JCAA/JG-PP Lead Free Solder Project: Combined Solder Project: Combined Environments Test

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Abstract
A combined environment testing was conducted for the Joint Council on Aging Aircraft/Joint Group on Pollution Prevention Lead free Solder project. The purpose of the project was to validate and demonstrate lead free solders as potential replacements for conventional tin-lead solders used on circuit card assemblies against the requirements of the aerospace and military electronics community.

The solder alloys tested include: Sn3.9Ag0.6Cu, Sn3.4Ag1.0Cu3.3Bi, Sn0.7Cu0.05Ni and Sn37Pb. These solder alloys were used to assemble various components on three different printed wiring board test vehicles: manufactured, rework and hybrid. The test vehicles were subjected to a combined environments test consisting of thermal cycling from –55 to 125 degrees Celsius at a ramp rate of 20 degrees Celsius per minute, dwell at the temperature extremes for 15 minutes and pseudorandom vibration of 10 g_{rms} for the last 10 minutes of the dwell periods. After every 50 cycles, the vibration level was increased by 5 g_{rms} until a maximum of 55 g_{rms} was reached. The test vehicles were electrically monitored using event detectors.

The solder joint failure data of a given component type, component finish and solder alloy were evaluated using Weibull analysis. The reliability of the lead free solder alloys was compared to the baseline tin-lead (Sn37Pb) solder alloy.
Keywords: Thermal cycle, vibration, lead free

Background

European, Asian and United States environmental regulatory actions and free market forces threaten the use of conventional tin-lead solders in aerospace and military electronics. The European Union has adopted legislation that governs the re-use and recycling of electronics waste known as the Waste from Electrical and Electronic Equipment (WEEE) Directive. In addition, Europe has begun implementing the Restriction of Hazardous Substances (RoHS) Directive that bans the use of lead and other substances starting on 1 July 2006. Japan has taken an active role in eliminating lead from consumer electronics with many major Japanese electronics companies announcing the move to lead free electronics. Future U.S. regulatory action may ban all solders containing lead.

Although currently exempt from the European legislation, there is a concern that a legislative body may ban the use of lead in aerospace and military electronics. Even with an exemption, aerospace and military electronics are being impacted by the consumer electronics manufacturer's move to lead free products. As more commercial electronics manufacturers move to lead free technology, aerospace and military programs will find it more difficult to procure electronic components fabricated with tin-lead solder. The commercial electronics sector is driving component and board suppliers to provide lead free surface finishes and alloys. Electronic component manufacturers are switching to lead free lead finishes. Lead free components are finding their way into aerospace and military electronics under government acquisition reform initiatives. As a result of the commercial lead free demand, it is possible that parts with tin-lead finishes may become impossible to procure or the acquisition costs for military grade tin-lead finished components may become prohibitive. The price of tin-lead solder may rise or the supplies of tin-lead solder may dwindle due to the lower market demand.

While work has been done to determine lead free reliability for commercial general and dedicated service electronic products, there has been little comprehensive data published on the reliability of lead free solders on high reliability, high performance electronic products. In May 2001, the Joint Council on Aging Aircraft (JCAA) and the Joint Group on Pollution Prevention (JG-PP) Lead free Solder project was initiated by the Department of Defense (DoD). A consortium consisting of a partnership between the DoD, National Aeronautics and Space Administration (NASA), and several defense electronics contractors was formed to evaluate lead free solders and to determine whether they are suitable for use in high reliability electronics.

This report summarizes the results of the combined environments test conducted as part of the JCAA/JG-PP Lead free Solder Project.

Methods, Assumptions and Procedures

The project consortium identified potential alloys for each of the three soldering processes: wave, reflow, and manual. The team selected the solder alloys listed in Table 1.

Table 1 - Solder Alloys

Solder Alloy	Nomenclature	Designation
Sn3.9Ag0.6Cu	Tin-Silver-Copper	SnAgCu
Sn3.4Ag1.0Cu3.3Bi	Tin-Silver-Copper-Bismuth	SnAgCuBi
Sn0.7Cu0.05Ni	Tin-Copper	SnCu
Sn37Pb (baseline)	Tin-Lead	SnPb

The combined environments test (CET) was conducted in accordance with the Joint Test Protocol, "Joint Test Protocol, J-01-EM-026-P1, for Validation of Alternatives to Eutectic Tin-Lead Solders used in Manufacturing and Rework of Printed Wiring Assemblies" (Revised April 2004). The purpose of the CET was to determine the reliability of solders under combined thermal cycle and vibration environmental exposures. The combined environments test was based on MIL-STD-810F, Method 520.2 and a modified highly accelerated life test (HALT), a process in which products are subjected to accelerated environments to find weak links in the design and manufacturing process. The project stakeholders felt that the combined environments test might provide a relatively quick method to identify comparative reliability differences between the lead free solder alloys against the eutectic tin-lead solder baseline.

The CET was conducted using a QualMark Model OVS-4 HALT/HASS chamber. The chamber was located in the Raytheon Environmental Test Laboratory (ETL) in McKinney, Texas. A photograph of the chamber is provided in Figure 1. The chamber utilizes liquid nitrogen for cooling and nichrome heater elements for heating. The chamber has thermal capability ranges from -100 to 200 degrees Celsius with ramp rates of up to 60 degrees Celsius per minute. The pseudorandom vibration spectra is generated by pneumatically driven vibrators attached to the bottom of the table with maximum levels of 60 g_{rms} and six degrees of freedom (X, Y, & Z axes with rotation in each axis simultaneously). The thermal and vibration environments can be applied separately or combined.

Figure 1 - Qualmark Model OVS-4 HALT/HASS Chamber

The CET was performed on the test vehicles utilizing a temperature range of –55 to 125 degrees Celsius with 20 degrees Celsius per minute temperature ramp. The dwell times at each temperature extreme consisted of a six-minute temperature stabilization period and a fifteen-minute soak. A 10 g_{rms} pseudorandom vibration was applied for the last 10 minutes of the cold and hot dwells. The initial test profile is graphically represented in

Figure 2. If significant failure rates were not evident after 50 cycles, the vibration levels were increased by 5 g_{rms} and cycling was continued for an additional 50 cycles. This process was repeated until a significant number of solder joints failed or 55 g_{rms} was reached. During cycles 501 through 550, vibration stress was applied continuously at 55 g_{rms} during the thermal cycle. The test was stopped after 550 cycles.

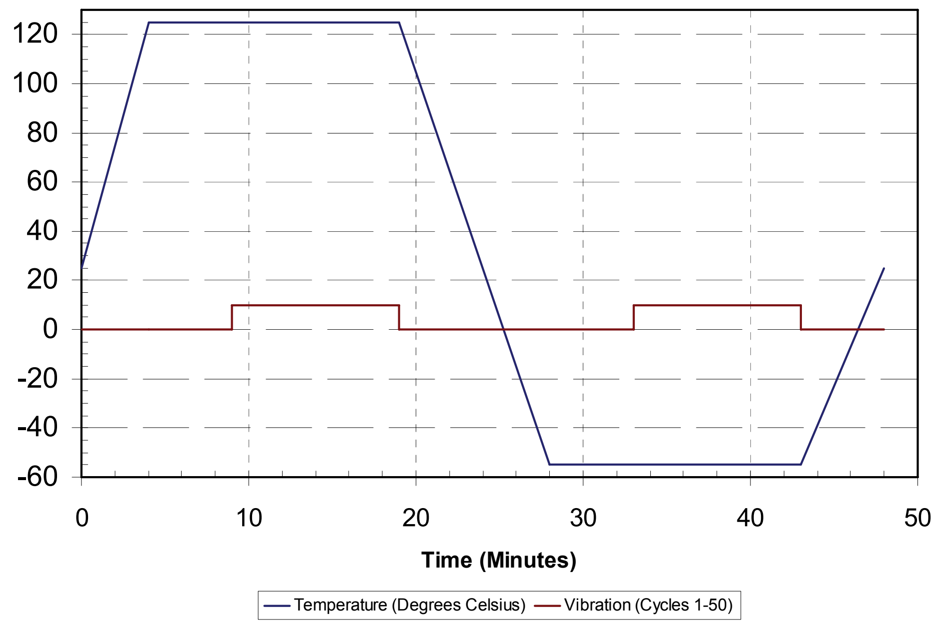

Figure 2 - Initial Combined Environments Test Profile

The test vehicle used in the CET consisted of three different circuit card assemblies designed per IPC-SM-785 and IPC-9701 to evaluate solder joint reliability. The printed wiring board test vehicles were designed and fabricated to comply with IPC-6012, Class 3. All boards had six layers and overall dimensions of 14.5 by 9 by 0.09 inch thick. The manufactured and rework board had a break-off coupon with resistors and capacitors to evaluate passive component reliability during the thermal cycle testing. This design feature allowed groups of capacitors and resistors to be removed from testing for destructive physical analysis at regular intervals during thermal cycling. The dimension of the board with the break-off coupon removed was 12.75 by 9 inch. There were three variations of the test vehicle: manufacture, rework and hybrid. The details of each variation are provided below. A photograph of the manufactured test vehicle is shown in

Figure 3.

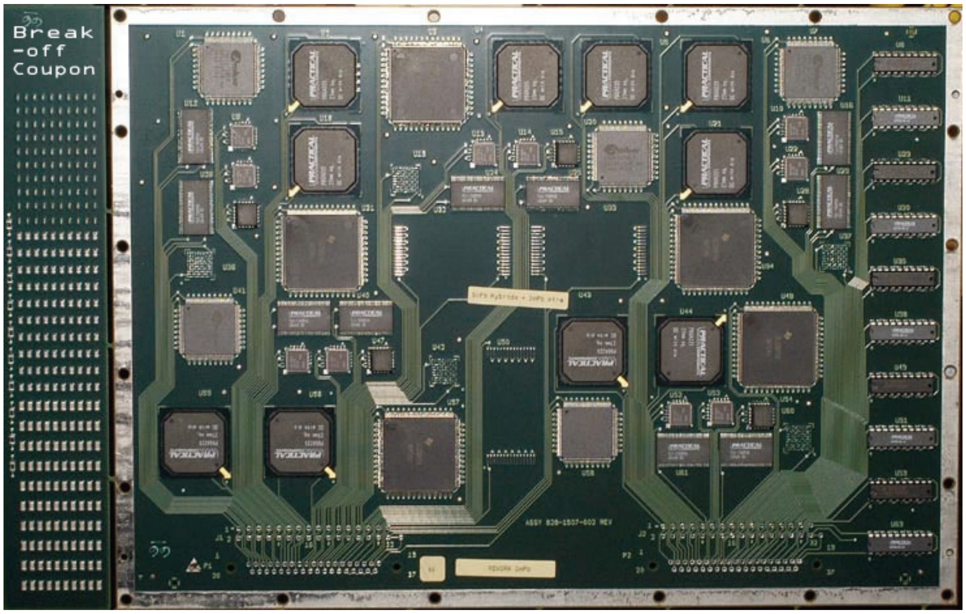

Figure 3 - Manufactured Test Vehicle

The test vehicle printed circuit board was designed with daisy-chained pads that were complementary to the daisy chain in the components. Therefore, the solder joints on each component were part of a continuous electrical pathway that was monitored during testing by an event detector. To eliminate premature failures that might be caused by vias and plated-through holes, each component had its own distinct circuit trace on the top surface of the board. Failure of one solder joint on a component during testing broke the continuous electrical pathway and was recorded as an event.

The test vehicles were assembled per J-STD-001, Class 3 requirements by BAE Systems, Irving, Texas (formerly Boeing Commercial Electronics).

The purpose of the manufactured test vehicle was to simulate the construction of current military circuit card assembly technology. The manufactured test vehicle was constructed of high glass temperature epoxy-glass laminate (170 degrees Celsius) with an immersion silver surface finish.

The test vehicle included a number of surface mount technology (SMT) and plated-through-hole (PTH) components representative of parts used in defense and aerospace electronics. Components were selected to represent those commonly found on legacy military systems as well as new emerging technologies. The team identified eleven different components that were included on the manufactured and rework test vehicles: ball grid arrays (BGA); ceramic leadless chip carriers (CLCC); plastic dual inline packages (PDIP); plastic leaded chip carriers (PLCC); thin quad flat packs (TQFP); and thin small outline packages (TSOP). The team selected 0402, 0805 and 1206 chip capacitors, and 1206 chip resistors on the break-off coupon. The daisy-chained component and component finishes are tabulated in Table 2.

Table 2 - Daisy-Chained Components and Lead Finishes on Manufactured and Rework Test Vehicles

Component	Lead Finish					
	AuPdNi	Sn	SnAgCu	SnAgCuBi	SnCu	SnPb
BGA-225			X			X
CLCC-20			X	X		X
PDIP-20	X	X				
PLCC-20		X				
TQFP-144						
TQFP-208	X					
TSOP-50					X	X

Five of each daisy-chained component type and lead finish was designed into the test vehicle. Each manufactured test vehicle includes one monitored plated-through-hole or via to monitor the reliability of the printed circuit board after exposure to the higher processing temperatures required with the lead free solders. The board included provisions for three hybrid and five chip scale package (CSP) components. These components were left off of the manufactured test vehicle due to design and component procurement problems. The hybrid and CSP components were assembled on the hybrid test vehicle as detailed below. Therefore, there are a total of 64 input/output (I/O) channels on each manufactured test vehicle with only 56 I/O channels actively monitored.

The manufactured test vehicles were assembled using the solder alloy combinations listed in Table 3. Five manufactured test vehicles of each configuration were tested.

Table 3 - Manufactured Test Vehicle Configurations

Sample Type	Laminate	Surface Finish	Reflow Solder	Wave Solder
Lead free Manufacture	High Tg FR-4	Immersion silver	SnAgCu	SnAgCu
Lead free Manufacture	High Tg FR-4	Immersion silver	SnAgCuBi	SnCu
Manufactured (control)	High Tg FR-4	Immersion silver	SnPb	SnPb

The purpose of the rework test vehicle was to simulate the construction of older, legacy military circuit card assembly technology for testing the suitability of using lead free solder in repairing older hardware built with tin-lead solder. The reason for including rework test vehicles in the test program was to determine if mixing lead free and a tin-lead solder on the same circuit card assembly had an adverse effect on part reliability. The rework consisted of component replacement on tin-lead assemblies using lead free solder.

The rework test vehicle was similar in design to the manufactured test vehicle. However the construction was slightly different in that the rework test vehicle was constructed of older technology, low glass temperature epoxy-glass laminate (135 to 140 degrees Celsius) with a hot air solder leveled (HASL) surface finish. A photograph of the test vehicle is provided in
Figure 4.

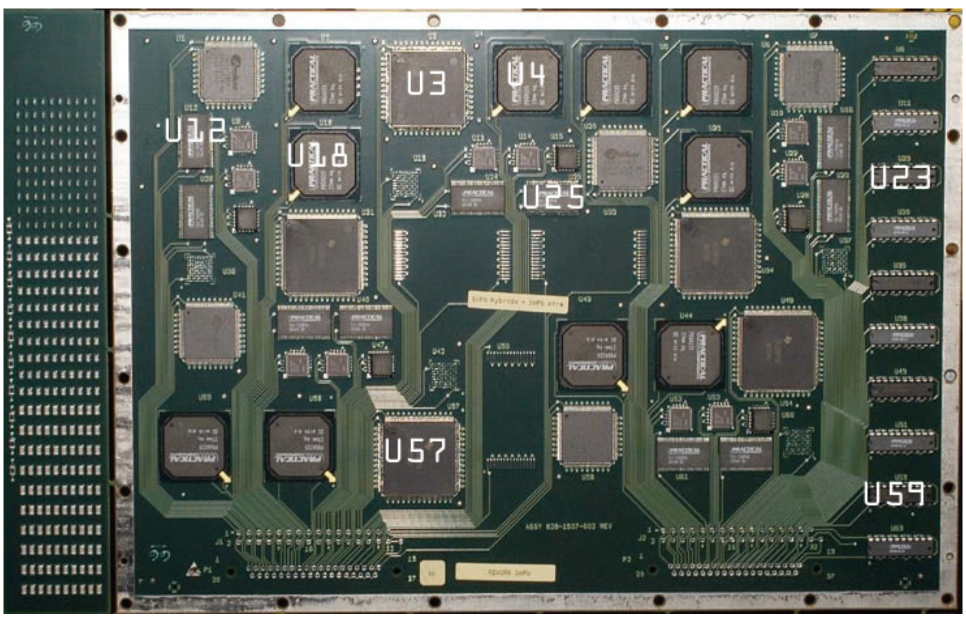

Figure 4 - Rework Test Vehicle Showing Reworked Component Reference Designators

The rework test vehicle included the same SMT and PTH components used on the manufactured test vehicle (see Table 2). Each rework test vehicle included one monitored plated-through-hole or via to monitor the reliability of the printed circuit board after exposure to the higher processing temperatures required with the lead free solders. The board included provisions for three hybrid and five CSP components. These components were left off of the rework test vehicle due to design and component procurement problems. Therefore, there are a total of 64 I/O channels on each rework test vehicle with only 56 I/O channels actively monitored.

The solder alloy combinations used on the rework test vehicles are listed in Table 4. All rework test vehicles were originally assembled with tin-lead solder. The two of each BGA-225, PDIP-20, TQFP-208 and TSOP-50 components were removed from the test vehicles (see Figure 4), the residual tin-lead solder wicked off the board pads and a new component soldered in place using the test solder alloys listed in Table 4. Lead free rework was accomplished using the tin-silver-copper; tin-copper (PDIP-20 rework only) and tin-silver-copper-bismuth (SMT rework only) solder alloys in wire form. Assemblies used as the experimental control samples were reworked using tin-lead solder. The BGA-225 components were reworked without using additional solder. The BGA components were removed using a hot air rework station. The residual solder on the board pads was removed using solder wick. Tack flux was applied to the board pads and a new BGA component was soldered using the hot air rework station without additional solder. Five rework test vehicles of each configuration were tested.

Table 4 - Rework Test Vehicle Configurations

Sample Type	Laminate	Surface Finish	Reflow & Wave Solder	SMT Rework Solder	PTH Rework Solder
Lead free Rework	Low Tg FR-4	HASL	SnPb	SnAgCu	SnAgCu
Lead free Rework	Low Tg FR-4	HASL	SnPb	SnAgCuBi	SnCu
Rework (control)	Low Tg FR-4	HASL	SnPb	SnPb	SnPb

The purpose of the hybrid test vehicle was to test the hybrid and CSP components that were left off of the manufactured test vehicles. The hybrid test vehicle was similar in construction to the manufactured test vehicle. The hybrid test vehicle was constructed of high glass temperature epoxy-glass laminate (170 degrees Celsius) with an immersion silver surface finish. A photograph of the test vehicle is provided in

Figure 5. The board included three hybrid and five chip scale package components. The test vehicle did not have the break-off coupon containing the passive components.

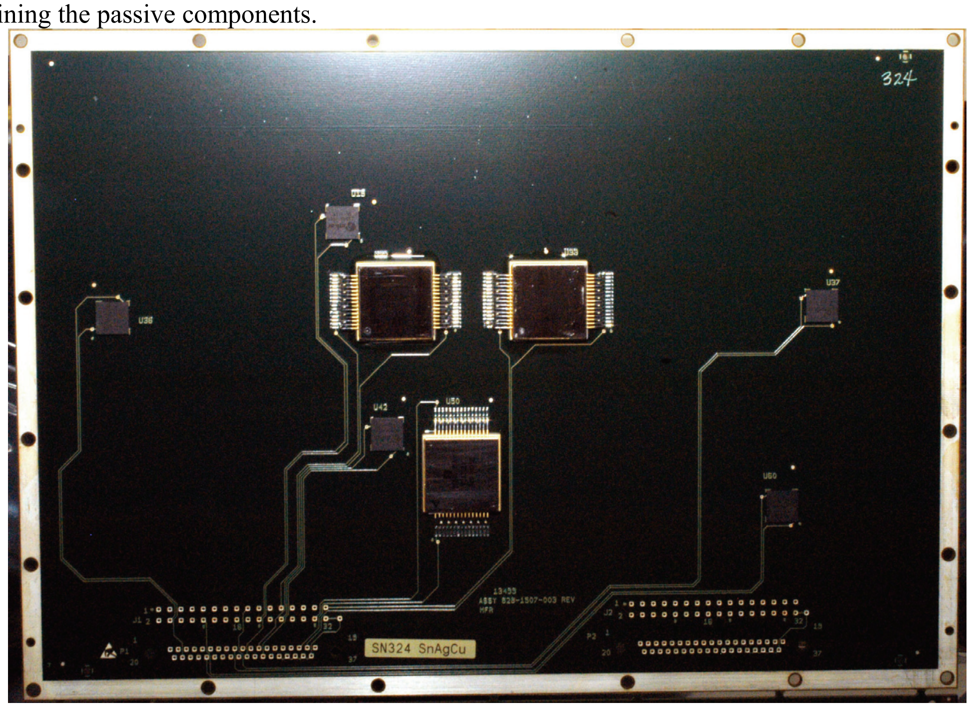

Figure 5 - Photograph of Hybrid Test Vehicle

The hybrid test vehicles were assembled by BAE Systems using the same solder paste and reflow processes used on the manufactured test vehicles. The test matrix for the hybrid test vehicles is listed in Table 5. The components and lead finishes are tabulated in Table 6. Since the hybrid test vehicle did not contain plated-through-hole components, the test vehicles were not exposed to wave solder. The hybrid components were bonded to the printed circuit board. Five hybrid test vehicles of each configuration were tested.

Table 5 - Hybrid Test Vehicle Configurations

Sample Type	Laminate	Surface Finish	Reflow Solder
Lead free Hybrid	High Tg FR-4	Immersion silver	SnAgCu
Lead free Hybrid	High Tg FR-4	Immersion silver	SnAgCuBi
Hybrid (control)	High Tg FR-4	Immersion silver	SnPb

Table 6 - List of Components and Lead Finishes on Hybrid Test Vehicles

Component	Lead Finish		
	SnAgCu	SnAgCuBi	SnPb
CSP-100	X		X
Hybrid-30	X	X	X

ETL personnel ran 15 test vehicles in the chamber at a time. The test vehicles were tested in three different groups. Manufactured test vehicles were tested first. The rework test vehicles were tested next and the hybrid test vehicles were tested last. ETL fabricated aluminum holding fixtures that held nine test vehicles in the first level and six test vehicles on the second level (see
Figure 6). The test vehicles were loaded in the fixture in random order.

Figure 6 - Test Vehicle Layout in Test Chamber

An Anatech event detector was used to continuously monitor the electrical continuity of each channel on the test vehicles. An event was defined as the interruption of continuity for a period of two microseconds and an increase in resistance of 1,000 ohms or more. A solder joint failure was defined as the first event with affirmation of the failure by nine or more additional events within ten percent of the cycles of the initial failure.

For this project, the team established the CET acceptance criteria for the lead free solder alloys as solder joint reliability better than or equal to the eutectic tin-lead controls at ten percent Weibull cumulative failures.

Results and Discussion
Manufactured test vehicles Results
The fifteen manufactured test vehicles were tested for 550 cycles. Failures at ten cycles or lower were deemed to be outliers and excluded by team consensus. The team felt these early life failures were due to manufacturing or testing anomalies and the data should be excluded to prevent skewing the test results. The test vehicle failures were inspected for lead damage or broken wires. Two wires were noted as broken on two manufactured test vehicles and the data were excluded. No apparent broken leads were observed during post-test inspection at 30x magnification using a binocular microscope.

The failure data were compiled by component type, component finish and solder alloy and tabulated in Table 7 and Table 8. Test vehicles soldered with tin-silver-copper-bismuth solder had fewer solder joints fail (59 percent of the components registering as a failure). Test vehicles soldered with tin-lead solder were ranked second (63 percent of the components registering as a failure). Lastly, the test vehicles soldered with tin-silver-copper had the worst performance (73 percent of the components registering as a failure). The plated-through-hole components were more robust to the conditioning, and not enough failed within the time allotted to be able to make reasonable estimates of lifetime.

Table 7 - Failed SMT Components by Component, Component Finish and Solder Alloy on Manufactured test vehicles

Component & Finish	Solder Alloy		
	SAC Paste	SACB Paste	SnPb Paste
BGA SnAgCu	100% (25 of 25)	80% (20 of 25)	
BGA SnPb	96% (23 of 24)	84% (21 of 25)	76% (38 of 50)
CLCC SnAgCu	100% (25 of 25)		
CLCC SnAgCuBi		80% (20 of 25)	
CLCC SnPb	100% (25 of 25)	100% (25 of 25)	100% (50 of 50)
PLCC Sn	0% (0 of 25)	0% (0 of 25)	0% (0 of 25)
TQFP-144 Sn	56% (14 of 25)	32% (8 of 25)	32% (8 of 25)
TQFP-208 AuPdNi	8% (2 of 25)	16% (4 of 25)	32% (8 of 25)
TSOP SnCu	100% (25 of 25)	36% (9 of 25)	
TSOP SnPb	100% (25 of 25)	100% (25 of 25)	76% (38 of 50)
Grand Total	73% (164 of 224)	59% (132 of 225)	63% (142 of 225)

Table 8 - Failed PTH Components by Component, Component Finish and Solder Alloy on Manufactured test vehicles

Component & Finish	Solder Alloy		
	SAC Wave	SnCu Wave	SnPb Wave
PDIP AuPdNi	0% (0 of 23)	4% (1 of 25)	8% (2 of 25)
PDIP Sn	0% (0 of 25)	4% (1 of 25)	0% (0 of 25)
PTH	0% (0 of 5)	0% (0 of 5)	0% (0 of 5)
Grand Total	0% (0 of 53)	4% (2 of 55)	4% (2 of 55)

The unpopulated plated-through-holes, PLCC-20 and PDIP-20 components experienced little or no failures. No additional data analysis was conducted on these components. The remaining failure data were analyzed by component type, component finish and solder alloy using ReliaSoft Weibull++6 software. First, the data were analyzed using 2-parameter Weibull analysis. The analysis settings included rank regression on X for analysis method, Fisher Matrix for confidence interval method and median ranks for rank method. The Weibull analysis included the Kolmogorov-Smirnov goodness-of-fit test. The goodness-of-fit test returns the probability that the respective critical value is less than the value calculated. High values, close to one, indicate that there is a significant difference between the theoretical distribution and this data set.

BGA-225 Results

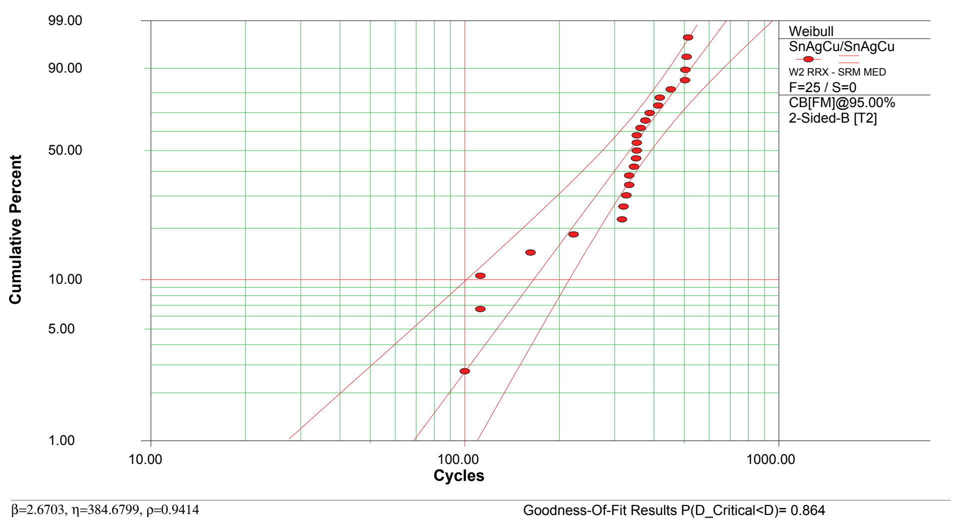

Figure 7 - Tin-Silver-Copper BGA-225 with Tin-Silver-Copper Solder Paste on Manufactured Test Vehicles

The 2-parameter Weibull plot for tin-silver-copper soldered tin-silver-copper BGA-225 components is shown in Figure 7. The plot includes the fitted line and the 95-percent confidence limits. The legend on the right of the chart indicates the solder alloy then component finish. The 2-parameter Weibull model provides a poor fit of the data given some of the data points fall outside the confidence limits and the goodness-of-fit result is near one. There appears to be a “stairstep” in the data indicating possible changes in stresses applied to the test vehicle or multiple failure modes in the solder joint failures. This stairstep was evident on other Weibull plots for other components. Many of the vertical jumps in the data occur where step increases in the vibration levels occurred as part of the test plan. The test logs were reviewed for potential chamber problems or test procedural issues. No other common cause for the stairstep could be identified.

The Weibull plot for tin-lead soldered tin-lead BGA-225 components is shown is
Figure 8. The 2-parameter Weibull model is an excellent fit of the data since all of the data fit inside the 95-percent confidence limits and the goodness-of-fit result is near zero. The improved fit is probably a result of the larger sample size for these components. As a result of the test vehicle and experimental design, there were twice as many tin-lead soldered tin-lead BGA-225 components as the lead free BGA-225 component combinations (50 vs. 25).

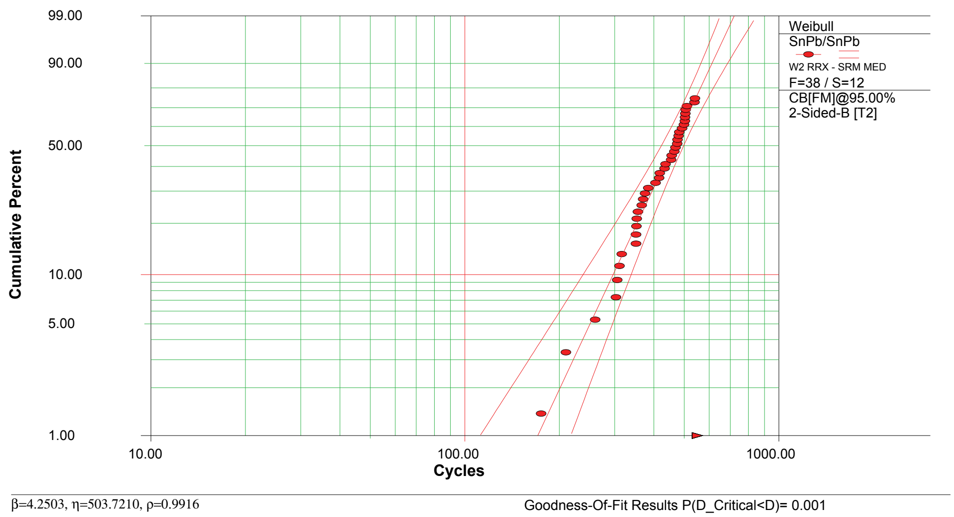

Figure 8 - Tin-Lead Soldered Tin-Lead BGA-225 on Manufactured Test Vehicles

Figure 9 contains Weibull plots of tin-silver-copper BGA-225 components soldered with lead free solders compared to tin-lead BGA-225 components soldered with tin-lead solder. The plot shows tin-lead solder performed best with tin-silver-copper-bismuth solder ranked second and tin-silver-copper solder ranked last.

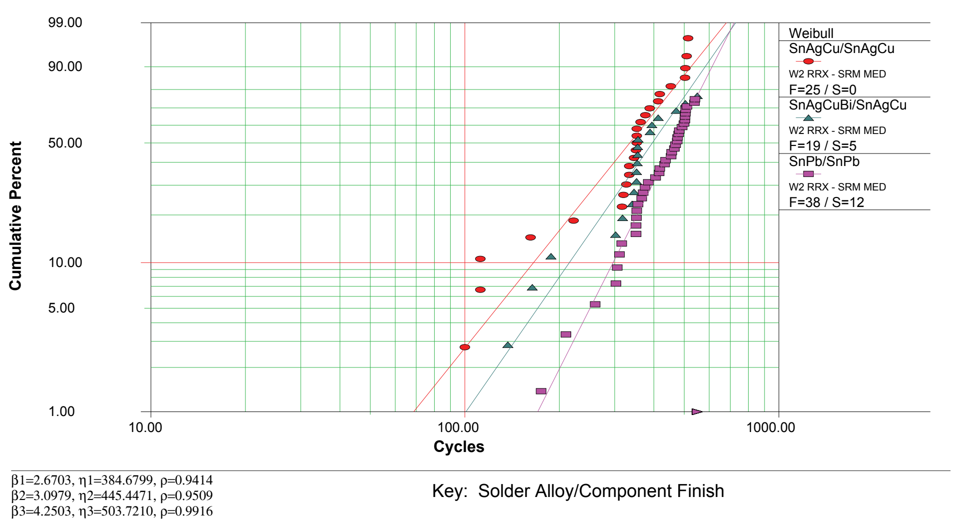

Figure 9 - Lead free Soldered Tin-Silver-Copper BGA-225 Compared to Tin-Lead Soldered Tin-Lead BGA-225 on Manufactured Test Vehicles

Figure 10 contains the Weibull plots for all of the combinations of component finish and solder alloy for the BGA-225 components on the manufactured test vehicles. Overall, tin-lead soldered tin-lead BGA-225 components were the most reliable.

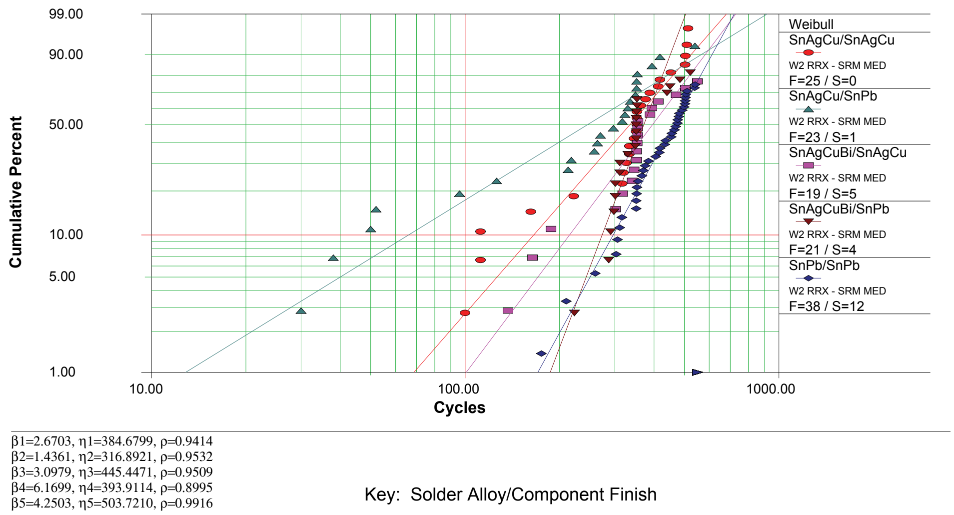

Figure 10 - BGA-225 on Manufactured Test Vehicles

The effect of tin-lead contamination on tin-silver-copper soldered BGA-225 components is shown in Figure 11. The plots show tin-lead degrades the early life performance of tin-silver-copper while the N(63%) values are similar.

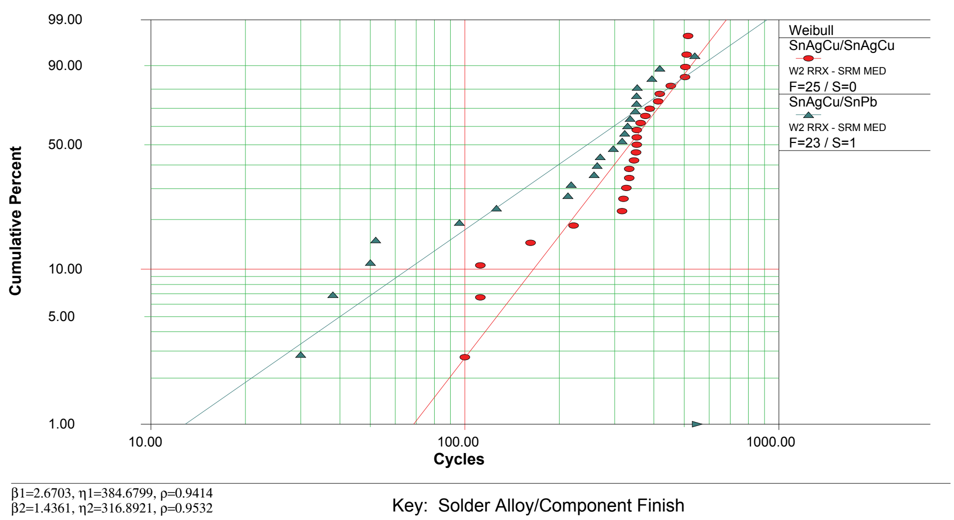

Figure 11 - Effect of Tin-Lead Contamination on Tin-Silver-Copper Soldered BGA-225 on Manufactured Test Vehicles

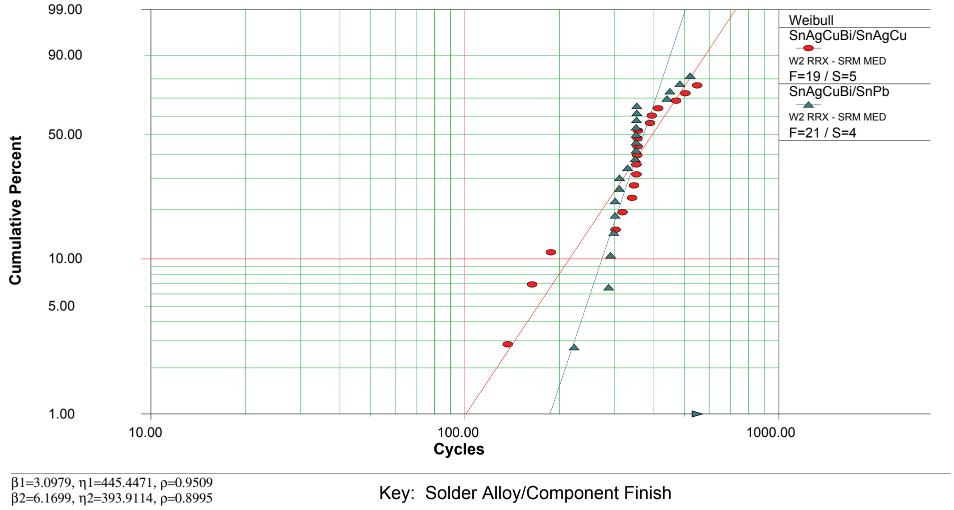

Figure 12 - Effect of Tin-Lead Contamination on Tin-Silver-Copper-Bismuth Soldered BGA-225 on Manufactured Test Vehicles

The effect of tin-lead contamination on tin-silver-copper-bismuth soldered BGA-225 components is shown in Figure 12. The plot shows little effect in the reliability performance of tin-silver-copper-bismuth when used to solder tin-silver-copper or tin-lead BGA-225 components.

CLCC-20 Results

Figure 13 contains Weibull plots of tin-silver-copper CLCC-20 components soldered with tin-silver-copper and tin-silver-copper-bismuth CLCC-20 components soldered with tin-silver-copper-bismuth compared to tin-lead CLCC-20 components soldered with tin-lead. The results were distinguishly different between the three samples. CLCC-20 components soldered with tin-silver-copper-bismuth solder performed best. CLCC-20 components soldered with tin-lead solder were ranked second and CLCC-20 components soldered with tin-silver-copper solder ranked last.

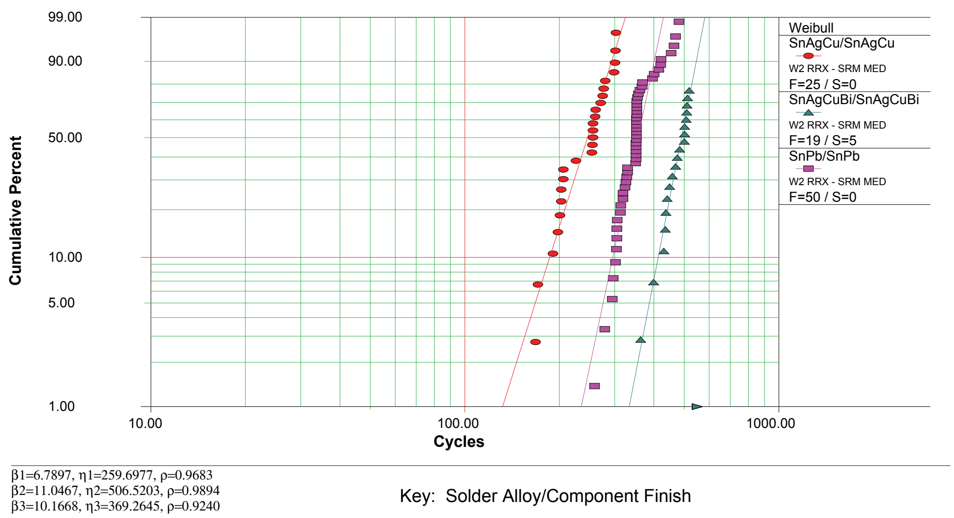

Figure 13 - Lead free Soldered Lead free CLCC-20 Compared to Tin-Lead Soldered Tin-Lead CLCC-20 on Manufactured Test Vehicles

Figure 14 combines Weibull plots of tin-lead CLCC-20 components soldered with lead free solders compared to tin-lead soldered tin-lead CLCC-20 components. The plot shows similar results in the ranking of reliability performance for the three solder alloys as the previous plot but with smaller separation between the three fitted lines.

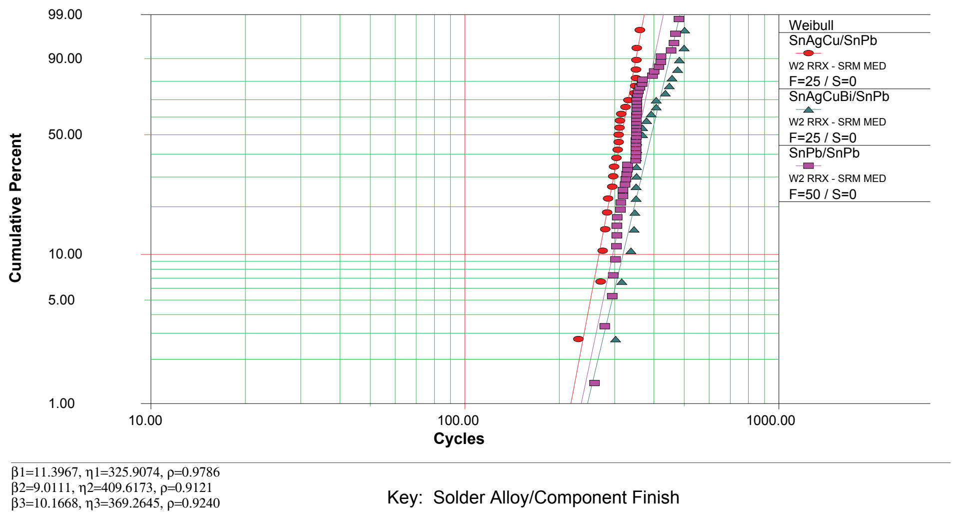

Figure 14 - Tin-Lead CLCC-20 on Manufactured Test Vehicles

Figure 15 contains the Weibull plots for all of the combinations of component finish and solder alloy for the CLCC-20 components on the manufactured test vehicles. Overall, tin-silver-copper-bismuth solder performed better than tin-lead solder and tin-lead solder performed better than tin-silver-copper solder. Specifically, the tin-silver-copper-bismuth CLCC-20 components soldered with tin-silver-copper-bismuth exhibited the best reliability. The tin-lead CLCC-20 components soldered with tin-silver-copper-bismuth were ranked second. The tin-lead CLCC-20 components soldered with tin-lead were ranked third. The tin-lead CLCC-20 components soldered with tin-silver-copper were ranked fourth. The tin-silver-copper CLCC-20 components soldered with tin-silver-copper were ranked last. While the tin-lead finish on the CLCC-20 appears to degrade the reliability when soldered with tin-silver-copper-bismuth solder, the tin-lead finish appears to improve the reliability with tin-silver-copper solder.

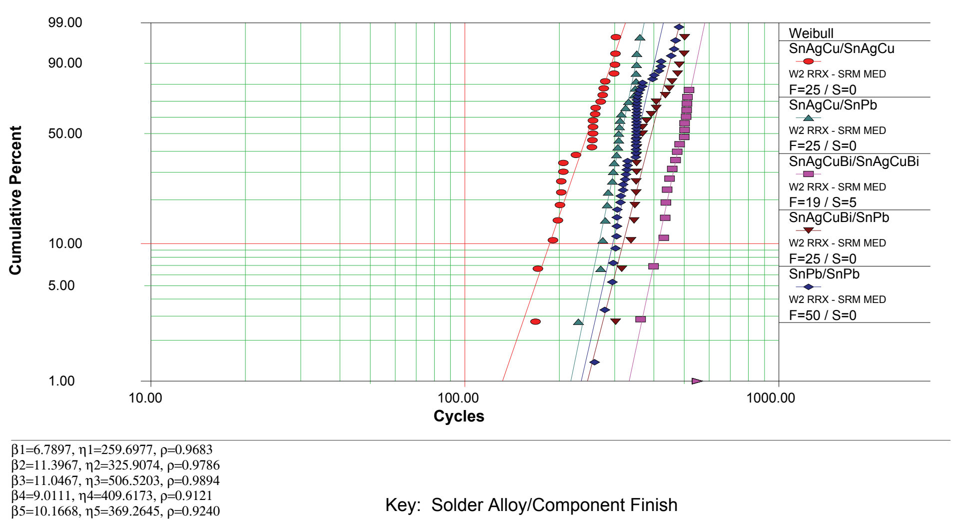

Figure 15 - CLCC-20 on Manufactured Test Vehicles

The effect of tin-lead contamination on tin-silver-copper soldered CLCC-20 components is shown in Figure 16. The presence of tin-lead appears to improve the reliability of the tin-silver-copper solder joint.

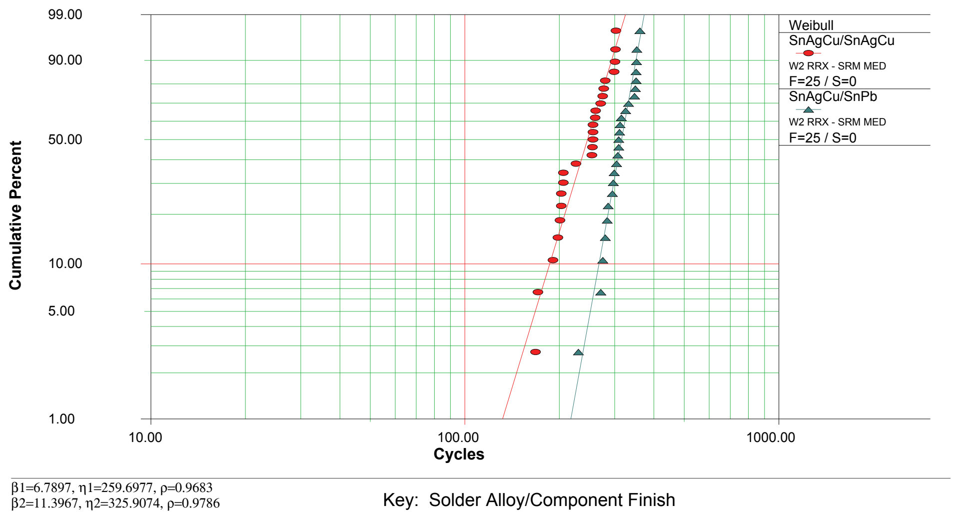

Figure 16 - Effect of Tin-Lead Contamination on Tin-Silver-Copper Soldered CLCC-20 on Manufactured Test Vehicles

The effect of tin-lead contamination on the tin-silver-copper-bismuth soldered CLCC-20 components is shown in Figure 17. The presence of tin-lead appears to degrade the reliability of the tin-silver-copper-bismuth solder joint.

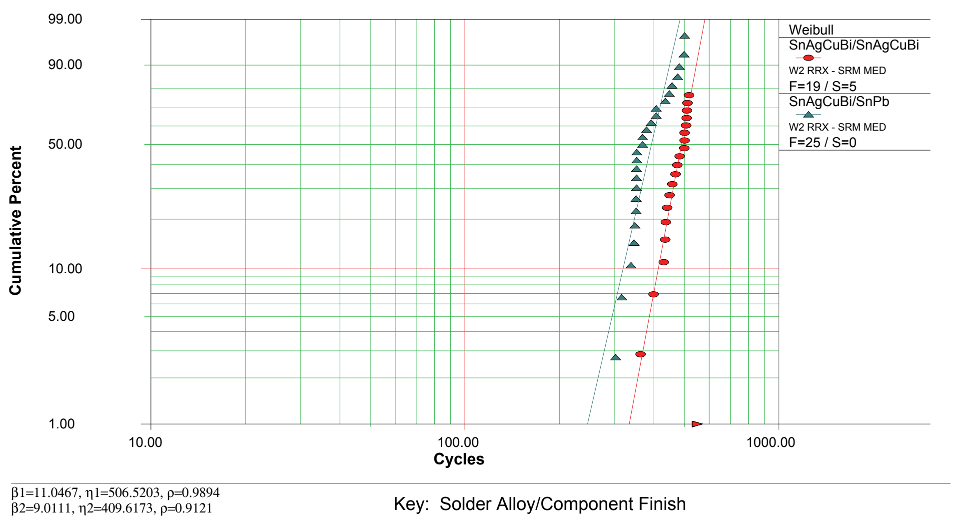

Figure 17 - Effect of Tin-Lead Contamination of Tin-Silver-Copper-Bismuth Soldered CLCC-20 on Manufactured Test Vehicles

TQFP-144 Results

Figure 18 contains Weibull plots of tin-silver-copper and tin-silver-copper-bismuth soldered tin TQFP-144 components compared to tin TQFP-144 components soldered with tin-lead. The plot shows tin-silver-copper-bismuth solder performed equally as well as tin-lead solder and tin-silver-copper solder performed the worst.

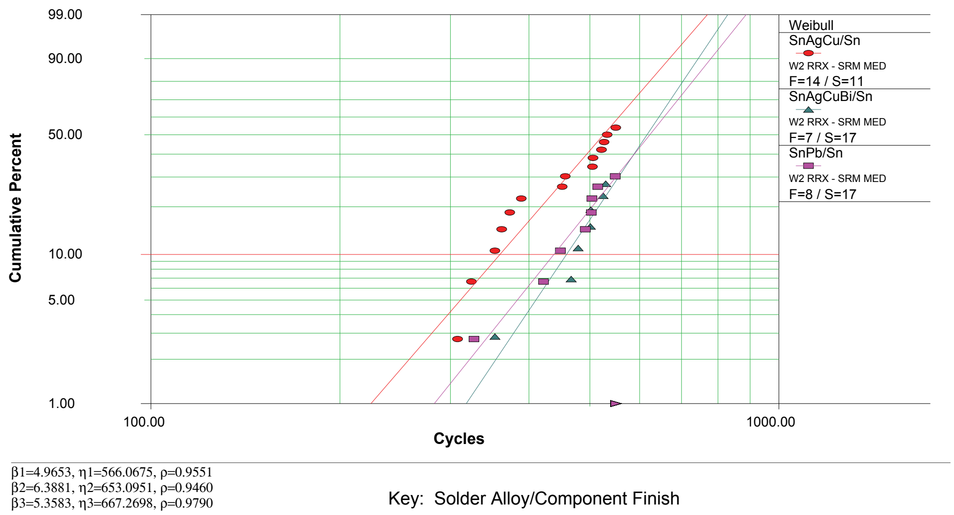

Figure 18 - TQFP-144 on Manufactured test vehicles

TSOP-50 Results

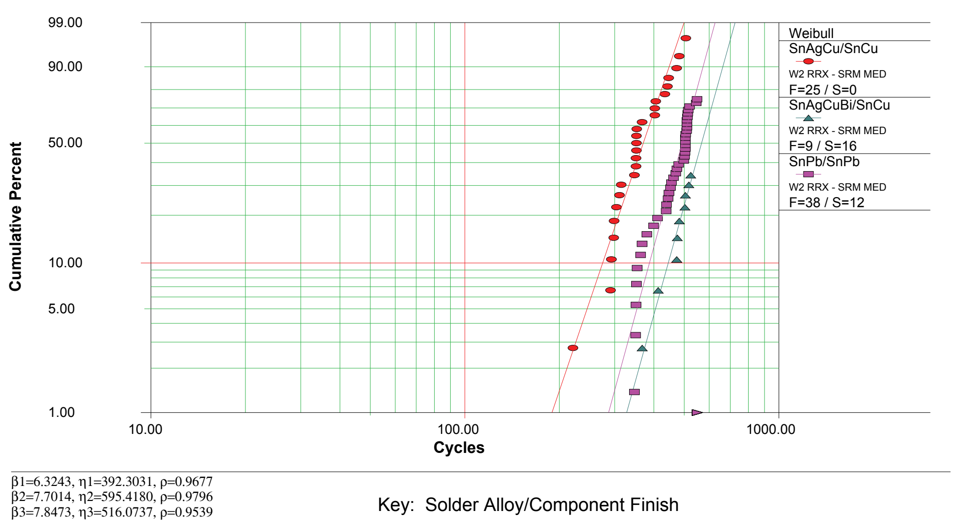

Figure 19 - Lead free Soldered Tin-Copper TSOP-50 Compared to Tin-Lead Soldered Tin-Lead TSOP-50 on Manufactured Test Vehicles

Figure 19 contains Weibull plots of tin-copper TSOP-50 components soldered with the lead free solder alloys compared to tin-lead soldered tin-lead TSOP-50 components. The plot shows tin-silver-copper-bismuth solder performed best with tin-lead solder ranked second and tin-silver-copper solder ranked last.

Figure 20 combines Weibull plots of tin-lead TSOP-50 components soldered with lead free solders compared to tin-lead soldered tin-lead TSOP-50 components. The plot shows tin-lead solder performed the best with tin-silver-copper ranked second and tin-silver-copper-bismuth ranked last.

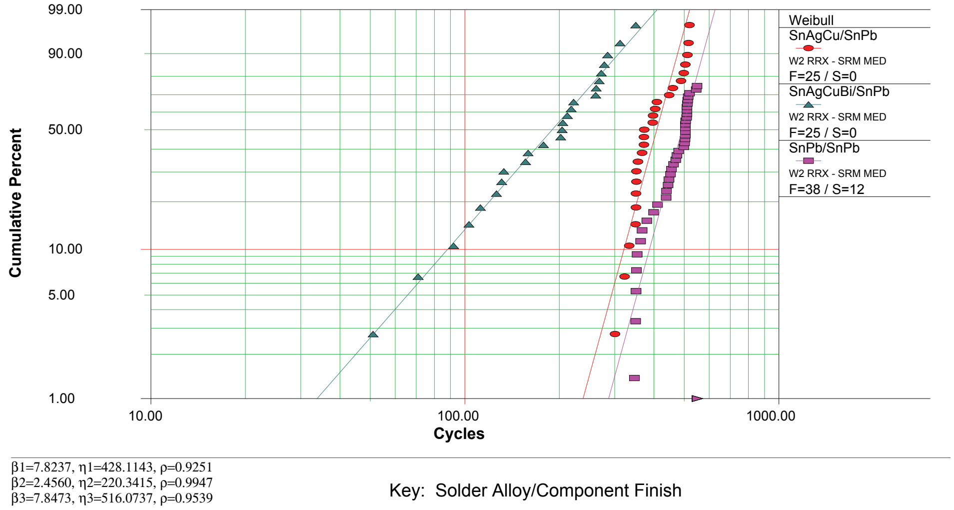

Figure 20 - Tin-Lead TSOP-50 on Manufactured Test Vehicles

Figure 21 contains the Weibull plots for all of the combinations of component finish and solder alloy for the TSOP-50 components on the manufactured test vehicles. Overall, the tin-silver-copper-bismuth soldered tin-copper TSOP-50 components performed better than tin-lead soldered tin-lead TSOP-50 components. Tin-silver-copper soldered tin-lead TSOP-50 performed better than tin-silver-copper soldered tin-copper TSOP-50 components. While the tin-lead finish on the TSOP-50 appears to dramatically degrade the solder joint reliability when soldered with tin-silver-copper-bismuth solder, the tin-lead finish appears to slightly improve the reliability with tin-silver-copper solder.

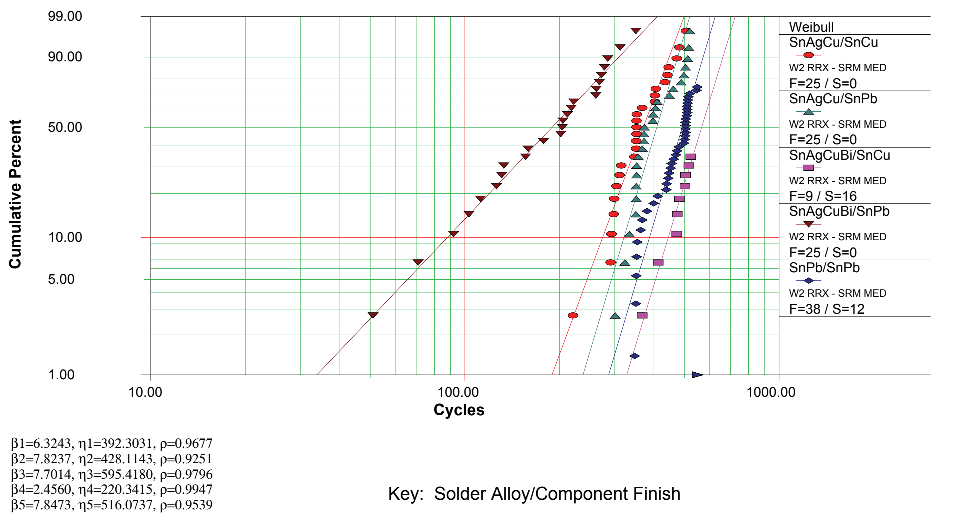

Figure 21 - TSOP-50 on Manufactured test vehicles

This phenomenon is similar with the observation made on the CLCC-20 components. However, the degradation of tin-silver-copper-bismuth solder joint reliability due to tin-lead component finish appears to be inversely proportional to the amount of tin-lead finish on the component. The amount of tin-lead on the CLCC-20 component is much greater than the amount of tin-lead on the tin-lead TSOP-50 components relative to the resulting solder joint. This effect should be further investigated with destructive physical analysis of the tin-silver-copper-bismuth soldered tin-lead CLCC-20 and TSOP-50 components. Microsection analysis may reveal an intermetallic compound that is formed in the presence of lower lead contamination levels and that reduces the overall solder joint reliability.

The effect of tin-lead contamination on the tin-silver-copper soldered TSOP-50 components is shown in Figure 22. The presence of tin-lead appears to slightly improve the reliability of the tin-silver-copper solder joint.

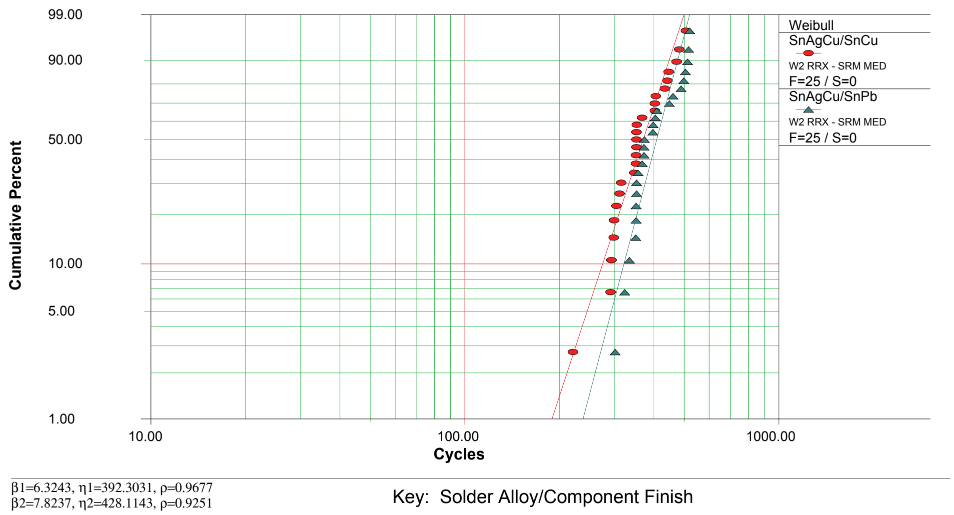

Figure 22 - Effect of Tin-Lead Contamination of Tin-Silver-Copper Soldered TSOP-50 on Manufactured Test Vehicles

The effect of tin-lead contamination on the tin-silver-copper-bismuth soldered TSOP-50 components is shown in Figure 23. The presence of tin-lead appears to severely degrade the reliability of the tin-silver-copper-bismuth solder joint.

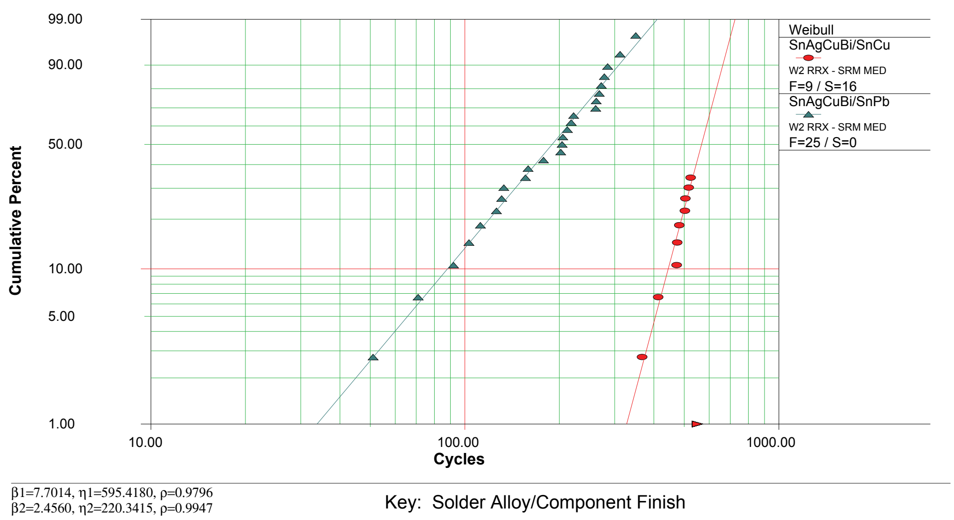

Figure 23 - Effect of Tin-Lead Contamination on Tin-Silver-Copper-Bismuth Soldered TSOP-50 on Manufactured Test Vehicles

Rework Test Vehicle Results

The fifteen rework test vehicles were tested for 550 cycles. The HALT chamber experienced an over temperature condition during cycle 537. The failure data were truncated at 536 cycles. Failures at ten cycles or lower were deemed to be outliers and not representative of the performance of this solder system, and thus, excluded from the analysis. The rework vehicle failures were inspected for lead damage or broken wires. One wire was noted as broken on a rework test vehicle and the datum was excluded. Due to the over temperature condition, a larger number of components were missing from the test vehicles at the conclusion of the test than was experienced with the manufactured test vehicles.

The failure data were segregated by component type, component finish and solder alloy and tabulated in Table 9 and Table 10.

Table 9 - Failed SMT Components by Component, Component Finish, Rework Status and Solder Alloy on Rework Test Vehicles

Component & Finish	No Rework	SAC Rework	SACB Rework	SnPb Rework
BGA SnAgCu	100% (80 of 80)	90% (18 of 20)		
BGA SnPb	98% (39 of 40)			90% (9 of 10)
CLCC SnAgCu	100% (50 of 50)			
CLCC SnAgCuBi	100% (50 of 50)			
CLCC SnPb	100% (50 of 50)			
PLCC Sn	7% (5 of 74)			
TQFP-144 Sn	61% (46 of 75)			
TQFP-208 AuPdNi	56% (25 of 45)	80% (8 of 10)	100% (10 of 10)	90% (9 of 10)
TSOP SnCu	100% (80 of 80)	100% (10 of 10)	100% (10 of 10)	
TSOP SnPb	98% (39 of 40)			100% (10 of 10)
PTH	0% (0 of 15)			
Grand Total	77% (464 of 599)	90% (36 of 40)	100% (20 of 20)	97% (29 of 30)

Test vehicles reworked with tin-lead solder had the best performance (74 percent of the reworked components registering as a failure). Test vehicles reworked with tin-silver-copper had the next best performance (86 percent of the reworked components registering as a failure). Test vehicles reworked with tin-silver-copper-bismuth solder had the most solder joints fail (100 percent of the reworked components registering as a failure). In general, reworked components failed more often than the unreworked components. The exception to this trend was the reworked BGA-225 components. Use of the hot air rework station may have exposed the BGA-225 components to hotter temperatures than they experienced during the original reflow solder process possibly resulting in maximized alloying between the solder ball, solder paste and substrate finish. The higher temperatures may have provided better solder melting and improved the solder joint reliability.

Table 10 - Failed PTH Components by Component, Component Finish, Rework Status and Solder Alloy on Rework Test Vehicles

Component & Finish	No Rework	SAC Rework	SnCu Rework	SnPb Rework
PDIP AuPdNi	0% (0 of 43)	70% (7 of 10)	22% (2 of 9)	11% (1 of 9)
PDIP Sn	0% (0 of 75)			
Grand Total	0% (0 of 118)	70% (7 of 10)	22% (2 of 9)	11% (1 of 9)

The plated-through-holes, PLCC-20 and unreworked PDIP-20 components experienced little or no failures. No additional data analysis was conducted on these components. The failed component data were analyzed by rework status, component type, component finish and solder alloy using ReliaSoft Weibull++6 software.

BGA-225 Results

Figure 24 contains Weibull plots of reworked tin-silver-copper BGA-225 components compared to reworked tin-lead BGA-225 components. The plot shows both samples had performed similarly.

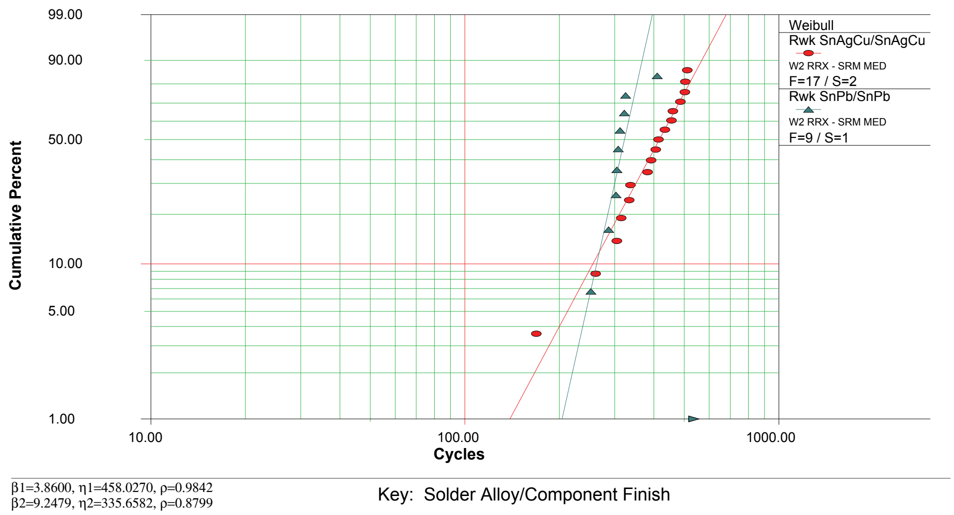

Figure 24 - Reworked BGA-225 on Rework Test Vehicles

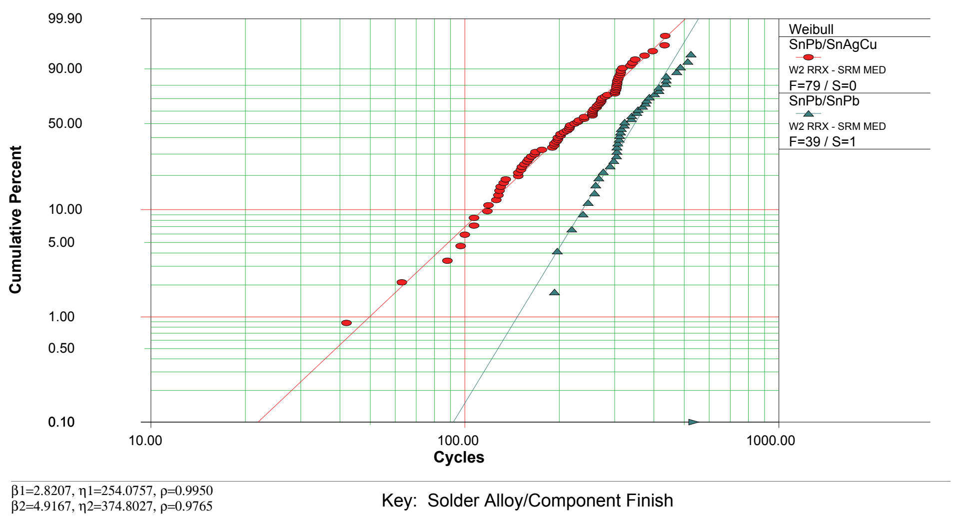

Figure 25 - Unreworked BGA-225 on Rework Test Vehicles

Figure 25 combines Weibull plots of unreworked tin-lead soldered tin-silver-copper BGA-225 components compared to unreworked tin-lead soldered tin-lead BGA-225 components. The plot shows tin-lead soldered tin-lead BGA-225 components perform better than the tin-lead soldered tin-silver-copper BGA-225 components. The use of a tin-lead solder profile during the solder reflow process may have been insufficient to cause the tin-silver-copper ball on the BGA-225 components to properly fuse with the tin-lead solder paste.

Figure 26 contains the Weibull plots for all of the combinations of rework status, component finish and solder alloy for the BGA-225 components on the rework test vehicles.

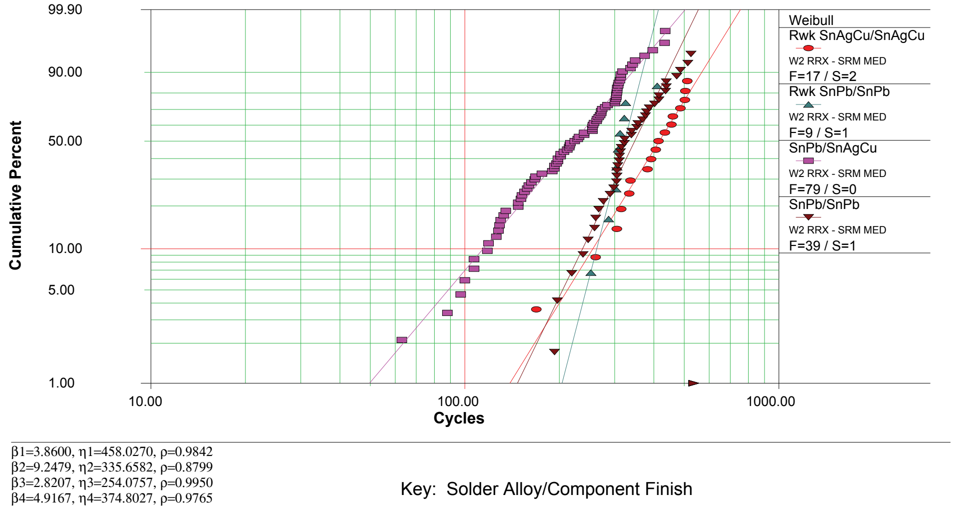

Figure 26 - BGA-225 on Rework Test Vehicle

CLCC-20 Results

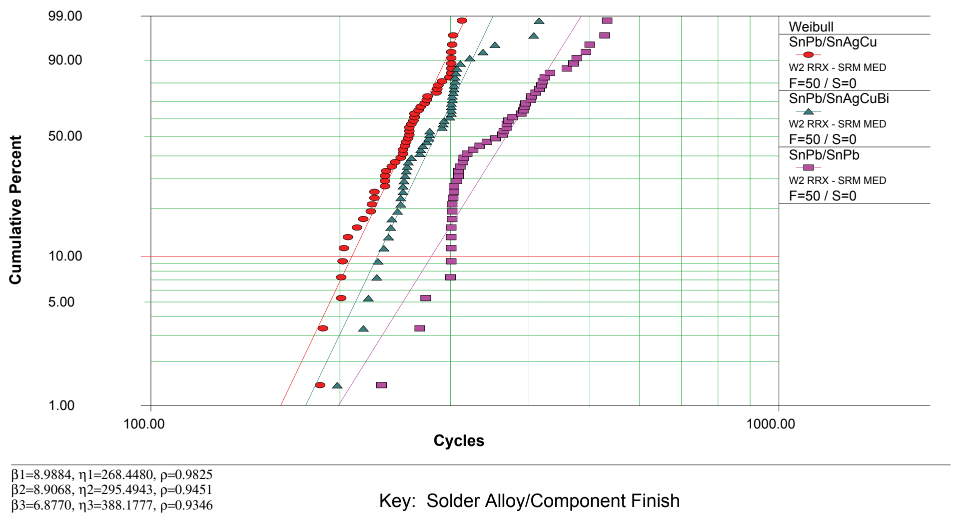

Figure 27 - CLCC-20 on Rework Test Vehicles

Figure 27 contains Weibull plots of tin-lead soldered tin-silver-copper and tin-lead soldered tin-silver-copper-bismuth CLCC-20 components compared to tin-lead soldered tin-lead CLCC-20 components. The results are distinguishly different for the three samples. Tin-lead soldered tin-lead CLCC-20 components performed best with tin-lead soldered tin-silver-copper-bismuth CLCC-20 components second and tin-lead soldered tin-silver-copper CLCC-20 components last. The use of a tin-lead solder profile during the solder reflow process may have been insufficient to cause the tin-silver-copper and tin-silver-copper-bismuth lead finishes on the CLCC-20 components to properly fuse with the tin-lead solder paste. In addition, the large amount of lead contamination on the tin-silver-copper-bismuth tinned CLCC-20 components did not appear to degrade the solder joint reliability as much as the degradation with the tin-lead TSOP-50 components soldered with tin-silver-copper-bismuth on the manufactured test vehicles.

PDIP-20 Results

The only PDIP-20 components that failed were seven reworked with tin-silver-copper solder, two reworked with tin-copper solder and one reworked with tin-lead solder. None of the unreworked PDIP-20 components failed.

Figure 28 contains Weibull plots of reworked tin-silver-copper soldered gold-palladium-nickel and reworked tin-copper soldered gold-palladium-nickel PDIP-20 components. Since only one reworked tin-lead soldered tin-lead PDIP component failed, a Weibull plot could not be generated and used as a baseline. While rework with tin-copper solder may be more reliable than rework with tin-silver-copper, there is not a sufficient sample size in which to draw statistically sound comparisons in solder alloy performance.

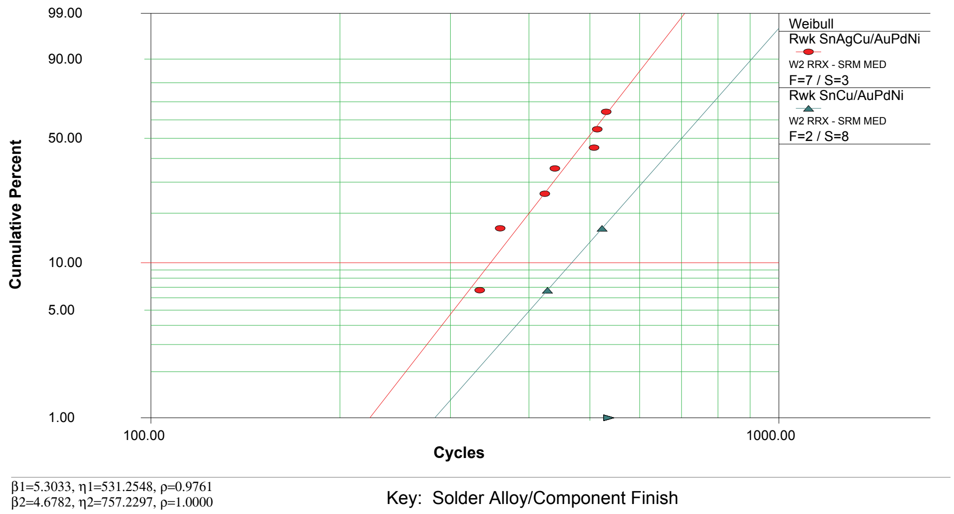

Figure 28 - Reworked PDIP-20 on Rework Test Vehicles

TQFP-208 Results

Figure 29 contains Weibull plots of gold-palladium-nickel TQFP-208 components reworked with tin-silver-copper, tin-silver-copper-bismuth and tin-lead solders. The plots show TQFP-208 components reworked with tin-lead solder performed best, TQFP-208 components reworked with tin-silver-copper ranked second and TQFP-208 components reworked with tin-silver-copper-bismuth solder ranked last.

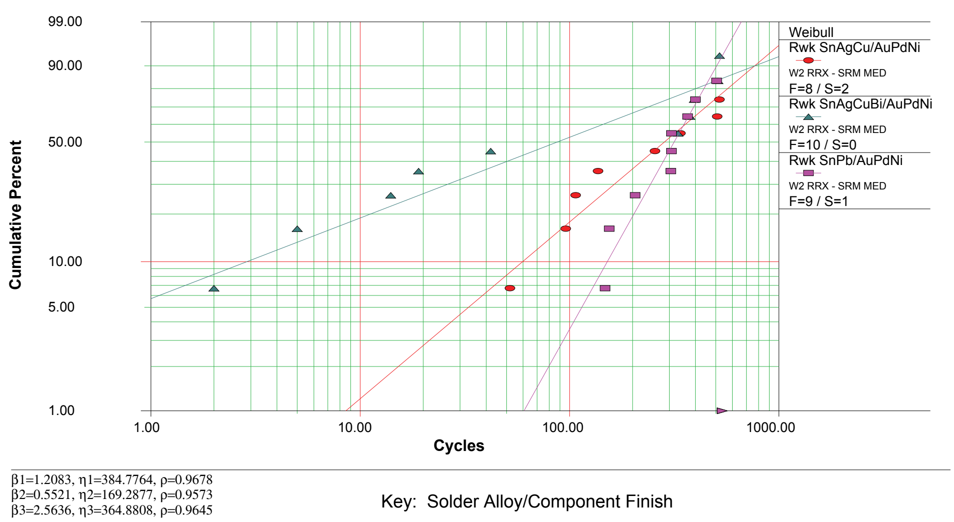

Figure 29 - Reworked TQFP-208 on Rework Test Vehicles

Figure 30 contains Weibull plots of all TQFP-208 components on rework test vehicles. The plots show unreworked tin-lead soldered gold-palladium-nickel TQFP-208 components performed best with reworked tin-lead soldered gold-palladium-nickel TQFP-208 components ranked second, reworked tin-silver-copper soldered gold-palladium-nickel TQFP-208 components ranked third and reworked tin-silver-copper-bismuth soldered gold-palladium-nickel TQFP-208 components ranked last.

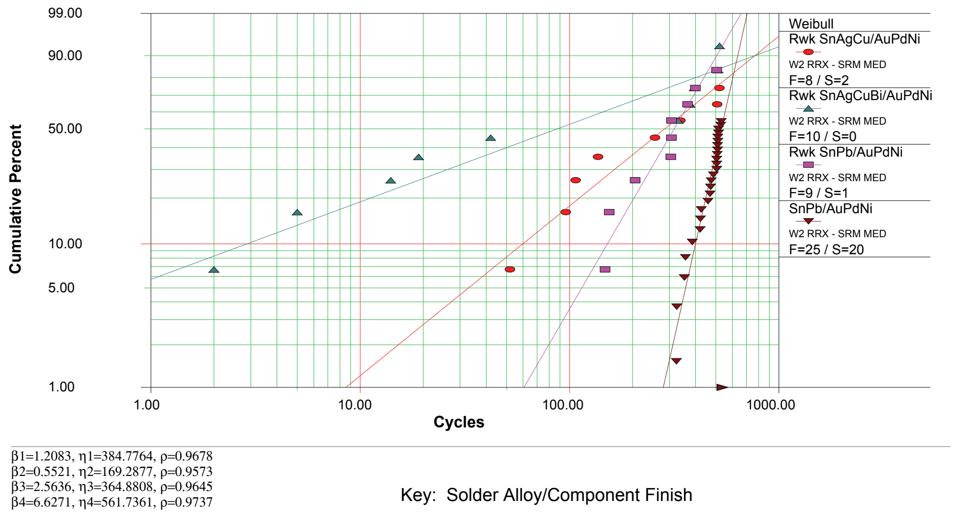

Figure 30 - TQFP-208 on Rework Test Vehicles

The reliability of the reworked tin-silver-copper-bismuth soldered TQFP-208 components was negatively impacted by the poor reliability of the reworked components at location U3 (see
Figure 31).

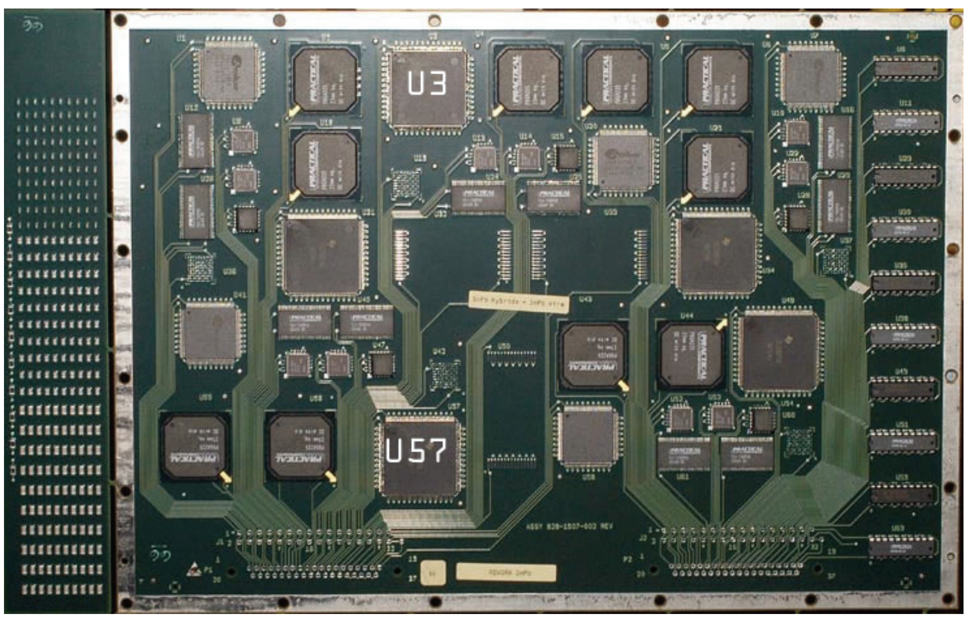

Figure 31 - Locations of U3 and U57 Reworked TQFP-208 Components

The failure data for the reworked components were further subdivided by component location and analyzed. Figure 32 shows the Weibull plots of U3 and U57 TQFP-208 components reworked with tin-silver-copper solder. The plot shows the U3 components failed faster than the U57 components.

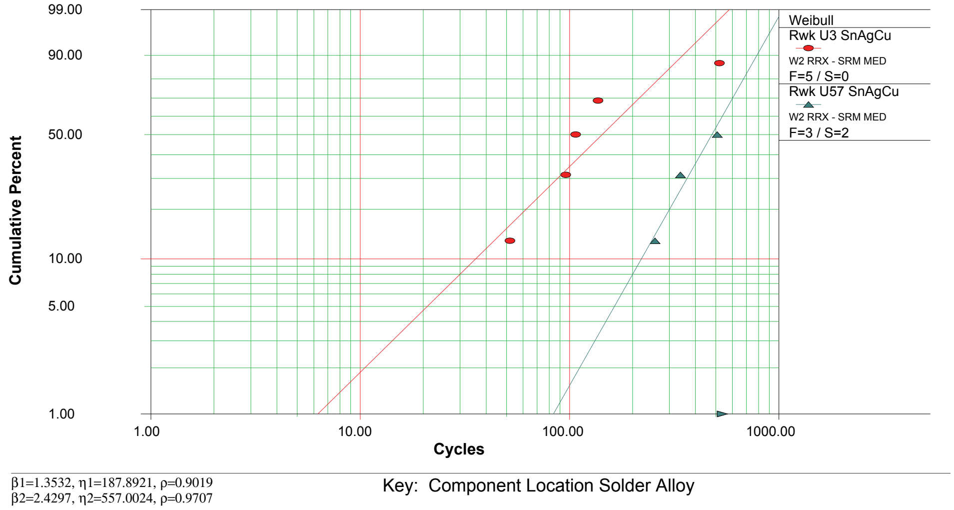

Figure 32 - Reworked U3 vs. U57 TQFP-208 with Tin-Silver-Copper Solder Wire on Rework Test Vehicles

Figure 33 shows the Weibull plots of U3 and U57 TQFP-208 components reworked with tin-silver-copper-bismuth solder. The plot shows the U3 components failed much faster than the U57 components.

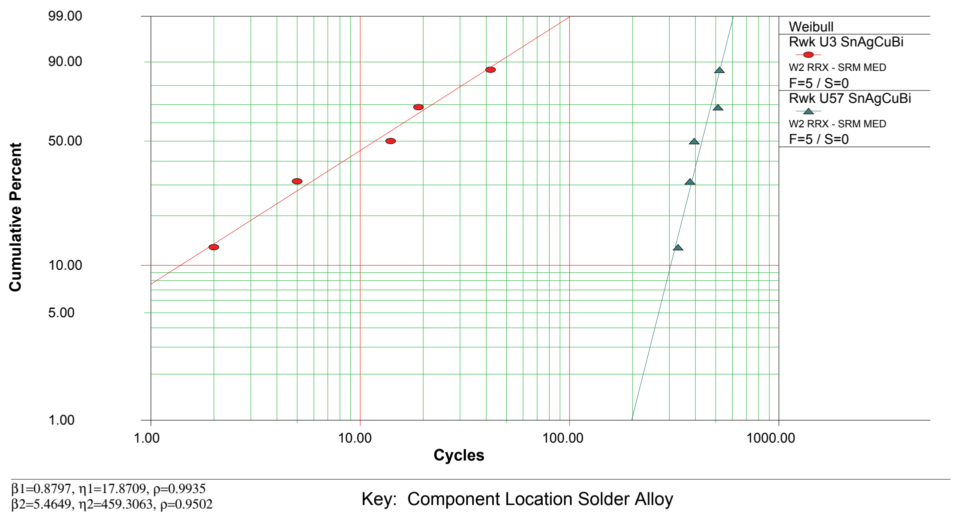

Figure 33 - Reworked U3 vs. U57 TQFP-208 with Tin-Silver-Copper-Bismuth Solder Wire on Rework Test Vehicles

Figure 34 shows the Weibull plots of U3 and U57 TQFP-208 components reworked with tin-lead solder. The plot shows the U3 components failed slightly faster than the U57 components.

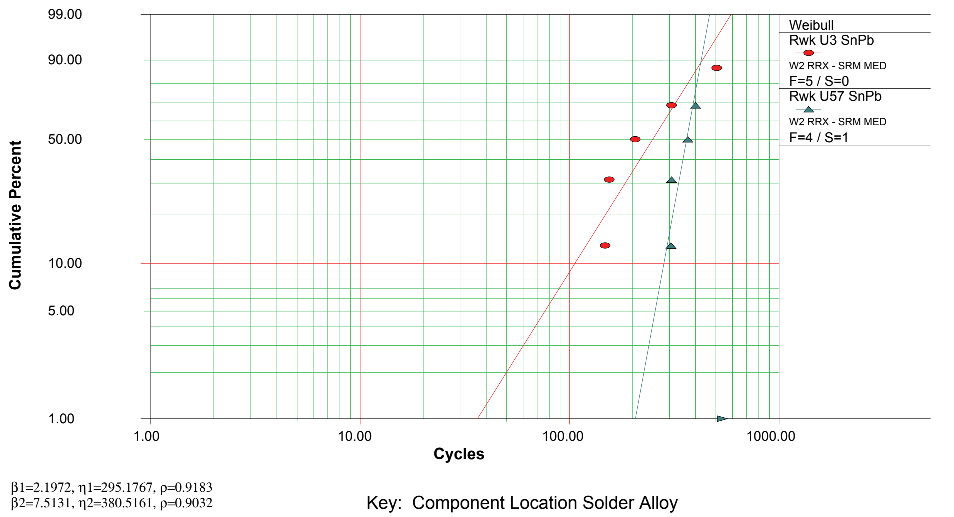

Figure 34 - Reworked U3 vs. U57 TQFP-208 with Tin-Lead Solder Wire on Rework Test Vehicles

Figure 35 shows the Weibull plots of U57 components reworked. The plot shows similar performance for the three solder alloys.

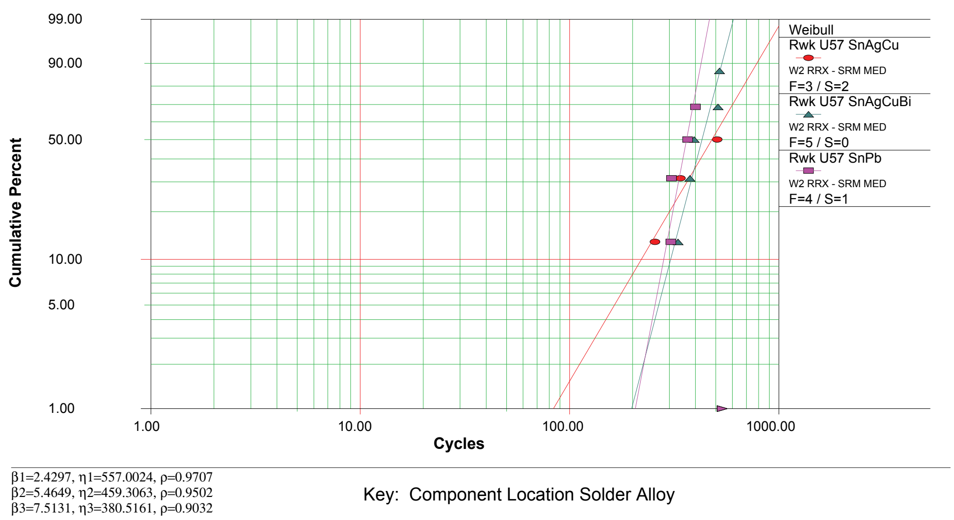

Figure 35 - Reworked U57 TQFP-208 on Rework Test Vehicles

Figure 36 shows the Weibull plots of U3 reworked components by rework solder alloy. The plot shows a large variation in solder alloy performance for U3 components. U3 components reworked with tin-silver-copper-bismuth failed much sooner than U3 components reworked with tin-solver copper solder. U3 components reworked with tin-lead solder performed the best. This data indicate the U3 location: 1) had a negative influence in solder joint reliability; 2) had a greater impact on the lead free solder alloys in general, and 3) greatly degraded the performance of tin-silver-copper-bismuth solder. Organic contamination or intermetallic formation on the U3 printed circuit board pads may be the cause of the solder joint reliability degradation. Destructive failure analysis is recommended to determine the actual cause.

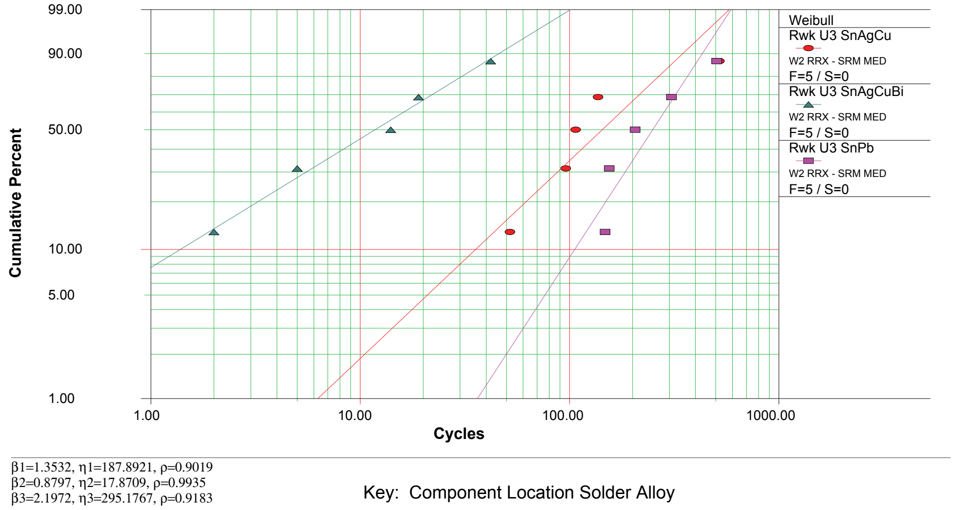

Figure 36 - Reworked U3 TQFP-208 on Rework Test Vehicles

TSOP-50 Results

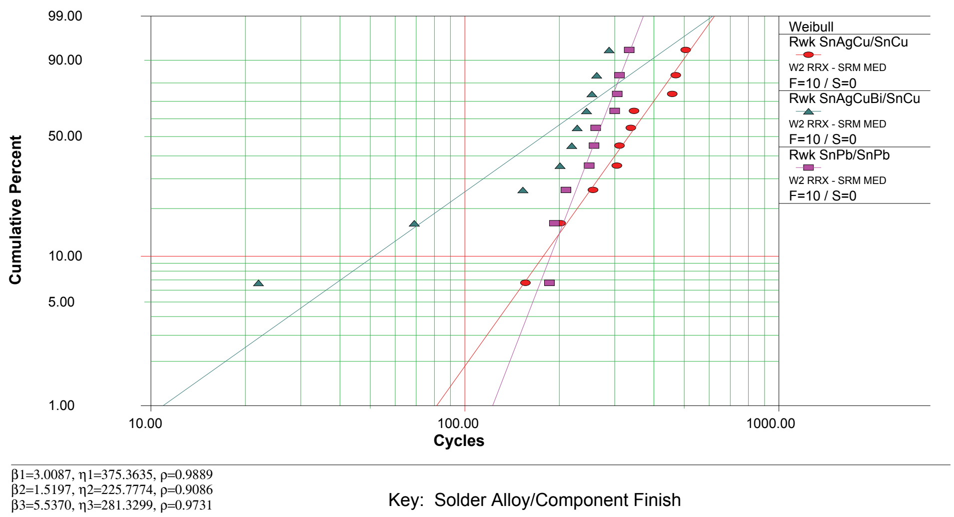

Figure 37 - Reworked TSOP-50 on Rework Test Vehicles

Figure 37 contains Weibull plots of the TSOP-50 components reworked with the lead free solder alloys compared to TSOP-50 components reworked with tin-lead solder. The plot shows tin-copper TSOP-50 components reworked with tin-silver-copper solder performed similarly to the tin-lead TSOP-50 components reworked with tin-lead solder. Tin-copper TSOP-50 reworked with tin-silver-copper-bismuth solder performed poorly. The poor performance of the tin-silver-copper-bismuth soldered TSOP-50 may be a result of the very small amounts of lead contamination left on the board pads from the rework action.

Figure 38 combines Weibull plots of unreworked tin-copper and tin-lead TSOP-50 components soldered with tin-lead solder paste. The plot shows the lead finish did not affect the solder joint reliability of the TSOP-50 components.

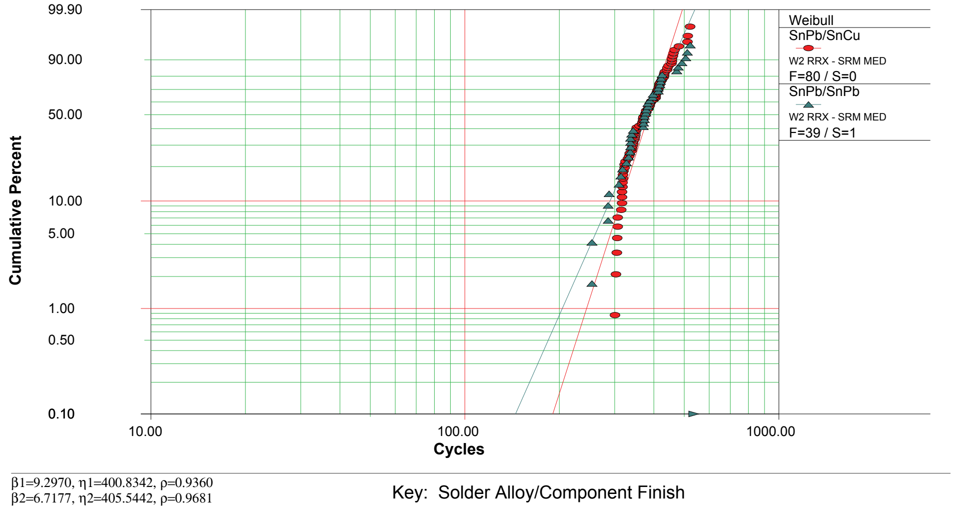

Figure 38 - Tin-Copper vs. Tin-Lead TSOP-50 with Tin-Lead Solder Paste on Rework Test Vehicles

Figure 39 contains the Weibull plots for all of the combinations of rework status, component finish and solder alloy for the TSOP-50 components on the rework test vehicles. Overall, the unreworked tin-lead soldered tin-copper and unreworked tin-lead soldered tin-lead TSOP-50 components performed better than the reworked TSOP-50 components. Reworked tin-silver-copper soldered tin-copper TSOP-50 components performed as well as reworked tin-lead soldered tin-lead TSOP-50 components. Reworked tin-silver-copper-bismuth soldered tin-copper TSOP-50 components performed the worst. Residual tin-lead solder left on the component pads appears to dramatically degrade the reliability of reworked TSOP-50 when soldered with the tin-silver-copper-bismuth solder.

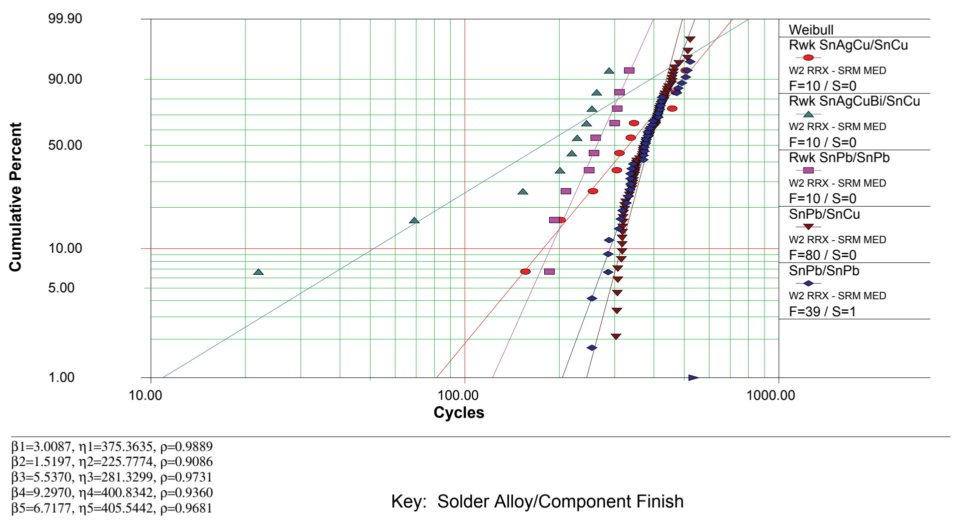

Figure 39 - TSOP-50 on Rework Test Vehicles

Hybrid Test Vehicle Results

The fifteen hybrid test vehicles were tested for 500 cycles. Failures detected at ten cycles or lower were excluded by team consensus. The team felt these early life failures were due to manufacturing or testing anomalies and the data should be excluded to prevent skewing the test results. One tin-silver-copper-bismuth soldered tin-silver-copper CSP-100 component failed during the second cycle and the datum was excluded from the Weibull analysis. The test vehicle failures were inspected for lead damage or broken wires. No wires or component leads were noted as broken on the hybrid test vehicles.

The failure data were segregated by component type, component finish and solder alloy and tabulated in Table 11. Test vehicles soldered with tin-silver-copper-bismuth solder had fewer solder joints fail (82 percent of the components registering as a failure). The test vehicles soldered with tin-silver-copper had the next best performance (92 percent of the components registering as a failure). Test vehicles soldered with tin-lead solder were the worst (100 percent of the components registering as a failure).

Table 11 - Failed Components by Component, Component Finish and Solder Alloy on Hybrid Test Vehicles

Component & Finish	Solder Alloy		
	SnAgCu Paste	SnAgCuBi Paste	SnPb Paste
CSP SnAgCu	100% (25 of 25)	100% (25 of 25)	
CSP SnPb			100% (25 of 25)
Hybrid SnAgCu	80% (12 of 15)		
Hybrid SnAgCuBi		53% (8 of 15)	
Hybrid SnPb			100% (15 of 15)
Grand Total	92% (37 of 40)	82% (33 of 40)	100% (40 of 40)

CSP-100 Results

Figure 40 contains Weibull plots of tin-silver-copper CSP-100 components soldered with lead free solders compared to tin-lead soldered tin-lead CSP-100 components. The plot shows the fitted line for the tin-silver-copper-bismuth solder crosses the other fitted lines making comparative analysis difficult and dependent on which part of the plots are used for the analysis. Based on ten percent cumulative failures, tin-lead solder performed best with tin-silver-copper-bismuth solder ranked second and tin-silver-copper solder ranked last.

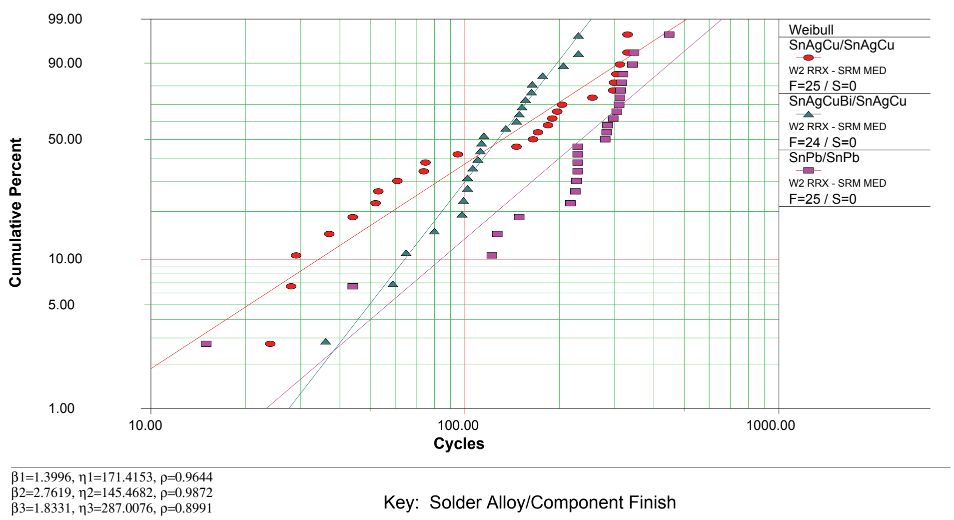

Figure 40 - CSP-100 on Hybrid Test Vehicles

Hybrid Results

Figure 41 contains Weibull plots of tin-silver-copper soldered tin-silver-copper and tin-silver-copper-bismuth soldered tin-silver-copper-bismuth hybrid-30 components compared to tin-lead soldered tin-lead hybrid-30 components. The plot shows tin-silver-copper-bismuth solder performed best, tin-silver-copper solder ranked second best and tin-lead solder ranked the worst.

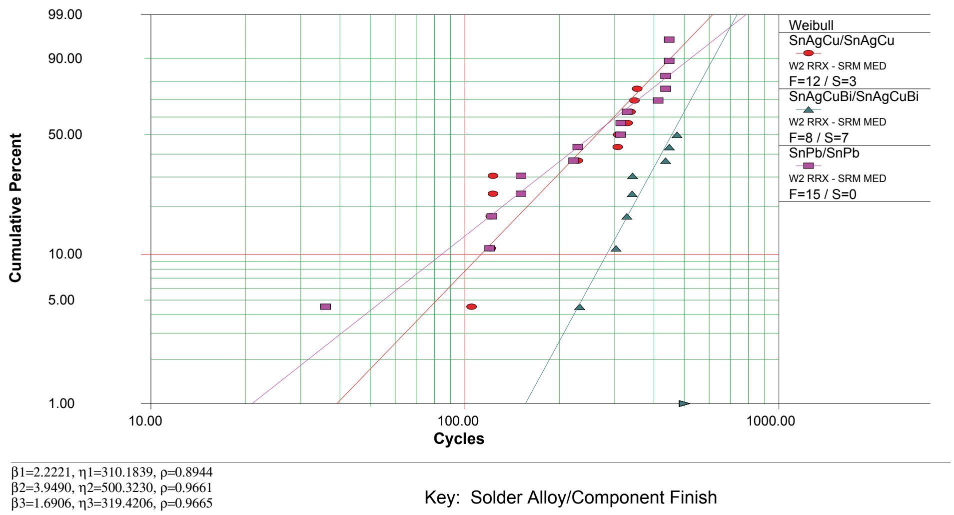

Figure 41 - Hybrid-30 on Hybrid Test Vehicles

Comparison of Manufactured and Rework Test Vehicle Results

The Weibull plots for tin-lead solder components on manufactured test vehicles were plotted with the Weibull plots of the unreworked tin-lead soldered components on rework test vehicles. The comparison was made to determine the effects of the differences in laminate materials and board surface finishes. The manufactured test vehicle boards were fabricated from high glass transition temperature laminate with immersion silver surface finish. The rework test vehicles were fabricated from relatively low glass transition temperature laminate with hot air soldered level surface finish.

The comparison of tin-lead soldered tin-lead BGA-225 components on manufactured and rework test vehicles is shown in

Figure 42. BGA-225 components on manufactured test vehicles were more robust than BGA-225 components on rework test vehicles.

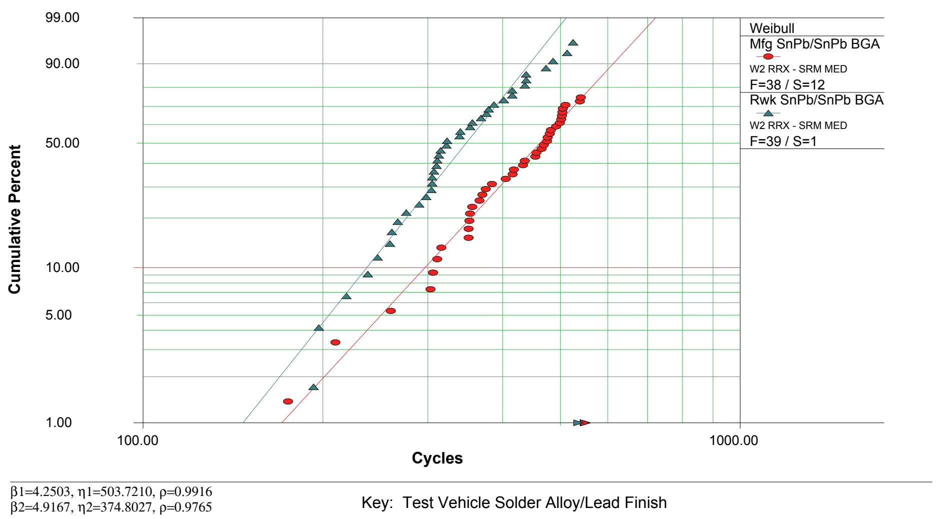

Figure 42 - Comparison of Tin-Lead Soldered Tin-Lead BGA-225 on Manufactured and Rework Test Vehicles

The comparison of tin-lead soldered tin-lead CLCC-20 components on manufactured and rework test vehicles is shown in

Figure 43. CLCC-20 components on manufactured test vehicles were similar in performance to the CLCC-20 components on rework test vehicles.

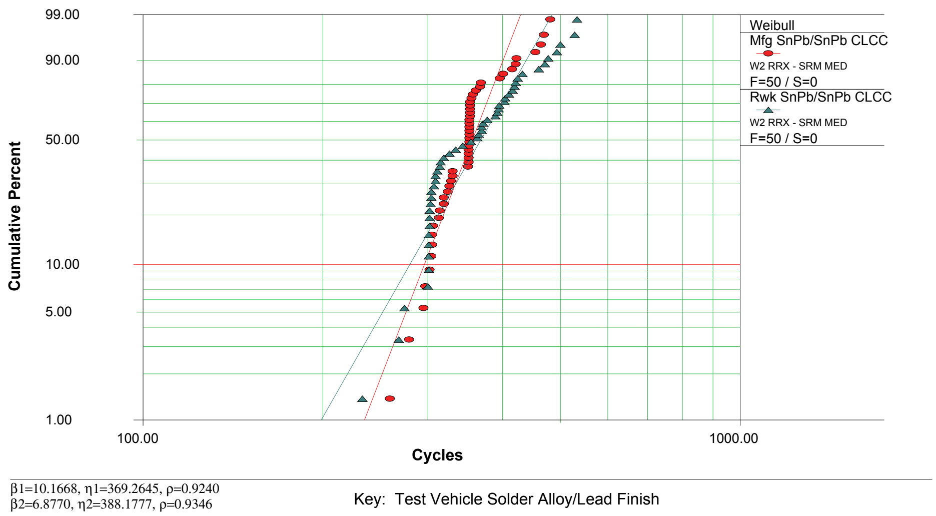

Figure 43 - Comparison of Tin-Lead Soldered Tin-Lead CLCC-20 Components on Manufactured and Rework Test Vehicles

The comparison of tin-lead soldered tin TQFP-144 components on manufactured and rework test vehicles is shown in Figure 44. TQFP-144 components on manufactured test vehicles were more robust than TQFP-144 components on rework test vehicles.

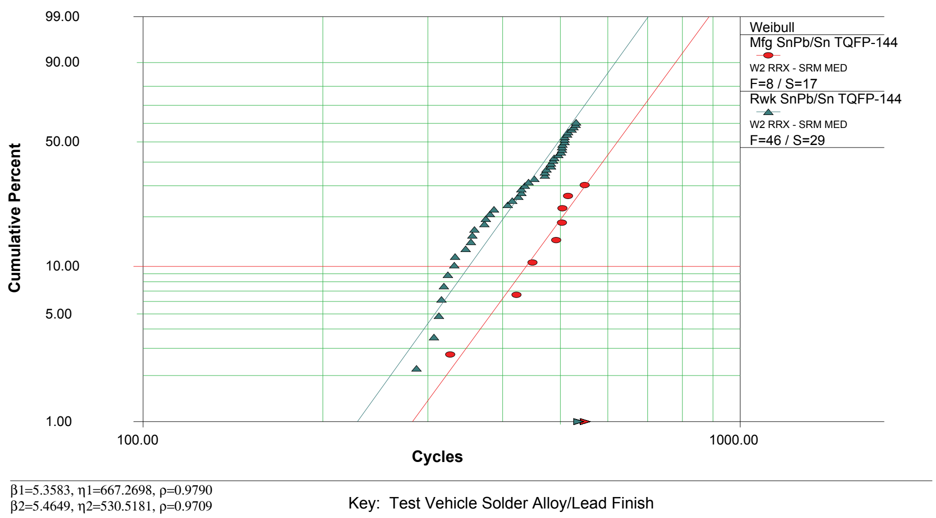

Figure 44 - Comparison of Tin-Lead Soldered Tin TQFP-144 Components on Manufactured and Rework Test Vehicles

The comparison of tin-lead soldered gold-palladium-nickel TQFP-208 components on manufactured and rework test vehicles is shown in

Figure 45. TQFP-208 components on manufactured test vehicles were more robust than TQFP-208 components on rework test vehicles.

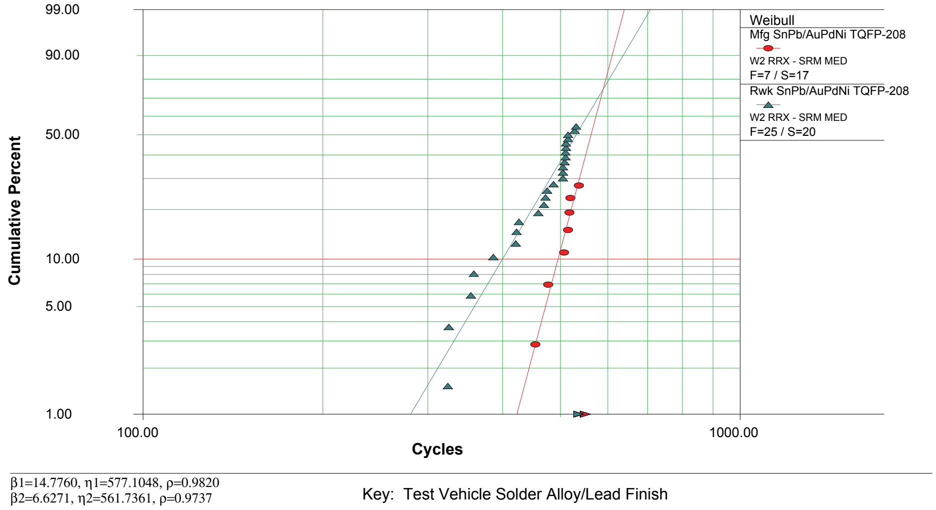

Figure 45 - Comparison of Tin-Lead Soldered Gold-Palladium-Nickel TQFP-208 Components on Manufactured and Rework Test Vehicles

The comparison of tin-lead soldered tin-lead TSOP-50 components on manufactured and rework test vehicles is shown in

Figure 46. TSOP-50 components on manufactured test vehicles were more robust than TSOP-50 components on rework test vehicles.

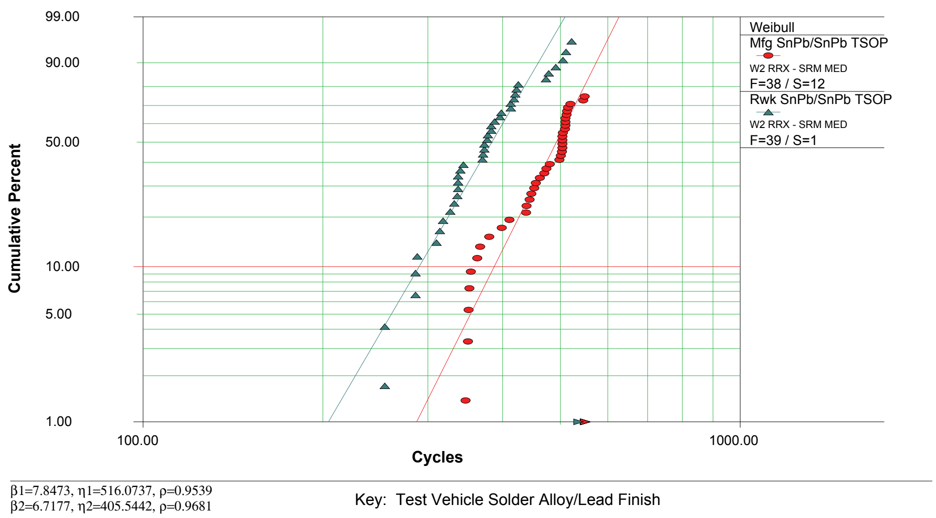

Figure 46 - Comparison of Tin-Lead Soldered TSOP-50 Components on Manufactured and Rework Test Vehicles

In general, the higher glass transition temperature laminate and immersion silver board surface finish appear to enhance the reliability of the solder joints.

Statistical Analysis

Additional statistical analysis was conducted on the manufactured test vehicle data using Statgraphics version 5 software. Variance component analysis was conducted and the software results are shown in Table 12 and graphically presented in

Figure 47. The analysis of variance table divides the variance of the cycles to failure into 5 components, one for each factor. Each factor after the first is nested in the one above. The goal of such an analysis is usually to estimate the amount of variability contributed by each of the factors, called the variance components. The factors included: solder paste; lead finish; component location along the x-axis (long axis of the board); component location along the y-axis; component type; plus unexplained error. The analysis shows that solder joint reliability was influenced by the choice of solder paste, but it was

probably less than either the choice of component or random noise. The analysis was only 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 or analysis. The analysis further shows that the influence due to lead finish or component location is very low.

Table 12 - Variance Components Analysis

Source	Sum of Squares	Df	Mean Square	Variance Component	Percent
TOTAL (Corrected)	1.31013E7	821			
Component	5.10579E6	6	850964	5985.63	35.02
Lead Finish	748189	5	149638	354.155	2.07
Solder Alloy	2.30537E6	18	128076	4182.98	24.48
X	1.152E6	106	10867.9	1028.77	6.02
Y	151403	29	5220.78	0.0	0.0
ERROR	3.63852E6	567	5538.08	5538.08	32.41

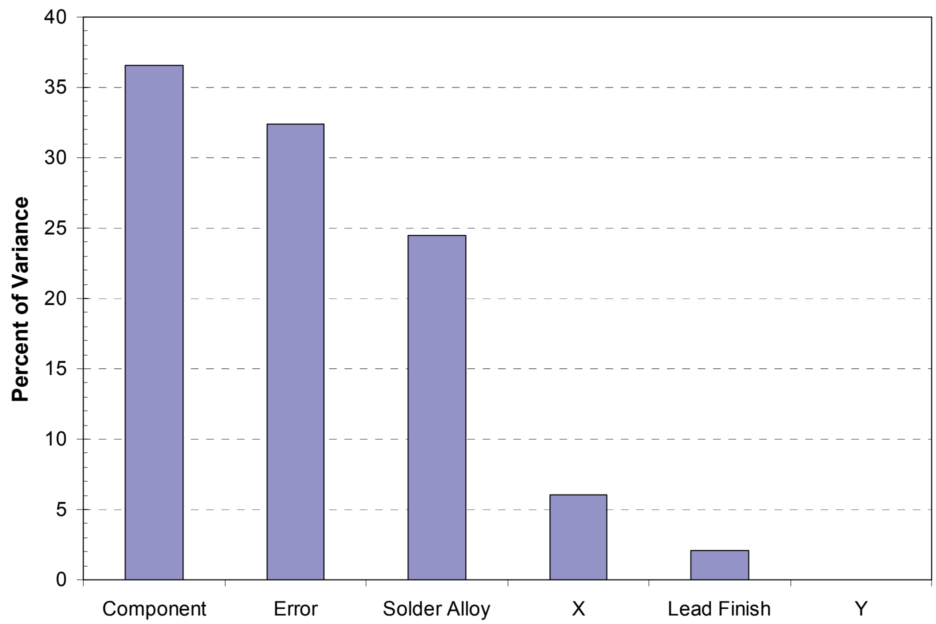

Figure 47 - Chart of Variance Components Analysis

Overall, the component type had 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 relative ranking of the different component types soldered with tin-lead solder is shown in
Figure 48. The plated-through holes, PDIP-20 and PLCC-20 components performed the best. The CSP-100 and hybrid components had the worst solder joint reliability in this evaluation.

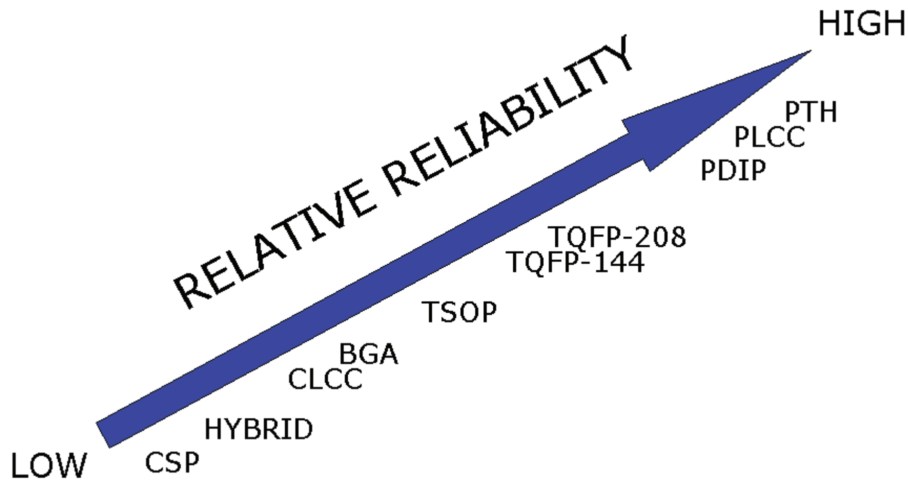

Figure 48 - Relative Reliability of Components for Tin-Lead Solder on Manufactured and Hybrid Test Vehicles

The solder alloy had a major secondary effect on solder joint reliability. In general, tin-silver-copper soldered components were less reliable than the tin-lead soldered controls. In general, tin-silver-copper-bismuth soldered components were more reliable than the tin-lead soldered controls with the exceptions of tin-lead BGA-225 components, tin-lead TSOP-50 components and reworked components due to the lead contamination in the solder joints.

The reliability of the lead free solder alloys compared to tin-lead controls is shown in
Figure 49. The graph summarizes the N (63%) values for the different component types; component finishes and solder alloys compared to the tin-lead controls. The shaded area of the graph shows the 95% confidence intervals for the tin-lead controls. Data within the bounded area indicate the lead free soldered components have similar performance to the tin-lead controls. Data outside the bounded area indicate the lead free soldered components have significantly different (better or worse) performance compared to the tin-lead controls. In general, tin-silver-copper soldered components had a higher failure rate than the tin-lead soldered controls. The components are listed from low to higher reliability. In general, tin-silver-copper-bismuth soldered components were more reliable than the tin-lead soldered controls with the exceptions of CSP-100 components, tin-lead BGA-225 components, tin-lead TSOP-50 components and reworked components due to the lead contamination in the solder joints.

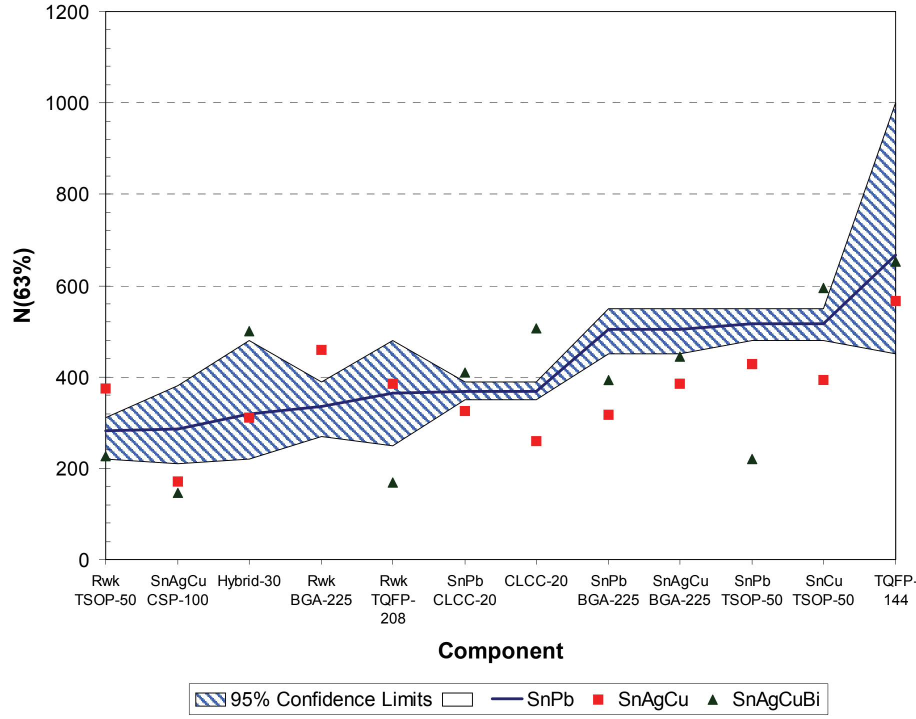

Figure 49 - Lead free Solders Compared to Tin-Lead Baseline Based on N(63%)

The reliability of the lead free solder alloys compared to the tin-lead controls based on N (10%) is shown in Figure 50 to aid in determining which lead free solders met the JTP acceptance criteria.

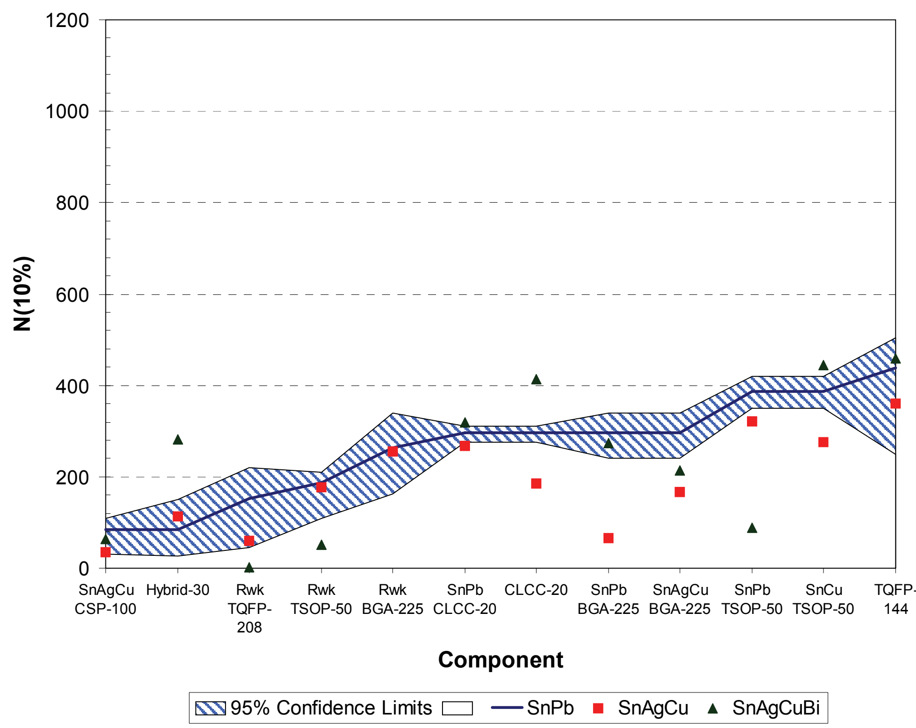

Figure 50 - Lead free Solders Compared to Tin-Lead Controls Based on N(10%)

Only seven lead free soldered samples met the JTP acceptance criteria of lead free solder joint reliability better than or equal to eutectic tin-lead controls at ten percent Weibull cumulative failures. The seven samples are tabulated in Table 13. Those samples include tin-silver-copper-bismuth soldered CLCC-20 components, TQFP-144 components and tin-copper TSOP-50 components on manufactured test vehicles, and tin-silver-copper-bismuth hybrid-30 components on hybrid test boards. The only tin-silver-copper soldered components that met the JTP acceptance criteria were the reworked BGA-225 on rework test vehicles and tin-silver-copper hybrid-30 on hybrid test vehicles. There were not enough failures of the more robust plated-through-hole parts to compare the performance of the tin-silver-copper and tin-copper solder alloys used in wave solder.

Table 13 - Samples Meeting the JTP Acceptance Criteria

Test Vehicle	Solder Alloy	Component Finish	Component Type
Manufacture	SnAgCuBi	SnAgCuBi	CLCC-20
Manufacture	SnAgCuBi	SnPb	CLCC-20
Manufacture	SnAgCuBi	Sn	TQFP-144
Manufacture	SnAgCuBi	SnCu	TSOP-50
Rework	N/A	SnAgCu	BGA-225
Hybrid	SnAgCuBi	SnAgCuBi	Hybrid-30
Hybrid	SnAgCu	SnAgCu	Hybrid-30

The component location on the test vehicle in the x-axis (along the long dimension of the board) and lead finish had minor effect on solder joint reliability. The component location relative to the y-axis had no effect on solder joint reliability.

Conclusions

Only seven lead free soldered components met the JTP acceptance criteria. Five of the components were soldered with tin-silver-copper-bismuth. The remaining two components were soldered with tin-silver-copper.

Overall, the component type had 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 solder alloy had a major secondary effect on solder joint reliability. In general, tin-silver-copper-bismuth soldered components were more reliable than the tin-lead soldered controls with the exceptions of tin-lead BGA-225 components, tin-lead TSOP-50 components and reworked components due to the lead contamination in the solder joints. In general, tin-silver-copper soldered components were less reliable than the tin-lead soldered controls. The lower reliability of the tin-silver-copper solder joints does not necessarily rule out the use of tin-silver-copper solder alloy on military electronics based on these results.

Overall, component location on the board and component lead finish had minor effect on solder joint reliability.

The effect of tin-lead contamination on the lead free solder alloy reliability was mixed. For tin-silver-copper, the effect of tin-lead contamination was minimal. There were small improvements in solder joint reliability on TSOP-50 components on manufactured test vehicles and reworked BGA-225 components on rework test vehicles. There was a slight degradation in solder joint reliability on BGA-225 on manufactured test vehicles and reworked TQFP-208 and reworked TSOP-50 on rework test vehicles.

For tin-silver-copper-bismuth solder alloy, the effect of tin-lead contamination was much greater. There was no effect on solder joint reliability on BGA-225 on manufactured test vehicles. There was a slight degradation in solder joint reliability on CLCC-20 components on manufactured test vehicles. There was major degradation in solder joint reliability on TSOP-50 components on manufactured test vehicles and reworked TQFP-208 components and reworked TSOP-50 components on rework test vehicles. The amount of solder joint reliability degradation appears to be inversely proportional to the amount of tin-lead contamination in the solder joint. Therefore, soldering with tin-silver-copper-bismuth solder requires precise control of the lead contamination. The level of control required may not be available to military depots and might pose an unacceptable risk to weapons systems. Therefore, the use of tin-silver-copper-bismuth solder may be precluded on some or all military electronics even though the alloy exhibits improved resistance to low cycle fatigue over the tin-silver-copper alloy.

In general, reworked components were less reliable than the unreworked components. This is especially true with reworked leaded components including the TQFP-208, PDIP-20 and TSOP-50 components. The exception was the reworked BGA-225 components. The reworked tin-silver-copper BGA-225 components were more reliable than even the tin-silver-copper soldered tin-silver-copper BGA-225 components on the manufactured test vehicles. This suggests the reworked BGA-225 components experienced higher processing temperatures from the hot air rework process which may have resulted in improved alloying between the component ball and residual tin-lead solder on the board pads (no additional solder was added in BGA-225 rework).

When comparing the performance of components on manufactured and rework test vehicles, the higher glass transition temperature laminate and immersion silver board surface finish of the manufactured test vehicle appear to enhance the reliability of the solder joints.

Based on the results of this test, few recommendations are proposed. The results of the CET should be compared to the results of the pure thermal cycling and vibration tests executed in the JCAA/JG-PP Lead free Solder Project. If the general results and conclusions are similar, then the CET might be used to accelerate the testing of future lead free solder alloys.

Further investigation in terms of destructive physical analysis and microsection analysis are recommended for the reworked components and in particular the lead free solder reworked U3 and U57 TQFP-208 components.

Since this test evaluated only solder joint reliability, additional tests must be done to validate assembly reliability with respect to the effect of higher reflow temperatures on printed circuit boards and functional integrated circuits. Additional testing on some functional military electronics is warranted.

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