As originally published in the SMTA International Conference Proceedings.

NASA-DoD COMBINED ENVIRONMENTS TESTING RESULTS

Cynthia Garcia
Raytheon Company
McKinney, TX, USA
cynthia_garcia@raytheon.com

ABSTRACT
As part of the NASA-DoD Lead-Free Electronics project, combined environments testing was performed to validate and demonstrate lead-free solders as potential replacements for conventional tin-lead solders against aerospace and military electronics industry requirements for circuit card assemblies.

Solder alloys Sn3.0Ag0.5Cu, Sn0.7Cu0.05Ni (≤0.01Ge) and Sn37Pb were used to assemble components on two different printed wiring board test vehicles: manufactured and rework. The rework test vehicles included BGA-225, CSP-100, PDIP-20, and TSOP-50 components that were removed and replaced.

The test vehicles were subjected to thermal cycling from -55 to 125 degrees Celsius, a ramp rate of 20 degrees Celsius per minute, and dwelling at each temperature extreme for 15 minutes in a HALT (highly accelerated life test) chamber. Pseudorandom vibration was applied continuously throughout the life test beginning at 10 g_{rms} and increased by 5 g_{rms} after 50 cycles until a maximum of 55 g_{rms} was reached. The test vehicles were electrically monitored for 650 cycles using event detectors.

Solder joint failure data of a given component type, component finish and solder alloy were evaluated using 2-parameter Weibull analysis. The reliability of each lead-free solder alloy tested was compared to the baseline Sn37Pb solder alloy.

Key words: Lead-free, tin-lead, solder, reliability testing

INTRODUCTION

In November 2006, the NASA-DoD Lead-Free Electronics Project and a consortium formed to build on the results from the 2005 JCAA/JG-PP Lead-Free Solder Project. The new project focused on the rework of tin-lead and lead-free solder alloys and includes the mixing of tin-lead and lead-free solder alloys[1]. The majority of testing mirrored the testing completed for the JCAA/JGPP Lead-Free Solder Project. Combined environments test was one of several tests selected by the consortium to determine lead-free solder joint reliability under both thermal cycle and vibration environmental exposures, replicating the field environment.

METHODS, ASSUMPTIONS AND PROCEDURES

Solder Alloys

Solder alloys Sn3.0Ag0.5Cu, Sn0.7Cu0.05Ni (≤0.01Ge) and Sn37Pb were selected by the consortia for testing. Tin-Silver-Copper (Sn3.0Ag0.5Cu or SAC305) is the leading choice of the commercial electronics industry for lead-free solder. Alloys with compositions within the range of Sn3.0-4.0Ag0.5-1.0Cu have a liquidus temperature around 217 degrees Celsius and have similar microstructures and mechanical properties to that of tin-lead solder[1].

Tin-copper (Sn0.7Cu0.05Ni(≤0.01Ge) or SN100C) is commercially available and the general industry trend has been to switch to the nickel stabilized tin-copper alloy over standard tin-copper due to its superior performance.

Tin-lead (Sn37Pb) or eutectic tin-lead is the baseline solder alloy.

Test Vehicle

The test vehicle was a circuit card assembly designed per IPC-SM-785 and IPC-9701 to evaluate solder joint reliability[2,3]. The test vehicle printed wiring board was designed and fabricated per IPC-6012, Class 3[4]. The board had six layers and an overall dimension of 12.75 X 9 X 0.09 inches thick[1].

There were two variations of the test vehicle; manufactured and rework. A sample of a manufactured and rework test vehicle is shown in Figure 1.

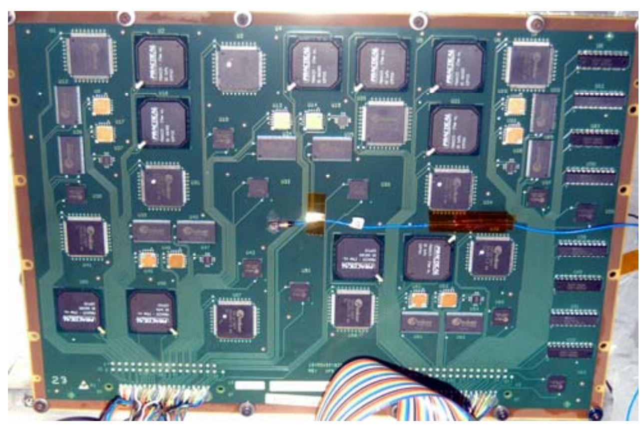

Figure 1 Manufactured and Rework Test Vehicle without Break-Off Coupon

Project stakeholders and participants selected immersion silver as the surface finish for the majority of the test vehicles. In addition, two test vehicles had electroless nickel/immersion gold (ENIG) surface finish.

Test vehicle printed circuit boards were designed with daisy-chained pads that complemented the daisy chain in the components. The solder joints on each component had a continuous electrical pathway monitored by an event detector during the test. Each component had its own distinct pathway (channel). Table 1 lists the test vehicles received from the consortium member that manufactured the test vehicles for testing.

Table 1 List of test vehicles received for CET.

Type of Test Vehicle (Batch)	Serial Numbers
SnPb Manufactured (C)	20 – 24
Lead-Free Manufactured (E)	69 – 73, 97*
Lead-Free Manufactured (G)	116 – 120
Lead-Free Rework (A)	163, 180 – 183
Tin-Lead Rework (B)	139 – 143, 158*
*ENIG test vehicle	

A thermal aging procedure was applied to the test vehicles to establish a common starting “state” in terms of solder joint microstructure, printed wiring board stress state, surface finish oxidation condition, and intermetallic phase formation/thickness[1].

TEST PLAN

Electrical Continuity

An event detector conforming to IPC-SM-785 was used to monitor the electrical continuity of each channel on the test vehicles. The failure criteria measured by the event detector will be 10 events per channel with an interruption of electrical continuity (≥ 1,000Ω) for periods greater than 0.2 µsec per IPC-SM-785[2].

Combined Environments Test

Combined environments test (CET) was based on MIL-STD-810F, Method 520.2 and a modified Highly Accelerated Life Test (HALT), a process that subjects products to accelerated environments to find weak links in design and/or manufacturing[5](see Figure 2). CET was used to determine the reliability of solder alloys subjected to combined thermal cycle and vibration environmental exposures in a shorter period of time. The results of the CET are used to compare performance differences in the lead-free test alloys against the baseline tin-lead alloy.

Test Profile

Combined environments test utilized a temperature range of -55 to 125 degrees Celsius with a 20 degrees Celsius per minute ramp rate. The dwell time at each temperature extreme is the time required to stabilize the test vehicles plus a 15-minute soak. Pseudorandom vibration began at 10 g_{rms} and was applied during the entire thermal cycle. After the first 50 cycles, the vibration levels were incremented by 5 g_{rms} until a maximum of 55 g_{rms} was reached or until 50 to 63% of the total components had failed; which ever occurred first[6]. The test profile is graphically represented in Figure 3. Because 50 to 63% failures were not achieved at 500 cycles, testing continued until 650 cycles were completed.

Figure 2 CET Performed in HALT/HASS Chamber

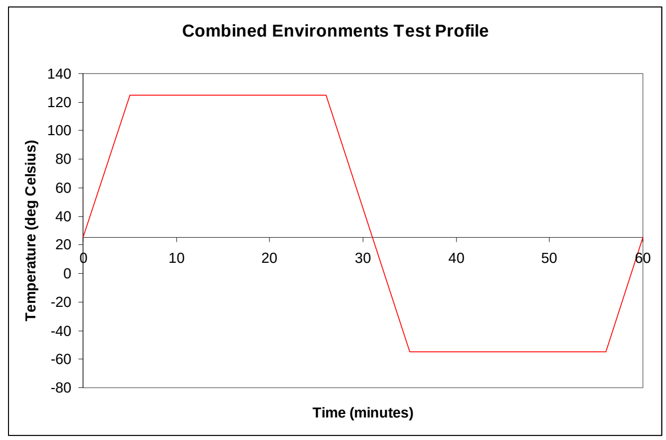

Figure 3 Initial Combined Environments Test Profile

Test Execution

First, test vehicles were inspected and ribbon cables were manually soldered to the test vehicle ports, P1 and P2, plated-through holes using eutectic tin-lead solder. Epoxy adhesive was added to provide strain relief to the ribbon cable solder joints during test[6].

The test vehicles were tested in two groups. The manufactured test vehicles were tested first followed by the rework test vehicles. The rework set included one manufactured test vehicle, SN 97, which is one of two ENIG board finish test vehicles. Custom aluminum holding fixtures held nine test vehicles on the first level and six on the second (see Figure 4). The test vehicles were loaded onto the fixtures in random order, documented by Figure 5.

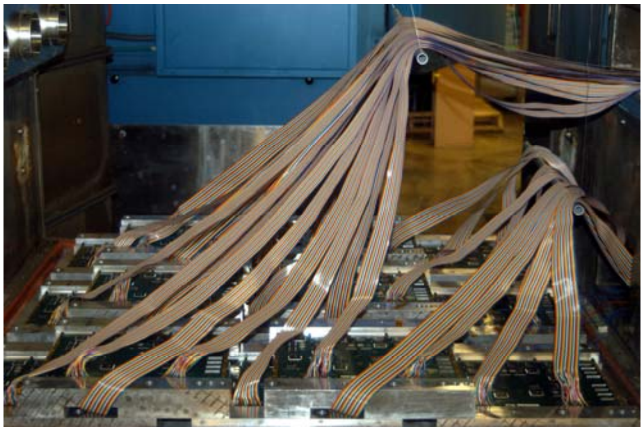

Figure 4 Test Vehicles in Test Chamber

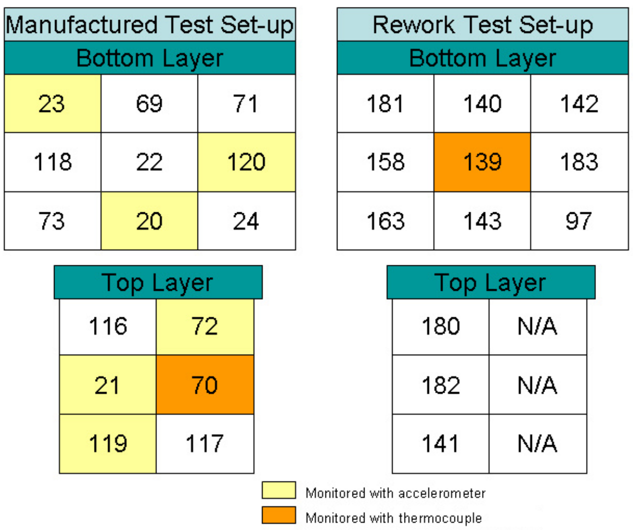

Figure 5 Manufactured and Rework Test Chamber Set-up.

RESULTS AND DISCUSSION

Pretest Inspection

The manufactured and rework test vehicles were inspected per J-STD-001, Class 3 requirements[7]. Overall, the manufactured test vehicles did not have any significant quality issues or concerns. The solder joint appearance was acceptable and did not have the grainy appearance documented in the previous JCAA/JGPP testing[8]. Similarly, the rework test vehicle solder joints were acceptable.

Pretest Inspection – Manufactured

The manufactured test vehicles were found to have the following anomalies:

- SN 23 – Board warped by 0.277 inch off the table from the bottom right corner.
- SN 97 – Board warped at the bottom left, not measured.
- SN 120 – Board warped by 0.350 inch off the table from the bottom right corner.

Pretest Inspection – Rework

Some rework test vehicles had solder balls on the back side of components near rework sites and others were found to have small areas of delamination near rework sites as well. One test vehicle had a burned area on the PWB laminate and others were slightly warped from the thermal cycling process before testing. The following anomalies were noted:

- SN 139, 141 & 142 – Boards were cut beyond the dimensions along the left side, some hardware holes were sliced.
- SN 180 – Vias were completely filled in ports P1 and P2.
- SN 182 – Board warped at the bottom left, not measured, very minor.
- SN 183 – Board warped at the bottom left, not measured, very minor

Manufactured Test Vehicles Results and Discussion

The manufactured test vehicles were cycled a total of 650 times. Events or failures logged at ten cycles or less were deemed outliers by a consortium consensus and were excluded from data analysis. The consortium decided that early life failures were due to a manufacturing or test anomaly. Therefore, outliers were removed to prevent skewing the data analysis, but a second Weibull plot was used to compare the difference between the data including the outliers. All test vehicles were inspected for lead damage and broken wires at the conclusion of testing.

The data was compiled by test vehicle serial number, component type, and component finish. The data shows test vehicles 23, 97, 116 and 69 exhibited less than twenty failed components. This observation suggests these test vehicles may have experienced lower thermal and/or vibration stresses during test due to their location in the chamber.

The data was also segregated by component type, component finish and solder alloy. Test vehicles soldered with tin-lead solder had the fewest solder joint failures overall. Test vehicles soldered with tin-silver-copper solder were second best. Lastly, test vehicles soldered with tin-copper solder paste had the worst performance.

The following sections provide the Weibull analysis for each component type. The plots include the fitted line and the 95-percent confidence limits. The legend on the right indicates the component type, solder alloy then component finish. A summary of manufacturing testing results is shown in Table 2.

BGA-225 Results and Discussion

The Weibull plot for tin-silver-copper 405 BGA-225 components soldered with tin-silver copper 305 solder paste is shown in Figure 6. The 2-parameter Weibull plot is a poor fit of the data given some data points fall outside the confidence limits and the fitted line has a ρ value less than 95-percent. There is a “stair step” in the data approximately at 500 cycles. No common cause for the stair step could be identified. A similar stair step phenomena occurred in the previous JCAA/JG-PP Lead-Free Electronics study in 2005, where other project members reported a stair step in thermal cycle testing[8].

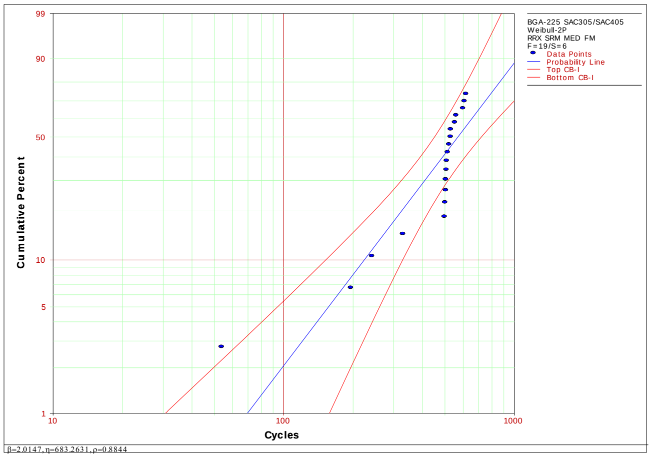

Figure 6 Weibull Plot of Tin-Silver-Copper 405 BGA-225 with Tin-Silver-Copper 305 Solder Paste on Manufactured Test Vehicles

The Weibull plot for tin-lead BGA-225 components soldered with tin-copper solder paste is shown in Figure 7. The 2-paramater Weibull plot is a good fit of the data. The fitted line has a ρ value of 96-percent. There also appears to be a "stair step" in the data. This data has an outlier which was removed and re-plotted in Figure 8, showing the change in slope. The same scale was used for both Weibull plots in Figure 7 and Figure 8 for comparative purposes.

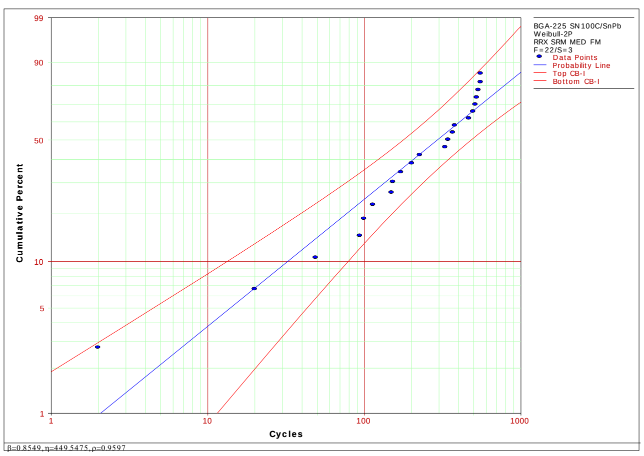

Figure 7 Weibull Plot of Tin-Lead BGA-225 with Tin-Copper Solder Paste on Manufactured Test Vehicles

The second Weibull plot for tin-lead BGA-225 components soldered with tin-copper solder paste is shown in Figure 8 less the outlier. This 2-paramater Weibull plot is an excellent fit of the data. The fitted line has a ρ value of 99-percent.

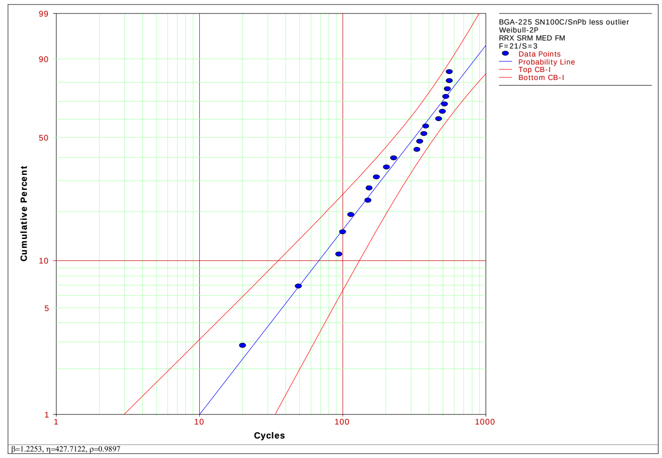

Figure 8 Weibull Plot of Tin-Lead BGA-225 with Tin-Copper Solder Paste on Manufactured Test Vehicles less one outlier

Figure 9 shows all the combinations of component finish and solder alloy for BGA-225 components on manufactured test vehicles. Based on N10 results, tin-lead BGA-225 components soldered with tin-lead solder paste and tin-silver-copper 405 BGA-225 components soldered with tin-silver-copper 305 solder paste had equivalent performance. The tin-silver-copper 405 BGA-225 components soldered with tin-copper solder paste combination performed second best. Mixing lead-free BGA-225 components with tin-lead solder paste performed the worst.

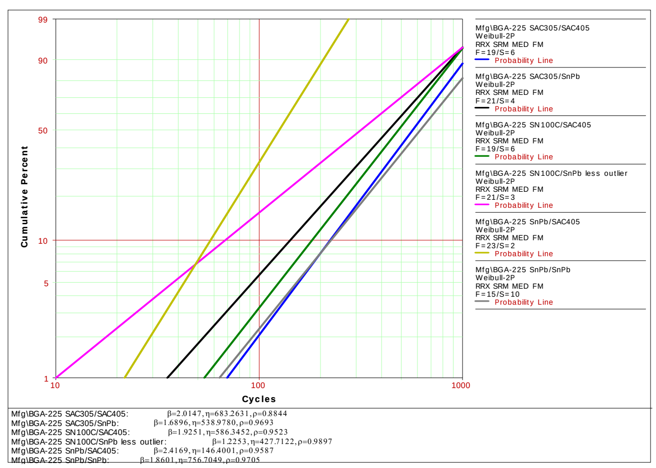

Figure 9 Weibull Plots of BGA-225 on Manufactured Test Vehicles

The effect of tin-lead contamination on tin-silver-copper 305 soldered BGA-225 components is shown in Figure 10. The plots show tin-lead degrades the early life performance of tin-silver-copper solder.

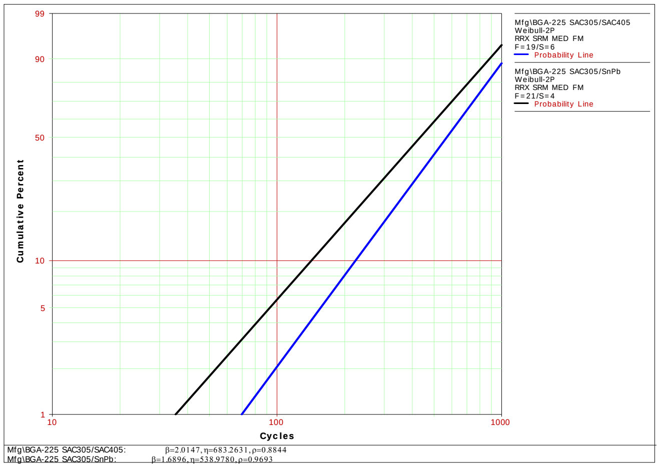

Figure 10 Effect of Tin-Lead Contamination on Tin-Silver-Copper 305 Soldered BGA-225 on Manufactured Test Vehicles

CLCC-20 Results and Discussion

Figure 11 shows all the combinations of component finish and solder alloy for CLCC-20 components on the manufactured test vehicles. Based on N10 results, tin-lead CLCC-20 components soldered with tin-lead solder paste performed the best. Tin-silver-copper 305 CLCC-20 components soldered with tin-lead performed second best. Tin-silver-copper 305 CLCC-20 components soldered with tin-copper solder paste performed the worst.

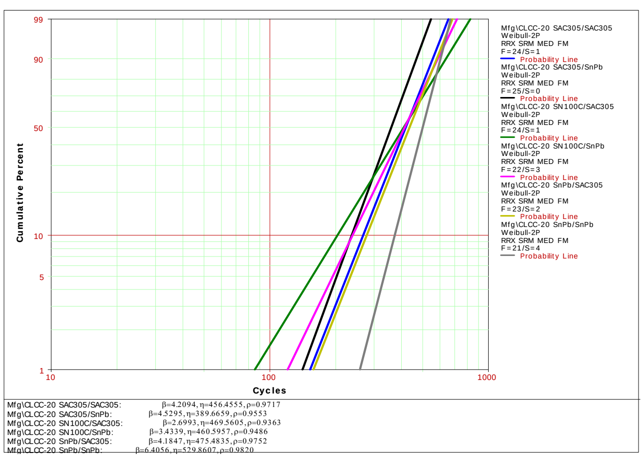

Figure 11 Weibull Plots of CLCC-20 on Manufactured Test Vehicles

CSP-100 Results and Discussion

Figure 12 shows the combinations of component finish and solder alloy for CSP-100 components on manufactured test vehicles. Based on N10 results, the tin-lead CSP-100 components soldered with tin-silver-copper 305 solder paste resulted as statistically equivalent and slightly better than tin-lead CSP-100 components soldered with tin-lead solder paste. Tin-silver-copper 105 CSP-100 components soldered with tin-lead solder paste performed the worst.

CSP-100 components exhibited higher than expected cycles to failure due to a PWB layout error. Because of the error, it took two solder joints from two different hemispheres in the footprint to fail and register as a component failure. CSP-100 components were expected to fail early.

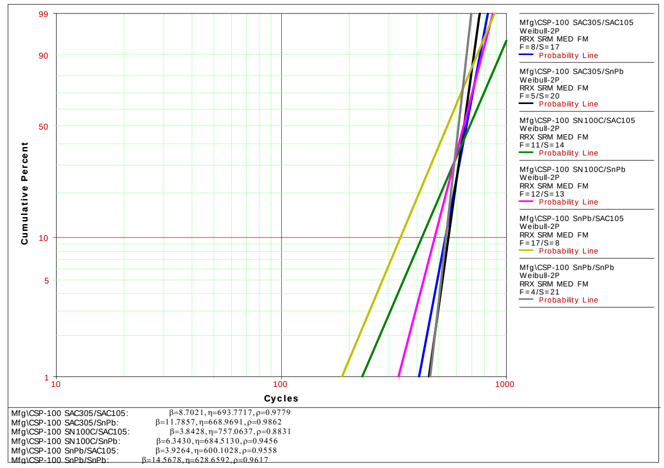

Figure 12 Weibull Plots of CSP-110 on Manufactured Test Vehicles

PDIP-20 Results and Discussion

There is not sufficient data to compare Weibull plots for all other combinations of PDIP-20 components. PDIP-20 results on manufactured test vehicles can be summarized by the chart in Figure 13. Only tin-copper finish PDIP-20 components recorded failures, 10-percent of the total population. Consortium members performing thermal cycle testing experienced early life failures with PDIP-20 components, but CET did not experience these results. A reason is under investigation.

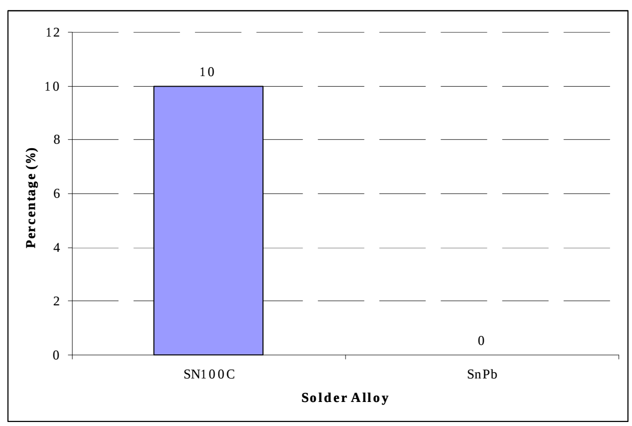

Figure 13 Percentage of Manufactured PDIP Failures by Wave Solder

TQFP-144 Results and Discussion

Figure 14 shows all the combinations of component finish and solder alloy for TQFP-144 components on manufactured test vehicles. Based on N10 results, matte tin TQFP-144 components soldered with tin-silver-copper 305 solder paste performed the best. Where matte tin TQFP-144 components soldered with tin-lead performed second best. Matte tin TQFP-144 components soldered with tin-copper solder paste performed the worst.

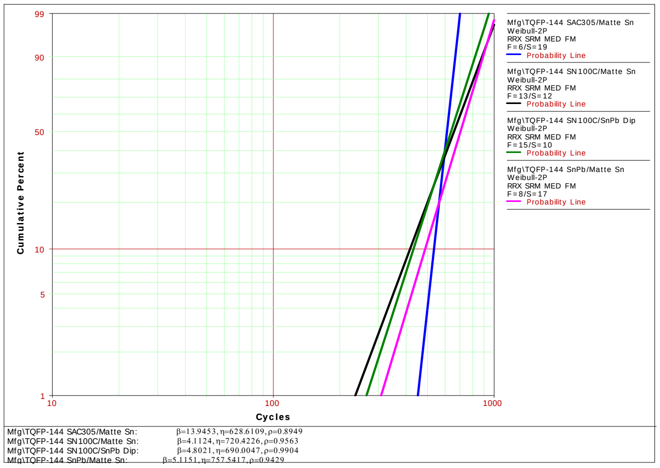

Figure 14 Weibull Plots of Tin TQFP-144 on Manufactured Test Vehicles

TSOP-50 Results and Discussion

Figure 15 shows all the combinations of component finish and solder alloy for TSOP-50 components on the manufactured test vehicles. Based on N10 results, the tin-bismuth TSOP-50 components soldered with tin-lead solder paste performed the best. Though, the plot shows that tin-lead TSOP-50 components soldered with tin-lead or with tin-silver-copper 305 solder performed equivalently and are more reliable, long term, than the tin-bismuth TSOP-50 components soldered with tin-lead solder paste.

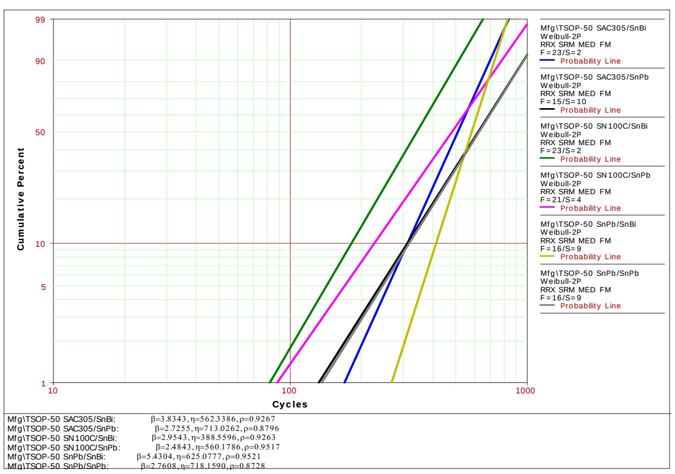

Figure 15 Weibull Plots of TSOP-50 on Manufactured Test Vehicles

Electroless Nickel Immersion Gold (ENIG) Manufactured Test Vehicle Results and Discussion

The Weibull plot comparing ENIG and immersion silver board finish for tin-lead BGA-225 components soldered with tin-silver-copper 305 solder paste is shown in Figure 16. The probability that manufactured tin-lead BGA-225 components soldered with tin-silver-copper 305 solder paste onto immersion silver board finish will last longer than tin-lead BGA-225 components soldered onto an ENIG board finish is 70%.

Figure 16 Comparison of ENIG and Immersion Silver Board Finish for Tin-Lead BGA-225 with Tin-Silver-Copper 305 Solder Paste

Table 2 Summary of Manufacturing Testing Results

Board Finish	Component	Alloy	Finish	Nf (10%)
ENIG	BGA-225	SAC305	SAC405	
ENIG	BGA-225	SAC305	SnPb	76
ENIG	CLCC-20	SAC305	SAC305	299
ENIG	CLCC-20	SAC305	SnPb	333
ENIG	CSP-100	SAC305	SAC105	
ENIG	CSP-100	SAC305	SnPb	
ENIG	PDIP-20	SN100C	Sn	
ENIG	PTH	SN100C	ENIG	
ENIG	QFN-20	SAC305	Matte Sn	
ENIG	TQFP-144	SAC305	Matte Sn	
ENIG	TQFP-144	SAC305	SnPb Dip	
ENIG	TSOP-50	SAC305	SnBi	
ENIG	TSOP-50	SAC305	SnPb	
ImAg	BGA-225	SAC305	SAC405	224
ImAg	BGA-225	SN100C	SAC405	182
ImAg	BGA-225	SnPb	SAC405	58
ImAg	BGA-225	SAC305	SnPb	142
ImAg	BGA-225	SN100C	SnPb	68
ImAg	BGA-225	SnPb	SnPb	226
ImAg	CLCC-20	SAC305	SAC305	267
ImAg	CLCC-20	SN100C	SAC305	204
ImAg	CLCC-20	SnPb	SAC305	278
ImAg	CLCC-20	SAC305	SnPb	237
ImAg	CLCC-20	SN100C	SnPb	239
ImAg	CLCC-20	SnPb	SnPb	373
ImAg	CSP-100	SAC305	SAC105	536
ImAg	CSP-100	SN100C	SAC105	422
ImAg	CSP-100	SnPb	SAC105	338
ImAg	CSP-100	SAC305	SnPb	553
ImAg	CSP-100	SN100C	SnPb	480
ImAg	CSP-100	SnPb	SnPb	539
ImAg	PDIP-20	SN100C	NiPdAu	
ImAg	PDIP-20	SnPb	NiPdAu	
ImAg	PDIP-20	SN100C	Sn	638
ImAg	PDIP-20	SnPb	Sn	
ImAg	PTH	SN100C	ImAg	
ImAg	PTH	SnPb	ImAg	
ImAg	QFN-20	SAC305	Matte Sn	
ImAg	QFN-20	SN100C	Matte Sn	520
ImAg	QFN-20	SnPb	Matte Sn	
ImAg	TQFP-144	SAC305	Matte Sn	535
ImAg	TQFP-144	SN100C	Matte Sn	417
ImAg	TQFP-144	SnPb	Matte Sn	488
ImAg	TQFP-144	SAC305	SnPb Dip	
ImAg	TQFP-144	SN100C	SnPb Dip	432
ImAg	TQFP-144	SnPb	SnPb Dip	
ImAg	TSOP-50	SAC305	SnBi	313
ImAg	TSOP-50	SN100C	SnBi	181
ImAg	TSOP-50	SnPb	SnBi	413
ImAg	TSOP-50	SAC305	SnPb	312
ImAg	TSOP-50	SN100C	SnPb	226
ImAg	TSOP-50	SnPb	SnPb	318

Rework Test Vehicle Results and Discussion

The reworked test vehicles were cycled 650 times. Events or failures that were ten cycles or less were deemed as outliers and the data points were excluded from the data analysis. The consortium decided that early life failures were caused by manufacturing, rework process issues or a test anomaly. The outliers were removed to prevent skewing the data analysis, but Weibull plots were created to compare the shift of the probability slope. All reworked test vehicles were inspected for lead damage and broken wires at the conclusion of testing.

The data was compiled by test vehicle serial number, component type, and component finish. The data shows reworked test vehicles 142 and 183 exhibited twenty (20) or fewer failed components. This observation suggests these two test vehicles may have experienced lower thermal and/or vibration stresses during testing due to their location in the chamber.

The data was segregated by component type, component finish and solder alloy. Test vehicles soldered with or reworked with tin-lead solder had the fewest solder joint failures. Test vehicles soldered with tin-silver-copper solder were second best. Lastly, the test vehicles soldered with tin-copper solder had the worst performance.

The following sections provide the Weibull analysis for each component type. The plots include the fitted line and the 95-percent confidence limits. The legend on the right indicates if the component was reworked, the component type, solder alloy then component finish. A summary of rework testing results of immersion silver surface finish test vehicles in shown in Table 3 and a summary of rework testing results of ENIG surface finish test vehicles in shown in Table 4.

Rework – BGA-225 Results and Discussion

The Weibull plot for reworked tin-silver-copper 405 BGA-225 components reworked with flux only on a reworked test vehicle is shown in Figure 17. The 2-parameter Weibull plot is not a good fit of the data due to several early life failures, shown at the right of the chart. The four early life failures are associated with having been reworked. This fitted line has a ρ value of 85-percent. The Weibull plot was plotted again excluding the early life failures, Figure 18.

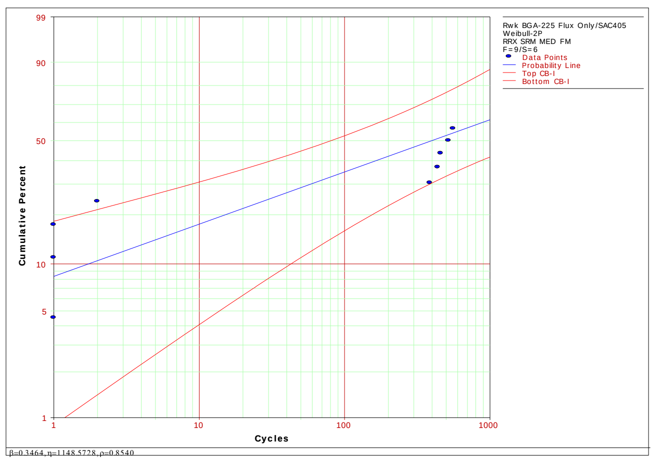

Figure 17 Weibull Plot of Reworked Tin-Silver-Copper 405 BGA-225 with Flux Only on Rework Test Vehicles

The Weibull plot for reworked tin-silver-copper 405 BGA-225 components reworked with flux only on a rework test vehicle less outliers is shown in Figure 18. This 2-parameter Weibull plot is an excellent fit of the data. The fitted line has improved to a ρ value of 97-percent. Removing the early life failures improved the probability slope dramatically.

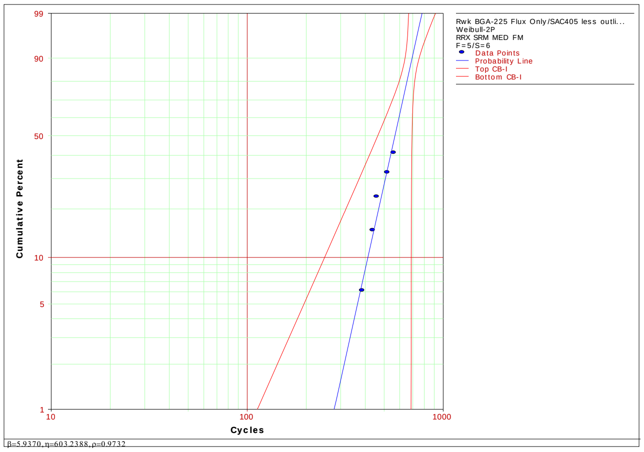

Figure 18 Weibull Plot of Reworked Tin-Silver-Copper 405 BGA-225 with Flux Only on Rework Test Vehicles less outliers

Figure 19 shows all the combinations of rework component finish and solder alloy for BGA-225 components on the rework test vehicles. Based on N10 results, the tin-silver-copper 405 BGA-225 components reworked with tin-lead solder paste, Batch A, less the outlier was the most reliable. The chart also shows tin-silver-copper 405 BGA-225 components soldered with tin-lead solder paste performed statistically as good as tin-silver-copper 405 BGA-225 components reworked with tin-lead solder paste.

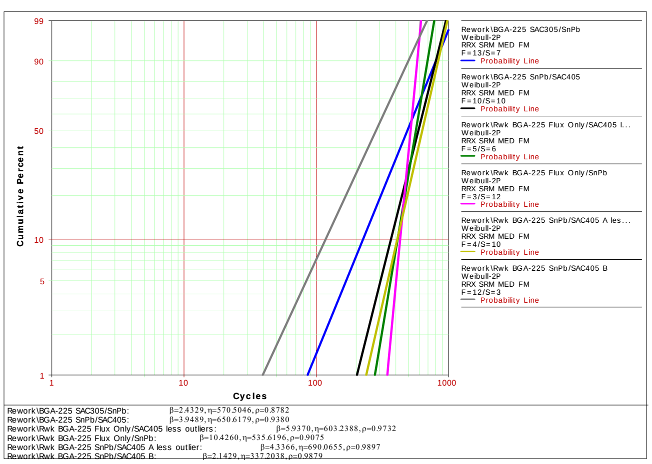

Figure 19 Weibull Plots of BGA-225 on Rework Test Vehicle

Figure 20 Weibull plot compares reworked BGA-225 components on rework test vehicles. Based on N10 results, reworked tin-silver-copper 405 BGA-225 components soldered with tin-lead solder paste less the outliers perform the best.

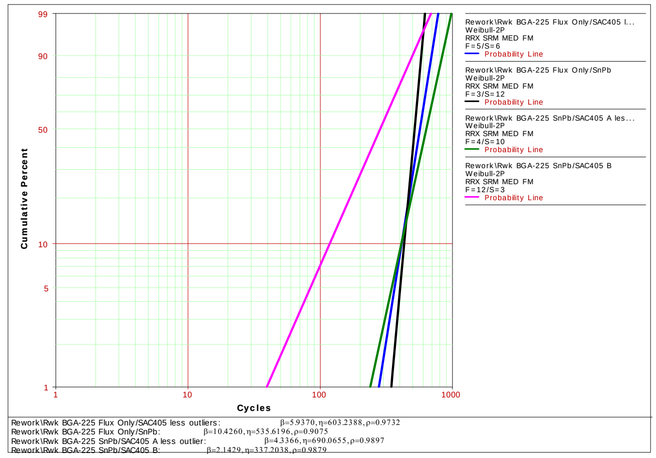

Figure 20 Weibull Plots of Reworked BGA-225 on Rework Test Vehicle

Rework – CLCC-20 Results and Discussion

Figure 21 Weibull plot compares the result of CLCC-20 components on reworked test vehicles. Based on N10, tin-silver-copper 305 CLCC-20 components soldered with tin-lead solder paste have better solder joint performance than tin-lead CLCC-20 components soldered with tin-silver-copper 305 solder paste.

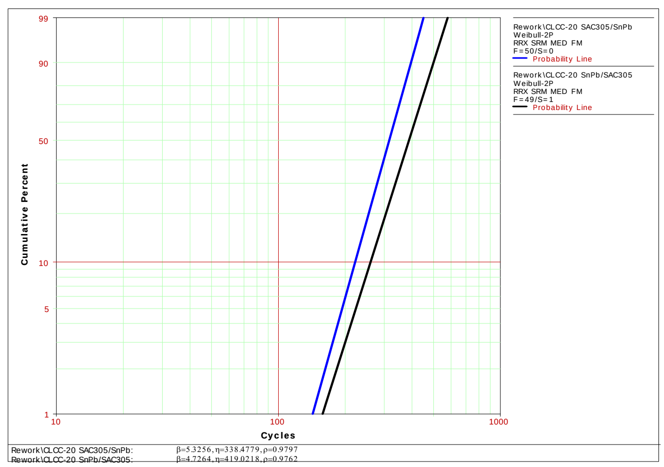

Figure 21 Weibull Plots of CLCC-20 on Rework Test Vehicles

Rework – CSP-100 Results and Discussion

Figure 22 combines all the rework CSP-100 component Weibull results on rework test vehicles. Based on N10 results, reworked tin-silver-copper 105 CSP-100 components reworked with flux only have the best solder joint reliability. Tin-silver-copper 105 CSP-100 components soldered with tin-silver-copper 305 solder paste performed second best.

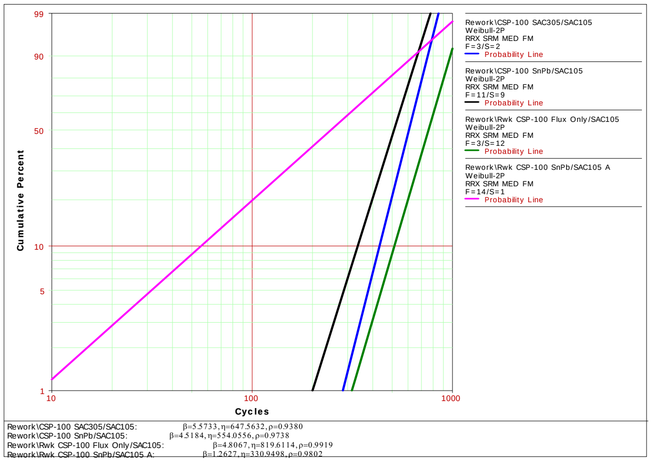

Figure 22 Weibull Plot of CSP-100 on Rework Test Vehicles

Rework – PDIP-20 Results and Discussion

The Weibull plot for reworked tin PDIP-20 components soldered with tin-lead solder on rework test vehicles is shown in Figure 23. The 2-parameter Weibull plot is a fair fit of the data where the fitted line has a ρ value of 89-percent. No other failures occurred to create additional Weibull plots for PDIP-20 components on reworked test vehicles.

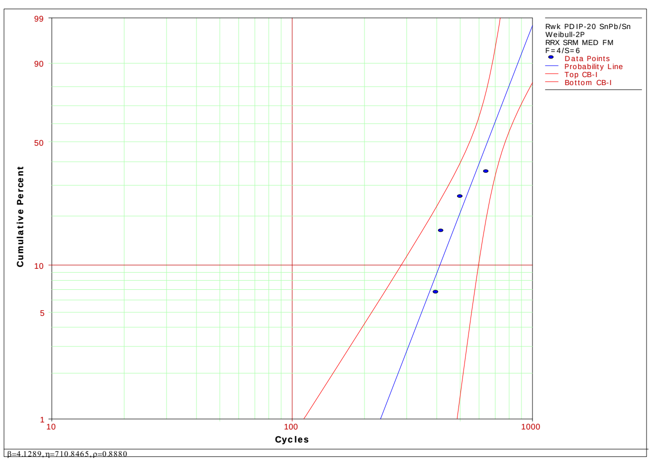

Figure 23 Weibull Plot of Reworked Tin PDIP-20 with Tin-Lead Solder on Rework Test Vehicles

Rework – TSOP-50 Results and Discussion

Figure 24 shows all the different Weibull plots generated for the TSOP-50 component on reworked test vehicles. It can be determined that tin-lead TSOP-50 components soldered with tin-lead solder paste on rework test vehicles performed better than any other combination of solder alloy and rework.

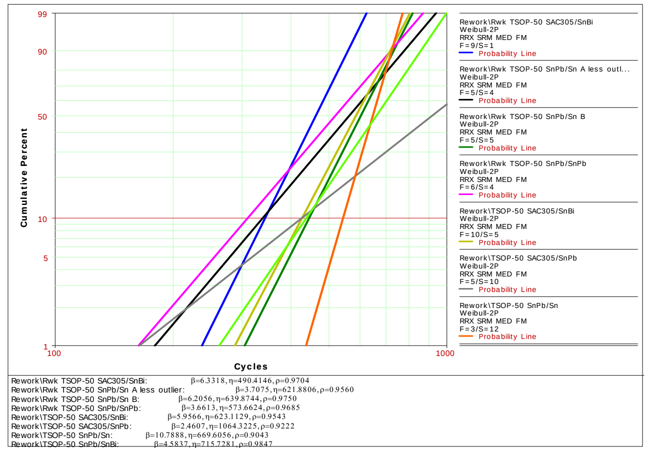

Figure 24 Weibull Plots of TSOP-50 on Rework Test Vehicles

Figure 25 shows the different Weibull plots generated for different combinations of reworked TSOP-50 components. It can be determined that reworked tin TSOP-50 components reworked with tin-lead solder paste, Batch B, performed better than the other combinations.

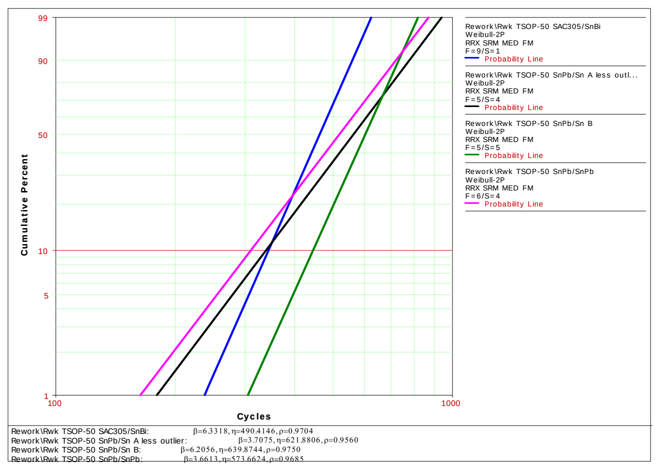

Figure 25 Weibull Plots of Reworked TSOP-50 on Rework Test Vehicles

Electroless Nickel Immersion Gold (ENIG) Rework Test Vehicle Results and Discussion

The Weibull plots comparing ENIG and immersion silver test vehicle board finishes for tin-silver-copper 405 BGA-225 components soldered with tin-lead solder paste is shown in Figure 26. Overall, the probability that immersion silver board finish performs better than the ENIG board finish is 72-precent.

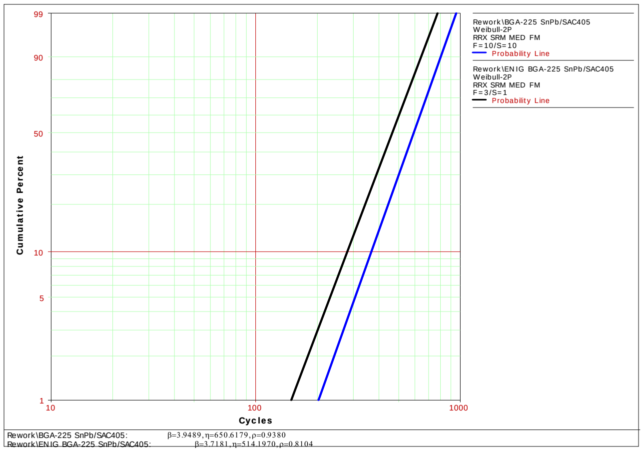

Figure 26 Comparison of ENIG and Immersion Silver Board Finish on Tin-Silver-Copper 405 BGA-225 with Tin-Lead Solder Paste on Rework Test Vehicles

The Weibull plots comparing ENIG and immersion silver test vehicle board finishes for reworked tin-silver-copper 405 BGA-225 components soldered with tin-lead solder paste is shown in Figure 27. Overall, the probability that ENIG board finish, less the outlier, performs better than the immersion silver board finish is 78-percent.

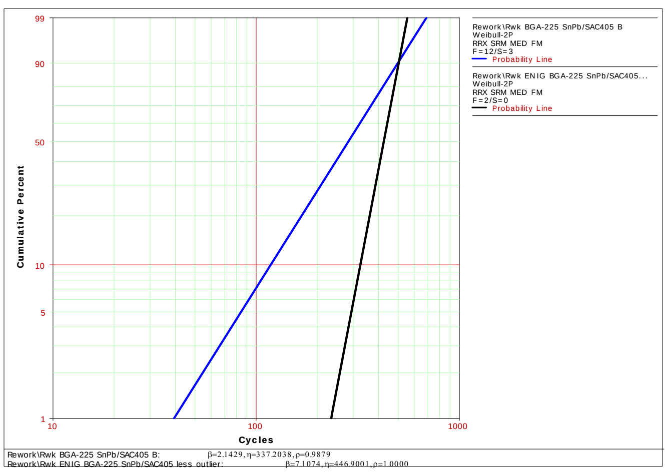

Figure 27 Comparison of ENIG and Immersion Silver Board Finish for Reworked Tin-Silver-Copper 405 BGA-225 with Tin-Lead Solder Paste on Rework Test Vehicles

The Weibull plots comparing ENIG and immersion silver test vehicle board finishes for tin-lead solder dipped TQFP-144 components soldered with tin-lead solder paste on rework test vehicles is shown in Figure 28. Overall, the probability that immersion silver board finish performs better than the ENIG board finish is 93-percent.

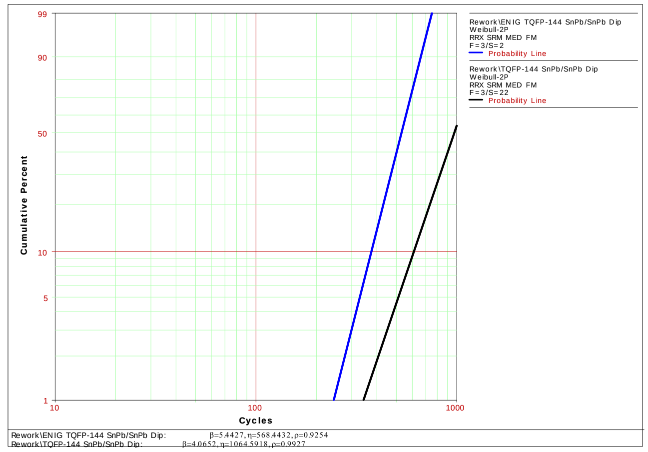

Figure 28 Comparison of ENIG and Immersion Silver Board Finish for Tin-Lead Solder Dipped TQFP-144 with Tin-Lead Solder Paste on Rework Test Vehicles.

Table 3 Summary of Rework Testing Results of Immersion Silver Surface Finish Test Vehicles

Component	Alloy	Finish	New Finish	Rework Solder	Nf (10%)
BGA-225	SAC305	SAC405	SAC405	Flux	413
BGA-225	SAC305	SAC405	SAC405	SnPb	411
BGA-225	SnPb	SAC405			368
BGA-225	SAC305	SnPb			226
BGA-225	SnPb	SnPb	SAC405	SnPb	118
BGA-225	SnPb	SnPb	SnPb	Flux	432
CLCC-20	SnPb	SAC305			260
CLCC-20	SAC305	SnPb			222
CSP-100	SAC305	SAC105	SAC105	Flux	513
CSP-100	SAC305	SAC105	SAC105	SnPb	56
CSP-100	SAC305	SAC105			432
CSP-100	SnPb	SAC105			337
CSP-100	SAC305	SnPb			
CSP-100	SnPb	SnPb	SAC105	SnPb	
CSP-100	SnPb	SnPb			
PDIP-20	SnPb	NiPdAu			
PDIP-20	SN100C	Sn	Sn	SN100C	
PDIP-20	SN100C	Sn			
PDIP-20	SnPb	Sn			
PDIP-20	SnPb	SnPb	Sn	SnPb	412
PTH	SN100C	ImAg			
PTH	SnPb	ImAg			
QFN-20	SnPb	Matte Sn			
QFN-20	SAC305	SnPb			
TQFP-144	SAC305	NiPdAu			
TQFP-144	SnPb	NiPdAu			
TQFP-144	SAC305	SAC305			143
TQFP-144	SnPb	SnPb Dip			612
TSOP-50	SAC305	Sn	Sn	SnPb	339
TSOP-50	SnPb	Sn			544
TSOP-50	SAC305	SnBi	SnBi	SAC305	344
TSOP-50	SAC305	SnBi			427
TSOP-50	SnPb	SnBi			438
TSOP-50	SAC305	SnPb			426
TSOP-50	SnPb	SnPb	Sn	SnPb	445
TSOP-50	SnPb	SnPb	SnPb	SnPb	310

Table 4 Summary of Rework Testing Results of ENIG surface finish Test Vehicles

Component	Alloy	Finish	New Finish	Rework Solder	Nf (10%)
BGA-225	SnPb	SAC405			281
BGA-225	SnPb	SnPb	SAC405	SnPb	326
BGA-225	SnPb	SnPb	SnPb	Flux	
CLCC-20	SnPb	SAC305			220
CSP-100	SnPb	SAC105			
CSP-100	SnPb	SnPb	SAC105	SnPb	
CSP-100	SnPb	SnPb	SnPb	Flux	
PDIP-20	SnPb	NiPdAu			
PDIP-20	SnPb	Sn			
PDIP-20	SnPb	SnPb	Sn	SnPb	
PTH	SnPb	ENIG			
QFN-20	SnPb	Matte Sn			
TQFP-144	SnPb	NiPdAu			
TQFP-144	SnPb	SnPb Dip			376
TSOP-50	SnPb	Sn			
TSOP-50	SnPb	SnBi			
TSOP-50	SnPb	SnPb	Sn	SnPb	393
TSOP-50	SnPb	SnPb	SnPb	SnPb	161

STATISTICAL ANALYSIS

Additional statistical analysis was performed using another type of software. Variance component analysis was conducted on all the data (includes rework and ENIG) and the software results are shown in Figure 29. The analysis of variance divides the variance of the cycles to failure into three components, one for each factor. The goal of such an analysis is to estimate the amount of variability contributed by each of the factors, called the variance components analysis. The factors included: component type, lead finish and solder alloy or paste, as well as unexplained error.

This analysis shows that solder joint reliability was influenced by the choice of lead finish, but it was less significant than the choice of component type or random noise. The analysis is an approximate estimate since censored values (samples that did not fail) were left at their last measured cycle. The random noise would include other factors not included in the experiment of analysis. The analysis further shows the influence due to solder alloy/ paste is not a factor.

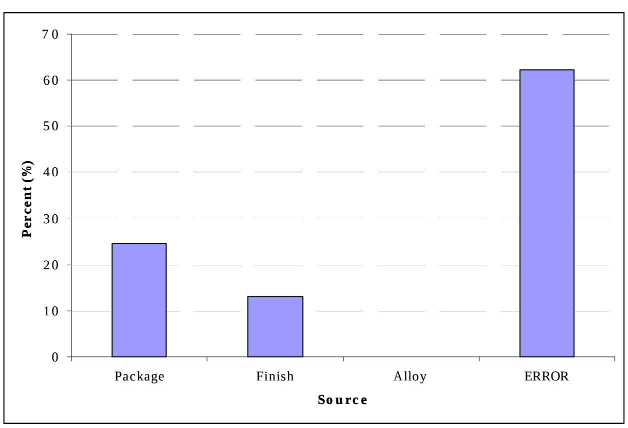

Figure 29 Chart of Variance Component Analysis of All Data

The data was also separated to analyze solder joint reliability of the manufactured test vehicles only, excluding rework and ENIG data. The ENIG sample size is too small to develop statistically based recommendations and the rework data includes several different combinations making it difficult to compare specific combinations of solder and lead finish. It is also suspected, that the high result of unexplained variation came from the rework data set.

Thus variance component analysis was conducted on the manufactured data less ENIG and the software results are shown in Figure 30. The analysis shows that solder joint reliability was influenced by the choice of solder alloy and random noise, but it was not as significant as the choice of component type. Again, the analysis was an approximate estimate since censored values were left at their last measured cycle. The random noise would include factors not included in the experiment of analysis. The analysis further shows that the influence due to component finish is not a factor.

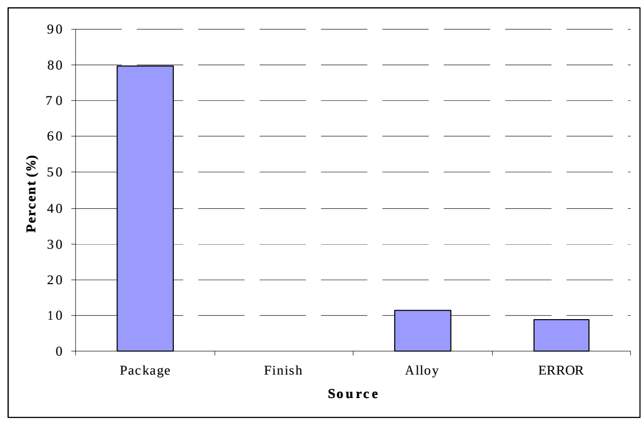

Figure 30 Chart of Variance Component Analysis of Manufactured Data

Overall, from the two variance component analysis the component type resulted as the greatest effect on solder joint reliability performance. Plated-through-hole components proved to be more reliable than surface mount technology components. The relative ranking of the different component types used with tin-lead and tin-copper solder on manufactured test vehicles less ENIG is shown in Figure 31. The immersion silver finished plated-through-hole (PTH), tin PDIP-20, nickel-palladium-gold PDIP-20, matte tin QFN-20 and tin-lead dipped TQFP-144 components performed the best, most had zero failures. The tin-lead and tin-silver-copper 405 BGA-225 components had the worst solder joint reliability performance.

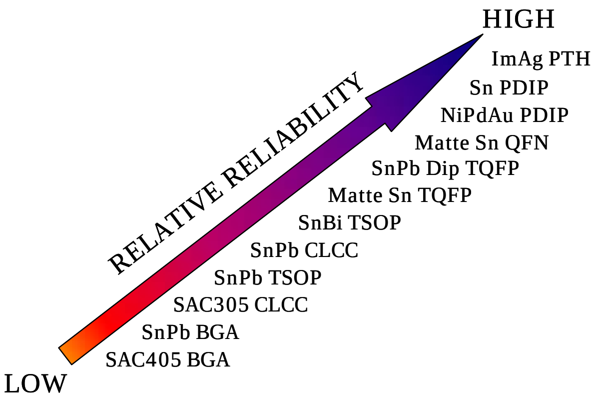

Figure 31 Relative Reliability of Components for Tin-Lead Solder and Tin-Copper Solder on Manufactured Test Vehicles less ENIG

The relative ranking of the different component types and finishes soldered with tin-silver-copper 305 solder paste on manufactured test vehicles less ENIG is shown in Figure 32. The matte tin QFN-20 and tin-lead dipped TQFP-144 components performed the best, none recorded a failure. The tin-silver-copper 405 and tin-lead BGA-225 components had the worst solder joint reliability performance. No PTH components were soldered with tin-silver-copper 305 solder paste.

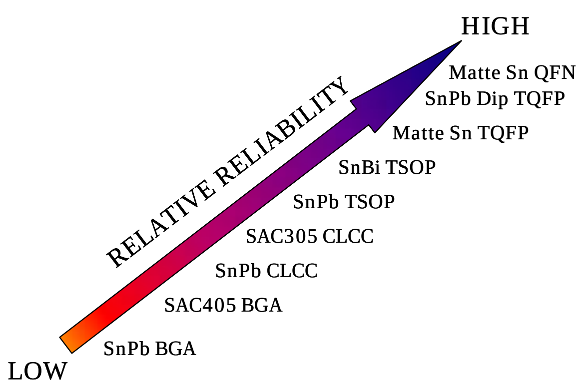

Figure 32 Relative Reliability of Components for Tin-Silver-Copper 305 Solder on Manufactured Test Vehicles less ENIG

The interaction and 95-percent confidence intervals plot for BGA-225 components including all the data is shown in Figure 33. The plot shows that tin-lead BGA-225 components soldered with either tin-silver-copper 305 or tin-copper solder paste will result in reduced solder joint reliability when compared to the baseline, tin-lead solder paste. The mixing of tin-lead BGA-225 components with lead-free solder pastes will result in reduced reliability. Though, mixing tin-silver-copper 405 BGA-225 components with tin-silver-copper 305 solder paste will result in better solder joint reliability than any of the other component finish and alloy combinations.

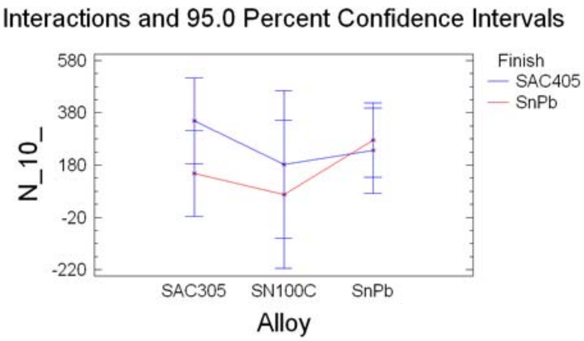

Figure 33 Interaction and 95-Percent Confidence Intervals for BGA-225 Components - All Data

Comparing Statistical Analysis with 2005 JCAA/JG-PP Study

The statistical analysis of this study was compared with the statistical analysis of the 2005 JCAA/JG-PP Lead-Free Solder Project[8]. Consider that these studies are not exactly the same, the factors involved were different, yet both studies found similar results. Component or package type resulted as the main factor significantly affecting overall solder joint reliability; refer to the side-by-side comparison of variance component analysis in Figure 34. Note the variance components analysis from 2009 reflects the manufactured data only. The main difference from the 2005 study is the inclusion of component location on the test vehicle in the x- and y-axis. The 2009 study did not include component position because results from the 2005 study shows a minor to neglible effect on solder joint reliability along the x-axis. The effect to solder joint reliability along the y-axis had no effect; therefore, the two factors were excluded from the 2009 study.

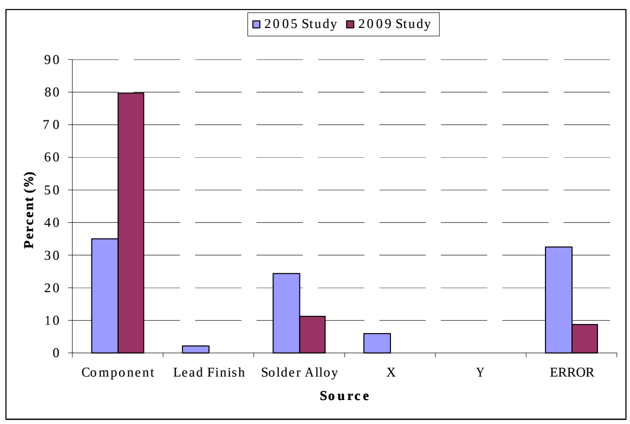

Figure 34 Comparison Chart of Variance Components Analysis of both the 2005 JCAA/JG-PP Lead-Free Solder Project and the 2009 NASA-DoD Lead-Free Solder Electronics Project Manufactured Data[8]

Both analyses found that plated-through-hole components proved to be more reliable than the surface mount technology components. Both studies also found that the choice of solder alloy has a secondary effect on solder joint reliability.

In general, tin-silver-copper soldered components were less reliable than the tin-lead soldered controls. In general, reworked components were less reliable than the manufactured (unreworked) components.

CONCLUSIONS

Overall, component type has the greatest effect on solder joint reliability performance. The plated-through-hole components proved to be more reliable than the surface mount technology components. The plated-through-holes, PDIP-20, TQFP-144 and QFN-20 components performed the best. The BGA-225 components performed the worst.

Solder alloy had a secondary effect on solder joint reliability. In general, tin-lead finished components soldered with tin-lead solder paste were the most reliable. In general, tin-silver-copper soldered components were less reliable than tin-lead soldered controls. Though, the lower reliability of the tin-silver-copper 305 solder joints does not necessarily rule out the use of tin-silver copper solder alloy on military electronics. In several cases, tin-silver-copper 305 solder performed statistically as good as or equal to the baseline, tin-lead solder.

The effect of tin-lead contamination on BGA-225 components degrades early life performance of tin-copper solder paste, but it can also degrade early life performance of tin-silver-copper 305 solder paste. The effect of tin-lead contamination on BGA-225 components soldered with tin-silver-copper 305 solder paste was less than the effect on tin-lead contamination on tin-copper solder.

CSP-100 components are the exception, where tin-lead CSP-100 components soldered with tin-silver-copper 305 solder paste performed better than or equal to tin-lead CSP-100 components soldered with tin-lead solder paste. The chip scale package components were not drafted correctly during the design stage, therefore CSP-100 component results can only be used to compare within the chip scale package type.

The probability plots of soldering tin-lead and tin-silver-copper 305 solder components onto electroless nickel immersion gold (ENIG) finished test vehicles were compared using BGA-225 and CLCC-20 components. In general, tin-lead components soldered with tin-silver-copper 305 solder paste onto immersion gold surface finish performs better than tin-silver-copper 305 components soldered onto ENIG surface finish test vehicles. One exception is the performance of tin-lead CLCC-20 components soldered with tin-silver-copper 305 solder paste onto an ENIG surface finished test vehicle which performed better than the immersion gold test vehicle. Keep in mind, the ENIG sample size consisted of two.

In general, reworked components are less reliable than unreworked components. This is especially true with reworked lead-free CSP-100, reworked lead-free BGA-225 and unreworked lead-free TQFP-144 components; these components did not survive beyond 200 cycles. About 40-percent of the outliers were early life failures from lead-free BAG-225 components reworked with flux only. Another 30-percent of early life failures came from lead-free TQFP-144 components that were not reworked but were adjacent to rework sites. The exceptions were the immersion gold plated-through-hole components, nickel-palladium-gold TQFP-144, matte tin and tin-lead QFN-20, and tin PDIP-20 components, where a majority of these components were soldered with tin-lead solder and did not fail. Approximately, 37-percent of rework test vehicle components soldered with tin-lead solder paste failed, whereas, 53-percent of rework test vehicle components soldered with tin-silver-copper 305 solder paste failed. This suggests that reworking surface mount technology components with lead-free solder continues to pose processing challenges.

When comparing the performance of components on manufactured and rework test vehicles, the immersion silver surface finish of the manufactured test vehicles appears to enhance the reliability of the solder joints.

ACKNOWLEDGEMENTS

The author wants to thank Bill Beair, Bill Vuono and Gary Eiland with McKinney Circuit Card Assembly for providing the event detectors and Mark Taylor, Larry Taylor and Bob Sparks with the Raytheon Environmental Test Laboratory for executing the test.

We also want to thank consortia members Jelena Bradic, Linda Woody and Keith Howell for volunteering in providing the failure analysis studies of the selected components from our CET test vehicles.

Special thanks to Kurt Kessel from the NASA Technology Evaluation for Environmental Risk Mitigation (TEERM) Principle Center for managing the NASA-DoD Lead-Free Electronics Project.

REFERENCES

[1] Kessel, Kurt R., et al. NASA-DoD Lead-Free Electronics Project Plan. 2009.

[2] IPC-SM-785: Guidelines for Accelerated Reliability Testing of Surface Mount Solder Attachments. January 2009.

[3] IPC-9701: Performance Test Methods and Qualification Requirements for Surface Mount Solder Attachments. February 2009.

[4] IPC-6012A: Qualification and Performance Specification for Rigid Printed Boards. October 2009.

[5] MIL-STD-810F, Method 520.2: Temperature, Humidity, Vibration, and Altitude.

[6] Raytheon Systems Company, Test Procedure, Combined Environments Test. 2009.

[7] IPC/EIA J-STD-001: Requirements for Soldered Electrical and Electronic Assemblies. January 2009.

[8] Jeff Bradford, Felty, Russell, JCAA/JG-PP Lead-Free Solder Project: Combined Environments Test. Raytheon Company, August 2005.