NASA/DOD LEAD-FREE ELECTRONICS PROJECT: -20°C TO +80°C THERMAL CYCLE TEST

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ABSTRACT
Thermal cycle testing was conducted by Boeing Research & Technology (Seattle) for the NASA/DoD Lead-Free Electronics Project. The NASA/DoD Project is testing the reliability of lead-free solder joints against the requirements of the aerospace/military community and is building on the prior work done by the Joint Council on Aging Aircraft/Joint Group on Pollution Prevention (JCAA/JG-PP) Lead-Free Solder Project.

Test vehicles were assembled using lead-free and SnPb solders and a variety of component types and the test vehicles were then thermally cycled from -20°C to +80°C. At the time that this paper was written, 11,676 thermal cycles had been accumulated.

The solder joints on the components were electrically monitored using event detectors and any solder joint failures were recorded on a Labview-based data collection system. The failures of a given component type attached with SnPb solder were compared to the failures of the same component type attached with lead-free solders by using Weibull analysis.

Key words: lead-free, thermal cycle, Weibull, CTE, NASA, DoD

INTRODUCTION
Aerospace and military electronics are currently exempt from the European RoHS (Restriction of Hazardous Substances) Legislation which bans lead use in electronics. However, as the international commercial electronics industry changes over to lead-free technology in order to satisfy the European legislation, it is becoming increasingly difficult for aerospace and military programs to procure electronics made with SnPb solder. For this reason, the NASA-DoD Lead-Free Electronics Project was started in 2006 to determine whether lead-free solders and finishes (before and after rework) are suitable for use in high reliability electronics. The Project is managed by NASA. The NASA-DoD Lead-Free Electronics Project includes members from the U.S. Air Force, BAE Systems, Boeing, Celestica, Harris, Lockheed Martin, NASA, NAVSEA Warfare Centers (Crane), Raytheon, Rockwell-Collins, ACI, Lockheed Martin, and Texas Instruments, among others. This project is a follow-on to the 2001 Joint Council on Aging Aircraft/Joint Group on Pollution Prevention (JCAA/JG-PP) Lead-Free Solder Project which was the first group to test the reliability of lead-free solder joints against the requirements of the aerospace/military community.

The Project members wrote a Project Plan [1] which describes the assembly of the test vehicles and the testing to be done. The testing includes thermal cycling, vibration, mechanical shock, combined vibration/thermal cycling, and copper dissolution testing.

OBJECTIVE AND APPROACH
The objective of this study was to determine the effects of thermal cycling (-20°C to +80°C) on the relative reliability of lead-free and tin/lead solder joints (i.e., which solder survives the longest).

The test vehicle designed for this project was a six-layer circuit board 12.75 inches wide by 9 inches high by 0.090 inches thick (32.39 cm by 22.86 cm by 0.23 cm) (Figures 1 and 2). The design used 0.5 ounce copper and a laminate with a high glass transition temperature (Tg of 170 degrees C, Isola 370HR). The test vehicle was populated with 63 components consisting of ceramic leadless chip carriers (CLCC's), QFN's, Alloy 42 TSOP's, TQFP's, BGA's, CSP's, and PDIP's. The components contained internal wire bonds so that once mounted on the test vehicle, each component would complete an electrical circuit that could be monitored during testing. Failure of a solder joint would cause a break in the electrical circuit that could be detected by an event detector. Each test vehicle also had a daisy-chained net of twelve 0.016 inch (0.041 cm) diameter plated through holes so that the reliability of the holes could be determined. The plated through holes were filled with solder during the wave solder operation. Each component location on the test vehicles was given a unique reference designator number.

The solder alloys selected for test were:

Sn3.0Ag0.5Cu paste for reflow soldering (abbreviated as SAC305)
Sn0.7Cu0.05Ni for wave soldering and as a paste for reflow soldering (abbreviated as SN100C)
Sn37Pb for reflow and wave soldering (abbreviated as SnPb)
Sn4.0Ag0.5Cu for BGA balls (abbreviated as SAC405)
Sn1.0Ag0.5Cu for CSP balls (abbreviated as SAC105)

The SAC305 alloy was chosen because it is currently the preferred alloy for use in lead-free commercial electronics. The SN100C alloy was chosen because it has been widely used around the world with good results. SAC405 and SAC105 are alloys commonly used in the balls on area array devices. Finally, eutectic SnPb was included to act as the control alloy.

The test vehicles were divided into two types, i.e., "Manufactured" test vehicles and "Rework" test vehicles. Both types were made using an immersion silver board finish (although an ENIG PWB finish was used on a few of the test vehicles). The lead-free "Manufactured" and "Rework" test vehicles were assembled using lead-free solders and lead-free reflow and wave soldering profiles. The SnPb "Manufactured" and "Rework" test vehicles were assembled using eutectic SnPb solder and SnPb reflow and wave soldering profiles and were used as the controls. A 5-mil laser cut stencil was used during paste application.

As the name suggests, selected components on the "Rework" test vehicles were reworked. The components were removed; residual solder was cleaned from the pads using solder wick; and new components were attached using either SnPb or lead-free solder.

The "Rework" test vehicles were also populated with a number of mixed technology components (i.e., SnPb paste combined with a lead-free component finish or lead-free paste combined with a SnPb component finish).

The CLCC's with a lead-free termination finish were produced by dipping of gold-plated CLCC's into the respective molten solders. In addition, some tin-plated TQFP's were dipped into either molten SnPb or molten SAC305 to simulate a tin whisker mitigation process.

The component finishes used included SnPb, matte Sn, SnBi, SAC305, SAC405, and SAC105.

Table 1 lists the components used on the SnPb and lead-free "Manufactured" test vehicles; the finish on each component; and the solders used for assembly.

Table 2 lists the components used on the SnPb and lead-free "Rework" test vehicles; the finish on each component; the solders used for assembly; and which components were actually reworked.

One hundred and ninety three test vehicles were assembled at BAE Systems in Irving, TX. One hundred and twenty of these test vehicles were "Manufactured" PWA's and seventy three were "Rework" PWA's. The reflow profiles for initial assembly using either SnPb or the lead-free solder pastes are shown in Figures 3 and 4. The wave soldering profiles used for tin/lead and lead-free wave soldering can be found in [1]. Wave soldering with SnPb was done at BAE Systems and the lead-free wave soldering was done at Scorpio Solutions in Garfield Heights, Ohio. Eighteen components were reworked on each of the "Rework" test vehicles (six BGA's; six CSP's; two PDIP's; and four TSOP's). In general, solder wire was used for reworking the components. The BGA's and CSP's, however, were replaced using flux only or by applying paste to the balls and then using a hot air rework station to form the solder joints (see Table 2). During rework of the BGA's and CSP's, a SnPb thermal profile was used for the SnPb "Rework" test vehicles and a lead-free thermal profile was used on the lead-free "Rework" test vehicles. The rework profiles for removing and replacing the BGA's and the CSP's using a hot air rework station can also be found in [1]. All rework was done at BAE Systems, Lockheed Martin, and Rockwell-Collins. Each rework site focused on the test vehicles for a specific test to eliminate effects due to site-to-site variations in rework procedures.

After assembly and rework, all test vehicles were thermally aged at 100°C for 24 hours. Twenty one test vehicles were then delivered to Boeing for testing using a -20°C to +80°C thermal cycle. These consisted of 5 SnPb "Manufactured" test vehicles; 5 lead-free "Manufactured" test vehicles assembled with SAC305 paste; 6 SnPb "Rework" test vehicles; and 5 lead-free "Rework" test vehicles. All of the test vehicles had an immersion silver PWB finish except for one SnPb "Rework" test vehicle (Test Vehicle 156) which had an ENIG PWB finish.

On the SnPb "Rework" test vehicles, all of the CLCC's were finished with SAC305 (on the pads and in the castellations) and assembled with SnPb paste which resulted in lead-free solder joints contaminated with Pb after assembly (see Table 2). In addition, some of the BGA's combined SAC405 balls with SnPb solder paste which resulted in lead-free solder joints contaminated with Pb (on reworked and unreworked BGA's). Also, some of the CSP's combined SAC105 balls with SnPb solder paste (reworked and unreworked). This mixing was done intentionally in order to determine the effects of lead-contamination upon lead-free solder reliability. Inductively coupled plasma (ICP) spectroscopy was used by Boeing to quantify the amount of Pb in these solder joints on one of the SnPb "Rework" test vehicles (see Table 3; Test Vehicle ID # 149). The solder joints were removed with a scalpel, dissolved in mixed nitric/hydrochloric acid, and the solution was analyzed by ICP spectroscopy.

On the lead-free "Rework" test vehicles, all of the CLCC's and QFN's were finished with SnPb and assembled with SAC305 paste which resulted in lead-free solder joints contaminated with Pb after assembly (see Table 2). In addition, some of the BGA's combined SnPb balls with SAC305 solder paste which resulted in lead-free solder joints contaminated with Pb (on unreworked BGA's). Also, some of the CSP's combined SAC105 balls with SnPb solder paste (after rework). This mixing was done intentionally in order to determine the effects of lead-contamination upon lead-free solder reliability. Again, inductively coupled plasma (ICP) spectroscopy was used by

Boeing to quantify the amount of Pb in these solder joints on one of the Pb-Free "Rework" test vehicles (see Table 3; Test Vehicle ID # 193).

All of the ICP analyses appeared reasonable with the possible exception of the two TSOP's and the BGA U43 analyses. The copper content for these components were higher than expected. It is probable that copper was removed from the test vehicle pads along with the solder when the solder joints were cut from the test vehicle using a scapel.

The Thermotron thermal cycling chamber used for this test is shown in Figure 5. The test vehicles were held vertically in racks (see Figure 6) which allowed airflow between the vehicles. The thermal cycle used was -20°C to +80°C with dwell times of 30 minutes (hot dwell) and 10 minutes (cold dwell) and ramp rates of approximately 9.5°C/minute (cooling) and 7.2°C/minute (heating). Figure 7 shows actual air and test vehicle temperatures recorded during the test.

Each of the 63 components and the PTH net on each test vehicle were individually monitored using Analysis Tech 256STD Event Detectors (set to a 300 ohm threshold) combined with Labview-based data collection software (Figure 8).

For those component types that had a significant number of failures, Weibull plots of the failure data were created to determine the beta (slope) and the characteristic lifetime (time to fail 63.2% of the population, also called alpha or eta) for each component type. In some cases, the last few components to fail were suspended because the data points fell well off of the linear portion of the Weibull plot. No early component failures were suspended.

Using the following equation, the number of cycles required to fail a specific percentage of components, F(t), can be calculated if alpha and beta are known.

$$tp = \alpha\,[-\ln\{1-F(t)*0.01\}]^{1/\beta}$$

One of the goals of this test was to produce data that could be used to verify life prediction models that are being developed for SnPb and lead-free solders. With this goal in mind, CTE measurements were made on selected components to yield the data required by thermal cycle models (see Table 4 and Figure 9). A Netzsch 402 Dilatometer was used to make the CTE measurements. Additional data on the components (dimensions, CTE's, etc.) can be found on the project's website [2]. Many of the components types used on the NASA/DoD test vehicle were also used on the JCAA/JG-PP Lead-Free Solder Project test vehicle and characterization data for these components and for the PWB laminate can be found in [3].

RESULTS

At the time that this paper was written, 11,676 thermal cycles had been accumulated. All of the TSOP-50's and many of the ceramic leadless chip carriers (CLCC-20's) and TQFP-144's had failed. No failures were seen for the pure Pb-free BGA-225's and CSP-100's and the PDIP-20's and QFN-20's had almost no failures. Note: In the following sections, the solder is listed first followed by the component finish, e.g., SnPb/Sn.

Results for CLCC-20's

The combination of a Pb-free solder with a Pb-free component finish (SAC305/SAC305) slightly outperformed the SnPb/SnPb control. For the mixed solders, SAC305/SnPb was approximately equivalent to the SnPb control and SnPb/SAC305 performed slightly worse than the SnPb control (Figure 10).

No CLCC's were reworked.

Results for TSOP-50's

With the Alloy 42 TSOP's, the combination of a Pb-free solder with a Pb-free component finish (SAC305/SnBi) outperformed the SnPb/SnPb and SnPb/Sn controls (Figure 11).

Surprisingly, SnPb/SnPb TSOP's that were reworked with either SnPb/Sn or SnPb/SnPb performed much better than the SnPb/Sn and SnPb/SnPb controls (Figures 12 and 13). It was thought that maybe the reworked components had larger solder joints since the rework was done by hand using solder wire. However, microsections of TSOP solder joints from as-assembled test vehicles did not show any apparent differences between reworked and unreworked TSOP's (Figures 14 and 15). This observation can not be explained at this time but the cause may become apparent during post-test failure analysis. All microsections of as-assembled test vehicles used in this paper were done by Sandia National Laboratories for the Project and are used with permission.

In contrast to the reworked SnPb solder joints, reworked SAC305 solder joints exhibited reduced reliability when compared to unreworked SAC305/SnBi joints (Figure 16).

Results for BGA-225's

At 11,676 cycles, all of the control BGA's (SnPb solder/SnPb balls) and the SAC305/SnPb mixed technology BGA's had failed. No failures were noted for the pure Pb-free BGA's (SAC305/SAC405).

SnPb/SnPb BGA's reworked with flux/SnPb outperformed the unreworked SnPb/SnPb controls. As with the reworked SnPb TSOP's, this increase in reliability after rework is not understood. No failures were seen for SAC305/SAC405 BGA's reworked with flux/SAC405 (Figure 17).

SAC305/SAC405 reworked with SnPb/SAC405 had only one failure (at 307 cycles). SnPb/SnPb reworked with

SnPb/SAC405 had three failures (at 74, 861, and 11,372 cycles).

BGA's with mixed solders underperformed the SnPb/SnPb controls (Figure 18). Both SAC305/SnPb and SnPb/SAC405 BGA's had early failures when compared to SnPb/SnPb. A microsection of a SnPb/SAC405 BGA (pre-test) showed the expected incomplete solder mixing that results from the use of a SnPb reflow profile (Figure 20). Microsections of several SAC305/SnPb BGA's (pre-test) showed voiding at the PWB pads which could explain the early failures observed for that combination (Figure 21).

Results for CSP-100's

At 11,676 cycles, all of the control CSP's (SnPb solder/SnPb balls) had failed. No failures were noted for the pure Pb-free CSP's (SAC305/SAC105) or for the SAC305/SAC105 CSP's reworked with flux/SAC105.

SnPb/SnPb CSP's reworked with flux/SnPb outperformed the unreworked SnPb/SnPb controls (Figure 19). As with the reworked SnPb TSOP's and BGA's, this increase in reliability after rework is not understood. SAC305/SAC105 and SnPb/SnPb joints reworked with SnPb/SAC105 exhibited no failures.

CSP's with mixed solders (SAC305/SnPb) outperformed the SnPb/SnPb control (Figure 19). In contrast to the SAC305/SnPb BGA's, no early failures were seen.

Results for TQFP-144's

With the TQFP-144's, SAC305/Sn performed better than the controls (SnPb/Sn and SnPb/NiPdAu, Figure 22).

Dipping Sn plated leads in either SAC305 or SnPb was explored as a potential tin whisker mitigation technique. SAC305 combined with SAC305 dipped leads performed better than than the SnPb/Sn control. SnPb solder combined with SnPb dipped leads was equivalent to the SnPb/Sn control (Figure 23).

Results for PDIP-20's

At 11,676 cycles, only three PDIP failures were observed (at 6061, 7121, and 10,041 cycles).

Results for QFN-20's

At 11,676 cycles, only one QFN failure was observed (at 7 cycles).

Results for Plated-Through Holes (PTH's)

No PTH net failures were noted (out of 21 nets).

The overall test results for pure SnPb and SAC305 solder joints are summarized in Figure 24. The number of thermal cycles needed to fail 63.2% of each component population is shown for each component type for which there was sufficient data. In every case, SAC305 outperformed eutectic SnPb solder regardless of the component type. The difference in performance between the SnPb and SAC305 solders appeared to increase as the components became more compliant.

It has been shown that conditions that highly stress the solder joints by maximizing the CTE difference between the PWB and the component will favor SnPb over SAC [4]. Conversely, conditions that minimize the stress put on the solder joints (e.g., use of compliant components such as BGA's and/or a thermal cycle with a small delta T) will favor SAC over SnPb. The current test falls into the latter category (small delta T) and we can say with some confidence that the lead-free alloys tested will outperform eutectic SnPb under field conditions that are less stressful than the -20 to +80°C thermal cycle test conditions.

The thermal cycling data from this project can be used to validate computational models for predicting solder joint lifetimes. A validated thermal cycle model will allow field lifetimes to be predicted for any component on any circuit assembly design under any field condition.

CONCLUSIONS

Under the conditions of this test, Sn3.0Ag0.5Cu (SAC305) solder joints were always more reliable than eutectic SnPb joints regardless of component type (CLCC, TSOP, BGA, CSP, or TQFP). These results suggest that SAC305 will outperform eutectic SnPb under field conditions that are less stressful than the -20 to +80°C thermal cycle test conditions used in this test.

Rework of the SnPb solder joints on the TSOP's, BGA's, and CSP's increased their performance as compared to unreworked controls. This result was unexpected and no explanation can be offered at this time. In contrast, rework of SAC305 solder joints decreased their performance (based on TSOP data only).

The use of mixed solder systems with BGA's (SAC305/SnPb and SnPb/SAC405) resulted in some early failures (as compared to a SnPb/SnPb control). In contrast, the CSP's assembled using a mixed solder system (SAC305/SnPb) performed better than the SnPb/SnPb controls.

ACKNOWLEDGEMENTS

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REFERENCES

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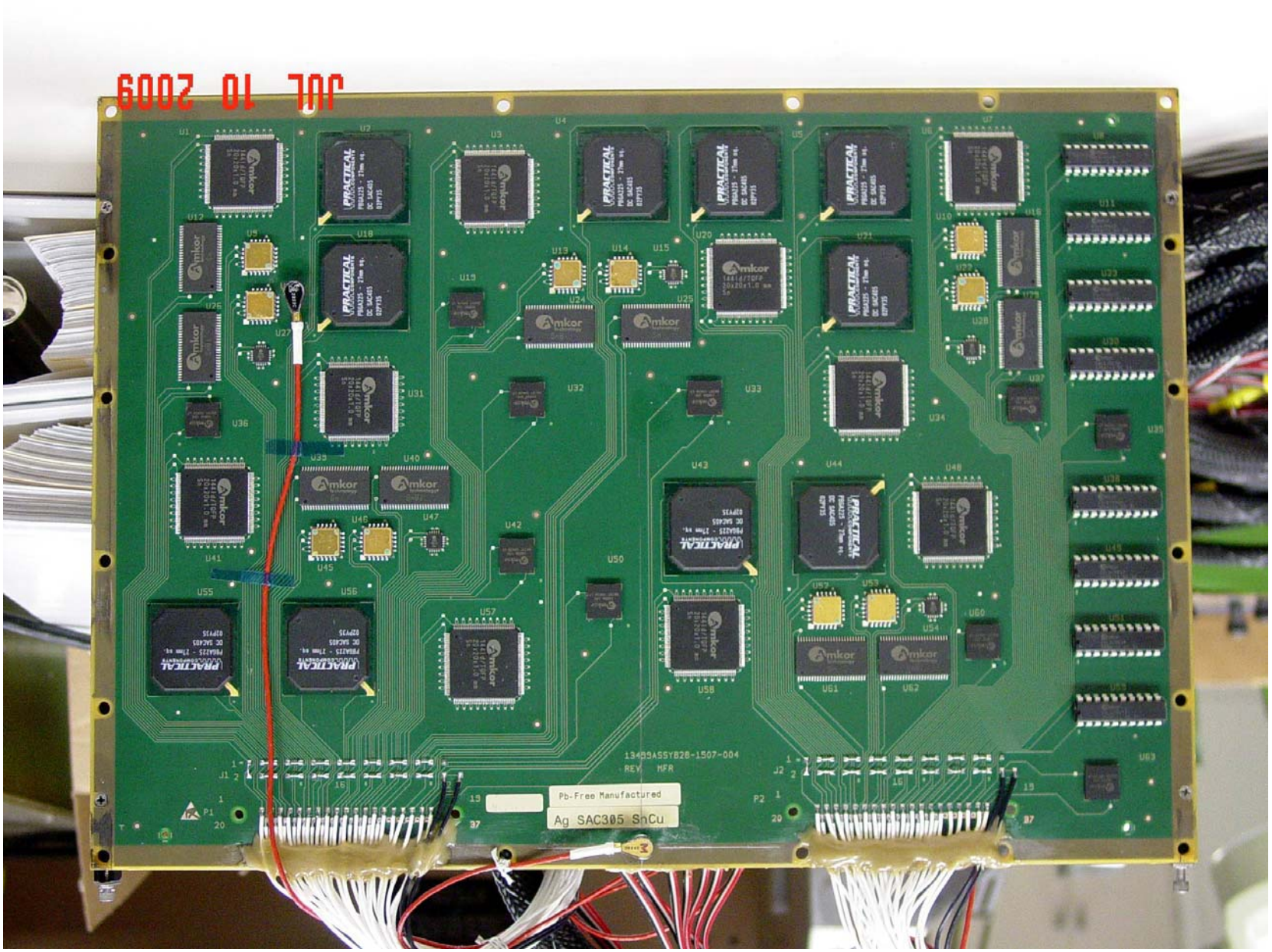


Figure 1. NASA/DoD Test Vehicle

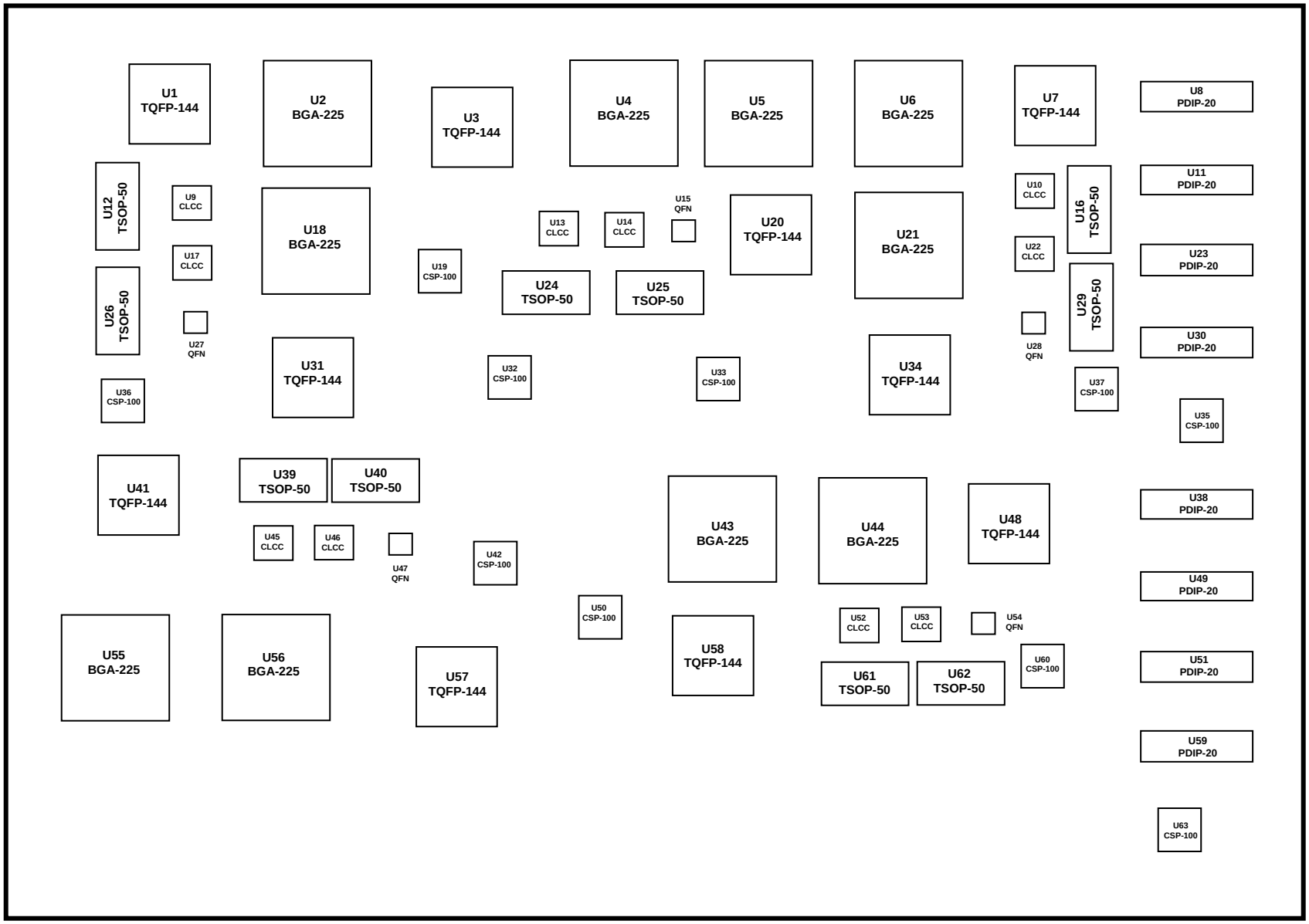


Figure 2. NASA/DoDTest Vehicle Schematic

Table 1. Assembly Matrix for “Manufactured” Thermal Cycle Test Vehicles

		SnPb "Manufactured" Test Vehicles (Test Vehicles 10 - 14)			Pb-Free "Manufactured" Test Vehicles (Test Vehicles 50 - 54)		
RefDes	**Component**	**Component Finish**	**Reflow Solder Alloy**	**Wave Solder Alloy**	**Component Finish**	**Reflow Solder Alloy**	**Wave Solder Alloy**
						Set A	
U18	BGA-225	SAC405	SnPb		SnPb	SAC305	
U43	BGA-225	SAC405	SnPb		SnPb	SAC305	
U04	BGA-225	SAC405	SnPb		SnPb	SAC305	
U06	BGA-225	SAC405	SnPb		SnPb	SAC305	
U55	BGA-225	SAC405	SnPb		SnPb	SAC305	
U02	BGA-225	SnPb	SnPb		SAC405	SAC305	
U05	BGA-225	SnPb	SnPb		SAC405	SAC305	
U21	BGA-225	SnPb	SnPb		SAC405	SAC305	
U44	BGA-225	SnPb	SnPb		SAC405	SAC305	
U56	BGA-225	SnPb	SnPb		SAC405	SAC305	
U09	CLCC-20	SAC305	SnPb		SnPb	SAC305	
U13	CLCC-20	SAC305	SnPb		SnPb	SAC305	
U22	CLCC-20	SAC305	SnPb		SnPb	SAC305	
U46	CLCC-20	SAC305	SnPb		SnPb	SAC305	
U53	CLCC-20	SAC305	SnPb		SnPb	SAC305	
U10	CLCC-20	SnPb	SnPb		SAC305	SAC305	
U14	CLCC-20	SnPb	SnPb		SAC305	SAC305	
U17	CLCC-20	SnPb	SnPb		SAC305	SAC305	
U45	CLCC-20	SnPb	SnPb		SAC305	SAC305	
U52	CLCC-20	SnPb	SnPb		SAC305	SAC305	
U32	CSP-100	SAC105	SnPb		SnPb	SAC305	
U33	CSP-100	SAC105	SnPb		SnPb	SAC305	
U35	CSP-100	SAC105	SnPb		SnPb	SAC305	
U50	CSP-100	SAC105	SnPb		SnPb	SAC305	
U63	CSP-100	SAC105	SnPb		SnPb	SAC305	
U19	CSP-100	SnPb	SnPb		SAC105	SAC305	
U36	CSP-100	SnPb	SnPb		SAC105	SAC305	
U37	CSP-100	SnPb	SnPb		SAC105	SAC305	
U42	CSP-100	SnPb	SnPb		SAC105	SAC305	
U60	CSP-100	SnPb	SnPb		SAC105	SAC305	
U08	PDIP-20	NiPdAu		SnPb	See Final Report		SN100C
U23	PDIP-20	NiPdAu		SnPb	See Final Report		SN100C
U49	PDIP-20	NiPdAu		SnPb	See Final Report		SN100C
U59	PDIP-20	NiPdAu		SnPb	See Final Report		SN100C
U11	PDIP-20	Sn		SnPb	See Final Report		SN100C
U30	PDIP-20	Sn		SnPb	See Final Report		SN100C
U38	PDIP-20	Sn		SnPb	See Final Report		SN100C
U51	PDIP-20	Sn		SnPb	See Final Report		SN100C
U15	QFN-20	Matte Sn	SnPb		Matte Sn	SAC305	
U27	QFN-20	Matte Sn	SnPb		Matte Sn	SAC305	
U28	QFN-20	Matte Sn	SnPb		Matte Sn	SAC305	
U47	QFN-20	Matte Sn	SnPb		Matte Sn	SAC305	
U54	QFN-20	Matte Sn	SnPb		Matte Sn	SAC305	
U01	TQFP-144	Matte Sn	SnPb		SnPb Dip	SAC305	
U07	TQFP-144	Matte Sn	SnPb		SnPb Dip	SAC305	
U20	TQFP-144	Matte Sn	SnPb		SnPb Dip	SAC305	
U41	TQFP-144	Matte Sn	SnPb		SnPb Dip	SAC305	
U58	TQFP-144	Matte Sn	SnPb		SnPb Dip	SAC305	
U03	TQFP-144	SnPb Dip	SnPb		Matte Sn	SAC305	
U31	TQFP-144	SnPb Dip	SnPb		Matte Sn	SAC305	
U34	TQFP-144	SnPb Dip	SnPb		Matte Sn	SAC305	
U48	TQFP-144	SnPb Dip	SnPb		Matte Sn	SAC305	
U57	TQFP-144	SnPb Dip	SnPb		Matte Sn	SAC305	
U12	TSOP-50	SnBi	SnPb		SnPb	SAC305	
U25	TSOP-50	SnBi	SnPb		SnPb	SAC305	
U29	TSOP-50	SnBi	SnPb		SnPb	SAC305	
U39	TSOP-50	SnBi	SnPb		SnPb	SAC305	
U61	TSOP-50	SnBi	SnPb		SnPb	SAC305	
U16	TSOP-50	SnPb	SnPb		SnBi	SAC305	
U24	TSOP-50	SnPb	SnPb		SnBi	SAC305	
U26	TSOP-50	SnPb	SnPb		SnBi	SAC305	
U40	TSOP-50	SnPb	SnPb		SnBi	SAC305	
U62	TSOP-50	SnPb	SnPb		SnBi	SAC305	

Table 2. Assembly Matrix for "Rework" Thermal Cycle Test Vehicles

		SnPb "Rework" Test Vehicles (Test Vehicles 129 - 133 and 156 [on ENIG])					Pb-Free "Rework" Test Vehicles (Test Vehicles 169 - 173)				
RefDes	Component	Original Component Finish	Reflow Solder Alloy	Wave Solder Alloy	New Component Finish	Rework Solder	Component Finish	Reflow Solder Alloy	Wave Solder Alloy	New Component Finish	Rework Solder
U04	BGA-225	SAC405	SnPb				SnPb	SAC305			
U55	BGA-225	SAC405	SnPb				SnPb	SAC305			
U05	BGA-225	SAC405	SnPb				SnPb	SAC305			
U44	BGA-225	SAC405	SnPb				SnPb	SAC305			
U18	BGA-225	SnPb	SnPb		SAC405	SnPb	SAC405	SAC305		SAC405	SnPb
U43	BGA-225	SnPb	SnPb		SAC405	SnPb	SAC405	SAC305		SAC405	SnPb
U06	BGA-225	SnPb	SnPb		SAC405	SnPb	SAC405	SAC305		SAC405	SnPb
U02	BGA-225	SnPb	SnPb		SnPb	Flux Only	SAC405	SAC305		SAC405	Flux Only
U21	BGA-225	SnPb	SnPb		SnPb	Flux Only	SAC405	SAC305		SAC405	Flux Only
U56	BGA-225	SnPb	SnPb		SnPb	Flux Only	SAC405	SAC305		SAC405	Flux Only
U09	CLCC-20	SAC305	SnPb				SnPb	SAC305			
U10	CLCC-20	SAC305	SnPb				SnPb	SAC305			
U13	CLCC-20	SAC305	SnPb				SnPb	SAC305			
U14	CLCC-20	SAC305	SnPb				SnPb	SAC305			
U17	CLCC-20	SAC305	SnPb				SnPb	SAC305			
U22	CLCC-20	SAC305	SnPb				SnPb	SAC305			
U45	CLCC-20	SAC305	SnPb				SnPb	SAC305			
U46	CLCC-20	SAC305	SnPb				SnPb	SAC305			
U52	CLCC-20	SAC305	SnPb				SnPb	SAC305			
U53	CLCC-20	SAC305	SnPb				SnPb	SAC305			
U32	CSP-100	SAC105	SnPb				SnPb	SAC305			
U35	CSP-100	SAC105	SnPb				SnPb	SAC305			
U63	CSP-100	SAC105	SnPb				SnPb	SAC305			
U36	CSP-100	SAC105	SnPb				SAC105	SAC305			
U50	CSP-100	SnPb	SnPb		SnPb	Flux Only	SAC105	SAC305		SAC105	Flux Only
U19	CSP-100	SnPb	SnPb		SnPb	Flux Only	SAC105	SAC305		SAC105	Flux Only
U37	CSP-100	SnPb	SnPb		SnPb	Flux Only	SAC105	SAC305		SAC105	Flux Only
U33	CSP-100	SnPb	SnPb		SAC105	SnPb	SAC105	SAC305		SAC105	SnPb
U42	CSP-100	SnPb	SnPb		SAC105	SnPb	SAC105	SAC305		SAC105	SnPb
U60	CSP-100	SnPb	SnPb		SAC105	SnPb	SAC105	SAC305		SAC105	SnPb
U08	PDIP-20	NiPdAu		SnPb			Sn		SN100C		
U23	PDIP-20	NiPdAu		SnPb			Sn		SN100C		
U49	PDIP-20	NiPdAu		SnPb			Sn		SN100C		
U59	PDIP-20	Sn		SnPb			Sn		SN100C		
U30	PDIP-20	Sn		SnPb			Sn		SN100C		
U38	PDIP-20	Sn		SnPb			Sn		SN100C		
U11	PDIP-20	SnPb		SnPb	Sn	SnPb	Sn		SN100C	Sn	SN100C
U51	PDIP-20	SnPb		SnPb	Sn	SnPb	Sn		SN100C	Sn	SN100C
U15	QFN-20	Matte Sn	SnPb				SnPb	SAC305			
U27	QFN-20	Matte Sn	SnPb				SnPb	SAC305			
U28	QFN-20	Matte Sn	SnPb				SnPb	SAC305			
U47	QFN-20	Matte Sn	SnPb				SnPb	SAC305			
U54	QFN-20	Matte Sn	SnPb				SnPb	SAC305			
U03	TQFP-144	NiPdAu	SnPb				NiPdAu	SAC305			
U31	TQFP-144	NiPdAu	SnPb				NiPdAu	SAC305			
U34	TQFP-144	NiPdAu	SnPb				NiPdAu	SAC305			
U48	TQFP-144	NiPdAu	SnPb				NiPdAu	SAC305			
U57	TQFP-144	NiPdAu	SnPb				NiPdAu	SAC305			
U01	TQFP-144	SnPb Dip	SnPb				SAC 305 Dip	SAC305			
U07	TQFP-144	SnPb Dip	SnPb				SAC 305 Dip	SAC305			
U20	TQFP-144	SnPb Dip	SnPb				SAC 305 Dip	SAC305			
U41	TQFP-144	SnPb Dip	SnPb				SAC 305 Dip	SAC305			
U58	TQFP-144	SnPb Dip	SnPb				SAC 305 Dip	SAC305			
U29	TSOP-50	Sn	SnPb				SnBi	SAC305			
U39	TSOP-50	Sn	SnPb				SnBi	SAC305			
U61	TSOP-50	Sn	SnPb				SnBi	SAC305			
U16	TSOP-50	SnBi	SnPb				SnPb	SAC305			
U40	TSOP-50	SnBi	SnPb				SnPb	SAC305			
U62	TSOP-50	SnBi	SnPb				SnPb	SAC305			
U12	TSOP-50	SnPb	SnPb		SnPb	SnPb	Sn	SAC305		Sn	SnPb
U25	TSOP-50	SnPb	SnPb		SnPb	SnPb	Sn	SAC305		Sn	SnPb
U24	TSOP-50	SnPb	SnPb		Sn	SnPb	SnBi	SAC305		SnBi	SAC305
U26	TSOP-50	SnPb	SnPb		Sn	SnPb	SnBi	SAC305		SnBi	SAC305

Mixed SnPb/Pb-Free

Sn Plating Dipped for Whisker Mitigation

SuperM.O.L.E.(r) Gold SPC V5.22 - Lead Free.mpc
File Tag:SM_SORMBED_000139 Date: 12/02/07

M.O.L.E.(r) STATUS
Max Internal T: 27C
Battery: 4.246
Points: 424

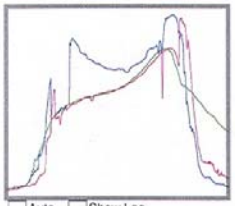
Active: X234XX
Interval: 00:00:01.0

Date: 12/02/07
Time: 09:25:47 V08.58

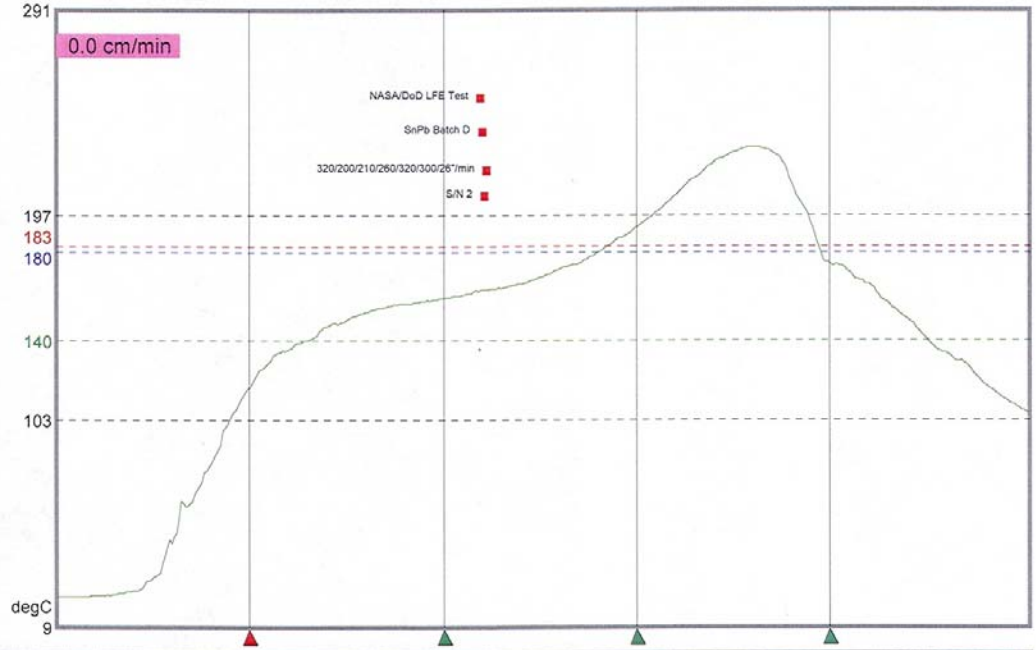
Tool status box

NASA/DoD Lead Free

26"/min
826-00004-205



Auto Show Lag

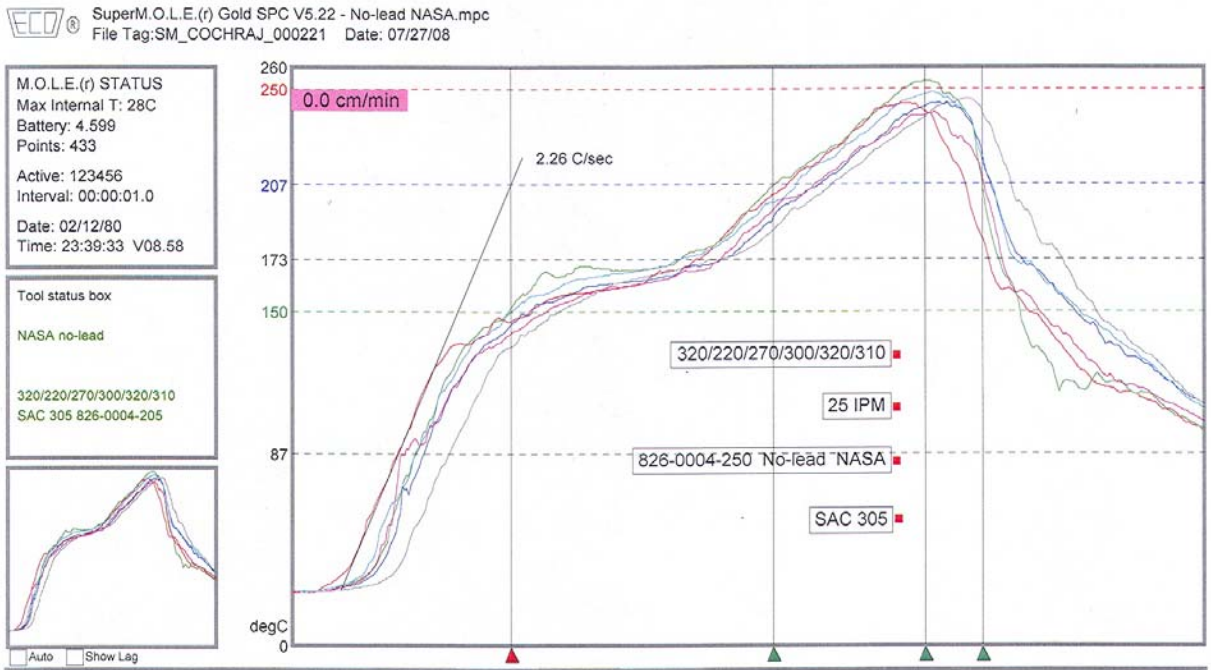


	Value	C1 = 00:01:24 r	C2 = 00:02:48 r	C3 = 00:04:12 r	C4 = 00:05:36 r	Units
◦	open					
◦	bad t/c					
▪	below U50 CSP center edge	119	159	192	174	degC
◦	trailing end U4/U55					
◦	open					
◦	open					

	T Above Ref	Low = 140	Med = 180	Hi = 183	Cure Factor	Units
◦	open					
◦	bad t/c					
▪	below U50 CSP center edge	00:04:32	00:01:37	00:01:32	0%	Time
◦	trailing end U4/U55					
◦	open					
◦	open					

	Statistics	Minimum	Minimum X	Maximum	Maximum X	Average	Std Deviation	Units
◦	open							
◦	bad t/c							
▪	below U50 CSP center edge	23	00:00:00 r	228	00:05:00 r	143.9	56.1	degC
◦	trailing end U4/U55							
◦	open							
◦	open							

Figure 3. Reflow Profile for SnPb Solder Paste (Source: BAE Systems)



	Value	C1 = 00:01:43 r	C2 = 00:03:48 r	C3 = 00:05:00 r	C4 = 00:05:27 r	Units
•	South of U37 CSP	146	203	239	182	degC
•	North of U32 hybrid	144	193	242	218	degC
•	North of U42 CSP	151	207	253	204	degC
•	North of U4	140	196	238	209	degC
•	South of U58	149	199	248	216	degC
•	North of U36 CSP	134	187	237	238	degC

	T Above Ref	Low = 150	Med = 207	Hi = 250	Cure Factor	Units
•	South of U37 CSP	00:03:57	00:01:24	00:00:00	0%	Time
•	North of U32 hybrid	00:04:17	00:01:21	00:00:00	0%	Time
•	North of U42 CSP	00:04:02	00:01:38	00:00:19	0%	Time
•	North of U4	00:03:54	00:01:21	00:00:00	0%	Time
•	South of U58	00:04:29	00:01:33	00:00:00	0%	Time
•	North of U36 CSP	00:04:15	00:01:25	00:00:00	0%	Time

	Statistics	Minimum	Minimum X	Maximum	Maximum X	Average	Std Deviation	Units
•	South of U37 CSP	24	00:00:00 r	243	00:04:48 r	151.6	56.7	degC
•	North of U32 hybrid	24	00:00:00 r	244	00:05:06 r	151.9	59.8	degC
•	North of U42 CSP	24	00:00:06 r	253	00:04:59 r	152.7	63.2	degC
•	North of U4	24	00:00:00 r	239	00:05:04 r	148.5	58.2	degC
•	South of U58	24	00:00:00 r	248	00:05:02 r	156.3	60.1	degC
•	North of U36 CSP	24	00:00:04 r	246	00:05:18 r	150.6	63.5	degC

Figure 4. Reflow Profile for SAC305 Solder Pastes (Source: BAE Systems)

Table 3. Chemical Analysis of Solder Joints Contaminated with Pb (by ICP Spectroscopy)

Component	Ref. Des.	Test Vehicle ID	Reworked?	Component Finish	Board Finish	Solder	%Ag	%Cu	%Pb	%Sn	%Bi	%Au
BGA-225	U04	149	No	SAC405	Ag	Sn37Pb	3.46	0.94	3.77	91.71	0.00	0.13
BGA-225	U04	193	No	Sn37Pb	Ag	SAC305	0.31	0.26	33.91	65.44	0.00	0.08
BGA-225	U43	193	Yes	SAC405	Residual SAC	Sn37Pb	3.13	3.18**	5.52	88.07	0.00	0.10
CLCC-20	U09	149	No	SAC305	Ag	Sn37Pb	1.35	0.49	24.68	73.48	0.00	0.00
CLCC-20	U09	193	No	Sn37Pb	Ag	SAC305	1.92	0.39	16.46	81.19	0.04	0.00
CSP-100*	U33	149	Yes	SAC105	Residual Sn37Pb	Sn37Pb	0.90	0.73	1.81	96.23	0.00	0.33
CSP-100*	U33	193	Yes	SAC105	Residual SAC	Sn37Pb	0.83	0.63	4.43	93.82	0.00	0.29
QFN-20	U15	193	No	SnPb	Ag	SAC305	3.39	0.85	0.93	94.83	0.00	0.00
TSOP-50	U16	149	No	SnBi	Ag	Sn37Pb	0.44	2.68**	35.73	61.06	0.09	0.00
TSOP-50	U16	193	No	SnPb	Ag	SAC305	3.53	6.10**	1.51	88.86	0.00	0.00

*PWB Cu pads had to be cut from the CSP balls. This operation also removed that end of each ball.
** Copper may have been removed from the PWB pads when the solder joints were cut from the test vehicle.

Figure 5. Thermal Cycle Chamber

Figure 6. Test Vehicles in Thermal Cycle Chamber

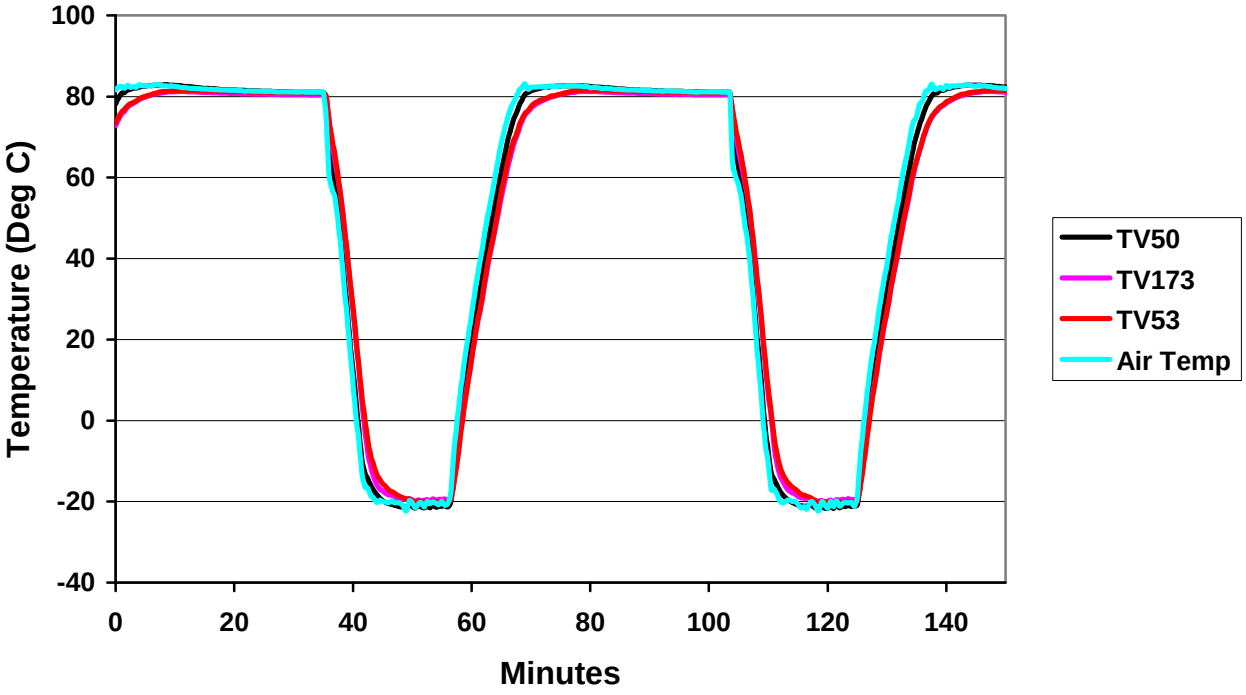


Figure 7. Thermal Cycle (-20°C to +80°C)

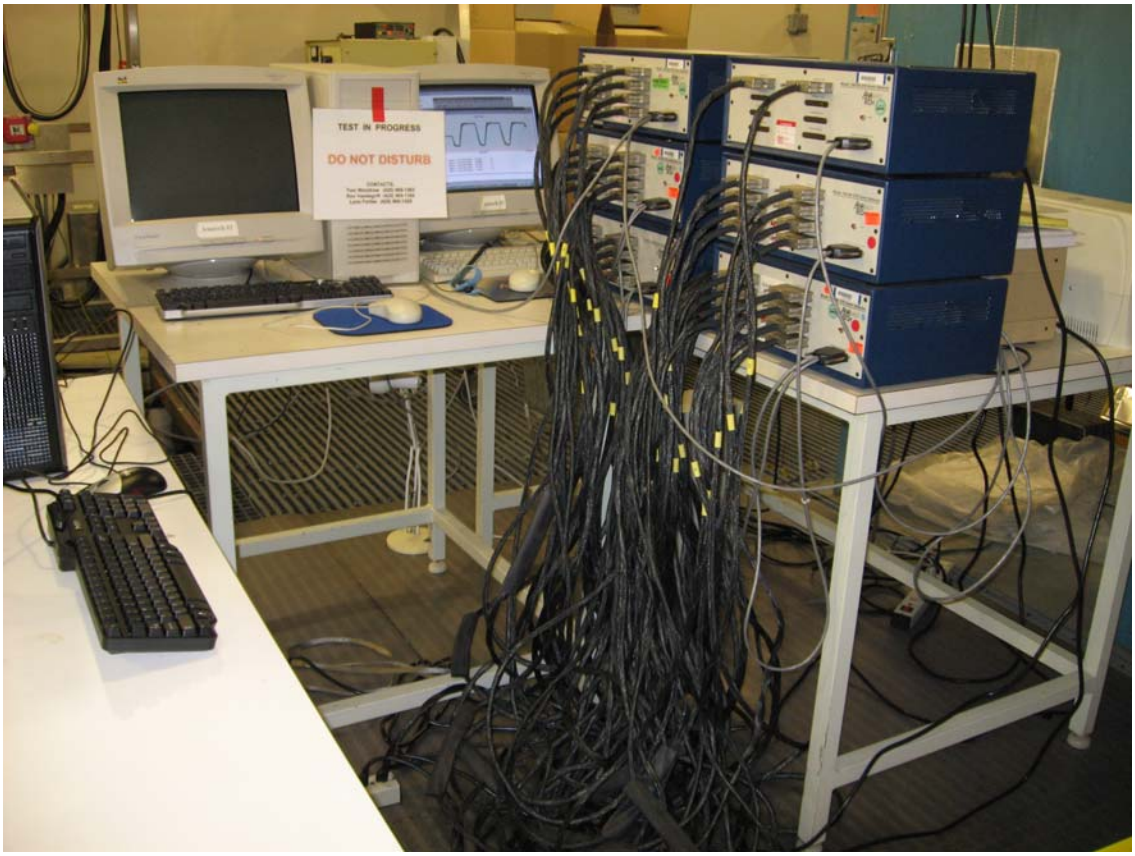


Figure 8. Event Detectors and Data Collection System

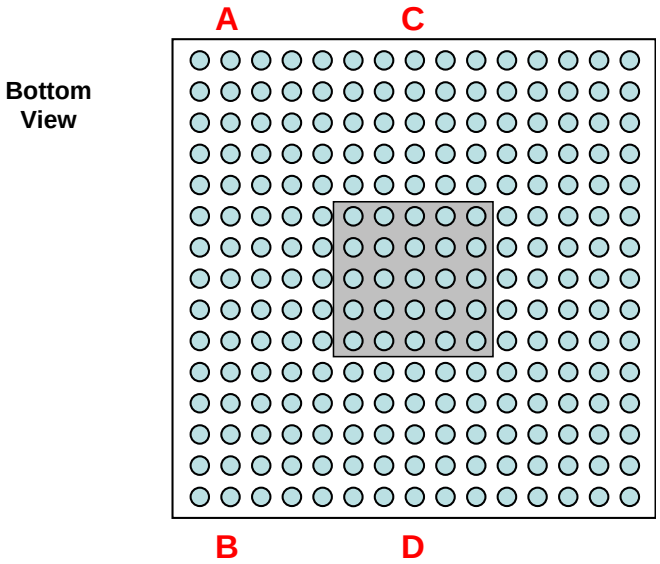
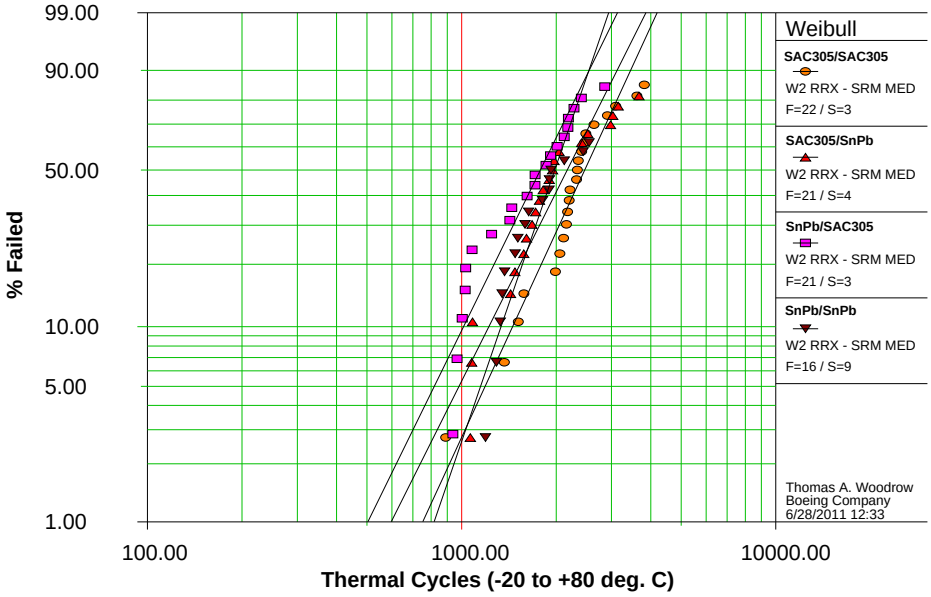


Figure 9. BGA-225 CTE Measurement Points

Table 4. CTE Measurements on Selected Component Types

Component	Component Finish	CTE (x 10-6 cm/cm/°C)		
		Measurement 1	Measurement 2	Average
BGA-225, A to B	SnPb	15.3	15.9	15.6
BGA-225, C to D	SnPb	13.0	13.5	13.3
BGA-225, A to B	SAC405	15.2	15.9	15.6
BGA-225, C to D	SAC405	12.6	12.6	12.6
CSP-100	SnPb	8.9	9.1	9.0
CSP-100	SAC405	8.5	8.6	8.6
CSP-100	SAC105	7.7	8.6	8.2
QFN-20	SnPb	14.9	15.1	15.0
QFN-20	Sn	15.3	15.6	15.5

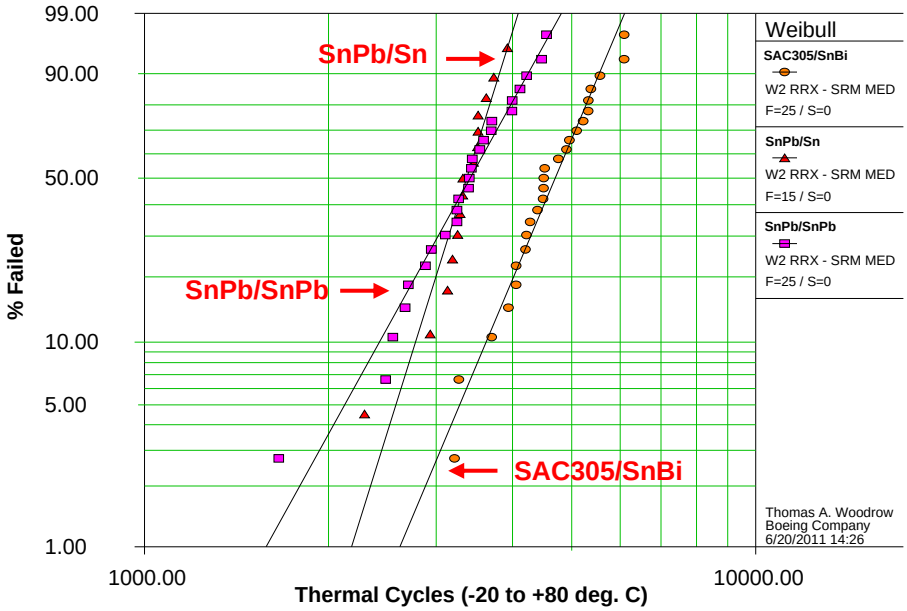
Notes:
1. CTE's were measured in accordance with ASTM E228 on a Netzsch Model 402 dilatometer.
2. The measurements were performed over the range of -55 to 125°C.
3. The values for CTE given in the table are average values over the indicated temperature range.



β1=3.5658, η1=2732.5943, ρ=0.9664
β2=3.2819, η2=2426.2009, ρ=0.9360
β3=3.3468, η3=1988.0529, ρ=0.9434
β4=4.7909, η4=2137.7196, ρ=0.9052

Key: Solder Alloy/Component Finish

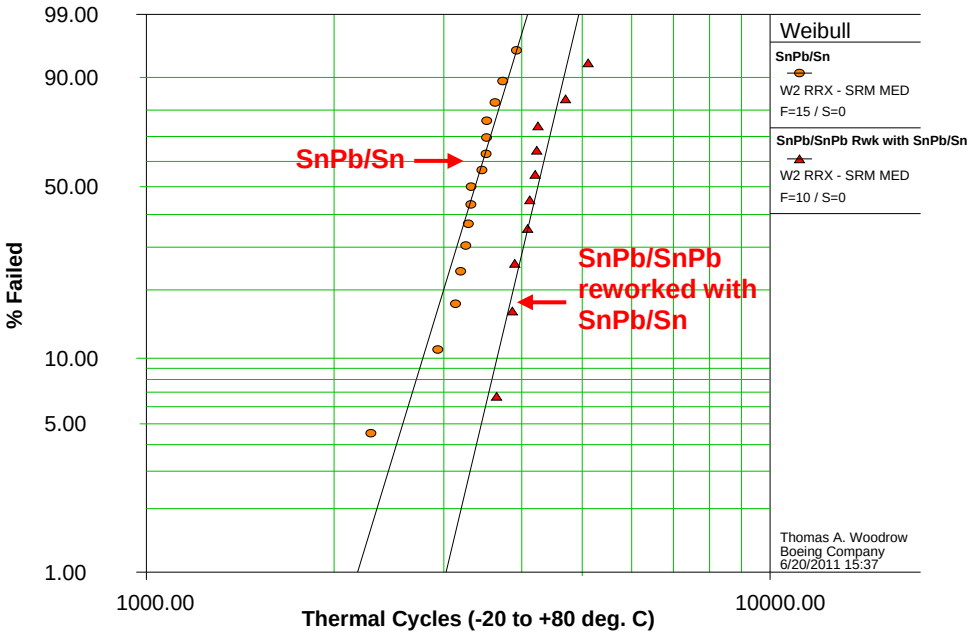
Figure 10. Weibull Plot of CLCC-20 Data



β1=7.2378, η1=4942.8859, ρ=0.9835
β2=9.7584, η2=3497.0642, ρ=0.9473
β3=5.5063, η3=3645.8470, ρ=0.9828

Key: Solder Alloy/Component Finish

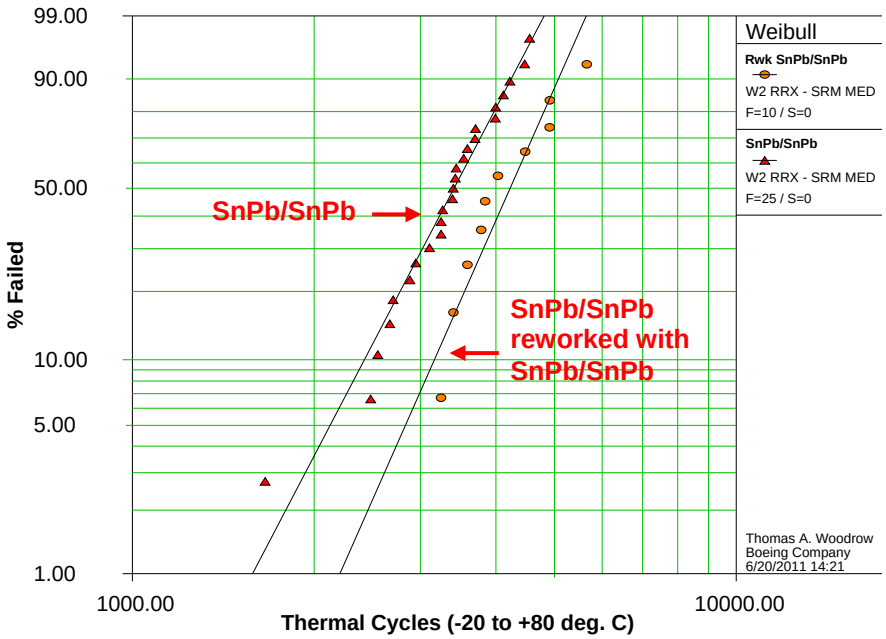
Figure 11. Weibull Plot of TSOP-50 Data



β1=9.7584, η1=3497.0642, ρ=0.9473
β2=12.4950, η2=4370.7731, ρ=0.9207

Key: Solder Alloy/Component Finish

Figure 12. Weibull Plot of TSOP-50 Data



β1=6.5246, η1=4467.9686, ρ=0.9478
β2=5.5063, η2=3645.8470, ρ=0.9828

Key: Solder Alloy/Component Finish

Figure 13. Weibull Plot of TSOP-50 Data

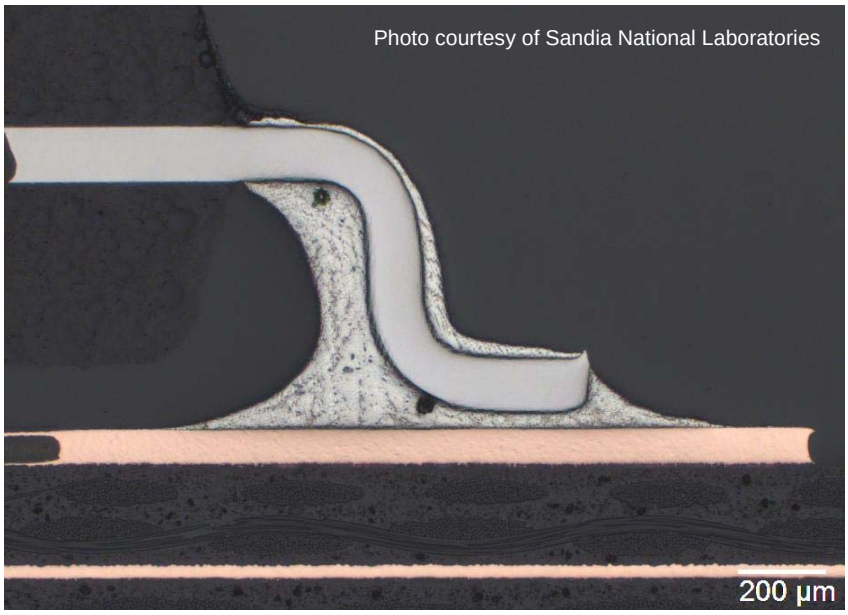


Figure 14. SnBi TSOP-50 Assembled with SnPb Solder (Pre-Test Microsection)

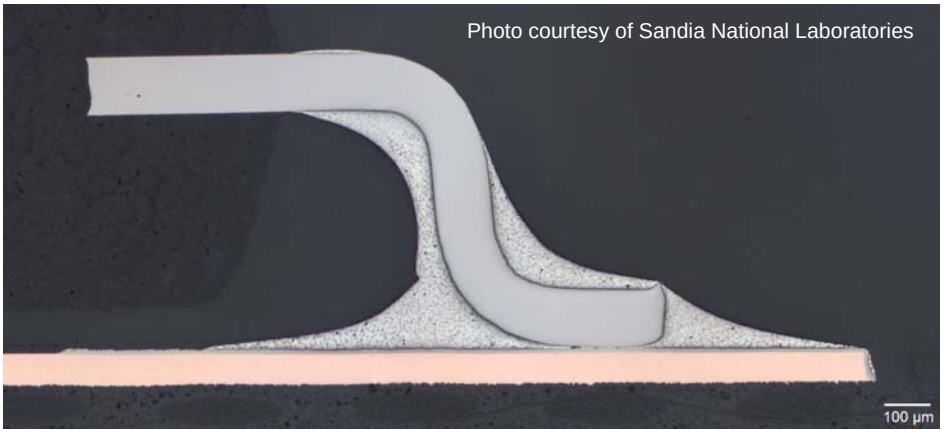
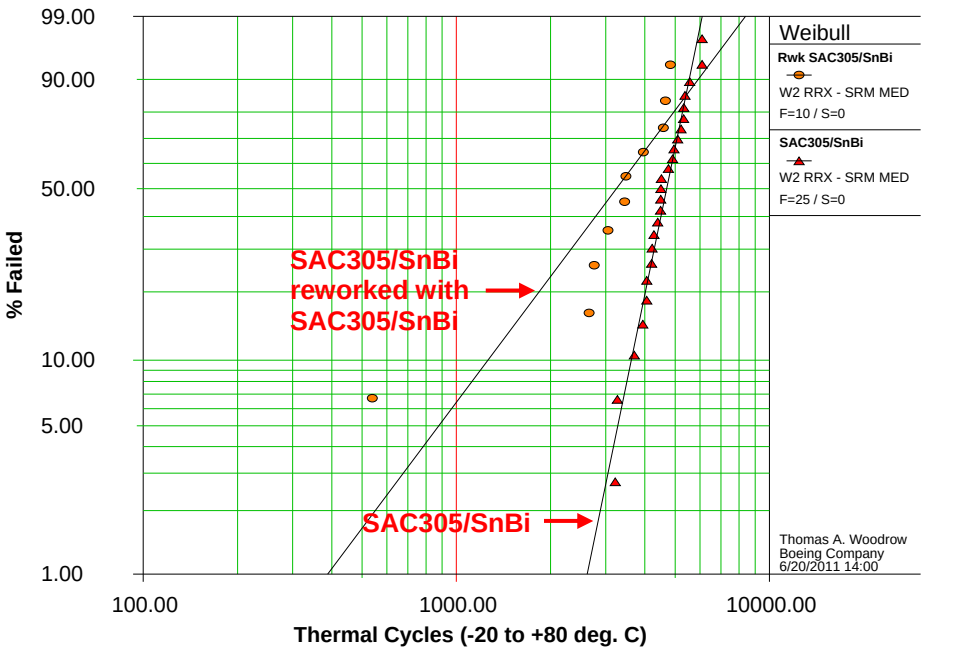


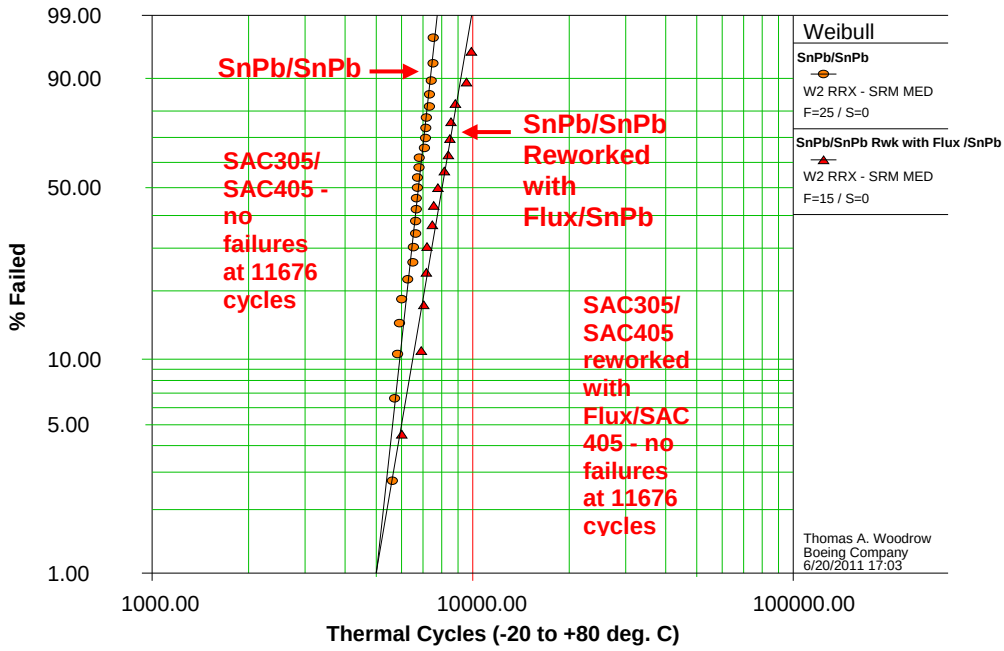
Figure 15. SnPb/SnPb TSOP-50 Reworked with SnPb/SnPb (Pre-Test Microsection)



β1=1.9936, η1=3901.5564, ρ=0.8766
β2=7.2378, η2=4942.8859, ρ=0.9835

Key: Solder Alloy/Component Finish

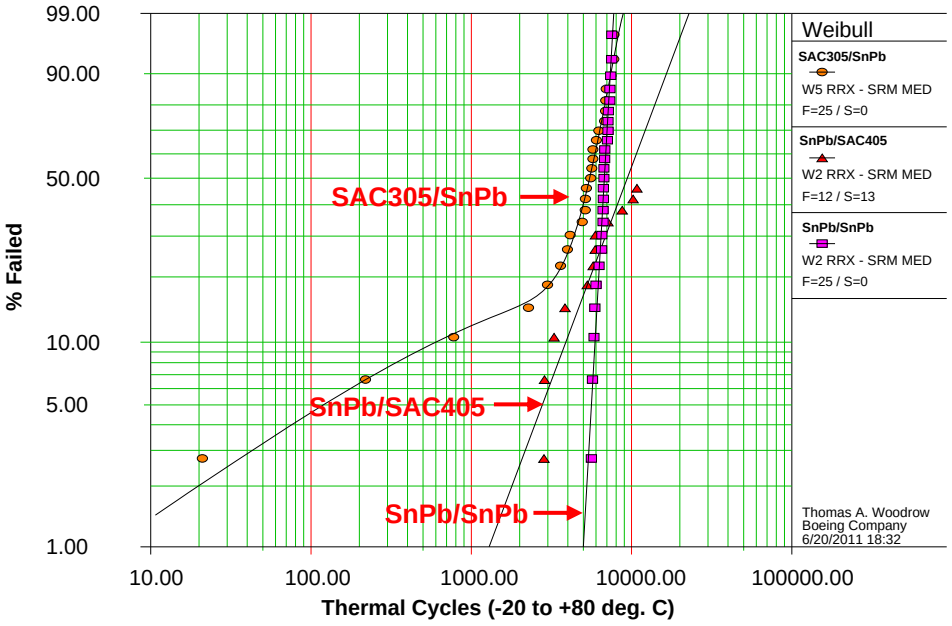
Figure 16. Weibull Plot of TSOP-50 Data



β1=14.0212, η1=6953.2528, ρ=0.9814
β2=8.9342, η2=8359.9217, ρ=0.9763

Key: Solder Alloy/Component Finish

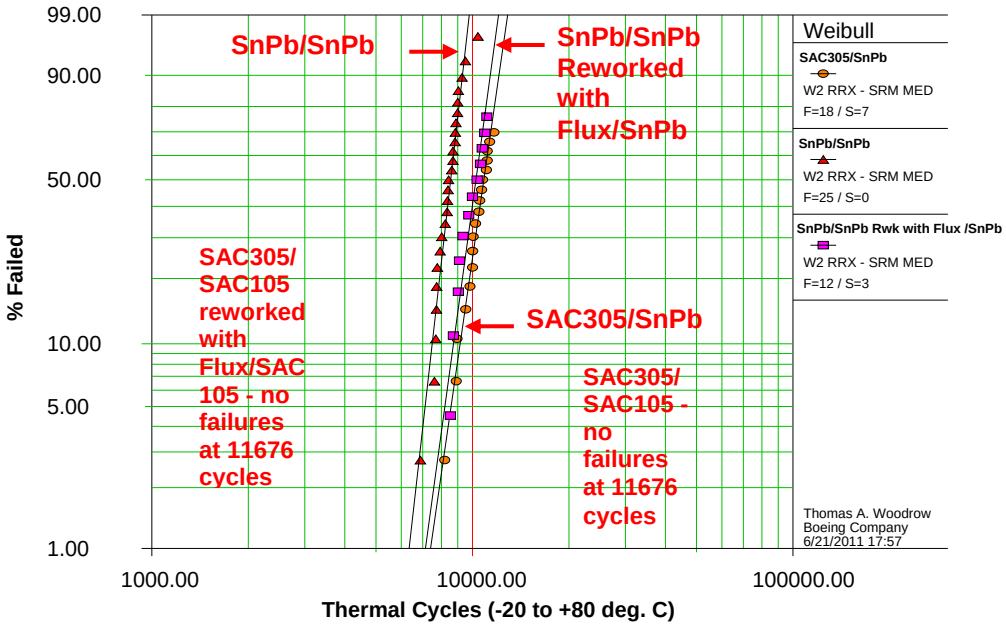
Figure 17. Weibull Plot of BGA-225 Data



β1[1]=0.5644, η1[1]=901.2608, P1[1]=0.1826 ; β1[2]=4.7275, η1[2]=6302.7439, P1[2]=0.8174
β2=2.1325, η2=1.1174E+4, ρ=0.9349
β3=14.0212, η3=6953.2528, ρ=0.9814

Key: Solder Alloy/Component Finish

Figure 18. Weibull Plot of BGA-225 Data (Mixed Solders)



β1=11.0651, η1=1.1218E+4, ρ=0.9911
β2=14.2044, η2=8779.4419, ρ=0.9670
β3=11.6464, η3=1.0585E+4, ρ=0.9612

Key: Solder Alloy/Component Finish

Figure 19. Weibull Plot of CSP-100 Data

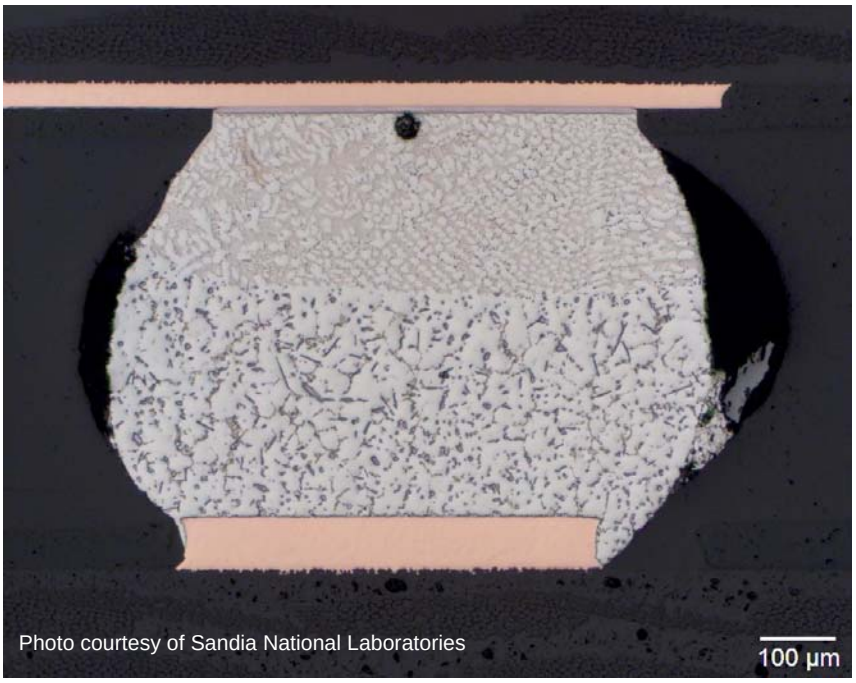


Figure 20. BGA-225 with SAC405 Balls Assembled with SnPb Paste (SnPb Reflow Profile; Pre-Test Microsection)

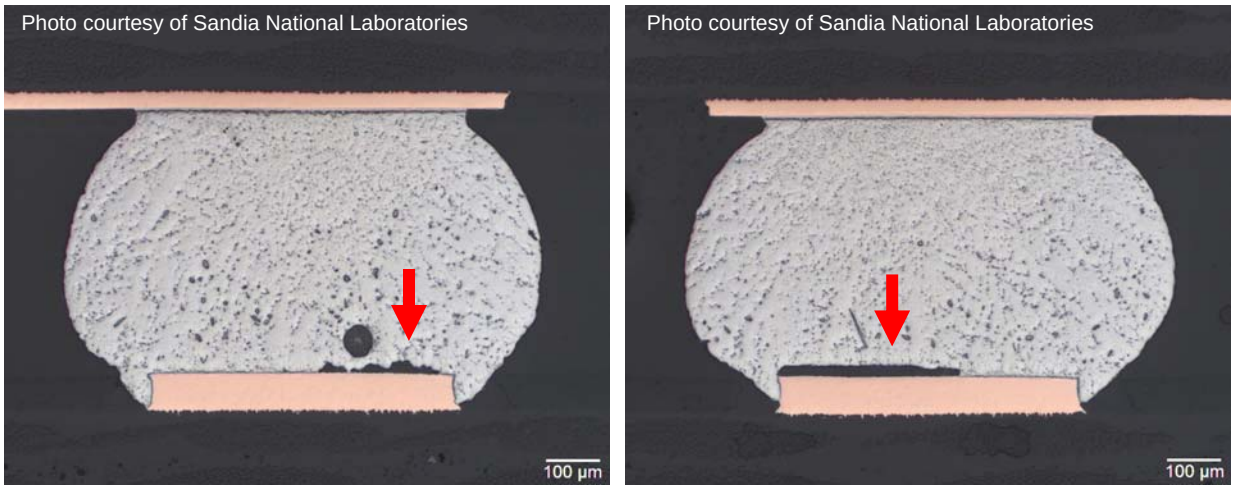
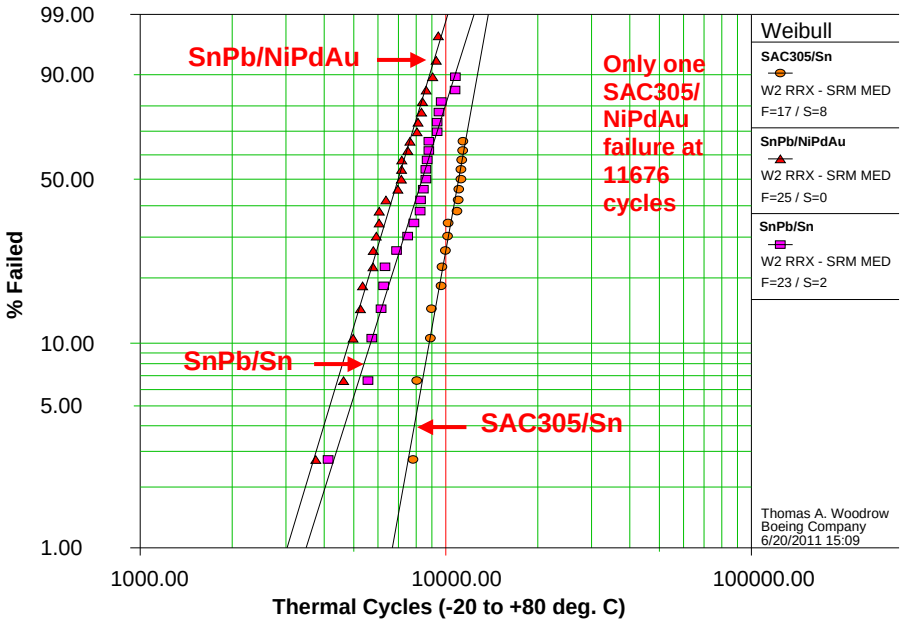


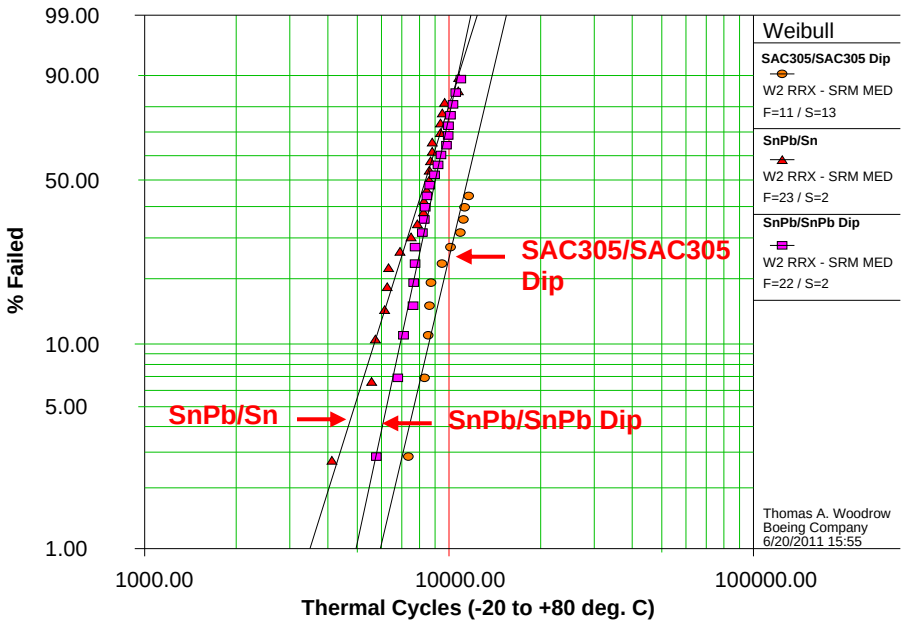
Figure 21. BGA-225 with SnPb Balls Assembled with SAC305 Paste (Pb-free Reflow Profile; Pre-Test Microsection)



β1=8.4634, η1=1.1514E+4, ρ=0.9846
β2=5.0626, η2=7511.8983, ρ=0.9927
β3=4.8409, η3=9032.9926, ρ=0.9877

Key: Solder Alloy/Component Finish

Figure 22. Weibull Plot of TQFP-144 Data



β1=6.4225, η1=1.2176E+4, ρ=0.9479
β2=4.8409, η2=9032.9926, ρ=0.9877
β3=7.0514, η3=9503.6298, ρ=0.9887

Key: Solder Alloy/Component Finish

Figure 23. Weibull Plot of TQFP-144 Data (Dipped Leads)

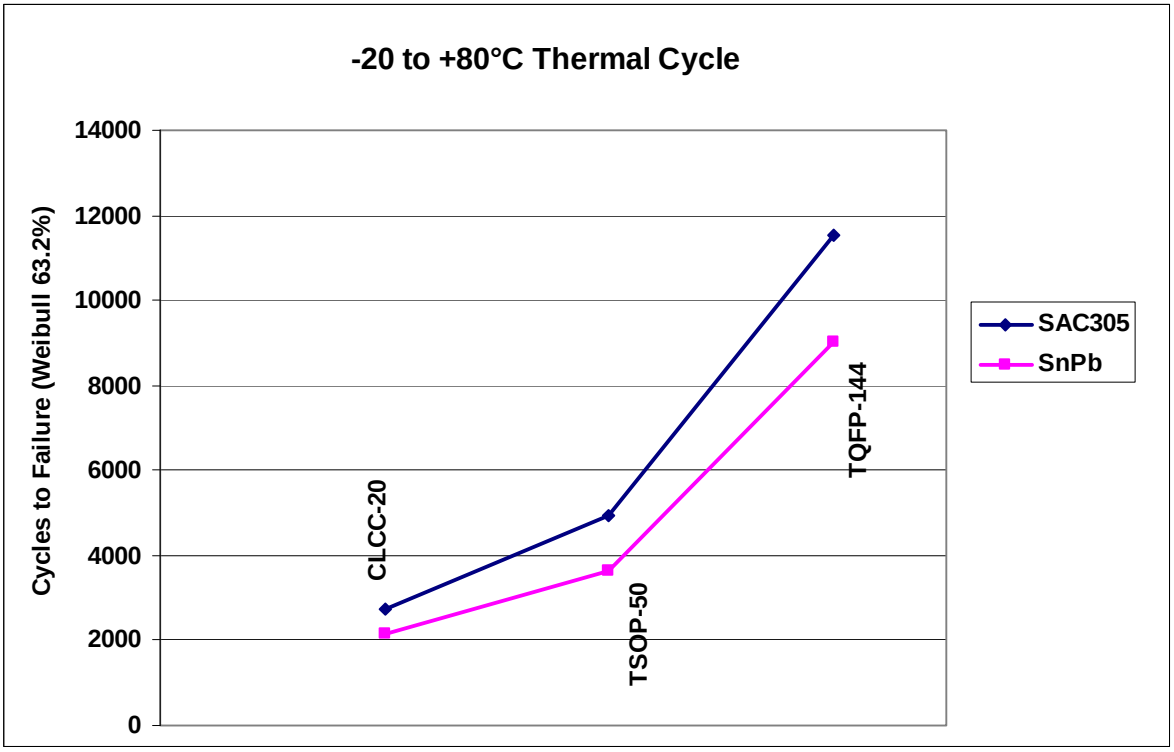


Figure 24. Reliability Comparison of Eutectic SnPb and SAC305 Solder Joints on Various Components during the -20°C to +80°C Thermal Cycle Test (There Were Not Enough Lead-Free Failures to Compare the BGA's, CSP's, QFN's, or PDIP's).