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LEAD-FREE ELECTRONICS: RELIABILITY AND RISK MITIGATIONS

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ABSTRACT

The use of lead-free components in electronic modules destined for defense applications requires a deep understanding of the reliability risks involved. In particular, pad cratering, tin whiskers, shock and vibration, thermal cycling and combined environments are among the top risks. Testing and failure analysis of representative assemblies across a number of scenarios, including with and without risk mitigations, were performed to understand reliability of lead-free assembly approaches, in comparison with leaded and mixed solder approaches. The results lead to an understanding of lead-free reliability and how to improve it, when required. This outcome is resulting in user acceptance of lead-free electronics, which is timely given the increasing scope of lead-free legislation.

INTRODUCTION

Components with lead-free terminations have become the overwhelming majority of electronic device packages available for today's sophisticated computing systems. This is largely a result of the EU's RoHS and WEEE legislation that severely restricts the use of six substances, including lead. Industries whose product categories were directly included in the legislation have long since transitioned to lead-free assemblies. Other industries have been proceeding more slowly due to reliability concerns. The defense industry, in particular, is concerned about the reliability impacts to its systems because of their unique attributes (e.g. harsh environments, long life, mission/safety-critical, repairability).

The RoHS re-cast (aka RoHS2, enacted in 2011) has changed the rules of the game with respect to previous lead-free exemptions and product categories. A "catch-all" category has been introduced – "other electrical and electronic equipment not covered by any of the [other] categories" [1]. Defense equipment is still out of scope (by virtue of an exemption), but this is a notable change in that defense equipment is now recognized as a product category in the RoHS legislation. There are some thoughts that the defense equipment exemption, among others, could be removed in 2021 when the next general review of RoHS takes place. Dual-use COTS equipment could be pushed to lead-free even earlier depending on its non-defense uses. Either way, these changes accelerate the need to understand the reliability impacts of lead-free components and assembly, and determine which approaches may be more effective than others.

Currently, there are three fundamental approaches to dealing with lead-free components:

1. Leaded solder approach - Re-process lead-free parts (e.g. reball ball grid arrays, or BGAs) with tin-lead and solder with tin-lead.
2. Lead-free solder approach - Assemble lead-free parts with lead-free solder, e.g. SAC305 (tin-silver-copper solder alloy – 96.5% Sn, 3.0% Ag, 0.5% Cu).
3. Mixed solder approach – Lead-free BGAs soldered with tin-lead

The first two approaches are known as "pure" solder assembly methods, as there is no mixing of the two fundamentally different solder materials. The tin-lead approach (#1) is more costly because of the part re-processing, however solder joints are presumably brought to the heritage reliability of native tin-lead. The lead-free approach (#2) produces the relatively new lead-free solder microstructure, however much work has been done to understand and mitigate reliability risks, plus recurring costs are lower. The mixed solder approach attempts to get both the lower costs and high reliability, however testing at both the solder joint and assembly level has produced surprising results [2].

This paper will present test results for several of the top lead-free reliability risks. These risks have been outlined in reports generated by a group of deep subject matter experts known as the Lead-Free Electronics Manhattan Project (LFEMP) [3] [4]. This group has highlighted the many risks involved in dealing with lead-free components, not just with a lead-free assembly approach (#2 above) but also with mixed soldering (#3), and to a lesser extent, tin-lead soldering (#1). The LFEMP work, in addition to other sources [5], form the basis of any plan to address reliability concerns associated with the seemingly inevitable move to lead-free.

PAD CRATERING RISK

One of the highest risks associated with assembling lead-free components is pad cratering, which is the fracturing of printed circuit board (PCB) material underneath a solder pad due to a bending mechanism (e.g. assembly/test handling, mechanical shock, vibration, etc.). See Figure 1.

Pad cratering is an insidious failure mode because it can easily go undetected and is therefore a serious threat to long-term reliability. One of the main drivers of pad cratering is PCB materials with filler particles used to reduce the coefficient of thermal expansion (CTE). The fillers make the PCB material more brittle, thus pad cratering is an unintended consequence of mitigating for another lead-free risk (higher assembly temperatures). It should also be noted that pad cratering can and does occur on any of the three approaches described above (leaded, lead-free, and mixed).

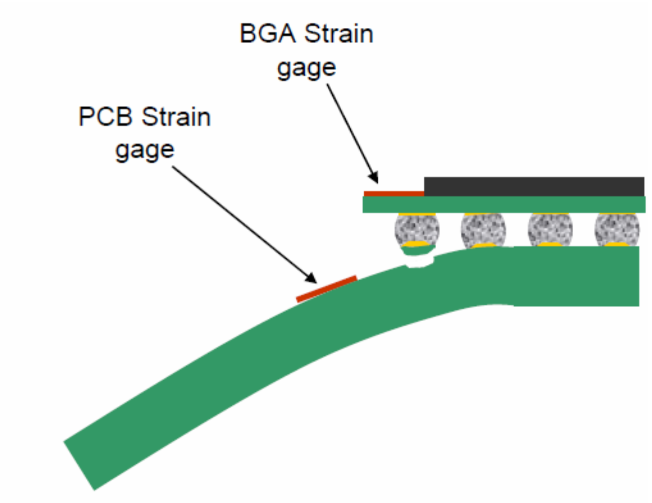

Figure 1: Diagram of pad cratering due to bending mechanism (exaggerated) – Courtesy: Universal Instruments

There are several risk mitigations available to deal with pad cratering, however representative assembly testing is required to determine which ones are more effective than others. Four-point bend testing is one such test approach, where BGAs soldered to PCBs are either stress tested or cyclically tested to failure. In this case, cyclic testing was performed with a 2.5 mm crosshead travel distance and 10 mm/s crosshead travel speed, producing a maximum deflection of approximately 3.35 mm at the center of the test board. Each BGA quadrant/corner was continuously monitored for electrical continuity. See Figure 2.

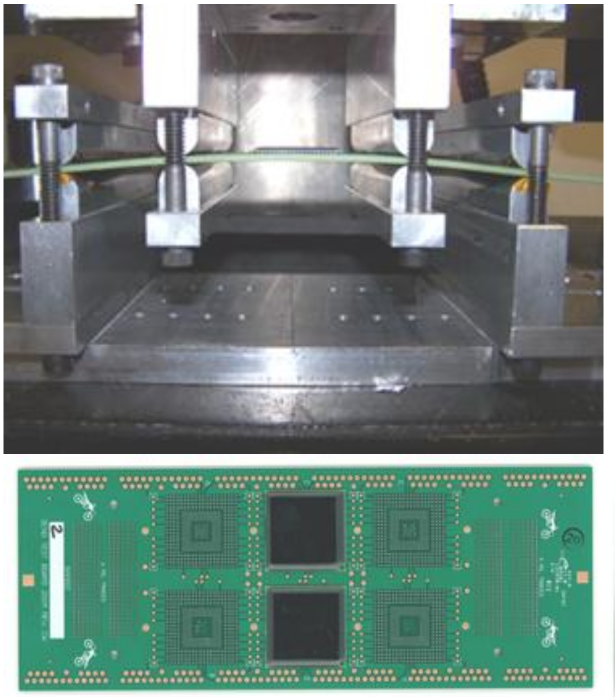

Figure 2: Four point bend testing apparatus and test vehicle – Courtesy: Universal Instruments

Four-point cyclic bend testing was conducted on two different pad cratering mitigations, and then compared to the base case of a standard PCB. The failure data for all three cases were plotted and a 3-parameter Weibull curve was determined to be a good fit to each data set (see Figure A1 in Appendix). The 3-parameter Weibull distribution is beneficial because it allows for extrapolation/calculation of a failure-free time (aka the Weibull distribution location parameter, γ). The results in Figure A1 show that one mitigation (#2) substantially outperformed the other (#1), with a failure-free life of 2317 cycles versus 875 cycles. Both mitigations were better than the standard PCB, which had a failure-free time of only 338 cycles. The clearly superior results for mitigation #2 have led to its deployment in CWDS lead-free assemblies. Mitigation #1 was used previously but has since been retired.

TIN WHISKER RISK

The tin whisker risk is likely the most notorious issue related to lead-free use in defense applications. Substantial strides forward have been made in the last several years in understanding tin whisker growth mechanisms, environments, and mitigations. Conformal coating plays an essential role as a risk mitigation, but there are also approaches such as lower risk component finishes and cleaning to be considered in an overall risk mitigation strategy [6]. Representative assembly testing is currently underway to compare the benefits of different mitigations on both leaded and lead-free assemblies. These results will be published at a later date.

VIBRATION

Random Vibration Testing

One of the harsh environments more unique to defense electronics applications is vibration. Sine and/or random vibration are often present on defense platforms and electronic modules and systems must be designed for and tested to these environments. In fact, there are multiple combined environments that need to be considered in addition to vibration (e.g. mechanical shock, temperature cycling, etc.); however these are beyond the scope of this paper. Work is being done to understand the reliability impacts of lead-free components in these combined environments.

Vibration testing has been conducted to understand the relative reliability of leaded, lead-free, and mixed solder approaches. A first test was part of a larger designed experiment investigating many lead-free reliability factors, including thermal cycling, different PCB surface finishes and the effects of various mitigations (e.g. edge bonding, underfill). A test vehicle was designed to be representative of CWDS product, and populated with representative component packages. Various samples were built for several different cases. Two assemblies were built and tested for each of the following vibration test cases:

a) Tin-lead HASL (hot air solder leveling) PCB finish, tin-lead component finishes (including BGA solder balls), tin-lead soldered (211-214°C peak reflow)
b) Immersion silver PCB finish, lead-free component finishes (including BGA solder balls), lead-free (SAC305) soldered (243-248°C peak reflow)
c) Electrolytic nickel-gold PCB finish, lead-free component finishes (including BGA solder balls), lead-free (SAC305) soldered (243-248°C peak reflow)
d) Tin-lead HASL PCB finish, lead-free component finishes (including BGA solder balls), tin-lead soldered (222-226°C peak reflow)

Figure 3: Random vibration test vehicle

Each assembly was subjected to random vibration with the following characteristics:

- Z-axis (perpendicular to plane of board)
- Constant PSD (power spectral density), 20-2000 Hz
- 0.04 g^2/Hz for 1.5 hours, then 0.1 g^2/Hz for 4 hours, then 0.2 g^2/Hz for 2 hours, for a total test time of 7.5 hours
- Failure detection of each component per IPC-9701 (Anatech event detector)

Cumulative failure times were recorded for each failed component on each assembly. As expected, the largest, stiffest component packages had the most failures. Figure A2 shows bar charts depicting and comparing the failure times for each of the failed component locations (shown as reference designators, U##). The average failure times of the two assemblies for each case are plotted.

Figure A2 shows that lead-free reliability can be substantially better than tin-lead or mixed solder approaches. The lead-free case with nickel-gold PCB finish is clearly the best combination. However, a deeper understanding is required as to why this case was the best. Failure analyses of each of the cases showed that many failures were due to pad cratering, either on the PCB side, or in the case of some of the ceramic packages, on the component side. Note that pad cratering mitigations were not applied on these test vehicles. Failure analysis of the lead-free case with nickel-gold PCB finish showed an unusual solder joint interconnect (see Figure 4, top photo), one that was affected by the nickel overhang typical of electrolytic NiAu finishes. It was surmised that these solder joints protected against early pad cratering failures due to a more compliant interconnect between joint and PCB pad, compared to the typical solder joint that encapsulates the solder pad (see Figure 4, bottom photo). The nickel-gold finish solder joints also resulted in taller solder joints.

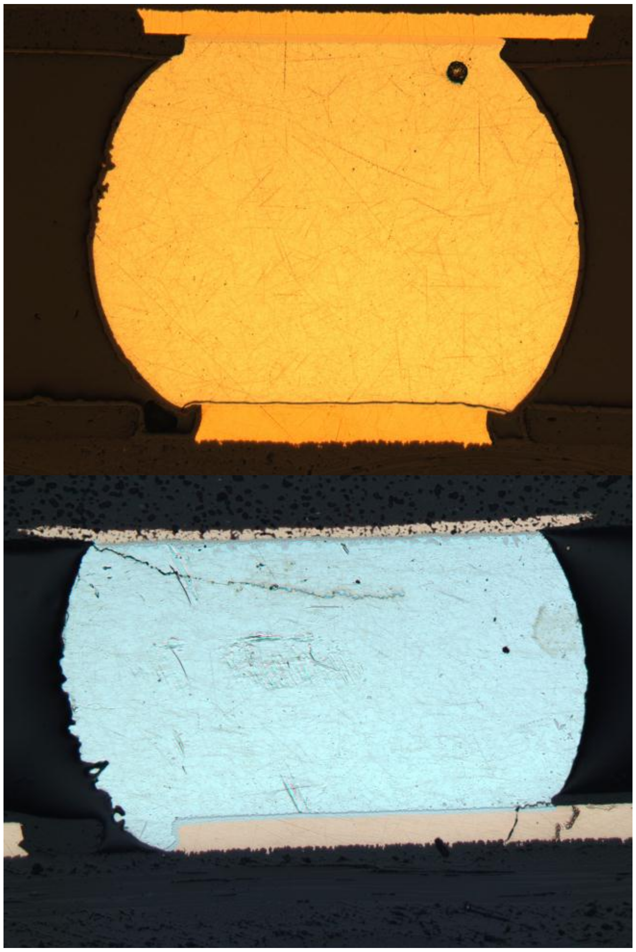

Figure 4: Random vibration test failure analysis photos – Top: Lead-free solder joint on NiAu PCB finish, Bottom: Lead-free solder joint on Lead-free HASL PCB finish (with trace crack and pad cratering) – Courtesy: Universal Instruments

Note that all the above random vibration testing was performed without mitigations such as edge bonding or underfill. Such mitigations are known to significantly improve vibration test results for any solder approach. Underfill, in particular, is known to provide the most improvement. However, it may not be sufficient on its own in some cases; for example, random vibration of a tin-lead electronics module caused pad cratering and required a combination of three different mitigations to overcome, including a non-reworkable underfill.

Sine Vibration Testing with Thermal Aging

Sine vibration testing results in better failure statistics than random vibration by virtue of its periodic nature, which allows for recording of stress cycles. A sine vibration test vehicle was designed to provide failure data for a variety of BGA components in order to compare the following two cases:

- Lead-free soldered assemblies with nickel-palladium-gold finished PCBs. The BGAs were lead-free (either SAC305 or SAC405) and the solder used was SAC305.
- Tin-lead soldered assemblies with HASL finished PCBs. Most of the BGAs for this case were originally lead-free but reballed to tin-lead by an approved reballer.

Figure 5 shows an assembled test vehicle and Figure 6 shows a sample assembly in the sine vibration fixture. The long edges of the assembly were clamped to provide the mode shape shown in Figure 7, in order to obtain similar displacements and stresses along each of the three curvature “folds”. Components of the same type along each of the “folds” could then be grouped together to provide more failure data for comparison. This approach was confirmed with accelerometer data from various points on the test vehicle.

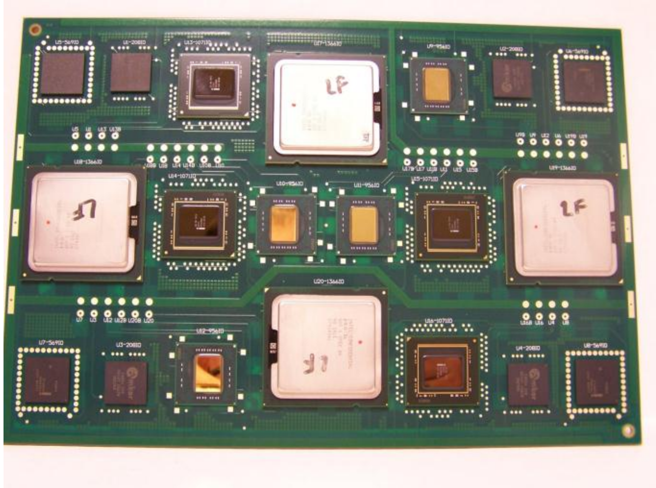

Figure 5: Sine vibration test vehicle

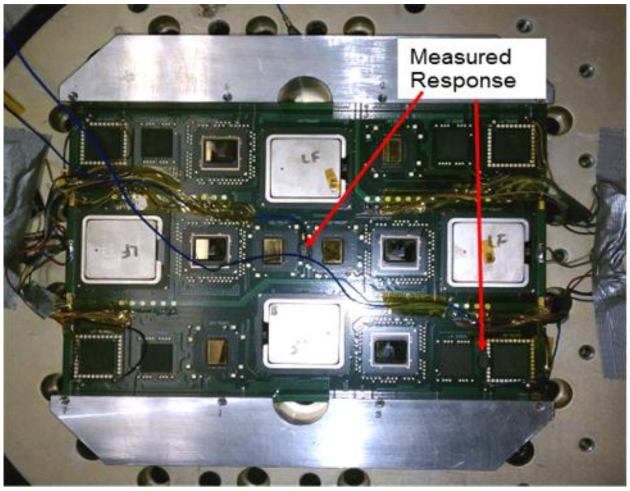

Figure 6: Sine vibration test assembly in fixture

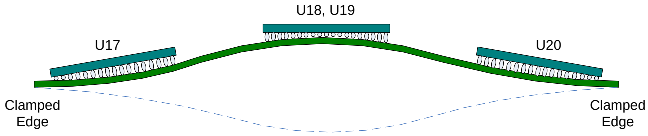

Figure 7: Resonant vibration mode shape of test vehicle (viewed from short edge)

Prior to vibration, each of the test assemblies was thermally aged for 500 hours at 125°C in order to test aged solder joints that may be similar those in storage or use for several years. The reason behind doing this was knowledge that lead-free SAC305 solder softens with aging and this has been shown to reduce performance in laboratory load-controlled shear testing [7]. Note that vibration testing is considered to be closer to displacement-controlled than load-controlled.

Three assemblies of each of the two cases were subjected to the following sine vibration parameters:

- 0.9 G input at the resonant frequency (159 Hz) for an output response of 38.7 G. This level was calculated to provide approximately 0.015” of deflection along the centerline of the board.
- Subsequent output responses of 45G, 50G, and 60G with corresponding calculated deflections of 0.0174”, 0.0196”, and 0.0236”, respectively.
- Each step stress was applied for 4 hours for a total test time of 16 hours for each assembly.

Failure data was recorded and collected for several of the component packages. Unsurprisingly, components along the long centerline experienced the earliest failures. Some components along the other two curvature “folds” did not fail. Failure data was plotted, and 2-parameter Weibull lines were fit to the data, for those component groups for which there were at least 6 failures. There were three such groups:

1. The two largest BGAs along the centerline (U18, U19). The lead-free case had a characteristic life, or η (63.2% failure) of 1.6 x 10^6 cycles, and the tin-lead case had a characteristic life of 3.6 x 10^5 cycles.
2. The other two largest BGAs (U17, U20). The lead-free case had η = 2.16 x 10^6 cycles, and the tin-lead case had η = 3.07 x 10^6 cycles.
3. Two smaller BGAs along the centerline (U14, U15). The lead-free case had η = 4.7 x 10^6 cycles, and the tin-lead case had η = 1.3 x 10^6 cycles. In this case, it is also useful to compare the life at 1% failure since the two data sets did not have a similar Weibull slope. The lead-free 1% failure life was 5.7 x 10^5 cycles, and the tin-lead 1% failure was 1.9 x 10^4 cycles.

The above results were surprising since lead-free was expected to perform worse than tin-lead under vibration, especially after thermal aging. Unfortunately, failure analysis did not provide additional clues to explain this performance. The failures were difficult to find and those that were found were fine cracks in the bulk solder. Also, there was little pad cratering (note that pad cratering mitigations were in place). A possible explanation for the better lead-free performance is that the 500 hour thermal aging caused softening of the solder and a resultant increase in ductility, which helped vibration survivability. Models are being developed in the industry to help understand and explain this behavior.

THERMAL CYCLING

Accelerated thermal cycling (ATC) is often used to understand and compare lead-free solder joint reliability to tin-lead and mixed solder approaches. Two ATC tests were run in parallel with the two vibration tests presented above.

ATC (-40/125°C)

The first test was ~3000 cycles of -40/125°C ATC (15 minute dwells) of 73 unique test cells comprising a large designed experiment. Significant failure data was accumulated for 49 of the test cells, but learning was also gained from the remaining test cells, for example application of an underfill material resulted in no lead-free component failures after 2895 cycles (when the testing was stopped on those components).

The test vehicle was the same as Figure 3 but with no added metalwork and connectors. Most of the packages tested were representative of parts used on CWDS electronic assemblies at the time (circa 2008) and consisted of the following:

- BGA208 from Practical Components
- CSP84 from Micron
- FS48 from Xilinx
- CBGA360 from Freescale
- CBGA1023 from Freescale
- PBGA1156 from Practical Components
- TSOP54 from Topline

Selected results are as follows (see Figure A3 for example Weibull plot):

- 7 of 7 component package types with tin-lead terminations passed the ANSI/VITA 47 C4 thermal cycling requirement (500 cycles of -55/105°C) at 1% failure rate when soldered with tin-lead solder. The PCB finish was tin-lead HASL.
- 6 of 7 packages with lead-free terminations passed the VITA 47 requirement above when soldered with SAC305 solder. The PCB finish was immersion silver. The failed package was the BGA208. Note that no pad cratering mitigations were in place.
- 4 of 7 packages with lead-free terminations passed the VITA 47 requirement above when soldered with tin-lead solder. The PCB finish was tin-lead HASL. The failed packages were: BGA208, CBGA360, and CBGA1023.

As expected, the tin-lead cases were the best performers given the relatively harsh thermal cycle; however the lead-free cases also did well. The mixed cases performed the worst and, combined with other data on mixed solder, this approach was prohibited from use on CWDS electronic modules.

Many other results were obtained from this test, however for brevity, only two additional ones are presented here:

- A comparison between the PBGA1156 package with native tin-lead solder balls versus one with lead-free solder balls replaced with tin-lead ones (i.e. reballed). Both cases were soldered with tin-lead solder and had tin-lead HASL PCB finish. The ATC results are very close as seen on Figure A4.
- A non-reworkable underfill was applied beneath all lead-free packages on a total of 6 lead-free test boards (3 with lead-free HASL PCB finish, 3 with electrolytic NiAu finish), for a total of 168 underfilled parts. No failures were seen on any of the parts after 2895 thermal cycles (when the test was stopped).

ATC (-55/105°C)

The second thermal cycling test presented in this paper was run in parallel with the sine vibration testing discussed above. Thermal cycling parameters were ~3000 cycles of -55/105°C with 30 minute dwells. The main objective of this test was to compare the reliability of lead-free assemblies to reballed tin-lead assemblies (same approved reballer as in the -40/125°C ATC test above). The reason behind this objective is that many current electronics devices are only available with lead-free terminations, leaving two assembly approaches (lead-free and reballed tin-lead), with the mixed solder approach having been excluded.

The test vehicle was the same as Figure 5. The packages tested were as follows:

- BGA208 from Practical Components (note: the reballed tin-lead case actually had native tin-lead solder balls for this package)
- FC-BGA569 from Intel
- FC-BGA1071 from Intel
- FC-BGA956 from Intel (note: the daisy chain on this part was non-functional, so periodic cross-sectioning was performed instead of resistance monitoring)
- LGA1366 from Intel (note: this part was converted to a BGA, SAC305 for the lead-free case, and eutectic SnPb for the reballed tin-lead case)

ATC results are as follows:

- All of the lead-free cases had better reliability than the reballed tin-lead (e.g. Figure A5 for FC-BGA569), except for one (the BGA208).
- The BGA208 package had a better characteristic life for the lead-free case, however the life at 1% reliability was worse (see Figure A6). Failure analysis showed that the two early failures in Figure A6 were interfacial failures between the bulk solder and component pad (see Figure 8). This type of failure had not been seen on any of the previous BGA208 packages tested, so was considered anomalous, and may have been caused by component pad defects from the manufacturer.

- All of the cases, both lead-free and reballed tin-lead, had acceptable reliability according to the ANSI/VITA 47 C4 requirement (500 cycles of -55/105°C), at 1% failure rate.

These ATC results were somewhat surprising given that tin-lead was expected to outperform lead-free in the harsh thermal cycling environment. However, the PCBs used for this experiment were representative of CWDS electronic assemblies at the time (circa 2010) and included the use of pad cratering mitigations. This appears to have improved the lead-free results relative to PCBs with no pad cratering mitigation. In addition, the solder balls on 3 of the lead-free BGAs (FC-BGA569, 1071 and 956) were SAC405 composition, which is known to be more reliable than SAC305 in ATC.

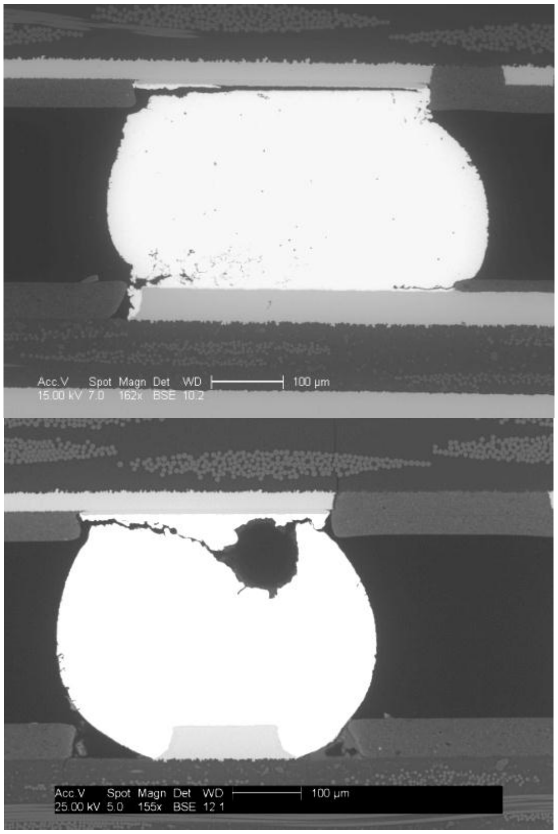

Figure 8: Cross sections of failed BGA208 solder joints (top – interfacial crack on early failure; bottom – bulk solder crack on typical failure)

CONCLUSIONS

Electronic modules required for today’s sophisticated defense systems rely heavily on commercial off the shelf (COTS) components. The majority of these components are only offered with lead-free terminations. Understanding and mitigating the risks posed by the use of these parts is essential to maintaining the high reliability required in defense systems. Several years of testing many different risk scenarios have shown that a lead-free assembly approach can be designed to achieve a high level of reliability. In particular, the following key risks required understanding and proven mitigations:

- Pad cratering
- Tin whiskers
- Shock & Vibration
- Thermal cycling
- Combined environments

Various mitigations are available for each risk, with some working well in more than one area, and others not working at all or less than expected. Testing of representative packages, PCBs, and assembly processes resulted in the confidence required to move forward with select mitigations in a lead-free approach for rugged, deployable electronic products. These results are leading to user acceptance of lead-free electronics.

Ongoing vigilance is required to ensure that high reliability continues to be achieved. As more experience is gained with lead-free, and new mitigations/approaches to dealing with lead-free components become available and are proven, electronics reliability will continue to improve.

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7. **Vikram Venkatadri, Liang Yin.** *Accelerating the Effects of Aging on the Reliability of Lead Free Solder Joints in a Quantitative Fashion.* Binghamton, NY : Universal Instruments, 2009.

APPENDIX

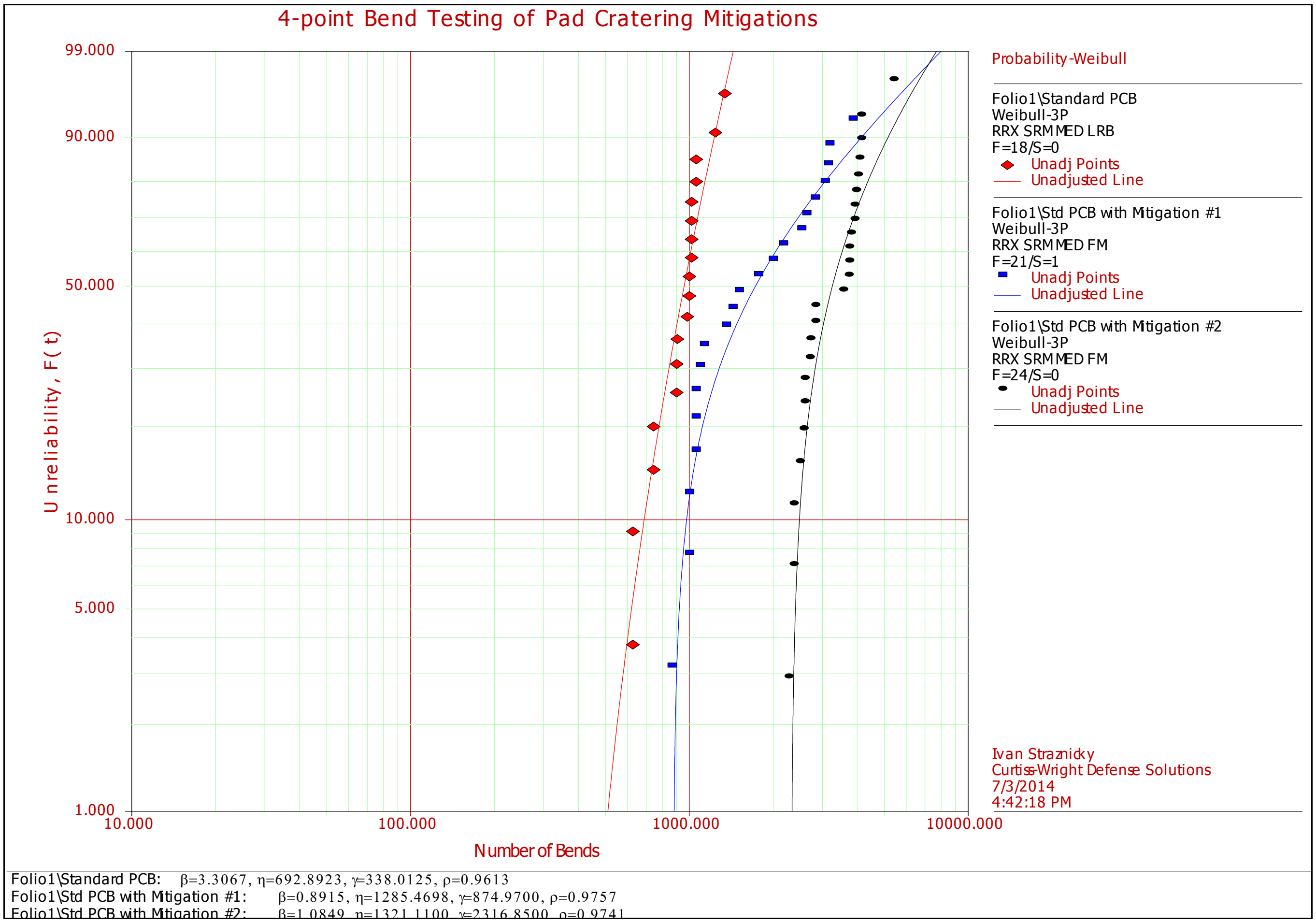
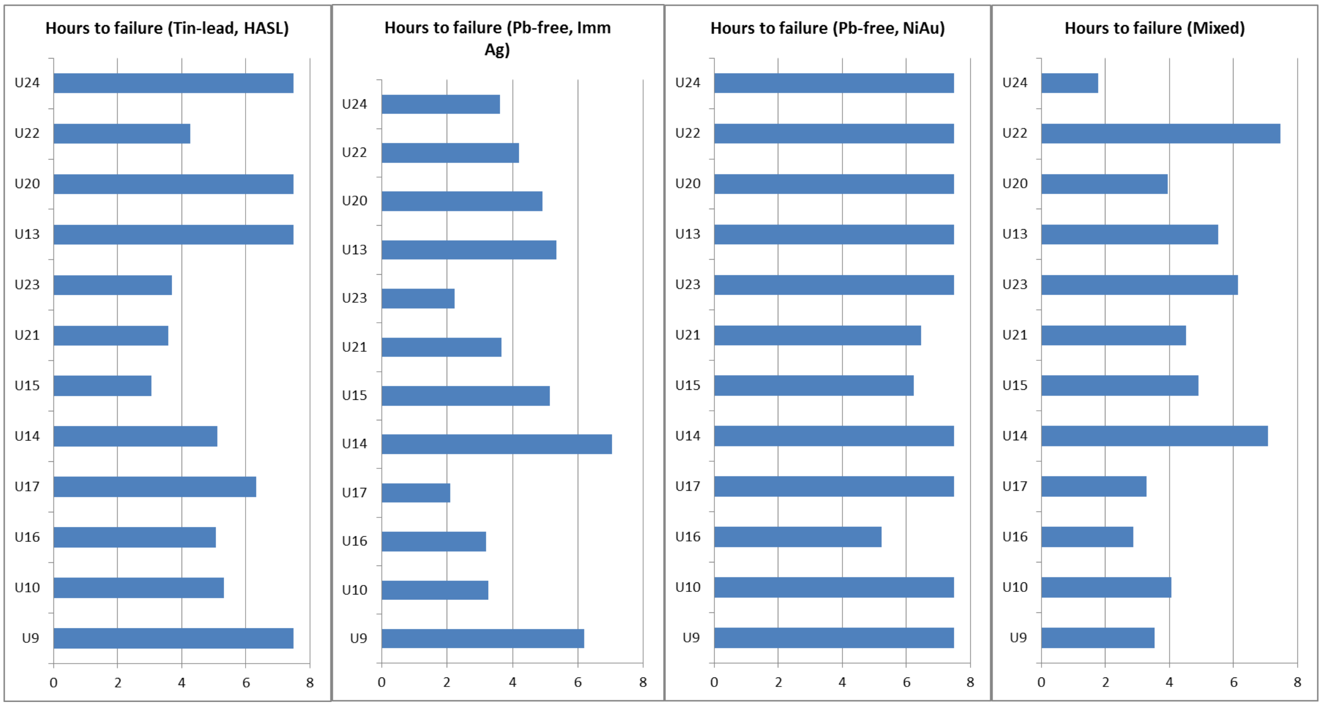


Figure A1. Four point bend test results for standard PCB and two different pad cratering mitigations.


Hours to failure (Tin-lead, HASL)

Hours to failure (Pb-free, Imm Ag)

Hours to failure (Pb-free, NiAu)

Hours to failure (Mixed)

Figure A2. Random vibration test results for four cases – Tin-lead solder with HASL PCB finish (6.59 hours average failure time); Lead-free solder with immersion silver PCB finish (5.93 hours average failure time); Lead-free solder with Nickel-Gold PCB finish (7.18 hours average failure time); Mixed solder with HASL PCB finish (5.91 hours average failure time).

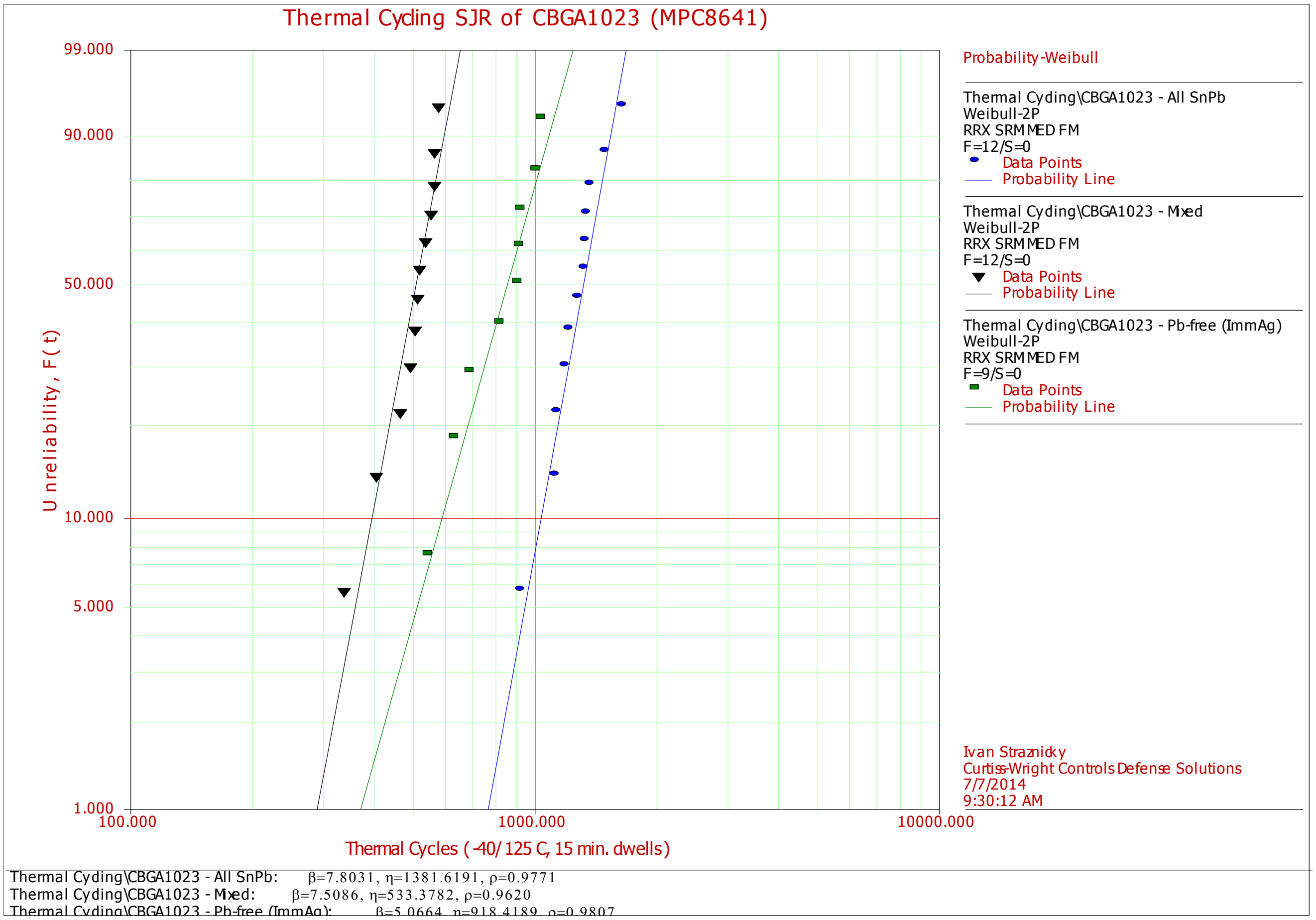


Figure A3. ATC results for tin-lead, lead-free, and mixed solder CBGA1023 package.

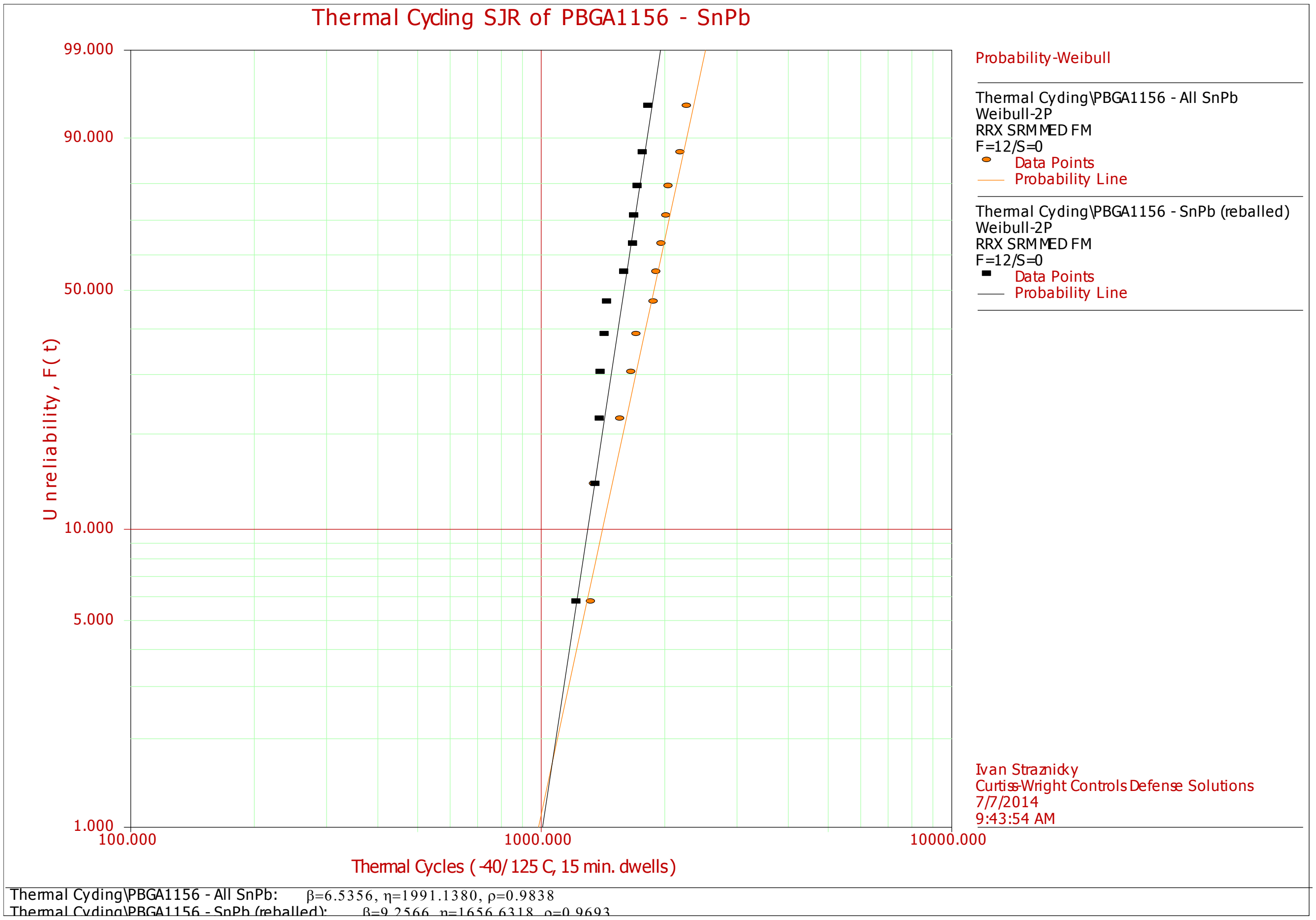


Figure A4. ATC results for native tin-lead and reballed tin-lead PBGA1156 package.

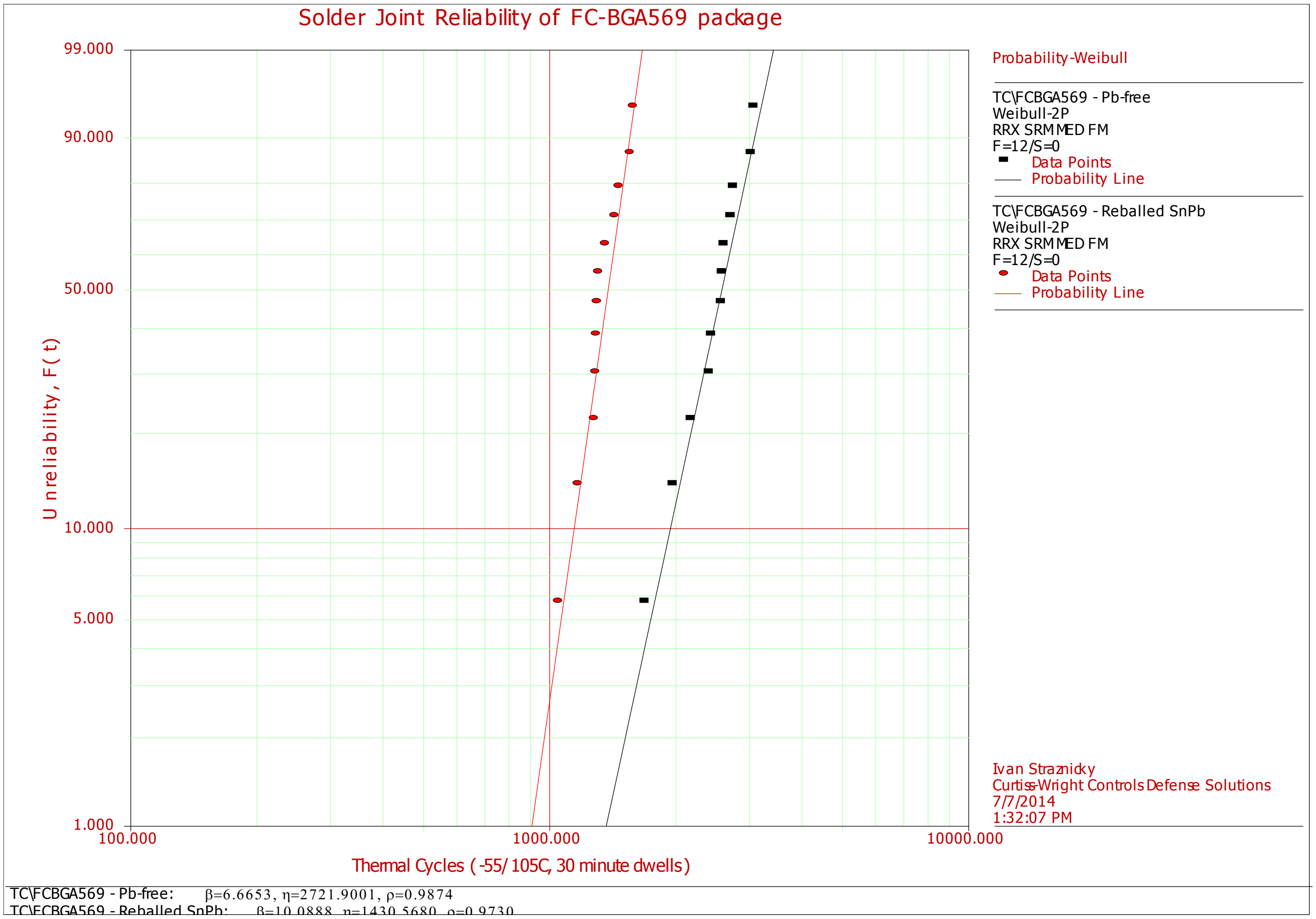


Figure A5. ATC results for lead-free and reballed tin-lead FC-BGA569 package.

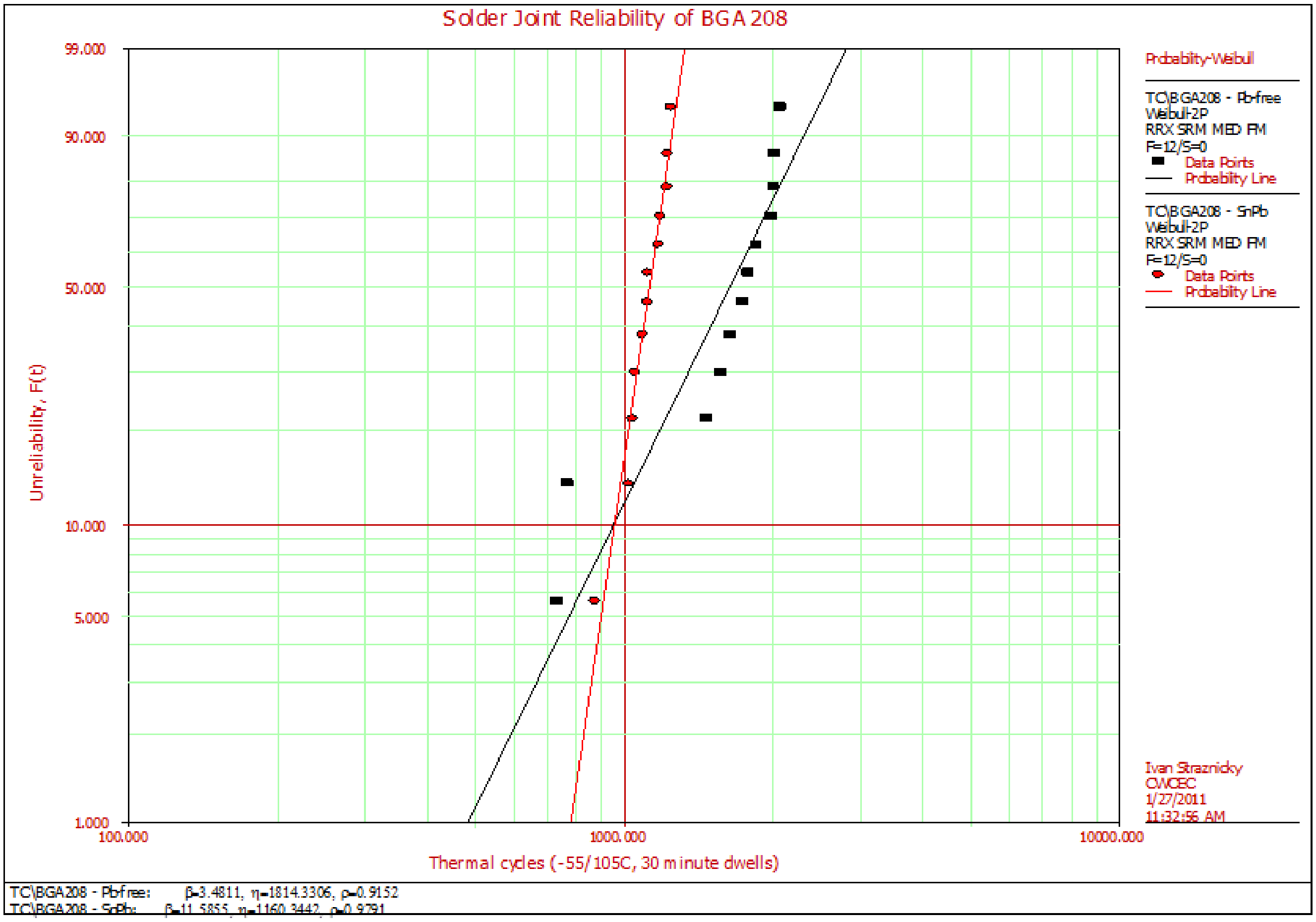


Figure A6. ATC results for lead-free and tin-lead BGA208 package.