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JCAA/JG-PP No-Lead Solder Project: -55ºC to +125ºC Thermal Cycle Testing Status Report

David Hillman and Sarah Olson
Rockwell Collins Inc.
Cedar Rapids Iowa

Abstract
The use of conventional tin-lead (Sn/Pb) solder in circuit board manufacturing is under ever-increasing political scrutiny due to environmental issues and new regulations concerning lead, such as the Waste Electrical and Electronic Equipment (WEEE) and the Restriction on Hazardous Substances (RoHS) Directives in Europe. In response to this, global commercial electronic manufacturers are initiating efforts to transition to lead-free assembly. Lead-free (Pbfree) materials will be finding their way into the inventory of aerospace and military assembly processes under government acquisition reform initiatives. Any potential banning of lead compounds could reduce the supplier base and adversely affect the readiness of missions led by NASA and the DoD. The Joint Council on Aging Aircraft (JCAA)/ Joint Group on Pollution Prevention (JGPP) Lead-Free Solder Project, a partnership between DoD, NASA and OEMs, was initiated to examine the reliability of Pbfree solders exposed to harsh environmental conditions representative of NASA and DoD operational conditions. This paper reports results to date on the JCAA/JGPP consortia -55ºC to +125ºC thermal cycle testing. The main goal of the thermal cycle testing effort is to generate data from test boards that are representative of IPC Class III High Performance Electronic Products.

Portions of this paper were originally presented at the SMTAI Conference in October 2005.

Background
Thermal cycle testing was conducted by Rockwell Collins Inc. for the JCAA/JGPP No-Lead Solder Project. The JCAA/JGPP Consortium is the first group to test the reliability of lead-free solder joints against the requirements of the aerospace/military community.
The solder alloys selected for test were:

Sn3.9Ag0.6Cu (SAC) for reflow and wave soldering
Sn3.4Ag1.0Cu3.3Bi (SACB) for reflow soldering
Sn0.7Cu0.05Ni (SNIC) for wave soldering
Sn37Pb (SnPb) for reflow and wave soldering

Test vehicles were assembled using these solders and a variety of component types. Thermal cycle testing was then conducted on the test vehicles using a -55ºC to +125ºC temperature range in accordance with the IPC-9701 specification.

Objective
The objective of the study was to evaluate the solder joint integrity of selected Pbfree solder alloys compared to Sn63/Pb37 solder alloys for a -55ºC to +125ºC temperature range.

Procedures
Test vehicle
The test vehicle used in the thermal cycle testing was 14.5 inches wide by 9 inches high by 0.090 inches thick, and contained 6 layers of 0.5 ounce copper. The test vehicle was designed to meet IPC-6012, Class 3, Type 3 requirements. Two different test vehicle laminates were selected for the testing program. The first laminate was FR4 per IPC-4101/26 with a minimum Tg of 170ºC with an immersion silver surface finish. This laminate was selected to represent "manufactured" printed wiring assemblies that were designed for use in Pbfree soldering processes. A total of 119 "manufactured" test vehicles were produced. The second laminate was FR4 per IPC-4101/21 with a minimum Tg of 140ºC with a hot air solder leveled (HASL) surface finish. This laminate was selected to represent "legacy" printed wiring assemblies that were not specifically designed for Pbfree soldering processes. A total of 86 "legacy" test vehicles were produced. Figure 1 illustrates the test vehicle design.

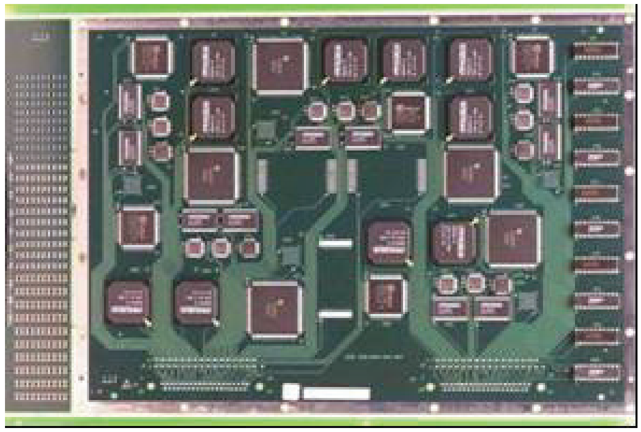

Figure 1: Test vehicle design

Test Components

A variety of component types and component surface finishes were included on the test vehicle. The CLCC and TSOP component types were selected due to industry acknowledged solder joint integrity issues in Class III High Performance electronic products. The DIP components were selected to represent plated thru hole technology. The PLCC, TQFPs, BGAs and capacitor/resistors were selected to represent surface mount technology. Table 1 lists the various component types and their surface finishes.

Table 1. Component types and finishes

Component Type	Component Finish
CLCC -20	SnPb
	SnAgCu
	SnAgCuBi
PLCC-20	Sn
TSOP-50	SnPb
	SnCu
TQFP-144	Sn
TQFP-208	NiPdAu
BGA-225	SnPb
	SnAgCu
DIP-20	Sn
	NiPdAu
0402 Capacitor	Sn
0805 Capacitor	Sn
1206 Capacitor	Sn
1206 Resistor	Sn

Investigation Test Matrix

The investigation test matrix was designed to investigate the impact of the thermal cycle conditioning on both the manufactured and legacy test vehicles (Figure 2). A select number of components were reworked on the legacy test vehicles (Table 2).

Table 2. Components reworked on the legacy test vehicles.

Legacy "Rework" Control Test Vehicles				
Location Number	Component Type	Qty Per Vehicle	Component Finish Before Rework	Component Finish After Rework
U25	TSOP 50	1	SnPb	SnPb
U12	TSOP 50	1	SnPb	SnPb
U57	TQFP 208	1	AuPdNi	AuPdNi
U3	TQFP 208	1	AuPdNi	AuPdNi
U18	PBGA 225	1	SnPb	SnPb
U4	PBGA 225	1	SnPb	SnPb
U59	PDIP 20	1	AuPdNi	AuPdNi
U23	PDIP 20	1	AuPdNi	AuPdNi

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U18	PBGA 225	1	SnPb	SnAgCu
U4	PBGA 225	1	SnPb	SnAgCu
U59	PDIP 20	1	AuPdNi	AuPdNi
U23	PDIP 20	1	AuPdNi	AuPdNi

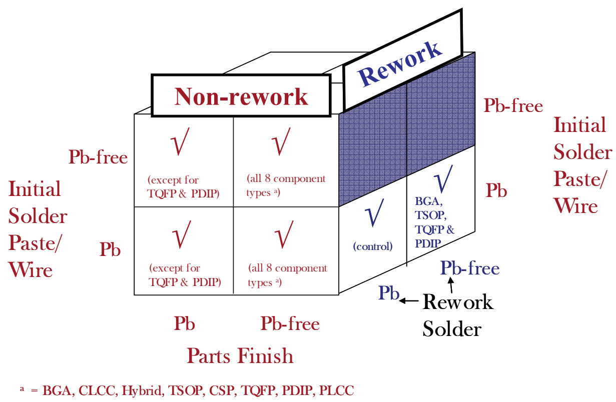


Figure 2. Test matrix

Test Vehicle Assembly

The 205 test vehicles (119 manufactured and 86 legacy) were assembled at the BAE Systems Irving Texas facility. A detailed description of the specific tin/lead and Pbfree soldering processes was detailed in a earlier publication [1]. The solder joint quality of all test vehicles was confirmed with X-ray inspection and visual inspection in accordance with the IPC-JSTD-001/IPC-A-610 specifications.

Thermal Cycle Parameters and Methodology

The temperature cycle range used in the investigation was -55ºC to +125ºC with a 30 minute dwell at the high temperature extreme and a 10 minute dwell at the low temperature extreme. A maximum temperature ramp of 10°C/minute was used in the testing. The continuity of the components was continuously monitored throughout thermal cycle testing by an event detector in accordance with the IPC-9701 specification. Each component was treated as a single resistance channel. An event was recorded if the resistance of a channel exceeded 300 Ω for more than 0.2 µsec within a 30-second period. A failure was defined when a component either:

- Exceeded the maximum resistance for 15 consecutive events,
- Had five consecutive detection events within 10% of current life of test, or
- Became electrically open.

Once a solder joint was designated a failure, the event detection system software excluded it from the remainder of the test. Detailed temperature profiling was conducted prior to the beginning of the thermal cycle conditioning to insure that each test vehicle was subjected to uniform, consistent exposure to the test chamber temperatures. In the Rockwell Collins testing, a total of 15 manufactured test vehicles and 15 legacy test vehicles were placed in the chamber. Figure 3 illustrates the thermal cycle temperature profile for the -55ºC to +125ºC testing and the resulting measured test vehicle temperatures with a time lag due to thermal inertia. Figure 4 illustrates the test vehicles positioned in the -55ºC to +125ºC test chamber.

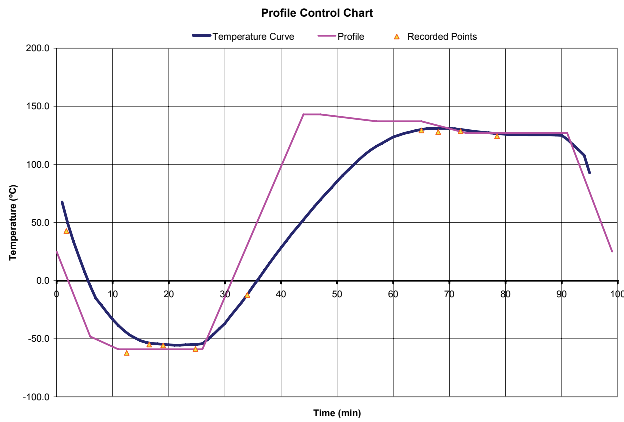


Figure 3. Thermal cycle profile for the -55ºC to +125ºC conditioning.

Figure 4. Test vehicles loaded into the -55ºC to +125ºC test chamber.

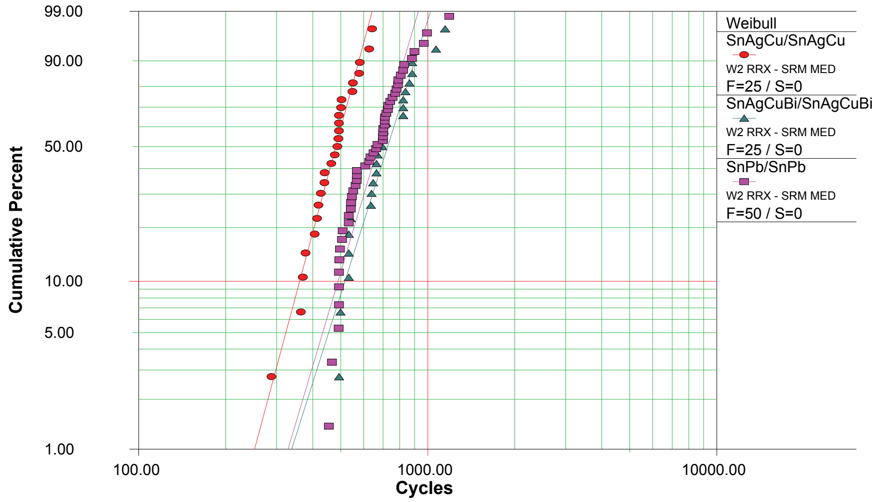
Test Results

The test vehicles completed a total of 4743 thermal cycles during 12 month test duration. Table 3 lists the final component population failure rates after completing 4743 thermal cycles.

Table 3. Component population failure rates after 4743 thermal cycles

Component Type	Total Failures	Total Population	Percent Failed
BGA 225	257	300	85.7
CLCC 20	300	300	100
PDIP 20	24	300	8
PLCC 20	8	150	5.3
TQFP 144	136	150	90.7
TQFP 208	110	150	73.3
TSOP 50	296	300	98.7

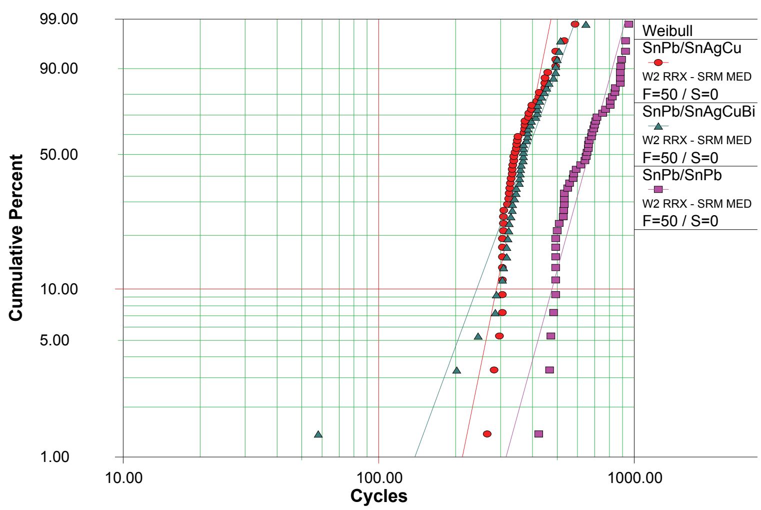
A complete statistical analysis and extensive failure analysis was still being completed at the time of manuscript submission. However, some initial preliminary conclusions can be drawn from the data analysis to date. Initial data analyses were conducted for the CLCC 20 and TSOP 50 components as nearly both component types experienced 100% population failure. Industry data [2, 3] has demonstrated that both the CLCC and TSOP component styles undergo solder joint integrity degradation under IPC Class 3 use environments due to mismatch with the printed wiring assembly coefficient of thermal expansion (CTE). The CLCC components utilized three different termination finish/solder paste alloy combinations (SAC/SAC, SACB/SACB, SnPb/SnPb) resulting in statistically different thermal cycle performance. On the manufactured test vehicles (170ºC Tg), the characteristic life of the SAC solder alloy was approximately 200 cycles less than the SACB or SnPb solder alloys. On the legacy test vehicles (140ºC Tg), both the SAC and SACB solder alloys had significantly shorter life (> 300 thermal cycles) than the SnPb solder alloy. A comparison of the manufactured test vehicles and the legacy test vehicle CLCC results in essentially the same characteristic life. Figures 5-7 illustrate the CLCC thermal cycle test results.



β1=6.5409, η1=508.6653, ρ=0.9864
β2=5.5317, η2=776.3182, ρ=0.9453
β3=5.9047, η3=716.4935, ρ=0.9326

Key: Solder Alloy/Component Finish

Figure 5. CLCC test results for the manufactured test vehicles (170ºC Tg)



β1=7.6691, η1=387.3908, ρ=0.8914
β2=4.2149, η2=412.5278, ρ=0.8758
β3=5.6773, η3=708.6388, ρ=0.9368

Key: Solder Alloy/Component Finish

Figure 6. CLCC test results for the legacy test vehicles (140ºC Tg)

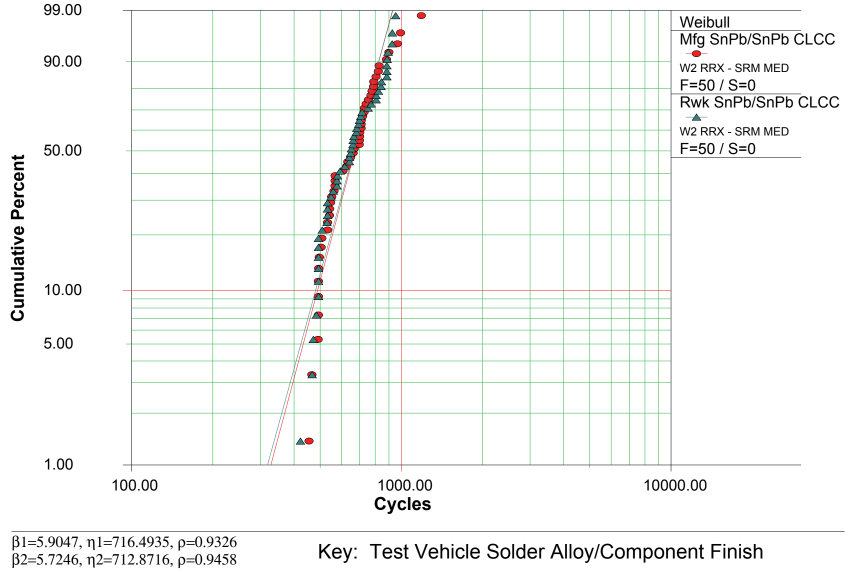


Figure 7. Comparison of CLCCs on Manufactured and Legacy test vehicles.

The TSOP components utilized two different lead finishes (SnCu and SnPb) with three solderpaste alloy combinations (SnPb, SAC, SACB), resulting in statistically different performance levels. The two TSOP surface finishes and SnPb or SAC solderpaste combinations had similar thermal cycle performance. However, the SACB solderpaste/SnPb surface finish had the worst performance and the SACB solderpaste/SnCu surface finish had the best performance. A possible bismuth/lead solder joint microstructure interaction is suspected but failure analysis will be needed to confirm that hypothesis. The data analysis of the TSOP components on the legacy test vehicles showed that SACB/SnCu and SnPb/SnPb combinations had lower performance than the other TSOP solder alloy/component finish combinations. Figures 8-9 illustrate the TSOP thermal cycle test results.

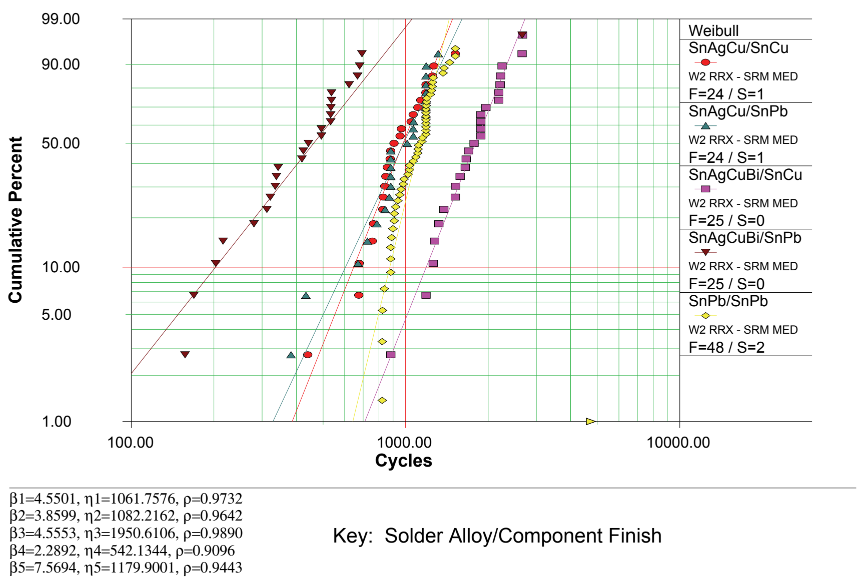


Figure 8. TSOP test results for the manufactured test vehicles (170ºC Tg)

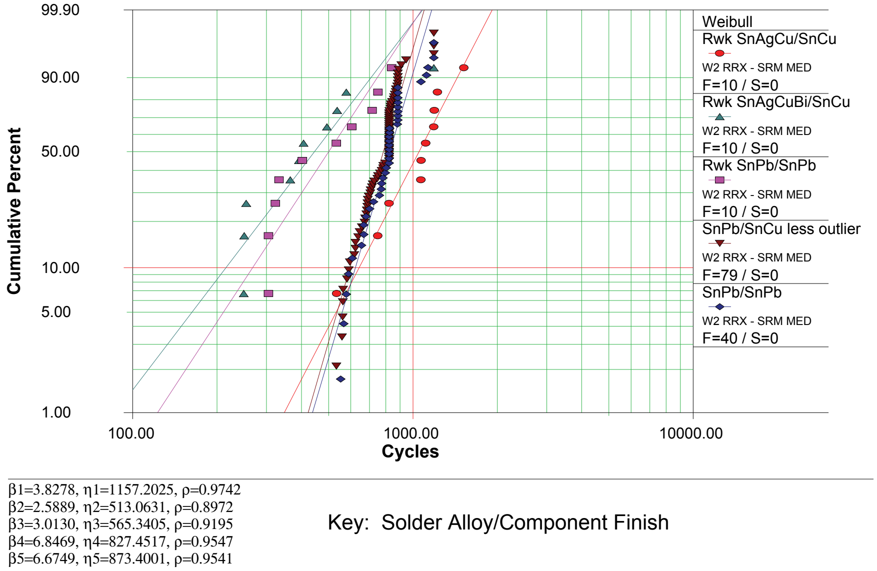


Figure 9. TSOP test results for the legacy test vehicles (140ºC Tg)

In addition to conducting statistical analysis to determine the solder alloy/component finish solder joint thermal cycle fatigue life; extensive failure analysis was conducted to determine if tin whiskers were present. Tin whiskers are a topic of critical concern to the aerospace and military electronics sector. Extensive industry investigations [4] and industry specification [5] creation efforts are currently being undertaken. Tin whiskers are single crystal filament structure that extrude from tin surfaces and can cause electrical failure of printed wiring assemblies. Other metals such as zinc and cadmium have also been shown to produce whiskers [6]. The specific root cause parameter set that leads to whisker growth is not yet fully understood by the electronic industry. Each component on the thermal cycle test vehicles was examined for the presence of tin whiskers under a minimum of 100X magnification. The surface mount TSOP, TQFP, PLCC, and the plated thru hole DIP components were the primary focus of the examinations.

Figures 10-14 illustrate typical tin whiskers found on the TSOP components with SnCu surface finish. This TSOP component was from the legacy test vehicle. It was originally reflow soldered with a SnPb solder alloy and then manually reworked with a SAC solder alloy as part of the overall rework impact segment of the investigation test matrix (Figure 2). Tin whiskers were found on lead surfaces that were not soldered (the upper knees of the component leads and lead faces) and would be characterized as dense fields with a "worm-like" appearance. SEM EDX analysis was used to confirm that the whiskers were comprised of tin (Figure 15).

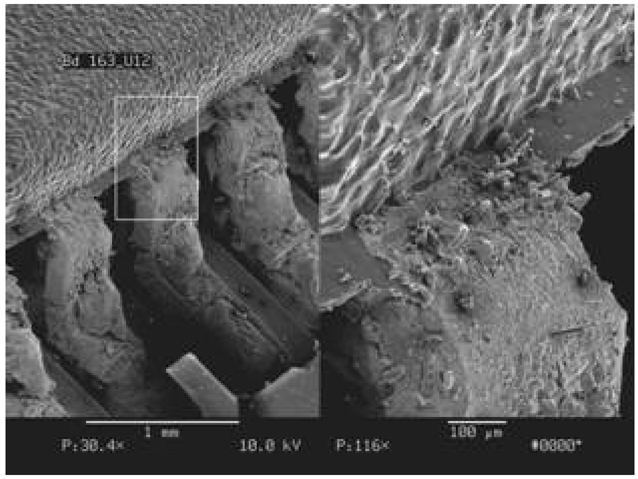


Figure 10. SEM image of TSOP component with SnCu surface finish showing tin whiskers on upper knee of lead (Component U12, test vehicle 163)

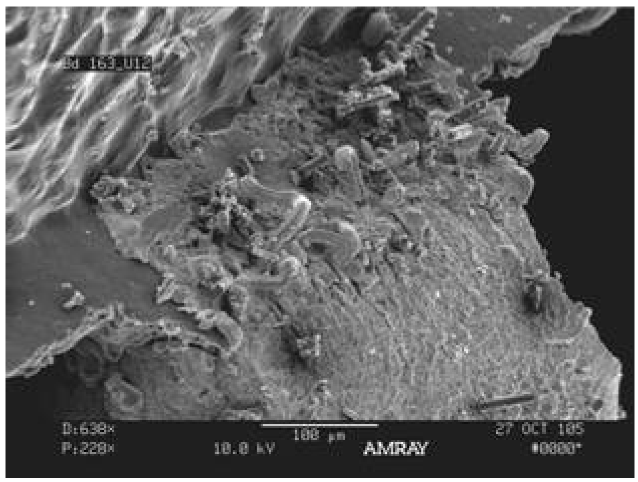


Figure 11. Close up SEM image of TSOP component with SnCu surface finish showing tin whiskers on upper knee of lead (Component U12, test vehicle 163)

Figure 12. High magnification SEM image of TSOP component with SnCu surface finish showing individual tin whisker on upper knee of lead (Component U12, test vehicle 163)

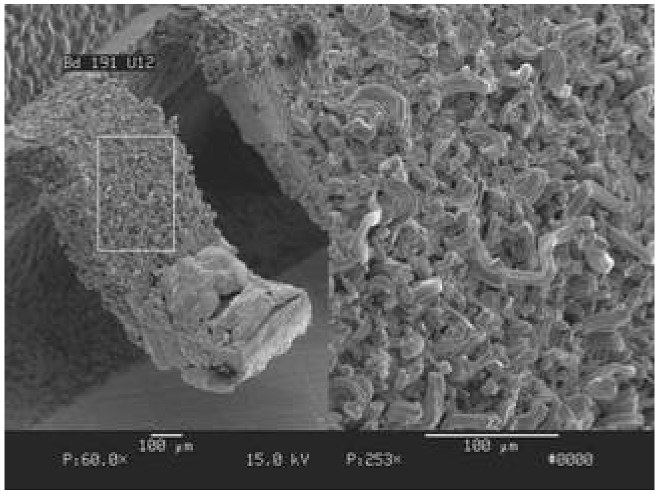


Figure 13. SEM image of TSOP component with SnCu surface finish showing tin whiskers on lead face (Component U12, test vehicle 191)

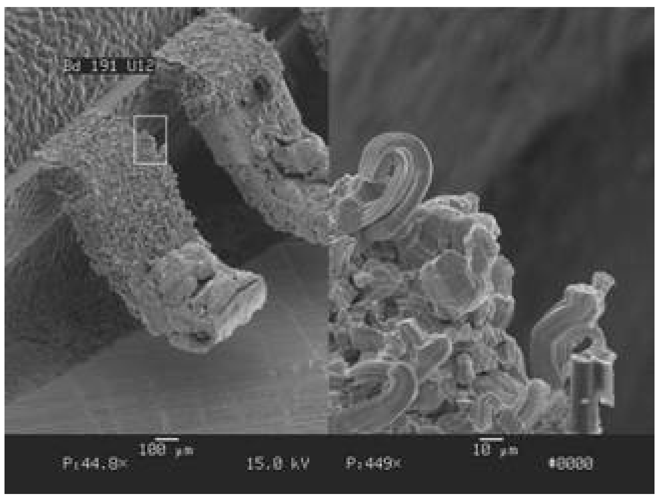


Figure 14. SEM image of TSOP component with SnCu surface finish showing tin whiskers on upper knee edge of lead (Component U12, test vehicle 191)

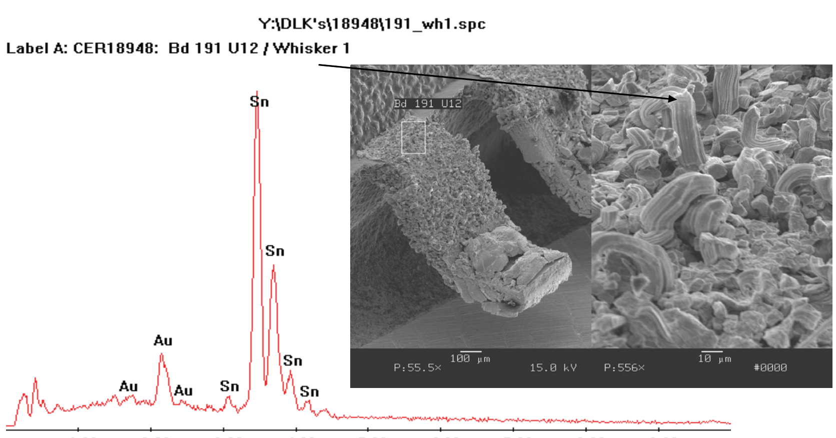


Figure 15. SEM EDX scan of an individual tin whisker, TSOP component with SnCu surface finish, showing chemical composition. Note gold (Au) presence due to SEM preparation procedure (Component U12, test vehicle 191)

Only a handful of whiskers were observed on the TQFP components for all of the test vehicles. However, the whiskers observed were of significant interest. Figures 16-18 illustrate a TQFP component, with a matte tin surface finish, on a legacy test vehicle that was soldered with SnPb solder. Small lead (Pb) whiskers were found on the upper knee of the component lead. The Pb whisker phenomena were also observed sporadically on the TSOP components with SnPb surface finish (Figures 19-21). The Pb whiskers observed in this investigation were significantly larger than those documented in other industry investigations [7].

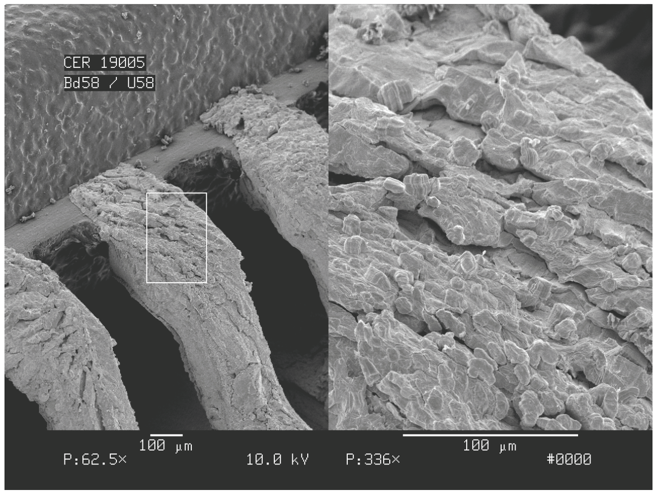


Figure 16. SEM image of whiskers, TQFP component with matte tin surface finish (Component U58, test vehicle 58)

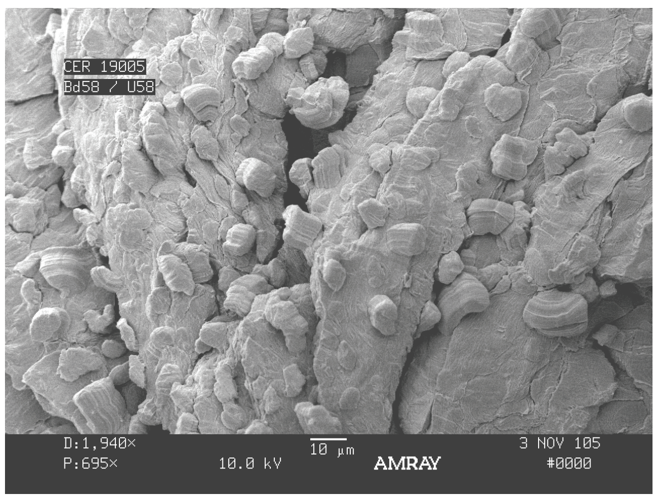


Figure 17. Magnified SEM image of whiskers, TQFP component with matte tin surface finish (Component U58, test vehicle 58)

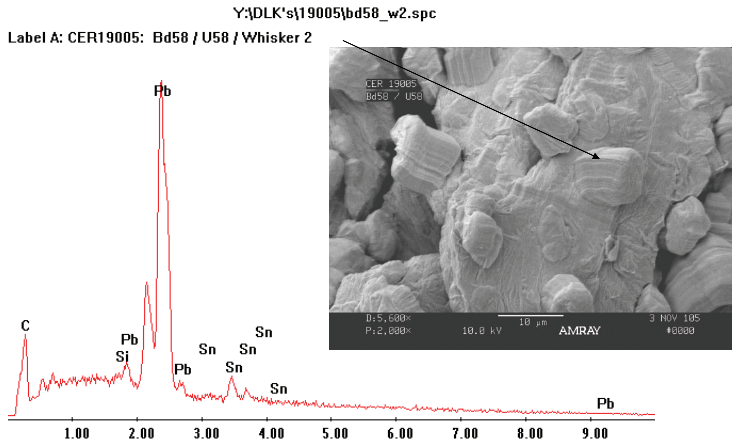


Figure 18. SEM EDX scan of an individual whisker, TQFP component with matte tin surface finish, showing Pb chemical composition. (Component U58, test vehicle 58)

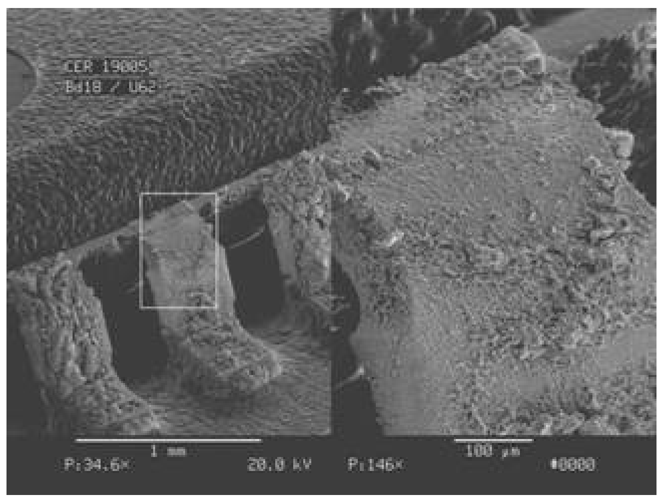


Figure 19. SEM image of TSOP component with SnPb surface finish showing whiskers on upper knee of lead (Component U62, test vehicle 18)

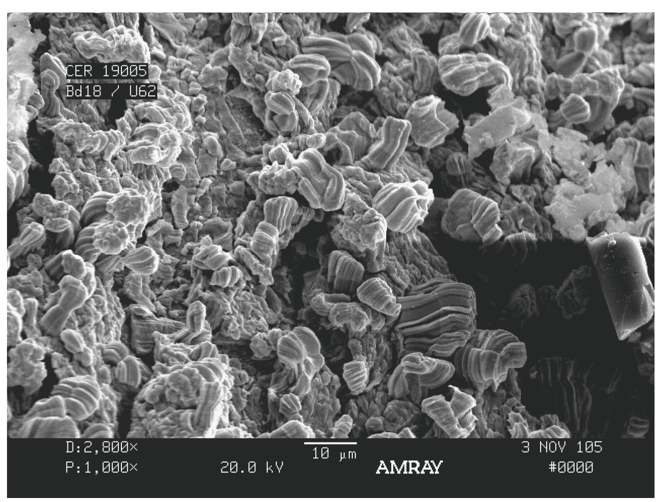


Figure 20. Magnified SEM image of TSOP component with SnPb surface finish showing whiskers on upper knee of lead (Component U62, test vehicle 18)

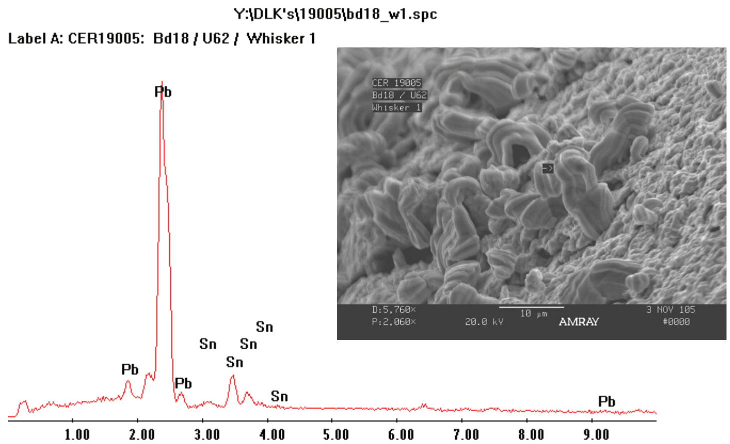


Figure 21. SEM EDX scan of an individual whisker, TSOP component with SnPb surface finish showing Pb chemical composition (Component U62, test vehicle 18)

No whiskers (either Sn or Pb) were observed for the PLCC or DIP components. Table 4 lists the summary of the whisker observations for the -55ºC to +125ºC thermal cycle test vehicles.

Table 4. Whisker Observation Summary

Component Type	Component Finish	Whisker Observations	Typical Whisker Diameter	Typical Whisker Length	Maximum Length Observed
TSOP	SnPb	Significant Whiskering Observed	8 µm	5 - 20 µm	50 µm
	SnCu	Significant Whiskering Observed	8 µm	10 - 30 µm	120 µm
DIP	Sn	No Whiskers Observed	NA	NA	NA
PLCC	Sn	No Whiskers Observed	NA	NA	NA
TQFP	Sn	Sporatic Whiskering Observed	8 µm	8 - 12 µm	12 µm
Note: Whiskers observed with severely twisted/contorted shapes or with stubby shapes					

Future Work

The complete failure analysis and statistical analysis of the test vehicles/components for the -55ºC to +125ºC thermal cycle testing will be available as part of the JCAA/JGPP consortia Joint Test Report (JTR) documentation to be published in February 2006.

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References

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