materials, production and test equipment towards the consortium projects. In return, they get to select particular component geometries, materials and technologies that they are interested in, jointly decide on the testing methodologies and share the results. In addition, member companies are able to work collaboratively with competing or potential customer companies through the consortium framework. The University of Massachusetts Lowell (UML) and the Toxics Reduction Institute (TURI) have provided project management, communications and leadership throughout the different phases of testing. Funding was initially provided by TURI for Phases I and II, and from the EPA for phases III and IV. Testing results are published in national and professional society conferences, as a well as a book edited by Shina and authored by the consortium members. It was published in April 2008 by McGraw-Hill entitled, “Green Electronics Design and Manufacturing. “

MATERIAL SELECTION FOR LEAD FREE EVALUATION

The selection of the materials was constrained by the resources available and the amount of testing parameters to be evaluated. The technique of Design of Experiments (DoE) was used to try to separate the effect of each parameter on the overall performance of quality and reliability of the PWBs. The test parameters were as follows:

1. Components. There were 886 SMT components (BGAs, microBGAs, resistors, TSOPs, PQFPs, PQFN, and MLFs), and 21 THT components (connectors, LEDs, DC/DC convertors, and capacitors) provided for assembly on each side of each test vehicle.

2. Solder types. There were 24 PWBs that were assembled with lead free materials and solders, 8 that were assembled with leaded solder and 3 Halogen free PWBs that were assembled with lead free solders.

3. PWB finishes. There were 4 types of surface finishes:

- Electroless Nickel Immersion Gold (ENIG). This surface finish involves using both electroless and immersion technologies to deposit the metallic surface finish.
- Hot Air Solder Leveling (HASL). Lead free alloy Sn100C was used. It is comprised of mostly tin, but also includes 0.6% copper, 0.05% nickel, and 0.0055% germanium.
- Organic Solderability Peservatives (OSP).
- Nano materials surface using nanosilver particles dispersed in a polymer (polyaniline), with a thickness between 45 to 65 nm. This was selected because it has the potential of addressing major lead free implementation challenges such as copper dissolution during rework and process improvement for assembly of lead free THT components.

4. Solder Compositions. There were 4 different solder pastes for assembly of the SMT components:

- Tin/silver/copper alloy (SAC305) with no clean chemistry flux (from two different suppliers).
- Tin/silver/copper alloy (SAC305OA) with organic acid chemistry flux.
- Tin lead alloy with no clean chemistry flux for baseline data source.

Three (3) different solder alloys were used in for the assembly of the THT components:

- Tin/silver/copper alloy (SAC305).
- Tin/copper alloy (Sn100C) at two different operation settings, 295 and 310 temperatures
- Tin/lead alloy for baseline purposes.

5. Laminates. Two different laminate materials were used:

- FR-4 laminate material was designed for use in lead free assembly environments (32 test vehicles) and has a glass transition (T_g) temperature of 180^{o}C.
- Halogen-free flame retardants laminate with a glass transition (T_g) temperature of 180^{o}C was used for three (3) test vehicles.

6. Test Vehicles. The test vehicles were designed with the help of consortium members as well as components and equipment provided. Thirty five (35) test vehicles were assembled at two locations and shown in Figure 1. The test vehicles were 8” (inches) wide by 10” long, contained 20 layers and are 0.110” thick.

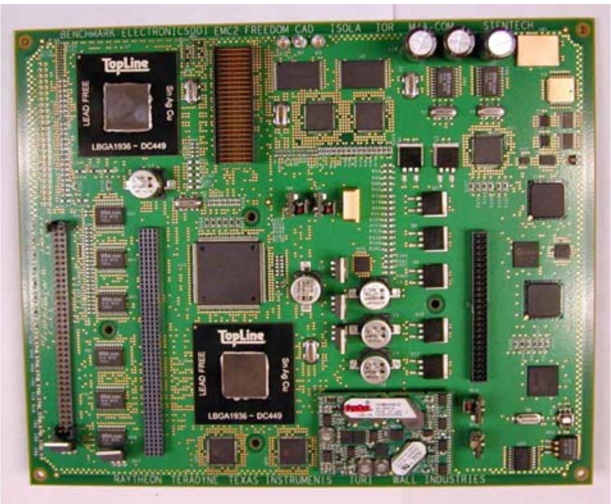

Figure 1. New England Consortium phase IV Vehicle

7. Experiment Matrices: These matrices are based on DoE principles and were used to selectively determine individual contribution of each parameter. They are shown in the following Tables 1, 2 and 3 for the 35 test vehicles

Table 1. Lead free Test Vehicles, Phase IV DoE

Test Vehic.	SMT Solder	TH Solder	Surface Finish	Lam-inate
1	SAC305 - 1	SAC305	ENIG	FR4
2	SAC305 - 1	SAC305	ENIG	FR4
3	SAC305 - 1	SAC305	HASL	FR4
4	SAC305 - 1	SAC305	HASL	FR4
5	SAC305 - 1	SAC305	OSP	FR4
6	SAC305 -1	SAC305	OSP	FR4
7	SAC305 - 1	SAC305	Nano	FR4
8	SAC305 - 1	SAC305	Nano	FR4
9	SAC305OA	Sn100C 1	ENIG	FR4
10	SAC305OA	Sn100C 1	ENIG	FR4
11	SAC305OA	Sn100C 1	HASL	FR4
12	SAC305OA	Sn100C 1	HASL	FR4
13	SAC305OA	Sn100C 1	OSP	FR4
14	SAC305OA	Sn100C 1	OSP	FR4
15	SAC305OA	Sn100C 1	Nano	FR4
16	SAC305OA	Sn100C 1	Nano	FR4
17	SAC305- 2	Sn100C 2	ENIG	FR4
18	SAC305- 2	Sn100C 2	ENIG	FR4
19	SAC305- 2	Sn100C 2	HASL	FR4
20	SAC305- 2	Sn100C 2	HASL	FR4
21	SAC305- 2	Sn100C 2	OSP	FR4
22	SAC305- 2	Sn100C 2	OSP	FR4
23	SAC305- 2	Sn100C 2	Nano	FR4
24	SAC305- 2	Sn100C 2	Nano	FR4

The DoE experiments were not full factorial, especially when examining the effects of the Halogen free laminates, given that the consortium was limited in resources. It was decided to use t-tests for comparison of this parameter. The baseline leaded PWBs were replicated with one commonly used leaded solder, and shown in Table 2.

Table 2. Tin Lead Test Vehicles, Phase IV DoE

Test Vehicle	SMT Solder	TH Solder	Surface Finish	Lam-inate
25	Tin Lead	Tin Lead	ENIG	FR4
26	Tin Lead	Tin Lead	ENIG	FR4
27	Tin Lead	Tin Lead	HASL	FR4
28	Tin Lead	Tin Lead	HASL	FR4
29	Tin Lead	Tin Lead	OSP	FR4
30	Tin Lead	Tin Lead	OSP	FR4
31	Tin Lead	Tin Lead	Nano	FR4
32	Tin Lead	Tin Lead	Nano	FR4

All three (3) Halogen free test vehicles were made with OSP laminate finish, as shown in Table 3. All were soldered with SAC305 (2 NC, one soldered with Organic acid). The Halogen Free laminates were made with FR4.

Table 3. Halogen free Test Vehicles, Phase IV DoE

Test Vehicle	SMT Solder	TH Solder	Surface Finish	Lam-inate
33	SAC305-1	SAC305	OSP	HF
34	SAC305-1	SAC305	OSP	HF
35	SAC305OA	SAC305	OSP	HF

SMT ASSEMBLY PROCESS

SMT component assembly for all test vehicles was performed using an electroformed nickel stencil with thickness at the bottom of 0.005", and the top thickness of 0.004". A printer was used with print speed of 0.51 ips, front and rear blade pressure of 19.4 lbs, a separation speed of 0.055 ips, and a separation distance of 0.098". Reflow was performed using an oven with ten (10) heating zones and three (3) cooling zones. The thermal profile used for all test vehicles was a ramp to peak.

Three (3) thermal profiles were used. One for tin lead test vehicles with a target peak temperature in the range of 210-218^{o}C, and target time above liquidus (TAL) of 60-90 seconds. The second for tin lead vehicles whose top side contained BGA components with lead free solder balls, which required a hybrid profile to melt the tin lead solder pastes as well as the lead free solder on the BGA components. The target peak temperature for the hybrid profile was in the range of 222-230^{o}C, and the target TAL was in the range of 60-90 seconds (Shina, 2008).

The third temperature profile was for the lead-free test vehicles. All three lead-free solder pastes used contained the SAC305 alloy at a melt temperature of 217^{o}C. The profile has a target peak temperature in the range of 240-248^{o}C, and a TAL of 60-90 seconds (Morose, 2006).

The profile is shown in Figure 2, using the data from six (6) thermocouples to calibrate the profile to the ranges selected.

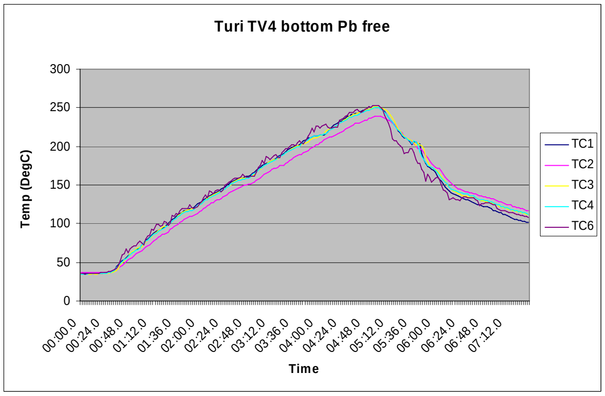

Figure 2. Bottom side lead free profile, phase IV DoE.

THT ASSEMBLY PROCESS

The Soldering equipment used had robotic multiwave and selectwave soldering capabilities. The multiwave process uses a robot system to pick up, hold, and dip the test vehicle onto multiple nozzles that are mounted on a product specific nozzle plate; hold time being referred to as "dwell time". In order to reduce thermal stress, a target preheat temperature was used in the range of 110-115^{o}C for all 32 test vehicles. A summary of the parameters used for soldering THT technology test vehicles is given Table 4.

Table 4. THT Soldering Parameters

Parameter	SAC 305	Sn100 (1)	Sn100 (2)	Tin Lead
Vehicle Number	1 – 8	9 - 16	17 - 24	25-32
Multiwave Pot Temp.	295^{o}C	295^{o}C	310^{o}C	270^{o}C
Multiwave Dwell Time	13 sec.	13 sec.	16 sec.	7 sec.
Selectwave Pot Temp.	300^{o}C	300^{o}C	310^{o}C	270^{o}C
Selectwave Nozzle Size	8 mm	8 mm	8 mm	4 mm

QUALITY INSPECTION RESULTS

Inspection was performed using associates at Benchmark Electronics. They were trained in IPC-A-610 Revision D standard for Class 3 High Performance Electronic Products by a training leader from MA/Com Tycoelectronics. In addition, an X-ray inspection machine was also used for automatic inspection. All defects were identified on a component lead basis, so that a single component can have multiple defects. A total of 4,689 defects were identified for all 35 test vehicles. The tabulation of defects by solders, component technology and defects per test vehicle is given in Table 5, showing no significant differences in total defects/test vehicle type, as well as in THT or SMT component technologies

Table 5. Summary of visual defects

Component Type	LF Test Vehicles (1-24)	Tin/lead Vehicles (25-32)	HF Laminate (33-35)
SMT	112	24	9
THT	3,062	1,091	391
Tot Defects/TV	132	139	133

SMT INSPECTION ANALYSIS

The inspection data for the SMT component defects were analyzed using the MINITAB ® software. Graphs for Mean effects and interactions are shown in Figures 3 and 4. While all parameters of solder types and surface finish were not significant, the SAC305 OA solder paste had a higher mean defect rate (8.0 defects/PWB) than the overall average of 4.1 defects/PWB. Conversely, the nano surface finish had the lowest mean defect rate (2.75 defects/PWB), compares with the other finishes that ranged between 4.0 and 5.5 defects/test vehicle.

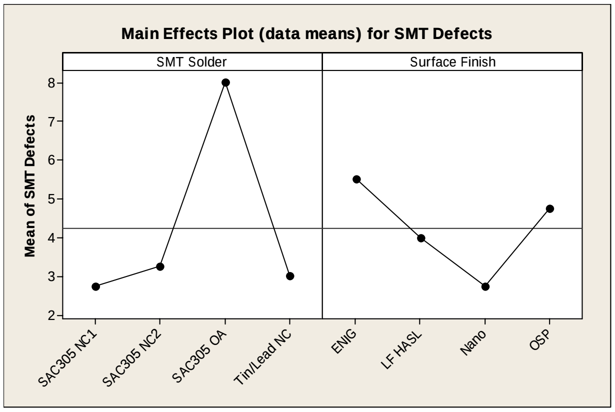

Figure 3. Main effects plot for the SMT defects

The parameter interaction plot, shown in Figure 4, indicates uneven performance between the different surface finish parameters when compared against multiple solder compositions. The combination with the highest defect level was the SAC 305OA solder paste and the OSP finish with 10 defects/PWB. The lowest mean defect level was the tin lead solder paste and the nano surface finish with zero defects/PWB.

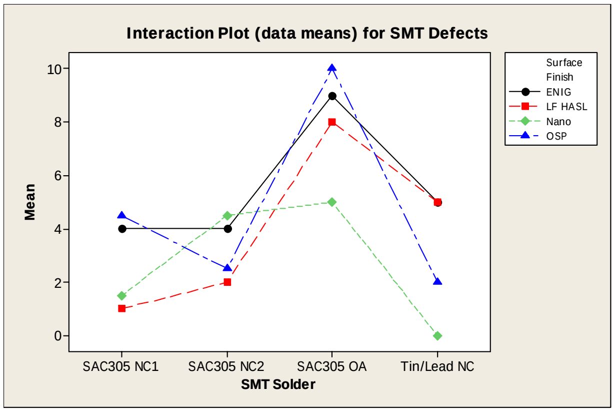

Figure 4. Interaction Plot for SMT Defects

An interesting result is the performance of the nano surface finish, which had had the lowest overall defect rate for all types of solders tested, while it had the highest defect rate for the SAC305 2 solder paste. This indicates that a certain negative reaction is occurring in this combination which has to be avoided, lest the supplier resolves this issue. This plot also reveals that the HASL surface finish had the lowest defect rate for both the SAC305 1 and SAC305 2 solder pastes.

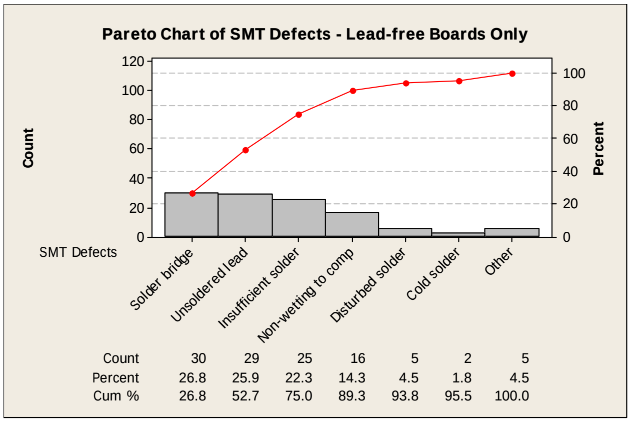

Figure 5. Pareto Chart of SMT defects

Figure 5.is a Pareto Chart for the SMT defects for lead free PWBs only. The chart reveals that solder bridges, unsoldered leads, insufficient solder, and non-wetting to component were the most prevalent defect categories. The other category includes two voiding defects, one solder splatter defect, one non-wetting to pad defect, and one tombstoned defect. For THT defects, solder bridges and tombstoning were the only defect categories found.

The three (3) Halogen free test vehicles had a much lower defect rate (3.0 defects/PWB), when compared to their equivalent FR4 PWBs (7.25 defects/PWB), all having OSP surface finish and soldered with two types of lead free solders.

THT INSPECTION ANALYSIS

The inspection data for the THT component defects were analyzed using the MINITAB ® software. Graphs for Mean effects and interaction are shown in Figures 6 and 7. Due to drift that occurred during the multiwave operations, only sixteen test vehicles were included in the analysis (only one replicate of each combination). The two best performing solders were Sn100C 1 and the SAC305 with 79.25 and 95.75 defects/PWB respectively. The two best performing surface finishes were HASL and ENIG with 51.5 and 83.75 defects/PWB respectively.

The interaction Plots in Figure 7 indicate the need for carteful selection of materials to obtain good quality visual results. HASL exhibited the best overall performance, while ENIG had the worst variability in performance versus the solders tested in the DoE. More testing is required as solder suppliers tune their materials.

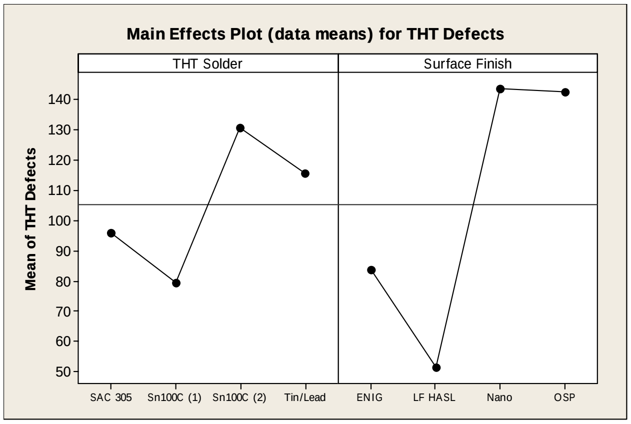

Figure 6. Main effects plot for the THT defects

Unlike the SMT interactions (Figure 4), the Nano and OSP finishes in THT testing showed similar interactions versus solders as shown in Figure 7.

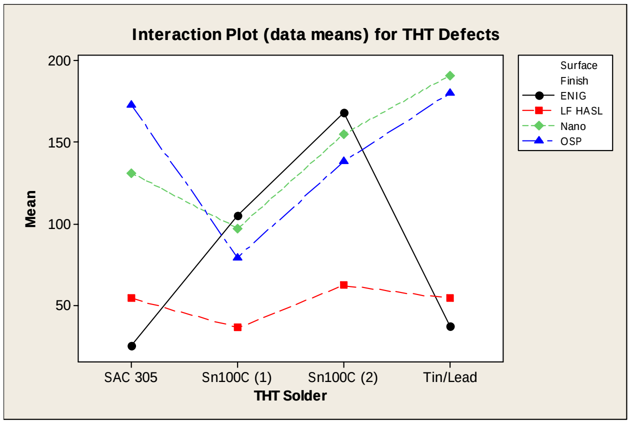

Figure 7. Interaction Plot for THT Defects

For the tin lead test vehicles, 98.5% of the defects were either `insufficient solder" or "solder bridging." For the assembly of THT components with lead-free solder, the most prevalent defect type was insufficient solder (53.6%), the second most prevalent was solder bridging (37%), and the third most was solder splatter (5.5%).

The three (3) Halogen free test vehicles soldered with tin lead had a much lower defect rate (130 defects/PWB), when compared to their equivalent FR4 test vehicles (177 defects/PWB), all having OSP surface finish and soldered in two types of lead free solders (SAC 305 NC, OA).

VISUAL INSPECTION CONCLUSIONS

The defect rate was much higher for THT components than for SMT components in lead free soldering, indicating the need for further THT process optimization. For SMT, no statistically significant difference was found for the 3 solders or within the 4 surface finishes used.

For THT components, there was no statistically significant difference for the solder types, but there was for the surface finishes. ENIG exhibit the most variability when used with various solders.

For THT components, the highest defect level was the combination of OSP and nano surface finish. The finish was applied by taking OSP clad PWBs, stripping the OSP finish, then applying the nano finish, which could have contributed to this high defect rate. In addition, there was a time delay between conducting the SMT and THT assembly. Therefore, it is recommended to try to minimize this time delay by conducting both operations in the same day. In summary, high quality assembly of components with lead free solder is achievable with careful selection of solder and finish materials.

RELIABILITY TESTING PLANS

Reliability testing phase is being performed in two major phases. Half of the test vehicles are being subjected to thermal cycling testing, and the other half to vibration testing. The thermal testing is in progress at this time, having completed 1,470 cycles. Vibration testing will completed by December 2008.

The thermal cycling test was designed to adhere to the IPC-9701standard "Performance Test Methods and Qualification Requirements for Surface Mount Solder Attachments". Thermal cycle testing to 63% failures was conducted to characterize the failure distribution. This test included continuous monitoring of the daisy chains on the test vehicle, performed by a data logger. Failure is defined as a maximum of 20% nominal resistance increase for a daisy chain circuit within a maximum of five consecutive reading scans.

Each of the 16 DoE and the two halogen free test vehicles to be thermally cycled has fourteen daisy chains for monitoring during cycling.

The thermal cycling dwell time at the temperature extremes was 15 minutes instead of 10 minutes in the IPC IPC-9701standard. The authors believe that the standard was developed to address tin/lead solder materials. SAC solders have a lower creep rate than tin/lead solders, which limits the amount of SAC solder damage during short dwell times. (Manock, 2008) The thermal profile used is shown in Figure 8.

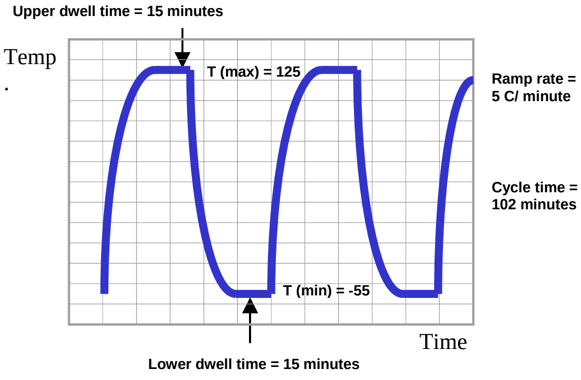

Figure 8. Thermal profile for Temperature cycling

Four of the 14 chains on the test vehicles were connected to discrete components (i.e. 0404, 0603, and 0805 resistors). The other ten daisy chains are connected to one component per daisy chain. Figure 9 shows the actual test setup in the environmental chamber.

Figure 9. Thermal cycling in the Chamber

RELIABILITY RESULTS TO DATE

For the purposes of analyzing the results of the thermal cycling data, a minimum of 63% of failures is preferred in order to plot the Weibull distribution for a single component type, From this distribution various points of interest can be calculated such as a number of cycles to 1% cumulative failure (N_1), number of cycles to 50% cumulative failure (N_{50}), or characteristic life (N_{63}). Weibull probability plots were used to model the failure data obtained using the Minitab® software formula:

$$F(x) = \{ax^{a-1} * e^{-(x/b)^a}\} / ba, x>0$$

After 1,470 thermal cycles, Nine out of the twelve lead-free test vehicles have experienced failures for the U16 (ceramic chip array BGA) and three out of the four tin lead PWBs have experienced failures for the same component. Figure 10 shows the Weibull distribution for the U16 component on a Lead free PWB.

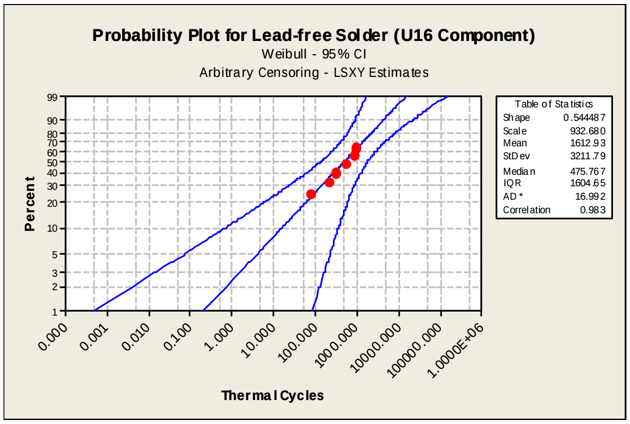

Figure 10. Weibull plot for U16 on a lead Free PWB

The Weibull distribution was used to determine the percent of test vehicles that are anticipated to fail by a particular time under test conditions. Table 6 shows the percentile failures of U16 using Weibull estimates.

Table 6. Percentiles Failures of U16 using Weibull Plots

Percent Failures	Designation	Lead free Percentile	Tin lead Percentile
1	N_1	0.0008	8.5
10	N_{10}	0.5	82.4
20	N_{20}	3.4	170.0
30	N_{30}	12.0	267.4
40	N_{40}	31.4	378.3
50	N_{50}	71.2	507.9
60	N_{60}	150.7	665.0
63.2	$N_{63.2}$	190.5	723.5
70	N_{70}	313.6	865.6
80	N_{80}	683.6	1,145.5
90	N_{90}	1,788.0	1,618.6

The only other component to fail was the 0805 resistor with the percentile failures shown in Table 7.

Table 7. Percentiles Failures of 0805 using Weibull Plots

Percent Failures	Designation	Lead free Cycles	Tin lead Cycles
1	N_1	0.2	9.4
10	N_{10}	15.0	85.9
20	N_{20}	59.3	174.4
30	N_{30}	140.4	271.5
40	N_{40}	271.6	381.1
50	N_{50}	475.8	508.3
60	N_{60}	794.3	661.5
63.2	$N_{63.2}$	932.7	718.3
70	N_{70}	1,311.6	855.9
80	N_{80}	2,235.2	1,125.6
90	N_{90}	4,314.9	1,578.1

Tables 6 and 7 indicate a dilemma shown in the 2 components that have reached a 63.2% failure rate after 1,470 thermal cycles to date. It seems that the inflection point, at which the reliability levels of the lead free and the tin lead test vehicles switch are at different designation points for the two components.

For the ceramic chip BGA (U16), in the range N_1–N_{50}: tin lead has higher reliability than lead free, while in the range N_{60}–N_{90}, lead free has higher reliability than tin lead. For 0805, at N_1 is the point at which lead free exhibits higher reliability than tin lead, while at N_{10}–N_{90}, tin lead has a higher reliability than lead free.

RELIABILITY CONCLUSIONS TO DATE

Thermal cycling is ongoing, having completed 1,470 cycles. Several issues were concluded while others need to be resolved by further testing and analysis:

- Halogen free test vehicles had early failures for all components. Further development is needed in Halogen free before it is viable as a bromide replacement for fire retardant functions.
- Test vehicles with High Tg FR4 laminate material are robust with only 2 component types (ceramic chip BGA and 0805 resistor) surpassing 63% failure threshold after 1,470 cycles of severe thermal conditions.
- Ceramic chip BGA component (U16) showed that tin lead is more reliable than lead-free for early failures, but less reliable for wear out failures. This is a crossover mechanism that indicates multiple failure modes.
- Resistor 0805 resistor showed reverse reliability properties than ceramic chip BGA.

In conclusion, there is inadequate data collected to date in order to fully evaluate tin lead versus lead free reliability.

FURTHER STUDY

The consortium plans to complete the reliability and subsequent failure analysis in 2009. The plan is to finish the phase IV project by the end of the grant period in September 2009.

- Complete thermal cycling until 63% failure threshold has been achieved for components on all daisy chain circuits.
- Conduct vibration testing on half of the test vehicles (16 in the full DoE + 2 Halogen free)
- Failure analysis of failed components to determine actual failure modes.

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